REPUBLIC OF ZIMBABWE

MINISTRY OF LANDS, AGRICULTURE, WATER AND
RURAL RESETTLEMENT

SECTORAL REPORT B2: GROUNDWATER RESOURCES MANAGEMENT AND DEVELOPMENT

VOLUME 3

NATIONAL WATER RESOURCES MASTER PLAN

2020 - 2040

VisionRI

JUNE 2020

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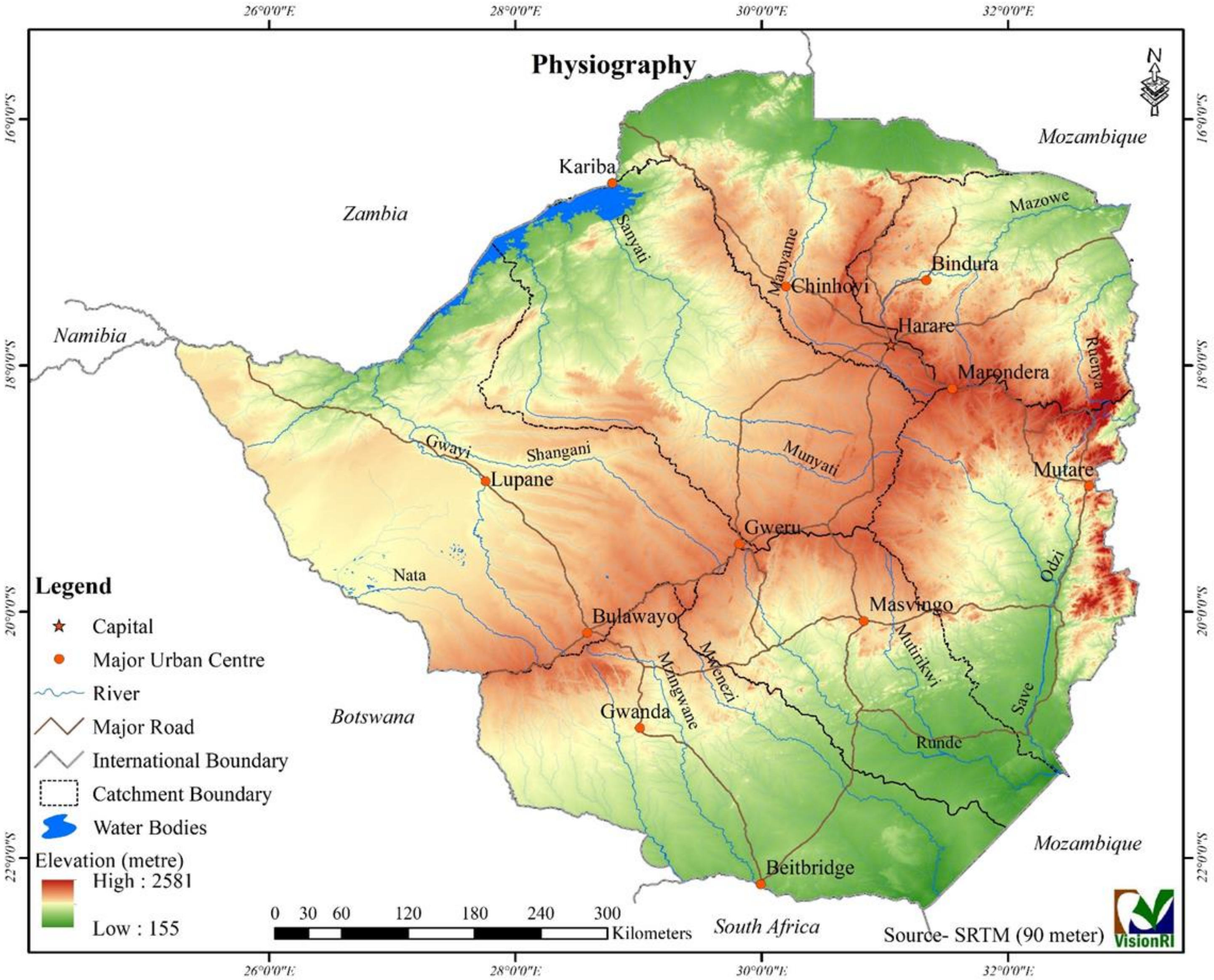
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Major Road
International Boundary
Catchment Boundary
Water Bodies
Elevation (metre)
High : 2581
Low : 155
0 30 60 120 180 240 300 Kilometers
Source- SRTM (90 meter)
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ABBREVIATIONS AND ACRONYMS

AHP	Analytic Hierarchy Process
AMD	Acid mine drainage
BGS	British Geological Survey
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CWD	Consecutive wet days
DDF	District Development Fund
EIA	Environmental Impact Assessment
EMA	Environmental Management Agency
GDE	Groundwater Dependent Ecosystem
GIS	Geographic Information System
GMI	(SADC) Groundwater Management Institute
HNP	Hwange National Park
IGRAC	International Groundwater Resources Assessment Centre
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
MEPD	Ministry of Energy and Power Development
METHI	Ministry of Environment, Tourism and Hospitality Industry
MLAWRR	Ministry of Lands, Agriculture, Water and Rural Resettlement
MODFLOW	(USGS) Modular Finite-Difference Flow Model
MSF	Médecins Sans Frontières/Doctors Without Borders
NAC	National Action Committee
NCU	National Coordination Unit
NGO	Non-Governmental Organisation
NIHR	National Institute of Health Research
NMPRWSS	National Master Plan for Rural Water Supply and Sanitation
NRZ	National Railways of Zimbabwe

NWRMP	National Water Resources Master Plan
RCP	Representative Concentration Pathway
RWIMS	Rural WASH Information Management System
RWSN	Rural Water Supply Network
SADC	Southern African Development Community
SAZ	Standards Association of Zimbabwe
TWI	Topographic wetness index
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children's Fund
USGS	United States Geological Survey
VLOM	Village Level Operation and Maintenance
WASH	Water, Sanitation and Hygiene
WB	World Bank
WRM	Water Resources Management
ZINWA	Zimbabwe National Water Authority

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The principal authors of the Master Plan were:

- John Rao Nyaoro, who was the Team Leader;
- Lovemore M. Zinyama, Deputy Team Leader;
- Ashenafi K. Amenu – Water supply, sanitation and hygiene;
- Joseph Chaumba - Gender and social inclusion;
- Edward Chikuni - Hydropower development;
- Lisben Chipfunde - Water quality and pollution control;
- Johannes Makadho - Agriculture and irrigation development;
- Hodson Makurira - Surface water resources/hydrology;
- Nelson Marongwe - Natural resources and environmental management;
- Arnold Moyo - GIS;
- Mosupatsila M. Nare - Legal, policy and institutional frameworks;
- Richard J.S. Owen - Groundwater resources/hydrogeology;
- Pushpendra Singh Rajpoot - GIS;
- J.P. Singh - Development economics;
- Leonard Unganai - Climate change;
- Sandra R. Zenda - Ecology and environmental flows; and
- Albert Muyambo – Large dams engineering

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The National Water Resources Master Plan is presented in the form of a Main Report, Catchment areas Plans along with an Executive Summary and 16 supplementary thematic reports on various aspects of the country's water resources management and development relevant to the Master Plan. The supplementary reports fall into 16 thematic/sector reports on the following:

- Socio-Economy of Zimbabwe;
- Surface Water Resources Management and Development;
- Groundwater Resources Management and Development;
- Climate Change Vulnerability of Water Resources;
- Water Resources Atlas;
- Water Supply, Sanitation and Hygiene;
- Agriculture and Irrigation;

- Energy and Hydropower Production;
- Flood and Drought Disaster Management;
- Dam Safety Management Guidelines;
- Gender and Social Inclusion;
- Land Use and Environmental Flows;
- Water Quality and Pollution Control;
- Policies, Legal and Institutional Framework;
- Water Pricing and Tariff Setting; and
- Water Resources Database.

EXECUTIVE SUMMARY

INTRODUCTION

Groundwater, a fundamental component of Zimbabwe's water resources: This thematic report seeks to provide an overview of the fundamental role that groundwater plays in the water supply of Zimbabwe. Due to the semi-arid climate and the single rainy season, for much of the year, most of Zimbabwe does not have surface water and groundwater is the only perennial source of water. Moreover, groundwater can be found almost everywhere in the country and is typically reliable and clean, thus providing the water resource base for the nation. It is difficult to imagine Zimbabwe without groundwater and it is the role of groundwater managers to develop, protect, and manage this vital resource sustainably so that the society and environment can continue to grow and flourish.

Groundwater demand: Groundwater in Zimbabwe is used throughout the country, particularly in the rural areas, it is a vital and irreplaceable resource for domestic and primary water supply, including livestock and the natural environment. Almost every rural Zimbabwean depends on groundwater for much of the year and its use is expanding rapidly in urban areas as municipal supplies decline. The importance of groundwater for Zimbabwe cannot be over-emphasised.

Groundwater resources: Much of the groundwater in Zimbabwe occurs in crystalline rocks that are typically low yield, low storage capacity local aquifer systems that are highly dependent on regular annual recharge by rainfall. There are extensive regional sedimentary aquifer systems in Zimbabwe, but these occur in the peripheral areas around Zimbabwe's borders where the population densities are low and demand is correspondingly low.

Groundwater threats: Groundwater in Zimbabwe faces multiple threats. These include significantly reduced recharge due to climate change, leading in time to aquifer depletion, massive increased urban demand due to the failure of municipal water supplies to keep pace with urbanization and deterioration of groundwater quality, especially in high population density urban environments.

Groundwater recharge: The rate of groundwater recharge frames the long-term sustainable abstraction rate. The climate models developed for this National Water Resources Master Plan 2020-2040 predict that there will be a widespread reduction in annual rainfall combined with higher temperatures throughout Zimbabwe, leading to significantly reduced estimates of groundwater recharge, ranging from -3% for the Gwayi, and Manyame catchments to -38% for Mzingwane catchment.

Groundwater drought risk: The combination of widespread high and increasing groundwater demand, predicted reduction in recharge rates and low groundwater storage capacity of the aquifers combine to put Zimbabwe in the category of high to very high groundwater drought risk. Zimbabwe is ranked as the highest drought risk country in the SADC region. The capital city, Harare and its environs are particularly vulnerable (Villholth et al., 2013). Many boreholes in Harare are already seasonal or have dried up entirely, groundwater levels have declined significantly, and drillers are drilling ever deeper boreholes, despite the fact that almost no groundwater exists at these depths.

Management framework for groundwater in Zimbabwe: It is within this context that the groundwater resources of Zimbabwe must be managed and a key objective of this report is to provide guidelines and identify tools for sustainable groundwater management. At present, the national groundwater infrastructure is managed and maintained by the NCU, via its operational arm, the DDF. This is supported by the RWIMS online database which stores records of approximately 60,000 rural boreholes. The database provides timely information on the operational status of these rural water supply boreholes. The data in the RWIMS database is very focussed on groundwater infrastructure, including providing information on borehole breakdowns to maintenance crews from DDF. Most of the other groundwater infrastructure is in private hands and is owned and maintained by private individuals and entities.

Groundwater resources are managed by the Groundwater Division of ZINWA. The key management tool is the ZINWA groundwater database with approximately 24,000 records. This database contains data fields with hydrogeological resource information such as 'blowing yield', 'water strikes', 'static water level', 'abstraction' and so forth. But, with the exception of three well-fields, namely Nyamandlovu, Lomagundi, and Save, there is no monitoring data recording changes in the groundwater condition with time and use. Within the three well-fields, groundwater levels are monitored, but other critical data such as abstraction rates and rainfall are not monitored.

It may, therefore, be said that groundwater resource monitoring is functionally non-existent in Zimbabwe at present and the resource continues to be exploited without any significant monitoring of abstraction rates, water levels or water quality. There is no protection to ensure either resource sustainability or groundwater quality.

Key outputs of the groundwater thematic report: This report has collated the known information on groundwater resources in Zimbabwe, developed new maps to illustrate the distribution and quantification of the resources and present this information in a new and visual manner. The report further investigates the nexus between groundwater use and development, infrastructure maintenance, institutional roles, identifying some key issues and concerns for the sector. The key outputs from this study of the country's groundwater resources are:-

- Creation of a new suite of spatially explicit national groundwater maps that show aquifer productivity, groundwater recharge rates under present, and anticipated future climate, groundwater development potential (present and future climate), groundwater vulnerability to pollution, natural groundwater quality, and groundwater drought risk (present and future climates).
- Quantification of groundwater resources: Aquifer productivity (m) and groundwater recharge (mm/year).
- Catchment maps showing groundwater development potential and identification of proposed groundwater monitoring locations.
- Identification of priority aquifers with high development potential.
- Identification of key threats to groundwater resources.
- Identification of transboundary groundwater resources.
- Assessment of the impacts of climate change on groundwater in Zimbabwe.
- Institutional framework for groundwater management in Zimbabwe.
- Proposals for the development of a national groundwater monitoring network to be monitored at catchment and sub-catchment levels, while being maintained and analysed at the national level.
- Guidance for groundwater data capture, storage, and use.
- Key issues for groundwater pumping.
- Key issues and proposals for capacity development for the borehole drilling sector.
- Gender issues in groundwater resource management.
- Strategy for sustainable development and management of groundwater resources in Zimbabwe.

KEY FINDINGS AND RECOMMENDATIONS

A. Groundwater resources

i. Strengths and opportunities:

- The new suite of maps allows groundwater managers to appreciate the local groundwater conditions in a spatially explicit semi-quantitative manner for planning development and resource allocation. Using these maps as support tools, groundwater management can be carried out at the catchment level.
- Large extensive primary porosity aquifer resources with abundant groundwater resources are only found in the sedimentary formations around the sparsely populated periphery of Zimbabwe. The distances from the water demand are generally too far for economic exploitation. However, the Karoo aquifer to the north-west of Bulawayo has the potential to contribute significantly to that city's water supply at a moderate cost.
- The dominant rock types in Zimbabwe are secondary porosity crystalline rocks that have limited groundwater development potential. Nevertheless, there are natural conditions where locally high groundwater development potential does exist, and guidelines are provided for identifying such sites. Solar-powered pumping, with storage tanks, is an option for such high yield boreholes, which may then become nodes for local small-scale economic development.
- The installation of a national groundwater monitoring network will provide data for optimum use and sustainable management of groundwater and, if used wisely, may identify many positive opportunities for local groundwater development.

- Upgrading and prioritizing the ZINWA national groundwater database together with the capture of monitoring data and drilling logs will provide a better basis for groundwater development and sustainable management.

ii. Limitations and threats:

- A major threat to groundwater resources is in urban environments, particularly Harare, where demand for water significantly exceeds supply and the groundwater resource is close to exhaustion in certain parts of the city. Already many seasonal boreholes have dried up entirely, perennial boreholes are becoming seasonal, the water table has declined significantly, and drilling depths are deeper without finding any significant additional water. These conditions may rightly be called a crisis that needs urgent attention.
- Groundwater quality in high population density urban environments is becoming contaminated by human waste; and both salmonella and cholera have been identified in boreholes, for instance, in Budiriro, Glen View, and other high-density suburbs of Harare. Many residents in these areas prefer drinking borehole water to municipal water and the threat of water-borne disease outbreaks is high.
- The impacts of climate change are predicted to reduce groundwater recharge across Zimbabwe from -3% (Manyame and Gwayi catchments) to -38% (Mzingwane catchment).
- The RWIMS database records that 29% of rural water supply boreholes are already seasonal, and with the reduced groundwater recharge predicted due to climate change, even more boreholes are likely to become seasonal.
- The lack of borehole water level, water quality, and abstraction monitoring effectively means that there is insufficient information for groundwater managers to respond appropriately to these increasing adverse conditions.

B. Limitations of the institutional arrangements

- Groundwater resources management, through ZINWA, and the Catchment Councils and groundwater infrastructural installations and maintenance (NCU/DDF) are currently carried out by two different institutions in the rural areas. This can lead to blurring of boundaries between the roles and responsibilities of each of the institutions, duplication of activities and a possible tendency to unhealthy competition for resources and roles.
- ZINWA, the Catchment and Sub-catchment Councils are, in many cases, significantly under-resourced and this impacts on their capacity to manage the groundwater resources. There is limited understanding and culture of groundwater management.

C. Rural water supply

- Zimbabwe's rural water supply is fundamentally derived from groundwater resources. It is typically developed by drilling of boreholes and equipping these with the Zimbabwe model B bush pump. The RWIMS database records that approximately 50% of rural water points are not fully functional. The infrastructural cost and the downstream impacts on user communities of this high percentage of non-functioning water points are severe.
- Many recently drilled boreholes have limited lifespans (5 to 10 years) and this requires investigation as to the causes, review of the national drilling guidelines and capacity development in the borehole drilling sector. A significant increase in borehole lifespan will have a major positive impact on groundwater supplies.
- The Zimbabwe model B bush pump is well designed and very robust, but the proportion of non-functional boreholes is around 50%. Design modifications to the bush pump down-hole components would reduce the "down-time" for these pumps and increase their serviceability at the village level. Such innovations have the potential to significantly improve the functionality of the rural water supply network. Support for ongoing research on the down-hole components of the bush pump is recommended.

D. Strategy for sustainable groundwater management and protection in Zimbabwe

It is recommended that groundwater management be mandated and structured through the Groundwater Division of ZINWA but be devolved as much as possible to the local catchment authorities. The rationale for this is that groundwater flows tend to be slow and local, and this is best managed at a local scale.

The tools for management will include catchment groundwater maps as presented in this report, borehole positions (RWIMS), borehole yields and abstraction rates (estimated), groundwater level and water quality data from monitoring, seasonality of existing boreholes, and other relevant information.

When allocating permits, the local authority should make reference to all the available data such as mapped aquifer characteristics and recharge rates, borehole density, water demand, abstraction, monitored water levels and so forth, and allocate permits initially for a limited time period, particularly in water-stressed areas.

As the water level monitoring continues, the behaviour of the groundwater system will become much clearer, and it can be determined if the aquifer is being depleted or not. Groundwater management decisions can then be taken based on aquifer performance and the groundwater resource protected from depletion.

1. INTRODUCTION

1.1 INTRODUCTION

Groundwater in Zimbabwe is used throughout the country, particularly in the rural areas and is a vital and irreplaceable resource for domestic and primary water supply, including livestock. Almost every rural Zimbabwean uses groundwater every single day and its use is expanding rapidly in most urban centres as municipal supplies decline and become unsafe. Therefore, its importance cannot be over-emphasised.

However, much of the groundwater in Zimbabwe occurs in low yield, low storage capacity aquifers that are dependent on regular annual recharge by rainfall. Climate models predict that there will be a widespread reduction in annual rainfall combined with higher temperatures throughout Zimbabwe between now and 2040, leading to significantly reduced estimates of groundwater recharge, ranging from -3% for Gwayi and Manyame catchment areas to as much as -38% in the Runde catchment.

The combination of the widespread and growing demand for groundwater predicted reduction in recharge rates and low groundwater storage puts Zimbabwe in the category of high to very high groundwater drought risk. The map of groundwater drought risk (Villholth et al., 2013) for a future climate (IPCC SRES A1B scenario) shows that Zimbabwe is considered to be at a high to very high risk of future groundwater drought. It is within this context that the groundwater resources of Zimbabwe must be understood, developed, and managed for future generations. A key objective of this report is to assess the available resource, provide guidelines on its exploitation and identify tools for sustainable groundwater management.

The report is divided into eight chapters that provide a logical framework for national groundwater management and development.

Chapter 1 provides an overview of the content of the report, including:

- The structure of the report.
- An outline of strategies for the sustainable development of groundwater resources. These strategies focus on groundwater monitoring and groundwater data management and analysis to provide actual data on the changes that are occurring to the groundwater resource. Groundwater management can then proceed from an evidentiary basis of the changes taking place within the groundwater resources.
- The methodologies used for the preparation of this report. The report uses traditional methodologies such as literature reviews and analysis to obtain an understanding of the groundwater resources in Zimbabwe. In this review, the focus has been on the major aquifers in Zimbabwe which still have the potential for further development and on critical threats to groundwater especially quality deterioration and aquifer depletion.
- In addition, the study has employed GIS mapping with the Analytic Hierarchy Process (AHP) to construct new groundwater maps for Zimbabwe. AHP is a multi-criteria decision-making procedure that has been used to rank the various property input layers that combined constitute a means for mapping key groundwater variables such as annual recharge and groundwater volumes held in storage. These maps provide a spatially distributed semi-quantitative description of Zimbabwe's groundwater and they are a new addition to the suite of groundwater information presently available in Zimbabwe.
- A description of the management framework for groundwater management in Zimbabwe and the institutions involved in groundwater management. This includes a chapter on the interactions between surface water and groundwater and a framework for conjunctive management.

Chapter 2 provides a description of the groundwater resources in Zimbabwe. It commences with a focus on priority aquifers in Zimbabwe. These are the major sedimentary aquifers in the north-west, north, and south of the country. Although these aquifers have significant development potential, they occur in the sparsely populated regions of Zimbabwe, often with poor soils and drier climates.

The central, most populated parts of Zimbabwe are dominated by shallow local crystalline basement aquifers with limited potential. Specific high yield boreholes tend to be associated with faulting, lithological contacts, jointing or local occurrences of limestone/dolomite. There is a section that discusses the three well-fields in Zimbabwe, namely Nyamandlovu, Lomagundi, and Save.

The opportunities and limitations associated with further development of the groundwater resources are assessed and presented. Large scale and widespread development of groundwater resources is not widely encouraged and the focus is rather on monitoring, optimal use, and sustainable management of Zimbabwe's limited groundwater resources.

Critical threats to the groundwater resources are assessed and anthropogenic pollution of the groundwater poses a long-term threat to the groundwater quality. Groundwater quality in Zimbabwe is, for the most part, good and potable without treatment. However, the urban environments, in particular, generate a heavy pollution load on the land surface, and hence the underlying groundwater, leading to groundwater contamination, which has been implicated in the endemic typhoid threat in some high-density suburbs in Harare.

In addition, over-pumping of the aquifers in the urban environments, especially Harare, has become common since municipal piped-water supplies do not reach many parts of the city, and the quality of municipal water in Harare is perceived to be poor.

Thereafter, the approach in this chapter has been to develop detailed spatially explicit maps for a variety of key groundwater properties. These GIS maps have been developed using a variety of input parameters such as rainfall, land use, aquifer characteristics, topographic wetness, and other relevant data to generate a suite of groundwater output maps such as aquifer productivity, groundwater recharge, groundwater development potential, aquifer vulnerability to pollution, geogenic groundwater quality, and groundwater drought risk. Some of these maps are quantitative, such as aquifer productivity, and groundwater recharge, while others such as groundwater vulnerability to pollution, and geogenic quality are essentially qualitative maps. The groundwater quality maps have been developed based on largely theoretical approaches since confirmatory groundwater quality data is very sparse.

These GIS maps, combined with groundwater monitoring, will provide a new basis for sustainable management of the groundwater resources.

Transboundary aquifers are also discussed in this chapter. This includes aerial images of irrigation or other, developments that use groundwater from these transboundary aquifer systems and thus represent abstractions from these aquifer systems. There is a semi-quantitative assessment of the downstream impacts of the abstractions from these transboundary systems.

Chapter 3 discusses the impact of climate change on groundwater resources. Groundwater resilience to the impacts of climate variability and climate change are introduced. Maps of the key climate change parameters are presented and their impact on groundwater recharge are investigated. Groundwater recharge rates under present climate conditions and a future climate change scenario are presented as quantitative spatially detailed maps. The groundwater development potential under the CSIRO 4.5 RCP climate change scenario is presented and compared with the development potential under the present climate.

The analysis indicates that climate change will tend to have a negative impact on groundwater resources throughout Zimbabwe. The Mzingwane catchment in the south-west of the country is expected to be the hardest hit. Groundwater recharge is modelled to decline everywhere, except for a small area in the extreme north-west. Higher temperatures suggest that demand for groundwater will increase. Villholth et al. (2013) suggest that the groundwater drought risk in Zimbabwe will be in the high to a very high category by 2100 and that Zimbabwe will be the worst affected country in SADC.

Chapter 4 provides a brief overview of the institutions that manage groundwater in Zimbabwe. The Ministry responsible for water resources is the parent ministry that has oversight of all water management in the country. The Zimbabwe National Water Authority (ZINWA), is a parastatal under the parent ministry that has executive responsibility for water resources management.

In addition, there is the National Action Committee (NAC), a multi-ministerial committee set up to provide oversight of the WASH sector. Traditionally, NAC has focused on rural WASH but has been re-branded to superintend over the three sub-sectors of Rural WASH, Urban WASH, and Water Resources Management (WRM). The National Coordination Unit (NCU), is the executive arm of the NAC. Within the context of this NWRMP, there is a specific sectoral report that deals with legal and institutional issues.

There is a brief discussion on current uses and future demand for groundwater. The Water and Sanitation sectoral report addresses current use and future demand in more detail.

The issue of groundwater management is considered in the context of the Integrated Water Resources Management (IWRM) framework. The interaction between surface water and groundwater is discussed and opportunities for conjunctive management of the total water resource are presented.

There are brief overviews of the borehole drilling sector and the pumping technology sector. Some qualitative observations are made with regards to improve the performances of these sub-sectors and with regards to assess new technologies that may be locally appropriate.

The issue of gender equality in the groundwater sector has also been addressed in this chapter and strategies have been proposed to improve the numbers and status of women with decision-making authority in the groundwater sector.

Chapter 5 is a review of proposed groundwater projects for implementation during the life of this Master Plan. Key amongst these is the development of a National Groundwater Monitoring Network. This network is designed to be operated at a sub-catchment and catchment level as there is a need to devolve groundwater management to a local level. Groundwater flows, especially in crystalline rock terrains, seldom travel over great distances and local groundwater management is the appropriate scale.

The storage, analysis and use of groundwater data in a National Groundwater Database is another critical project. For wise groundwater use and effective management, it is essential that groundwater information is adequately captured and stored, and then scientifically analysed, and data and information disseminated to groundwater managers and other stakeholders, and the general public so that an understanding of the groundwater resources is spread to both water managers and the citizens.

A project is proposed for the improvement of drilling skills and capacity in the country in order to reduce the number of boreholes that fail within a short time after completion. The project proposes the development of suitable regulations, combined with capacity development courses. In this regard, it is noted that a short course, targeted at the NCU, delivered by SADC Groundwater Management Institute (GMI) and sponsored by UNICEF has been mooted for 2019.

Chapter 6 provides an analysis of the training and capacity building requirements to support the strategy of sustainable groundwater management. These include "gender in groundwater" strategies.

Chapter 7 presents an analysis of the costs of the proposed projects and an economic assessment of their benefits to the country. The final chapter is a summary of the key findings and recommendations.

1.2 STRATEGIES FOR SUSTAINABLE GROUNDWATER DEVELOPMENT IN ZIMBABWE

1.2.1 Sustainable groundwater management setting

In developing a strategy for sustainable groundwater management in Zimbabwe, it is necessary to establish the key fundamental conditions that will impact on this objective. These can be listed very briefly as follows:-

- Zimbabwe is a semi-arid country with erratic rainfall that has a high coefficient of variability.
- On an annual basis, rainfall in Zimbabwe is always less than potential evapotranspiration in all parts of the country, such that groundwater recharge only occurs during short periods when rainfall temporarily exceeds evapotranspiration. Groundwater recharge typically occurs during periods of consecutive wet days (CWD) of usually five days or longer during the summer rainy season.
- The aquifers in approximately 65% of the country are typically surficial weathered regolith of crystalline basement rocks with limited storage and local extent. These areas are also the most densely populated. The high storage primary porosity aquifers occur where the population and groundwater demand are low.
- There is a high human dependency on groundwater. In the rural areas, the population depends almost entirely on groundwater, with surface streams drying up shortly after the end of the rains. The dependency on groundwater is also growing rapidly in the urban areas, and especially in the capital city Harare, where the municipality has failed for many years to provide adequate piped water to residents.
- Groundwater quality, particularly in the high population density areas of the major cities is under threat, with waterborne diseases increasing there. Groundwater quality analyses in these areas show that some

boreholes may be seasonally contaminated with bacteria such as typhoid and cholera and these diseases have become endemic.

- In contrast, groundwater quality in rural areas is generally good and borehole water is typically potable without treatment.
- Many boreholes are seasonal and the RWIMS database (with some 60,000 boreholes) indicates that 29% of all boreholes are seasonal. There is strong anecdotal evidence that boreholes are drying up earlier and earlier each year in high demand environments such as Harare.
- The combination of these factors has resulted in Zimbabwe, particularly Harare and its environs, being flagged as "high and very high groundwater drought risk" (Villholth et al., 2013.). Groundwater Drought Risk is defined as the condition when the groundwater resources no longer meet the established groundwater demand.
- Monitoring data on groundwater levels are very limited and are only available for three well-fields in aquifers that have been developed for irrigation: Nyamandlovu, Lomagundi, and Save.
- There is almost no data on groundwater quality, although some NGOs (e.g. MSF) are collecting data on urban bacteriological groundwater quality.
- Climate change is expected to impact negatively on the groundwater resource availability in Zimbabwe (Villholth et al., 2013 and this study).

In addition to these country-specific issues, there are a number of other issues that are common to groundwater management in every environment. These include the following: -

- Aquifer dimensions (saturated thickness and lateral extents) and properties such as porosity, specific yield, and hydraulic conductivity are highly variable in the natural environment.
- Groundwater recharge is highly variable, occurs sporadically, and is derived from a variety of sources such as e.g. rainfall, and streambed seepage. It may be a direct recharge from rainfall or a focused recharge via a fissure or other highly permeable sub-surface feature.
- Groundwater development takes place as many as thousands of installations and many of these are not mapped.
- Groundwater abstraction is at the discretion of many tens of thousands of borehole users, and the volume abstracted is not known and even estimates are very imprecise.
- There are many thousands of unmapped local point and non-point sources of pollution that may impact on groundwater quality.
- The impacts of groundwater abstraction and/or pollution are very local and do not extend far, unlike abstractions from rivers. This means that measurements made will not necessarily be relevant at even modest distances from the measurement point.

It is within this complex framework that groundwater needs to be managed sustainably. Sustainability is the condition when there is a balance between groundwater demand; both human and environmental and groundwater recharge from all sources. Groundwater balance may be expressed by the following equation:-

Inflow to the GW System = Outflow from the GW System ± Change in GW Storage

$$R_r + S_i + I_g = E_t + T_p + O_g + S_e + \Delta S$$

INFLOWS
R_r = recharge from rainfall
S_i = recharge from streambed seepage
I_g = inflow from other groundwater basins

OUTFLOWS
E_t = evapotranspiration from groundwater
T_p = groundwater abstraction / pumping
O_g = outflow to other groundwater basins
S_e = baseflow discharge to streams

STORAGE CHANGES
ΔS = change ± to groundwater storage.

While R_r – recharge from rainfall has been estimated by various studies and has been estimated in this study and S_e – discharge to baseflow has been estimated from river flow data by ZINWA (Blue Book) and in this study, the other terms are not known.

Several other terms in the equation are potentially very significant, such as local recharge via stream-bed infiltration, groundwater pumping and local evapotranspiration from groundwater at Groundwater Dependent Ecosystems (GDEs) such as “dambo” wetlands. However, quantitative estimations of the groundwater fluxes from these processes are not known and potentially vary significantly over time.

To prescribe a “sustainable” quantitative groundwater management strategy in the context of this data-scarce environment is irresponsible. This is, in fact, the hard reality of the groundwater knowledge in Zimbabwe.

1.2.2 Groundwater monitoring

In a data-scarce environment with an absence of hard quantitative information, the water authority is faced with the problem of how to go about establishing sustainable groundwater management. The approach recommended by IGRAC (International Groundwater Resources Assessment Centre) and also accepted by ZINWA is to establish groundwater level (and quality) monitoring networks at several scales. Such monitoring networks need to be wisely designed to supply the requisite amount of information at a minimum cost.

Groundwater monitoring may be variously designed to provide information on the resource availability, its quality, volume abstracted, rate of replenishment, changes in groundwater levels with time, and provide the information required towards sustainable management of the resource. The detailed design, function, and operation of a proposed groundwater monitoring network for Zimbabwe will be discussed in a separate chapter and this lies at the very heart of sustainable groundwater management.

1.2.3 Groundwater mapping

One of the key activities in compiling this sectoral report of the NWRMP has been to develop a suite of groundwater maps. These maps provide spatially explicit information on the groundwater recharge (mm/year), aquifer potential (meters depth of water in storage), vulnerability to (anthropogenic) pollution, and geogenic (natural) groundwater quality.

The groundwater resource is highly heterogeneous and varies from locality to locality. Moreover, groundwater flow is slow and transfers from one locality to another take place on a time scale of the order of decades, centuries or longer. Thus groundwater needs to be developed locally and ideally allocated locally at the sub-catchment level.

The value of these spatially explicit groundwater maps is that they allow catchment managers to gain a spatial appreciation of the nature and distribution of the groundwater resources within their catchment/sub-catchment. The maps also show the position and density of existing boreholes (as per RWIMS database), which may be taken, to some extent, as a measure of the demand for groundwater. Unfortunately, data on the volumetric abstraction of groundwater from these boreholes is not recorded and can only be estimated.

1.2.4 Groundwater management

The development of a suite of groundwater maps at the national and catchment level for the current climate and a future climate (CSIRO RCP 4.5 for 2020–2040) provides groundwater managers with a functional tool for the quantitative management of groundwater.

By combining the spatial hydrogeological information, the borehole density and the groundwater level fluctuations that will be captured by the monitoring network, groundwater managers will be able to develop an appreciation of the resilience of the resource under changing demand and climate conditions. This information then provides groundwater managers with guidance on the allocation of further groundwater resources, and by the continuous monitoring, the sustainability of the groundwater resource can be assessed and abstraction can either be increased or reduced, as needed, depending on the monitoring data.

1.3 METHODOLOGY – GROUNDWATER IN THE NWRMP

This sectoral report focuses principally on the physical aspects of groundwater availability now and under future climate scenarios and technical projects that may be implemented to ensure sustainable management of the groundwater resources. Other aspects of groundwater resources management such as the legislative requirements to create an enabling environment for optimal management, the institutional framework, demand and future development, financing needs for sustainable management and optimum development are addressed in other specific sectoral reports.

This groundwater sectoral report, therefore, focuses on the following: -

a. Resource description: Description of priority aquifers and critical threats, mapping and quantifying groundwater resources, groundwater quality, transboundary aquifers.
b. Impact of climate change: The resilience of groundwater to climate change and drought, groundwater recharge and groundwater development potential under present climate and future climate.
c. Groundwater management: Brief description of the various institutions that are involved with and have an impact on groundwater management in Zimbabwe.
d. Integrated water resources management framework as applied to groundwater management including:-

- Strategies for conjunctive management of surface and groundwater resources;
- Brief description of current uses and anticipated future demand;
- Groundwater infrastructure including the borehole drilling sector and groundwater pumping options; and
- Opportunities and strategies to improve gender participation in groundwater management.

e. Groundwater projects: Identification of key projects and activities to promote sustainable groundwater development and management in Zimbabwe. These include:-

- Establishment of a catchment/sub-catchment level groundwater trend monitoring network;
- Review and updating of national groundwater database and archives;
- Detailed analysis of groundwater data and identification of key gaps;
- Advocacy for greater public understanding and protection of the groundwater resource; and
- Development and implementation of ongoing training and capacity building for the groundwater sector, including scientists, managers, drillers, supervisors, and maintenance personnel.

1.3.1 Methodology

Literature review: The review of the groundwater resources in Zimbabwe is based on an intensive literature review of professional reports, academic publications, and expert knowledge. In particular, the major aquifers and key groundwater potential in Zimbabwe have been identified and described in detail. Critical threats to the groundwater resources have been identified, including both over-pumping leading to aquifer depletion and groundwater quality threats emanating from a variety of anthropogenic activities such as high-density urbanization, waste management and mining.

GIS mapping: Groundwater is spatially heterogeneous, varying significantly from locality to locality, with low flow velocities. As a result, a dispersed spatially explicit way of describing this heterogeneity is useful in providing a locally applicable framework tool for groundwater management. A suite of GIS groundwater maps has been developed in order to provide such a management tool. These maps have been developed by the following steps:-

- Identification of the various properties and parameters that are sub-sets of the groundwater resource. For example, these may range from aquifer porosity to rainfall; from topographic wetness index to geology, from land use to temperature.
- Review of which of these property/parameter data sets are available as spatial digitized national maps.
- Developing a framework for relating clusters of properties/parameters to specific groundwater outputs such as aquifer storage capacity and groundwater recharge and groundwater vulnerability to pollution.
- Using the Analytic Hierarchy Process (AHP) methodology for ranking/weighting each of the properties within each cluster of properties/parameters in terms of their relative impact on the groundwater output. For example, what is the relative weighting of rainfall as compared to land-use in terms of groundwater recharge?
- Using the AHP to assign a weighting to the GIS maps that constitute the input maps that are combined together to produce the output maps.
- The maps have been developed at a national scale and output maps are available at both national and catchment scale.

- The collected maps, both the input and the output maps, are combined in a Water Atlas that is one of the NWRMP outputs.
- The GIS format (QGIS) maps are to be made available as web-based maps so that they can be accessed and updated by the client.

The suite of groundwater maps allows a comprehensive view of groundwater resources in Zimbabwe and is a major step forward in terms of describing, mapping and quantifying groundwater resources in the country. A more detailed description of the methodology for the development of the groundwater maps is provided in Chapter 3 of this report.

Climate change: The impact of climate change on groundwater resources has been described within the GIS mapping framework described above. Climate change scenario CSIRO RCP 4.5 for the period 2020 – 2040 has been developed by the climate expert working on the NWRMP and this scenario provides a national spatial map on a 50 km grid of future mean temperatures, annual rainfall, and consecutive wet days.

These climate change parameters are used as input maps for future groundwater recharge, and future groundwater development potential under the specific climate change scenario. Aquifer productivity (groundwater in storage) is not expected to change as a direct result of climate change. If groundwater abstraction exceeds groundwater recharge as a result of climate change, then there will, in time, be an indirect impact on aquifer productivity.

Groundwater projects: A number of groundwater projects are recommended, arising out of this groundwater sectoral report. Key amongst these is the installation of a nation-wide groundwater trend monitoring network. In addition, at the catchment level, based on local information, additional defensive monitoring for groundwater quality and compliance monitoring with regards to groundwater abstraction is recommended.

Additional groundwater projects include: -

- The setting out of groundwater development plans for every sub-catchment and catchment;
- Revitalizing and renewal of the groundwater database and archiving systems to include the analysis of the data;
- Groundwater advocacy amongst all sectors of the population to ensure its safe use and sustainable management; and
- Training and capacity building programs for a variety of groundwater sectors.

1.3.2 Integrated Water Resources Management IWRM in groundwater management

The major part of this sectoral report focuses on a scientific description of the groundwater resources and the challenges facing the sustainable use of these resources. In this context, a review of how groundwater resources management has been envisaged within the framework of IWRM is presented. In addition to the core IWRM principles[1], all water should be managed as a unitary combined resource. Surface water and groundwater should be co-managed and there should not be separate management and a separate accounting of water resources between groundwater and surface water.

In Zimbabwe, the division of the nation into seven catchments and 47 sub-catchments for water resources management encompasses the philosophy of co-management of surface and groundwater resources. However, in practice, management of groundwater and surface water is often carried out independently without a clear understanding of the effects of abstraction and use of the surface water resource on the groundwater balance and vice versa. In reality, the use of water from any part of the hydrologic cycle will have a downstream impact on every other part of the hydrologic cycle, even if that impact is neither immediate nor obvious and such impacts may occur at some distance from the original disturbance. In water-scarce catchments, this can have negative consequences for sustainable water management and a wise investment in water resources development.

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[1] (https://www.futurelearn.com/courses/sustainability-society-and-you/0/steps/4626)

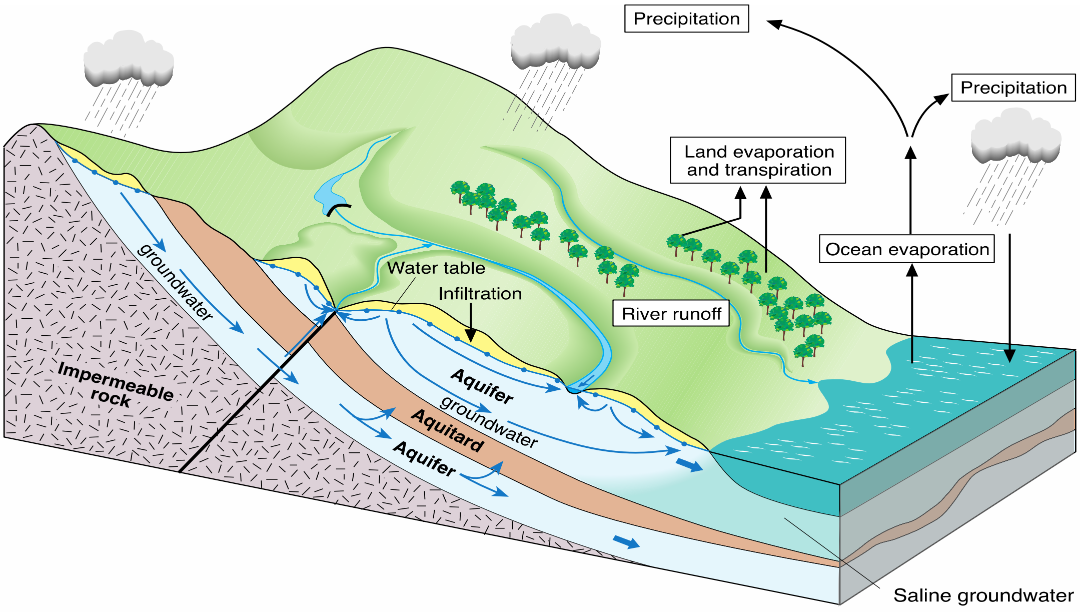


Figure 1: Hydrologic cycle showing inter-linkages between surface water and groundwater.

The hydrologic cycle (Figures 1 and 2) clearly shows some of the interactions between the surface and groundwater but it is less specific in guiding co-management. Integrated conjunctive management of surface and groundwater has lagged behind for various reasons:

- Institutional separation of groundwater and surface water management;
- Different knowledge and skill systems required for surface and groundwater management; and
- Aquifer systems do not always coincide with river basin boundaries.

As a result, groundwater management tends to receive less attention, except in arid and semi-arid climates where surface water is less available. There is a need to integrate groundwater and surface water management to ensure better overall water management and allocation.

This sectoral report highlights a variety of opportunities that exist for conjunctive use and integrated management of surface and groundwater resources. However, it should be noted that institutional integration lies at the core of such conjunctive management.

The idea of unified water resources management is often more complex in the water sector since there are so many varied stakeholders who wish for control over their water use. These include urban authorities, commercial agriculture and irrigation, natural resources and environmental agencies as well as domestic and livestock users.

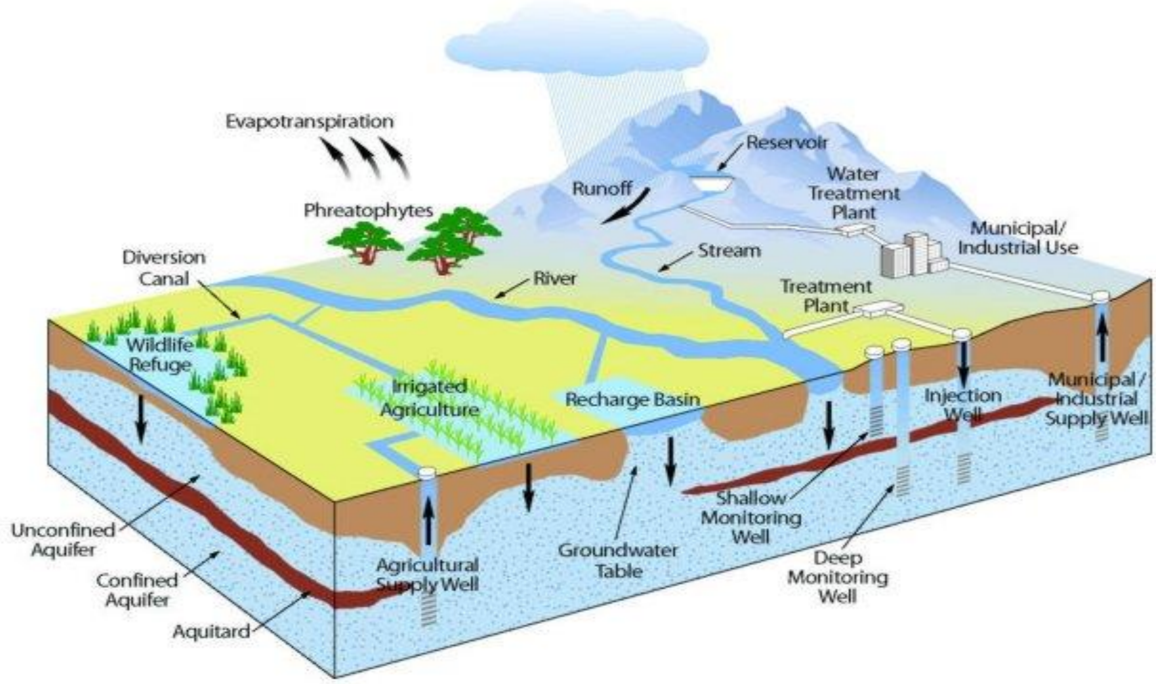


Figure 2: Interactions between surface water and groundwater.

Groundwater management is highly complex. There are multiple users with multiple wells and abstraction is not easily controlled by a central authority. The resource itself is complex and heterogeneous and its extent and properties are difficult to map and assess. The impacts of over-pumping can lead to long term or even permanent damage to the aquifer, but this may not be evident until irreversible damage has been done to the local groundwater resource. Users are not able to see aquifer depletion and may continue pumping for non-essential uses even as the resource is drying up.

If monitoring of water levels is carried out, it does not provide a clear picture of the wider impacts on the groundwater throughout the aquifer. In many instances, the professional skills to analyse and interpret groundwater data are lacking.

The illustration below (Figure 3) provides a comprehensive framework for groundwater management. The establishment of such a management framework needs to be carried out in coordination with surface water management instruments to achieve optimum water efficiency.

As suggested in Figure 3, groundwater management is complicated for a variety of reasons. Integrating its management into surface water management systems is a complex task that requires flexibility of approach as well as real information and data. In resource sparse economies, the failure of the groundwater system is often the first time that management measures are applied. Sometimes this can be too late, as in the case of saline intrusion and the resource can be lost to future generations.

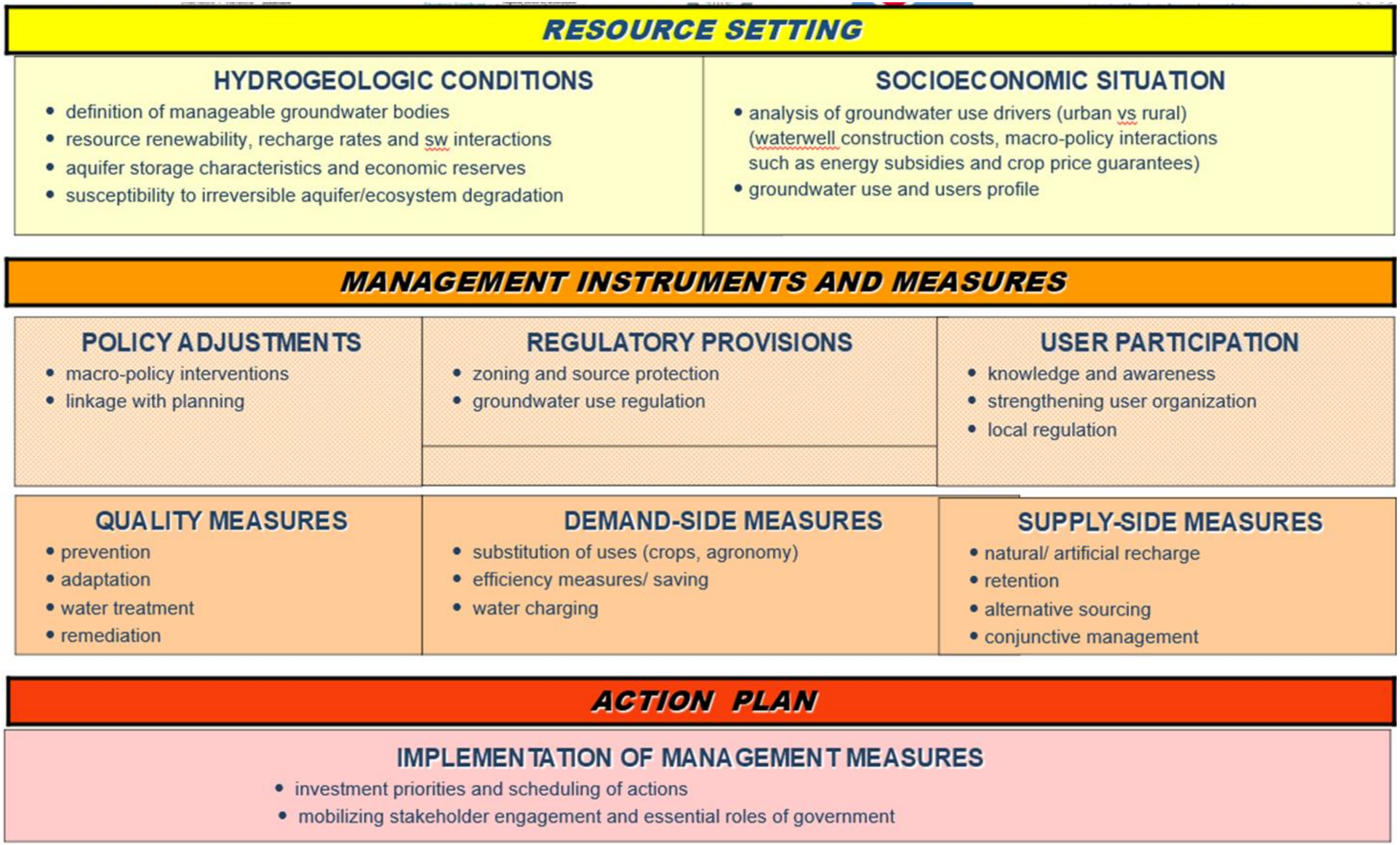
However, an analytical approach, backed up by focused groundwater monitoring, can provide early warning of impending threats. This requires foresight in terms of allocating funding to groundwater monitoring and adequate regulations to allow appropriate management instruments to be applied.

1.3.3 Conjunctive management

The conjunctive management of groundwater and surface water resources is a wise way of optimizing water resources. It requires a firm understanding of the timing, direction, and extent of various water fluxes, both surface and groundwater. Thereafter management allocations of different water resources can take place in order to minimize the volume of water that “goes to waste” either as evaporation or as run-off out of the catchment. This is often a case of appropriate timing so that surface water is used first during hot dry periods to reduce evaporation losses and groundwater might be artificially recharged during periods of peak flows.

The subject of conjunctive management is dealt with more fully in Chapter 4 of this report where a number of different conjunctive management options are presented.

In summary, the IWRM paradigm is equally applicable in groundwater management as in surface water management. It includes not just resource management but also the institutional, regulatory, and social issues that are embedded in the IWRM framework.



RESOURCE SETTING

HYDROGEOLOGIC CONDITIONS

- definition of manageable groundwater bodies
- resource renewability, recharge rates and sw interactions
- aquifer storage characteristics and economic reserves
- susceptibility to irreversible aquifer/ecosystem degradation

SOCIOECONOMIC SITUATION

- analysis of groundwater use drivers (urban vs rural) (waterwell construction costs, macro-policy interactions such as energy subsidies and crop price guarantees)
- groundwater use and users profile

MANAGEMENT INSTRUMENTS AND MEASURES

POLICY ADJUSTMENTS

- macro-policy interventions
- linkage with planning

REGULATORY PROVISIONS

- zoning and source protection
- groundwater use regulation

USER PARTICIPATION

- knowledge and awareness
- strengthening user organization
- local regulation

QUALITY MEASURES

- prevention
- adaptation
- water treatment
- remediation

DEMAND-SIDE MEASURES

- substitution of uses (crops, agronomy)
- efficiency measures/ saving
- water charging

SUPPLY-SIDE MEASURES

- natural/ artificial recharge
- retention
- alternative sourcing
- conjunctive management

ACTION PLAN

IMPLEMENTATION OF MANAGEMENT MEASURES

- investment priorities and scheduling of actions
- mobilizing stakeholder engagement and essential roles of government

Figure 3: Groundwater management framework

2. GROUNDWATER RESOURCES

2.1 INTRODUCTION

Groundwater in Zimbabwe is a widely used resource yet information about the resource remains sparse. Many of the key opportunities for groundwater development are not known, nor are many of the key threats. This chapter identifies these key opportunities and threats.

Most of these threats and opportunities have, by and large, arisen without the knowledge of neither the professional water managers nor the general public. Underpinning this lack of knowledge on the status of this critical water resource, lies a lack of proper collection, and management of groundwater information and a lack of monitoring of groundwater levels, abstraction rates and quality.

It may be cogently argued that this is the key threat, and the key priority is the institution of groundwater monitoring and the collection, archiving, and analysis of all groundwater data as it arises.

2.2 IDENTIFICATION OF KEY AQUIFERS

Zimbabwe cannot be described as a country rich in groundwater resources, and in fact, the reverse is true. It is to a large extent underlain by local shallow regolith aquifers that are developed on crystalline basement rocks, principally granites, gneisses, and greenstone-belt rock. These are secondary porosity aquifers of local extent and depth.

These basement rock aquifers constitute approximately 60% of the country and account for a mere 21% of the total estimated groundwater in storage (552 km^3), but 63% of estimated groundwater recharge (1,160 x 10^6 m^3/year – 4950 x 10^6 m^3/year) (Lamont Engineering, 1995). Nevertheless, there do exist significant opportunities to expand groundwater use in specified localities.

2.2.1 Primary porosity sedimentary aquifers

i. Karoo aquifers

The Karoo aquifers in Zimbabwe (in the northwest, the north along the Zambezi Valley, southeast and south of the country) cover approximately 84,000 km^2 and are estimated to hold 1,050 km^3 of groundwater in storage, which is 12 x 10^6 m^3/km^2. The Karoo aquifers are distributed around the periphery areas of Zimbabwe (Figure 4), in areas that are all generally sparsely populated which may explain why these aquifers have not yet been heavily exploited. The Karoo basins in the south-central aquifer were formed and filled with sediments during Carboniferous – Jurassic times. These basins were considered to have been formed by extensional and trans-tensional stresses during the break-up of the Gondwanaland super-continent.

As can be seen from the map (Figure 4), the Karoo in Zimbabwe consists of a number of sedimentary basins along the northern and the southern borders of the country. In the north, are the Middle Zambezi and the Cabora Bassa basins. In the south, are the Tuli and Save basins.

These are all significant sedimentary basins with really extensive aquifers, both unconfined and confined. The northern basins were formed under different tectonic regimes compared with the southern basins and this has resulted in differences in the nature of the sedimentary fill in the basins. The northern basins are a result of fault-rifting along the basin margins, while the southern basins are a result of crustal flexural movements.

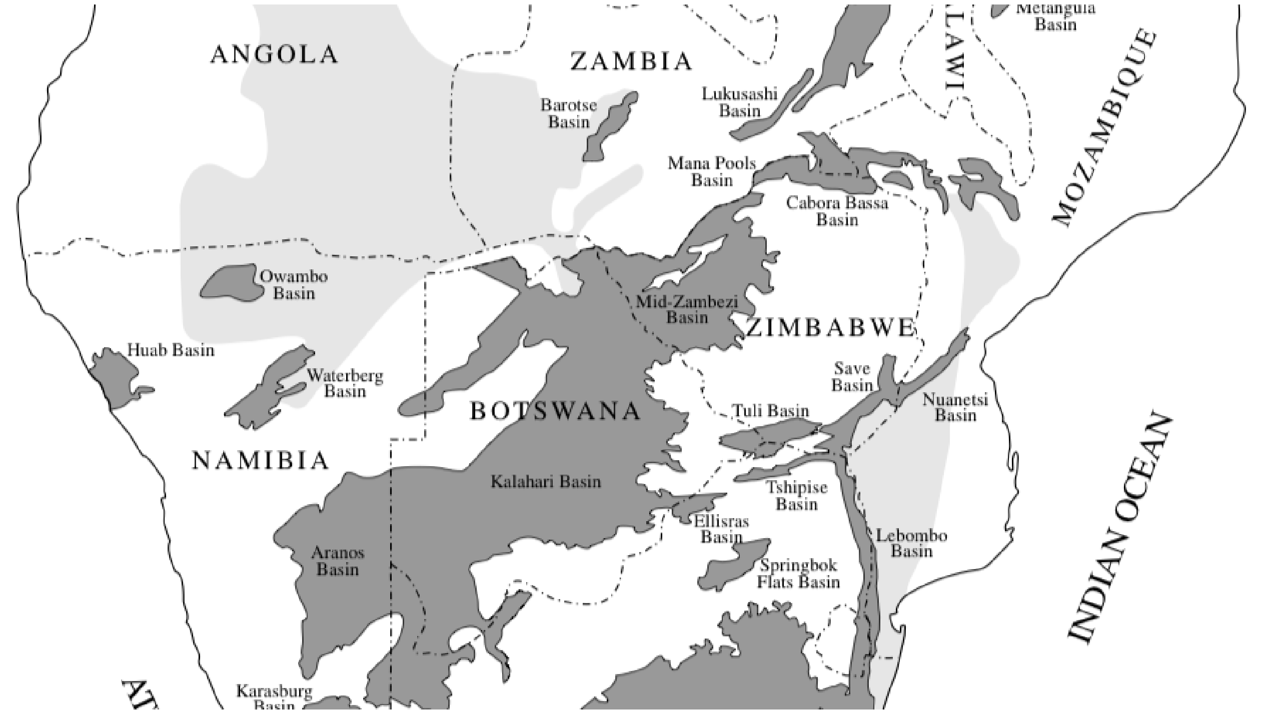


Figure 4: Karoo basins in Zimbabwe

Source: Catuneanu *et al.*, 2005

The stratigraphic sequence of the northern basins shows that they are quite coarse-grained and, therefore, likely to be productive aquifers. Figure 5 shows Karoo sediments more than 1000 m thick, with significant sandstone and coarse facies, especially in the Cabora Bassa Basin. These coarser sediments lie reasonably close to the surface, thus reducing development costs. These are, therefore, areally extensive, thick aquifers with favourable porosity and permeability properties. They are potentially very important productive aquifers.

It is, however, important to note that significant lateral variation in the nature of the Karoo sedimentary sequence does occur. Near the basin and sub-basin margins at fault displacements, productive aquifers with coarse clastic sediments occur as the proximal facies. Away from these basin and sub-basin margins, the sedimentary sequence is likely to be dominated by fine-grained distal facies sediments, and these are likely to be low permeability.

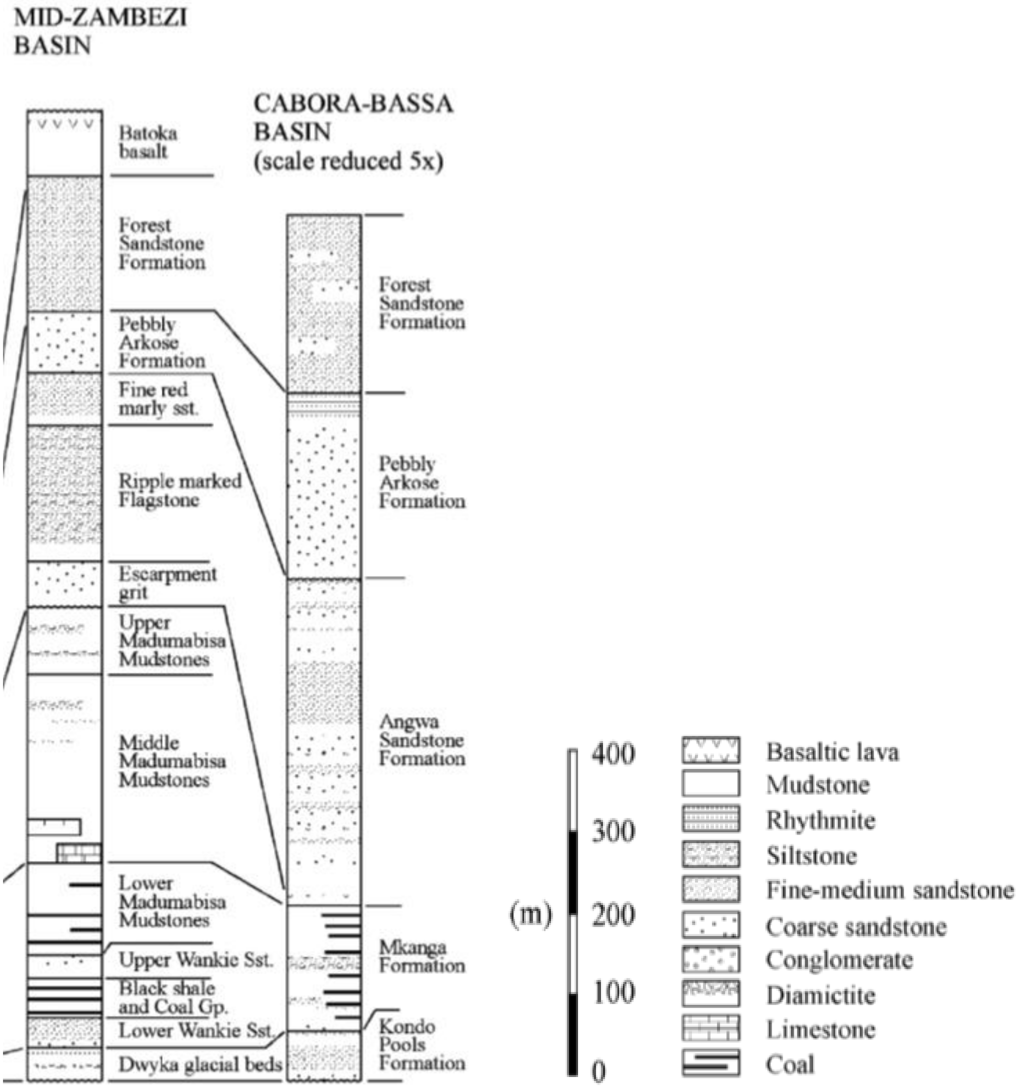


Figure 5: Karoo stratigraphic sequence in the Middle Zambezi and Cabora Bassa basins. Note the predominance of sandy and coarse-grained sediments, especially in the Cabora Bassa Basin, which is typical of faulted basins with steep gradients between the basin floor and the uplands.

Source: Catuneanu et al., 2005

The northern Karoo aquifers in Zimbabwe occur in areas where the population is sparse and water demand is generally quite low. The exception is Bulawayo City which lies not far south of the margin of the middle Zambezi basin, and which is already supplied by groundwater from the so-called Nyamandlovu aquifer. This aquifer also supports some 800 ha of irrigation (Figure 6). The Nyamandlovu aquifer and well field is discussed at the end of this section on Karoo aquifers.

Figure 6: The irrigation areas that use Karoo groundwater from the 'Nyamandlovu aquifer'. Irrigated area is approximately 800 ha. The scale (not shown) is 4.5 x 5 km (NS x EW).

Source: Image is from Google Earth imagery dated 19 Sept 2017.

2.2.2 Groundwater prospecting in the Mid-Zambezi Karoo basin

In order to develop the groundwater potential of the Mid-Zambezi Karoo sedimentary basin in an optimal way, it is essential to understand the tectonic and sedimentary processes involved in the creation and filling of the sedimentary basin; this is known as "basin analysis", and it is a vital component of prospecting for oil. Just as oil is found in preferred localities, so is it for productive groundwater aquifers. This is a vast field of study beyond the scope of this NWMP.

It is sufficient to understand that the Karoo basins in Zimbabwe are intra-continental (terrestrial) rift basins, produced by different tectonic pressures leading to crustal extension by rifting, or lateral strike-slip movements along transform faults or by crustal flexure. Each of these types of the tectonic basin has different basin geometries and they give rise to different styles of sedimentary fill.

In Zimbabwe, the Mid-Zambezi basin is an extensional half-graben basin: the Cabora Bassa basin is a combination of extensional (northern margin), and strike-slip (southern margin) tectonics, and the Tuli and Save basins are retro arc flexural foreland basins (Catuneanu et al., 2005).

As the geometries of these different basin styles differ, so does the sedimentary fill. For example, with faulted basin margins, such as rifted basins, fault movements produce a very abrupt margin with a great difference in elevation between the down faulted basin floor and the pre-existing land surface. Sediments then flow from the upland to fill this newly produced basin, and the energy for these sediment transfers is derived from the gradient and elevation differences between the basin floor and the upland. Since these gradients are steep, the energy is high and coarse and very coarse sediments are washed into the basin, particularly at the faulted basin margin. These sediments are known as the proximal facies, close to the basin margin. As one proceeds further into the basin, the gradient and the energy lessen, and finer-grained sediments are deposited in the mid-basin areas, known as the distal facies. A somewhat similar process also occurs in strike-slip basins. However, for flexural basins, the great difference in elevation and the steep gradients at basin margins are not developed. As a result, the energy to transport sediments into the basins is much less and a finer-grained sedimentary fill accumulates.

Fundamentally the search for groundwater is a search for thick sequences of coarse clastic sediments with high porosity and high permeability. The target is the proximal facies near the basin margins. Sedimentary basins may consist of many sub-basins all with faulted margins, and therefore, coarse proximal facies sediments may be found throughout the basin (Figure 7).

This is the type of exploration strategy that needs to be applied to the search for groundwater in the Karoo sedimentary basins in Zimbabwe. It is a complex and expensive task and requires basin analysis, followed by extensive airborne geophysical surveys and then test drilling. Nevertheless, the potential rewards are huge, with over 1000 km^3 of groundwater estimated to be in storage (Lamont, 1995).

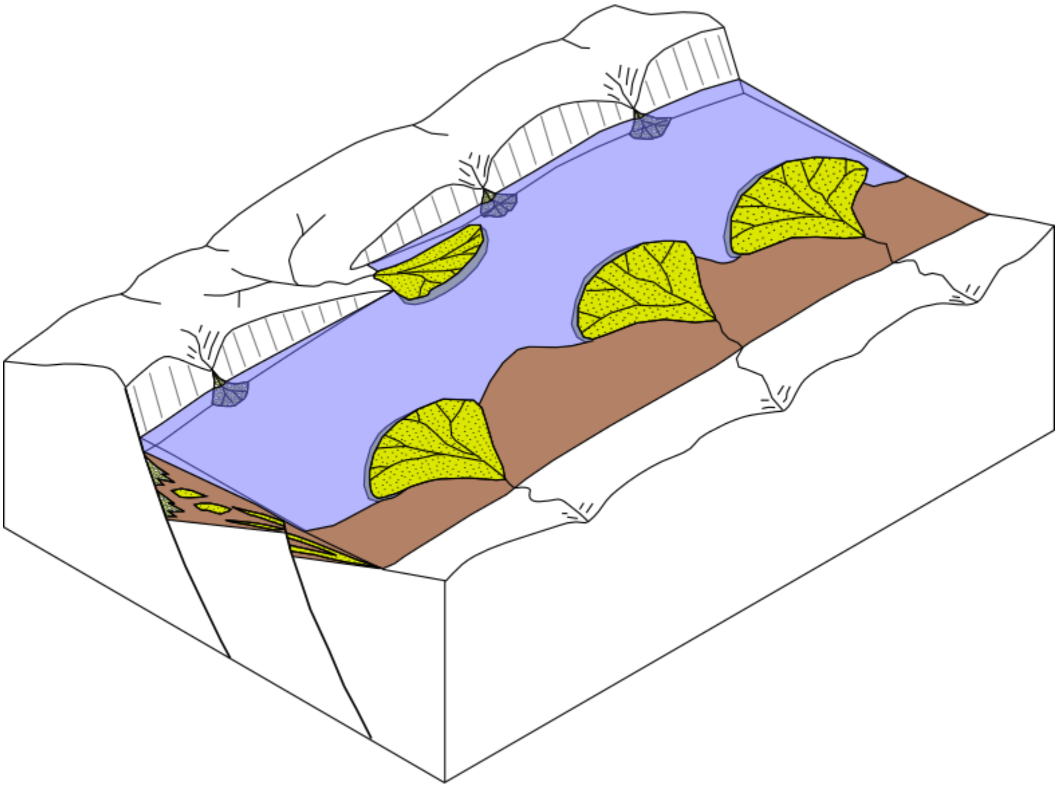


Figure 7: An extensional half-graben tectonic basin, similar to the Mid-Zambezi basin. Note the sub-basins, all with half-graben fault margins on one side. The grey fanglomerates can be seen at the basin margin and the green alluvial fans extend into the basin, both from the fault and the passive basin margin. The brown material is fine-grained mudstones and shales, while the purple material is water/evaporite beds.

In Zimbabwe, the Karoo basins lie at the periphery of the country and are generally lightly populated areas and for this reason, they have not been developed significantly. The most obvious opportunity is to develop groundwater for Bulawayo from the Karoo and Kalahari aquifers that lie to the north-west of the city. Already the Nyamandlovu well field had been developed in 1989 due to persistent water shortages of surface water supplies. The well-field development was accelerated in 1991 after a severe drought that almost emptied the water supply dams.

2.2.3 Key priority: groundwater for Bulawayo Municipality

Bulawayo faces a perennial water shortage, which is greatly exacerbated during dry years. Many solutions have been proposed, including the development of groundwater. The major primary porosity sedimentary Karoo and Kalahari aquifers occur to the northwest of the city of Bulawayo and extend to Hwange National Park and Dete.

These aquifers have the capacity to supply at least 30% of Bulawayo City water demand at prices significantly less than the proposed Gwayi-Shangani Dam and pipeline proposals (World Bank - Aide Memoire, 2013).

However, there is a need to carry out more detailed hydrogeological investigations using Time Domain Electromagnetic (TEM) airborne geophysical surveying, followed up by the drilling of pilot boreholes and extensive pumping tests to confirm resources. Once the information on the resources is adequate, then a more detailed comparison and the planning process can commence. It should be noted that there have already been a number of studies on this subject (e.g. World Bank – Aide Memoire: Bulawayo Water Supply, 2013).

2.2.4 Tuli and Save Karoo aquifers

The Karoo in the southern parts of Zimbabwe is a less extensive, the sediment thicknesses are somewhat less, and they are, on the whole, more fine-grained, and hence less productive. Figure 8 shows the stratigraphy of the Tuli and Save basins. As can be seen, the sedimentary fill consists largely of siltstones interbedded with mudstones, capped by productive wind-blown (aeolian) sandstone and Karoo basalt.

Such a finer-grained stratigraphy is expected since these sediments were deposited in a flexural basin as opposed to a faulted basin, and thus the depositional environment was much lower energy, allowing transport only of fine-grained sediments. Nevertheless, these two Karoo basins in southern Zimbabwe constitute extensive aquifer units and the potentially productive aeolian fine sandy sediments and Karoo basalts lie near the surface, thus reducing development costs.

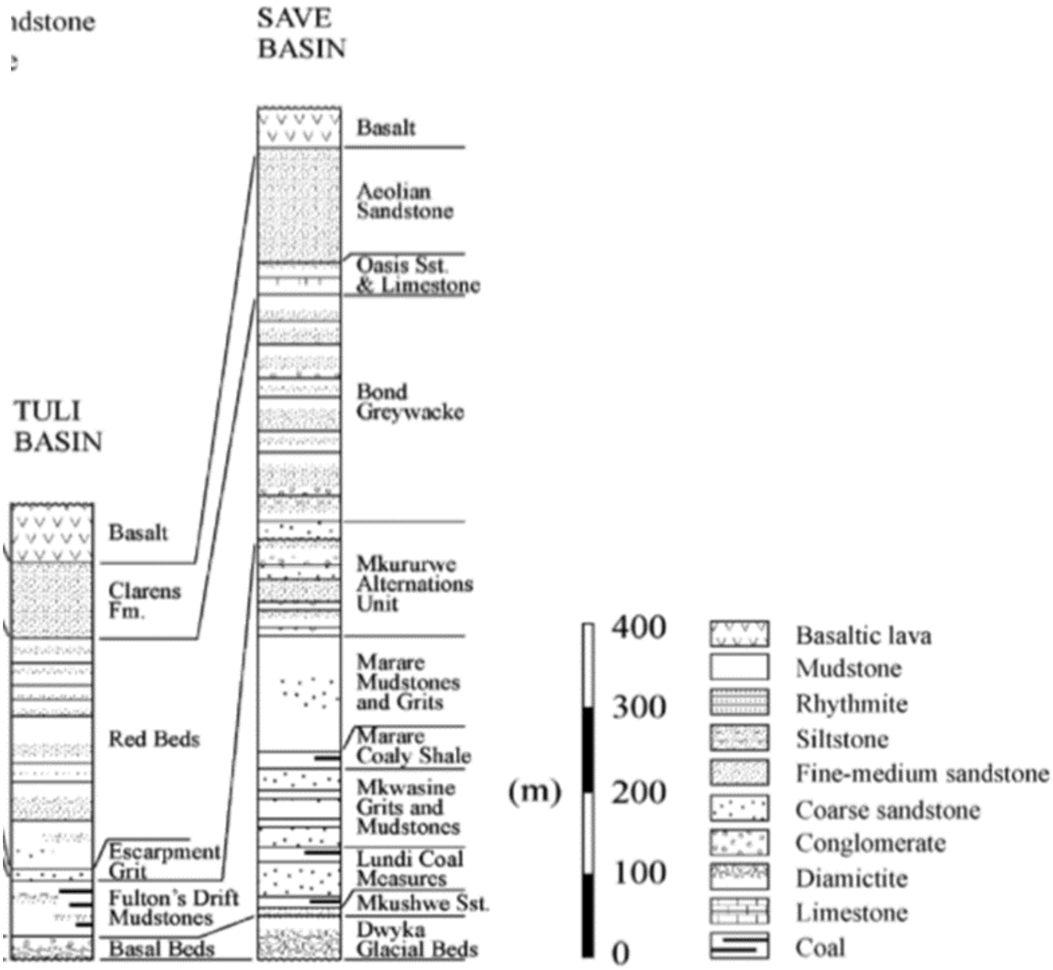


Figure 8: Karoo stratigraphy in southern Zimbabwe. Note that the fluvial sedimentary strata are largely fine-grained siltstones and mudstones as expected from a flexural basin setting. The two top formations, basalt and aeolian sandstone are not deposited as detritus under an elevation differential gravity energy regime but are volcanic emissions and windblown sands respectively.

Source: Catuneanu et al., 2005

2.2.5 Nyamandlovu well field

The Nyamandlovu well field lies at the southern margin of the mid-Zambezi Karoo basin. The well field has been developed in the upper-most sedimentary strata of the Karoo sediments, the Upper Karoo Forest Sandstone. This is an aeolian wind-blown sandstone deposited during an arid period at the end of the Karoo sedimentation and subsequently overlain by the extrusive Karoo basaltic lavas.

The "Nyamandlovu well field" is owned by ZINWA and consists of 101 boreholes drilled into the Upper Karoo Forest Sandstone in the vicinity of the small town of Nyamandlovu, some 35 km northwest of Bulawayo. Water level monitoring has been carried out there on a monthly since 1989. The data includes X, Y and Z readings and depth to the water level. Abstraction data from individual boreholes is not recorded in the groundwater database. However, some values for pumping from the Rochester storage tanks are available from ZINWA, via the Groundwater Division and the Gwayi catchment manager. This pumping from Rochester represents the total abstraction from the well field.

During its peak operation, the Nyamandlovu aquifer yielded approximately 27,000 m^3/day, and at present, it is capable of providing approximately 12,000 m^3/day. The average pumping figures for 2015-2019 are given in Table 1.

Table 1: Average daily abstraction from the Nyamandlovu aquifer for Bulawayo City Council and irrigation (ML/day)

Year	2015	2016	2017	2018*	2019
Daily discharge Ml/d	2.99	3.03	2.53	2.41	2.43
Bulawayo City Council	no data	no data	93%	85%	72%
For irrigation	no data	no data	7%	15%	28%

Data for 2018 was "cleaned"- value for farmer abstraction for October 2018 was an order of magnitude greater than expected.

The Nyamandlovu well field is used to supply water to Bulawayo and for irrigation. A maximum of approximately 800 ha is irrigated from the aquifer. Figure 6 shows the irrigated agriculture that obtains its water from the Nyamandlovu aquifer.

During periods when there is a demand for aquifer water from Bulawayo, then there is insufficient water to simultaneously supply the irrigation demand. The City of Bulawayo tends to prefer to use water from its water supply dams (cheaper water) when available than from ZINWA sources. Thus, it is only in drought/dry years that Bulawayo turns to the Nyamandlovu aquifer. In such drought times, there are conflicting demands between the irrigators and the City of Bulawayo that are yet to be resolved.

A second well field in the same area is being developed at Epping Forest, just a few kilometres to the west of the Nyamandlovu well-field. It is anticipated that this will supply a further 10,000 m^3/day. The boreholes in the Epping Forest Well Field are included in the Nyamandlovu database.

Nyamandlovu well field performance

The well-field monitoring data has been analysed and a summary is provided here. On average the water levels have declined between 1 m and 5 m, with an average decline of 2.65 m over a period of 22 years between 1989 and 2012.

A snapshot looks at the water level fluctuations in 14 boreholes (plotted as 2 plots of 7 boreholes each for clarity) in the Nyamandlovu aquifer shows that the water levels, in general, do not exhibit large annual fluctuations (Figure 9). However, four boreholes alongside rivers (Khami River and Umguza River – lowest four hydrographs ((series 1, 2, 3 and 5) in the lower plot) show significant annual fluctuations. These fluctuations indicate that these four boreholes are receiving annual recharge, quite probably from river flow, and they are therefore from an "unconfined" aquifer. The other boreholes in the two plots do not exhibit annual recharge and are most likely confined aquifers or possibly boreholes that are not pumped.

These hydrograph data show that the water levels are drawn down only slightly each year, approximately 5m for the unconfined boreholes and that the recharge compensates fully for the discharge. The confined boreholes show limited annual variation and the overall trend is only slightly negative. These data suggest that the Nyamandlovu aquifer has not been overexploited and that further development of the aquifer is possible, particularly if new areas are selected rather than pumping more from the already developed areas.

Figure 10 shows the locations of the 14 monitored boreholes in the Nyamandlovu aquifer, together with the infrastructure and geology of the area.

Future groundwater development in the mid-Zambezi Karoo basin

It should be noted that the Nyamandlovu well-field has not been developed in the most promising lithologies of the Karoo Basin. It lies in the aeolian Forest Sandstone at the top of the Karoo sequence at the southern margin of the Karoo basin and has a maximum thickness about 160 to 200 m.

The Karoo basin aquifer extends to the northwest beneath the basalt and the Kalahari sand where it thickens considerably to include the lower Karoo strata. Productive coarse clastic basin margin proximal facies will likely occur at favourable localities in the deeper basin. It may be expected that such coarse sediments will be highly productive and provide further well-field potential.

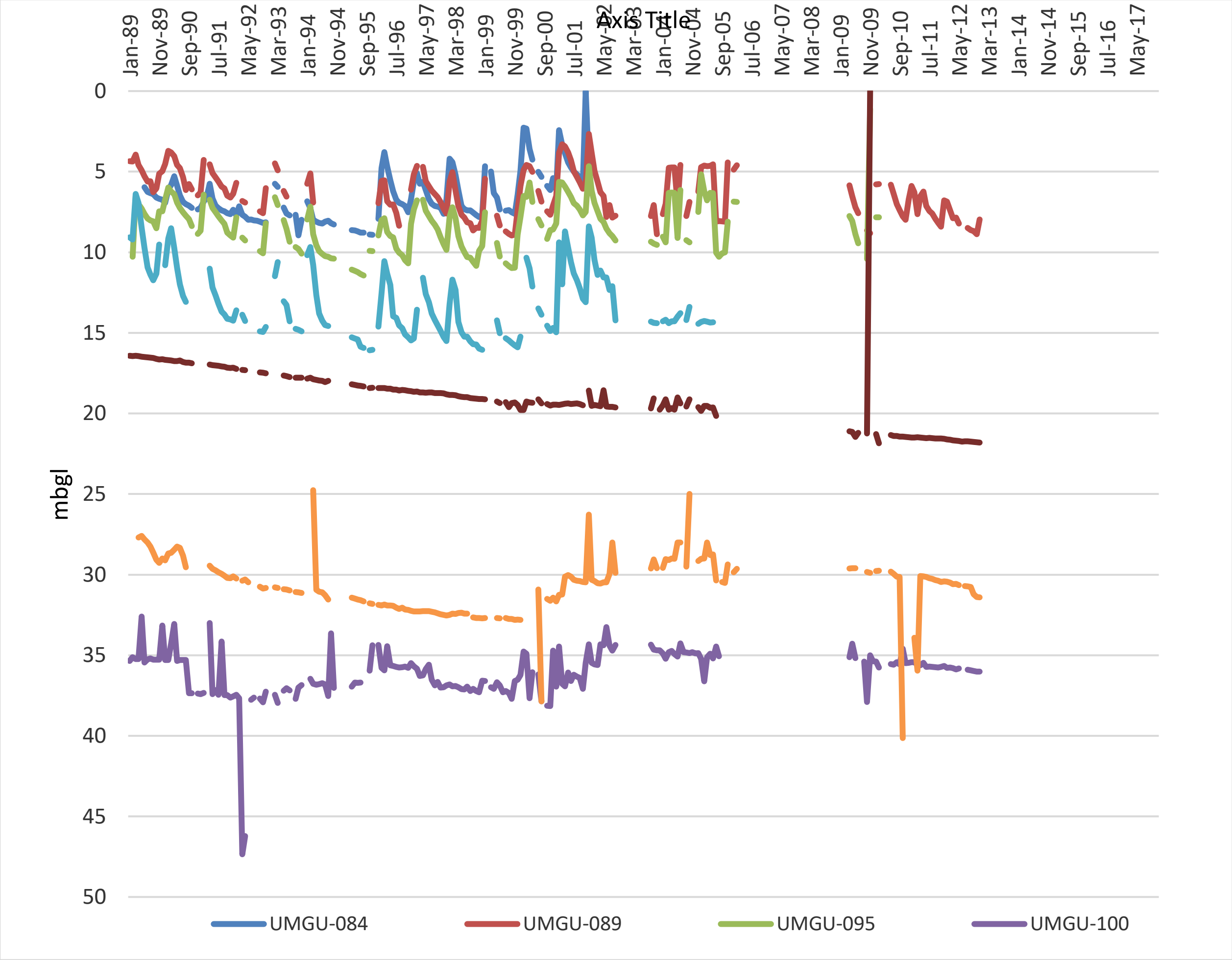


Figure 9: Selected boreholes – Nyamandlovu Well Field - borehole water level fluctuations (mbgl – meters below ground level) – 22-year period. The upper three boreholes exhibit unconfined aquifer behaviour with annual recharge while the lower 3 boreholes exhibit confined to semi-confined aquifer behaviour without annual recharge events. The boreholes with the shallow water levels are at the Umguza River Bridge and the Khami River Bridge locations.

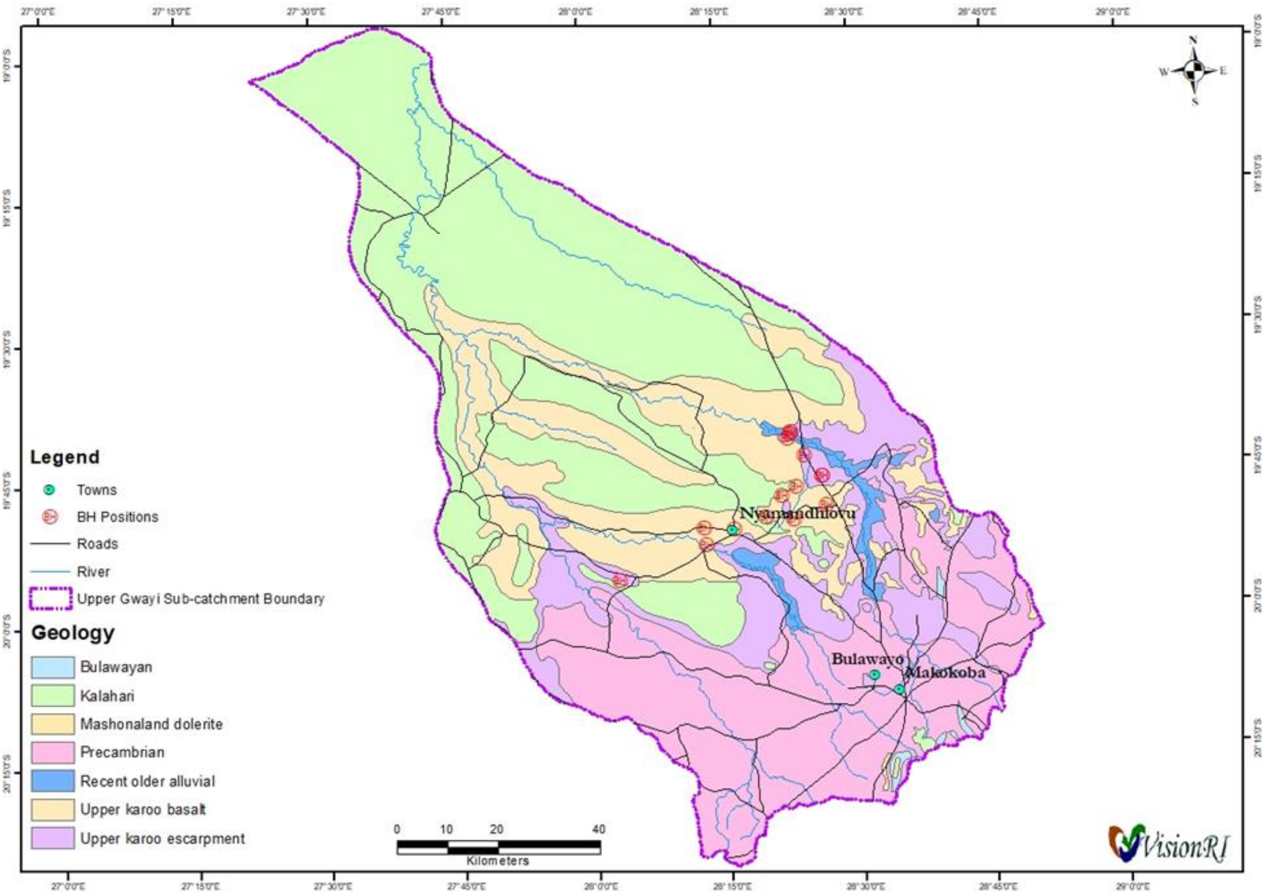


Figure 10: Nyamandlovu aquifer with boreholes in the hydrographs above

In addition to the ZINWA database for Nyamandlovu, further information on the Karoo (and Kalahari) aquifers in the Middle Zambezi basin comes from MacDonald (1970), who reports on a number of deep boreholes that were drilled along the Bulawayo-Victoria Falls railway line in order to supply water for the coal-fired steam trains that used to ply this route. Table 2 lists these boreholes and shows eight boreholes drilled at Nyamandlovu, Sawmills, Gwayi, and Intundla that penetrate, or partially penetrate the Upper Karoo Sandstone (UKS – Forest Sandstone) and the two boreholes at Sawmills that penetrate the Lower Karoo Sandstone (LKS).

Yields from these boreholes range from 0.108 to 1.44 ML per day (100 – 1440 m^3/d), although 7 out of the 8 boreholes yield more than 0.75 ML per day (750 m^3/d). The groundwater is neutral to alkaline (pH range: 7-9) and low salinity (TDS: 350-475 ppm) and hence is of reasonable quality, although it may be "hard" water that does not lather easily and will cause the scale to develop in pipelines and boilers.

Further evidence on Karoo groundwater comes from the Gokwe–Sengwa Coal Mine road construction project. Deep boreholes were drilled through the Madumabisa mudstone into the Lower Karoo sandstone along this highway. At least 3 of them struck strong flows of artesian groundwater; one borehole was discharging 40 l/s (3.45 ML/day) but has since declined to approximately 10 l/s.

Clearly, the Karoo aquifer in the Mid-Zambezi basin holds very substantial groundwater resources, with many individual boreholes capable of supplying 1 ML/day or more. However, to access such high yields and volumes of groundwater is not simply a case of drilling anywhere. A careful analysis of the sedimentary strata and the basin tectonics will be needed, as indicated in the preceding section.

Table 2: Karoo and Kalahari groundwater along Bulawayo–Victoria Falls railway line

	BH	Altitude	Depth	Cased	RWL	Yield Ml/d	PWL	DD	TDS ppm	pH	KS	BJ	UKS	LKS	BC	W
Nyamandlovu	G3/114	1,200	95	82	25	0.864	43	18	350	7		30	95			
Nyamandlovu	G3/115	1,198	66	66	23	0.994	37	14	360	7		24	66			
Nyamandlovu	G3/116	1,197	146	71	21	0.756	62	41	360	7		14	146			
Sawmills	G3/378	1049	332	302	15	1.442	61	46	475	9	9	48	189	332		
Sawmills	G3/463	1,048	413	332	16	1.440	61	45	450	9	2	50	198	379	413	
Gwayi	G3/77	986	110	73	34	0.502	62	28	343	7	107	110				
Gwayi	G3/78	987	95	95	15	0.742	28	13	334	7	93	95				
Gwayi	G3/79	1,001	110	73	33	0.467	62	29	336	7	109	110				
Gwayi	G3/483	988	238	194	22	0.108	83	62	840	9	95	109	238			KR
Gwayi	G3/483	988	134	41	18	0.972	61	43	350	7	95	109	134			KS
Gwayi	G3/484	985	96	34	13	1.620	41	28	350	7	94	96				
Intundla	G3/406	1,029	294	207	12	1	76	64	270	8	97	217	294			KR
Intundla	G3/406	1,029	268	27	11	1.767	20	9	266	8	97	207				KS
Intundla	G3/408	1,028	98	31	8	1.851	20	12	308	8	93	98				
Intundla	G3/409	1,028	98	25	9	1.808	16	7	238	8	97	98				
Ngamo	G3/50	1,019	37	28	15	0.408	24	10	329	7.2	37					
Ngamo	G3/63	1,018	62	34	14	0.816	28	14	315	7.2	62					
Ngamo	G3/64	1,018	62	38	14	0.396	24	10	339	7.3	62					
Kennedy	G3/56	1,029	64	35	8	0.871	62	54	545	7.4	64					
Kennedy	G3/58	1,028	62	38	9	0.391	56	48	518	7.3	62					
Water Loop	G3/132	1,056	86	37	20	0.711	36	15	224	7.9	86				86	
Water Loop	G3/134	1,057	105	93	20	0.624	53	32	168	7.3	94				105	
Water Loop	G3/136	1,056	86	36	21	0.795	35	14	280	7.5	82				86	

	BH	Altitude	Depth	Cased	RWL	Yield Ml/d	PWL	DD	TDS ppm	pH	KS	BJ	UKS	LKS	BC	W
Water Loop	G3/137	1,056	91	46	21	0.932	30	9	259	7.3	87				91	
Water Loop	G3/138	1,057	95	31	17	0.937	34	16	238	7.2	87				95	
Water Loop	G3/139	1,057	97	86	16	0.972	44	29	245	7.5	82				97	

Source: MacDonald, 1970

Notes: NRZ (National Railways of Zimbabwe) boreholes along the Bulawayo-Victoria Falls line. Boreholes in Karoo strata and Kalahari Sand. All values in m. Abbreviations are BH borehole; RWL rest water level; PWL pumping water level; DD drawdown; KS Kalahari sand; BJ Batoka basalt; UKS Upper Karoo sandstone; LKS Lower Karoo sandstone; BC Basement Complex; W water (which formation is providing the water – KR Karoo or KS Kalahari). The depths assigned to each formation is the depth at the base of the formation from the ground surface.

2.2.6 Kalahari aquifers: northwest Zimbabwe

The Kalahari Sand occurs almost entirely in the northwest of Zimbabwe with two minor occurrences in the central part of the country near Mvuma and Chivu (Figure 11). The Kalahari sand is considered to be the largest aquifer in Zimbabwe (Dennis and Hineson, 1964) and its groundwater potential is considered to be high to very high (Interconsult, 1987). It consists largely of well-sorted fine wind-blown aeolian sand and is estimated to hold approximately 1000 km^3 of groundwater in storage (Lamont, 1995).

The Kalahari occurs in one of the most sparsely populated areas of Zimbabwe where surface water is almost absent, and the soils are poor. These areas are generally used for forestry, where species such as teak (Baikiaea Plurijuga), Mahogany (or false mopane) (Guibourtia Coleosperma), Mukwa (Pterocarpus Angolensis) grow naturally and for wildlife and tourism as in the Hwange National Park (HNP) and the many safari operations found here. The groundwater here is mostly used for game watering, and innovative solar pumping systems have been installed in many of HNP boreholes in order to provide year-round water for the wildlife that flourishes here.

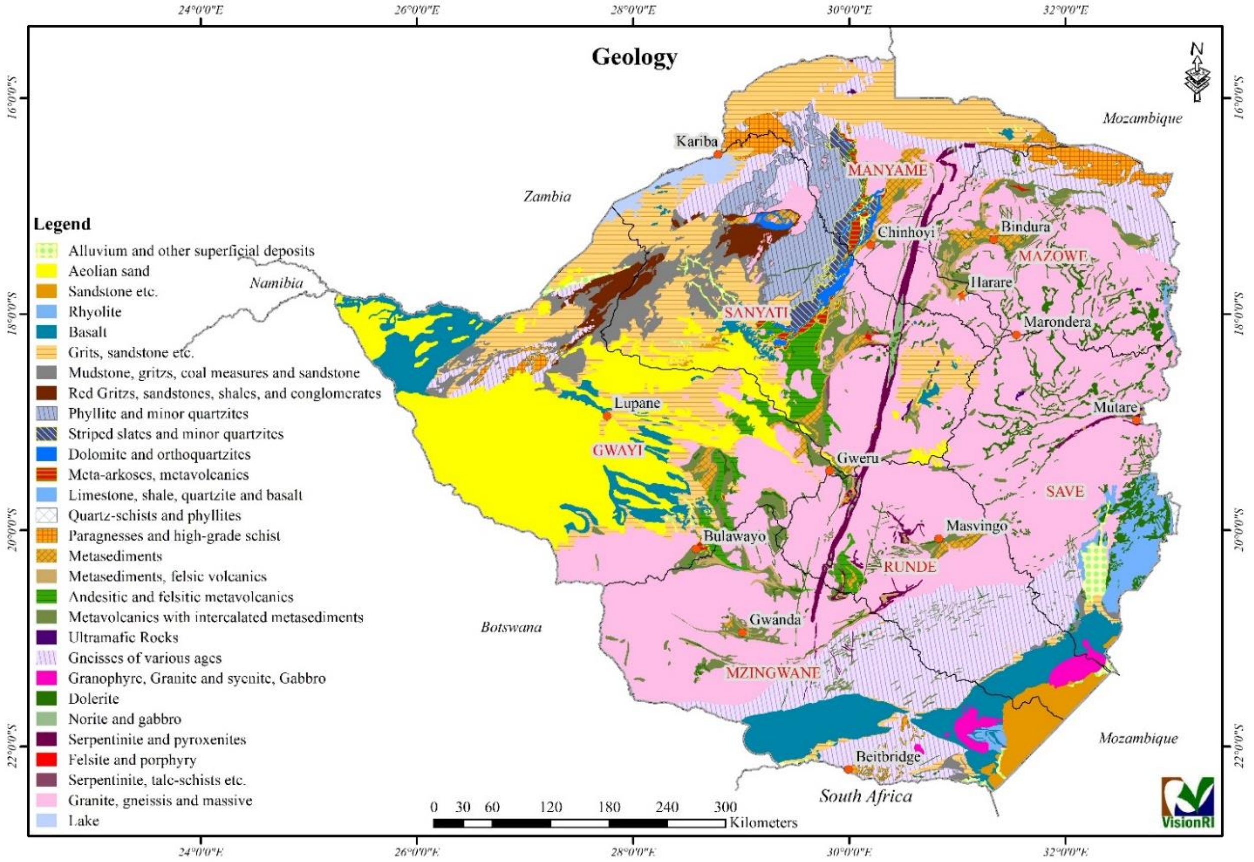


Figure 11: Geological map of Zimbabwe. The Kalahari sand is shown in yellow. The Karoo strata are shown in light brown (sedimentary formations) and dark turquoise (Karoo basalt)

i. Description of the Kalahari Sand in Zimbabwe

The Kalahari sand is one of the largest unconsolidated aeolian (wind-blown) sand bodies in the world. It is centred in the Kalahari Desert in Botswana and extends westwards to central Namibia, south into the Northern Cape Province, north into Angola, and east into western Zimbabwe and Zambia (Figure 12) (Haddon and McCarthy, 2005). It consists principally of fine unconsolidated wind-blown quartz sands but has lenses of silt and clay, unsorted gravel sands, and evaporite sequences that occur as a result of episodic wetter periods that led to fluvial transportation and deposition of these sediments. The basal beds of the Kalahari, known as the pipe sandstone, are commonly weakly cemented and intersected with many hollow tubes as a result of biotic activity and water flow.

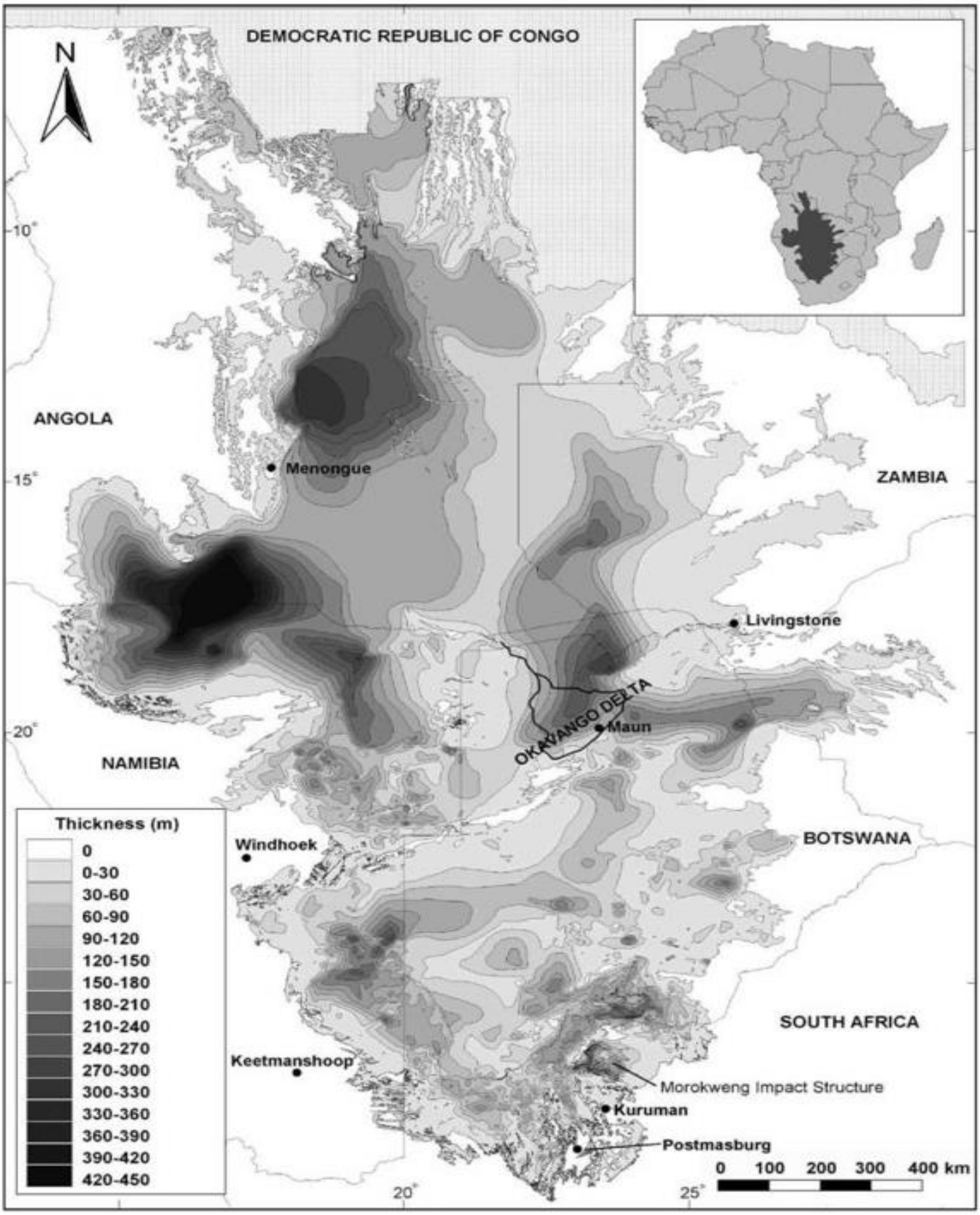


Figure 12: Distribution of the Kalahari sand in Africa, together with the Isopachs showing Kalahari thickness. In western Zimbabwe, the Kalahari thickness ranges from 0 m to 200 m at the Botswana border

Isopachs for the Kalahari in Zimbabwe shows that they vary in thickness from 0 to 200 m in north-western Zimbabwe. The thickness of the Kalahari beds is zero just east of the Bulawayo–Victoria Falls road and thicken westward towards the Botswana border where it attains a thickness of approximately 200 m (Figure 13) (Haddon and McCarthy, 2005).

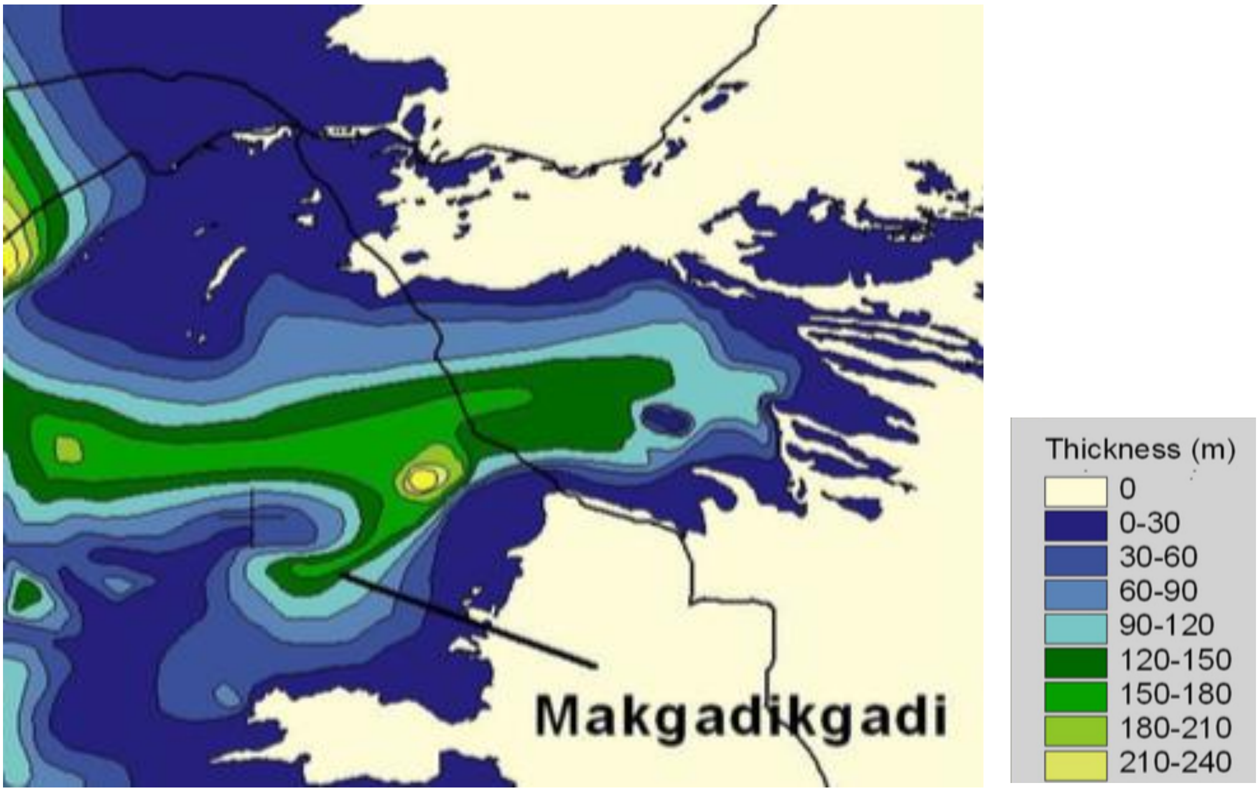


Figure 13: The Kalahari basin in NW Zimbabwe – isopach map showing the Kalahari sand thickness. The average thickness in Zimbabwe is estimated to be 60m

ii. Hydrogeology of the Kalahari Sand

The Kalahari sand is an unconfined aquifer open to the atmosphere. It thus can receive direct recharge from rainfall and is also susceptible to direct pollution from waste materials placed on the land surface or subsurface.

Volume of groundwater in storage: The porosity (35-40%) and the specific yield (20-30%) of Kalahari sand type aquifers are known to be quite high, and the hydraulic conductivity is estimated to in the range of 10–20 m/day (Morris and Johnson, 1967). Representative borehole logs from different areas (Figure 14) show the predominantly sandy nature of the Kalahari beds, supporting the assertion that the aquifer has excellent groundwater storage and yield properties.

The volume of groundwater that is at present in storage in the Kalahari sand may be assessed as the product of the saturated aquifer volume and the average porosity. The areal extent of the Kalahari sand in Zimbabwe has been measured from geological maps and is estimated at 26,190 km^2 (Lamont, 1995). Based on isopach maps (Figures 12 and 13) the average thickness of the Kalahari sand in Zimbabwe is estimated as 65 m, and the total aquifer volume as approximately 1,700 km^3. Based on 113 water level measurements in the Kalahari area in HNP in 2014 (Owen, 2016), the saturated aquifer volume is about 850 km^3. Given a porosity of 40%, this yields a volume of groundwater in the storage of about 335 km^3. Although significantly less than the 1,000 km^3 calculated by Lamont (1995), it is still a very large volume of water.

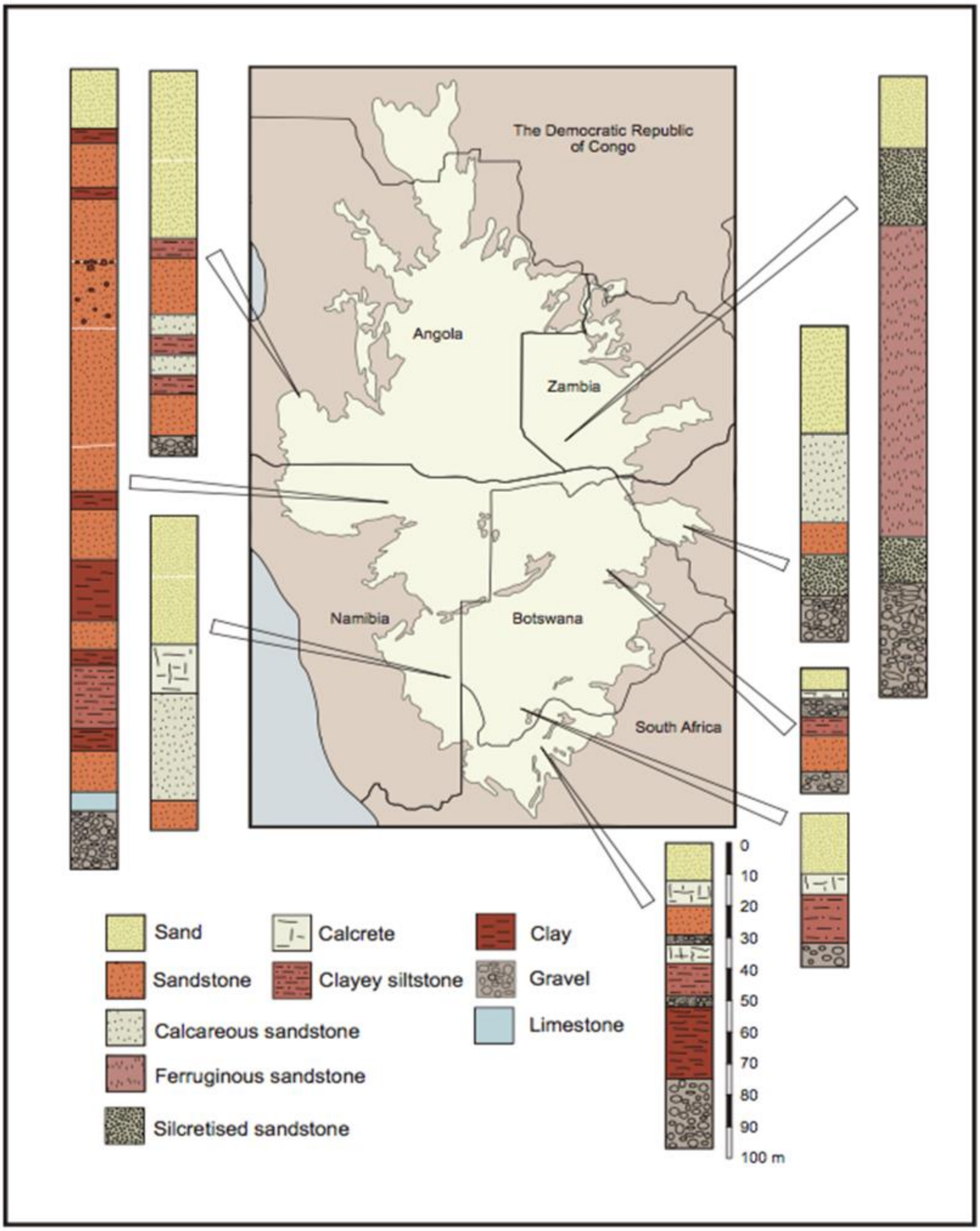


Figure 14: Representative borehole logs from different locations across the Kalahari basin (after du Plessis, 1993; Meixner and Peart, 1984; Pachero, 1976; Thomas and Shaw, 1990, 1991; Haddon, 2005). (Source: Haddon and McCarthy, 2005.

To calculate the extractable groundwater by pumping, the specific yield value should be used rather than the porosity: 26,190 km^2 (area) x 32 m (saturated thickness) x 0.3 (specific yield) = 251 km^3 extractable groundwater in storage.

The Kalahari sand in Zimbabwe represents a major groundwater resource held in storage. In order to assess its development potential, other issues include:-

- At what rate can groundwater be abstracted?

- What is the groundwater balance: i.e. the recharge rate vs the discharge rate?
- What is the quality of the groundwater?
- What are the potential uses for groundwater in this area?

What are the potential abstraction rates for Kalahari sand boreholes? The rate of abstraction from a borehole depends principally on the aquifer hydraulic conductivity (permeability) and the available drawdown.

Figure 14 shows typical stratigraphic profiles from various parts of the Kalahari basin. The profile for Zimbabwe shows 100m of Kalahari subdivided into about 30m of unconsolidated sand, 50 m of weakly cemented sandstone with different cementing agents and 20 m basal gravel. These may be considered highly favourable conditions for borehole yield. Values of 10 – 20 m/d are typical for the hydraulic conductivity of aeolian sands.

Table 2 provides some useful evidence from actual measured data from boreholes drilled into the Kalahari. These are boreholes that were drilled by National Railways of Zimbabwe along the Bulawayo/Victoria Falls railway line. From this table it can be seen between Gwayi, Intundla, Ngamo, Kennedy and Water Loop there are 19 boreholes drilled into the Kalahari sand. They have a combined yield of 18.266 ML/day, with an average yield of 0.903 ML/day (almost 1,000 m^3/day). The average drawdown for these 19 boreholes is 22 m. They have an average Kalahari sand thickness of 85 m and an average saturated sand thickness of 68 m. The boreholes lie towards the eastern edge of the Kalahari sand outcrop area where it is reputed to be thinnest. The average TDS is 315 ppm.

The measured data, though limited, presents a rather more favourable picture than that found in the literature. Saturated thickness, in particular, is approximately double that calculated from the isopach data.

What is the state of the groundwater balance? The question of recharge is considered to lie at the heart of the sustainability of the groundwater resource. In fact, the real question is: what is the groundwater balance? Are recharge and discharge in balance? What will be the impact of abstraction on recharge and discharge? These are not easy questions to answer in the absence of groundwater level monitoring.

Discharge: Discharges can be diffuse and difficult to measure. They include baseflows and spring-flows, evaporation, and transpiration losses (ET), inter-aquifer transfers and abstractions by pumping. Evapotranspiration by vegetation and evaporation is considered to completely deplete the annual soil moisture in the upper part of the soil but is estimated to be modest from the groundwater zone due to the considerable depth to the water table, usually >20m for most of Kalahari boreholes. Transpiration and evaporation vapour flux from such depths are limited and De Vries et al. (2000) estimate discharges to evaporation of approximately 1mm/year in the Kalahari.

Regional groundwater flows are based on the groundwater gradients, as determined by groundwater contours, and on the hydraulic conductivity of the aquifer materials. These may be either into or out of the Kalahari aquifer in Zimbabwe, depending on the relative elevations of the Kalahari water table.

Groundwater contours for the Kalahari sand in HNP indicate a groundwater gradient of 1:400, which contrast with the gradients measured by De Vries et al. (2000) at 1:1000 to 1:2000 in the Kalahari in Botswana. Literature values for the aeolian/Kalahari sand hydraulic conductivity range from 10 m/day (De Vries et al., 2000) to 20 m/day (Morris and Johnson, 1967).

Based on groundwater contours, groundwater flows westwards to the regional Magadigadi depression, with an altitude of 925masl, in eastern Botswana (De Vries et al., 2000). They estimate regional groundwater discharge of the order of 1mm/year over the areal extent of the Kalahari aquifer, based on the hydraulic gradient and hydraulic conductivity of the Kalahari sand.

Baseflow: Drainage of groundwater to streams: Few rivers are draining the Kalahari in Zimbabwe except the Gwayi to the east, which lies at an elevation of approximately 940 masl as compared to Main Camp at 1080 masl, indicating a groundwater gradient and hence baseflow to the Gwayi. However, groundwater elevation in Hwange National Park measured during February 2016 indicate that groundwater flow in this area is towards the west, and not towards the Gwayi River which lies to the east (Owen, 2016). This suggests that the influence of the Gwayi is quite localised.

The ZINWA "Blue Book - 2007" (Assessment of Surface Water Resources) provides the following information on baseflow discharge from the Kalahari catchments:

> "Sub-zones in which Kalahari sands are dominant have low MAR 5 – 16 mm/year, due to high infiltration rates, deep percolation and flat slopes. Water tables are generally below riverbeds in Kalahari sands, and therefore groundwater does not make a significant contribution to river flows. Deep Kalahari sands and low gradients on parts of the Gwayi Catchment inhibit groundwater flow towards streams. This contributes to low BFI of 0.21-0.30."

Baseflow discharge from the Kalahari is calculated in the range 1 – 4.8 mm/year.

Total Discharge: The sum of all discharge estimates is:

> 0.22 mm/year pumping +1 mm/year evapotranspiration + 1 mm/year regional discharge to Magadigadi basin + 1 - 4.8mm baseflow to Gwayi/local streams
>
> = 3.22 - 7.02 mm/year total discharge.

Additional information comes from intermittent monitoring of a single Intundla borehole, G3/409. In 1970, at the time of drilling, the RWL (rest water level) was 9mbgl; in 1995, the RWL at G3/409 was 16 mbgl and in 2014, RWL was 18 mbgl. These three readings show an overall declining trend of 9 m in 44 years or on average 20.45 cm/year. The Kalahari sand is estimated to have a specific yield of 0.3 and, therefore, this represents a total discharge of 6 mm/year, which is comparable to the upper end of the calculated total discharge values.

Recharge: Recharge tends to be quantified more frequently than discharge. Significant studies on groundwater recharge have been carried out in Botswana, which is largely covered by Kalahari sand. De Vries *et al.* (2000) discuss the relationship between rainfall and recharge in the Kalahari in Botswana, citing recharge rates as low as 1mm/year in the central Kalahari, with an annual rainfall of 350 mm/year, rising to 5mm/year recharge on the eastern fringes of the Botswana Kalahari with rainfall of 450 mm/year. They also note that many studies find that there is negligible recharge to the Kalahari with rainfall below 400 mm/year, citing the high porosity of the sand that can store 400 mm of rainfall in the upper meters within the rooting zone of the abundant savannah grass and woodland vegetation that thrives on the Kalahari sand. This vegetation then transpires this stored water in the dry season, leaving none for recharge. Beekman et al. (1996) found recharge rates of 10–15mm/year in sandy areas in eastern Botswana with rainfall of 500 mm/year.

Rainfall in the Kalahari sand area in Zimbabwe is in the range 400 to 550 mm/year. However, total rainfall is not a very accurate guide to groundwater recharge in western Zimbabwe's semi-arid climatic environment. The bulk of recharge here tends to take place in wet periods when there has been sufficient rainfall to temporarily satisfy the soil moisture deficit and the evapotranspiration demand, with additional surplus rain to percolate down to the groundwater zone. If we select a default recharge value of 5 mm/year, as suggested by De Vries et al. (2000), then the data suggests that the groundwater balance in the Hwange National Park is either in balance or probably marginally negative.

What is the quality of the groundwater? The Kalahari groundwater in Zimbabwe appears to be of good quality. From 11 samples tested under the NMPRWSS (1986), all samples fell within the guidelines for drinking water standards for Zimbabwe. From 19 samples tested by MacDonald (1970), all had TDS less than 550 ppm and the average pH was pH 7.45. However, Kalahari groundwater quality further to the west in Botswana and Namibia has a reputation for being saline, particularly in low rainfall areas where recharge is low or zero.

The Kalahari sand in Zimbabwe appears to receive additional recharge from streams such as the Umguza, Bembezi, Insiza and Gwayi, which rise on indurated rock and then discharge their flow into the unconsolidated Kalahari sand, freshening the water. Thus, the Kalahari water in the eastern parts of the Kalahari sand is good quality freshwater. Further west, water quality is reputed to decline becoming more saline (e.g. Jonker, 2016).

The demand for Kalahari groundwater: The areas of Zimbabwe that are covered by the Kalahari sand are very sparsely populated, and there is very limited demand for groundwater. Game watering in Hwange is a demand that is being met by a combination of solar pumping and diesel engines. The game watering demand has been estimated at 3 x 10^6 m^3/year. This amount is estimated to be 0.2 % of water held in storage and can be sustained for 500 years without a recharge.

Groundwater prospecting in the Kalahari sand: Although groundwater appears to be more or less ubiquitous and easily available in the Kalahari sand, a fairly high proportion of boreholes have saline water, and it is known that in Botswana and Namibia, groundwater salinity in the Kalahari is a major problem. Since the Kalahari covers such a large area of south-western Africa, it is of interest to investigate if there are specific conditions where fresh Kalahari groundwater is more likely to be located. The high salinity is presumed due to a suite of factors that include: the presence of evaporite sequences in the Kalahari, long residence times, extended flow paths, and limited recharge. Any environments that ameliorate any or all of these conditions are likely to provide improved groundwater quality.

Such environments may include enhanced local recharge due to seepage from surface streams or water reservoirs, or preferential groundwater flow paths which will result in improved groundwater flows with an increased freshening of the groundwater locally. Such preferential groundwater flow paths may be inherited from pre-existing drainage prior to the deposition of the Kalahari sediments. The concept of inherited drainage is shown in Figure 15 and may be considered to occur in most sedimentary basins, particularly those that are filled with more permeable sediments.

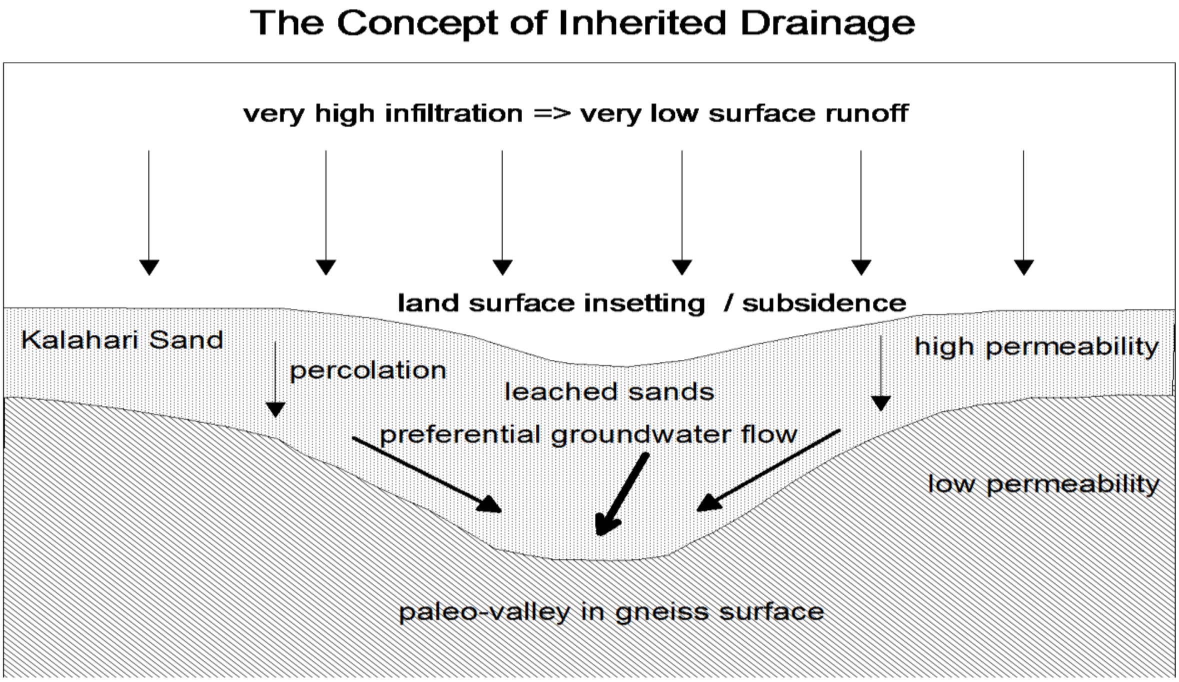


Figure 15: Inherited drainage. Rain falling on the loose sandy surface of the Kalahari infiltrates readily and there is almost no run-off, as evidenced by the lack of surface drainage in the Kalahari areas. The infiltrating rainwater then percolates through the Kalahari sand until it reaches the low permeability bedrock (gneiss surface in figure), and then it flows down the bedrock slope into the pre-existing valley and flows along the valley floor. This then becomes a preferential groundwater flow path with the leaching of the sediments in the valley floor leading to increased permeability and overlying land subsidence due to solute removal by leaching. In the image above, the land in-setting is exaggerated, and it may not be noticeable, particularly where the cover sediments are thick >20m)

Source: Owen and Dahlin, 2010

Exploration for such preferential groundwater flow systems may then be directed towards mapping of the sub-Kalahari bedrock and presents the possibility of greatly enhanced groundwater yields. In addition, in areas where the Kalahari groundwater is generally saline, such preferential flow paths hold the possibility of better water quality due to the greater groundwater flow leading to a freshening of the water.

2.2.7 Alluvial aquifers

Alluvial aquifers, or sandy riverbeds in active streams, occur in low gradient areas with slopes flatter than 1:400. It is at these gradients and lowers that the stream energy is insufficient to transport the larger sand particles which then settle out forming a sandy stream bed.

In Zimbabwe, such conditions for alluvial deposition are found in the southern Lowveld areas, the Zambezi Valley floor, at the northern base of the Mafungabusi escarpment, and similar areas of low stream bed gradients and low relief. Significant commercial irrigation development from alluvial groundwater occurs along the Limpopo River (reported in the chapter on transboundary groundwater) and along, for example, the Mzingwane

River. In addition, small scale garden irrigation has also been developed on streams such as the Mtshabezi, and Shashani, supported by Dabane Trust NGO.

Listed here are some of the active streams/rivers that host alluvial aquifers that are potentially suited to development. On-site investigations are always required to verify such factors as bedrock permeability and hence vertical seepage losses. In southern Zimbabwe, such active alluvial river channels are the Limpopo, Runde, Save, Mzingwane, Mwenezi, Shashe, Bubi, Mtshabezi, Sansukwe, Simukwe, Shashani, Tuli, Ramaquabane. In northern Zimbabwe, they are the Sessami, Shangani, Sengwa, and Gwayi Rivers.

Alluvial aquifers are "ribbon" aquifers, extending along the stream channel but with limited lateral extent or depth. They are, however, fully recharged annually with fresh water by streamflow and they have excellent hydraulic properties of storage and conductivity. They are close to the surface and thus relatively easy to exploit. They thus form an excellent reliable source of local good quality groundwater and have been widely developed in Zimbabwe and elsewhere (e.g. Botswana).

Given their limited areal extent and thickness, it is relevant to look for hydrogeological settings where the deposition of alluvium is enhanced, and the resultant alluvial aquifer is then extended either laterally or vertically or both. In fact, such conditions do occur when a stream crosses a geological boundary, and here alluvial river channels become either wider or deeper with a thicker alluvial fill. If the downstream lithology is more resistant to erosion, then the alluvial channel upstream of the boundary is widened by channel meander, and lateral erosion and deposition; if the downstream lithology is more easily eroded, then a waterfall develops downstream of that boundary by scouring as the river bed is scoured out resulting a deep pond. If stream flow is reduced (e.g. due to climate change) or a new source of sediment enters the stream system, this can then initiate a depositional environment, leading to a thicker deeper accumulation of alluvium at this location (Owen and Dahlin, 2005).

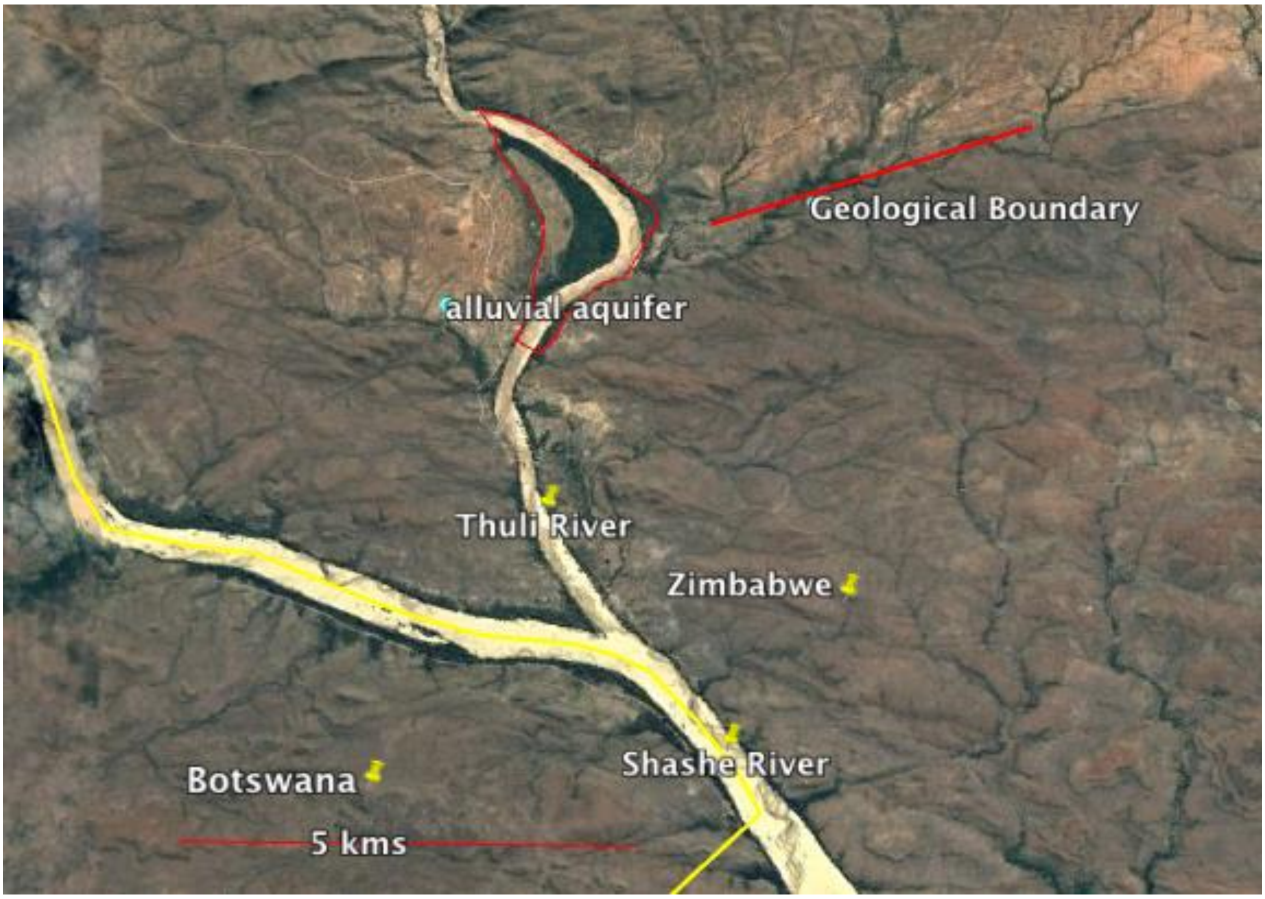


Figure 16: Alluvial aquifers – Shashe and Tuli rivers. Note the widening of the Tuli alluvial aquifer upstream of the geological boundary – with darker basalt to the south and lighter gneiss to the north. The dense riverine vegetation shows that the alluvial channel eroded laterally from the west towards the east as it looks for an easier flow path than through the resistant basalt downstream. This results in a significant increase in the lateral extent of the alluvial aquifer over the less resistant lithology.

Figure 16 is a Google Earth image of the extreme southwest of Zimbabwe at the Botswana border and shows the Tuli alluvial channel flowing across a geological boundary. Upstream of the boundary, the channel is significantly wider due to lateral erosion, as expected when the harder rock is downstream. A somewhat similar process of aquifer enlargement also occurs when the hard rock is upstream, except that the increase in aquifer dimensions is in the vertical thickness of the aquifer overlying the less resistant downstream formation.

As can be seen from the aerial imagery, alluvial aquifers are easily identified by the white sand in the riverbed. In Botswana, they are known as 'sand rivers', and are widely developed for small, intermediate and large-scale irrigation, village and domestic use. The method described for locating areas of enhanced development of these alluvial sands provides an easy means of identifying significantly larger aquifers that offer substantially more water.

Alluvial aquifers are capable of supporting significant developments, for example:

i. The Limpopo River west of Beitbridge has approximately 10,000 ha irrigation developed on both sides of the Limpopo in Zimbabwe and South Africa.

ii. The Save River in Middle Save were some 15,000 ha. irrigation is supported by dam releases from the Osborne Dam on the Odzi River upstream.

iii. The Mzingwane River with some 1500 ha supported by Zhove Dam releases upstream.

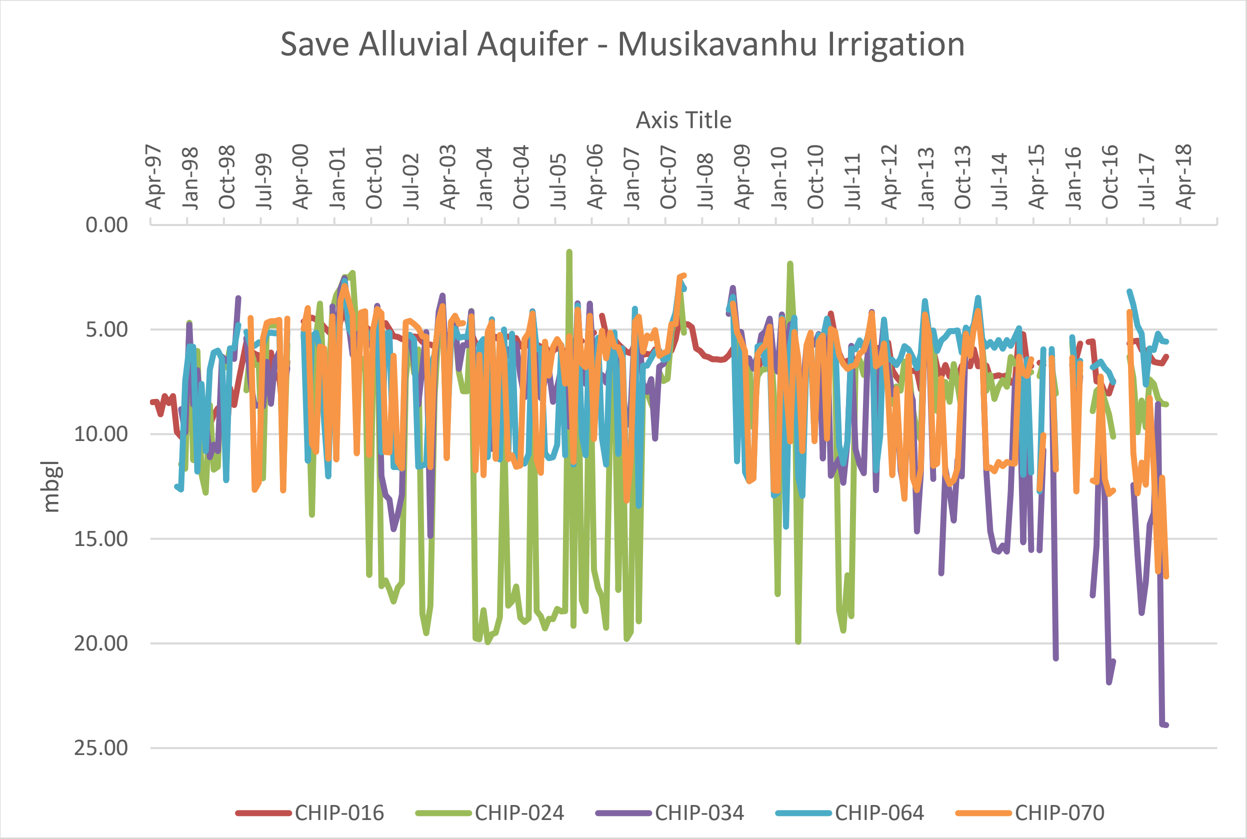


Figure 17: Borehole hydrographs from the Save alluvial aquifer – Middle Save irrigation scheme. These show very high annual variations up to 15 m indicating high recharge rates by direct infiltration from the river flow, almost certainly supported by dam releases from Osborne Dam. However, there is no information on whether the boreholes are pumped or at rest and these extreme fluctuations may also represent pumped and not-pumped states.

A major irrigation development, Middle Save, along the Save River (Figure 18), abstracts water from alluvial sands by means of pumping from ponds excavated into the alluvial riverbed. Hydrograph data for the Save aquifer (Figure 17) shows that the water levels in the alluvial aquifer are drawn down very substantially on a monthly or even more frequent basis, with variations of 20 m or more. While abstraction can account for 20 m declines in water levels, a rise of 20 m in water level cannot be accounted for by direct recharge from rainfall, which is quite low in this area (350-600 mm/year), and in fact, most of these water level fluctuations occur in the dry season. There can be no doubt that this recharge is a result of infiltration from river flows, and Osborne Dam releases and that without recharge from river flows, the alluvial aquifer would not be able to sustain this level of abstraction.

The actual abstraction rates are not known since water is not being abstracted by an institution but by a large number of private farmers. However, some well yields from the Save aquifer have been recorded in the ZINWA groundwater database (Table 3). These show that the Save alluvium support very high yields (Table 3) as a result of the very high permeability of the river sands. The large water table fluctuations shown in the hydrographs show that the storage in the aquifer is limited and that the recharge is high, and that recharge occurs several times each year.

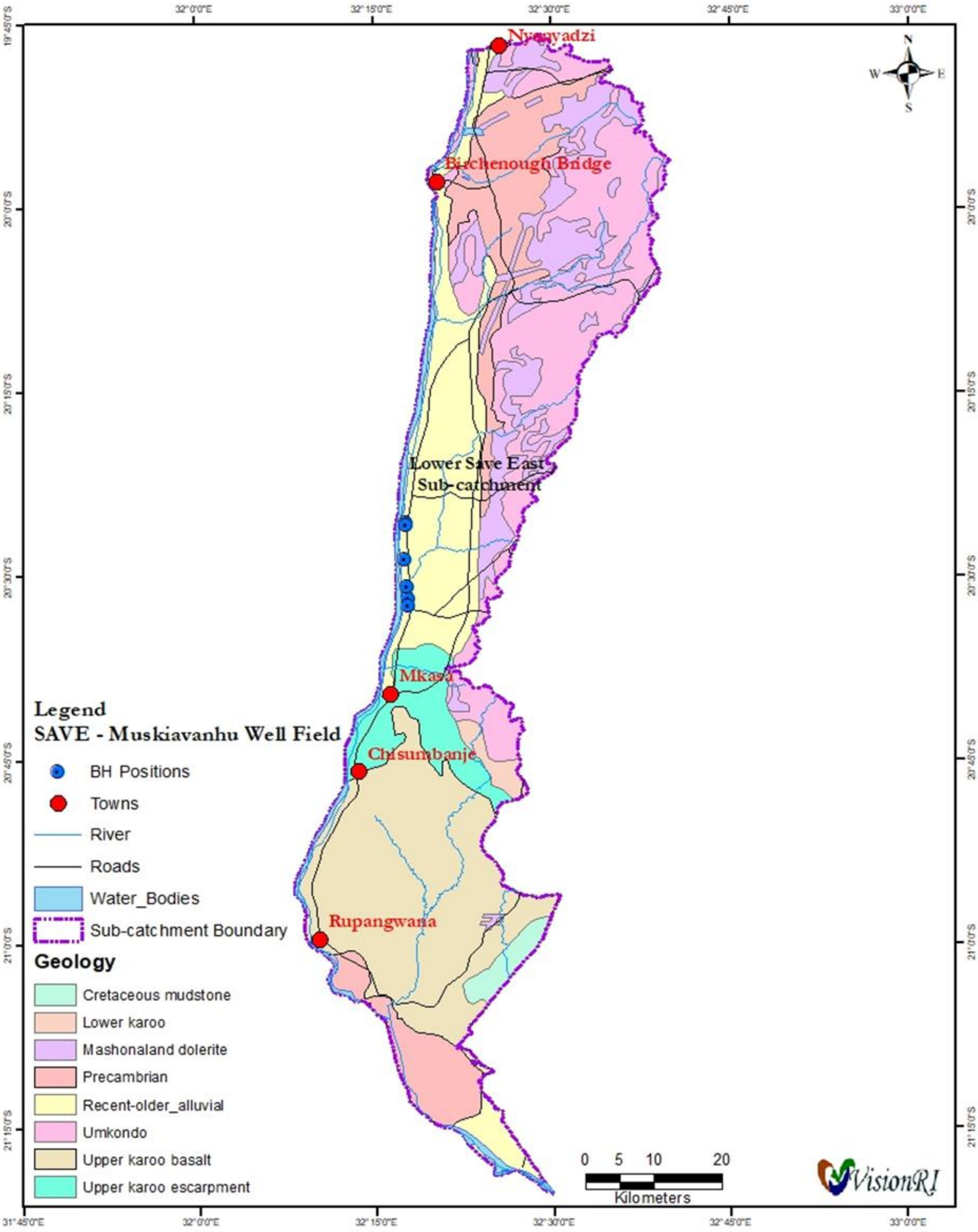


Figure 18: Lower Save East sub-catchment with Musikavanhu irrigation well field developed from the alluvial aquifer.

Table 3: The 64 highest yielding boreholes in the ZINWA groundwater database all occur in the Lower Save East sub-catchment, and the geology is recorded as alluvium sand.

Sub-Catchment	Well ID	Blowing Yield (litres/sec)
Lower Save East	0-CHIP-010	100.00
Lower Save East	0-CHIP-058	100.00
Lower Save East	0-CHIP-002	95.00
Lower Save East	0-CHIP-013	95.00
Lower Save East	0-CHIP-001	90.00
Lower Save East	0-CHIP-005	90.00
Lower Save East	0-CHIP-006	90.00
Lower Save East	0-CHIP-064	90.00
Lower Save East	0-CHIP-011	85.00
Lower Save East	0-CHIP-032	85.00
Lower Save East	0-CHIP-021	80.00
Lower Save East	0-CHIP-067	80.00
Lower Save East	0-CHIP-031	75.00
Lower Save East	0-CHIP-044	75.00
Lower Save East	0-CHIP-065	75.00
Lower Save East	0-CHIP-068	75.00
Lower Save East	0-CHIP-009	70.00
Lower Save East	0-CHIP-012	70.00
Lower Save East	0-CHIP-015	70.00
Lower Save East	0-CHIP-018	70.00
Lower Save East	0-CHIP-047	70.00

Note: It is unlikely that these are the only boreholes in Zimbabwe with such yields, but they are not recorded in the groundwater database.

Alluvial systems: One of the key questions in determining the productivity of alluvial aquifers is the water balance, particularly since these aquifers tend to be local and limited in size. Alluvial aquifers are almost invariably fully recharged each year by river flow from the upper catchment.

A key potential outflow is via a seepage through the riverbed, which is controlled by the permeability of the bedrock underlying the alluvial sands. If the bedrock is impermeable, then the alluvial water will not be lost to seepage, but if the bedrock is permeable, then alluvial water can drain away to deeper levels, and into less permeable strata. It is then less easily accessed. If the bedrock is impermeable, the alluvial water level in the channel tends to stabilize around 1m depth below the sand surface, which is the approximate maximum depth for evaporation from the sand. If in the absence of abstraction, the water depth is greater than 1m, then this indicates that the bedrock is permeable.

Development of alluvial aquifers: Many of the alluvial aquifers in Zimbabwe occur in the southern 'low-veld', a semi-arid part of the country with limited available water. The presence of these alluvial aquifers offers an opportunity for the development of small-scale local irrigation to provide improved nutrition and food security. In these areas, the population is most often settled along with the stream courses, where they obtain their water supply from the alluvial sands. Spaced development of gardens along these alluvial channels would appear to be an option worth developing, and Dabane Trust NGO has a programme that specifically develops small scale water from these alluvial channels, and delivers it to garden plots developed alongside the river channel.

The development of alluvial water is often by means of well-point or drive points which are driven into the sand bed below the water table and the water is extracted by suction lift. For larger commercial irrigation developments, a series of drive points linked to a manifold and a suction lift pump at the riverbank have been used. Alternately, boreholes have been drilled into the alluvial plain alongside the river channel. Hand pumps such as the rower pump, treadle and "simbi" pumps have also been used for small garden development as well as suction lift motorized pumps.

One issue has been the water salinity. As the channel aquifers have been pumped down, saline water from the alluvial plains has flowed into the channels, and this saline water is not well suited to irrigation. Salinization of irrigated land is a world-wide problem. For Mzingwane and Save, freshwater releases from Zhove and Osborne Dams respectively have helped to mitigate the ingress of saline water from the alluvial plains, and this is an aspect of alluvial water abstraction that needs to be monitored very closely.

Summary: There are many alluvial aquifers scattered in low relief areas, principally around the low altitude periphery of the country. These aquifers may have limited water, but they are annually recharged by fresh river flow and are easily accessible groundwater resource suitable for irrigation development, from garden scale to commercial scale. They often occur in areas with very limited alternative water supplies and may offer a critical productive water resource to communities living in these dry areas.

2.2.8 The issue of double counting for alluvial aquifers

A further question often asked by water managers: Is alluvial water surface water or is it groundwater? And how can we be sure that this water is not "double-counted", once as surface water and once as groundwater? The question of whether it is surface, or groundwater depends on your preference. It flows down the river channel, but it is stored in the sands beneath the channel floor. Since it is stored in earth materials, all the issues of porosity and hydraulic conductivity and hydraulic gradients are present in the analysis and measurement of alluvial groundwater and its movement.

The question of double counting requires more thought. It depends on where and when the counting takes place. If, for example, there is a river flow gauging station upstream of the alluvial abstraction, then this gauging station will have counted the river flow that in turn saturates the downstream riverbed sands and becomes alluvial groundwater. If you then count abstraction from these alluvial sands as new water, you will be counting this water twice. However, if there is no upstream gauging station and only a downstream gauging station, then counting the alluvial abstraction will not result in double-counting since the flows downstream will be reduced by the amount abstracted.

The Save well-field is probably a location where the issue of double counting should be considered. Water releases from Osborne Dam will presumably be counted as part of the annually available surface water resources. And water abstracted from the alluvial sands at the Save irrigation scheme may be counted as part of the annually available groundwater resources. However, the analysis of the well hydrographs for the Save alluvial aquifer shows recharge rates that far exceed the recharge that can be expected from infiltration of local precipitation. The alluvial aquifer is recharged from river flow water, most likely Osborne Dam release water.

2.2.9 Double counting for other aquifer systems

For other lithologies, the issue of double counting needs a similar analysis. In other words, where is the water being counted in the context of the direction and the rate of the flow in the groundwater system? Typically, the impacts of groundwater abstraction are local and tend not to impact on distant surface water flows. This is a generalization. It may be said to generally hold true in local fractured aquifer systems developed in crystalline basement aquifers.

In large sedimentary basins, when groundwater abstraction is of the large volume that exceeds the annual recharge rate, and where it continues for an extended duration, then, over time, the water level in the aquifer(s) will become depleted and the groundwater levels will decline. These declines impact on baseflow and perennial gaining streams will become ephemeral losing streams. The simultaneous decline in river flow with the increase in groundwater abstraction will offset to impacts of possible double counting.

For Karst aquifer systems, the groundwater flow rates are similar to surface water flow rates since flow takes place in large open solution channels developed by the dissolution of the soluble limestone. If a stream gauging weir measures flow upstream of a karst system and then the surface water flows downstream and onto the karst aquifer system, then this surface flow can readily recharge the underground karst aquifer system and the surface flows can disappear entirely into a sinkhole or swallow hole. This is known as interrupted drainage (Figure 19). If groundwater level monitoring is taking place in the karst aquifer system (such as is taking place in the Lomagundi aquifer), then these groundwater levels will be responding to the surface flows captured by the "interrupted drainage" system. In such circumstance, "double counting" of the water resources can take place: upstream of the karst aquifer first as surface water flow, and again within the karst aquifer as groundwater recharge.

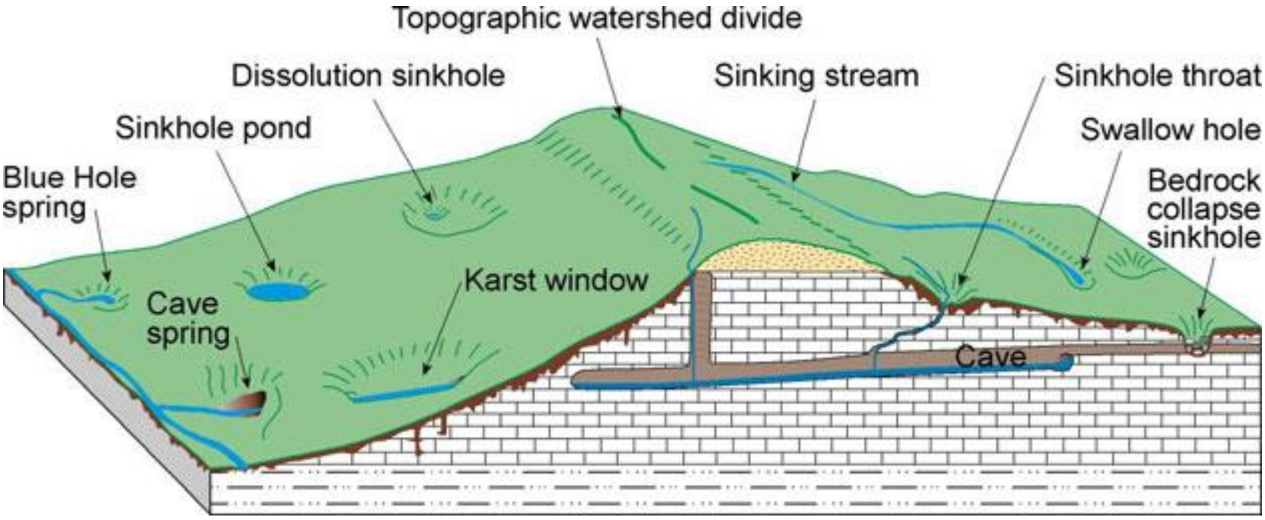


Figure 19: Interrupted drainage. If the surface flows are measured in the sinking stream (Qs ML/year) and then added to the cave spring discharge (Qgw ML/year), then there has been double counting. If instead of spring discharge, there is large scale groundwater abstraction, and that is counted, then there will have been double counting.

The Lomagundi dolomite aquifer in northern Zimbabwe is a possible candidate for double counting. However, it will require a detailed mapping of the aquifer system abstraction points, and abstraction rates together with both up and down-stream flow gauging of streams that flow across the aquifer system to identify possible double counting.

The issue of double counting is, therefore, one of understanding flow patterns, flow directions, flow rates and the distribution of gauging stations, whether for surface or groundwater.

2.3 SECONDARY POROSITY FRACTURED AQUIFERS

2.3.1 Karst aquifers

Karst aquifers occur in carbonate rock types such as limestone and dolomite that are soluble in weak acids, such as rainwater. This gives rise to solution channels and caverns as seen in limestone cave systems. The Lomagundi dolomites are a karst aquifer system. As secondary porosity fractured aquifers, these karst systems have moderately low porosities. However, they have extremely high permeabilities due to open channel flow along the solution channels. The result of these properties is that very high borehole yields are common, but high abstraction rates tend to lead to a rapid decline in aquifer water levels since storage is limited.

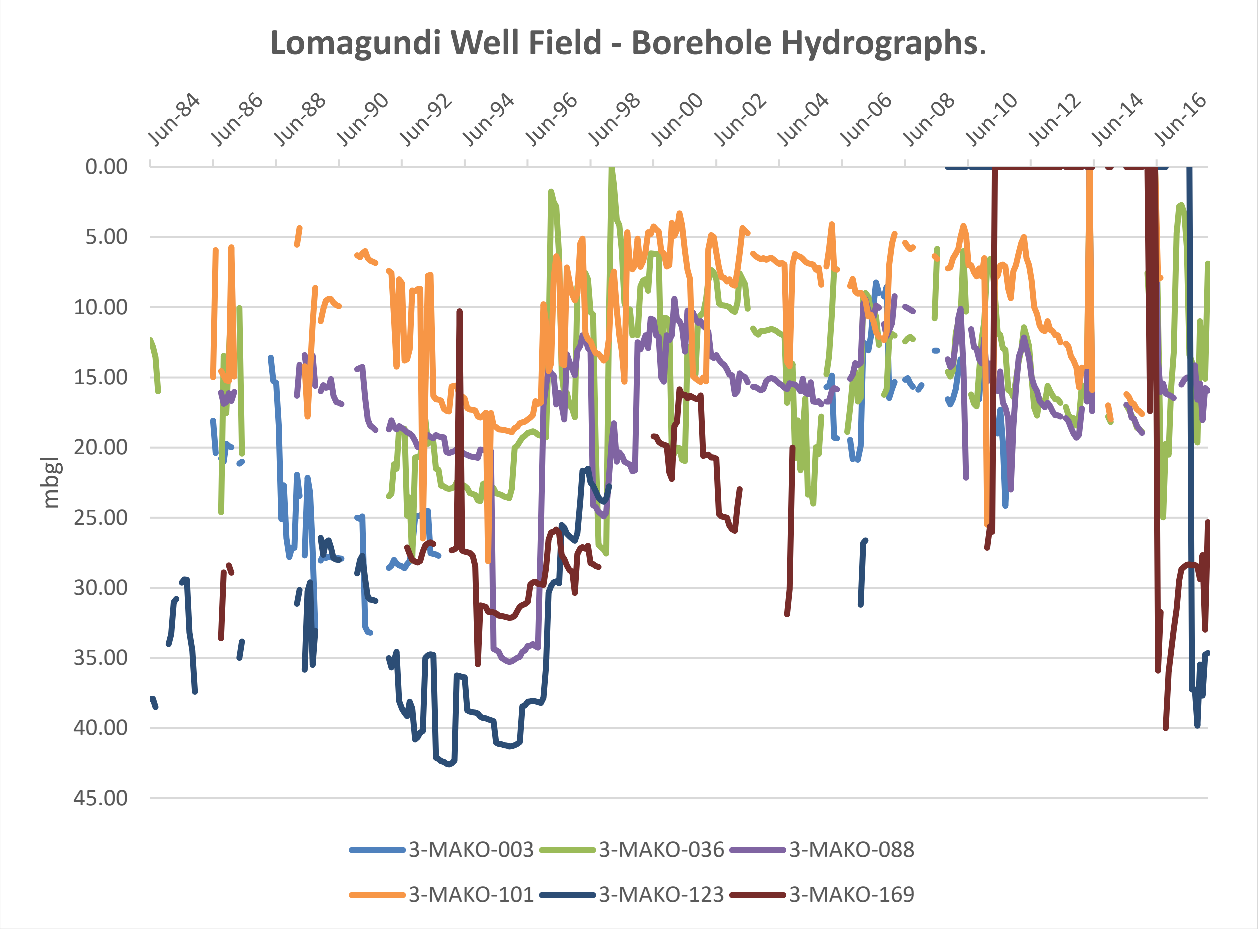


Figure 20: Well hydrographs from observation boreholes in the Lomagundi aquifer. There is no information on whether these data are from pumping boreholes or boreholes at rest. Hence the data can seem contradictory at times e.g. June 84 to June 92, while at other times they show similar trends and are more coherent, presumably reflecting aquifer behaviour e.g. June 94 to June 98 and June 10 to June 14.

The observation well hydrographs (Figure 20) show that there was a significant drawdown in the aquifer between 1992 and 1997 when water levels declined 10 to 20 metres in a space of 5 years, and then recovered quickly from around 2000 to 2015, most likely due to declines in irrigation abstractions associated with the fast track land reform. Water levels have again started to decline rapidly from 2016. The rapid fluctuations of the water levels suggest an unconfined aquifer receiving significant rapid recharge, which is likely to be a mixture of direct recharge from rainfall and focused recharge from river flow via sinkholes (see Figure 19). A further observation is that the water level changes, across all the observation boreholes, tend to follow a very similar trend, which is typical of karst systems since water level equilibrate rapidly due to the open channel flow.

In terms of further development of the aquifer and increasing abstraction rates, caution is advised. As can be seen from the map (Figure 21), the Lomagundi Dolomite aquifer is a rather thin arcuate body of modest aerial extent and that is a limitation of the volume of water that is available for abstraction.

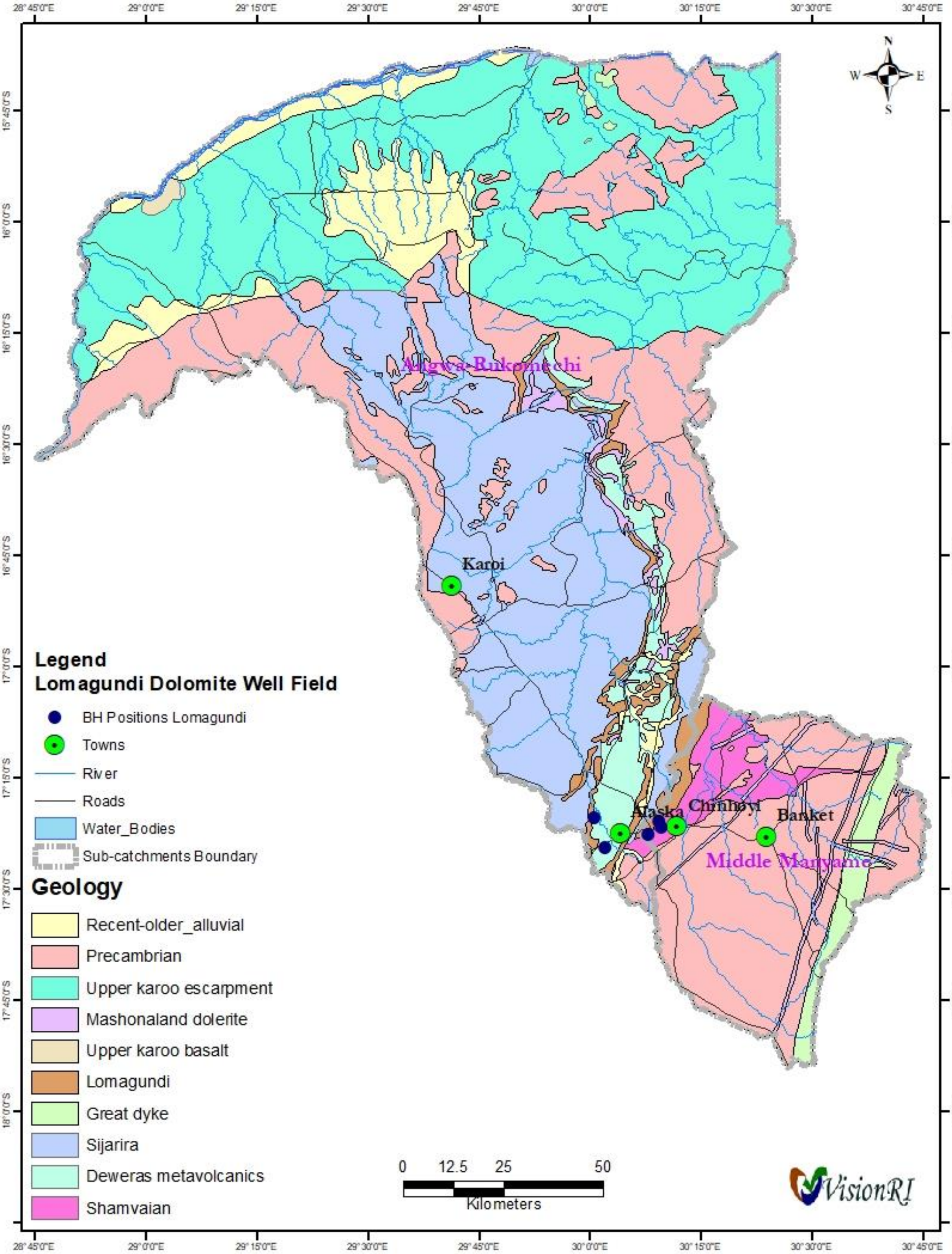


Figure 21: Lomagundi well field area. Note the Lomagundi Dolomite aquifer is a thin arcuate body (in brown colour)

An important factor in groundwater management here is that ZINWA has approximately 200 observation boreholes spread around the well field. Regular monitoring of these boreholes will provide early warning of excessive water level declines and allow ZINWA, and the water users to face the issues armed with actual data. This monitoring lies at the heart of any wise sustainable use of the groundwater resources.

2.4 FRACTURED AND WEATHERED REGOLITH AQUIFERS

2.4.1 High yield boreholes

Approximately 65% of Zimbabwe is covered by low productivity secondary porosity aquifers with low yield boreholes. Thus, Zimbabwe cannot be said to be a groundwater rich country. Nevertheless, there do exist opportunities for further groundwater development at selected localities within these aquifers. Such opportunities coincide with, for example, greater thickness of regolith developed and preserved due to favourable local conditions with regards to erosion and topographic wetness; or due to a favourable orientation of intersecting joints or productive faults, weathered and fractured lithological contacts.

The hydrogeological controls on such high yielding boreholes are to a significant extent understood and can guide in identifying localities with potentially higher borehole yields. These include stress field and fracture orientation, erosion surface and slope, and topographic wetness. For example, the principal compressive stress in Zimbabwe is generally oriented NE-SW and therefore fractures/joints in this orientation are likely to be under dilation pressure, and hence more open and with higher yields.

These high yield boreholes tend to be scattered across various parts of Zimbabwe as a result of local conditions. Arbitrarily we can assign a borehole yield value of > 2 litres/sec as a high yield borehole. Many of these higher yield boreholes are fitted with hand pumps that only pump 0.4 litres per second.

Table 4: Borehole blowing yields from the ZINWA groundwater database

Borehole Yield (litres/sec)	Number of Boreholes	Cumulative number of Boreholes
➢ 100	3	3
60-100	37	40
30-60	34	74
20-30	36	110
15-20	30	140
10-15	93	233
9-10	29	262
8-9	32	294
7--8	55	349
6-7	121	470
5-6	254	724
4-5	309	1,033
3-4	488	1,521
2-3	940	2,461
1-2	2,100	4,561
➢ 0	5,185	9,746
No data	8,871	18,617

Out of 18,617 boreholes in the ZINWA groundwater database, 9,746 have blowing yields recorded at the time of drilling. It should be noted that blowing yields recorded at the time of drilling often decline with time. The blowing yields for 4,561 boreholes are greater than 1 litre/second, and Table 4 and Figure 22 show the range in terms of yield. There are 2,461 boreholes (13.2%) with a yield greater than 2 litres/second. Many of these boreholes are fitted with hand pumps, although others, particularly the very high yield boreholes are pumped for productive use. The location of these boreholes is recorded, and they represent a distributed and dispersed productive groundwater resource. These high yield boreholes have been plotted on a map of Zimbabwe (Figure 23). This is not a comprehensive list of boreholes, but it serves to indicate that high yield boreholes are more common in the eastern and north-eastern parts of the country and that Zimbabwe has relatively few high yield boreholes.

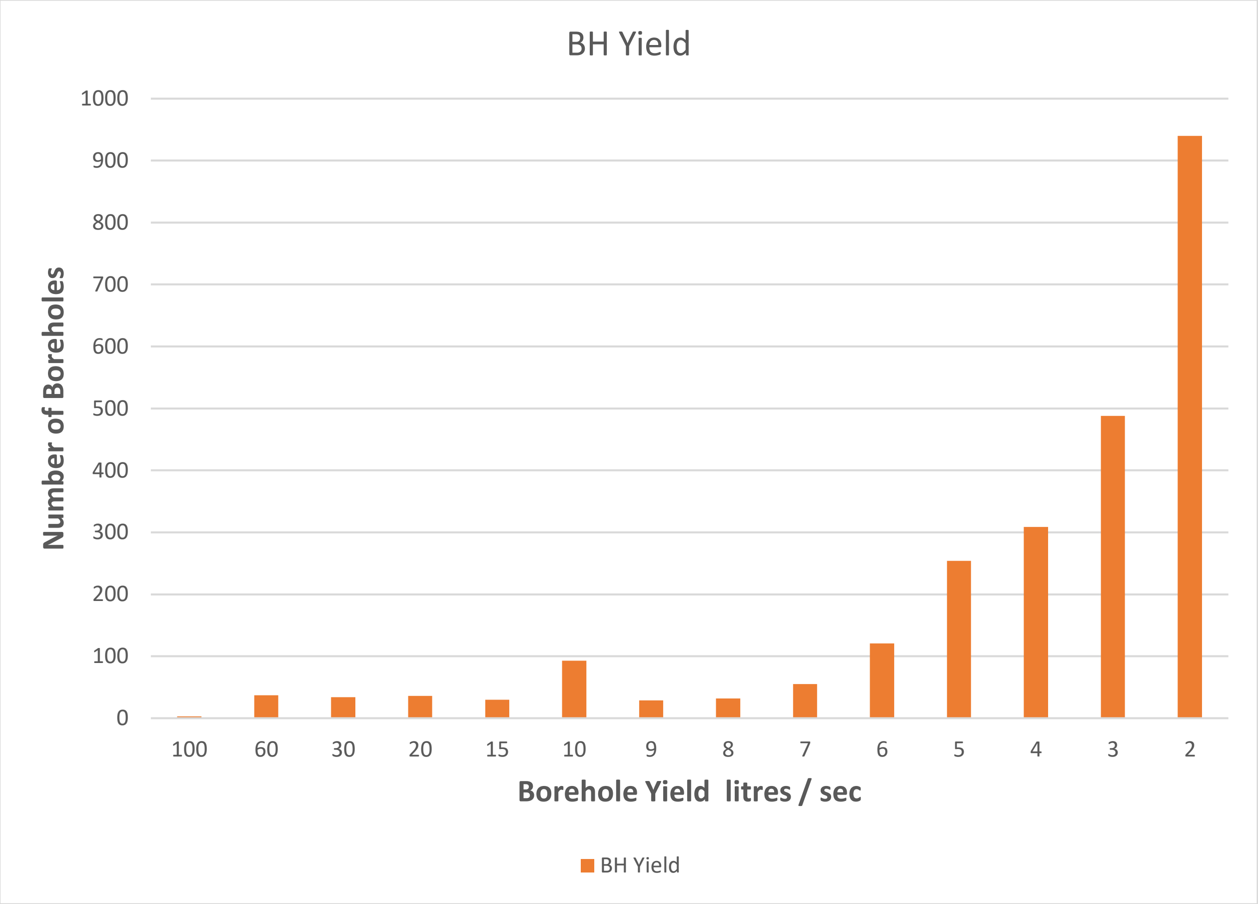


Figure 22: High yielding boreholes in ZINWA groundwater database.

There are many more boreholes in Zimbabwe than are recorded in the ZINWA groundwater database. Boreholes drilled on commercial farms were generally not recorded by the ZINWA Groundwater Division. The RWIMS database has 59,942 boreholes recorded but there are no numerical yield values recorded. Many of these boreholes will also be high yielding.

There exists the possibility that many of these boreholes can be fitted with motorized pumps to allow for an increased local water supply that may be used for a variety of activities such as nutrition gardens (NGADI project), irrigation, brick-making, food processing or micro-industries. In the 1990s, a pilot project was carried out at Romwe into the sustainability of groundwater use from basement aquifers for irrigated nutrition gardens. The project outcomes were positive, from the hydrogeological, agricultural, and socio-economic perspectives. It was planned to expand as the “NGADI” project and to develop 100 similar gardens in Masvingo Province, but this was never realized.

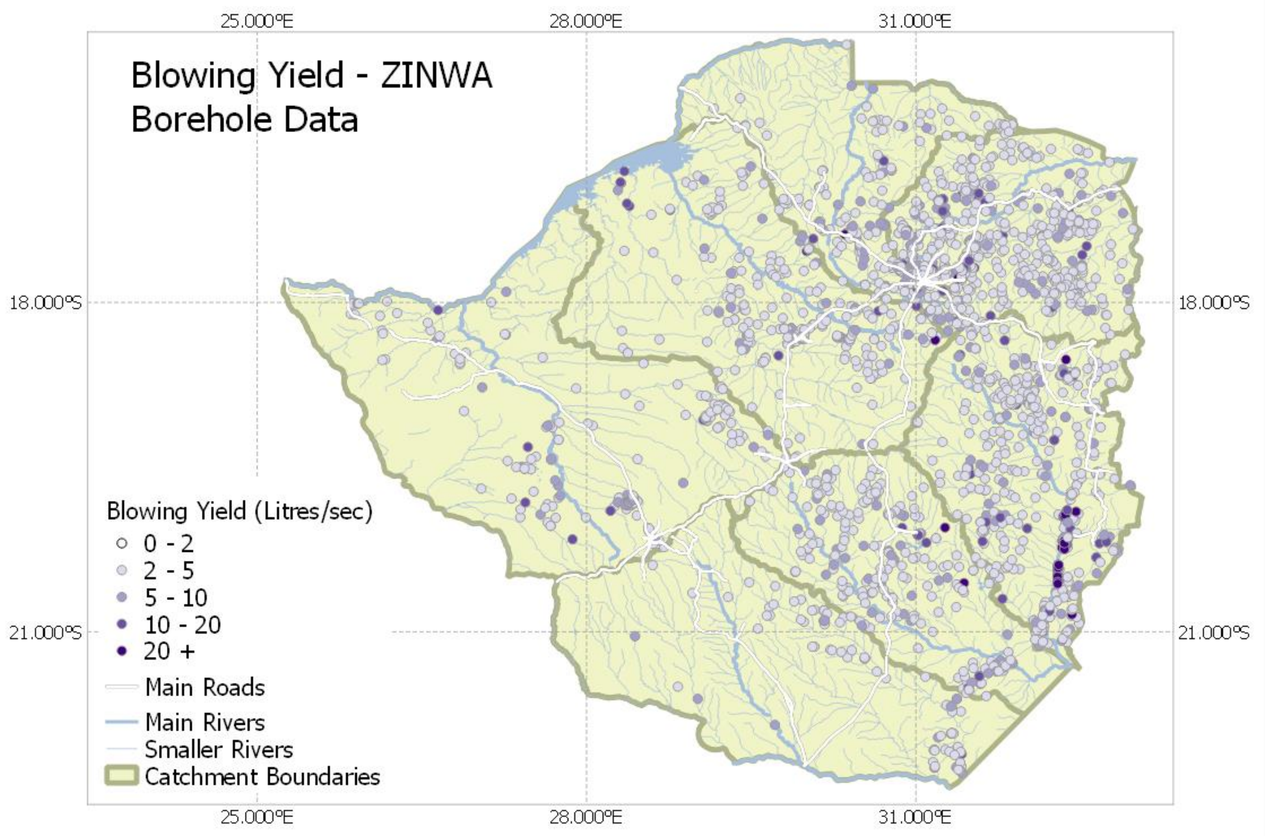
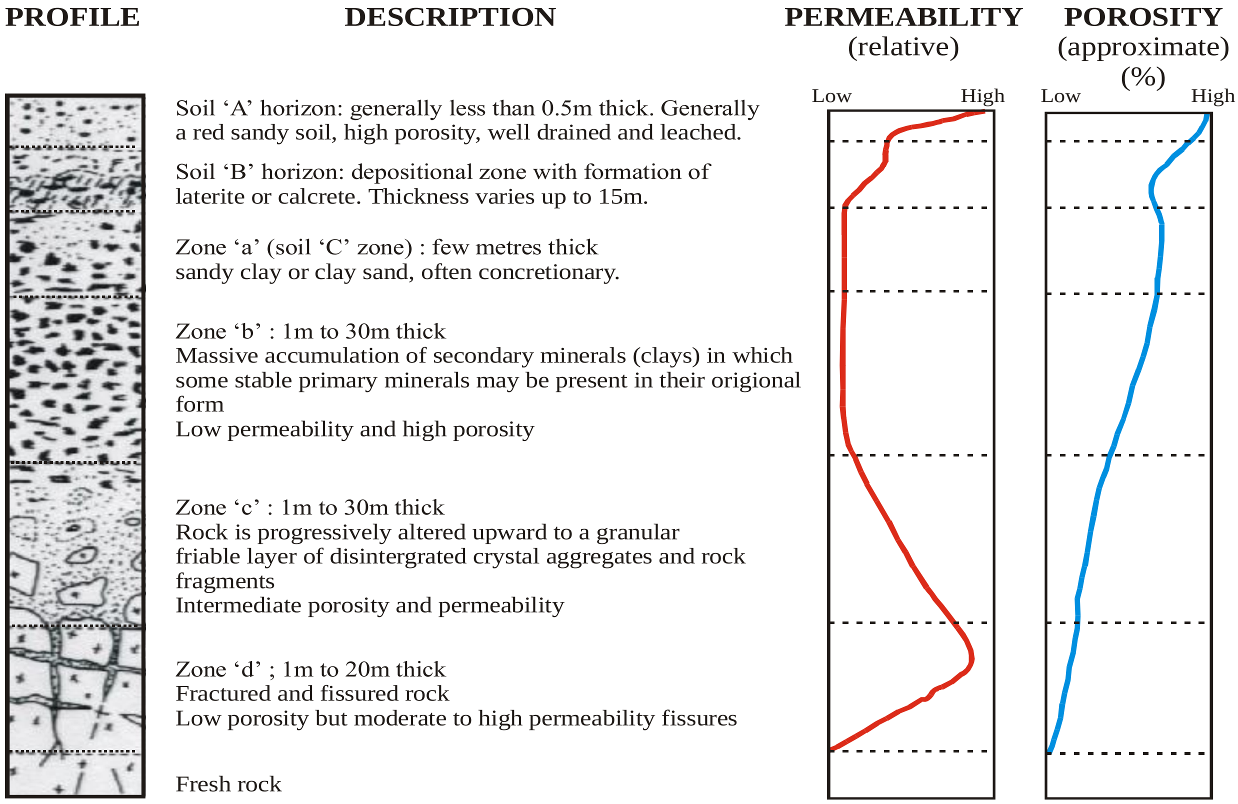


Figure 23: High yield boreholes in Zimbabwe: All boreholes in the ZINWA groundwater database with yield > 2 litres/second have been plotted.

In summary, there does exist a disbursed potential from Zimbabwe's groundwater resources for local small to medium scale economic production. A better understanding of the distribution of these resources will provide local communities and entrepreneurs access to valuable groundwater.

2.4.2 High yield boreholes in the fractured crystalline basement aquifers

When one drills a groundwater borehole in a crystalline rock area, one initially drills through the soil profile and then the weathered and decomposed rock near the surface, this is called the saprolite. As the depth increases, the rock typically becomes less decomposed and more intact and blockier; this is called the saprock. The saprolite and the saprock together form the weathered regolith. At depth, anywhere from 5 to 50 m in Zimbabwe, fresh intact bedrock is intersected. A typical vertical profile is shown in Figure 24 and the porosity and permeability profiles are shown alongside the lithological log.



Soil ‘A’ horizon: generally less than 0.5m thick. Generally a red sandy soil, high porosity, well drained and leached.

Soil ‘B’ horizon: depositional zone with formation of laterite or calcrete. Thickness varies up to 15m.

Zone ‘a’ (soil ‘C’ zone) : few metres thick sandy clay or clay sand, often concretionary.

Zone ‘b’ : 1m to 30m thick
Massive accumulation of secondary minerals (clays) in which some stable primary minerals may be present in their origional form
Low permeability and high porosity

Zone ‘c’ : 1m to 30m thick
Rock is progressively altered upward to a granular friable layer of disintergrated crystal aggregates and rock fragments
Intermediate porosity and permeability

Zone ‘d’ ; 1m to 20m thick
Fractured and fissured rock
Low porosity but moderate to high permeability fissures

Fresh rock

Figure 24: Typical regolith profile for crystalline rocks with porosity and permeability shown

Source: Acworth 1987

The bedrock essentially has no porosity or permeability and all the groundwater will be located in the weathered regolith. These are unconfined water table aquifers. It makes no sense to drill deep into the fresh unfractured rock below the regolith. It can also be seen that the permeability is at a maximum in the fractured part of the profile just above the fresh bedrock (Figure 24).

Based on this, when prospecting for groundwater in the crystalline basement it is advised to target fractured areas where groundwater occurs, and the permeability is high. Fractures and other linear features, such as dykes and geological contact zones, can often be seen quite easily on satellite images. Fractures are good groundwater targets, regardless of the rock type, since they represent areas where the rock is broken and hence has a higher porosity and permeability. Fracture intersections are even more productive.

Figure 25 shows a satellite image for a granitic area in the south-east of the country. A study of this image indicates that there is a fracture pattern and that there are certain dominant fracture orientations and most fractures fall into this pattern. In Zimbabwe, the principal fracture orientations are northeast-to-southwest (blue line), north-to-south (orange line) and northwest-to-southeast (red line), as shown in Figure 25.

Not all fractures orientations are equally productive when it comes to groundwater yield. Those fractures that are open are more productive while those that are closed tend to be less productive or even dry. However, generally speaking, any fracture orientation is more productive than unfractured rock.

Figure 25: Granitic crystalline basement. The lineaments are readily visible as "lines" on the image. Some of these lines represent straight river reaches (e.g. NE corner of the image); other lines, especially those oriented NE (blue line) are dykes. Fractures and fracture intersections are generally good for groundwater. Regional principal compressive stress is NE-SW oriented and therefore the NW fractures (red line) are under compression, while the NE fractures (blue line) are under dilation and tend to be most productive for groundwater (Image scale approximately 50 km x 80 km).

Fractures are more open or less open depending on the orientation of the regional tectonic stress field. Where the tectonic compressive stress is perpendicular to a fracture, that fracture will be compressed and closed, whereas if the compressive stress is parallel to a fracture, that fracture will tend to dilate and be open.

The regional tectonic stress field in Zimbabwe is such that σ_1 – the principal compressive stress orientation is NE-SW (www.world-stress-map.org). Thus, in Zimbabwe, fractures, joints or any other form of lineament that is oriented NE tends to be under dilation and productive for groundwater (Owen et al., 2007). Although this does not supersede the requirement for proper surveying, it is a useful practical tip for those involved in borehole site selection.

2.5 MANAGEMENT AND SUSTAINABLE DEVELOPMENT OF GROUNDWATER DEPENDENT ECOSYSTEMS

In Zimbabwe, there are three key groundwater-dependent ecosystems (GDEs): dambos and Kalahari contact springs, and alluvial flood plains. Alluvial groundwater has been discussed above in this chapter. The other two GDE types are found associated with specific hydrogeological settings and in these hydrogeological environments, such GDEs are widespread and present development opportunities, particularly for smallholder irrigation. Such wetlands, being groundwater-dependent, tend to be perennial rather than seasonal and this provides greater water security for any proposed developments.

In addition to these two key GDE system, there are local GDEs developed at "one-off" sites, such as discharge from individual artesian boreholes, spring flows from unique spring sites based on, for example, faulting, or other "one-off" situations.

The dambo and Kalahari contact spring GDEs offer opportunities that accrue to perennial, or at least long duration, water availability at the land surface. Such water flows/groundwater discharges, in the natural undeveloped environment, do provide ecosystems in terms of wetland flora and fauna that are valuable and useful to both humans and other species that inhabit these areas. Historically, such GDE wetland systems have been used for garden/micro-scale irrigation development.

2.5.1 Kalahari contact spring wetlands

The Kalahari unconsolidated aeolian sand is the most recent widespread deposition in Zimbabwe and where still present, it covers the underlying layers. The Kalahari is highly permeable and generally more permeable than the underlying bedrock. This gives rise to conditions well suited to contact springs, and in localities where the topography intersects the contact between the Kalahari and the underlying bedrock, there contact springs arise. The most common occurrences of these contact springs are between the Kalahari and the underlying low permeability basalt in the Lupane area, Matabeleland North and the contact springs between the Kalahari and the underlying basement gneiss in the Lower Gweru area. In these areas, perennial contact springs are found at discrete localities along the contact zone and most are developed for gardens and orchards.

2.5.2 Dambo wetlands

Dambo wetlands in Zimbabwe were studied extensively in the 1980s. Dambos in Zimbabwe covers approximately 1.2 million ha (Whitlow, 1985), representing an irrigation potential of approximately 200,000 ha (Bell et al., 1987). They also occur extensively in Malawi, Zambia, and Tanzania. Dambo wetlands occur principally on granite/granitic-gneiss terrain. Their prevalence in these lithological environments appears to be due to a number of key factors: -

- The sandy nature of the surface soils in these lithologies that promotes infiltration;
- Shallow slopes that facilitate infiltration and reduce surface runoff;
- The development of a duplex soil profile with a leached sandy upper layer overlying a heavy gleyed clay layer formed by the translocation of colloidal kaolinite vertically from upper to lower layer; and
- The upper sandy layer forms a perched aquifer resting on the gleyed clay, and water discharges at or near the surface when the topography intersects the sandy layer. This typically occurs halfway down the catena, in between the interfluves and the valley bottom.

Dambo wetlands are cultivated very widely throughout the sub-region and although there are concerns about their sustainability, there is also scientific documentation to suggest that, managed wisely, they can be used for irrigated garden development without significant degradation. The potential of GDE wetlands to support local small-scale irrigation appears to be immense. However, it is widely acknowledged (Faulkner and Lambert, 1991; Bell et al., 1987) that dambo cultivation should be practised with caution and that motorized ploughing and draining of dambos will have detrimental impacts. How to ensure that wise management is practised and how to avoid destructive practices needs to also be spelt out and integrated into land management policies and practices.

2.6 WELL FIELDS

The three well-fields in Zimbabwe have been discussed previously and a very brief summary is provided here.

i. Nyamandlovu well field (some 161 boreholes approximately 35 km northwest of Bulawayo: The aquifer formation is the Forest sandstone of some 100 m thickness, the uppermost sedimentary layer of the Karoo Supergroup. The aquifer is unconfined in the southwest and confined beneath the Karoo basalt (Batoka basalt) to the northwest. It was developed by ZINWA to supply water to the City of Bulawayo during the 1991 drought, but during non-drought years, the water is supplied to irrigators in the Nyamandlovu area. Water levels in most of these boreholes have been monitored monthly for 30 years from 1989 to the present. Abstraction has not been recorded for individual boreholes, although there is some data of total pumping from the well field.

ii. Lomagundi well field (approximately 198 boreholes): It outcrops near Chinhoyi as a narrow arcuate N-S body, extending approximately 150 km to the north. The aquifer formation is the Lomagundi dolomite, deposited in the Magondi Proterozoic basin. It is a karst system with high yield wells associated with solution caverns and channels. Earliest water level monitoring started around 1984 but became more widespread around 1990. Monitoring interval is monthly. The water is used mostly for irrigation. There are no abstraction data in the ZINWA records.

iii. Save well field (approximately 168 boreholes): It lies in the Save Valley, alongside the Save River, midway between Birchenough Bridge and Chisumbanje. The aquifer is the Save River alluvial sands and well hydrographs indicate that much of the water pumped is replenished by releases from the upstream Osborne Dam. The aquifer was developed to provide water for the Musikavanhu irrigation scheme. Monthly monitoring started in 1997 and became widespread in 2001. As is the case for the other aquifers, there are no abstraction data in the ZINWA well-field database.

It is recommended that groundwater modelling be carried out at the three well-fields in order to optimize aquifer productivity and to ensure sustainability. Attention is drawn to the importance of monitoring abstraction. Aquifer management cannot be effectively achieved without accurate abstraction records.

The Nyamandlovu and Save aquifers have been modelled previously and any new modelling can be built on the framework developed in the older models, hopefully without inheriting any false assumptions.

2.7 IDENTIFICATION OF CRITICAL GROUNDWATER THREATS

2.7.1 Introduction

The threat of groundwater becoming depleted and unavailable for human or biosphere use has been termed groundwater drought risk (Villholth et al., 2013). Typically, groundwater drought risk is highest when human dependence on and demand for groundwater is high and is combined with aquifers of low productivity and limited recharge. Such conditions prevail in much of Zimbabwe and the groundwater drought risk, especially in and around Harare has been classed as amongst the highest in SADC (Villholth et al., 2013). The sections of this report on groundwater mapping and groundwater and climate change expand on the issue of groundwater drought risk.

Zimbabwe is not blessed with abundant groundwater. 65% of the country is underlain by secondary porosity crystalline lithologies that are neither permeable nor porous in their fresh unweathered condition. This means that in these areas groundwater is only to be located in the surficial weathered regolith which extends no deeper than 50 or 60 meters, depending on the lithology, but which more typically is only 20 to 30 m deep. Although these crystalline basement aquifers have limited groundwater, the groundwater quality is generally very good and the depth to the water table is shallow, thus allowing easy access. These aquifers have been discussed above in the section on priority aquifers.

The remaining 35% of the country does have deep and extensive primary porosity sedimentary aquifer systems that contain abundant groundwater. The depth to groundwater is generally significantly deeper here and salinity, hard water, fluoride and other geogenic groundwater quality issues are more common in these areas.

The bulk of the population in Zimbabwe is located in areas underlain by the shallow low productivity crystalline basement aquifers. The key threats to groundwater in Zimbabwe are typically anthropogenic and these are discussed below.

2.7.2 Critical threats to groundwater

i. Lack of groundwater monitoring and groundwater management in all sectors: Despite the high risk of groundwater drought, there is little groundwater trend monitoring carried out in Zimbabwe by the water authorities. Groundwater levels are only recorded by ZINWA Groundwater Division at the three well-fields: Nyamandlovu (161 boreholes), Lomagundi (198 boreholes) and Save (168 boreholes). ZINWA has no other trend monitoring in the country: no recorded measurements of abstraction rates; not monitored water levels (except for the three well-fields); no water quality data.

   This is flagged as a critical threat and the primary groundwater project recommended by this report is the establishment of a nationwide network of groundwater monitoring boreholes.

ii. Over-pumping of urban groundwater: Many municipalities have been failing to supply water not only to existing ratepayers but in particular to new settlements, especially informal settlements. As a result, water users have drilled boreholes and dug wells to supply themselves with groundwater. Such users are required to obtain permits from the catchment councils and since there is no alternative water supply, the councils do tend to issue permits for domestic use on request.

Groundwater in parts of Harare is near exhaustion. The north-eastern quadrant of Harare has not had municipal water supply for ±15 years, and the households/users have been fully reliant on groundwater for self-supply. In many areas, the groundwater is now near exhaustion and more and more boreholes are drying up during the year. In drought years, poor groundwater recharge will push many of these boreholes to dry up, although they will probably revive after a period of good rains.

Urban boreholes in Bulawayo are in a similar condition and have also been developed by private users. Over the years, water levels have declined. Bulawayo municipality does, however, supply water to its residents on a regular basis and although there are periods where municipal water is rationed, water supplies do take place. This allows groundwater users to rest their boreholes when they show signs of stress.

Private urban groundwater abstraction is increasing in most municipalities and although controlled by the issuance of a "permit to drill", neither the abstraction rates nor the water levels are monitored. There is no official data on groundwater level changes in urban areas.

iii. Urban groundwater quality: It has been stated groundwater quality, rather than quantity, is the greatest threat to groundwater (UCL News August 2016). This statement is true for Harare and especially for the high-density suburbs. Waterborne bacteriological diseases, such as typhoid, have become endemic in Harare. Cholera is also an increasingly frequent health issue in Harare.

The formal high-density suburbs in Harare have been serviced with both by a waterborne sewage system and municipal treated water supply. However, the sewage lines have become blocked and frequent sewer burst occurs, discharging sewage into the local environment. There are also many pit latrines in these high-density suburbs.

The municipal water quality has declined over the years, and residents now prefer to drink borehole water. However, given the high and continuous contaminant load, the groundwater resources are now beginning to become contaminated. In particular, shallow unlined wells have become contaminated and typhoid and cholera bacteria have both been identified in deeper boreholes as well.

MSF–Belgium has been at the forefront of trying to supply clean groundwater to some of the high-density suburbs in Harare, notably Budiriro, Glen View, Mbare and Stoneridge. They have been pioneering various interventions ranging from infrastructural to community/social. Headworks inspections and repairs, in-line chlorination, and Health Clubs have all been put in place.

One of their innovative developments has been to install a very deep sanitary seal, 20 metres or more, around the borehole casing. The sanitary seals have thus far been cemented slurry, but bentonite seals are now being recommended, since bentonite does not dry solid and become rigid, but always remains plastic. Nevertheless, borehole contamination can still occur at depth by rapid groundwater transmission along fault zones. In the longer term, so long as large volumes of human waste are discharged by leaking sewers into the local environment, the underground water reservoir will in time become contaminated.

iv. Motorized groundwater pumping from shallow aquifers: Groundwater abstraction is increasing in rural areas (as in urban areas) using cheap generators and electric pumps that are now available at a fraction of the cost of hand pumps. Especially in peri-urban areas, where there is a high demand for vegetables for the urban markets, irrigation from groundwater is increasing rapidly using these cheap pumping technologies. As has been seen in the cities, motorized pumping from small local aquifers, especially to meet high irrigation demand, is probably unsustainable. It is advised that monitoring of abstraction rates and groundwater levels be instituted in these areas.

Solar water pumping is also becoming more widely used in Zimbabwe and is now the principal water supply system for wild-life water supply in Hwange National Park. However, the costs of solar groundwater pumping are still very high compared to standard submersible pumps and generator sets at this time.

v. Climate change threats to dambo wetlands: Dambo wetlands cover 1.28 million ha in Zimbabwe, of which 15–20 thousand ha are estimated to be used for irrigation, and they largely occur above 1,200 m elevations in areas with rainfall greater than 800 mm/year (Bell et al., 1987). Those dambos not used for irrigation are seen as a valuable resource for year-round livestock grazing.

Dambos are critical resources for the rural populations in Zimbabwe. However, Zimbabwe appears to presently lie at the climatic margin of dambo occurrence. The work by Bell et al. (1987) and predecessors such as Whitlow (1984) indicates that dambos are likely to be susceptible to climate change and that increased evaporation and decreased precipitation are both threats to their extent and capacity to provide shallow groundwater.

2.8 MAPPING GROUNDWATER RESOURCES IN ZIMBABWE

In order to approach the question of sustainable groundwater management in Zimbabwe, it is helpful to identify a framework within which groundwater resources can best be assessed.

2.8.1 Groundwater monitoring

At the outset, it is important to note that there is very limited data on groundwater in Zimbabwe. This condition is not unique to Zimbabwe alone but is a general condition of the groundwater resource everywhere due to the very high degree of heterogeneity, anisotropy, and 3D spatial complexity of groundwater reservoirs. Even where data is available, it tends to provide a rather limited understanding of the groundwater resources. In situations where groundwater data is very limited, such as Zimbabwe, assessment of the resource is generally done using a combination of theoretical analysis combined with limited local information. While such an approach is helpful, it is insufficient, particularly when the groundwater resource is under threat, either from pollution, over-abstraction leading to aquifer depletion or other threats such as climate change or river impoundments that may lead to changes in aquifer recharge or discharge.

The International Groundwater Resources Assessment Centre (IGRAC) strongly promotes the practice of groundwater monitoring as the best way to accurately assess groundwater resources. Monitoring should always be carried out for a defined purpose. In general, groundwater is monitored to provide a spatially distributed view of

- The groundwater levels in monitoring boreholes;
- The annual natural replenishment via recharge to the groundwater resource;
- The groundwater volumes held in storage;
- Abstraction rates and groundwater uses (and return flows);
- Groundwater quality; and
- Groundwater balance.

Since groundwater travels very slowly, with speeds ranging from a few meters per day to a few centimetres per century, anthropogenic impacts on groundwater conditions tend to be localized and do not have extensive “upstream and downstream” impacts. Furthermore, since the groundwater resource is highly variable spatially, a successful assessment system needs to capture that spatial variability.

Groundwater resource availability monitoring attempts to keep track of the groundwater balance by measuring the groundwater level response to various inflows and outflows from the groundwater system. It is based on regularly recording the groundwater levels in a suite of wells distributed across an aquifer. The groundwater level data is then used with other data sets that impact on groundwater recharge and discharge such as rainfall, base-flow and pumping, as well as monitoring other hydro geologically significant events.

Groundwater quality monitoring is also carried out for dynamic trend monitoring. It is advisable to appreciate that geogenic groundwater chemistry does not change much with time, but if an aquifer is pumped heavily and the water level lowers significantly, then the groundwater pumped from these lower levels is quite likely to have a naturally higher geogenic total dissolved solids (TDS) content and as a result, a higher electrical conductivity (EC).

Most other groundwater quality changes are likely to occur as a result of anthropogenic activity and therefore groundwater quality monitoring is often carried out in response to specific and impending threats such as local point sources of pollution (e.g. waste dumps) or diffuse pollution (e.g. urbanization, agriculture).

The development and installation of groundwater monitoring networks in Zimbabwe is strongly recommended. Such monitoring networks and monitoring protocols should be designed with care so that they meet to objectives of the monitoring program.

2.8.2 Assessment framework

One key focus of the NWRMP is to provide water resources, planners, and managers, with direct information on the availability, accessibility, affordability, and quality of the water resources. However, such information is not generally quantitatively available for the groundwater resources in Zimbabwe. The groundwater resources will have to be assessed in a semi-quantitative, spatially distributed manner largely by using estimates from literature and general theoretical information as a means to measure for the groundwater condition.

In the previous national water master plan (NMPRWSS – Interconsult, 1987), the groundwater resources assessment was focused strongly on the geology as the key parameter for assessing groundwater resources. A hydrogeological map of Zimbabwe was prepared, based directly on the geological units, and it classified the hydrogeological potential as either low, medium, or high.

Geology does provide an appropriate framework for assessing groundwater and hydrogeology. The geology of Zimbabwe has been mapped in some detail (at scales varying from 1:1m and 1:100,000 to locally large scale on mines) throughout most of the country, and this provides a valuable and appropriate framework for assessing the groundwater resources.

Geology is a key hydrogeologic variable and determines whether an aquifer is a primary porosity or fracture porosity; it determines whether the aquifer is surficial, unconfined and locally developed in the weathered regolith or whether it is a really extensive, extends to depth and may be confined. To a significant extent, it determines the bulk porosity and the thickness of the aquifer and hence the volume of water in storage. The groundwater chemistry and quality are often linked to the geology. The geology often determines the most appropriate development method to be used, whether dug well or deep drilling, the drilling method, the borehole construction, and the development technique.

In this NWRMP, a slightly different approach has been used, but one which nevertheless still holds the geology as a core hydrogeologic variable. The key groundwater recourses assessment tools are a new suite of spatially distributed maps. These maps are as follows:

- Groundwater recharge potential (current and future climate);
- Aquifer productivity;
- Groundwater development potential (current and future climate);
- Groundwater drought risk (current and future climate) (ref: Villholth et al., 2013);
- Groundwater vulnerability to pollution;
- Groundwater geogenic quality;
- Depth to the water table/thickness of the unsaturated zone;
- Borehole depth;
- Location of boreholes; and
- The RWIMS database maps – selected maps to highlight borehole seasonality and maintenance. (Rural Wash Information Management System – an online database managed by the National Coordination Unit).

Some of these maps have been previously available (e.g. Groundwater drought risk; RWIMS) but the rest of the maps have been developed during this project and are available at both national and catchment scale and are presented in this report and in the Water Resources Atlas, a companion output to the Master Plan reports.

Each of these output maps is produced by combining different spatial layers that impact on the final output map. For example, the aquifer productivity output map is dependent on a number of sub-characteristics such as aquifer class, aquifer porosity, aquifer thickness, aquifer transmissivity, borehole specific capacity, borehole yield, elevation, and slope. These are the spatial input maps.

The question then arises as to the availability and scale of the various map/data sub-sets and how they have been weighted or ranked relative to each other and then combined to provide a measure of the output parameter. The Analytic Hierarchy Process (AHP) (Saaty, 2008) has been used to weight and rank the various properties pairwise, and to thus provide a logical structured assessment of each particular groundwater resource condition.

Here we tabulate the parameters and sub-parameters that have been used to build the groundwater resources assessment maps. How these "building blocks" of groundwater resources assessments have been used in order to develop various groundwater maps are presented as a narrative so that the reader can understand how these maps have been produced and understand their strengths and their weaknesses and how they may be used to provide guidance towards sustainable groundwater resources management.

2.9 FRAMEWORK FOR GROUNDWATER MAP DEVELOPMENT

In this section, the parameters and sub-parameters used for assessing groundwater resources are discussed with an analysis of their role in groundwater resources assessment.

2.9.1 Key parameters and their constituent sub-parameters

Aquifer productivity: This describes the potential of an aquifer to sustain various levels of groundwater flow and/or abstraction from a properly sited and constructed borehole. It is, to some extent, a description of the aquifer's capacity to store groundwater and the volumes of groundwater held in storage as well as the aquifers capacity to release groundwater to pumping.

The following sub-characteristics have been used to create the aquifer productivity map and it should be noted that, apart from Elevation and Slope, all the sub-characteristics are principally derived from the lithology and the hydrogeological setting.

a) Aquifer classification;

  - Hydrogeology (lithology),
  - Primary or secondary porosity,
  - Average borehole yield,

b) Aquifer thickness;
c) Aquifer porosity;
d) Aquifer transmissivity;
e) Borehole specific capacity;
f) Borehole yield; and
g) Elevation and slope.

The information used for these sub-characteristics has been obtained from various literature sources and in particular, the NMPRWSS (1987) has been a key source of information. Table 5 shows the lithologically-based properties that have been used for the generation of the aquifer productivity map.

The properties that contribute to aquifer productivity all have the same spatial distribution as the lithological units, except the elevation and slope data, which have been derived from a DEM and applied as a contributing layer. Elevation and slope are related to erosion and hence to the thickness of the weathered regolith. Regolith thickness is a critical component of aquifer productivity for the crystalline basement aquifers. The other properties link to the storage capacity of the aquifer (a type of porosity, thickness, porosity) and to the well yield (transmissivity, well yield and specific capacity).

Ranking and weighting of the contribution of the different properties to aquifer productivity have been done using the Analytic Hierarchy Process (AHP) (Saaty, 2008). The resultant aquifer productivity output maps are shown in Figures 26 and 27. Figure 26 shows the aquifer productivity at a 100 m grid-scale while Figure 27 shows aquifer productivity at a 10 km grid scale. For the remainder of this section, the finer grid resolution maps only will be presented.

Masocha et al. (2014) first used this technique to develop a groundwater vulnerability map for Zimbabwe as part of a World Bank study on water quality in Zimbabwe (Murwira et al., 2013). Physical natural and anthropogenic factors (or properties) that impact on groundwater vulnerability were identified. Those properties that were available as spatial data, usually as raster images or shapefiles or gridded geo-referenced data, were identified. Thereafter the relative impact of the different properties on groundwater vulnerability was assessed using AHP matrices. This then provided the framework for combining the various input data layers to provide the output map: Groundwater Vulnerability.

The same approach has been used to develop a suite of different groundwater maps for this study.

Table 5: Aquifer productivity properties

Aquifer Class	Lithological Unit	Permeability /Porosity	Transmissivity (m^2/d)	Thickness (m)	Porosity (%)	Yield value (m^3/d)	Sp Cap Value (m^3/m/d)
Primary Porosity High Productivity	Kalahari sand	Primary	2,000	100	35	300-1,000	50-100
	Alluvial deposits	Primary	1,000	5	35	>1,000	>100
	Hwange SST (confined)	Primary	2,000	50	20	300-1,000	50-100
Primary Porosity Moderate Productivity	Karro Forest Sandstone	Primary	500	100	20	100-300	20-50
	Escarpment Grit	Primary	200	60	20	100-300	20-50
Primary Porosity Low Productivity	Madumabisa mudstone	Primary	100	60	20	20-50	<10
Secondary Porosity High Productivity	Lomagundi dolomite	Secondary	2,000	70	10	>1,000	>100
Secondary Porosity Moderate Productivity	Bulawayan metavolcanics	Secondary	500	50	10	100-300	20-50
	Tengwe Calcareous Sedimentary	Secondary	500	50	10	100-300	50-100
	Upper Karoo Basalt	Secondary	500	50	10	50-100	20-50
	Mashonaland Dolerite	Secondary	40	40	10	20-50	10-20
	Granite/Gneiss (African Erosion Surface)	Secondary	200	40	5	50-100	20-50
Secondary Porosity Low Productivity	Granite/Gneiss (Post African Erosion Surfaces)	Secondary	50	25	5	20-50	<10
	Cretaceous mudstones	Secondary	50	70	10	20-50	<10
	Shamvian	Secondary	10	40	5	<20	<10
	Umkondo Formation	Secondary	10	100	5	20-50	<10
	Sijarira	Secondary	10	100	5	20-50	<10
	Deweras	Secondary	10	60	5	20-50	<10
	Great Dyke	Secondary	50	40	10	20-50	<10

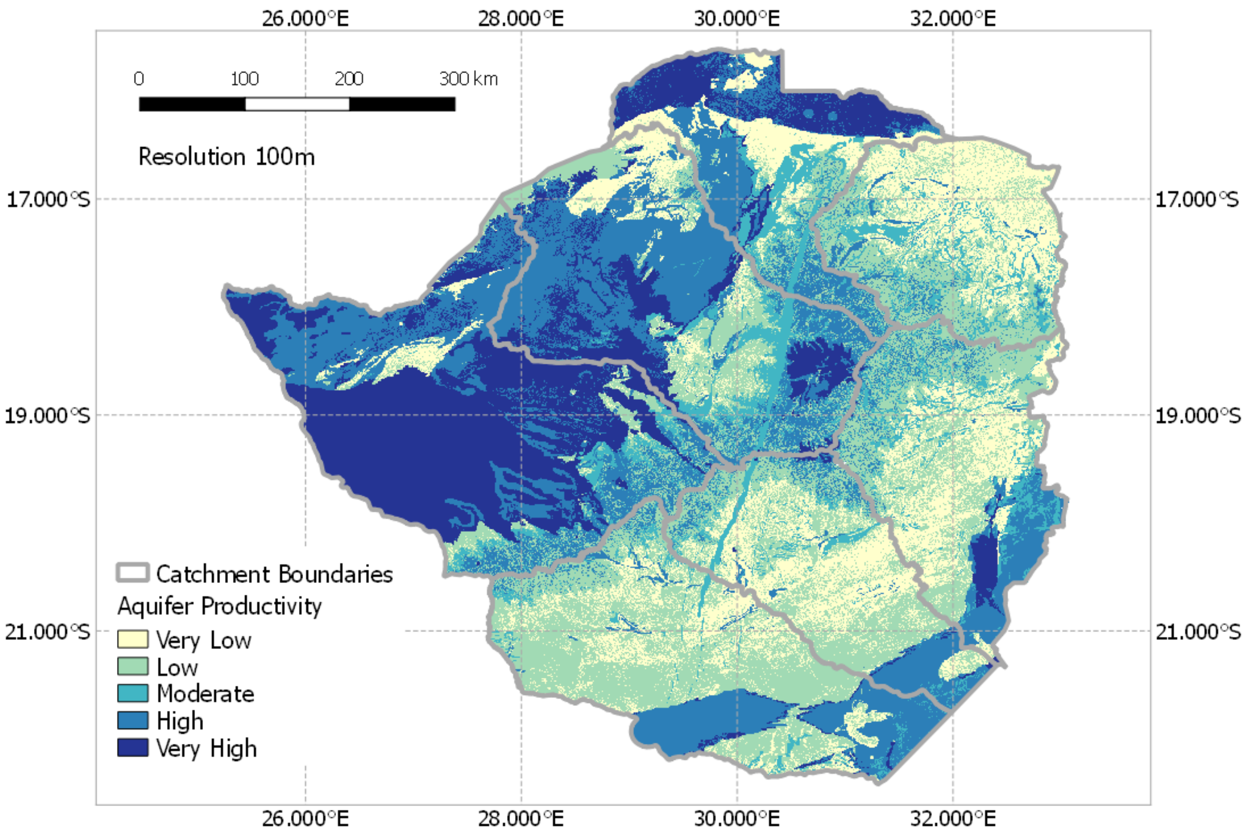


Figure 26: Aquifer productivity at a 100m grid scale. At this scale, the lithology is clearly defined as the basic component of Aquifer Productivity and this map looks rather similar to the geological map of Zimbabwe. Since all the properties (except Elevation and Slope) are spatially defined by the lithology, this is to be expected. The inclusion and ranking of the various properties provide differentiation in Aquifer Productivity throughout but without obscuring the boundaries of the lithologic units.

Each of the properties contributes to the final aquifer productivity ranking. The percentage contribution of the different properties to the aquifer productivity output map is calculated in the AHP matrix and is shown in table 6 below.

Table 6: Aquifer productivity AHP matrix

Aquifer productivity AHP matrix	Eigen vector	% contribution
Aquifer class	0.277	28
Aquifer thickness	0.283	28
Porosity	0.080	8
Transmissivity	0.221	22
Specific capacity	0.039	4
Yield	0.051	5
Elevation and slope	0.049	5

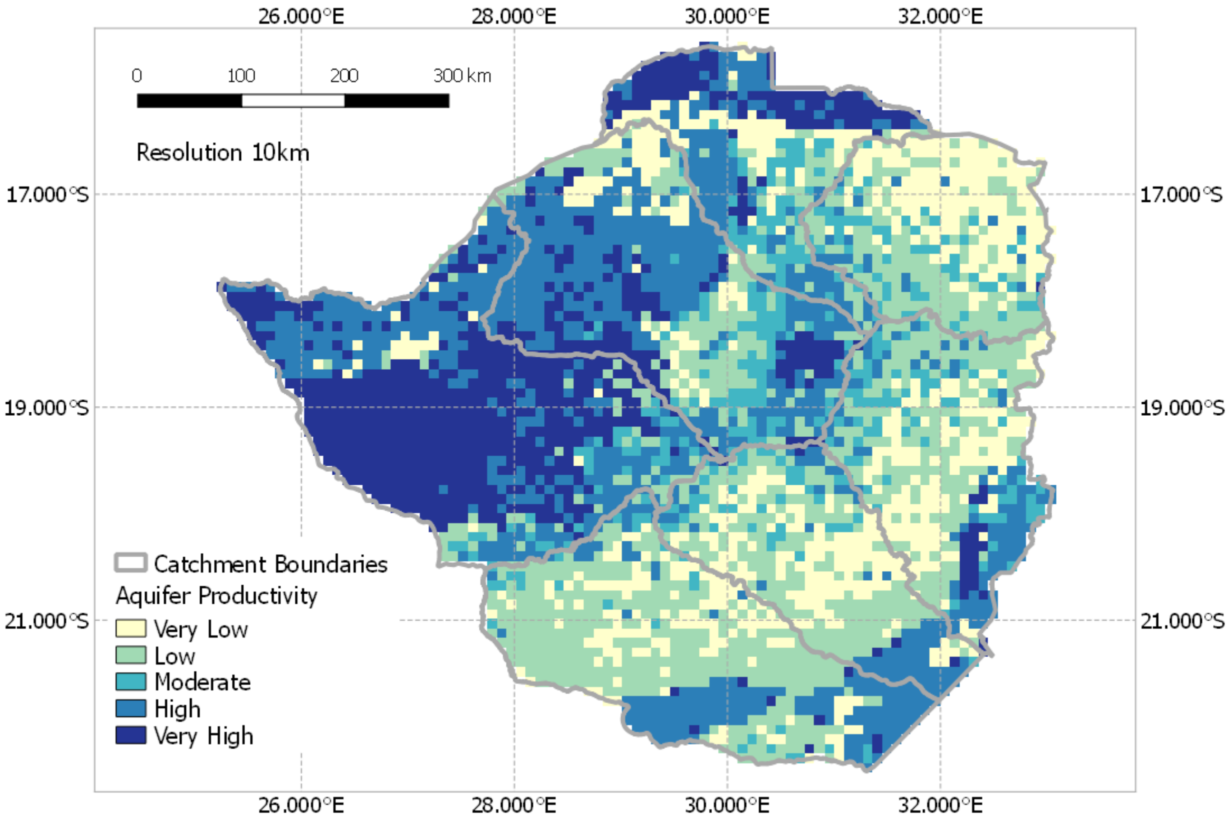


Figure 27: Aquifer productivity at a 10km grid scale. At this scale, the lithology is still discernible, but the boundaries are not sharp. However, the scale is more realistic in terms of the actual density of data and it is significantly less demanding in terms of computing power.

The aquifer productivity map has also been produced as a quantitative map where each class, from 'very low' to 'very high', has been assigned a depth as "metres of water" held in storage. It should be noted that this is not the saturated thickness, but rather the saturated thickness multiplied by the porosity, and it represents a volume of water held in storage.

The aquifer productivity volume will change if inflows via various recharge mechanisms are not balanced by outflows such as pumping and baseflow. There is insufficient information due to lack of monitoring of abstraction and water level data to provide an informed measure of the groundwater balance at this time and the aquifer productivity map is designed to provide a median estimate of the groundwater in storage.

Groundwater recharge potential: This describes the groundwater recharge potential of the aquifer unit based on 'direct' recharge due to rainfall. 'Focused' recharge by river or lakebed infiltration or via fissure or fault flow occurs at specific distributed sites and site-specific rates. There is insufficient data for it to be computed here and it is not considered except for special cases such as alluvial aquifers. However, in arid and semi-arid environments, focused recharge is often more important than direct recharge.

The rates of groundwater recharge are influenced by both the physical characteristics of the aquifer, such as its surface permeability, porosity and specific yield, as well as by environmental characteristics such as annual rainfall, consecutive wet days, vegetation cover, and topography, for example.

The groundwater recharge potential map has been created by combining a suite of different data that all have some impact on the groundwater recharge rates. These data are listed below:

a) Precipitation 50 km grid (present and future climate);
b) Consecutive wet days (CWD) 50 km grid (present and future climate);
c) Topographic wetness index (TWI);
d) Temperature mean 50 km grid (present and future climate);

e) Degree of confinement (confined/unconfined);
f) Depth to groundwater;
g) Aquifer surface permeability;
h) Baseflow index (BFI);
i) Vegetation type; and
j) Land-use.

The classification properties (a), (b) and (d) are environmental inputs into recharge. Properties (c) and (h) (to some extent) are topographic inputs into recharge. Properties (e), (f), (g) and (h) (to some extent) are hydrogeologic inputs into recharge and properties (i) (largely) and (j) are anthropogenic inputs into recharge. The data are available at various scales and in particular, the TWI data is available at a detailed scale from the digital elevation models available in the public sphere. The other data are available at much coarser scale, e.g. 50 km grid, sub-catchment, or lithologic unit scales.

The groundwater recharge potential has also been modelled at both 100 m grid and 10 km grid. Here only the groundwater recharge potential maps for present and future climate at 100 m grid-scale are presented (Figures 28 and 29).

The questions that arise are: How exactly are these maps produced? Are they a realistic assessment of the groundwater recharge potential? How are each of these parameters/properties ranked and weighted with regards to the final output classification for aquifer productivity or groundwater recharge potential or the other output maps developed in this study?

The table below, developed from the AHP matrix, show the percentage contributed to the groundwater recharge potential from each of the properties assessed.

Table 7: Groundwater recharge AHP matrix

Groundwater Recharge Matrix	% Contribution to Groundwater Recharge
Precipitation 50km grid (present and future)	26.7
Consecutive wet days 50km grid (present and future)	26.7
Topographic wetness index	17.2
T mean 50km grid (present and future)	9.8
Depth to groundwater/confinement	7.1
Aquifer surface permeability	5.2
Baseflow	3.4
Vegetation	2.0
Land-use	2.0

This has been done using the Analytic Hierarchy Process (AHP) developed by Saaty (2008).

> "The Analytic Hierarchy Process (AHP) is a theory of measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales. It is these scales that measure intangibles in relative terms. The comparisons are made using a scale of absolute judgments that represents how much more one element dominates another with respect to a given attribute" (Saaty, 2008).

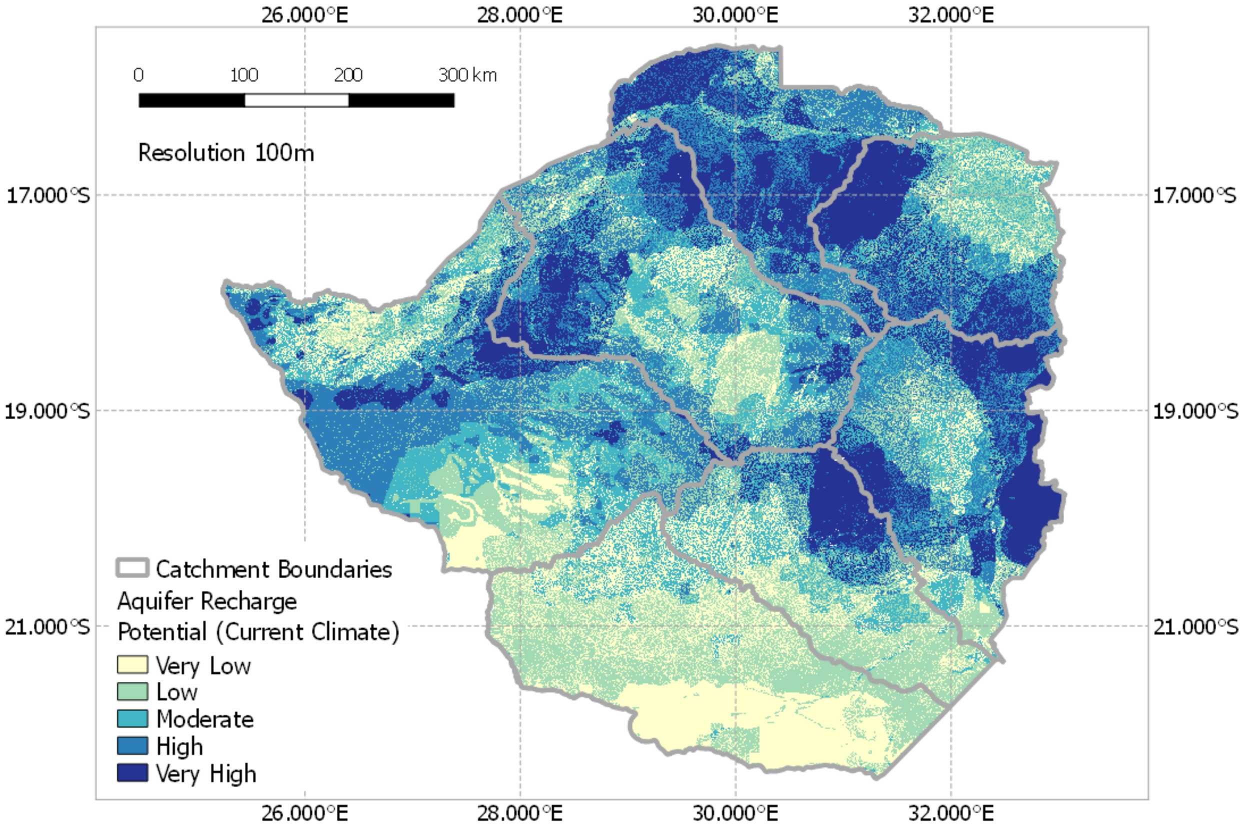


Figure 28: Groundwater recharge potential – current climate – at 100m grid scale. The impact of the hydrogeological units on recharge is muted and environmental properties such as rainfall and consecutive wet days are more significant than lithology. The impact of the TWI is revealed in showing streams on the map. In semi-arid climates, indirect recharge via stream bed infiltration is a very important and often the dominant component of the overall groundwater recharge. On the coarser 50km grid, the stream network is not visible at all.

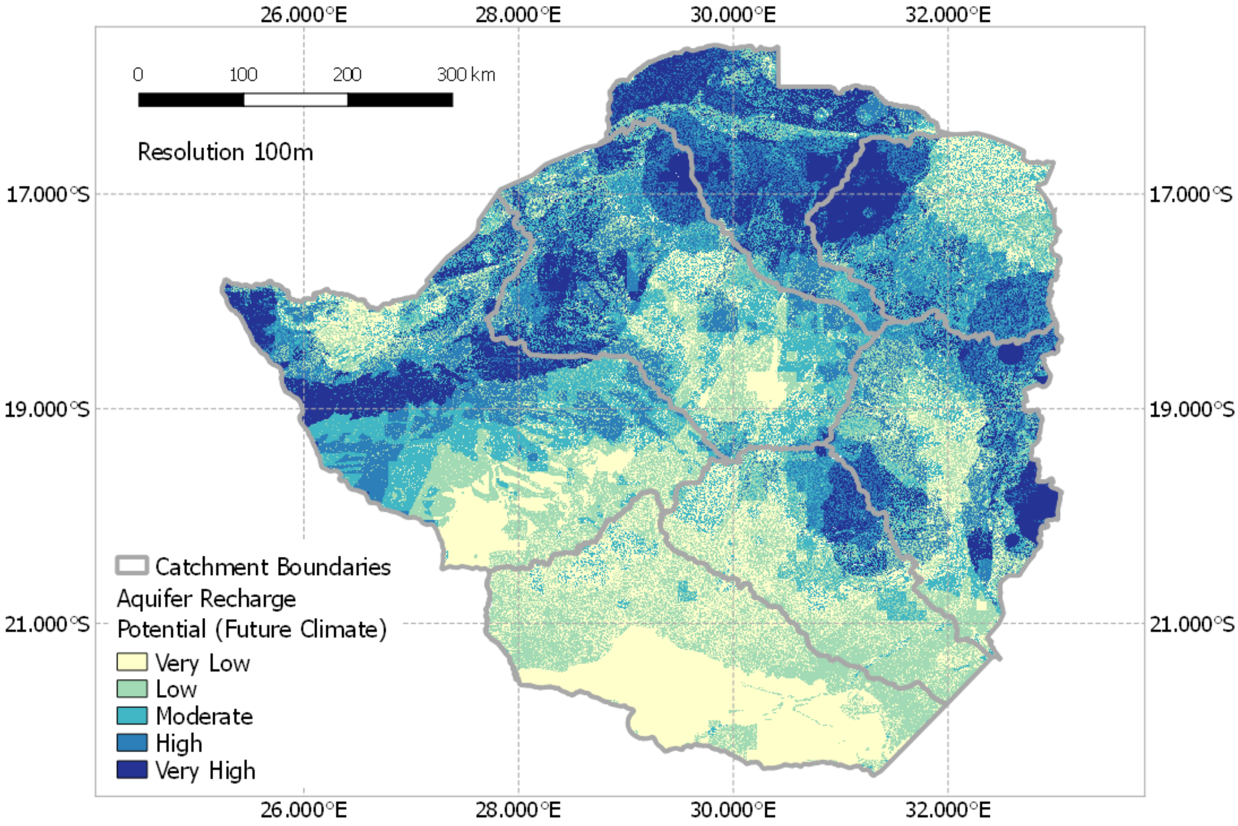


Figure 29: Groundwater recharge potential – future climate – at 100m grid scale. This map shows less recharge in all areas of Zimbabwe. By visual comparison with Figure 28, the climate-induced changes to the groundwater recharge potential can be assessed. Most of Zimbabwe is negatively affected with regards to groundwater recharge: the least affected areas appear to be the north-west and the north while the most affected appear to be the southern and south-western parts of the country.

Numeric quantitative values for groundwater recharge rates were obtained from various groundwater recharge studies that have been undertaken around the country, and also from the ZINWA (2007) baseflow maps. These groundwater recharge estimates have been used to assign values to the qualitative groundwater recharge classes.

In Table 8 below, the AHP used to develop the ranking for the groundwater recharge potential map is presented. It shows all the properties used in the development of the groundwater recharge potential maps and how they are ranked one against the other. Eigenvectors are then developed from these pairwise rankings which provide the relative importance of each of the properties with regards to groundwater recharge.

Just as an AHP is used to rank the impact of the different properties with regards to Groundwater Recharge Potential, so too there are AHP matrices to rank the impacts of the range of values within each property. For example, precipitation is a property that impacts on Groundwater Recharge Potential. The precipitation map provides for the spatial distribution of different levels of precipitation, as shown below. An AHP is developed to provide the relative impact values for different precipitation ranges. These values can be assigned to the precipitation map which can then be combined with all the other property maps, similarly, developed according to their own AHPs. The combined maps are summed according to the property AHP rankings in Table 8 to produce the groundwater recharge potential map.

Each of the properties has a range of values; for example, the range of precipitation values (mm/year) is:

>1,000	800-1,000	600-800	300-600	<300

Table 8: Analytic Hierarchy Process (AHP) for groundwater recharge potential

Properties contributing to groundwater recharge	Ppt 50k grid (present & future)	CWD 50k grid (present & future)	TWI	T Mean 50k grid (present & future)	Depth to Groundwater /Confinement	Aquifer Surface Permeability	Baseflow	Vegetation	Land-use	Nth Root of Product Values	Eigen Vector
Ppt 50k grid (present & future)	1.00	1.00	3.00	4.00	5.00	5.00	6.00	8.00	8.00	3.651	0.267
CWD 50k grid (present & future)	1.00	1.00	3.00	4.00	5.00	5.00	6.00	8.00	8.00	3.651	0.267
TWI	0.33	0.33	1.00	4.00	4.00	5.00	5.00	7.00	7.00	2.349	0.172
T Mean 50k grid (present & future)	0.25	0.25	0.25	1.00	2.00	3.00	4.00	6.00	6.00	1.335	0.098
Depth to groundwater/ confinement	0.20	0.20	0.25	0.50	1.00	2.00	3.00	5.00	5.00	0.969	0.071
Aquifer surface permeability	0.20	0.20	0.20	0.33	0.50	1.00	2.00	4.00	4.00	0.704	0.052
Baseflow	0.17	0.17	0.20	0.25	0.33	0.50	1.00	2.00	2.00	0.460	0.034
Vegetation	0.13	0.13	0.14	0.17	0.20	0.25	0.50	1.00	1.00	0.276	0.020
Land-use	0.13	0.13	0.14	0.17	0.20	0.25	0.50	1.00	1.00	0.276	0.020

In an AHP, each property is compared "pairwise" with one other property and their relative influence on, in this case, groundwater recharge potential, is assessed by e.g. literature or expert opinion. In the table above, the brown-fill cells are all the rankings of each property against itself e.g. Land-use vs Land-use and are all ranked 1.00, which means that they have an equal impact on groundwater recharge. The ranking of each property against every other property pairwise is assessed and given a value from the Saaty Continuous Scale below. For example, TWI is considered to be Moderately Less Important than Precipitation (rank 0.33 or 1/3) and Strongly More Important than Baseflow (ranking 5) and Very Strongly More Important than Land-use (ranking 8).

The eigenvector values in the last column indicate the relative importance of each factor with regards to groundwater recharge potential. The sum of all the eigenvectors is 1.00. For example, Precipitation and CWD each contribute 26.7 % to groundwater recharge, TWI 17.2 %, T Mean 9.8 %.

There are procedures to check the 'Consistency' of each AHP table: a Consistency Index and a Consistency Ratio.

Saaty Continuous Scale

1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely	Very strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely
Less important				Equal				More important

Table 9: AHP for precipitation ranges with regards to groundwater recharge potential

Rainfall(mm)	>1,000	800-1,000	600-800	300-600	<300	Nth Root of Product values	Eigen vector
>1,000	1	3	5	7	9	3.936	0.511
801-1,000	0.33	1	3	5	7	2.036	0.264
601-800	0.2	0.33	1	3	5	1	0.129
300-600	0.14	0.2	0.33	1	2	0.452	0.0588
<300	0.11	0.14	0.2	0.5	1	0.275	0.0357

All the different properties (CWD, TWI, T Mean, Baseflow) each have a range of values that are ranked against each other with regards to their impact on groundwater recharge potential. Each property and its range of values can thus be described by an AHP matrix, as shown for rainfall in Table 9.

The development of Eigenvector values for each value range (class) of each property allows the numerical summation of different properties to produce the final output map: in this case, Groundwater Recharge Potential.

Groundwater development potential (GDP): This category is a simple summation of the two principal categories that describe the physical groundwater resource, namely:

a) Aquifer Productivity (AP); and
b) Groundwater Recharge Potential (GRP).

Simply put in mathematical terms: GDP = (AP + GRP)/2

Groundwater development potential is a useful summary in map form that may be used as a management tool at catchment and national level since it combines the key factors of Aquifer Productivity and Groundwater Recharge.

Two maps are presented here:

a) Groundwater development potential at 100m under present climate; and
b) Groundwater development potential at 100m grid for future climate.

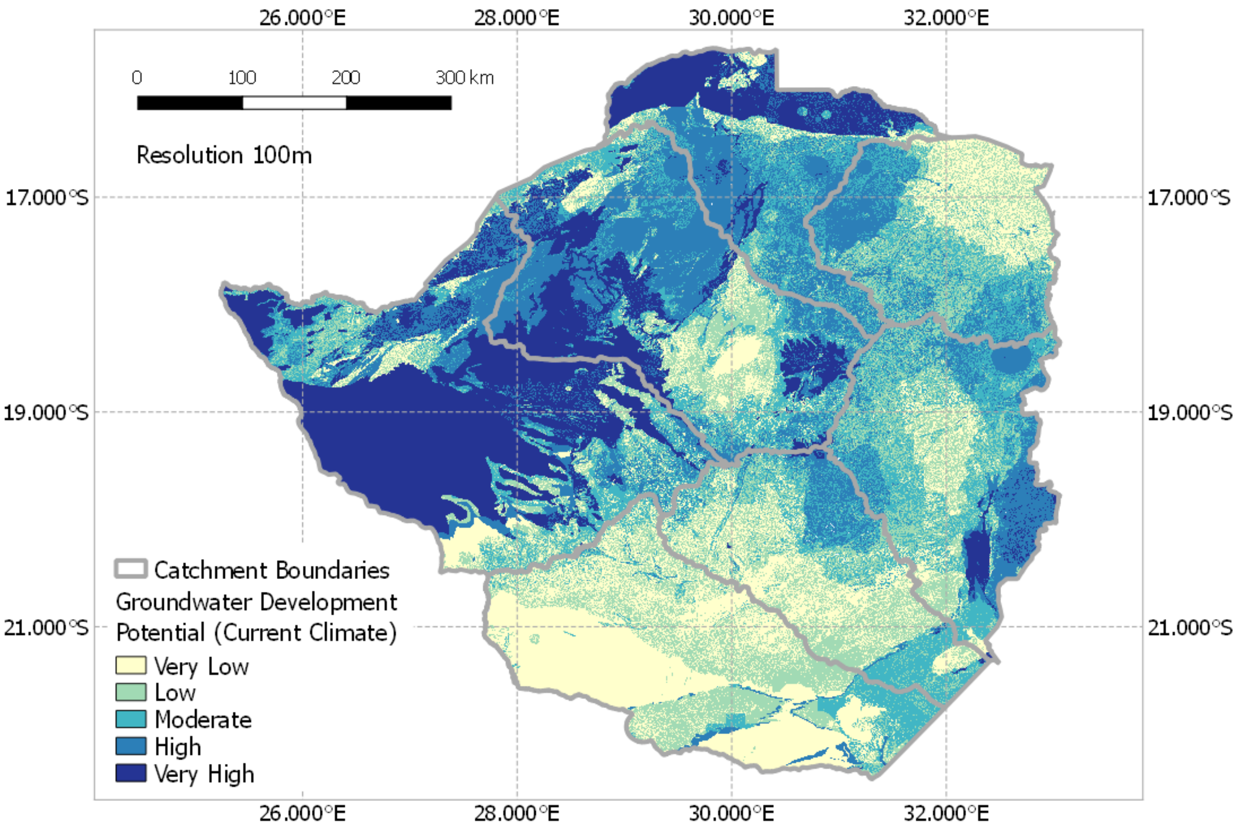


Figure 30: Groundwater development potential under the current climate.

The physical groundwater development potential map under the current climate (Figure 30) quite strongly mirrors the distribution of the hydrogeologic units. The primary porosity sedimentary aquifers in the north and northwest of the country show the greatest development potential while the secondary porosity crystalline aquifers in the dry southwest of the country show the least development potential. This groundwater development potential under future climate (CSIRO RCP 4.5) (Figure 31) is quite similar to the current situation, with no suggestion of major devastating impacts. It shows that the models predict a widespread but relatively modest reduction in physical groundwater development potential. However, the reduction is likely to be very severe in the low rainfall crystalline aquifer areas in the central southwest of the country.

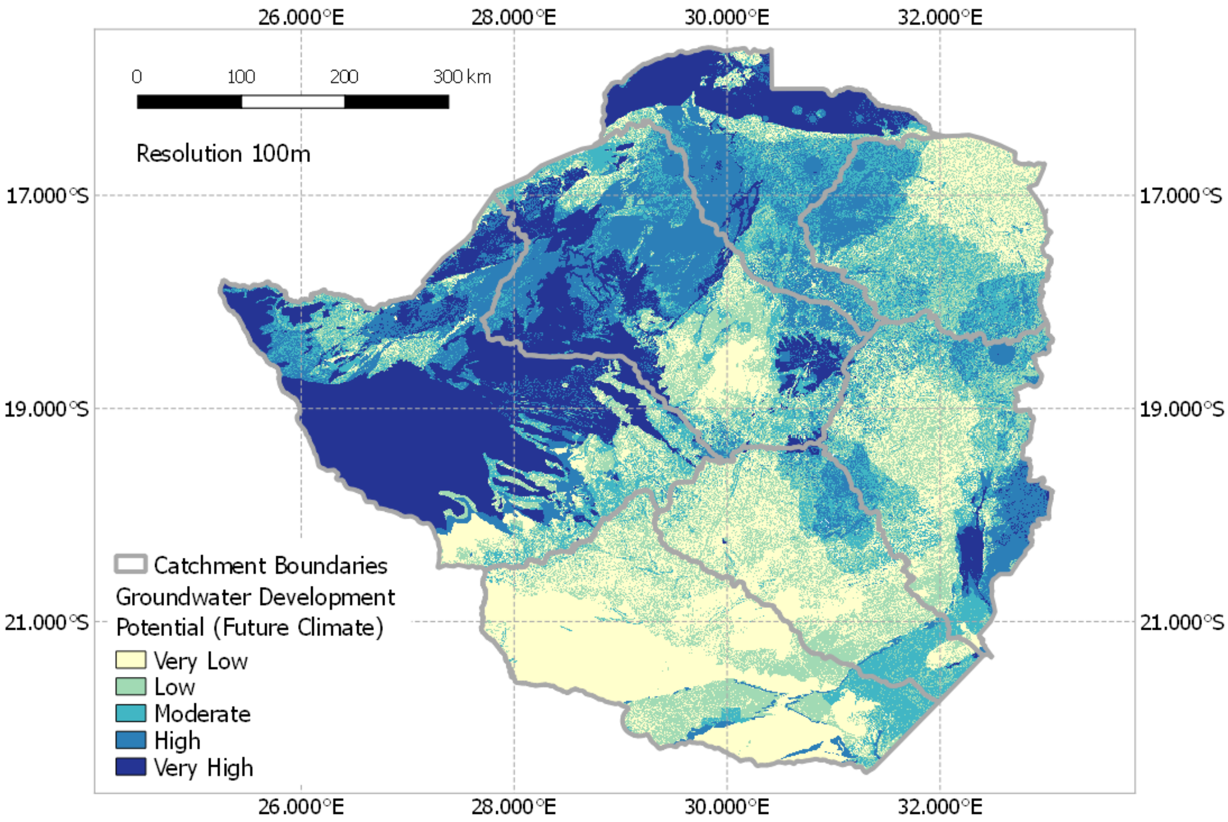


Figure 31: Groundwater development potential – under future climate.

Groundwater vulnerability to pollution: This map describes the vulnerability of the aquifer to point and diffuse sources of anthropogenic pollution loads applied at the surface or sub-surface by human activities.

The vulnerability to pollution is closely linked to the ease with which the groundwater system receives recharge, and hence the linked parameters are very similar to those used to map groundwater recharge potential. The role of the soil is particularly important since it is not only the soil permeability that needs to be considered but also the ability of the soil to attenuate pollutants by adsorption and absorption as they pass through the soil.

There are a number of groundwater vulnerability to pollution assessment tools in the public domain e.g. DRASTIC (Aller et al., 1985), GOD (Foster 1987) and so forth that provide semi-quantitative methods for assessing groundwater vulnerability. In this study, we have used a similar approach, using the AHP methodology for ranking and weighting the properties selected as impacting on groundwater vulnerability (Masocha and Owen, 2014). As shown in Figure 32, the deeper and confined sedimentary aquifers in the north, northwest and south of the country are the least vulnerable to pollution. The shallow granite aquifers and crystalline basement in the high rainfall areas throughout the country are the most vulnerable to pollution.

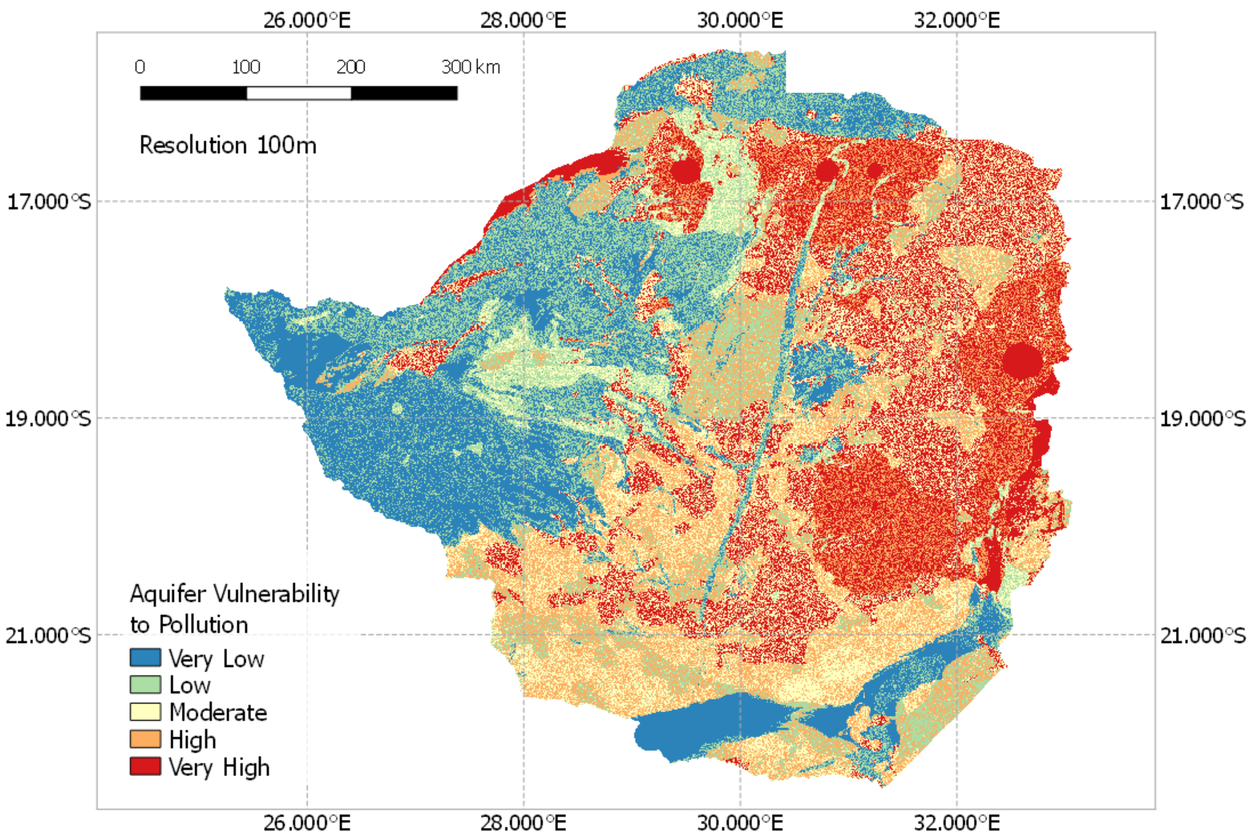


Figure 32: Groundwater vulnerability to pollution.

The properties that have been combined to provide a groundwater vulnerability to pollution map are listed below.

a) Land use;
b) Annual rainfall;
c) Aquifer type;
d) TWI;
e) Soil type;
f) Depth to groundwater; and
g) Vegetation type.

Table 10: Groundwater Vulnerability to Pollution

Groundwater Vulnerability to Pollution	% Contribution
Depth to groundwater	27.1
Annual rainfall	28.2
TWI	18.4
Landuse	12.2
Aquifer type	8.5
Vegetation type	5.7

It should be noted that groundwater vulnerability is different from groundwater pollution. Groundwater vulnerability describes the ease with which groundwater may become polluted.

Groundwater pollution, on the other hand, may occur when a pollution load is placed over a vulnerable groundwater source. Groundwater pollution, particularly in urban high-density communities, is often due to contamination by sewage wastes with bacteriological/viral contaminants such as faecal coliforms and bacteria such as salmonella or viruses such as cholera. This is becoming an increasing problem in the high-density suburbs of Harare, where typhoid has become endemic.

Geogenic groundwater quality: This describes the groundwater chemistry due to geogenic factors. The origin of geogenic groundwater quality is rock-water interactions. These are a product of the rock mass chemistry, the groundwater chemistry, the duration of the interaction and the amount of freshening of the groundwater by recharge. Generally speaking, groundwater is fresh when it is first recharged from meteoric sources (rainfall). Once it enters the ground, rock-water interaction begins. For the most part, these chemical reactions proceed slowly.

Geogenic groundwater chemistry is the signature of the rock water interactions. It is often plotted in a Piper diagram (Figure 33) or a Stiff diagram.

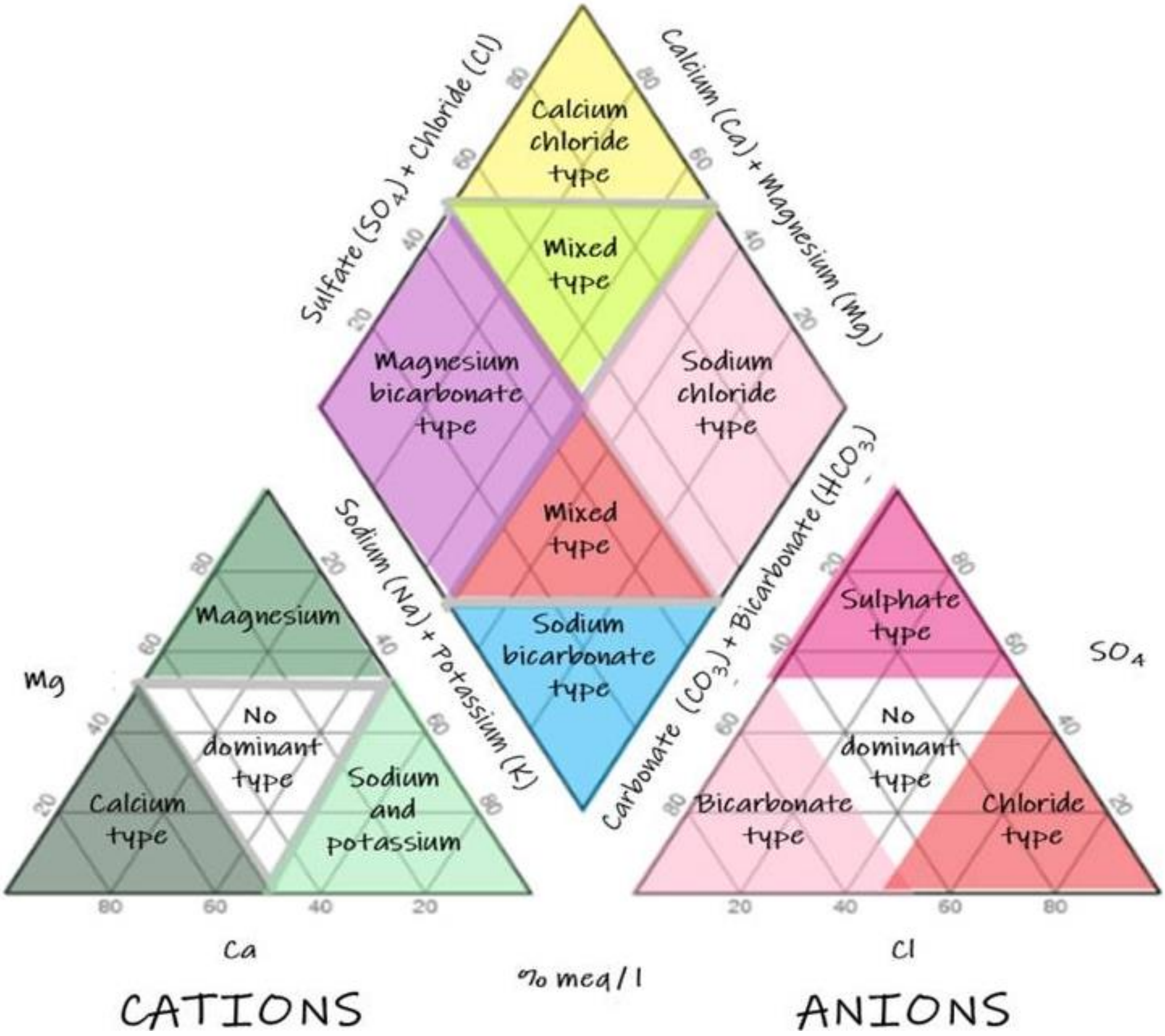


Figure 33: Groundwater chemistry–groundwater types. The Piper diagram shows the major cations and anions found in groundwater, and the different groundwater types based on the relative concentrations of the different cations and anions.

Shallow unconfined aquifers developed in the weathered regolith overlying crystalline bedrock tend to be relatively "fresh" water with low TDS (total dissolved solids). The groundwater in these shallow local aquifers has a relatively short residence time and as a result, the rock-water interactions have not had much time to dissolve soluble constituents. These are the most common conditions for the Zimbabwe craton, which is comprised of crystalline basement rocks.

Where groundwater residence is much longer, as tends to be the case for a really extensive sedimentary formations, particularly where they are confined beneath impermeable formations, then the groundwater becomes more saline and has a significantly higher TDS.

Another important factor in geogenic groundwater quality is the solubility of the mineral constituents of different rock types. Most rock-forming minerals are only marginally soluble in water, with some minerals being more soluble than others. The most common processes for chemical weathering are hydrolysis and oxidation. The most active zone for chemical weathering is the zone of the water table fluctuation. Based on theoretical concepts and data obtained from Interconsult (1987), we rank the different lithologies with regards to their susceptibility to chemical weathering.

The groundwater recharge is a further critical factor in geogenic groundwater quality. Recharge brings in freshwater to the groundwater reservoir and dilutes saline and brackish waters. Critical factors in the recharge rate are the depth to groundwater and the degree of confinement.

An AHP has been developed for theoretical geogenic groundwater quality. However, there is a lack of data to verify the AHP output rankings and there are other factors that may be significant. For example, the Save valley alluvial fill has localized zones with extremely high groundwater salinity due to lack of circulation and recharge of groundwater. Alluvial sands elsewhere have very fresh good quality water due to annual replenishment by streamflow. Therefore, the AHP and output map should be treated with caution. Table 11 provides some data to assess formation solubility (Interconsult, 1987).

The factors used in the AHP to map geogenic groundwater quality are:-

a) Groundwater residence time (estimated);
b) Solubility of rock constituents (lithology);
c) Groundwater recharge (and its associated parameters); and
d) Depth to groundwater (kriging)/Degree of confinement (confined/unconfined).

Table 11: AHP - Geogenic Groundwater Quality

AHP - Geogenic Groundwater Quality	% Contribution
Groundwater Recharge	39
Solubility lithology	39
Groundwater depth/confinement	14
Residence Time	9

The sedimentary formations (Madumabisa mudstone, Hwange Sandstone, Sijarira and Umkondo formations) have the worst geogenic water quality. Fluoride is reported in 80% of samples from the upper Hwange Sandstone (Figure 34). Table 12 shows sample data for most lithologies.

Table 12: Geogenic groundwater quality - the most common geogenic water quality problem in Zimbabwe is hardness (Source: Interconsult, 1987)

No. of Samples	Lithology	Geogenic Groundwater Quality										Solubility Ranking (# samples not compliant)			
	UNIT	#	pH	TDS	Fe	Ca	Hardness	Cl	SO4	F	Mn	#	<50 low	50-100 mod	>100 high
62 samples	1. Archean Granite Gneiss	62	0	2	1	0	17	17	0	1	0				
	percentage not compliant	%	0	3	2	0	27	27	0	2	0	61		mod	
39 samples	2. Bulawayan metavolcanics	39	0	0	3	0	0	0	0	0	12				
	percentage not compliant		0	0	8	0	0	0	0	0	31	39	low		
28 samples	3. Sijarira	28	0	0	3	7	14	0	0	3	2				
	percentage not compliant		0	0	11	25	50	0	0	11	7	104			high
6 samples	4. Dolomite	6	0	0	1	0	4	0	0	0	0				
	percentage not compliant	%	0	0	17	0	67	0	0	0	0	84		mod	
11 samples	5. Umkondo	11	0	2	0	0	8	1	0	0	0				
	percentage not compliant	%	0	18	0	0	73	9	0	0	0	100			high
24 samples	6A. Batoka Basalt	24	1	0	0	0	15	0	0	0	0				
	percentage not compliant	%	4	0	0	0	63	0	0	0	0	67		mod	
10 samples	6B. Forest Sandstone	10	0	0	0	0	4	0	0	0	0				
	percentage not compliant	%	0	0	0	0	40	0	0	0	0	40	low		
7 samples	6C. Escarpment Grit	7	3	0	0	0	0	0	0	0	0				
	percentage not compliant	%	43	0	0	0	0	0	0	0	0	43	low		
20 samples	6D. Madumabisa Mudstone	20	0	2	11	11	6	0	3	0	0				
	percentage not compliant	%	0	10	55	55	30	0	15	0	0	165			high

No. of Samples	Lithology	Geogenic Groundwater Quality										Solubility Ranking (# samples not compliant)			
	UNIT	#	pH	TDS	Fe	Ca	Hardness	Cl	SO4	F	Mn	#	<50 low	50-100 mod	>100 high
5 samples	6E. Hwange Sandstone	5	0	0	0	0	0	0	1	4	0				
	percentage not compliant	%	0	0	0	0	0	0	20	80	0	100			high
24 samples	7. Cretaceous Formation	24	7	4	0	0	4	0	0	0	0				
	percentage not compliant	%	29	17	0	0	17	0	0	0	0	63		mod	
11 samples	8. Kalahari Sands	11	0	0	0	0	0	0	0	0	0				
	percentage not compliant	%	0	0	0	0	0	0	0	0	0	0	low		

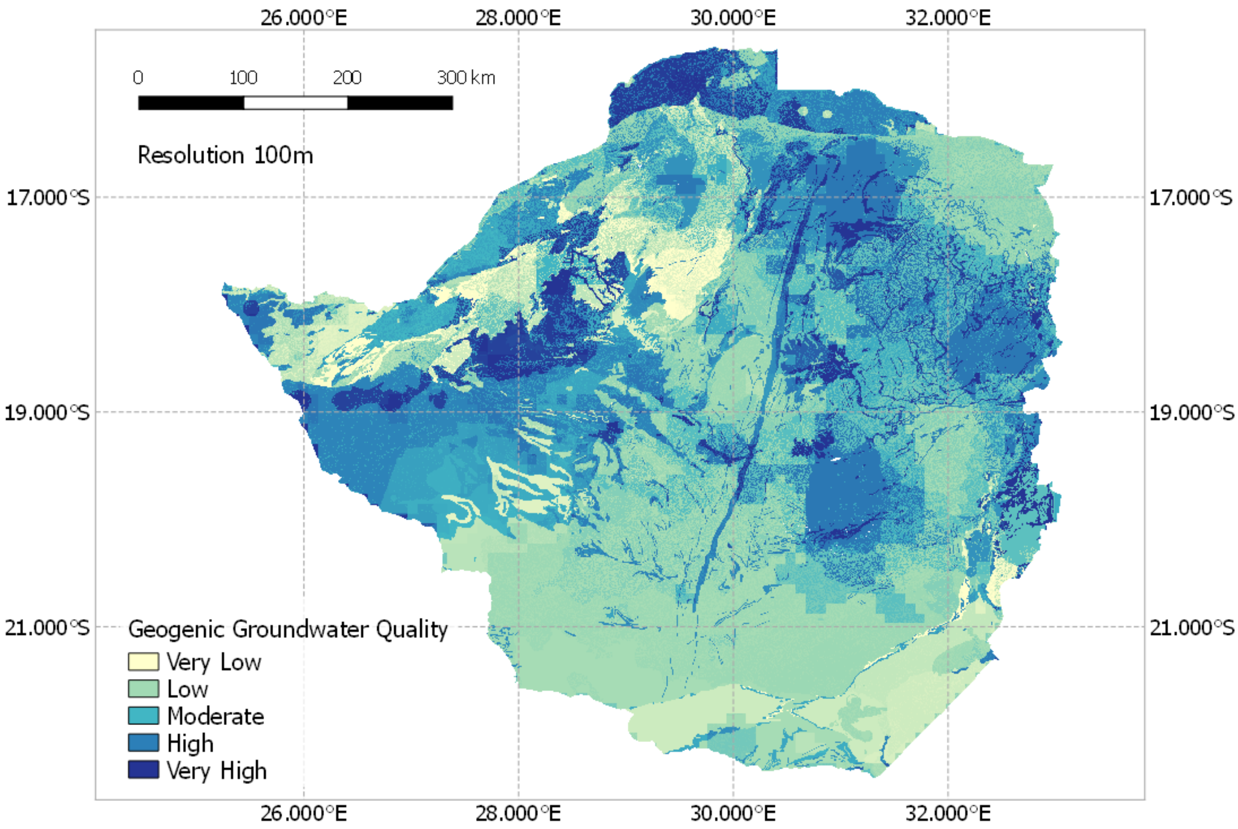


Figure 34: Geogenic groundwater quality. The geogenic groundwater quality map has been developed based on theoretical considerations backed by a small number of data. Low recharge rates, long residence times, soluble lithologies and deep confined groundwater contribute to mineralized geogenic groundwater quality. Very high and high ratings indicate fresh groundwater while very low and low indicate salinized groundwater.

Groundwater vulnerability to drought: This describes the resilience of various aquifer units on the impact of drought. Groundwater is considered to be "drought-resistant" because of the typically large volumes of groundwater that are held in storage. Thus, groundwater can be a buffer water supply that can be called upon in times of drought when surface water sources have dried up. However, aquifers differ very significantly in terms of how much groundwater is held in storage, depending on the porosity, areal extent, and saturated thickness. Extensive sedimentary aquifers may hold very significant volumes of groundwater in storage, while shallow local weathered regolith aquifers, which dominate in Zimbabwe, hold very much less water.

Groundwater recharge potential is an important factor, particularly in cases of extended drought or for climate change. Groundwater recharge tends to decline during dry years and in an extended drought there will be depletion of water in the aquifer and groundwater will be mined. Zimbabwe may be considered as a semi-arid country for most areas, except the eastern highlands and the north-eastern highlands which are more humid. As a result, groundwater recharge rates tend to be low and erratic.

Recently the term "Groundwater Drought Risk" has been coined, which includes not only the physical supply factors related to groundwater vulnerability to drought as indicated above but also the human demand factors. Human demand on groundwater may include primary domestic, livestock and irrigation demand, and it factors in the vulnerability of the population to diminished groundwater availability. Moreover, human demand for groundwater tends to increase during periods of drought when surface water supplies become scarce.

"Groundwater drought denotes the condition and hazard during a prolonged meteorological drought when groundwater resources decline and become unavailable or inaccessible for human use. Groundwater drought risk refers to the combined physical risk and human vulnerability associated with diminished groundwater availability and access during drought" (Villholth et al., 2013).

In certain situations, human demand may continuously outstrip groundwater recharge, leading to an unsustainable decline in groundwater levels and the drying up of aquifer systems in local environments, such as in parts of Harare. In other settings, it may only be during drought years that demand exceeds supply.

The Groundwater Drought Risk maps presented have not been developed by AHP during this project. We have rather presented the work by Villholth et al. (2013) using similar spatial data analysis processes.

The Groundwater Drought Risk analysis and spatial maps are presented in Chapter 3 on Groundwater and Climate Change.

2.9.2 The framework

There is a suite of six groundwater output maps that may be considered to describe the groundwater conditions in Zimbabwe:

- Aquifer productivity;
- Groundwater recharge potential (present and future climate);
- Groundwater development potential (present and future climate);
- Groundwater vulnerability to pollution;
- Geogenic groundwater quality; and
- Groundwater drought risk (present and future climate).

This suite of six output maps can be integrated to provide a semi-quantitative overview framework of the availability of the groundwater resources, its accessibility, its quality and its resilience to climate change and over-abstraction. We use both our assessments developed using AHP as well as some highly regarded assessments from literature (Villholth et al., 2013). These AHP analyses, integrated into a GIS mapping platform, constitute a methodology for the spatial analysis of the groundwater condition in Zimbabwe.

It needs to be stated that the AHP analyses of the ranking and weighting of each contributory factor are flexible and relative pairwise weightings and rankings may be changed as more evidence is gathered on any of these groundwater frameworks. Although this assessment strategy/modelling framework does not provide a detailed quantitative evaluation of groundwater availability and recharge in Zimbabwe, in time, used together with wisely focused groundwater monitoring and data integration, this framework may be used to improve the quantitative understanding Zimbabwe's groundwater resources.

2.10 QUANTIFYING GROUNDWATER RESOURCES

In quantifying the groundwater resources, three fundamental numerical values are needed: -

- The annual groundwater recharge from all sources (rainfall, streambed infiltration, focused recharge, irrigation return water);
- The volume of groundwater held in storage in the various aquifers; and
- The abstraction/demand for groundwater from all sources (pumping, baseflow, discharges to the environment, inter-aquifer discharges).

These represent the supply and demand of the groundwater balance and sustainable management of groundwater resources requires a clear understanding of these fluxes.

The qualitative groundwater maps presented in the previous section (Mapping Groundwater Resources) were developed using different input layers and ranking these inputs using the Analytic Hierarchy Process (AHP) (Saaty, 2008). The Analytic Hierarchy Process (AHP) was developed by Saaty (2008) as a structured method to apply for complex decision making. This procedure allowed the development of a suite of spatially differentiated qualitative groundwater maps of Zimbabwe as follows:

- Groundwater recharge potential (present and future climate): nine spatial layers (precipitation, consecutive wet days, topographic wetness index ((TWI)), mean temperature, depth to groundwater, aquifer surface permeability, baseflow, vegetation cover, and land use) that estimate the relative groundwater recharge rates.

- Aquifer productivity: a combination of seven spatial layers (aquifer class, saturated thickness, porosity, transmissivity, specific capacity, well yield, elevation, and slope) that together estimate the relative volume of groundwater in storage and the well yield.
- Groundwater development potential (present and future climate): a combination of the aquifer productivity and the groundwater recharge potential maps which provides a useful base-map for groundwater development and management.
- Groundwater vulnerability to pollution: six spatial layers (depth to groundwater, annual rainfall, TWI, land-use, aquifer type, vegetation cover) that map the relative ease with which groundwater may become polluted. Many of the layers are similar to the groundwater recharge input layers.
- Geogenic groundwater quality: four spatial layers (groundwater recharge, depth to groundwater/confinement, the solubility of lithotypes and groundwater residence time) which map key factors that lead to groundwater mineralization.
- Groundwater drought risk (present and future climate): multiple spatial layers that combine physical groundwater drought risk and human groundwater drought vulnerability, developed by Villholth et al. (2013), but not using the AHP methodology.

2.10.1 Groundwater quantification

The question then arises: How can these qualitative maps be converted to quantitative estimates of the groundwater resources? The term quantitative implies 'measured'. Measurements must be made in order to assess quantity. Although there are some groundwater databases in Zimbabwe, notably ZINWA and RWIMS, there is rather limited data that allow quantification of various groundwater properties.

In order to develop quantitative (or semi-quantitative) maps and models of groundwater in Zimbabwe, the approach taken was to apply the available quantitative data, usually as local experimental research data, to specific points on the developed spatial qualitative groundwater maps and extrapolate and extend that data to create a quantitative groundwater map. Due caution is necessary for using such extrapolated data, but we believe that they do provide useful quantitative guidelines. Not all the maps can be usefully quantified, and these then remain as spatially distributed qualitative maps. The developed maps that have been quantified are listed below.

Groundwater recharge potential (as mm/year recharge)

Groundwater recharge is the value that determines whether the current or planned groundwater abstraction is sustainable. If abstraction exceeds recharge, then groundwater mining is taking place. If abstraction is less than or equal to recharge, then groundwater is being sustainably used. Groundwater recharge fluctuates with not only the annual rainfall amount, but with the rainfall intensity and, especially, the number of consecutive wet days. These, and other parameters, have been mapped to produce a groundwater recharge potential map to which recharge quantities have been assigned (Figure 35).

Aquifer productivity (as the depth of water held in storage (m or mm): This provides managers with a quantity of groundwater held in storage, that may be called upon for use in development or as a buffer during drought periods. The use of meters or millimeters of water as a quantification unit then allows a direct assessment of the impact of groundwater recharge since recharge is measured as mm/year. Water in storage is the product of the aquifer saturated thickness and porosity. It would be more correct to use 'specific yield' rather than 'porosity', but values for specific yield in Zimbabwe are not well recorded. Other factors such as well yield and specific capacity are considered in the development of the AHP for aquifer productivity, but for management purposes, we focus on the development of a map of the groundwater held in storage. It should be noted that this is not a static figure, and groundwater reservoirs can and do get pumped dry. Zimbabwe, as a country, is ranked as having a high to very high groundwater drought risk (Villholth et al., 2013). For this reason, it is essential that groundwater monitoring is established, and the quantity of water held in storage be updated regularly.

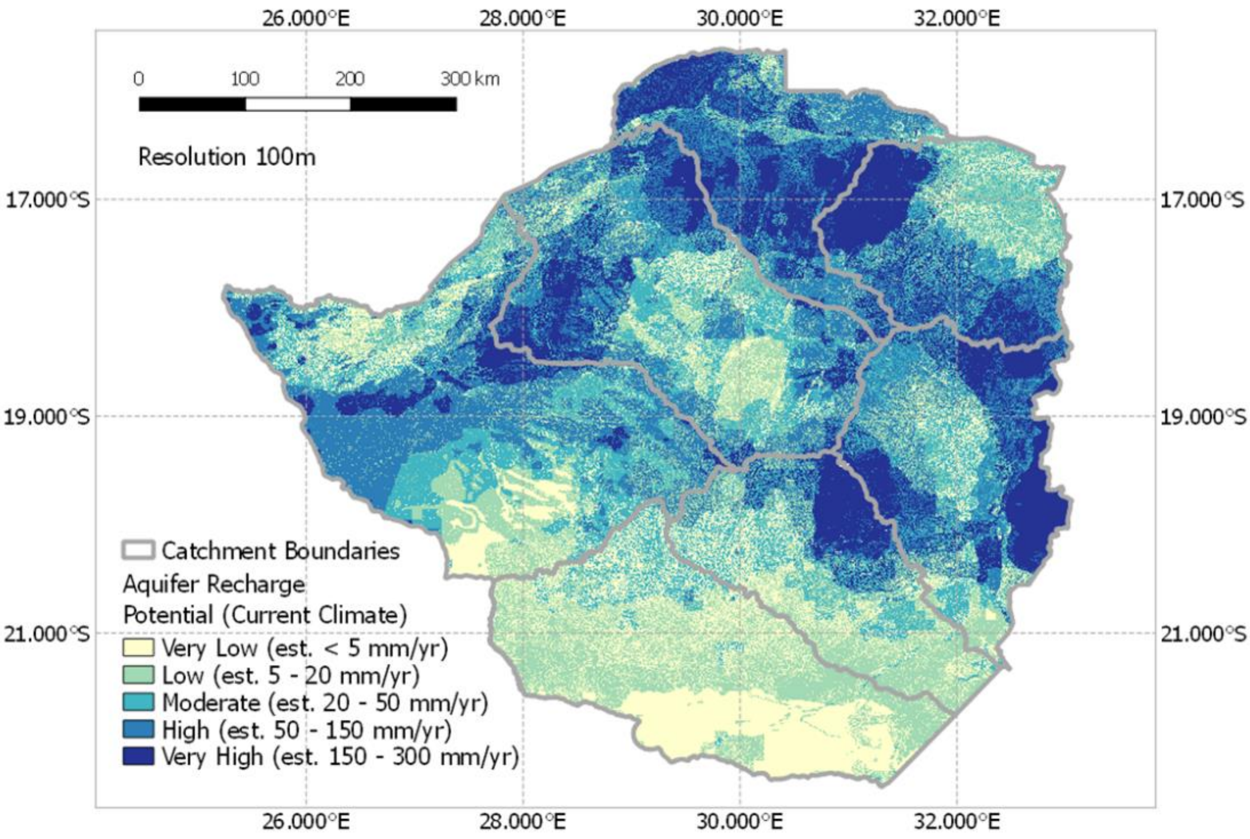


Figure 35: Groundwater recharge potential - the map has been quantified by allocating groundwater recharge rates calculated from specific studies in some of the different zones shown on the map, and also supplemented by literature values in similar environments.

Groundwater development potential: This is a combination of groundwater recharge potential and aquifer productivity. It provides a single convenient map for planners at catchment, sub-catchment, or national level to use when planning groundwater development. Existing boreholes are marked on the catchment level maps so that development can be planned with a spatial view of already existing boreholes. This map cannot be quantified because it is a combination of properties that have different units and therefore it retains qualitative descriptions from very high to very low.

Groundwater vulnerability to pollution: This describes the vulnerability of groundwater to pollution. Vulnerability to pollution is different from pollution risk, which takes account of anthropogenic factors such as waste disposal, waste management and so forth. Vulnerability to pollution is quite similar to groundwater recharge, in that high recharge provides the medium for pollutants to be carried into the groundwater zone. Land-use is a critical parameter in mapping groundwater vulnerability since it to some extent encompasses anthropogenic factors. Groundwater vulnerability has no units of measurement, and there is a dearth of groundwater quality data in Zimbabwe, thus precluding the use of statistical distribution of polluted boreholes. The vulnerability map, therefore, remains qualitative. However, it is noted that at this time (2018), urban groundwater in the high density/low-income suburbs, particularly in Harare, faces grave water quality challenges from microbial and microbiological contamination that have been implicated in cholera and typhoid epidemics that have become endemic in Harare.

Geogenic groundwater quality (natural groundwater quality due to geogenic factors): Rock-water interactions control the geogenic groundwater quality. Key drivers of this are the solubility of the mineral assemblages in different rock types; the residence time of the groundwater with older groundwater being more mineralized than recently recharged groundwater; the depth to the water table and the rate of recharge. Ideally, this type of map can be quantified by using electrical conductivity units (μS/cm) that are easily measured in the field. However, such data are not available, and we retain a qualitative map.

Groundwater drought risk (the condition when groundwater resources become unavailable for human use): These maps have been developed for SADC by Villholth et al. (2013) and map both physical drought risk and human groundwater dependence. There are no suitable units to describe this condition and these maps (present and future climate) are presented as qualitative maps.

2.10.2 Groundwater recharge potential

Baseflow: There is one quantitative spatial dataset that is linked to groundwater recharge, and that is baseflow. Baseflow is dry season streamflow or low flow and may be defined as groundwater discharge to streams. In a natural undisturbed catchment, baseflow is also considered to be equivalent to groundwater recharge.

Annual groundwater recharge raises the water levels in the aquifer and sets up a hydraulic gradient between the groundwater head in the aquifer and the elevation of the stream bed. Groundwater discharge then takes place as baseflow until there is no further hydraulic gradient between the groundwater level in the aquifer and the stream bed. Under natural conditions, provided there are no other outflows, annual groundwater recharge may be equated with baseflows.

However, where there are other discharges, such as groundwater abstractions, or inter-aquifer/inter-basin groundwater flows that may take place in deep sedimentary aquifers, then baseflow will tend to underestimate groundwater recharge. In Zimbabwe, the Gwayi catchment, underlain by Kalahari sands and the Karoo sedimentary basin, is considered to discharge deep groundwater westwards to the Magadigadi basin in Botswana and has anomalously low baseflow characteristics as a result.

In terms of groundwater pumping, there is an abstraction of groundwater from all basins, thus also resulting in baseflow being an underestimation of groundwater recharge. Where there are dam releases, usually in the dry season for irrigation, then these releases will complicate the analysis of baseflow and may lead to an overestimation of the groundwater recharge rate.

Therefore, the use of baseflow to estimate groundwater recharge needs to be applied with a clear understanding of other flows in and out of the water balance. In the following tables (Tables 13-15), baseflow data from the ZINWA database (2007) has been used to estimate annual groundwater recharge, noting also the issues mentioned above. The baseflow/groundwater recharge is then compared to pumping abstraction estimates so that a relationship between groundwater recharge and groundwater abstraction can be presented. In Figure 36, the two maps (baseflow and groundwater recharge) show similarities in the eastern, southern and central parts of Zimbabwe but diverge in the north and northwest, where recharge is estimated to be high and baseflow has been measured as low. These latter areas are underlain by deep sedimentary basins and may, therefore, be subject to significant inter-aquifer transfers out of the catchment by deep groundwater flows.

Table 13: Groundwater annual abstraction per catchment, based on blowing yields at the time of drilling recorded in the ZINWA database and then extrapolated to the total number of boreholes in the RWIMS database (64,879)

Catchment	SUM Blowing Yields (l/s) at time of drilling	Maximum estimated annual groundwater abstraction ZINWA boreholes with blowing yield data MCM	% of ZINWA boreholes with blowing yield data	No. of ZINWA boreholes with blowing yield data	Total No. of ZINWA boreholes in database	Estimated total number of boreholes in the catchment ** RWIMS	Estimated total annual abstraction from the catchment MCM
Gwayi	1,689	53	41	1,027	2,487	8,667	225
Manyame	2,334	74	55	1,241	2,274	7,925	235
Mazowe	3,220	102	67	2,594	3,900	13,591	266
Mzingwane	460	14	23	439	1,894	6,600	109
Runde	1,402	44	57	1,175	2,055	7,162	135
Sanyati	1,940	61	52	1,287	2,498	8,705	207
Save	7,132	225	57	1,984	3,509	12,229	693
National	18,177	573	52	9,736	18,617	64,879	1,910

Notes: The data is from the ZINWA Groundwater Branch database and it has 18,617 boreholes.
52% of these boreholes (9,736) have blowing yields recorded and the rest do not.
The estimated maximum abstraction from these 9,736 boreholes has been calculated as if these boreholes are pumping continuously at blowing yield rate*.
In practice, boreholes are usually pumped at 60 to 70% of the blowing yield and they are not usually pumped continuously.
The total number of boreholes** in Zimbabwe is estimated from the RWIMS database to be 64,879.
There will be other boreholes not in these two databases, particularly boreholes on commercial farms that may be heavily pumped.
The estimated total abstraction has been calculated as 50% of the maximum estimated abstraction extrapolated for all the boreholes in the catchment.

Table 14: Groundwater recharge estimates from baseflow measured in the sub-catchments / hydrological sub-zones.

Catchment	Avg: Sum of minimum baseflow (mm)	Avg: Sum of maximum baseflow (mm)	Catchment area (m^2)	Minimum annual baseflow volume (MCM) = groundwater recharge	Maximum annual baseflow volume (MCM) = groundwater recharge
Gwayi	3	7	88,340,936,682	257	609
Manyame	13	29	40,635,061,572	540	1,162
Mazowe	26	49	39,800,648,711	1,035	1,942
Mzingwane	4	9	62,840,932,287	258	551
Runde	9	17	41,300,417,156	388	709
Sanyati	7	14	70,100,994,213	518	990
Save	39	68	48,789,875,999	1,903	3,318
National	18	33	391,808,866,620	4,899	9,281

1. The baseflow data is the groundwater discharge via streams.
2. For local crystalline rock catchments (e.g. granite).
   i) Annual baseflow may be equated with the annual groundwater recharge in an undisturbed catchment.
   ii) Where there is groundwater abstraction, it will be at the expense of baseflow and in these circumstances, baseflow may be equated with the minimum value for annual groundwater recharge.
3. For deep sedimentary basins, there may be significant inter-aquifer transfers out of the catchment.
   i) In such cases, baseflow may be significantly less than annual groundwater recharge – e.g. Gwayi catchment.
4. Where there are reservoir/dam releases upstream of a gauging station, baseflow may be exaggerated and may be significantly more than groundwater recharge rates. e.g. Save catchment with releases from Osborne Dam. Other dams that will affect baseflow figures in this way include Mutirikwi, Mazvikadei, Tugwi-Mukosi and Zhove.

Table 15: Comparison of groundwater abstraction estimates from borehole data with groundwater recharge estimates from baseflow data

Catchment	Estimated total annual abstraction from the catchment MCM	Minimum annual baseflow volume (MCM) = groundwater recharge	Maximum annual baseflow volume (MCM) = groundwater recharge	% ratio: abstraction/recharge minimum	% ratio: abstraction/recharge maximum
Gwayi	225	257	609	88	37
Manyame	235	540	1,162	44	20
Mazowe	266	1,035	1,942	26	14
Mzingwane	109	258	551	42	20
Runde	135	388	709	35	19
Sanyati	207	518	990	40	21
Save	693	1,903	3,318	36	21
National	1,910	4,899	9,281	39	21

1. The estimated annual abstraction of groundwater ranges from 88 % of baseflow (Gwayi catchment) to 14 % of baseflow (Mazowe catchment).
2. Gwayi catchment has been identified as likely to underestimate recharge from baseflow due to deep groundwater inter-basin flows (e.g. to Botswana); Save catchment has been identified as likely to overestimate recharge from baseflow due to dam releases from Osborne Dam.
3. A more probable estimate of the ratio between groundwater abstraction and groundwater recharge can be better obtained from the other catchments, excluding catchments where there is substantial irrigation water flowing in the river channels from surface reservoirs and catchments with substantial inter-aquifer transfers.
4. The probable range of groundwater abstraction to groundwater recharge is in the range of 20 % to 40 %.

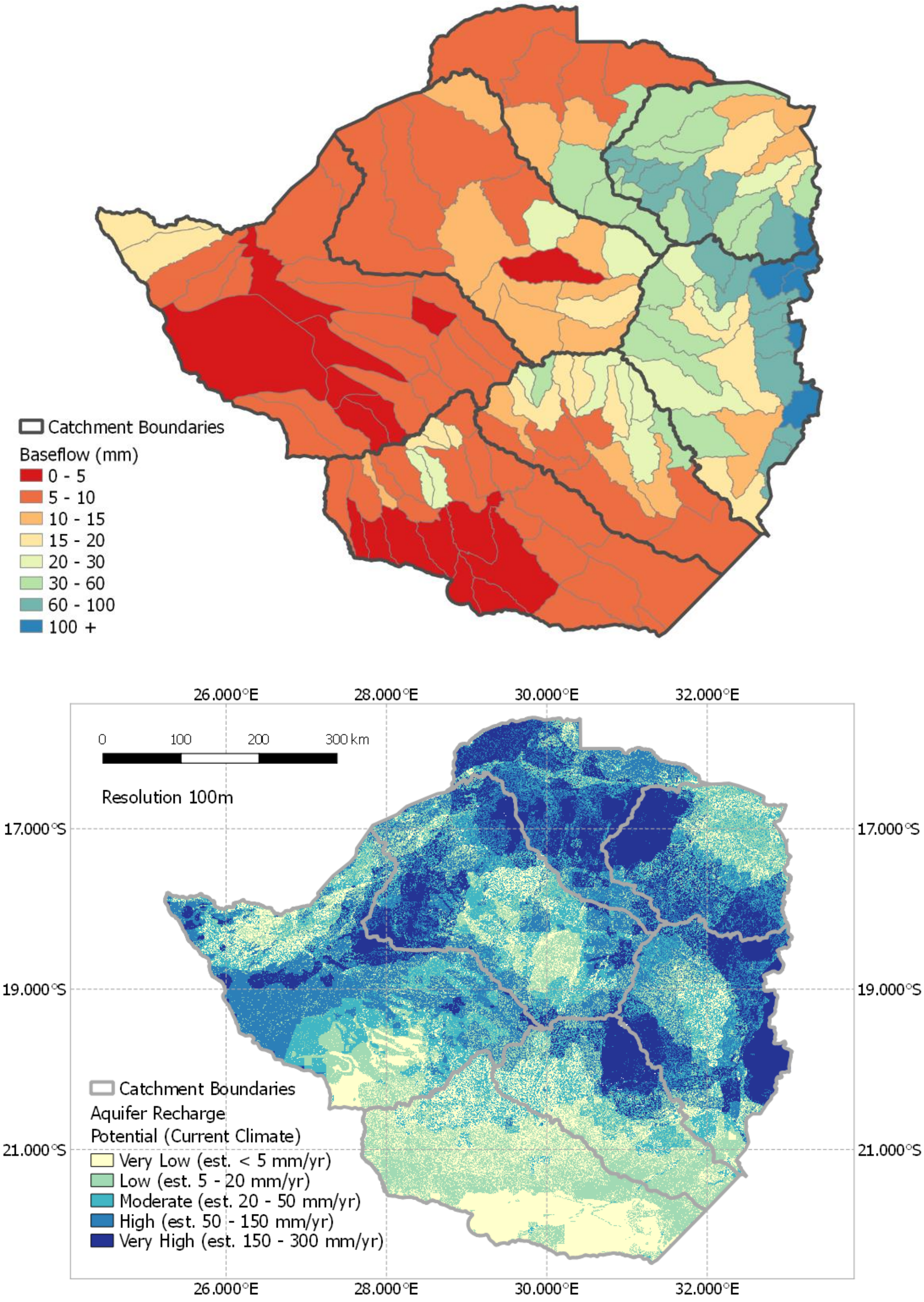


Figure 36: Comparison of baseflow (36a top) and groundwater recharge (36b below). Note the similarities between the baseflow and recharge, except for the Gwayi catchment, which has high recharge but low baseflow.

2.10.3 Quantitative mapping of groundwater recharge

The baseflow data provides a spatial view of the groundwater recharge potential. Baseflow is groundwater discharge and the annual baseflow data represents a minimum value for groundwater recharge. The groundwater discharge losses due to groundwater abstraction, evapotranspiration from the groundwater zone, seepage discharges at groundwater-dependent ecosystems (GDEs) and deep inter-basin flows in extensive sedimentary aquifers, all contribute to losses from the aquifer that as a result do not appear as baseflow. In some catchments, where gauging weirs have been placed just downstream of reservoirs, then reservoir releases lead to an artificial increase in the measured base flows.

The baseflow data suggest recharge rates ranging from a maximum of 68 mm/year in the Eastern Highlands and Save catchment to 3mm/year in the north-western Gwayi catchment, which is underlain by deep permeable sediments that are considered to discharge at depth to the west into the Magadigadi basin in Botswana.

Other data on recharge include reports from:

- Sibanda et al. (2009) in Nymandhlovu in western Zimbabwe, using a variety of methods, reported recharge 15-20 mm/year, which is 2.7-3.6 % of rainfall.
- Houston (1988) also suggested the value of 2–5% of annual rainfall in the semi-arid Masvingo province.
- Doll and Fiedler (2008) pointed out that the relationship between rainfall and groundwater recharge is not linear but more a logarithmic relationship.
- Wright (1992) suggested that for rainfall greater than 800 mm/year, groundwater recharge typically lies between 10 -20% of rainfall. This suggests a groundwater recharge of 80 to 160 mm in the wetter north-eastern parts of Zimbabwe.
- Jasechko and Taylor (2015), using isotopic data from 15 sites in the tropics, revealed that groundwater recharge in the tropics is near-uniformly biased to intensive monthly rainfall.
- Owen (unpublished), using water table fluctuations and estimated specific yield data (5 to 10%) in a crystalline basement site, estimated average groundwater recharge rates in Harare of 165 to 330 mm/year with a range from 54 mm/year to 540 mm/year for the period 2010 to 2018. The impact of consecutive wet days (CWD) (Figure 37) is critical for effective groundwater recharge (Figure 39).

Other research (e.g. Kotchoni et al., 2018) identify a minimum annual rainfall threshold before groundwater recharge takes place, as well as identifying the importance of rainfall intensity and the impact of consecutive wet days. Cuthbert et al. (2016) discuss the importance of focused recharge from streambed infiltration as compared to direct recharge from precipitation. In semi-arid and arid areas, focused recharge becomes critical and, in many instances, it is only through focused recharge that any groundwater recharge occurs.

It should be clear that mapping recharge accurately requires a lot of direct measurements, and Zimbabwe does not have that many measurements. However, based on a variety of factors (see AHP for groundwater recharge potential), a quantitative map for groundwater recharge has been developed (see Figure 38b). This relative distribution of groundwater recharge potential map is considered to provide a well-balanced perspective on recharge based on ten different input parameters. Based on the considerations discussed above and the few local measured recharge rates, quantitative values have been assigned to the different recharge classes as follows.

Table 16: local measured recharge rates, quantitative values assigned to the different recharge classes

Groundwater Recharge Class	Estimated Range of Groundwater Recharge mm/year
Very Low	< 5 mm/year
Low	5 – 20 mm/year
Moderate	20 – 50 mm/year
High	50 – 150 mm/year
Very High	150-300 mm/year

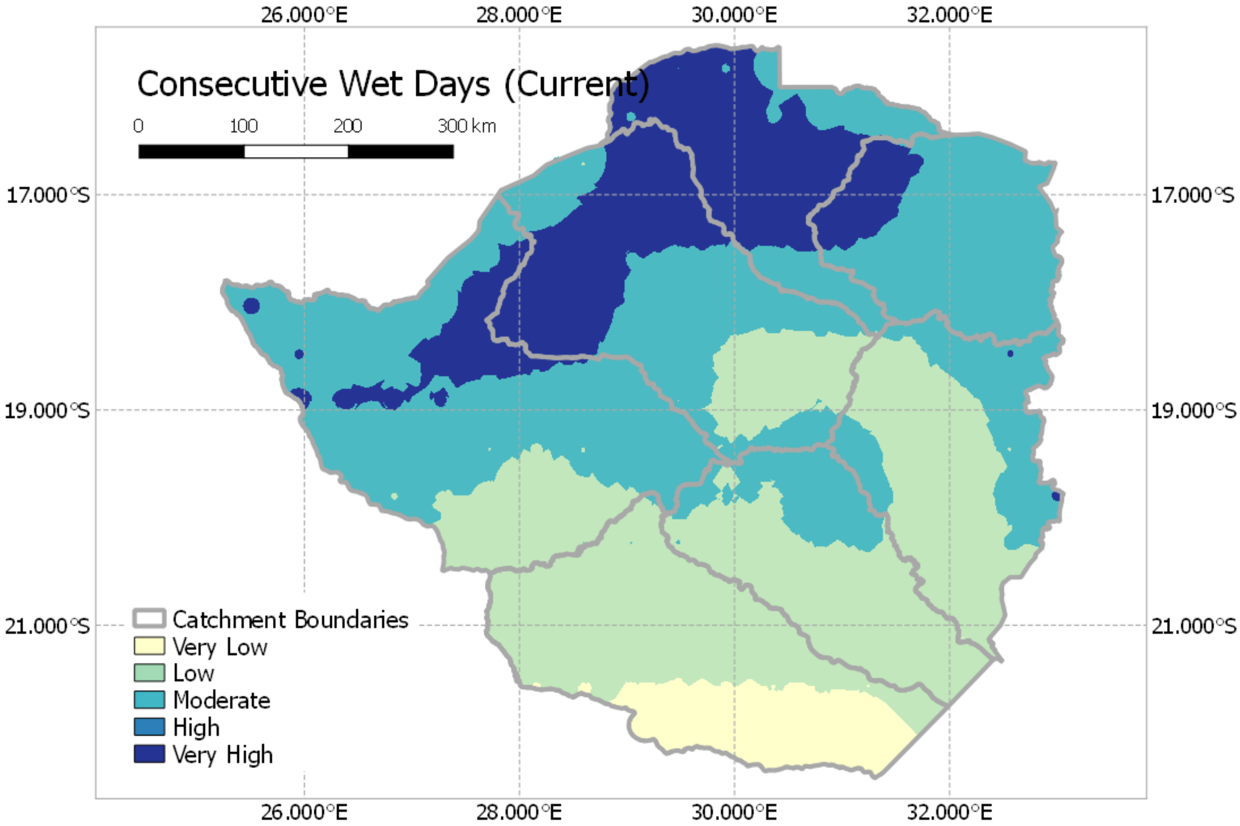


Figure 37: Consecutive wet days – current climate.

Consecutive wet days (CWD) is also flagged as critical for direct groundwater recharge in the tropics. The high ranking of CWD to the north of the country (Figure 37) explains the high mapped groundwater recharge rates in the northern parts of Zimbabwe (see Figure 36b).

A plot of daily rainfall against groundwater levels (Owen, unpublished) measured in unconfined Archean meta-basalts in Harare shows groundwater recharge for the period 2010 to 2018 (Figure 38). Recharge occurs annually with an average rise in the water table of 3.32m and a range from 1.08m (2015/16) to 5.43m (2016/17). It has been observed that the annual recharge occurs rapidly during periods with several consecutive wet days. If rainfall is intermittent, water levels become static or may even decline during the rainy season (Figure 39).

Detailed inspection of the rainfall-recharge hydrographs shows that recharge occurs preferentially after a number of consecutive wet days (Figure 40). Once the profile has become thoroughly wetted, recharge proceeds rapidly with all additional rainfall percolating down to the water table. Based on the relationship between this late rainfall and the water level rises in the monitoring well, a specific yield value of 10% (0.10) has been estimated for this site. Morris and Johnson (1967) indicate a specific yield value of 15% for crystalline basement weathered regolith aquifers.

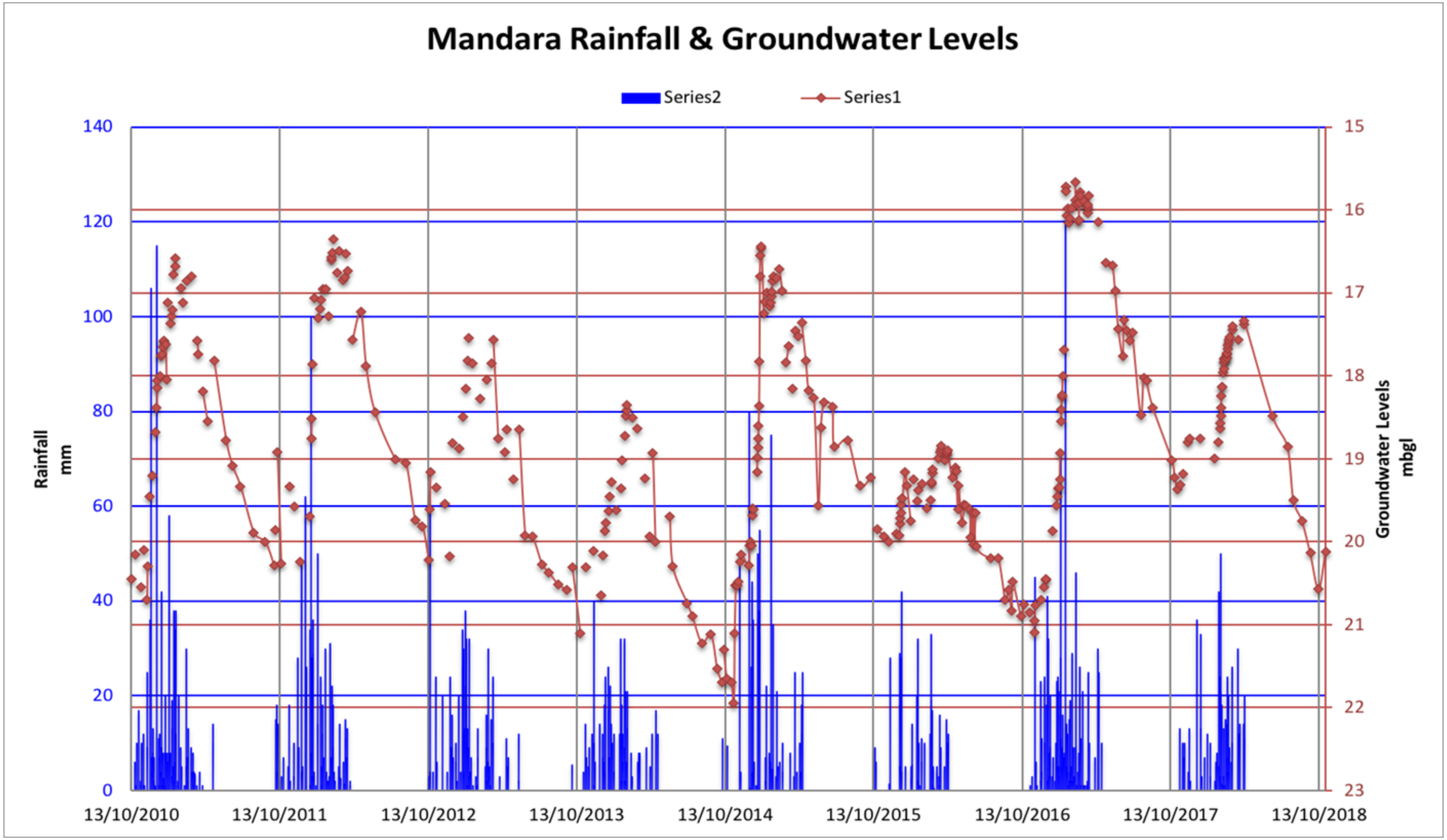


Figure 38: Harare monitoring borehole on metabasalt - rainfall against groundwater level. Brown line is groundwater level and blue bars are daily rainfall values. Figures 39 and 40 show detail.

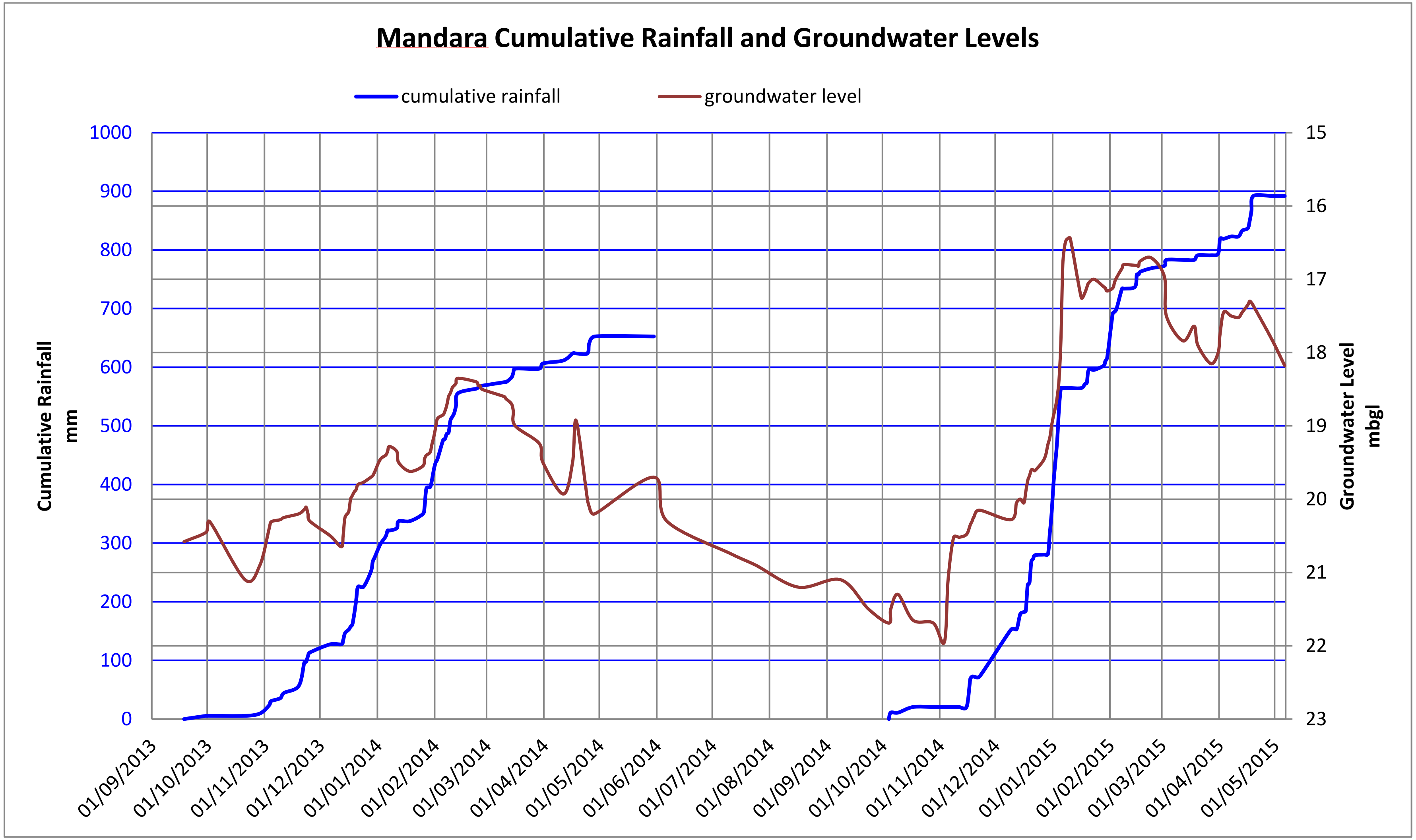


Figure 39: Plot of groundwater levels versus cumulative rainfall. Wet periods are shown where the blue cumulative rainfall graph rises steeply, and these are strongly linked to steep rises in the groundwater levels (brown line). Where rainfall is intermittent and low, the groundwater levels level off and decline.

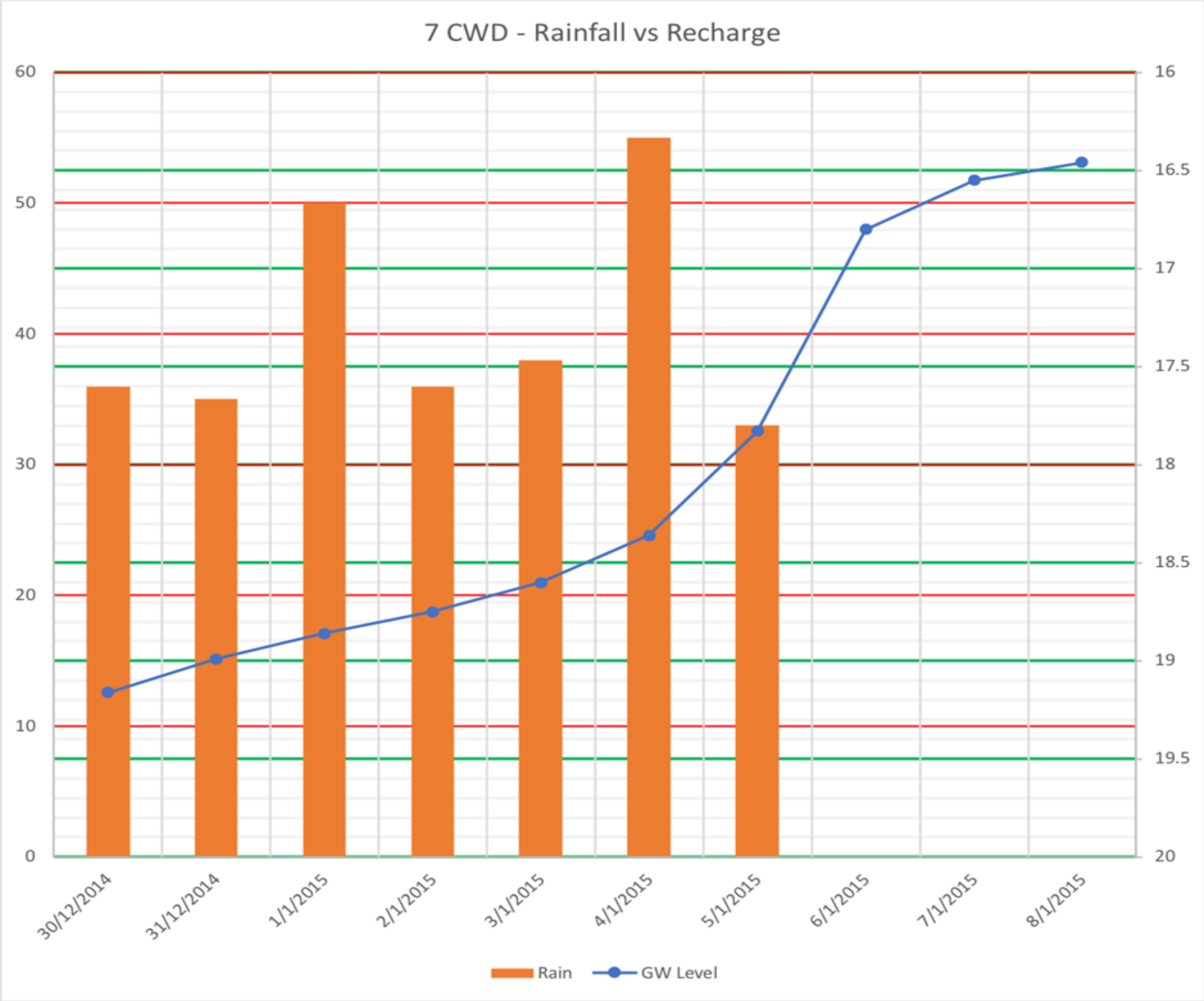


Figure 40: Consecutive wet days vs groundwater recharge. Rainfall: left vertical axis in mm. Groundwater level: Right vertical axis in m. The figure shows 7 days of rainfall. The groundwater level rises steadily and more rapidly towards the end of the rainy spell, rising almost a meter on the day following the last rain. The plot suggests that it takes two days for 55mm rainfall event on 4/1/2015 to reach the water table on 6/1/2015. The total rise in the water level is 2.7 m for a total rainfall of 283 mm. The ratio of rainfall (0.283 m) to water level rise (2.700 m) suggests a specific yield value of 10.5 %. There are a number of antecedent rainy days and the fact that the groundwater levels show an immediate response to the rainfall in the plot indicate that soil moisture deficits had already been satisfied by the start of this rainy period. It is, therefore, logical to suggest that all this rainfall becomes groundwater recharge – 283 mm of groundwater recharge.

2.10.4 Summary on groundwater recharge potential

Groundwater recharge is considered to be the yardstick by which sustainable groundwater management is achieved. If abstractions exceed groundwater recharge, then the aquifer is being mined and will dry out in time. If abstractions can be kept below recharge, then sustainable management can be achieved. It should be noted that any level of groundwater abstraction will have an impact on the various fluxes in the water balance. Reversible impacts include:

- Water levels decline, increased pumping lifts and costs;
- Borehole yield reduction;
- Spring flow/baseflow reduction; and
- Phreatophytic vegetation stress.

If pumping increases, then irreversible impacts start to occur:

- Aquifer compaction;

- Transmissivity reduction;
- Saline water intrusion;
- Ingress of polluted water; and
- Land subsidence and related impacts.

In order to avoid permanent irreversible damage to the aquifers, it is essential to be able to monitor the balance between recharge and abstraction. Both recharge and abstraction are difficult and complex to measure accurately. The water balance is, therefore, most easily and successfully done by monitoring the groundwater levels overtime at dedicated monitoring wells. The development of groundwater monitoring is discussed in this report and the locations for groundwater trend monitoring boreholes are suggested on catchment maps.

The national map of groundwater recharge potential (Figure 35) (also available for each catchment at 10 km grid resolution) estimates the annual groundwater recharge rates for different recharge zones. These maps may be used as quantitative planning tools for the management of groundwater development. However, they should in no way detract from the need for routine groundwater trend monitoring but rather be used as complementary tools.

2.10.5 Aquifer productivity

Aquifer productivity has been mapped using a suite of aquifer parameters as follows:

- Aquifer class – this is a combination of the type of porosity (primary or secondary) and the well yield productivity (high, medium-low).
- Aquifer thickness – this is the estimated saturated thickness of the aquifer (m). It should be noted that aquifer thickness will change and reduce if groundwater is being mined.
- % porosity - the total volume of the pores spaces as a percentage. When multiplied by the saturated aquifer volume, it gives the volume of groundwater in storage.
- Transmissivity - this parameter measures the groundwater flow through a 1m width of the entire saturated thickness of the aquifer under a unit hydraulic gradient. It is a term commonly used in hydrogeology to express the productivity of an aquifer (m2/day).
- Specific capacity – this is a well function term. It expresses the discharge from a pumping well per unit of drawdown - (m3/day/m = m2/day).
- Well yield – this data is usually available at the time of drilling (as is the specific capacity) as a "blowing" yield. This provides a rough estimate of the well yield (m3/day). Typically, it is recommended that the well be pumped at a maximum ± 65% of the blowing yield.
- Elevation and slope- elevation and slope are linked to the saturated thickness of the crystalline basement weathered regolith aquifers. The elevated African erosion surface has been less eroded than the lower post-African surface. In addition, shallow slopes help to preserve the weathered profile intact, while steep slopes promote erosion. The thickness of the weathered regolith is critical to the productivity of basement regolith aquifers.

In presenting a qualitative map for productivity, two key elements are being measured by the "aquifer productivity". These are the storage elements (porosity, saturated aquifer thickness, transmissivity, elevation, and slope) and the well yield elements (specific capacity, well yield) (Table 11). These have different units of measure: volume (m3) and volume/time (m3/day). As a result, it is difficult to provide a single numerical value that captures both storage and yield components. For quantification of aquifer productivity, we have chosen to focus on the storage component (Figure 41). While both aquifer storage and well yield are important parameters for groundwater management, in a semi-arid environment where groundwater resources are under threat from over-abstraction, it is more important to focus on the groundwater storage aspect.

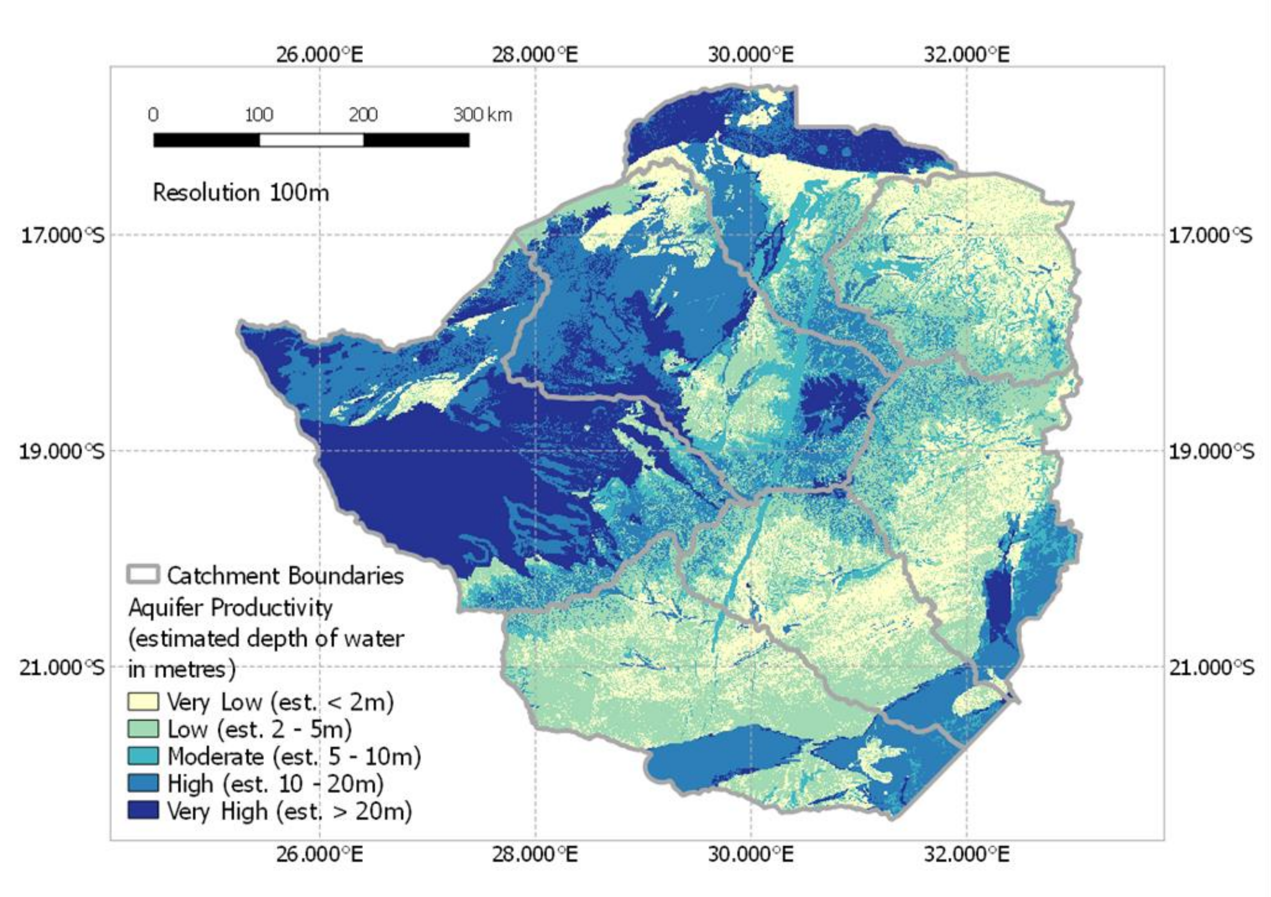


Figure 41: Aquifer productivity, which is a combination of aquifer storage and well yield.

Well yield is often controlled by very local conditions with high yield wells side by side with low yield wells. Nevertheless, it is reasonable to say that some aquifer units are characterized by high well yields while others are characterized by low yields. The well yield may be more a local management issue in terms of determining how many wells may be needed for certain development, while the groundwater in storage is more critical in determining how much groundwater may be abstracted safely and sustainably. Whether this abstraction comes from ten wells or one well, the total abstraction versus the total storage is the key value for water balance management.

Based on this approach, we have developed a quantification for aquifer productivity as shown in Table 17. These values correspond well with storage values measured in m of water (< 1m, 1-10m, 10-25m, 25-50m, >50m) as determined by the British Geological Survey (BGS).

(https://www.bgs.ac.uk/research/groundwater/international/africanGroundwater/mapsDownload.html).

Table 17: Aquifer productivity for different aquifer types

Aquifer Class	Aquifer Types	Permeability/Porosity %	Thickness (m)	Porosity %	Aquifer Productivity m of water
Primary Porosity High Productivity	Kalahari sand	Primary	100	35	35
	Alluvial deposits	Primary	5	35	1.75
	Hwange SST (confined)	Primary	50	20	10
Primary Porosity Moderate Productivity	Karro Forest Sandstone	Primary	100	20	20
	Escarpment Grit	Primary	60	20	12
Primary Porosity	Madumabisa mudstone	Primary	60	20	12

Aquifer Class	Aquifer Types	Permeability/Porosity %	Thickness (m)	Porosity %	Aquifer Productivity m of water
Low Productivity					
Secondary Porosity High Productivity	Lomagundi dolomite	Secondary	70	10	7
Secondary Porosity Moderate Productivity	Bulawayan metavolcanics	Secondary	50	10	5
	Tengwe Calcareous Sedimentary	Secondary	50	10	5
	Upper Karoo Basalt	Secondary	50	10	5
	Mashonaland Dolerite	Secondary	40	10	4
	Granite/Gneiss (African Erosion Surface)	Secondary	40	5	2
Secondary Porosity Low Productivity	Granite/Gneiss (Post African Erosion Surfaces)	Secondary	25	5	1.25
	Cretaceous mudstones	Secondary	70	10	7
	Shamvian	Secondary	40	5	2
	Umkondo Formation	Secondary	100	5	5
	Sijarira	Secondary	100	5	5
	Deweras	Secondary	60	5	3
	Great Dyke	Secondary	40	10	4

Table 18: Value table for aquifer productivity in Zimbabwe – the depth of water (in metres) held in storage under natural conditions.

Aquifer Productivity	Depth of water held (in metres)
Very low	< 2 m
Low	2 - 5 m
Moderate	5 – 10 m
High	10 – 20 m
Very High	> 20m

Figure 41 represents aquifer productivity in Zimbabwe, which is a combination of aquifer storage and well yield. For the purposes of groundwater management, we present here a quantification of the depth of water held in the aquifer. The depth of water multiplied by the areal extent of the aquifer gives a quantitative estimate of the volume of groundwater in storage. The sedimentary Karoo basins in the north, north-west and south fall into the 10-25 m water depth class, and the Kalahari sand in the north-west is in the 25-50 m water depth class. As can be seen from both Figure 41 and Table 18, the sedimentary aquifers hold large volumes of groundwater in storage as compared to the crystalline basement aquifers.

It should also be noted that groundwater can be mined when abstraction exceeds recharge for an extended period and in such cases the water levels in the aquifer decline and the volume in storage declines. It is the objective and role of groundwater management to sustainably manage the groundwater resources. To do this effectively, groundwater level and quality monitoring need to be carried out routinely so that the trends in groundwater storage and quality can be observed from actual data. The total volume of groundwater for each lithologic unit in Zimbabwe has been previously estimated by Lamont Engineering (1995) (Table 19).

Table 19: Groundwater volumes in storage in Zimbabwe

Unit	Areal extent km²	Saturated thickness m	Porosity %	Volume groundwater in storage km³
1: Archean Granite and Gneiss	208,045	40	5	416
2: Greenstone – metabasalt	27,224	50	10	136
4: Lomagundi calcareous facies	1,578	70	10	11
6a: Karoo Batoka basalt	27,425	50	10	137
6b: Karoo Forest sandstone	41,430	100	20	829
6d: Madumabisa mudstone	15,166	60	20	91
7: Cretaceous	10,693	80	10	86
8: Kalahari sand	26,190	100	35	917
9: Alluvial deposits	2,564	5	35	5
10: Unlabelled units	28,685	40	5	57
Total	389,000	595		2,685

Source: Lamont, 1995

2.10.6 Estimates of groundwater quantities in Zimbabwe

Based on work done during this study, groundwater resources, both as groundwater in storage (meters depth of water) and as annual groundwater recharge (mm depth of water/year) have been quantified on a catchment basis. Previous assessments were based on lithologies and reported as depths (storage) and depths/year (recharge) for different lithologies (Table 13) (Lamont, 1995).

Although the methodologies used in this study also assessed volumes of groundwater in storage and annual recharge based on a suite of data including lithologies as well as environmental data, the use of GIS mapping techniques allows the assessment of groundwater quantities on a catchment basis. Table 20 shows the groundwater in storage and the annual groundwater recharge on a catchment basis as assessed in this study, using the methodology described in this chapter.

Table 20: Zimbabwe groundwater in storage and annual recharge

Catchment	Estimated Groundwater Storage (Mega Litres)	Estimated Groundwater Recharge (Mega Litres per Year)
Gwayi	1,440,595,686	5,685,822
Manyame	466,681,353	5,582,370
Mazowe	160,399,025	4,151,687
Mzingwane	399,700,350	653,499
Runde	222,236993	2,494,973
Sanyati	831,427,321	5,841,285
Save	306,272,548	5,278,741
Zimbabwe	3,813,690,631	29,542,108

In the chapter on Groundwater Projects, we also present more detailed catchment maps showing both annual recharge volumes and stored volumes of groundwater in a spatially distributed manner. These maps will allow catchment managers to plan their groundwater resources development and management within a framework of the distribution of the groundwater resources.

2.10.7 Conclusion

Quantification of groundwater resources is known to be complex. The aquifer volumes, the aquifer storage properties, the groundwater recharge rates – all these are highly variable both in space and in time. Abstraction and groundwater discharge are diffuse and equally difficult to quantify.

All these issues present problems for groundwater managers. This report provides a quantitative framework for the management of Zimbabwe's groundwater. If used in conjunction with regular and routine groundwater level and quality monitoring, it should provide a useful tool for groundwater managers for the future up to 2040. However, if it is used without the back-up and verification of routine monitoring, it will be insufficient to guarantee sustainable groundwater management.

Groundwater managers should be under no illusions. The groundwater resources in much of Zimbabwe are in a fragile state and have been mapped as high to very high groundwater drought risk (Villholth et al., 2013). Already many parts of Harare are experiencing groundwater drought as boreholes dry up due to increased pumping as a result of the failure of municipal water supplies. Many boreholes in the high-density suburbs have been tested with typhoid and cholera bacteria and unacceptably high total bacterial counts.

Wise and competent groundwater management, monitoring of water levels and water quality, management of abstractions and demand, open and accessible recording of the data – these are all vital requirement to preserve and sustain our groundwater resources for future generations.

2.11 GROUNDWATER QUALITY IN ZIMBABWE

“Critically, we also found that the greatest threat to groundwater in the region is water quality, not depletion." – Richard Taylor, UCL.

An understanding of groundwater quality in Zimbabwe is based on a very limited number of measured data. Groundwater quality is, more and more, being seen as the most significant threat to groundwater resources. It is, therefore, a vital part of this report to bring attention to groundwater quality issues in Zimbabwe.

This assessment of groundwater quality has been subdivided into two components:

1. Geogenic groundwater quality: This is the groundwater quality due to the natural conditions that impact on it such as lithology, mineral solubility, recharge with freshly infiltrated groundwater, groundwater age or residence time or rainwater chemistry. Geogenic groundwater quality tends to be diffuse rather than localized; it occurs as a result of groundwater-rock interaction. The groundwater becomes mineralized when this interaction is of long duration and the groundwater becomes old (decades to millennia), in rock media that are soluble in water, and where there is a limited freshening of the groundwater by annual recharge.

2. Anthropogenic groundwater quality: This is the groundwater quality due to pollution loading on the surface as a result of human activities. These pollution loads may be point sources such as solid waste disposal facilities, or acid mine drainage from mine waste tips, or they may be diffuse due to application of agricultural chemicals or aerosols from motor traffic. It occurs when the applied pollution load exceeds the attenuation capacity of the unsaturated zone. Attenuation of pollution occurs by adsorption, absorption, ion exchange, neutralization, and related chemical processes. Groundwater is most vulnerable to pollution applied on top of shallow aquifers overlain by permeable soils that are subject to high direct recharge by infiltration.

An interesting observation is that there is no explicit connection between geogenic groundwater quality and anthropogenic groundwater quality. In fact, it can be cogently argued that there is a negative correlation between the two. Due to a lack of groundwater quality trend monitoring, there is very limited information on the groundwater quality status in Zimbabwe.

2.11.1 Geogenic sources of groundwater pollution

On a national scale, geogenic groundwater quality issues are minor and localized, and it is generally considered that Zimbabwe has no major geogenic groundwater quality issues. Approximately 67% of Zimbabwe is covered by impermeable crystalline basement rocks. The aquifers occur in the surficial weathered regolith, usually not much deeper than 40m, and are regularly recharged by rainfall. In addition, most of the rock types in the basement complex are not highly soluble. Thus, groundwater in the crystalline basement areas of Zimbabwe are typically shallow, locally recharged and have short residence times. They tend to be good quality freshwater. As a result, Zimbabwe has a reputation for good quality groundwater as a whole, with only minor geogenic water quality issues.

The geogenic groundwater quality problems that do exist tend to occur in sedimentary basins in specific localities that are distant from the recharge areas and are thereby associated with poor groundwater circulation. In the confined parts of the lower Karoo, groundwater flow paths tend to be several tens to hundreds of kilometres, and groundwater residence times may exceed several hundreds of thousands of years. Due to these long flow paths and extended residence times, the groundwater in these aquifers tends to be quite highly mineralized (Murwira et al., 2013).

The National Master Plan for Rural Water Supply and Sanitation, volume 2.2 (Interconsult, 1987) tabulated some inorganic geogenic groundwater quality analyses (Table 21). A scan of the table shows that for most analyses, geogenic groundwater quality is not a major problem. Hardness is the most common water quality problem where samples exceed the WHO guidelines for drinking water quality. In the sedimentary Karoo strata, water quality issues are more predominant with a very high percentage of samples from the Hwange sandstone having excess fluoride. The fluoride in groundwater is shown to occur in the Madumabisa mudstones and lower Karoo sandstone units. Gokwe North, Hwange, Beitbridge and Save Valley are all areas where geogenic groundwater fluoride has been observed in the groundwater (Figure 42).

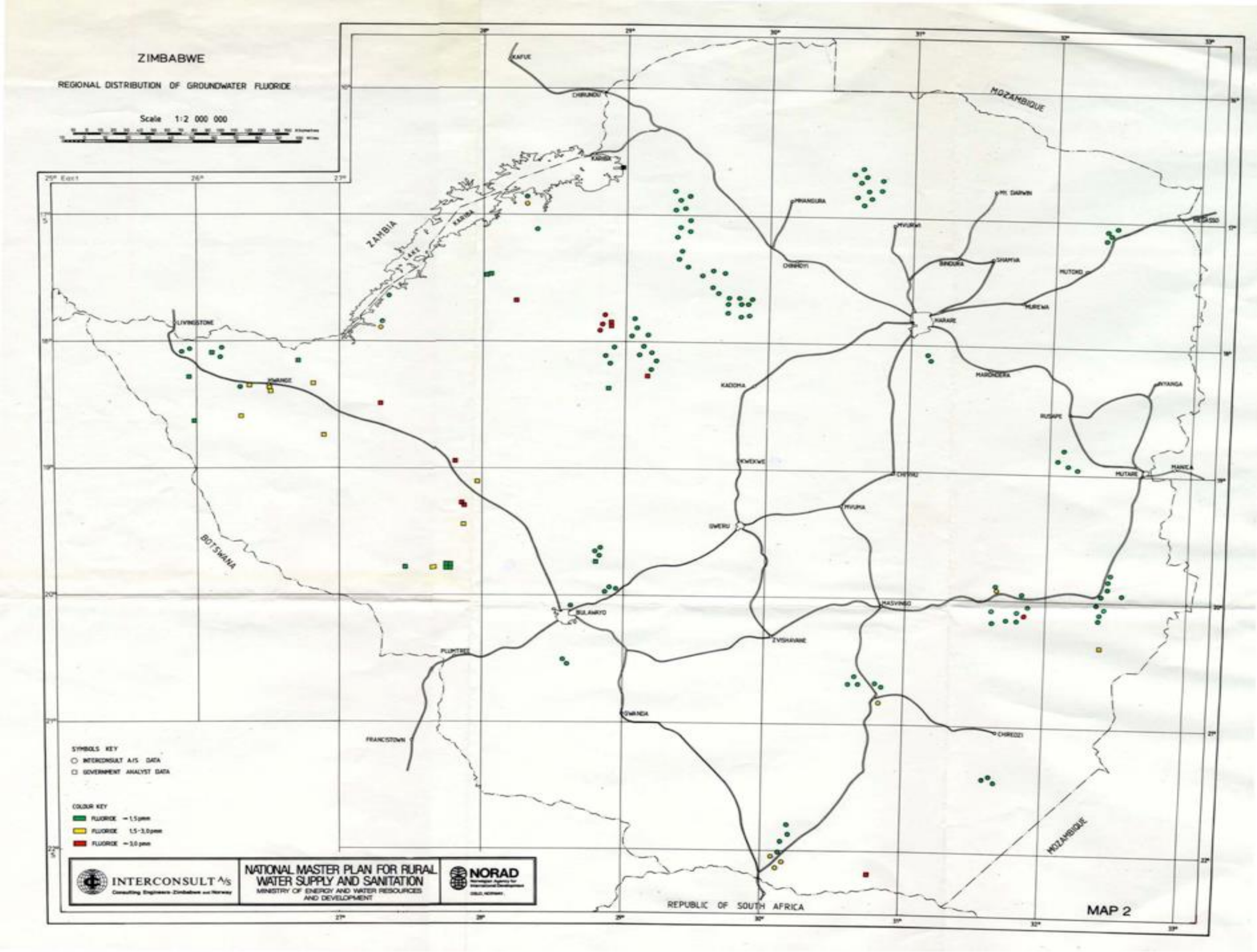


Figure 42: Fluoride in groundwater in Zimbabwe

Source: Interconsult, 1987

Table 21: Geogenic groundwater quality in Zimbabwe (Source: Interconsult, 1987)

	Unit	No.	pH	TDS	Fe	Ca	Hard-ness	Cl	SO4	F	Mn
62 samples	1. Archean Granite Gneiss	62	0	2	1	0	17	17	0	1	0
	percentage not compliant	%	0	3	2	0	27	27	0	2	0
39 samples	2. Bulawayan metavolcanis	39	0	0	3	0	0	0	0	0	12
	percentage not compliant	%	0	0	8	0	0	0	0	0	31
28 samples	3. Sijarira	28	0	0	3	7	14	0	0	3	2
	percentage not compliant	%	0	0	11	25	50	0	0	11	7
6 samples	4. Dolomite	6	0	0	1	0	4	0	0	0	0
	percentage not compliant	%	0	0	17	0	67	0	0	0	0
11 samples	5. Umkondo	11	0	2	0	0	8	1	0	0	0
	percentage not compliant	%	0	18	0	0	73	9	0	0	0
24 samples	6A. Batoka Basalt	24	1	0	0	0	15	0	0	0	0
	percentage not compliant	%	4	0	0	0	63	0	0	0	0
10 samples	6B. Forest Sandstone	10	0	0	0	0	4	0	0	0	0
	percentage not compliant	%	0	0	0	0	40	0	0	0	0
7 samples	6C. Escarpment Grit	7	3	0	0	0	0	0	0	0	0
	percentage not compliant	%	43	0	0	0	0	0	0	0	0
20 samples	6D. Madumabisa Mudstone	20	0	2	11	11	6	0	3	0	0
	percentage not compliant	%	0	10	55	55	30	0	15	0	0
5 samples	6E. Hwange Sanstone	5	0	0	0	0	0	0	1	4	0
	percentage not compliant	%	0	0	0	0	0	0	20	80	0
24 samples	7. Cretaceous Formation	24	7	4	0	0	4	0	0	0	0
	percentage not compliant	%	29	17	0	0	17	0	0	0	0
11 samples	8. Kalahari Sands	11	0	0	0	0	0	0	0	0	0
	percentage not compliant	%	0	0	0	0	0	0	0	0	0
0 samples	9. Alluvial Deposits	0	salinity issues in Save valley but no analyses								
0 samples	10. Mashonaland Dolerite	0		no analyses							

Legend	0-10%	11-20%	21-30%	31-40%	>40%
	▨	▨	▨	▨	▨

Saline groundwater (TDS > 2000 mg/l) is relatively rare in Zimbabwe (Figure 43) but such values have been measured in boreholes in the arid Beitbridge district and the Cretaceous sediments along Zimbabwe's southeastern border with Mozambique. Some saline groundwater has also been recorded along the Zambezi valley, presumably associated with deep groundwater in the escarpment fault zone and the deep Kalahari in northwestern Zimbabwe, likely related to the evaporite sequences in the Kalahari beds. Highly saline groundwater has been observed in some parts of the Save Valley. Similarly, elevated salinity also occurs in the Karoo basins in Zimbabwe, especially in the confined parts of the aquifers where there is no active recharge. Where associated with coal measures, high TDS produces water with an unpalatable sulphurous taste in the groundwater (Murwira et al., 2013).

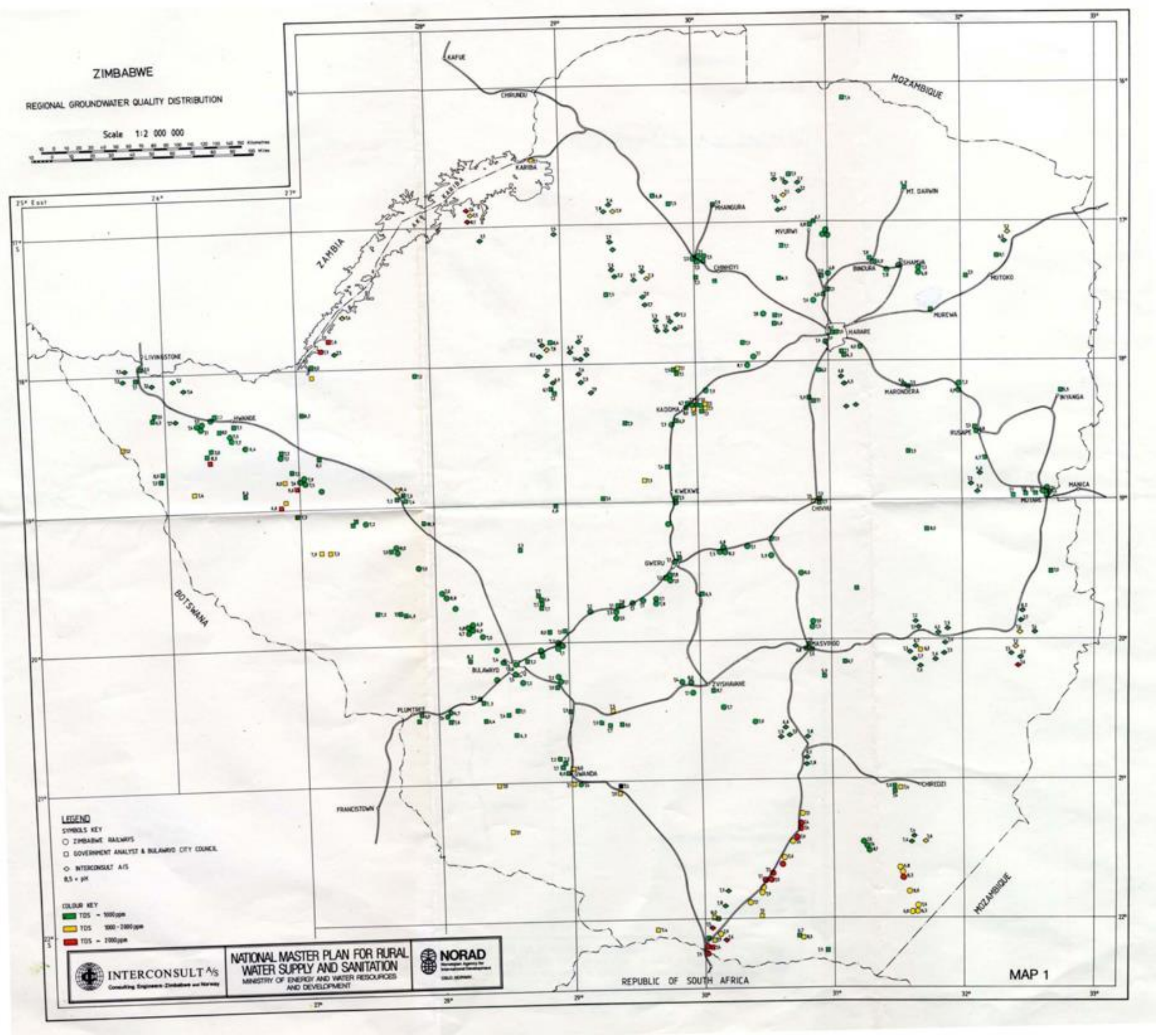


Figure 43: Distribution of groundwater with high TDS (Source: Interconsult, 1987)

It should be noted that the number of groundwater quality samples is small and that the understanding of groundwater quality in Zimbabwe is far from complete. A map of geogenic groundwater quality (Figure 44) has been developed using a variety of generic criteria that impact on geogenic groundwater quality and ranking them using the Analytic Hierarchy Process (Saaty, 2008). The criteria used are: -

- Groundwater recharge rates;
- The solubility of the lithologies – based on Table 16 (Interconsult, 1987);
- Depth to groundwater and the degree of confinement; and
- Groundwater residence time.

Geogenic groundwater quality is a result of rock-water interaction, and the listed properties are linked to the likely degree of chemical dissolution and resultant groundwater quality. In Figure 44, the darker tones indicate fresher good quality groundwater while lighter tones suggest more saline groundwater. In general, the deeper sedimentary aquifers tend to have more saline groundwater while the shallow fractured rock aquifers are usually fresher groundwater. Arid areas tend to have more saline groundwater than humid areas.

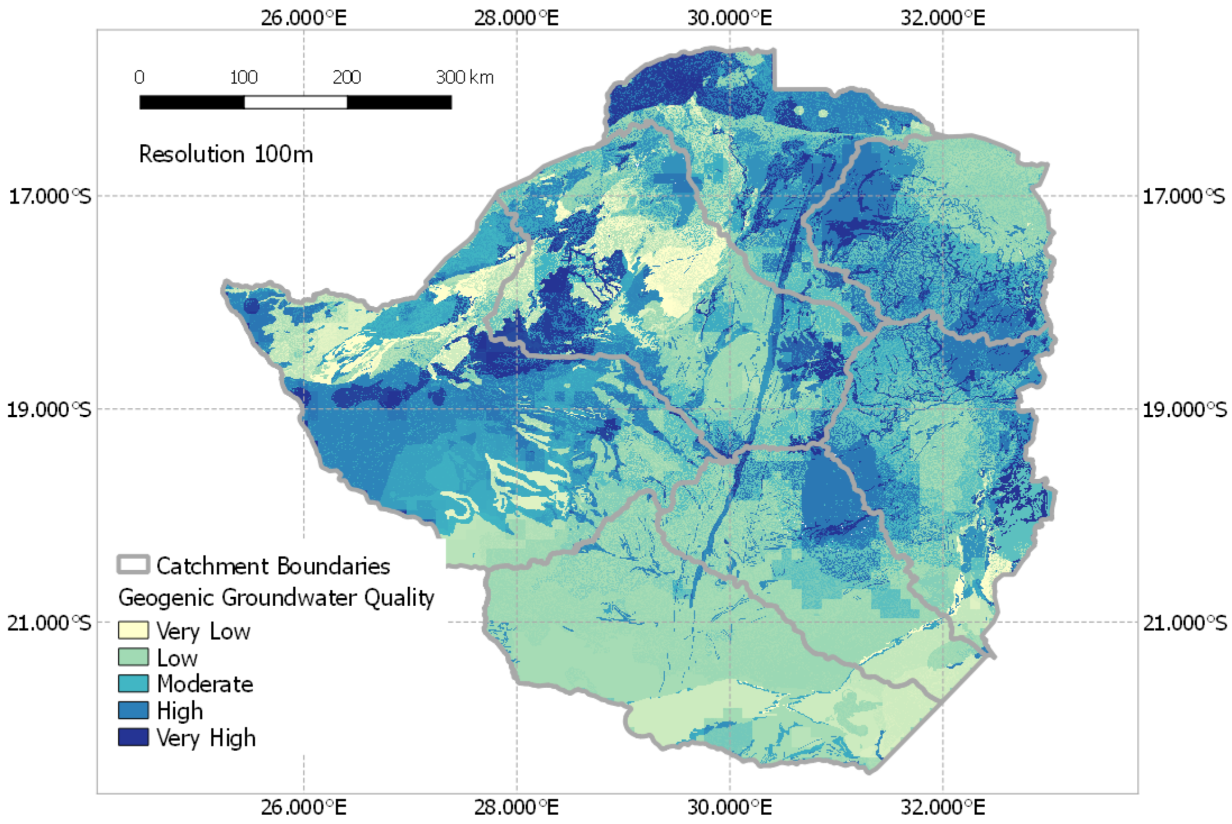


Figure 44: Geogenic groundwater quality. A very high ranking (dark blue) is good quality and very low (pale yellow) is poor quality.

2.11.2 Anthropogenic sources of groundwater pollution

Groundwater quality may be affected by direct recharge of polluted water generated from a suite of point and non-point sources of pollution. In addition, groundwater may be polluted by river-bed infiltration of polluted river water at some distance from the primary pollution source. Groundwater pollution is a rapidly growing issue in Zimbabwe, particularly in urban areas, especially Harare, where microbial contamination with typhoid and cholera has been recorded in boreholes in the high-density suburbs such as Budiriro, Glen View and Mbare. Many of the anthropogenic activities that generate groundwater pollution are occurring without adequate safeguards.

2.11.3 Mapping groundwater pollution

Groundwater pollution arises as a result of seepage to the groundwater from myriad sources. In Zimbabwe, these sources include many hundreds of thousands of pit latrines and septic tanks, leaking sewer lines, overloaded sewage treatment plants and waste ponds, unlined municipal waste dumps, industrial and mining effluents, accidental spills, as well as diffuse sources such as agricultural fertilizers, pesticides and herbicides, aerosol emissions from vehicles and factories, and pollutants transported by the stream drainage system.

To map all these sources of pollutants would be a major task that lies beyond the brief of this NWRMP. Furthermore, not all pollutant loads at the surface reach and contaminate the groundwater system. The actual pollution of the groundwater depends on two interlinked factors as follows: -

- The pollution load, which includes both the volume of the pollutant, its persistence in the environment, its mobility through the unsaturated zone and its toxicity.
- The vulnerability of the groundwater system, which is the ease with which pollutants can reach the water table.

The combination of these two factors then constitutes the Groundwater Hazard Risk. A heavy and continuous pollution load onto a vulnerable aquifer constitutes a high groundwater hazard risk.

A common approach used to manage groundwater pollution has been to assess the "Groundwater Vulnerability to Pollution". If the vulnerability of the aquifer system has been assessed, then it becomes possible to apply appropriate restrictions to waste disposal practices for a particular aquifer. Deep aquifers overlain by impermeable materials may need little protection while shallow aquifers under permeable soil cover will need more protection from pollutants. It also depends on the intended use of the groundwater and drinking water supplies require a higher degree of protection than water that may be used, for example, in cooling processes.

Various well-established groundwater vulnerability assessment techniques have been developed. The best known of these techniques is DRASTIC, which is an acronym that stands for:

D – depth to water;
R – net recharge;
A – aquifer media;
S – soil media;
T – topography;
I – impact of the vadose zone; and
C – aquifer hydraulic conductivity.

It can be seen that some of these properties are in fact repetitions; e.g. aquifer media and aquifer hydraulic conductivity are similar; soil media and impact of the vadose zone are also similar. Nonetheless, the DRASTIC model is helpful in that it focuses attention on key properties that need to be assessed in order to understand the vulnerability of groundwater to pollution. Subsequent models have used different properties.

For this study we have mapped the following properties for vulnerability assessment: -

- Rainfall;
- Topographic Wetness Index;
- Groundwater Depth;
- Aquifer Type;
- Land Use; and
- Vegetation.

To some extent, these six properties were selected because national geo-referenced maps of these data are available. These six properties effectively assess the net recharge, the impact of the vadose zone and the aquifer hydraulic conductivity, which are some of the fundamental properties that control aquifer vulnerability. As shown in Figure 45, the shallow unconfined aquifers in the high rainfall/high recharge areas are the most vulnerable to pollution, while the deep confined and semi-confined aquifers in the low rainfall areas are the least vulnerable to pollution.

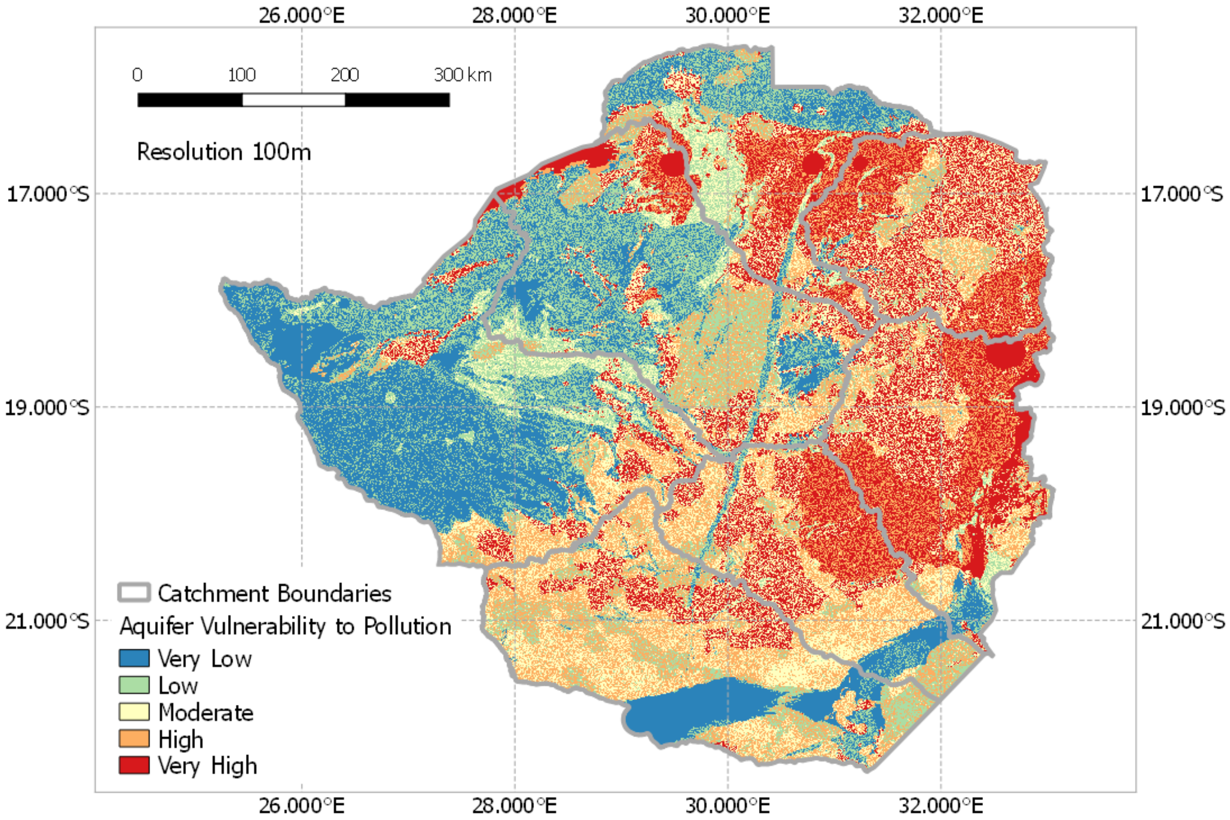


Figure 45: Aquifer vulnerability to pollution

Once the aquifer vulnerability is known, then it becomes more practical to identify groundwater pollution hotspots and overlay them onto the vulnerability map, producing a groundwater quality risk map.

2.11.4 Groundwater quality risks

Some key sources of groundwater quality risk are discussed below (Murwira et al., 2013).

Mining: A major source of groundwater anthropogenic pollution is mining, and mine waste disposal sites. There are over 8000 mines of various sizes scattered across Zimbabwe, mostly gold mines in the greenstone/gold belt terrain, but also chrome and platinum mines along the Great Dyke and coal mines in the lower Karoo coal measures.

Metalliferous mines are strongly associated with Sulphide minerals, and in the geological environment, most metals are found as mineral compounds of Sulphur. Most mines have open shafts, waste rock dumps and tailings dams where these sulphide minerals, such as pyrite, FeS2, are exposed to the atmosphere and circulating groundwater. When FeS_2 reacts with oxygen O_2 and water H_2O, they produce sulphuric acid H_2SO_4. This is known as acid mine drainage (AMD). The sulphuric acid subsequently dissolves susceptible heavy metals, which are then in solution and mobilized to enter the surface and groundwater systems.

The finely ground rock material in the tailings dams presents a very large surface area of exposed sulphide minerals and therefore these mine tailings dams generate the large volumes of acid mine drainage (Moreno-Madrinan et al., 2010) and the associated pollution loads. Most metal mines tend to generate AMD. However, the chrome and platinum mines on the Great Dyke are often associated with serpentinites that generate alkali weathered materials with high pH, and in such an alkaline environment, AMD is minimized.

It is anticipated that the sulphide load in the tailings dams constitutes an AMD threat that will persist for several generations until all the sulphides have been consumed by AMD. Mines and mine dump, therefore, constitute a very widespread suite of point pollution threats to groundwater in terms of heavy metal contamination, both now and into the future.

All mining activities in Zimbabwe are now subject to EMA effluent discharge regulations, but many thousands of historic mining waste dumps and tailings dams are generating acid mine drainage (Moreno-Madrinan et al., 2010) and releasing toxic heavy metal enriched acid water to the environment. The industry is in a similar position and old abandoned dumps of industrial wastes are still sources of toxic leachate to the groundwater system.

Sewage disposal: Domestic sewage in the urban areas is generally managed by water-borne sewage networks, with septic tanks in the low-density residential areas. Pit latrines are the principal form of domestic waste management in rural areas. Sewage treatment plants are often overburdened due to the rapid expansion of the urban population and lack of investment in new infrastructure. The combined Harare sewage treatment plants (the main ones: Firle, Crowborough, plus a number of smaller local plants) are perhaps the most overloaded in the country and far exceed their design capacity. As a result, large volumes of partially treated and untreated domestic waste are discharged into both the surface water and the groundwater drainage. Sewage treatment plants also discharge wastewater to 'sewage farms' for use as fertilizer. In most cases, there is little on-going assessment or groundwater quality monitoring of the impacts on the local groundwater systems. Sewage spillages and discharges from municipal wastewater treatment plants have been measured by EMA and a sample of the most egregious spills in Harare are listed in Table 22. Lesser overloading occurs in most other municipal environments.

Table 22: Table shows a small sample of some of the wastewater discharges to the environment in Harare.

Local Authority (Town/City)	Name of treatment plant/pump station	Design Capacity	Current Influent Received	Discharge volumes into the environment	Effluent Class	Receiving Environment
Harare	Firle STP	144ML/day	143ML/day	54ML/day into surface water 36ML/day land application 53ML/day spillages	Unit 5a & 5b above limit Unit 1& 2 –Red Unit $- Blue	Mukuvisi River Churu Farm,
	Crowborough STP	54ML/day	110ML/day	0ML/day into surface water 36ML/day land application 74ML/day spillages	Unit 1&2 –Yellow	Marimba River
	Hatcliffe STP	2.5ML/day	3.5ML/day	3.5ML/day surface water	Red	Gwebi River
	Borrowdale Brooke PS	1.5ML/day	1.5ML/day	1.5ML/day surface 1.5ML/day Spillages	Above limit	Umwisindale River

Sewage discharge is heavily implicated in the pollution of Harare's surface water dams and although few groundwater quality data are available, it is anticipated that these sewage discharges also constitute a significant groundwater pollution risk.

Broken sewer pipes: The impact of sewage pipe bursts on groundwater quality in the high-density suburbs in both Harare and Bulawayo is a serious cause for concern particularly in light of the frequent outbreaks of water-borne diseases such as cholera and typhoid. Due to the decline in the delivery of municipal water supplies, water both for consumption and for flushing the waste system has declined. As a result, sewers become blocked and burst, leaking effluent into the ground and thus contaminating groundwater. Such sewer pipe bursts are quite common in some high-density suburbs in Harare such as Budiriro and Glen View.

Often these leaks are difficult to locate and may persist for a long time before they are repaired. These areas have experienced endemic typhoid for at least a decade, and some boreholes in these areas have been repeatedly tested with typhoid and other unsafe bacteria (MSF, 2019). Although the link between contaminated boreholes and broken sewer lines has not been definitively proven, it certainly seems to be a possible source of the contamination of the groundwater.

At the same time, the frequency of supply and the quality of the treated municipal water has declined, and residents have to rely on groundwater from shallow hand-dug wells and drilled boreholes. Due to suspicions about municipal water in Harare, groundwater has now become the preferred source of drinking water in the high-density suburbs.

However, as noted above, the groundwater may not be entirely safe. MSF (Belgium) has been carrying out an urban WASH program, based on protecting groundwater supplies, in some of the high-density suburbs of Harare (especially Budiriro and Glen View) in order to combat the rise of typhoid and cholera. They have recorded the presence of a variety of bacteria, notably salmonella (typhoid) and cholera, in some boreholes and shallow wells in their program areas.

In Bulawayo, total coliforms and faecal coliforms which pose a threat to human health were found in 27% and 8% respectively of the sampled borehole sites (n = 32) drawn from the Matsheumhlope basement aquifer (Mangore and Taigbenu, 2004).

Pit latrines: Pit latrines and septic tanks constitute tens of thousands of minor point sources of local bacterial contamination of the shallow groundwater table. Although groundwater is protected by natural filtration against bacteria of faecal origin if proper controls are in place, there is evidence that faecal coliforms from pit latrines are contaminating the shallow groundwater in some parts of the country. This may occur when pit latrines are located too close to water supply wells or boreholes. Although less common, the ground formation may fail to attenuate the bacterial load if the flow is fracture flow rather than seepage flow. This process results in bacterial contamination of underground water.

For informal high-density suburbs, sanitation is generally by means of pit latrines and the impact on the groundwater is more widespread and diffuse. Work done in the semi-formal settlement of Epworth (near Harare) reported significantly elevated levels of coliform bacteria in groundwater samples collected from shallow wells and boreholes scattered throughout the settlement. The highest levels of coliforms (> 10,000 CFU) were measured in water samples from the old parts of the settlement with a high density of pit latrines (Zingoni et al., 2005). It was, therefore, concluded that most parts of Epworth lack safe groundwater for human consumption. This finding suggests that pit latrines impact both surface and groundwater quality.

A report on the impact of pit latrines on groundwater quality from Chihota communal lands (Dzwairo et al., 2006) found that faecal coliforms were detected in groundwater from some drinking water wells located in sandy soils and on deeply weathered and fractured igneous rocks in the Goromonzi district (Conboy and Goss, 2000).

Solid waste dumps: All urban settlements in Zimbabwe use solid waste dumps to dispose of their solid waste materials. Many of these solid waste dumps are poorly constructed and poorly managed without impermeable linings nor leachate collection nor treatment facilities.

Waste is generally not separated into waste streams with domestic, industrial, and chemical wastes all being disposed of in the same dump. As a result, mixed toxic leachate is generated and discharged into the groundwater system, and this may further discharge as baseflow to the stream system. Golden Quarry and Teviotdale/Pomona dumpsites in Harare are two examples of such facilities. At Pomona, there are four groundwater quality monitoring boreholes, but the monitoring schedule and results of the monitoring are not available to the public. At other municipal solid waste dump sites, groundwater quality monitoring is usually not taking place.

The capacity to measure persistent organic pollutants (POPs) such as PCB's (Poly-Chlorinated Biphenyls) from solid waste dumps is very limited in Zimbabwe hence such pollutants may already be in the aquifers but remain undetected.

Industry: Industry generates effluent and other toxic waste and, in many cases, such waste is not properly treated nor safely disposed of. Older factories established before the adoption of cleaner technologies in production processes were in the habit of discarding industrial waste into unlined pits and effluent back into the stream system. Such practices have declined with increased environmental understanding and improved legislation and management practices, but the threat to groundwater for these practices still resides in the sub-surface. Chemical industries, leather tanneries and industries that use large volumes of water and discharge bulk effluent back into the drains, such as the dairy, textile and paper and pulp industries, all contribute to groundwater quality degradation.

Land degradation and reduced recharge: Decline in groundwater quality may also occur as a result of land degradation. Removal of vegetation cover and erosion of topsoil results in increased run-off coefficients and a concomitant decrease in groundwater recharge. This decrease in recharge creates a threat to groundwater quality in that there is less freshwater entering the aquifer. As a result, the remaining groundwater is older and becomes relatively more saline with time. Thus, protecting and restoring recharge and retention rates is an important component in protecting the groundwater quality and has been identified as a key strategy in protecting our groundwater resources.

A similar reduction in recharge occurs when urban development takes place, covering the land surface with concrete, tar, and other impermeable surfaces. Such developments reduce the area of recharge and the recharge rate. For this reason, the development of groundwater recharge areas and urban wetlands for housing, infrastructure or commerce should be discouraged and only take place with extreme caution and a proper appreciation of the long-term impacts on groundwater quality. The requirements for an environmental impact assessment (EIA) should always be met in full and should include an appreciation on the impact of development on groundwater recharge and groundwater quality.

Excessive pumping: A further potential threat to groundwater quality arises from excessive pumping that results in unsustainable drawdown in the water levels. Under such conditions, older and less fresh groundwater can be mobilized from the deeper parts of the aquifer, mixing with the fresher better-quality groundwater, and thereby reducing the overall groundwater quality.

With the reduction in potable water distribution by municipalities, many private individuals and companies have turned to boreholes to supply their water needs. This increased abstraction together with declining recharge due to land use and climate change suggests that the groundwater resources will continue to be steadily drawn down over time, with an attendant reduction in the quality.

Recent groundwater sampling from boreholes at the University of Zimbabwe suggest that only 2 % of rainfall becomes recharge, which is equivalent to a recharge rate of 1 litre/second per km2 (Muchineri, 2013). Although pumping rates for Harare groundwater are not known, estimates suggest that abstraction rates in the range of between 10 and 15 litres/second per km2 are likely in areas that do not receive municipal water. Moreover, Harare municipal water is widely reputed to be of poor quality, and many people prefer to use groundwater for domestic purposes, even if municipal water is supplied. Moreover, since self-supply of groundwater is less expensive than purchasing municipal water, this problem of over-pumping is likely to persist even if municipal water supplies were ever to resume fully.

Clearly, there should be considerable concern about the over-abstraction of the groundwater in Harare. Anecdotal evidence from drilling companies in Harare suggests that the water-table has already declined approximately 10m in some areas of Harare. One company (Get Wet) indicated at a workshop with ZINWA that whereas previously they used to drill 40 to 60m in Borrowdale, Harare, they now drill 80 to 150m deep boreholes. Thus, excessive and unmonitored pumping in Harare constitutes a very significant threat not only to groundwater resources but also to groundwater quality.

2.11.5 Knowledge gaps in groundwater quality

A major issue with regards to groundwater quality management in Zimbabwe is that there is very limited data available. Work on groundwater quality has been limited to a few scattered studies. For example, Mabvira (2003) and Ashton et al. (2001) produced general overviews on the impact of mining on water quality in Zimbabwe. Meck et al. (2009 and 2010), Ravengai et al., (2001), Ruzive (2000), Musiwa et al., (2004) and Ngwenya (1997) have also assessed the impacts of specific mining sites on water quality, but none of these studies specifically focused on groundwater quality. In addition, Ravengai et al., (2004 and 2005) presented data on the impact of industrial effluent on groundwater from a single site in Harare. Love et al., (2006) and Zingoni et al., (2006) reported on the impact of diffuse pollution on groundwater from several localities around Harare.

The ZINWA groundwater branch hosts a national groundwater database. This database has entry fields for groundwater quality data for each borehole, but for the most part, these fields are not populated. Where the fields are populated, the data are usually for a single instance in time and there is almost no time-series data to show changes to groundwater quality. There are no data on persistent organic pollutants in groundwater and the laboratory capacity to measure such components is not available in Zimbabwe.

During this study, a basic groundwater vulnerability map was produced, but it has not been tested against actual data. There are no contaminant load maps identifying point and diffuse sources of potential groundwater contamination, such as mines, solid waste dumps, industrial developments, and agrochemical farming. There are no groundwater hazard maps that combine the groundwater vulnerability with the location of sources of pollution and the risk to humans, livestock, and commerce. The development and production of such maps will be an important step towards managing groundwater quality in Zimbabwe. Geogenic groundwater quality maps are available for fluoride and TDS (MWRED-Norad, 1985), but only have few data points.

There is a need to know more about the groundwater quality especially in areas where groundwater is heavily used, and in areas where it is a strategic resource. This is particularly true of the major urban centres, especially where the surface water sources and the treatment and distribution infrastructure are insufficient to meet demand. In these areas, groundwater is widely used for domestic water supply and the quality of the groundwater is vital.

It is important to understand the impact of major point sources, such as solid waste dumps and mines, on the groundwater quality, as well as the extent and distribution of pollution associated with such point sources. The persistence and attenuation of pollutants in the groundwater system need to be known. Similarly, understanding the impact of agriculture and the application of fertilizers and agrochemicals on groundwater quality is required. Finally, the vulnerability of groundwater in Zimbabwe must be assessed, particularly in relation to sensitive areas, such as the cities.

2.12 TRANSBOUNDARY AQUIFERS

According to IGRAC (2017 – SADC-GMI Hydrogeology Atlas), Zimbabwe has six transboundary aquifers (Figure 46). These transboundary aquifers may be classified according to three key criteria: -

1. Is there ongoing significant groundwater abstraction taking place e.g. irrigation?
2. Are they linked directly to a transboundary river?
3. Is there signify`cant natural or induced flow within the aquifer from one transboundary state to others?

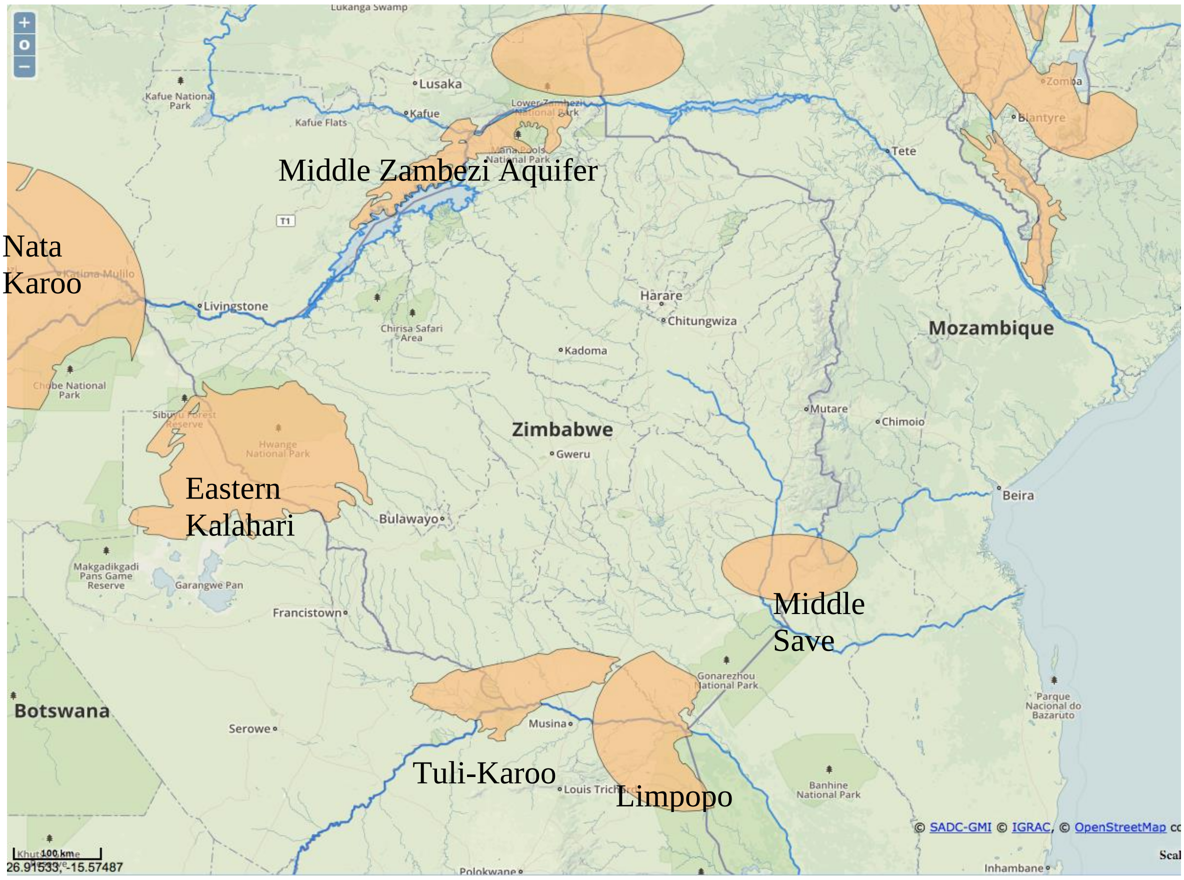


Figure 46: Transboundary aquifers of Zimbabwe

Source: IGRAC, 2017

Based on the above criteria, we can tabulate the transboundary aquifers as shown in Table 23.

Table 23: Transboundary aquifers in Zimbabwe as identified by IGRAC 2017/IWMI 2014

Aquifer Name and Aquifer Lithology	Sharing Countries	Trans-boundary River	Groundwater Development	Transboundary Impact
Tuli Karoo sub-basin* Alluvial aquifer along Limpopo River. Upper Karoo sandstones / basaltic volcanic.	Botswana, South Africa, Zimbabwe.	Limpopo	± 10,000 ha irrigation – two separate blocks. 2000 ha block in Zimbabwe. Irrigated with groundwater. No major development from the Upper Karoo sandstone aquifer.	Alluvium recharged by river flow and abstraction has a direct impact on river flow. Rain: 300-450 mm/year Recharge: V Low - Low
Limpopo Basin Alluvial aquifer along Limpopo River. Volcanics and Basement	South Africa, Zimbabwe Mozambique	Limpopo	No significant development. Chikwarakwara smallholder scheme (65ha.) uses river water.	Thick alluvial aquifer known at Groot Vlei but not developed. Not significant.
Middle Save* Save alluvial aquifer.	Zimbabwe Mozambique	Save	± 15,000 ha irrigation in Zimbabwe. Irrigated with groundwater but recharged by dam releases.	The aquifer is not transboundary but abstracts significant water from transboundary Save River.
Middle Zambezi Aquifer* Upper Karoo sandstones / basaltic volcanic.	Zambia, Zimbabwe	Zambezi	Old Chirundu Estate 250 ha. Zambia centre pivots 2000 ha. Irrigation with river water.	Chirundu Estate now abandoned. Centre pivots in Zambia irrigated by Kafue river water.
Nata Karoo sub-basin Kazungula	Botswana, Namibia, Zimbabwe	Zambezi, Chobe	No significant groundwater development.	Chobe wetlands
Eastern Kalahari / Karoo Basin. Pandamatenga*	Botswana, Zimbabwe	No river	Pandamatenga (Botswana) ± 25,000 ha irrigation with Zambezi river water. No groundwater development.	Transboundary Kalahari sand and Upper Karoo sandstone aquifers. Rain: 400-600 mm/year. Recharge: Low-Mod The natural hydraulic gradient in the Kalahari sands from east to west -> gw flows to Botswana

Of the six transboundary aquifers in Zimbabwe, only two have any significant development of groundwater. The other four transboundary aquifers are not developed at this stage. The two, Limpopo and Middle Save, are both, to a large extent, alluvial aquifers alongside active river channels. The transboundary impacts of large-scale groundwater abstraction from these two aquifers are likely to result in significantly reduced surface flows in the associated transboundary rivers, since it is river flow water that recharges the aquifers.

Figure 47: Middle Save alluvial aquifer ± 15,000 ha. Water pumped from the alluvial aquifer is recharged by river flow at the expense of downstream river discharge.

In the case of Middle Save (Figure 47), the Save alluvial aquifer is not transboundary at all. It is the impact of groundwater abstraction on Save River flows that has a transboundary impact as reduced river discharge downstream in Mozambique. This could amount to 300 to 400 Mm^3 per year (15 m^3/s) reduced flow in the Save River. It must be noted that much of this river flow could be derived from releases from Osborne Dam.

The Limpopo-Tuli Karoo sub-basin alluvial aquifer (Figure 48) is more directly transboundary with groundwater abstraction taking place on both the South African and the Zimbabwean sides of the border, which is marked by the Limpopo River. Approximately 10,000 ha of irrigation takes place using mostly alluvial groundwater. Although there may be deeper boreholes tapping into the upper Karoo Sandstone confined aquifer, this aquifer is not significantly developed. Irrigation consists of ± 2000 ha on the Zimbabwean side of the river and ± 8000 ha on the South African side of the river. This groundwater abstraction is considered to be largely at the expense of river flow, and the alluvial aquifer is considered to be fully recharged by annual river flows. The irrigation demand and hence the reduction in river flow is estimated at ± 260 Mm^3 per year.

Figure 48: Tuli Karoo sub-basin - Limpopo Transboundary alluvial aquifer. Note two irrigation areas, one in the west of the image near Rhodes Drift Lodge on the border between South Africa and Botswana and the other to the east of the image on the border between South Africa and Zimbabwe.

The other four transboundary aquifers have no significant groundwater abstraction associated with them at this time. However, since they have been designated as transboundary aquifers, they are shown here together with some comments on their nature and status.

The Limpopo Basin transboundary aquifer, at the triple junction between Zimbabwe, South Africa, and Mozambique, is known to host some productive alluvial beds up to 90 meters thick (Hineson et al., 1961). However, no significant development has taken place, except for a smallholder scheme some 65 ha at Chikwarakwara on the Zimbabwean side, which is supplied by surface water.

The satellite image (Figure 49) reveals that the alluvial aquifer is only developed alongside the river channel. There is no wide alluvial plane here, but rather a deeply scoured channel as anticipated with the hard, resistant rock formation upstream and the soft erodible formation downstream.

Figure 49: Limpopo Basin transboundary alluvial aquifer.

The Middle Zambezi-Chirundu (Figure 50) transboundary quaternary alluvial aquifer has only minor irrigation development on the alluvial plain, some 250 ha that is still being irrigated on land that was previously farmed for irrigated sugar cane by Chirundu Estates. On the Zambian side of the river, there is ±2,000 ha of irrigation under centre pivot. However, this development is 5 km from the river and it seems likely that it is irrigated with river water, probably from the Kafue River.

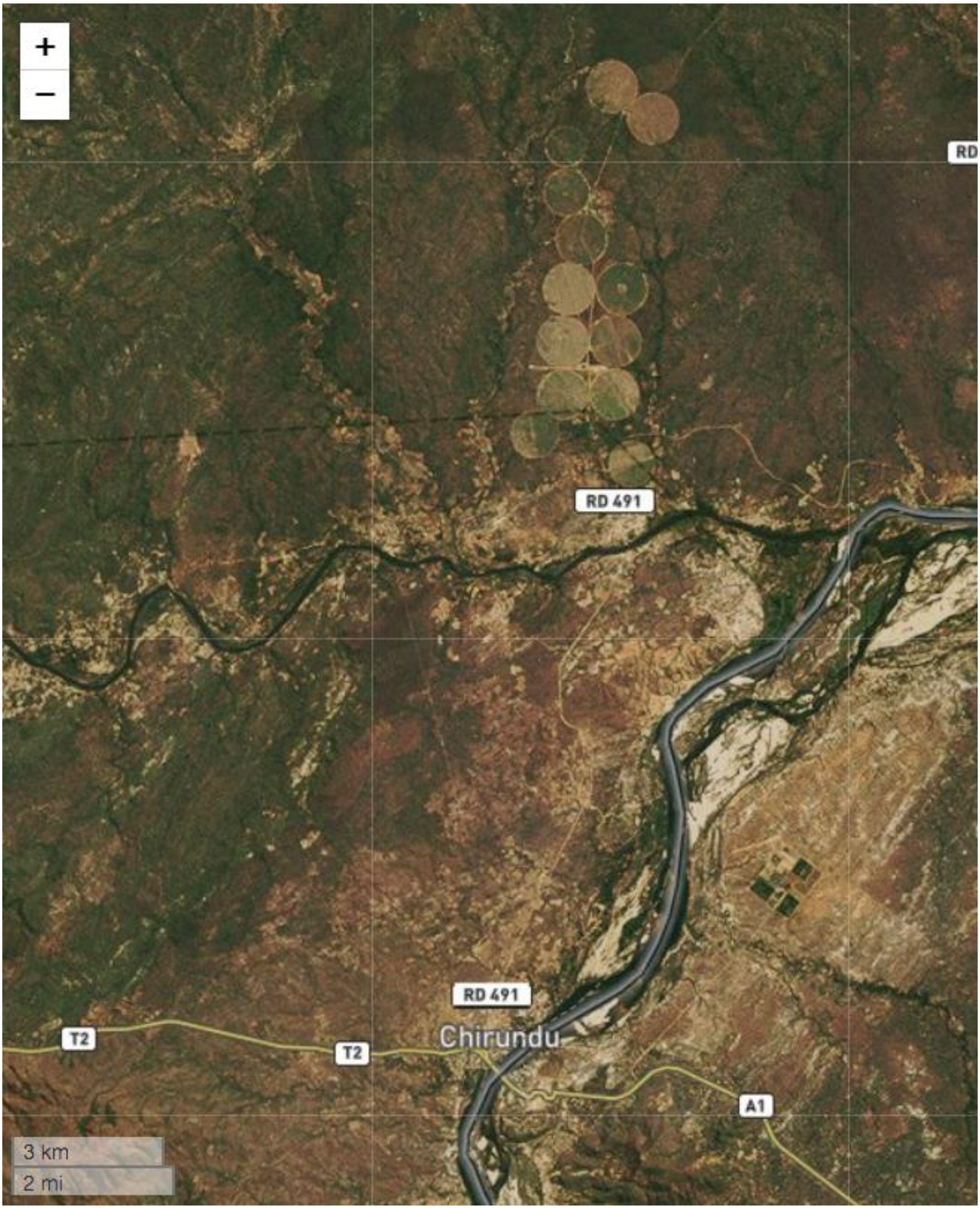


Figure 50: Middle Zambezi-Chirundu transboundary aquifer.

Further upstream on the Zambezi River, at Kazangula, near the confluence with the Chobe River (Figure 51), IGRAC identify another transboundary aquifer, the Nata Karoo basin. Study of the satellite imagery shows an extensive wetland terrain with no irrigation development.

Figure 51: The Nata Karoo sub-basin at Zambezi-Kazangula.

The final transboundary aquifer is not associated with a river. This is the Kalahari/Upper Karoo sandstone transboundary aquifer between Botswana and Zimbabwe (Figure 52). This transboundary aquifer is considered to occur in two layers, the top layer consisting of unconsolidated Kalahari sands, and a deeper confined/semi-confined Karoo sandstone aquifer underlying the Kalahari sand. There is ±25,000 ha of irrigation developed at Pandamatenga in this locality. However, it is not irrigated from groundwater, but with Zambezi River water.

Transboundary flows from Zimbabwe into Botswana do occur due to the natural hydraulic gradient which declines from Zimbabwe towards the Magadigadi pans, which are the local base level. The hydraulic gradients towards the Magadigadi pans have been measured at between 1:1,000 and 1:2,000, and groundwater discharge flows are considered to be minimal, in the region of 1mm/year (De Vries et al., 2000).

Figure 52: Kalahari/Upper Karoo transboundary aquifer.

2.12.1 Concluding remarks on transboundary aquifers

There are two transboundary aquifers in Zimbabwe that have an impact on the other riparian states. These are: -

- Limpopo alluvial aquifer ± 260 Mm3/year abstractions as estimated.
- Middle Save alluvial aquifer ± 400 Mm3/year abstraction as estimated.

Both of these aquifers are alluvial aquifers in direct contact with the Limpopo and Save Rivers, respectively. These aquifers receive their recharge water from river flow, and it is the impact on river flow that is transboundary. The alluvial sediments act as a temporary store for groundwater, which is discharged by pumping and recharged by river flows, and, in the case of the Save River, by dam releases from the upstream Osborne Dam. In both cases, the impact is to substantially reduce river flows to Mozambique, the downstream riparian state, in the Limpopo and Save Rivers, respectively. However, it should be noted that the river flow in the Save River is supplemented by Osborne Dam releases.

3. GROUNDWATER AND CLIMATE CHANGE IN ZIMBABWE

3.1 INTRODUCTION

Climate change brings greater unpredictability to the climate, and particularly to temperature, evaporation, precipitation amounts, intensity, duration, sequences of wet days, and seasonal changes, as well as an entire suite of downstream impacts. The 2018/2019 rainy season in Zimbabwe certainly seems to suggest that the impacts of climate change are already upon us. The country first experienced a severe nationwide hydrological drought, and then towards the end of the season, Cyclone Idai struck, with flooding, crop destruction, landslides, infrastructure damage and significant loss of life.

For Zimbabwe, the CSIRO 4.5 RCP climate change scenario suggests increasing temperatures with slightly decreasing rainfall throughout the country. The number of consecutive wet days is also marginally lower, except for the north-western corner of the country, where an increase in consecutive wet days has been modelled.

Groundwater has traditionally been a water resource that is used during periods of drought when surface water tends to dry up more rapidly than groundwater. However, when drought conditions are prolonged, such as during climate change, then groundwater is not immune to these meteorological changes and also becomes adversely impacted. What will be the role of groundwater in a future under climate change when the nation may have to adapt to a drier and hotter climate?

3.2 GROUNDWATER DROUGHT RISK

One response to the threat of climate change has been an increasing focus on groundwater. While groundwater science accepts that in the short to medium term, groundwater in storage can generally provide a buffer during drought, the issue of the impact on groundwater resources of long-term climate change needs to be addressed. This concern has led to the coining of a new term: “groundwater drought”.

Recent work in SADC addresses the issue of groundwater drought risk and groundwater drought (Villholth et al., 2013), which is characterized as follows: -

> “Groundwater drought denotes the condition and hazard during a prolonged meteorological drought when groundwater resources decline and become unavailable or inaccessible for human use. Groundwater drought risk refers to the combined physical risk and human vulnerability associated with diminished groundwater availability and access during drought.”

In their work, Villholth et al. (2013) carried out a composite mapping analysis in order to produce spatial maps of the groundwater drought risk throughout SADC, including Zimbabwe. Sections of their analysis and results are included in this chapter on Groundwater and Climate Change in Zimbabwe.

3.3 SOME KEY CHARACTERISTICS OF GROUNDWATER RESOURCES WITH REGARDS TO DROUGHT

Groundwater is a water resource that often plays a key role in arid and semi-arid environments for a number of reasons.

- Evaporation losses are minimal;
- It has very long residence times and does not discharge quickly; and
- There are generally very large volumes held in storage.

However, there are also certain negative aspects of groundwater.

- Recharge is likely to be episodic and erratic in drier climates;
- Groundwater tends to become more saline when a recharge is not regular; and
- Crystalline rock aquifers with only fracture porosity are low porosity (± 2%) and are surficial, not extending to any great depth. Hence the volumes in storage are limited.

For the purposes of this discussion on groundwater and climate change, the focus will be on two key characteristics of the groundwater resources in Zimbabwe: -

1. The volumes of groundwater held in storage in Zimbabwe's aquifers; and
2. The changes to the recharge rates under climate change scenarios predicting a hotter and drier climate.

A further factor to be considered is the impact of increased demand on the groundwater resources as formerly perennial surface water resources become seasonal, and seasonal surface waters dry up altogether.

3.4 GROUNDWATER VOLUMES IN STORAGE

The aquifer productivity map of Zimbabwe classifies groundwater resources as very high to very low potential (Figure 41), and Tables 13 and 14 provide volumes of groundwater in storage. The major part of Zimbabwe is underlain by low potential aquifers and to make matters worse, these low potential aquifers are located in those areas with the highest population, while the high potential aquifers are mostly in sparsely to very sparsely populated areas.

A further question is how much water is actually in storage in these aquifers? Such questions become more urgent during periods of extended drought. Since groundwater aquifers have uncertain physical boundaries and varying porosities, all hidden below the surface, a precise answer is not possible, and although estimates have been made, groundwater monitoring is essential, especially during periods of persistent drought.

A further vital factor in terms of groundwater management under climate change are the issues of groundwater demand and human vulnerability to groundwater drought. This is more than just the population density, but also includes access to alternative sources of water and financial wealth to afford e.g. drilling boreholes.

A comparison of the population density map (Figure 53) and the aquifer productivity map (Figure 41) shows a striking correlation between high population density and low groundwater productivity. Conversely, low population density correlates with high groundwater productivity.

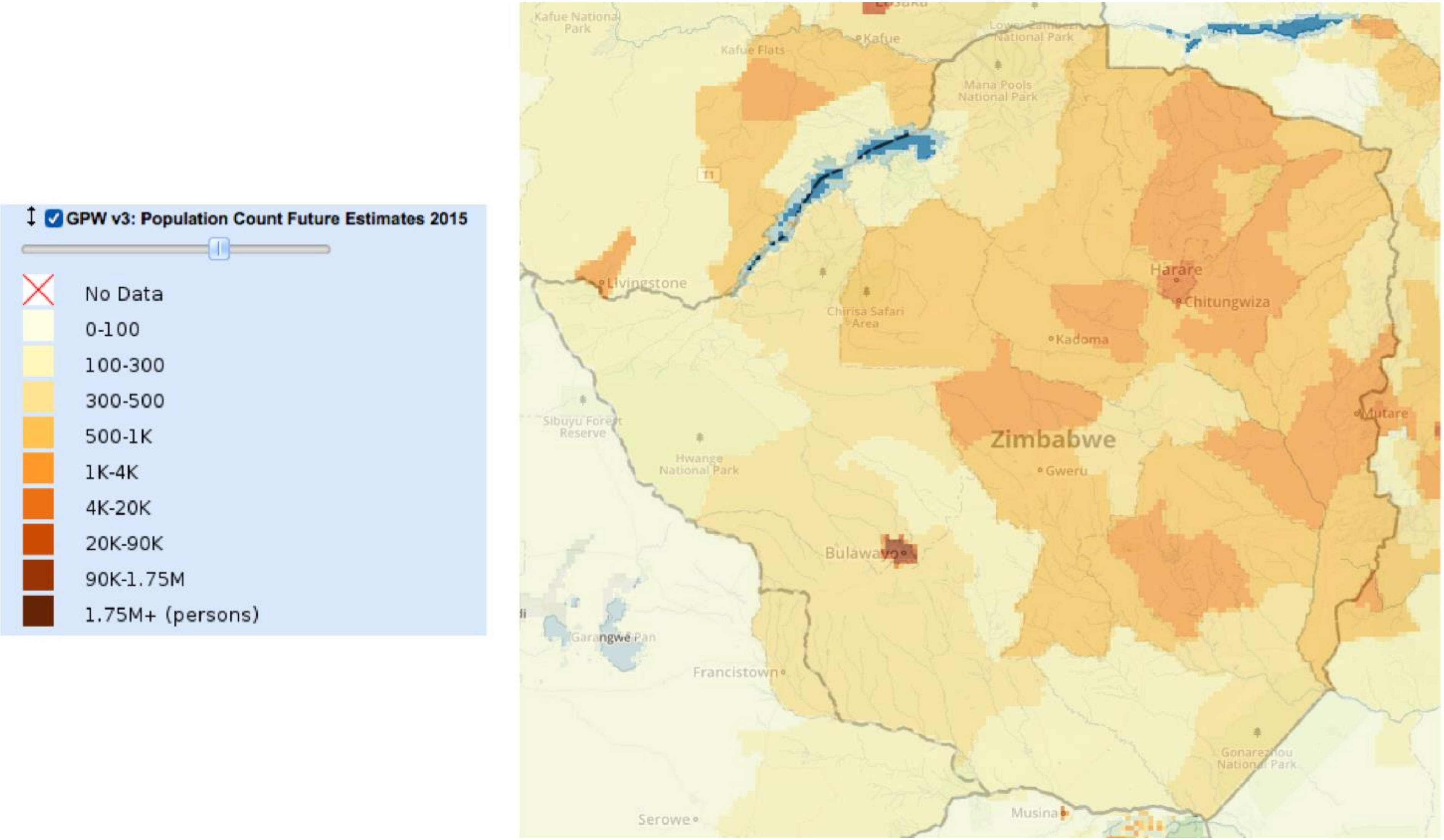


Figure 53: Population density map of Zimbabwe.

Source: SADC Groundwater Information Portal

Table 24 is similar to Table 19, except that it includes an additional column: Groundwater in Storage per km². It estimates how much water "presently" exists within each lithological unit per km². The word 'presently' is deliberately used here since this table does not take into account the pumping from the aquifers that will have lowered the water tables. In certain areas such as northeast Harare, which has not received municipal water for over 15 years, the lowering of the water table has been dramatic, and the aquifers in these parts of Harare are now near the point of exhaustion.

Table 24: Estimated volume of groundwater in storage for individual hydrogeological units and sub-units.

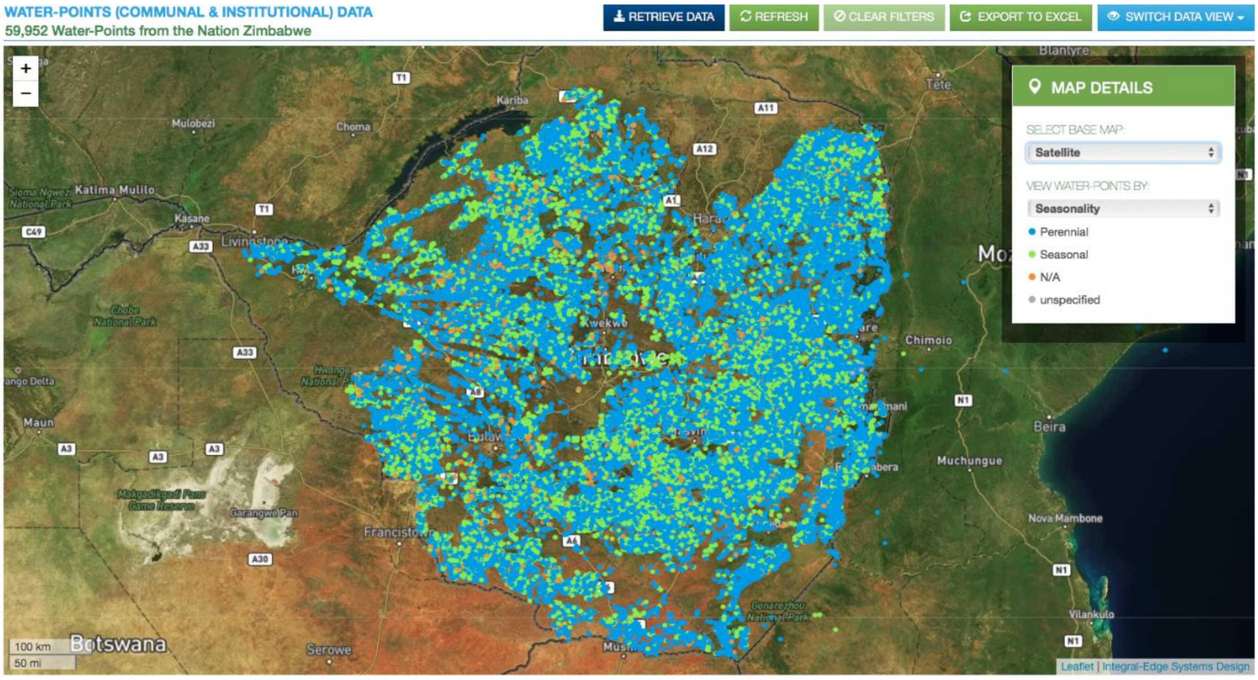
Unit no.	Areal extent (km²)	Average Saturated Thickness of Aquifer unit (m)	Porosity of aquifer material (%)	Total volume groundwater in storage (km³)	Groundwater in storage per km² (ML/km²)
1: Archean Granite and Gneiss	208,045	40	5	416	2,000
2: Greenstone – metabasalt	27,224	50	10	136	5,000
4: Lomagundi calcareous facies	1,578	70	10	11	6,970
6a: Karoo Batoka basalt	27,425	50	10	137	5,000
6b: Karoo Forest sandstone	41,430	100	20	829	20,000
6d: Madumabisa mudstone	15,166	60	20	91	6,000
7: Cretaceous	10,693	80	10	86	8,040
8: Kalahari sand	26,190	100	35	917	35,000
9: Alluvial deposits	2,564	5	35	5	1,950
10: Unlabelled units (Great Dyke, dolerites)	28,685	40	5	57	2,000
Total	**389,000**			**2685 km³**	

Notes: It is noted that not all the water held in an aquifer can be pumped out for practical considerations and at least 20% is likely to remain inaccessible in the aquifer.

The areal extent of individual hydrogeologic units from Lamont (1995); average saturated thickness of hydrogeologic units from NMPRWSS (1987); Aquifer porosity values from various sources in local and international literature and databases. To provide some perspective, a rural hand-pump probably pumps around 5 ML per year.

The spatial distribution of these groundwater resources will be displayed in the catchment maps in a later chapter in this report, and thereby provide the catchment managers with a useful quantitative tool for allocating and protecting groundwater.

These estimates for groundwater in storage suggest that there is significant groundwater in storage, particularly with regard to rural primary water supplies. Based on this data, groundwater should be able to meet its role in providing rural domestic water supplies during periods of drought and dry years. However, the RWIMS (Rural WASH Information Management System) database indicates that 29% of rural water supply boreholes are already seasonal and that these boreholes are distributed nationwide (Figures 54). Clearly, there is a need for monitoring the groundwater in Zimbabwe closely and managing it wisely to ensure sustainability.



WATER-POINTS (COMMUNAL & INSTITUTIONAL) DATA
59,952 Water-Points from the Nation Zimbabwe

MAP DETAILS

SELECT BASE MAP: Satellite

VIEW WATER-POINTS BY: Seasonality

Figure 54: Perennial and seasonal water supply wells nation-wide. Green dots are seasonal boreholes

Source: RWIMS online database: Ncuwash.org

3.5 GROUNDWATER RECHARGE WITH CLIMATE CHANGE

Groundwater recharge in Zimbabwe has been addressed in the previous chapter of this report. In this section, we look specifically at the potential impacts of climate change on groundwater recharge. Groundwater is regarded as being, to some extent, drought-proof. The groundwater resource is stored underground beyond the reach of evaporative demand. However long-term climate change will inevitably affect groundwater resources. The most immediately affected part of the groundwater cycle is groundwater recharge since groundwater recharge is directly affected by the climate.

Many factors contribute to the amount of groundwater recharge. Those that are specifically climate-linked may be listed as follows: -

- Annual rainfall amount;
- Rainfall variability;
- Rainfall intensity;
- Consecutive wet days;
- Temperature;
- Evaporation demand;
- Vegetation cover; and
- Land use.

All of these factors are, to some extent, impacted by climate change, and they, in turn, will impact on the groundwater recharge rates.

A further issue with spatial recharge mapping is that the mapping methods used are aimed towards direct recharge by rainfall, but in arid and semi-arid environments, focused recharge via stream bed infiltration or fissure flow, although very localized, becomes a more important source of groundwater recharge. To some extent, this can be overcome by mapping baseflow in a spatially distributed manner and applying that to the recharge calculations.

Groundwater recharge has been mapped for Zimbabwe for the present climate (1985 to 2015) and a future (2020-2040) climate model CSIRO RCP 4.5. These two maps are shown side by side in Figure 55. The maps show a general decrease in groundwater recharge across the country under a future climate. The northern part of the country is the least affected, and the extreme northwest shows a slight increase in groundwater recharge rates. In general, there are more areas of lighter pale low recharge tones and reduced areas with darker blue high recharge tones. There is an average national decline in groundwater recharge of 17%. The range is from minus – 3% up to minus – 38%. The southern catchments are most severely affected by declines in groundwater recharge. The north and northwestern catchments fare better although they too are expected to experience a decline in groundwater recharge under the impact of climate change. The changes have been quantified in Table 25. They represent a severe depletion in groundwater recharge rates.

Table 25: Percent change in annual groundwater recharge by catchment – current (1985-2015) and future (2020-2040) climate

Catchment	Estimated Groundwater Storage (Mega Litres)	Estimated Groundwater Recharge Current Climate (Mega Litres per Year)	Estimated Groundwater Recharge Future Climate (Mega Litres per Year)	Percentage change in annual recharge: current to future climate
Gwayi	1,440,595,686	5,685,822	5,519,490	-3
Manyame	466,681,353	5,582,370	5,396,201	-3
Mazowe	160,399,025	4,151,687	3,321,401	-20
Mzingwane	399,700,350	653,499	505,966	-23
Runde	222,236,993	2,494,973	1,549,832	-38
Sanyati	831,427,321	5,841,285	4,873,626	-17
Save	306,272,548	5,278,741	3,623,581	-31
Zimbabwe	3,813,690,631	29,542,108	24,660,742	-17

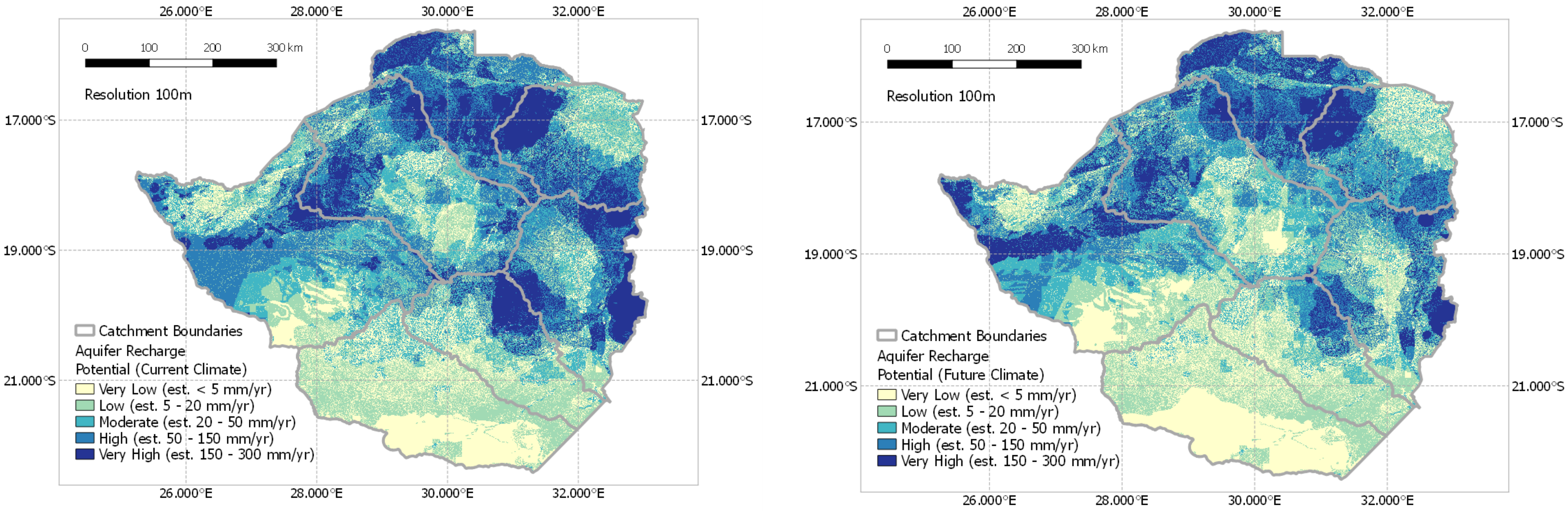


Figure 55: Two groundwater recharge scenarios – present climate (1985–2015) (left) and future climate (2020–2040) under CSIRO RCP 4.5 (right)

For planning purposes, the sustainable development of groundwater is taken at 10% of the estimated groundwater recharge as presented in Table26. The 10% was taken for Zimbabwe aquifers because of their shallow deth some being 30-40 metres and therefore, overpumping could lead to groundwater mining and land subsidence.

Table 26: Annual sustainable development of groundwater by catchment (10% of estimated groundwater recharge) (10^6 x m^3)

Catchment Area	Area (km^2)	10% of the estimated groundwater recharge			
		2018	2020	2030	2040
Gwayi	87,960	570	560	560	560
Manyame	40,497	560	540	540	540
Mazowe	34,944	420	330	330	330
Mzingwane	62,451	70	51	51	51
Runde	41,056	250	150	150	150
Sanyati	74,534	580	480	480	480
Save	48,448	530	360	360	360
Total	**389,890**	**2,980**	**2,470**	**2,470**	**2,470**

3.6 AQUIFER DISCHARGE/DEPLETION

The rate at which aquifers are depleted of groundwater, either by natural processes or by pumping, is also a critical factor in assessing the impact of climate change on the groundwater resources. Aquifers are depleted in groundwater by four key processes: -

1. Discharge to stream baseflow;
2. Losses to evapotranspiration at groundwater discharge zones;
3. Abstraction by pumping; and
4. Inter-aquifer transfers by large areally extensive aquifers.

There is very limited quantitative data or information on such processes in Zimbabwe. What will be the impact of climate change on these aquifer discharge processes?

Baseflow: Scanlon et al. (2002) state that the use of baseflow discharge to estimate recharge is based on a water-budget approach, in which recharge is equated to discharge. Baseflow discharge, however, is not necessarily directly equated to recharge because pumping, evapotranspiration, and underflow to deep aquifers may also be significant. These other discharge components should be estimated independently. This suggests that as groundwater recharge is affected by climate change, so baseflow will be similarly affected, thus maintaining the groundwater balance. As recharge decreases, so baseflow too will decrease, and vice versa. It is suggested here that a similar balance will be maintained with evapotranspiration, and for similar reasons. However, underflow of old (centuries to millennia) groundwater to deep aquifers may well be entirely unaffected by climate change, except in the very long term.

Abstraction by pumping: This discharge is more complex to predict. However, it is likely to be the reverse of the natural system. As the climate dries and recharge decreases, the human demand for groundwater is likely to increase, and in a more humid climate, the demand is likely to decrease.

3.7 GROUNDWATER IN CLIMATE CHANGE

The preceding sections have identified the complex interplay between climate and groundwater recharge and groundwater discharge. In this section, we present the issue of “groundwater drought risk”, a term developed by Villholth et al. (2013) working in the SADC region.

When considering the potential impacts of increased temperatures and aridity and reduced rainfall on groundwater, there are a suite of factors that need to be assessed. The terms “groundwater drought” and “groundwater drought risk” have been used to express a condition where: “Groundwater drought denotes the condition and hazard during a prolonged meteorological drought when groundwater resources decline and become unavailable or inaccessible for human use. Groundwater drought risk refers to the combined physical risk and human vulnerability associated with diminished groundwater availability and access during drought.” (Villholth et al., 2013).

Villholth et al. (2013) mapped the SADC region for “groundwater drought risk”. This work provides a suitable basis for a perspective on the vulnerability of Zimbabwe’s groundwater to the risks emanating from groundwater drought and climate change. They identify a mixture of supply and demand factors that are contributory to groundwater drought risk as shown in the hierarchy chart below (Figure 56).

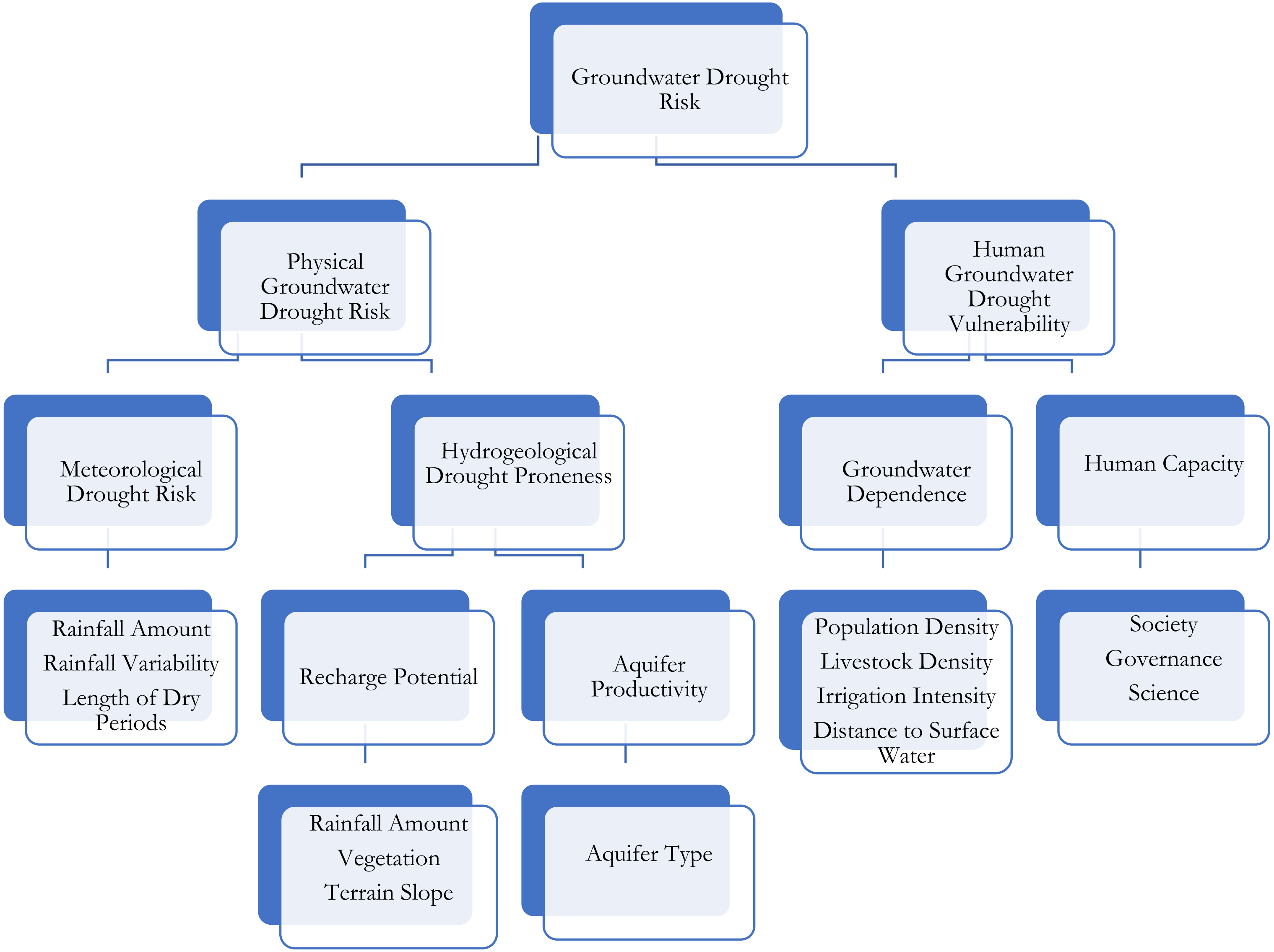


Figure 56: Hierarchy chart of groundwater drought risk factors

Source: Villholth et al., 2013

The chart identifies demand factors, principally based around human groundwater dependence and human vulnerability to drought and supply factors, principally linked to climate, aquifer productivity and groundwater recharge.

They then produced a suite of regional SADC maps that include: -

- Climate sensitivity;
- Aquifer productivity;
- Recharge potential;
- Groundwater dependence;
- Groundwater drought risk; and
- Groundwater drought risk projected for future climate using IPCC SRES A1B scenario for the year 2100.

The two groundwater drought risk maps for Zimbabwe are shown here (Figure 57). The two maps show that Zimbabwe, under its present climate and groundwater demand, maybe classed largely as moderate to high groundwater drought risk; and for the more densely populated parts of the country, it is classed as high risk, and even very high risk in the major urban centres. The depletion of groundwater resources in urban areas, particularly Harare, has been identified as one of the most serious threats for groundwater drought risk in the SADC region (Villholth et al., 2013).

For the projected future climate IPCC SRES A1B year 2100 and groundwater demand, most of Zimbabwe is mapped as high to very high groundwater drought risk. The key factors that lead to Zimbabwe's high groundwater drought risk ranking are: -

- The relative sensitivity to climate change, with most of Zimbabwe, predicted to have higher temperatures and lower rainfall due to global warming and climate change.
- The low/very low productivity crystalline basement aquifers that cover most of the country.
- The relatively high population density living in these low productivity aquifer areas.
- A high to very high dependence on groundwater, particularly in the rural areas, but also with increasing dependence on groundwater in urban areas.

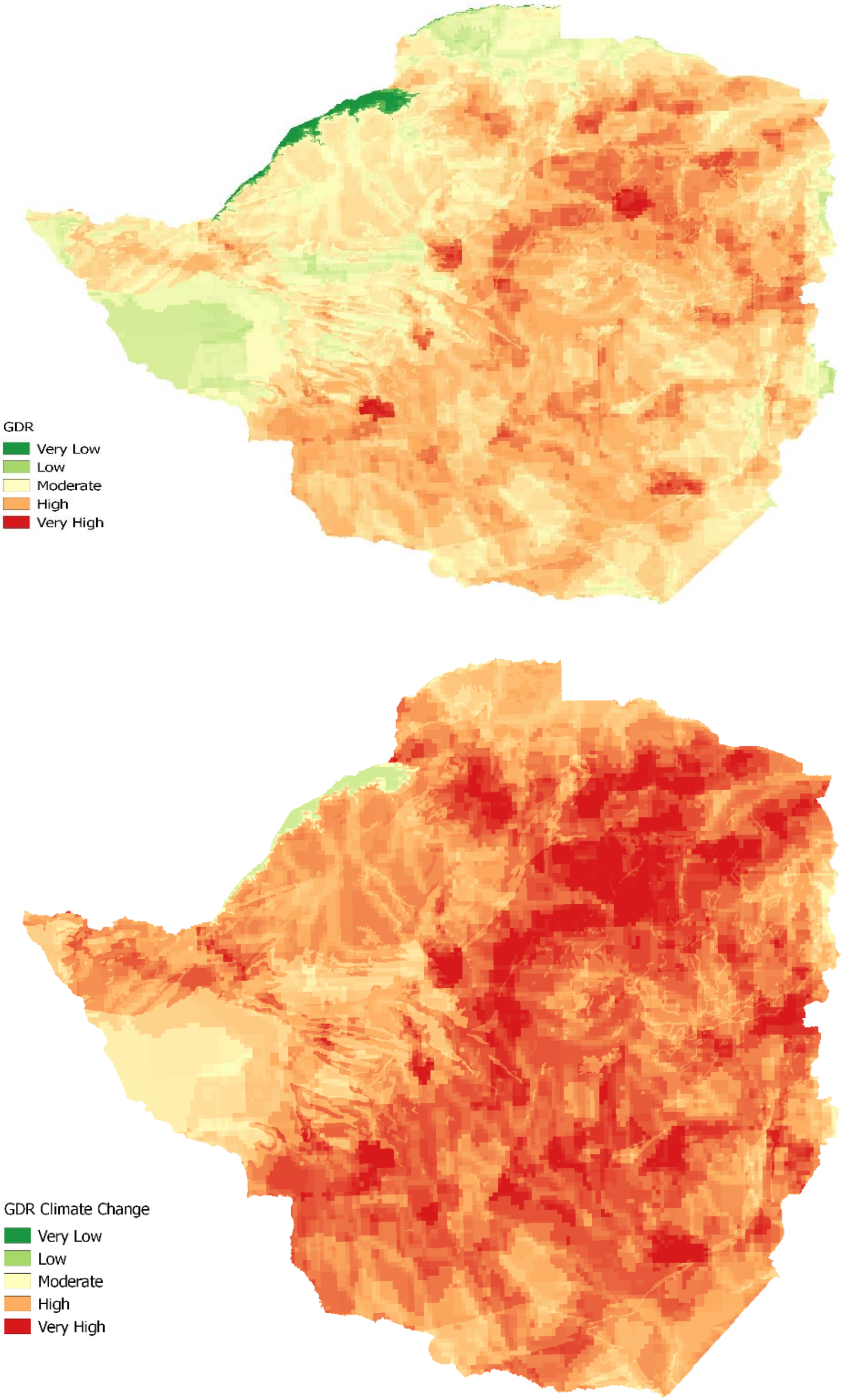


Figure 57: Groundwater drought risk (present climate – at the top) and with climate change to the year 2100 under climate scenario IPCC SRES A1B scenario (bottom) This scenario posits the greenhouse gas emissions for the A1B scenario are based on a balanced emphasis on all energy sources for a "convergent" world with developing regions gradually becoming developed.

Source: Villholth et al., 2013

If groundwater recharge declines, as expected under the climate change scenarios, and there is increasing human demand and dependence, then groundwater drought will become a reality for many people in Zimbabwe, and many groundwater resources will decline and become unavailable or inaccessible for human use.

Already we can see that many of Zimbabwe's rural water supply boreholes are already seasonal (see RWIMS map – Figure 54). Anecdotal evidence from Harare is that many seasonal private boreholes are drying up earlier every year. Drilling companies indicate that the groundwater table has been getting steadily deeper in Harare. More and more groundwater is being pumped but abstraction is almost entirely unmonitored. Unfortunately, there are few formal records of these changes, but there can be little doubt that they are taking place, albeit unmonitored and unrecorded.

Groundwater drought risk is already on our doorstep, and it must be given serious attention. Groundwater monitoring and groundwater management should be one of the highest priority natural resources challenges for the national government. As can be seen in the two images (adapted from Villholth et al., 2013), Zimbabwe is a country that already faces high groundwater drought risk over much of the country. The scenario with climate change (IPCC SRES A1B scenario for 2100) is far worse with a very high rating for groundwater drought risk over most of the country.

3.8 RESPONSES TO GROUNDWATER DROUGHT RISK AND CLIMATE CHANGE

In many environments, groundwater has been identified as a key buffer against climate variation so that short term climate shocks, particularly droughts, can be ameliorated. And this has also, to some extent, been the case in Zimbabwe. However, in recent time, the increase in demand, particularly in those urban areas where municipalities have failed to provide piped water, coupled with the decline in recharge due to climate change and the low productivity aquifer systems, have combined to make Zimbabwe highly vulnerable to groundwater drought.

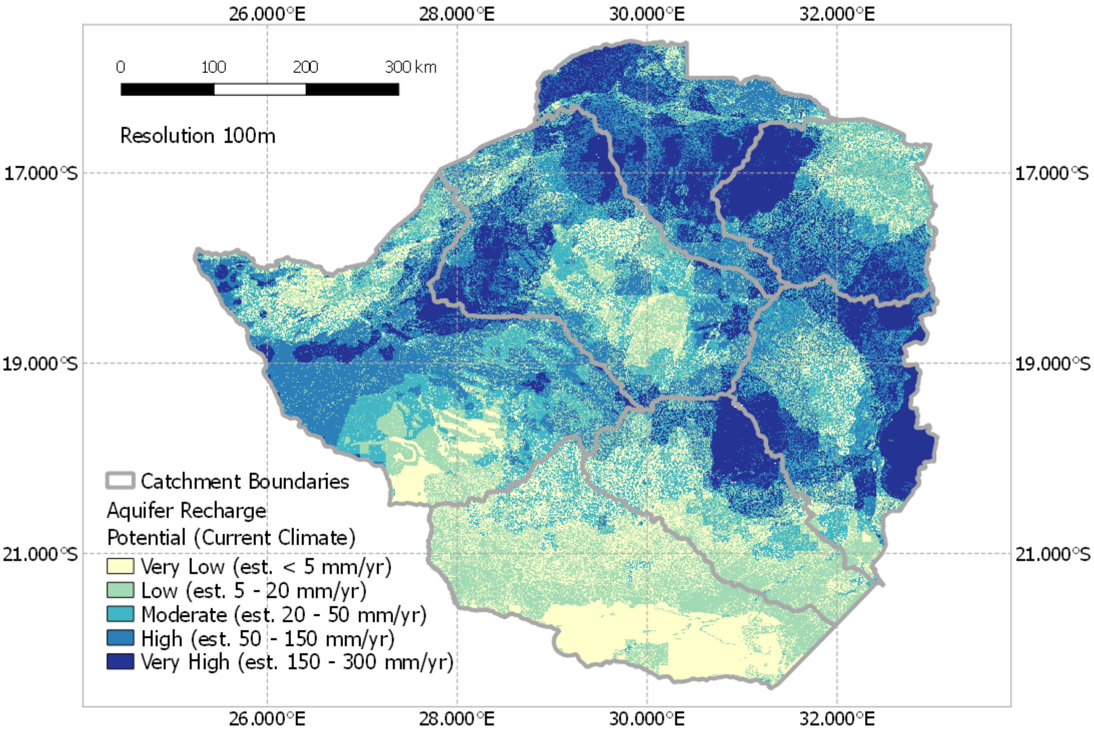
Given these factors, the key responses would appear to be directed more towards demand management since the supply-side options are very limited. Demand management should start with awareness campaigns of the limitations of the groundwater resource in Zimbabwe, backed up by hard evidence of the number of boreholes that are drying up, the declining water tables and the rates of abstraction compared to the rates of recharge.

The issues of demand management in groundwater are well known, and there are a variety of demand management activities that can help to reduce the rate of abstraction across all sectors of society. However, they require a very significant degree of user compliance. Such wide-spread user compliance generally requires that users are well informed and kept up to date about the condition of the groundwater resource and that they are made aware of the impact of their groundwater usage practices.

On the positive side, the localized basement fracture porosity aquifers tend to be discontinuous and thus self-limiting in terms of over-abstraction. Excessive pumping in one locality may not affect another locality that is not hydraulically connected.

There are exceptions, and there are large areally extensive sedimentary aquifers, especially in the northwest and, to a lesser extent, the extreme southeast/south and the north of the country. These large primary porosity aquifers hold large volumes of groundwater in storage, and thus can provide a significant water buffer for even extended dry periods, and they are not so vulnerable to groundwater drought. Probably the most significant buffer capacity lies to the north-west of Bulawayo in the Karoo and Kalahari aquifers, which have been assessed as being able to supply significant water to the City of Bulawayo (World Bank - Aide Memoire, 2013).

3.9 GROUNDWATER AND CLIMATE CHANGE MAPS



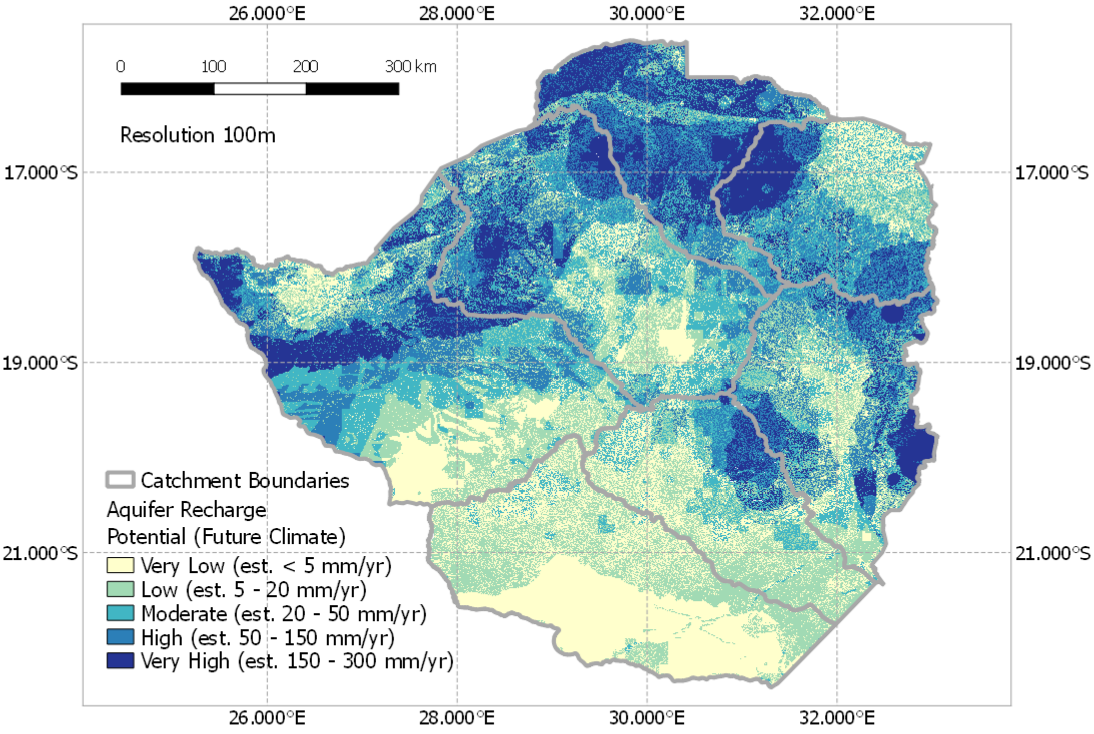
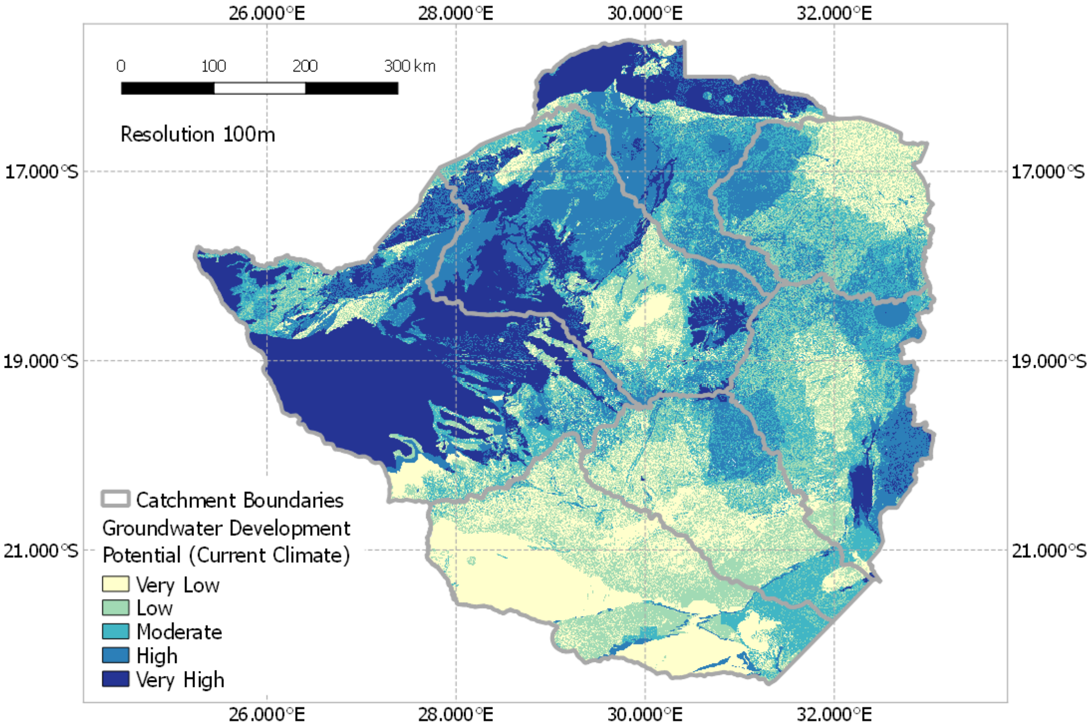


Figure 58: Aquifer recharge potential under current climate 1986-2015 (top) and future climate 2020-2040 (bottom).

In the future climate scenario, all areas of Zimbabwe are expected to have lower groundwater recharge rates, except the extreme north-west of the country around Victoria Falls/Hwange in the Gwayi catchment.



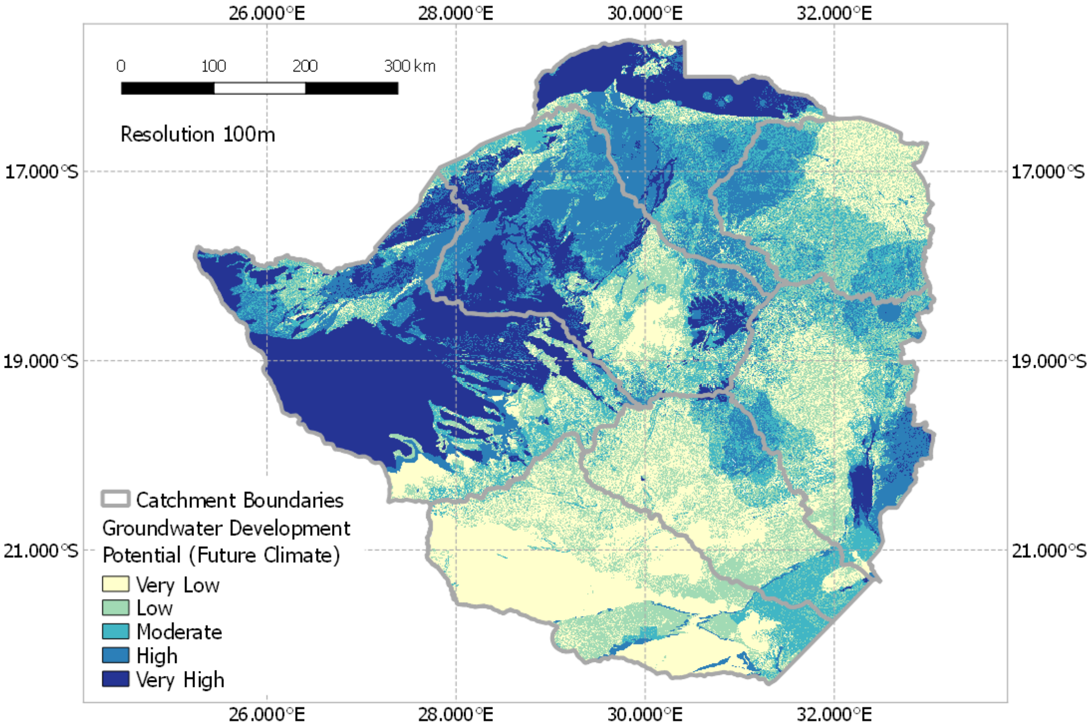


Figure 59: Groundwater development potential under current climate 1986-2015 (top) and future climate 2020-2040 (bottom).

Groundwater development potential is the sum of groundwater recharge potential and aquifer productivity. The future climate scenario shows that groundwater development potential is slightly less in the crystalline basement aquifers throughout the country but is relatively unchanged for the sedimentary aquifers in the peripheral areas around the national borders.

We present the groundwater and climate change maps at a coarser scale with 10 km pixel size. The reality is that the data density is insufficient to accurately portray the groundwater condition at a finer scale. Nevertheless, many of the boundaries in the national maps, such as lithological boundaries, vegetation cover or rainfall classes are mapped as linear features, and these shapes, such as the shape pattern of the geological lithologies, are recognized by Zimbabwean professionals and by the Zimbabwean public as a whole. Thus, the finer scale maps are useful in that they draw attention to, for example, the role of geology in mapping groundwater resources.

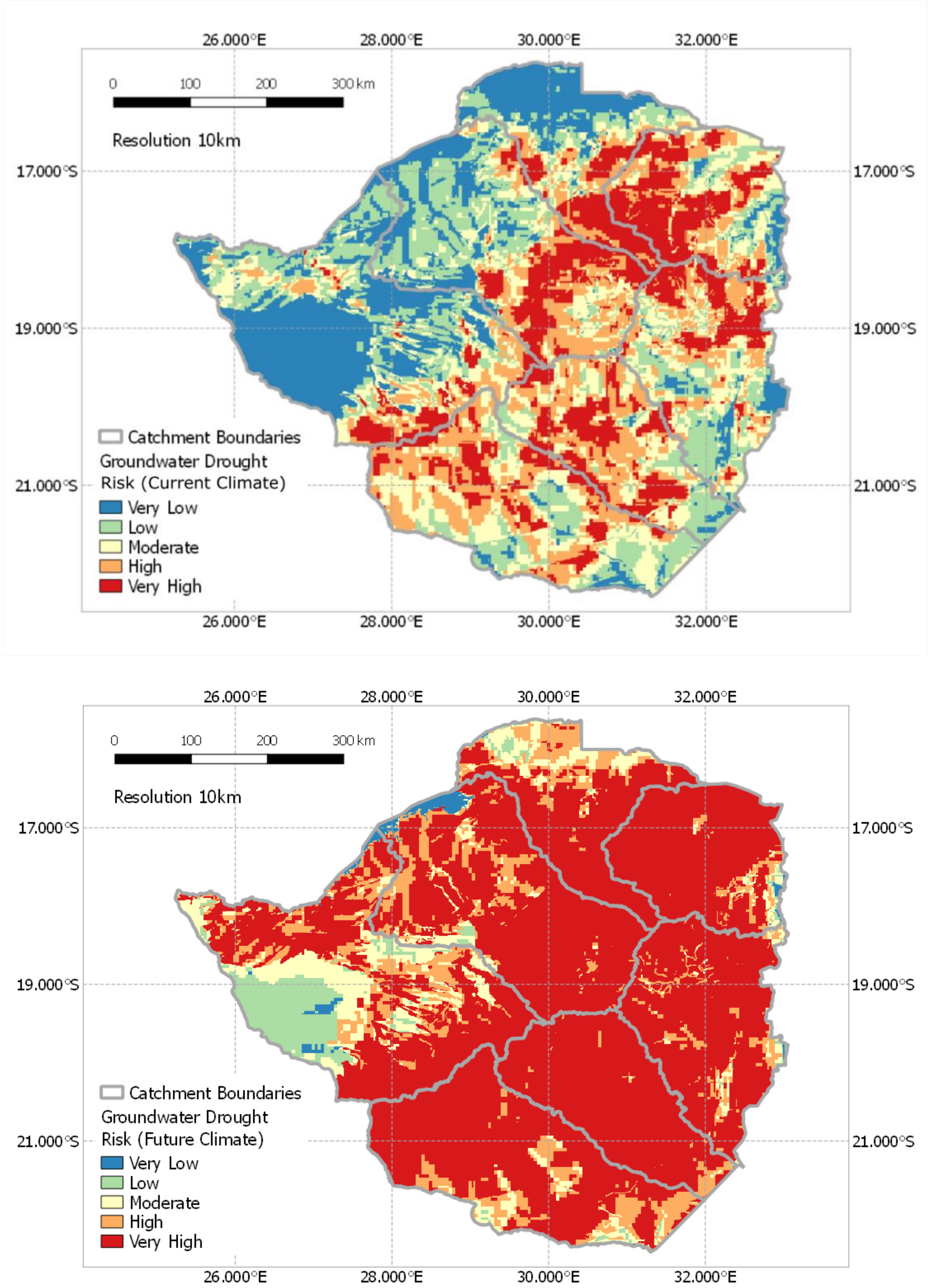
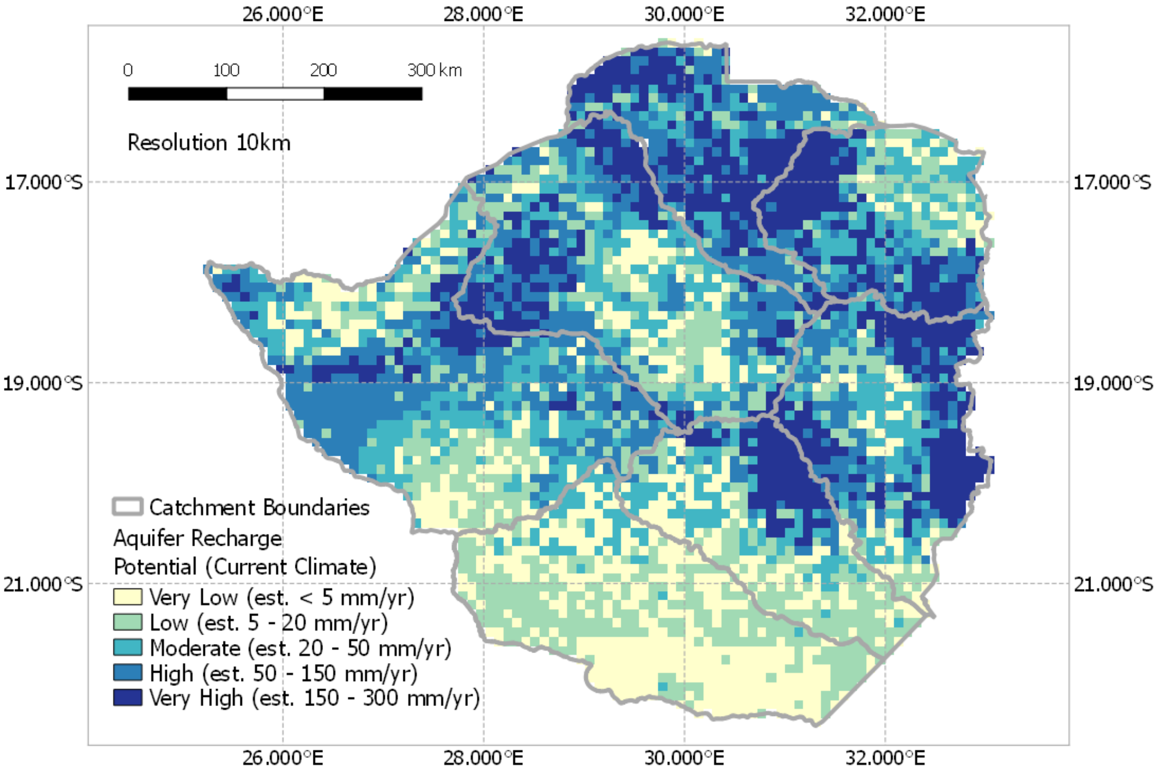


Figure 60: Groundwater drought risk at 10 km pixel grid - current climate (top) and future climate (bottom).



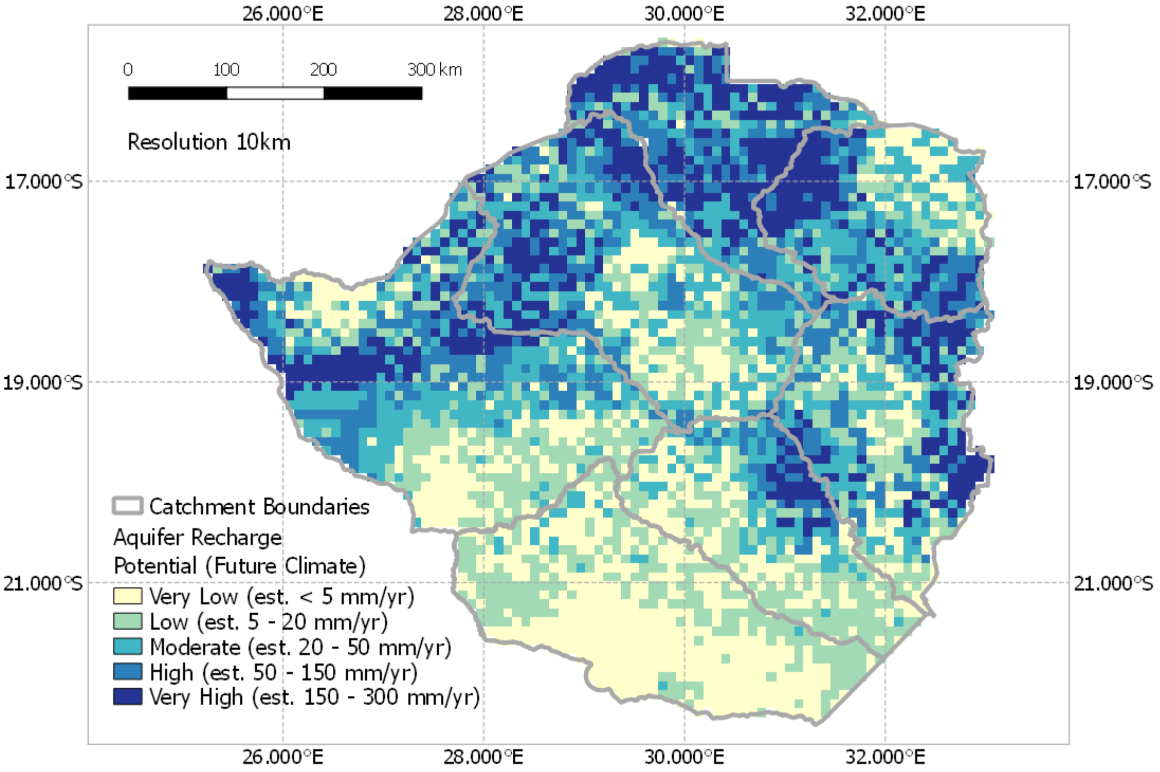
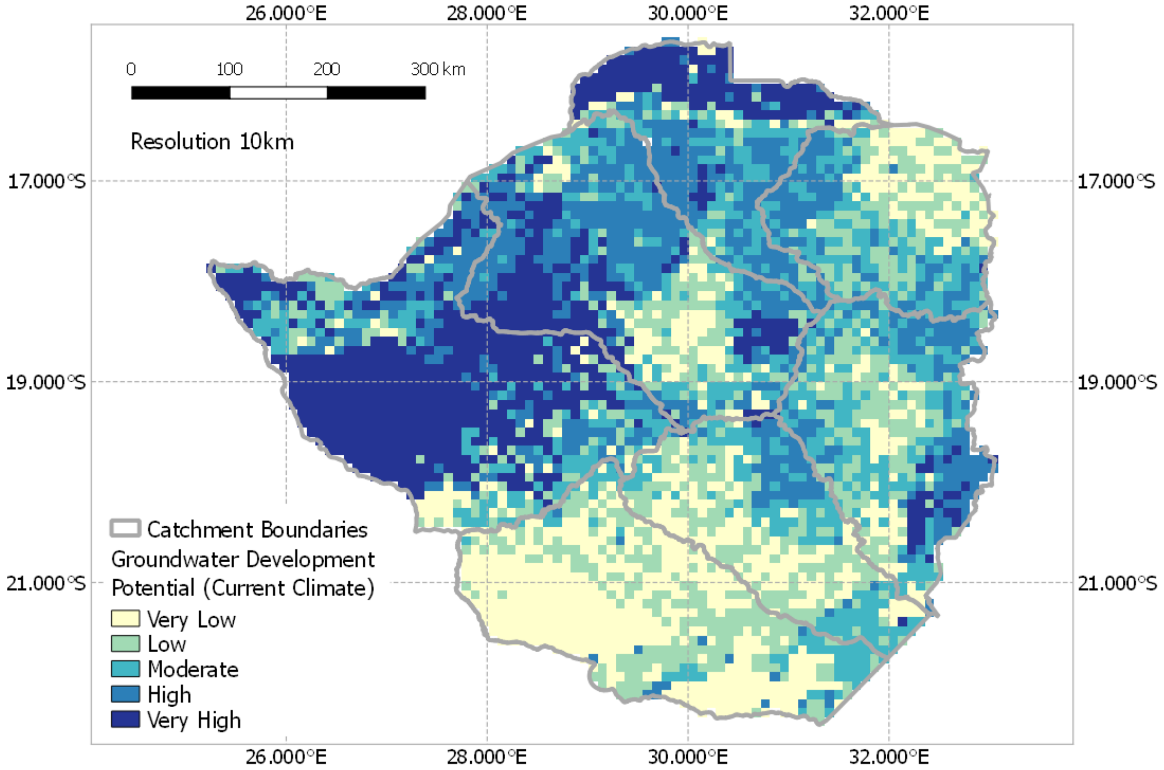


Figure 61: Aquifer recharge potential at 10 km pixel grid - current climate (top) and future climate (bottom).



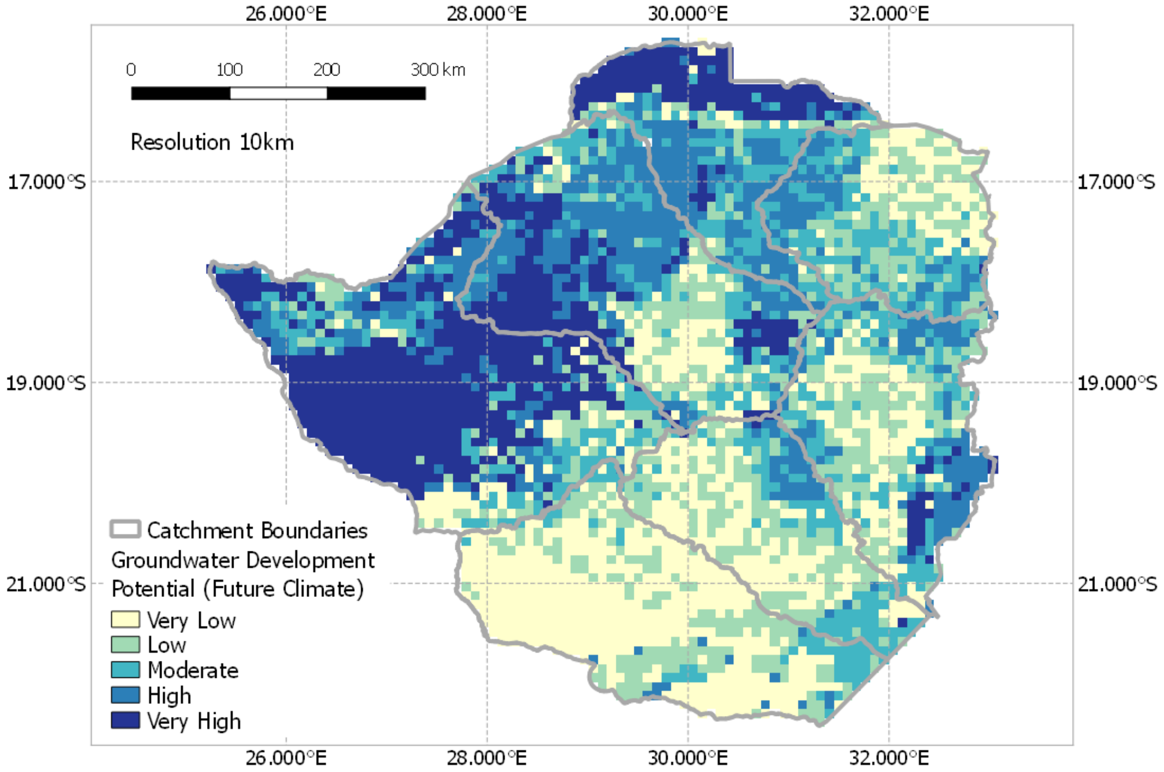


Figure 62: Groundwater development potential at 10 km pixel gird - current climate (top) and future climate (bottom).

4. GROUNDWATER INSTITUTIONS AND GROUNDWATER MANAGEMENT

4.1 GROUNDWATER INSTITUTIONS IN ZIMBABWE

The institutional framework for water management in Zimbabwe is the subject of a separate sectoral report in which the mandates and responsibilities of the various bodies are discussed. In this groundwater report, the institutions involved in groundwater management, apart from the parent Ministry of Lands, Agriculture, Water and Rural Resettlement (MLAWRR), are identified with a brief overview of their role in groundwater management.

Ministry of Environment, Tourism and Hospitality Industry (METHI): Until the changes introduced following the general election and formation a new government in August 2018, the Ministry of Environment, Water and Climate was responsible for water and climate change portfolios. The water and climate change mandates have since been moved to an enlarged Ministry of Lands, Agriculture, Water and Rural Resettlement (MLAWRR). METHI remains responsible for the Environmental Management Agency.

Zimbabwe National Water Authority (ZINWA) is a wholly government-owned entity tasked with managing the country's water resources. Its mission is to sustainably deliver quality water to all. ZINWA owns most of the major water supply dams in the country.

The Groundwater Department of ZINWA provides technical advice on groundwater planning, development and management to the government and the parent Ministry. The Groundwater Department houses the National Groundwater Archives and also owns and manages and monitors the three major well-fields at Nyamandlovu, Lomagundi and Save.

Catchment Councils: There are 7 catchments in Zimbabwe, and these are managed by seven catchment councils. Catchment Councils are water users and stakeholders and are assisted by technical and managerial staff provided by ZINWA. There are 47 sub-catchments. In terms of groundwater, permits to drill and permits to abstract groundwater are issued by the catchment/sub-catchment councils.

National Action Committee (NAC): NAC is a grouping of several stakeholder ministries involved in Rural WASH. The executive arm of the NAC is the NCU – the National Coordination Unit. It manages a national online database and is a coordinating unit for the development and maintenance of groundwater supplies for the rural WASH sector. The RWIMS online database is successful in ensuring that rural water point and pump breakdowns can be instantly reported at source by the user community. If parts and fuel are available, repairs are usually carried out in a short time.

District Development Fund (DDF): The DDF is the NAC operational arm that carries out borehole drilling and groundwater infrastructure installation and maintenance in the communal areas. The DDF has operational units based in every district and is central to rural WASH and borehole maintenance.

It is noted that NAC, NCU, and DDF all operate in administrative units defined by the country's administrative provinces and districts. In contrast, ZINWA operates in administrative units defined by the seven River Catchments, and 47 sub-catchments. At present, the catchment and sub-catchment councils appear to be spectacularly under-resourced.

4.2 INTEGRATED WATER RESOURCES MANAGEMENT (IWRM) IN GROUNDWATER MANAGEMENT

This report will not discuss in full detail the topic of groundwater management in IWRM but will seek to highlight a few factors relevant to Zimbabwe.

Water is essential to all life and underpins the quality of life everywhere. Zimbabwe may be classed as semi-arid, especially in the western and southern regions of the country. Surface water is generally not perennial in most parts of the country except the eastern highlands. Groundwater, therefore, plays an essential role in the national water supply and is used almost ubiquitously, even where large supply storage dams are servicing urban communities.

Some of the key aspects of the Zimbabwe groundwater resource are listed here:

- Groundwater resources in Zimbabwe are widespread and occur almost everywhere.
- They are generally quite shallow, usually between 10 and 30m deep, and thus not excessively expensive to access.
- The water quality is, for the most part, potable without treatment.
- The groundwater mostly occurs in secondary porosity fractured and regolith aquifers with low potential.
- It is usually adequate and suitable for domestic and livestock use.
- The country has a high to very high groundwater drought risk rating.
- Generally, the groundwater is insufficient to sustain widespread irrigation or other uses that require continuous heavy abstraction. Neither the storage potential nor the groundwater balance is sufficient to support such levels of abstraction.
- Local high yielding boreholes do occur and can be successfully developed for commercial use such as irrigation, provided they are carefully monitored and managed. However, clusters of such boreholes, all being heavily pumped, are often not sustainable.
- Groundwater is typically strongly linked to the land where it occurs. Land rights and groundwater rights are intertwined in nature.
- The only significant groundwater pipeline in Zimbabwe is just 35 km in length from Nyamandlovu to Bulawayo.
- Maintenance of the groundwater infrastructure is an essential component that needs adequate resources and focuses to ensure the availability of water for the population, and especially the rural population. Figure 63 shows at the national level the functionality of rural water points (RWIMS online database: www.ncuwash.org).
- Groundwater level, abstraction and quality monitoring need to become an integral part of groundwater use.

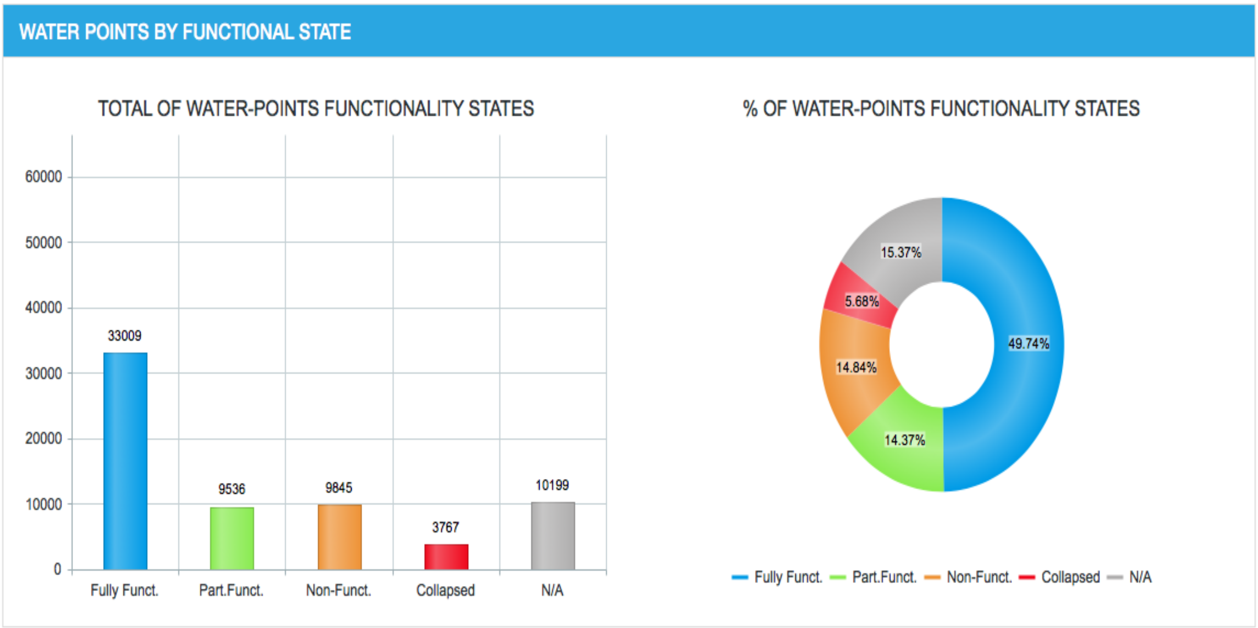


Figure 63: The challenge of rural WASH – national water point functionality. 50 % of rural water points are fully functional and 50% are either not functional or are partially functional

Source: RWIMS database

These bulleted points show that groundwater plays a vital role in the well-being of almost all of Zimbabwe's citizens. They also show that there is not a widespread huge untapped groundwater resource that can be a key driver in changing the way Zimbabweans live. As the Government of Zimbabwe and ZINWA strive to fulfil their role in providing fresh water to all the citizens, the overarching message from the groundwater resource is one that is more focused on protection, maintenance of existing groundwater infrastructure, monitoring and management of existing developments rather than planning for large scale new developments. This is not to say that there should be no focus on new developments, particularly in our sedimentary aquifer systems, or upgrading of under-utilized local high yield wells. There will always be room for local improvements.

4.3 SURFACE WATER–GROUNDWATER INTERACTIONS AND CONJUNCTIVE USE

Groundwater and surface water are part of the same hydrological cycle (Figure 64) and the use or abuse of one of these water resources will inevitably have an impact on the other. Surface water-groundwater interactions take place in different locations across the environment, in both directions, at different seasons and different rates. They are affected by climate and weather, the abstraction of surface and groundwater, impoundment, and diversion of rivers, and may transfer polluted as well as freshwater. Despite these fundamental linkages, surface water and groundwater are often managed by different institutions or by different branches of the national water authority.

For integrated water resources management, it is of critical importance to assess the scale, location, timing and direction of surface water – groundwater interactions. Such water fluxes take place across the environment but are may change in terms of location, timing, scale, and direction. As a result, the assessment of these interactions is complex and difficult.

Surface water-groundwater interactions may be summed as follows:

- Groundwater and surface water interact continuously through the hydrologic cycle.
- The hyporheic zone (stream bed) is the zone of the most interaction.
- Flows occur from surface water (streams, lakes) to groundwater and vice-versa depending on the hydraulic gradient.
- Interactions occur not only as water volume fluxes but also as chemical and water quality fluxes.
- The direction and rate of these fluxes changes with time and season.
- Interactions are influenced by anthropogenic activities such as pumping, drainage or impoundment.

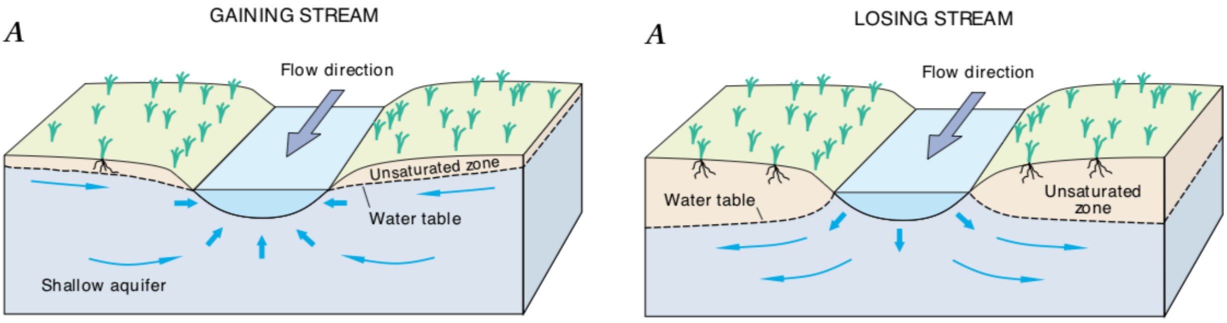


Figure 64: Surface water-groundwater interactions - a stream may be gaining in one season (left) and losing in another season (right); it may be gaining in one reach and losing in another.

Water resources management includes understanding both the nature, direction, timing and volume of these fluxes. A sound understanding of surface water-groundwater interactions lies at the core of catchment water management and optimum conjunctive use of water resources.

4.3.1 Key differences between surface water and groundwater flow

Some key differences between surface water and groundwater are summarized below and in Figure 65. These differences provide a framework for conjunctively managing water resources in an optimum way by using surface and groundwater at different times and stages during the hydrologic cycle.

i. Location:

- Surface flows occur in specific locations, streams, and lakes, principally controlled by topography.
- Groundwater flows tend to be distributed broadly throughout the sub-surface. The topography is less important than the formation of hydraulic conductivity and hydraulic gradient.

ii. Duration:

- Surface water flows are of short duration, usually a few weeks to a few months.
- Groundwater flows take place slowly over years, decades, and millennia.

iii. Velocity:

- Surface flows are rapid, on the scale of metres/sec.
- Groundwater flows are slow, on the scale of metres/year or less.

iv. Evaporation:

- Surface water is subject to high evaporation losses.
- Groundwater is largely protected from evaporation losses.

v. Quality:

- Surface water is vulnerable to bacteriological contaminants and surface pollution but may be more readily refreshed and cleaned.
- Groundwater is largely protected from pollution but may be mineralized. Restoring a polluted groundwater resource may take decades or longer.

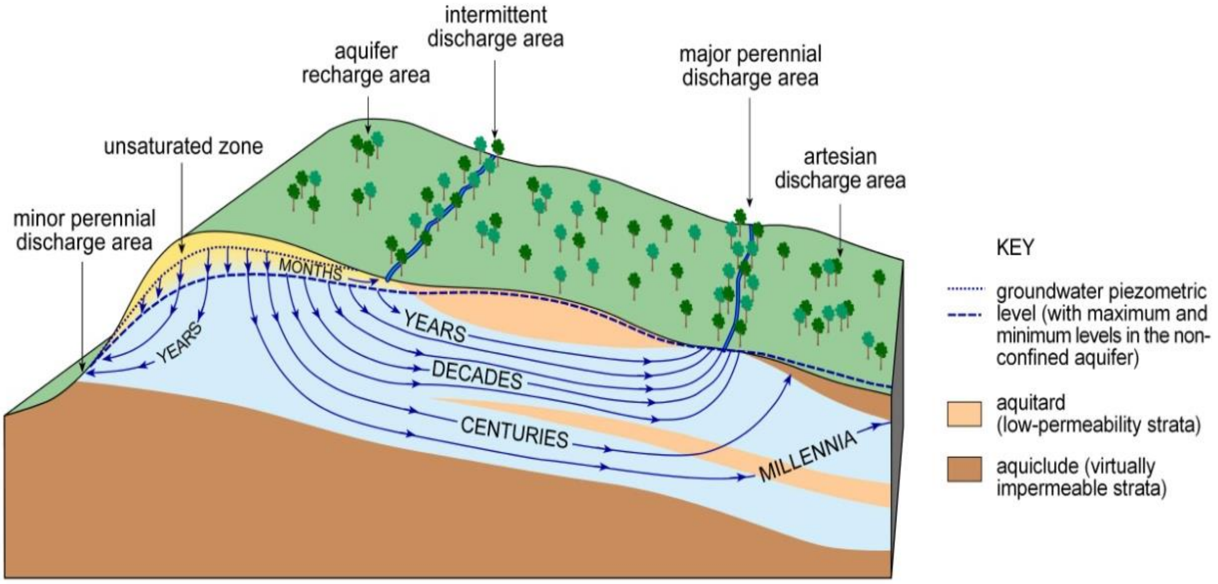


Figure 65: The age of groundwater, the volume held in storage and the rate of movement are very different from surface water.

Groundwater is in continuous slow movement from recharge areas (usually upland areas) to lower-lying discharge areas (springs, baseflow, wetlands and coastal zones). Natural flow through an aquifer is usually at low velocities, ranging from < 0.001 m per day to > 1 m/day. The rate of flow and hence the turn-over time for groundwater is orders of magnitude slower than for surface water and hence groundwater requires a different management paradigm.

4.3.2 Baseflow

Baseflow is the groundwater component of streamflow. It is perhaps the most significant interaction between surface water and groundwater. It varies depending on the climate, the permeability of the basin and the topography amongst other factors (Figure 66). In dry climates, there may be no baseflow. If the groundwater level is always below the riverbed level, there will be no baseflow. In wet climates where the groundwater level is always higher than the riverbed level, baseflow, and hence streamflow, will be perennial. And in intermediate climates where the water table fluctuates so that it is sometimes above and sometimes below the riverbed level, then baseflow will be seasonal.

Surface water-groundwater interaction is also affected by human activities e.g. pumping. In the example depicted in Figure 67, baseflow is initially reduced as a result of pumping (Q1), and as pumping is increased (Q2) with increased drawdown, baseflow ceases and instead there is surface water flow to the pumping borehole via the groundwater system. In terms of allocating water for environmental flow requirements, it can be seen that such groundwater abstraction will have a direct impact on environmental flows.

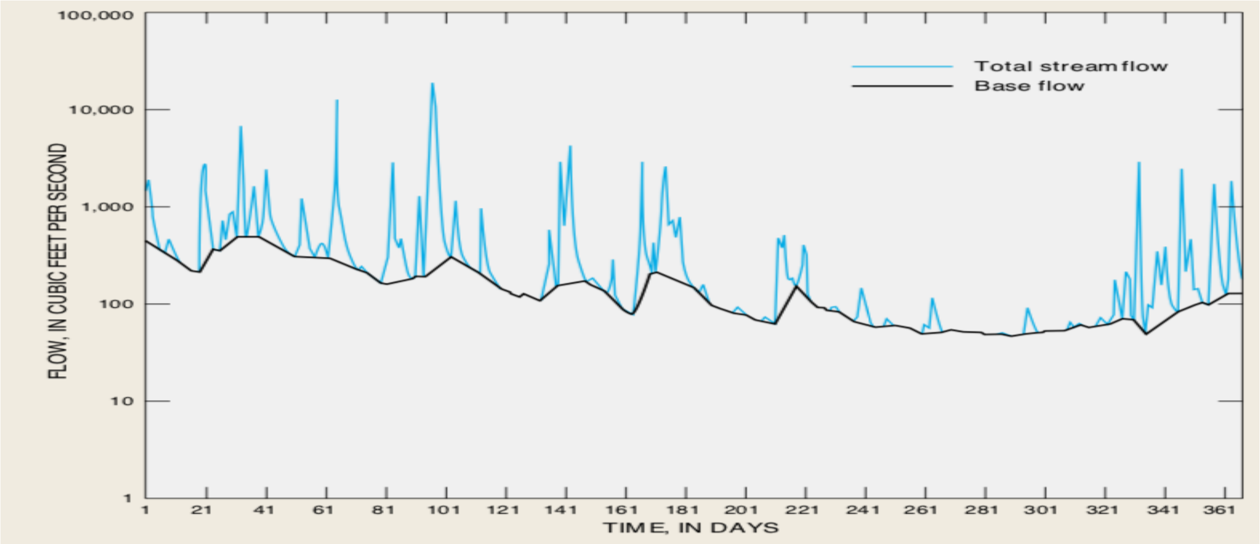


Figure 66: Stream flow hydrograph showing the surface flow and the baseflow components.

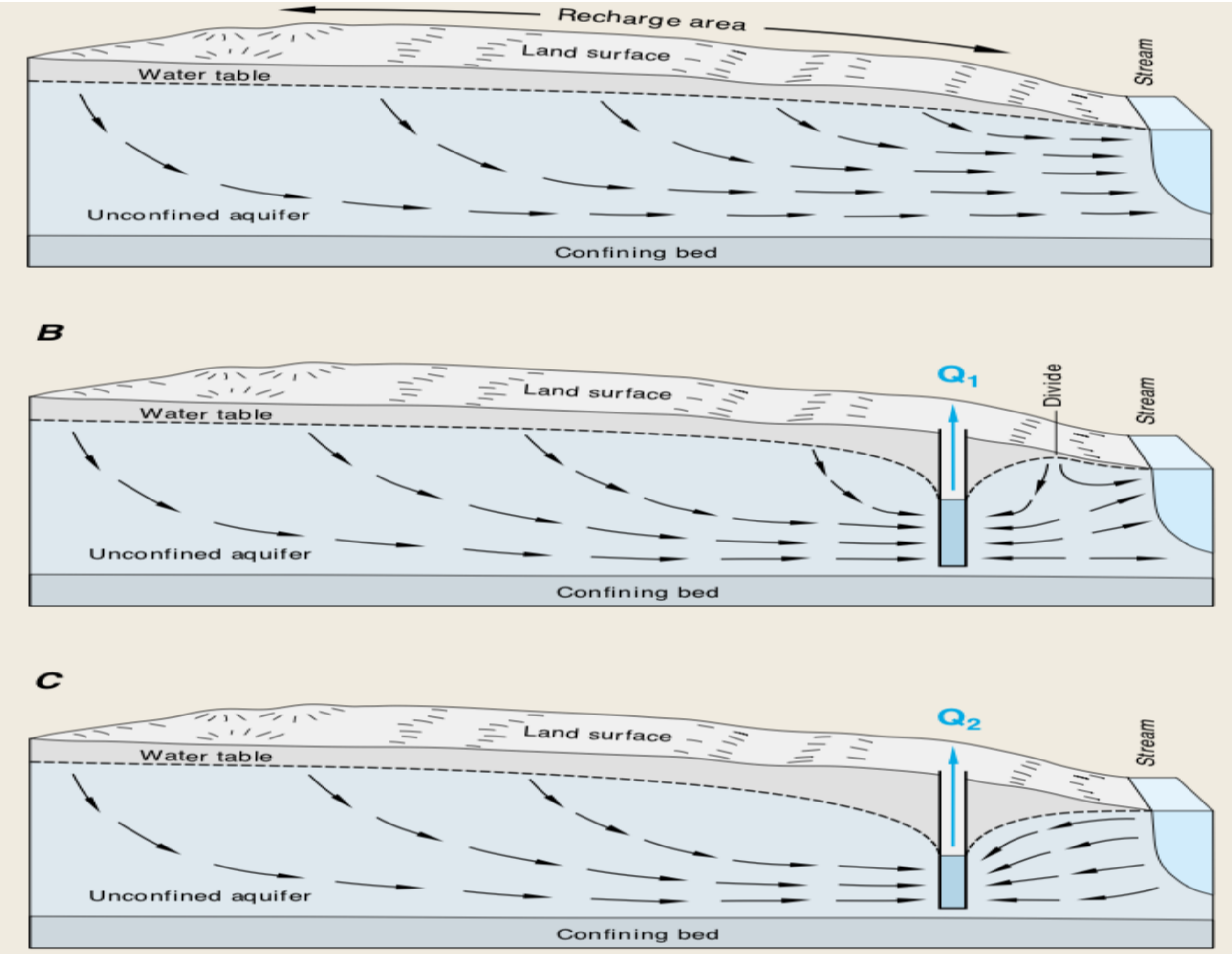


Figure 67: Surface water–groundwater interaction is affected by human activities e.g. pumping.

In catchments with impermeable bedrock, baseflow tends to be limited since there is limited infiltration and groundwater recharge. Typically, crystalline rock fractured aquifer systems tend to be low permeability and the aquifer depths tend to be shallow with the result that seasonal baseflow is more likely than perennial baseflow. However, where the weathered regolith is deep and the rainfall season is extended over the entire year, then baseflow may be perennial. The eastern highlands of Zimbabwe around parts of the Nyanga and Mutasa districts are examples.

In highly permeable catchments, baseflow is increased at the expense of surface flow. In catchments such as the Chalk (England) and the Kalahari sand in Zimbabwe, a high percentage of precipitation infiltrates the land surface as direct recharge, resulting in increases to the groundwater elevation and an extended or perennial baseflow. The Kalahari sand in Zimbabwe has very few surface drainage channels and supports numerous perennial springs in some areas, such as Silobela and Lower Gweru, where inter-basin transfers are not taking place. In other catchments, such as Gwayi, which is largely underlain by deep Kalahari and Karoo basin sediments, there is very low baseflow. This is most likely due to deep regional groundwater flow systems discharging groundwater to the regional base-levels, either into the Zambezi River to the north or into the Magadigadi basin to the west.

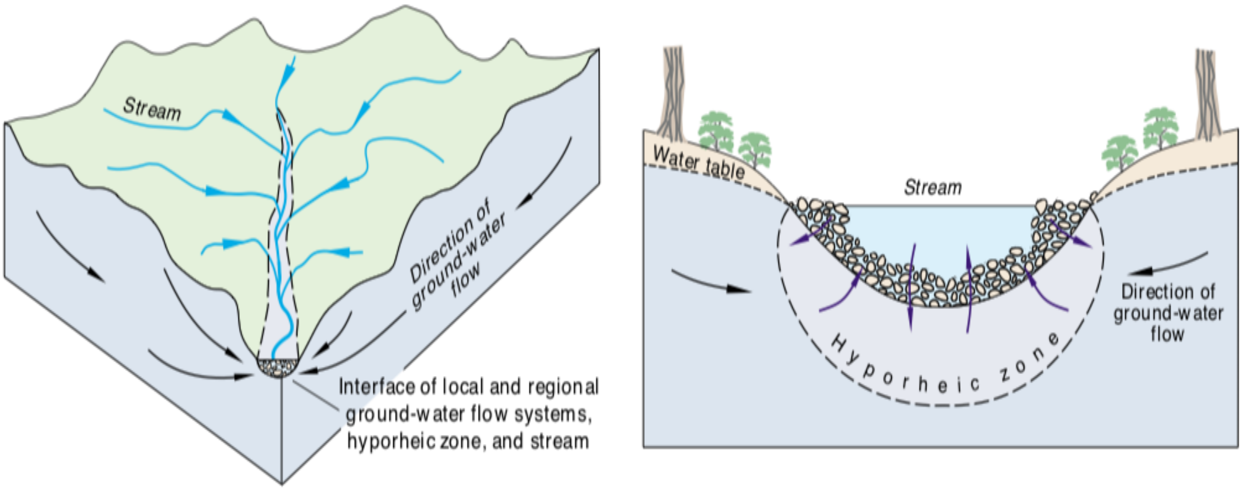


Figure 68: Streambeds and banks are unique environments where groundwater that drains the sub-surface interacts with surface water that drains the surface landscapes.

As with streams and lakes, wetlands can also receive groundwater inflows, or they may provide recharge to the groundwater, or do both, depending on the season: -

- Wetlands that occupy depressions in the land surface have interactions similar to lakes and rivers.
- Wetlands can be present on slopes where the water table intersects the land surface, resulting in groundwater discharge, giving rise to the development of a wetland. Such Groundwater Dependent Ecosystems (GDE) is often due to the presence of a perched aquifer resting on a shallow impermeable layer overlain by more permeable aquifer materials.
- Riverside wetlands may receive floodwaters from river flow that are retained in the flood plains and seep into the underlying groundwater system. However, they may also receive groundwater discharge from bank storage and locally elevated groundwater zones. In summary, these areas have especially complex hydrological interactions, subject to periodic water level changes.

4.3.3 Reduction of groundwater discharge to springs and stream baseflow

The rate of groundwater discharge as spring-flow, or as artesian-well discharge or as baseflow will not be constant and it will fluctuate as the hydraulic head changes. These changes will be seasonal. Groundwater recharge may be, and frequently is, delayed and occurs at some time later than the recharge event. This is due to the time it takes for recharge water to travel through the unsaturated zone and to reach the saturated zone and have an impact on the hydraulic head at the discharge site.

In addition, human activities such as groundwater pumping, groundwater injection, surface water impoundment and stream diversions, will affect the hydraulic head differences and hence the rate and sometimes the direction of groundwater-surface water fluxes.

Natural groundwater discharge to the land surface is generally an expression of the fact that the groundwater hydraulic head lies above the land surface at the point of discharge. Any activity or event, natural or man-made, that lowers the groundwater hydraulic head will have an impact of reducing the groundwater discharge (Figure 69). This is a natural and inevitable side effect of any groundwater pumping.

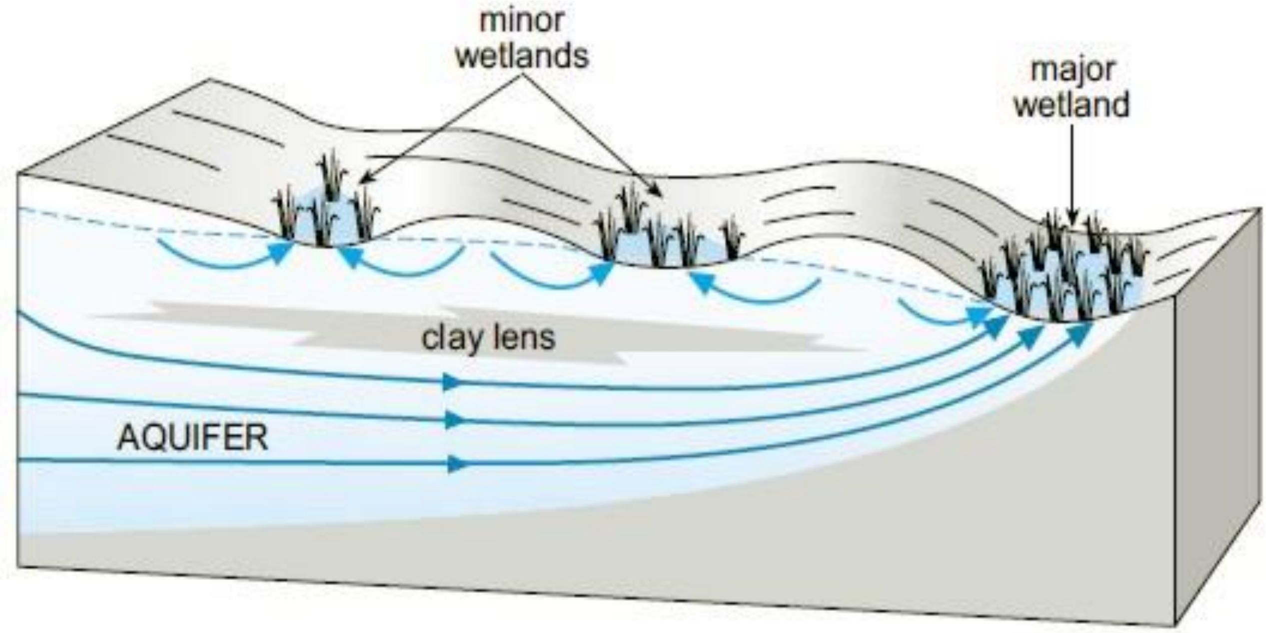


Figure 69: Many wetlands are groundwater discharge zones and are then characterized as groundwater-dependent ecosystems. Local water table lowering will affect the minor wetlands while the major wetlands that are fed by large regional flow systems will be much more resilient.

Natural groundwater discharges produce groundwater-dependent ecosystems (GDEs). All such natural discharges are taken from the top of the groundwater column, and any groundwater abstractions are, in some way or another, at the expense of GDEs. Some wetland GDEs may be more resilient than others, depending on the nature of the groundwater system that supports them (Figure 69).

4.3.4 Direct groundwater-surface interactions

Groundwater use from shallow unconfined aquifers

- Groundwater use/pumping from shallow unconfined aquifers delays the timing and reduces the amount of surface run-off in the rainy season and decreases baseflow in the dry season, and also decreases spring flow and seepage discharges.
- Such baseflow may be of critical importance especially during the periods of low flow and in semi-arid climates.
- Shallow groundwater discharges as springs or seeps often provide perennial or seasonal groundwater to groundwater-dependent wetland ecosystems and the communities that survive from these resources.

Pollution/contamination transfer between the two resources

- Interaction between surface water and groundwater can cause pollution to be transferred from one to the other.
- Groundwater pollution can more persistent and may persist for decades or even centuries thereby reducing water resources availability for generations to come.

Groundwater recharge is impacted by surface water use

- Damming rivers and abstracting water reduce downstream flows for focused groundwater recharge through river-bed infiltration.
- River-bed infiltration is usually the major component of groundwater recharge in arid and semi-arid environments.
- Irrigation excess and wastewater discharge (assume regulated/permitted discharge) are also sources of groundwater recharge.

4.3.5 Conjunctive management of groundwater and surface water

One of the significant advantages of integrated water resources management is that groundwater and surface water is managed as a single resource by a single institution responsible for the sustainable use of all water resources. Conjunctive management allows water resources managers to use the most appropriate water source for any particular time or location.

Examples of opportunities for conjunctive management may include the followings: -

i. Groundwater holds large volumes of water in storage, while surface water storage is moderate or small and often ephemeral.

   - A conjunctive management strategy could suggest allocation of surface water resources before they run off away from the area of demand, or before they are lost to evaporation. It should, however, be noted that evaporation should not be viewed entirely as water lost since it will be beneficial for down-wind precipitation.
   - In contrast, groundwater use can be increased in the dry season to offset the shortfall from ephemeral surface water sources.
   - Groundwater resources can provide a buffer in times of drought and water scarcity.

ii. Managed aquifer recharge (MAR)

   - This can be a way of capturing excess surface water during the rainy season when floodwaters are flowing unused out of the catchment.
   - MAR requires that suitable aquifers are identified and that the flow systems within these aquifers are well understood so that the water that is pumped into the aquifers are neither lost to deep discharge flow systems nor local wetlands nor become salinized by saline groundwater in the system.
   - Recharging aquifers in this way will not only provide additional dry season water resources but will also allow for natural purification of any bacterial contamination in the surface water during infiltration.

iii. Groundwater may be developed where demand is dispersed, and moderate, while the development of surface water may be more appropriate where the demand is focussed and on a large-scale, such as urban development or for irrigation.

iv. Conjunctive management can be used to balance upstream and downstream interests and demands, particularly with regards to the timing of water supplies. Surface water flows are rapid and may be released from storage reservoirs to meet critical urgent downstream demands, while groundwater flows are slow and may be retained for later use.

v. Financing of groundwater development and monitoring is a key area for flexibility. In many instances, private and individual development of the groundwater resource takes place, particularly if the basin authority establishes a positive enabling environment such as, for example, subsidies for electricity or borehole drilling. This may reduce demand for surface water and allow it to be allocated elsewhere, while at the same time developing groundwater resources in the catchment for economic and domestic use.

vi. Water resources managers can better balance the different competing needs in the catchment through the integration of the entire suite of available water sources.

vii. Short term demand may be met by cheaply and rapidly developed groundwater while major construction of large scale surface water resources may take more time to bring on-stream.

In summary, conjunctive management of surface and groundwater should always be an integral part of river basin planning and water resources management across the entire basin and through the different seasons.

4.4 PUMPING GROUNDWATER AND BOREHOLE DRILLING IN ZIMBABWE

4.4.1 Pumping

The subject of pumping groundwater is too large for this NWRMP. Nevertheless, it is of value to briefly discuss some of the issues involved in pump choice to enable managers to approach the subject in a balanced and informed manner.

The choice of the pump type chosen depends on a variety of factors:

1. The productivity of the borehole – i.e. the long term estimated borehole yield and thus the maximum sustainable pumping yield.
2. The demand for groundwater.
3. The finances available for installation and operation and maintenance.
4. The potential and planned economic productivity.
5. The types of pumping devices available and their suitability in terms of maintenance and robustness.
6. The availability of different power sources.
7. The technological capacity of the user community and service providers.

4.4.2 Situation analysis

There are a variety of different pumping devices used in Zimbabwe.

- In the rural communal areas, Zimbabwe model B Bush Pumps are mostly used.
- In commercial farming areas, mono-pumps and electric submersibles connected to the national power grid were most common. The land reform (2000) destroyed some of this infrastructure.
- In peri-urban areas, electric submersibles pumps powered by small generators are used for small scale irrigation to produce vegetables and other fresh produce for urban markets.
- In national parks and game reserves, solar panels powering electric submersibles and diesel driven mono-pumps are used.
- In urban areas, electric submersibles connected to the national grid are used.

The following observations are made:

- The Model B Bush Pump is robust and widely used and well-accepted but the most common repairs to the leather cups and the rubber seals on the piston require the lifting of the rising main which requires heavy lifting equipment such as a block and tackle. As a result, down-hole maintenance is not a village level operation but requires external support. There is some private work (www.aquamor.info) ongoing with regards to the downhole components of the bush pump so that the piston with cups and seals can be lifted on the rods without the necessity of lifting the rising main. This would then make village level maintenance much simpler. Such work, including field testing, should be officially supported.
- The Model B bush pump headworks, in particular, are robust and easily maintained and have been developed following extensive field testing and the highest-level engineering design. These headworks components are unsurpassed on any hand-pump, and Zimbabwe should not abandon them. The various models of bush pump have stood the test of time as a reliable and robust groundwater pump in the rural areas of Zimbabwe for many decades.
- Solar pumping installations are becoming more popular and more robust. Installation costs are high, vandalism and theft are significant issues, and storage reservoirs are needed since pumping cannot take place at night or during overcast weather unless expensive battery systems are included.
- Continuous pumping by solar-powered submersible pumps run the risk of depleting low yield boreholes and local low productivity aquifers.

- Solar pumping appears to be a good alternative for high value, high demand for rural water supplies such as growth points and national parks/resorts. However, the initial costs and other issues mentioned suggest that solar pumping is not, at this time, an option for widespread use in rural areas.
- Electric submersibles are relatively cheap to buy but are reliant on grid power or generators. There is a danger of over-pumping resulting in depletion of the aquifer resources, particularly for irrigation and in areas of high demand.

Over-pumping has resulted in significant depletion in major urban centres such as Harare where groundwater levels have already declined by ±15 m and more and more boreholes dry up earlier each year (anecdotal information from drilling companies).

In summary, there are no simple solutions for groundwater pumping and each environment needs to be assessed for the optimum solution. Initiatives such as the RWIMS database are extremely valuable in helping to keep track of borehole functionality and seasonality.

The hand-pump is likely to form the backbone of rural water supply for many decades to come. Solar and electricity grid installations are simply too costly and also pose a threat of over-pumping to the small local aquifers with low annual recharge rates.

Zimbabwe is blessed to have a locally developed and locally manufactured hand pump of superb quality that is robust, ergonomic, and well accepted by the population. The headworks are open and visible and simple maintenance is possible. In terms of robustness, durability and village level maintenance, this top part of the Model B Bush Pump is unmatched anywhere.

The main issue is that the most common maintenance and repair requirements are to the downhole components, in particular the leather cups and the rubber nitrile seals on the piston. To do this, the rising main with the water column needs to be lifted. This requires heavy lifting equipment (tripod and block and tackle/winch) and reduces the ability of the local community to affect basic maintenance and repair procedures on the Model B Bush Pump.

However ongoing research by the pump designer, Dr P Morgan (www.aquamor.info), is focused on developing down-hole designs that will allow the lifting of the piston directly on the rods, without the need to lift the rising main. Since the similar down-hole design is already in use by the India Mk 4, and the AfriDev pumps, although for shallower depths, the development of a similar down-hole structure for bush pumps seems quite achievable, although different materials are likely to be used and design modifications are likely to be required.

It is recommended that the Model B Bush Pump be retained as the back-bone of rural domestic water supply and that there be allocated a continuous budget to monitor bush pump performance and to identify design improvements and eliminate weaknesses as they occur and incorporate these into updated versions of the pump.

This trusted symbol of Zimbabwe's rural water supply infrastructure should be kept in service and valued for the robust service it provides to millions of users.

4.4.3 Drilling

Background: The drilling sector in Zimbabwe is not fully regulated. Any company can become a drilling company; they just need a company registration and a drilling rig and crew who can operate the rig. There is no certification requirement for drilling companies to be registered as drilling companies nor to have an annually renewable license to drill.

Permits are required to drill boreholes, and these are issued by the catchment councils. The requirements for a permit are not stringent and in general, they are issued without any on-site inspection or investigations. Drillers are required to submit drilling completion forms, but there are no sanctions if such forms are not submitted.

Permits to abstract groundwater are required for commercial use, and in the urban areas, for domestic use. Annual fees are paid to the catchment council for these permits. In rural areas, domestic primary use groundwater abstraction does not attract any fees nor requires any license.

The issues: At present, drilling companies compete for the market share on a price for services basis. Since there is no regulatory framework, many unskilled and non-professional drilling companies have entered the market since there is a very high demand for groundwater across the country.

Drilling then takes place in an unsupervised environment, with unskilled drillers, and the result is that there are an increasing number of poorly drilled boreholes that have a limited lifespan. The reduced lifespan of boreholes is causing significant concern in the government sector (notably NCU and DDF), donor organizations such as UNICEF as well as NGOs such as World Vision. While there are capacity development courses on offer, there is little incentive for drilling companies to improve their capacity.

Recommendations: It is recommended that: -

- water authorities review the existing regulations and make amendments to enforce the registration of drillers with the annual issuance of licenses to operate, subject to the submission of all borehole completion reports, and other regulatory requirements.
- water authorities take the lead in developing and promulgating enforceable codes of practice to cover all aspects from drilling, installation to equipping of boreholes. The Standards Association of Zimbabwe (SAZ) has already produced a set of guidelines for water borehole drilling standards.
- capacity development courses be provided with respect to borehole drilling, borehole drilling supervision, drilling contracting, and specification of materials, borehole siting and catchment management.
- drilling companies and development agencies be encouraged by various incentives and regulations to ensure that their personnel are trained to ensure a better service provision leading to well-constructed boreholes with long service life.
- drilling and groundwater data be stored in purpose developed databases at catchment and national level.

Summary: A detailed analysis of groundwater pumping and drilling has not been presented in this Hydrogeology component of the National Water Resources Master Plan. The development and maintenance of basic groundwater infrastructure is very much a component of a successful groundwater supply sector.

This chapter has touched very briefly on some of the key issues and highlights their importance. However, the details of a successful rural water supply system are myriad and complex and include issues such mechanical engineering, spare parts supply chain, training and capacity building, institutional frameworks, gender, and community participation, water user group formation, maintenance and management and, the perennial shortage, finances. These issues are left for a different study.

4.5 GENDER IN GROUNDWATER

4.5.1 Introduction

In traditional African societies, the core responsibility of women and girl children is to collect, store and use water for the upkeep of the family. Due to the high costs of constructing and maintaining piped water schemes to supply rural populations with clean potable water, groundwater has proved to be the most affordable source of water for the rural populations in Africa. The uses of water include caring for the family, providing drinking water, cooking, washing, cleaning, watering, and maintaining sanitation. In Africa, most of the work in fetching water is done by women. Despite their position as the main users of water, women have been marginalized when it comes to policy and decision-making related to water resources management and project implementation. Gender mainstreaming is one process which can help to address the gender imbalances in water resources management.

Women have been marginalised in groundwater management in various ways and for varied reasons: -

- Women's subordinate positions in their marriage, family, and community have placed them in the lowest position in society.
- Lack of access to and control over land and other properties. The tendency is that people with resources (cash, bicycle, cattle) are the ones who are normally elected to top positions of responsibility in the villages. Few women have such resources leading to their being left out when it comes to responsibilities for the village.
- Low levels of participation of women in decision-making and governance.

4.5.2 Gender and groundwater in Zimbabwe

- The majority of the people living in rural areas are women and children who have to stay behind and take care of the livestock and the fields whilst the men move to urban areas to work. Many men work elsewhere and will only come home once or twice in a year.
- The women continue to play their traditional roles of fetching water and firewood and looking after the family.
- Although they are the main users, women have often been left out of the management and maintenance of water points. It is mostly men who get trained as pump minders, pump mechanics and caretakers, although women are the principal users of such technologies.
- Few women in Zimbabwe have attained a technical education in the fields of science and engineering. This has created gender imbalance at top-level management.
- There is a lack of women participating in decision making and management of groundwater resources.

4.5.3 How can the imbalances be addressed?

The gender imbalances in Zimbabwe may be considered a wider issue related to the patriarchal nature of Zimbabwean society. We will focus only on the issue of women in groundwater management.

Our strategy focuses on increasing the number of women who enrol in technical education related to groundwater management, specifically hydrogeology and water resources engineering and management. The approach proposed is to develop advocacy materials appropriate to all levels of education from primary through to tertiary. These advocacy materials can identify the range of career opportunities in the field of groundwater management and encourage girls and women to enter these fields of education.

The core of the problem is that there are very few women enrolling for Earth Sciences/Engineering courses at university and correspondingly few graduates, and so the pool of women who are academically qualified to enter the variety of groundwater and related professions is very limited.

It is considered that the problem first arises at the school leaver/university undergraduate level. Geology (Earth Sciences) is not a school subject and as a result, scholars do not have a well-founded understanding of role and scope of Earth Sciences. The image of Geology tends to be very strongly linked to the Mining/Mineral Exploration sector, where the image is one of working underground in gumboots and a hard hat or exploring for minerals in a remote camp far from schools and clinics. This is just not attractive for many young women entering university and choosing their degree programme.

Geology needs to be re-branded as Earth Sciences and the varied and stimulating career options in Groundwater, Hydrology, Environmental Geology, Ecology, Remote Sensing, Analytical Geochemistry, Geophysics, Engineering Geology, Geoinformatics and Modelling, need to be brought to the attention of female school leavers/university entrants and also promoted at the undergraduate level in our universities. The perspective is that a major awareness campaign at high schools and universities would be the first step in this initiative.

4.5.4 Activities

- Establish contact with the Gender and Water Alliance to set up a joint working group for Gender in Groundwater.
- To develop awareness materials on career opportunities in Earth Sciences aimed at secondary school girls (O and A level girls) and undergraduate students. The awareness materials will highlight the relationship between earth sciences and water, groundwater and environmental sciences and identify the whole range of exciting careers that are possible with such academic qualifications.
- Produce draft awareness materials (electronic and print versions) such as attractive and informative posters, pamphlets, CDs, and web pages.
- Strategies for reproduction and distribution of these materials on a wide scale can be prepared to focus on global organizations (e.g. UNESCO/UNICEF), national education ministries, girls' high schools and universities. A pilot project may be designed/initiated to test the efficacy of the distribution strategy in a small number of catchments.
- A suite of indicators to assess the impact of the program should be developed.

4.5.5 Outputs

- Production of a suite of awareness materials relating earth sciences to career opportunities in water, especially groundwater, and environment.
- Establishment of a working group with the Gender and Water Alliance.
- Establishment of links with global institutions involved in education (e.g. UNESCO/UNICEF) for the production and dissemination of such materials in Zimbabwe and elsewhere in Africa.
- More women to be included in water point committees and be trained as caretakers for water points.
- Preparation of a strategy to distribute these materials in a small number of pilot catchments.

5. GROUNDWATER MONITORING

5.1 THE CONCEPT OF GROUNDWATER MONITORING

Groundwater monitoring is a suite of activities that allow groundwater managers to gain an appreciation of the groundwater resources. The monitoring cycle commences with the objectives of monitoring and the management questions that need to be answered. Figure 70 explains the steps involved in this cycle.

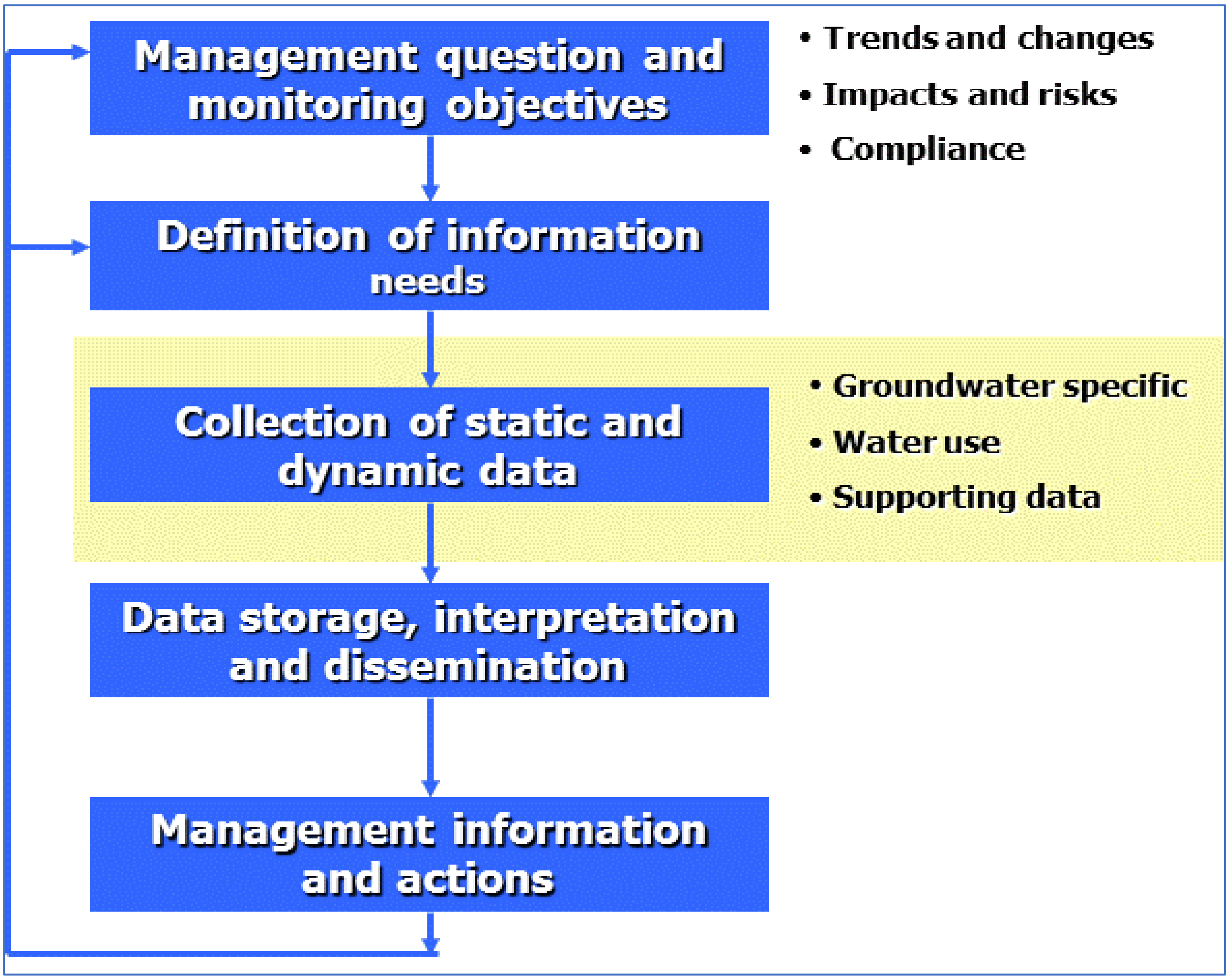


Figure 70: The groundwater monitoring cycle.

5.1.1 Types of groundwater monitoring

There are four basic types of groundwater monitoring based on the purpose/function of the monitoring programme. These are: -

i. Trend/reference monitoring: To assess how the groundwater system is behaving in general. Is the water level declining? or is it increasing? Or is it static? Is the water quality potable, or not? Is the water quality deteriorating over time or is it freshening?

   Trend monitoring provides a reference background against which groundwater managers can gauge the trends that are affecting the general groundwater resources. Trend monitoring networks need to be carefully designed in order to assess the changes to the groundwater reservoir in different hydrogeologic, topographic, land-use, rainfall, temperature, and vegetation environments. A typical technique for trend monitoring is to identify hydro-climatic zones, with known climate and hydrogeology, and monitor one catchment as a template for similar catchments. Trend monitoring is seen as a suitable method for catchments and sub-catchments to keep a record of the groundwater conditions in their catchments.

Groundwater abstractions will also be reflected by trend monitoring and these abstractions should be recorded in any trend monitoring system. If abstractions are not recorded, then some of the observations made during trend monitoring are likely to be misinterpreted.

Without such trend monitoring networks, Zimbabwe's groundwater managers and groundwater users are essentially flying blind. Groundwater resources may be depleting across entire sub-catchments, such as the Upper-Manyame sub-catchment, yet groundwater managers have little measured data to use for the sustainable management of the resource.

For a country such as Zimbabwe, which has been identified as being mostly in the high to very high groundwater drought risk categories (Villholth et al., 2013), the absence of groundwater trend monitoring networks is irresponsible and dangerous and is likely to lead to the drying out of groundwater resources, especially during the late dry season and irreversible pollution at vulnerable localities.

Detailed design of such local catchment trend monitoring networks will be expanded on later in this chapter, using one or two selected Zimbabwean sub-catchments to provide practical examples. Trend monitoring networks for all the catchments will be presented in the chapter on Groundwater Projects.

ii. Defensive/protection/early warning monitoring: Where there are valuable groundwater resources, we can monitor around them to get a warning from any impending threats, whether over-pumping and water-level declines or quality issues due to pollution or aquifer depletion.

Defensive early warning monitoring is typically used where there is a public potable domestic water supply or well-field, such as the Nyamandlovu well-field in Matabeleland North. Alternately such defensive monitoring may be set up around critical groundwater supplies used for industry or irrigation.

Defensive monitoring networks provide a warning of approaching threats, such as pollution plumes or declining levels, that allow groundwater managers to modify the abstraction rates or to introduce other measures to ameliorate or avoid the impending problems.

iii. Impact monitoring: When there is a threat to a groundwater resource or well-field, we can monitor the impact of that threat. The threat may be due to over-pumping, or it may be a pollution/contamination threat due to a nearby point source of pollution or suspected high levels of non-point source pollution.

Impact monitoring is normally established around know pollution point sources such as e.g. municipal solid waste management sites, waste disposal facilities from mining, industry and intensive agricultural developments.

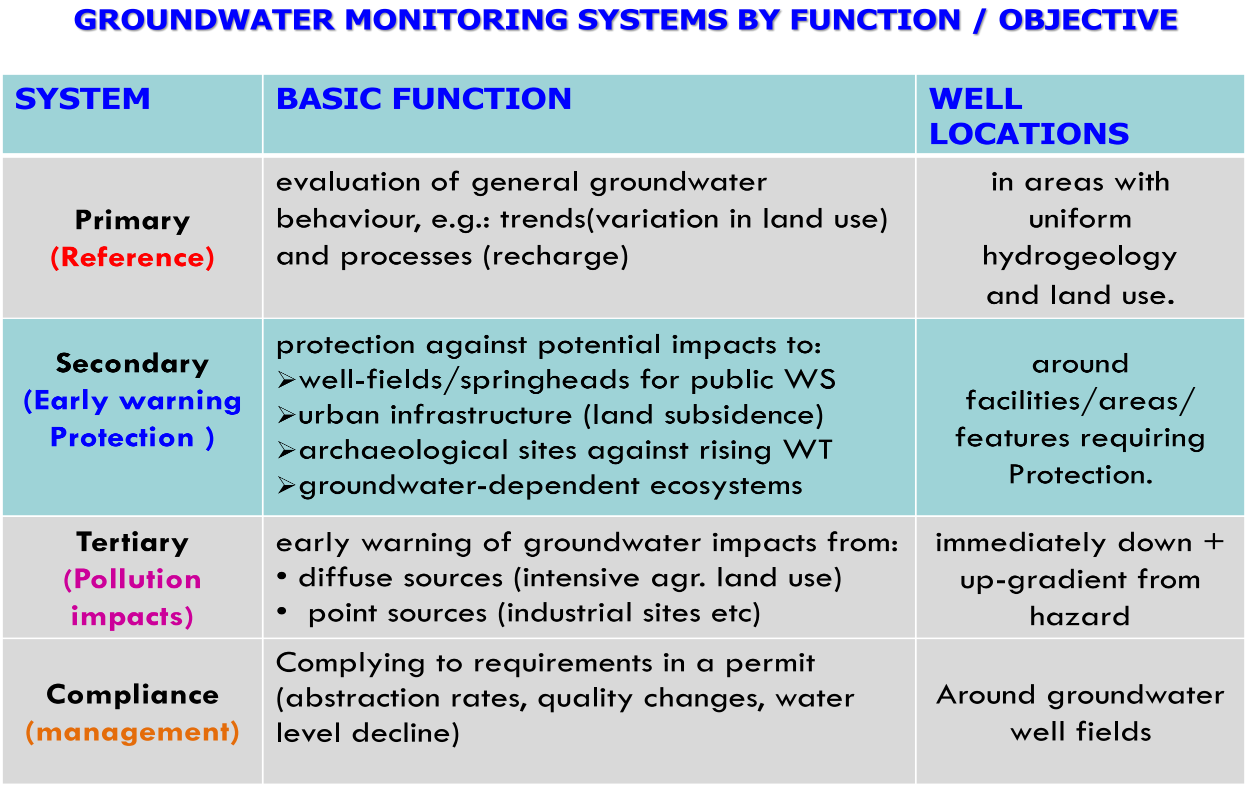
Non-point source pollution from urbanization and large-scale commercial agriculture may not appear as dramatic as point source pollution, yet the total discharge of pollutants to the environment from such diffuse sources probably far exceeds that from point sources. Where such developments exist, local "trend monitoring" networks are recommended.

A further source of impact is excessive abstraction. This is a problem that bedevils many urban societies, particularly in the developing world. Urbanization often proceeds in an organic and unplanned manner and at a pace that exceeds the capacity of the urban authorities to provide municipal water supplies and water-borne sewage removal. As a result, people turn to self-supply from local groundwater resources. Such abstractions may exceed the natural groundwater recharge rates leading to declining groundwater resources. In high-density settlements, if waterborne sewage removal is not installed, local human waste discharges will, over time, lead to contamination of the groundwater resources. However, in the case of Harare, the sewage removal network has become unsafe due to breakages and is locally a source of groundwater contamination.

Monitoring in multi-threat environments, such as high-density urban development, becomes a complex problem with impact monitoring required for local high discharge boreholes that may be used as a public or commercial water supply and local trend monitoring in the broader context. The trend monitoring should include seasonal bacteriological water quality monitoring. Monitoring high abstraction rates should also be coupled with investigations into groundwater recharge rates and the development of groundwater maps.

iv. Monitoring abstraction and compliance of users with their permits for management purposes: Compliance monitoring is an essential part of groundwater management. It requires information on the distribution of boreholes and the abstraction rates. Generally, there may be thousands of boreholes in a catchment with a variety of abstraction rates. All these boreholes should be mapped using GPS to record their location and elevation. The sheer numbers of boreholes and users can make it very difficult for groundwater managers to monitor abstraction and compliance and it is often more successful to introduce a system of stakeholder participation in the management of their local groundwater resources.

Such stakeholder management systems need to be carefully thought out and designed to benefit the groundwater user community. Many individual users will be reluctant to participate and share data on their groundwater use, yet groundwater is a common pool resource, and it can only be managed properly in a holistic manner.



GROUNDWATER MONITORING SYSTEMS BY FUNCTION / OBJECTIVE

SYSTEM	BASIC FUNCTION	WELL LOCATIONS
Primary (Reference)	evaluation of general groundwater behaviour, e.g.: trends(variation in land use) and processes (recharge)	in areas with uniform hydrogeology and land use.
Secondary (Early warning Protection)	protection against potential impacts to: ➢well-fields/springheads for public WS ➢urban infrastructure (land subsidence) ➢archaeological sites against rising WT ➢groundwater-dependent ecosystems	around facilities/areas/ features requiring Protection.
Tertiary (Pollution impacts)	early warning of groundwater impacts from: • diffuse sources (intensive agr. land use) • point sources (industrial sites etc)	immediately down + up-gradient from hazard
Compliance (management)	Complying to requirements in a permit (abstraction rates, quality changes, water level decline)	Around groundwater well fields

Figure 71: Monitoring systems by function

5.1.2 When and where to monitor

The preceding section has discussed the different monitoring environments, and one might now think that universal monitoring need only be introduced. However, in practical terms, groundwater monitoring on a national basis is a large scale operation and it may be too expensive, impractical and unnecessary to introduce monitoring everywhere at the same time.

During the early stages of aquifer development and when only modest groundwater withdrawals are taking place, it is generally unnecessary to establish monitoring networks. However as abstraction increases, or recharge declines due to climate change or other factors, the impacts of groundwater abstraction begin to be felt in a number of negative ways, and then both the need and the support for monitoring the groundwater system also increase (Figure 72).

The impacts of declining groundwater levels are often reversible, but may become irreversible if abstraction is excessive, and include the following:

i. Declining borehole yields and increased pumping costs;
ii. Reduction in base-flows and spring discharges;

iii. Phreatophytic vegetation stress;
iv. Seasonal and/or permanent drying up of shallow and low yielding boreholes;
v. Aquifer compaction and transmissivity reduction; and
vi. Declining water quality and saline water intrusion.

Impacts 1, 2 and 3 in the list above are inevitable aspects of any groundwater development. Impacts 4, 5 and 6 are the result of excessive abstraction and 5 and 6 are irreversible changes.

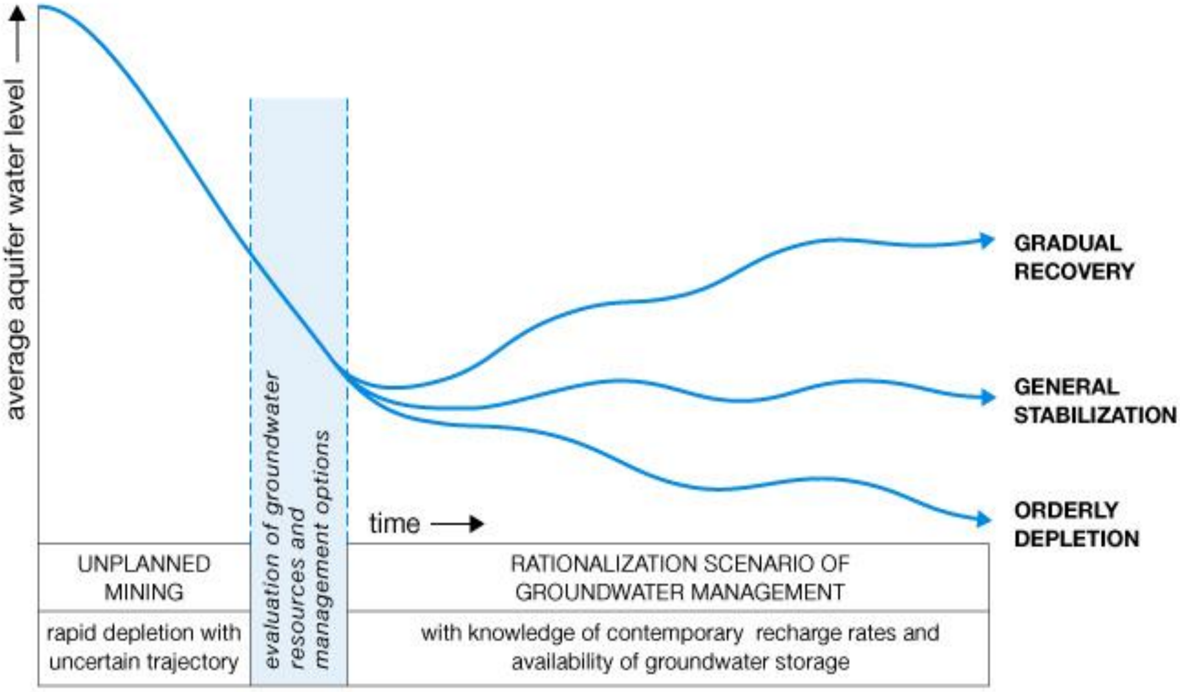


Figure 72: Groundwater development leading to decreasing water levels, the introduction of monitoring and management of abstraction to stabilize the groundwater levels.

The groundwater conditions and groundwater drought risks in Zimbabwe are such that the need for groundwater monitoring is urgent and essential so that effective management measures can be introduced in order to ensure sustainable groundwater management.

Some of the key challenges facing groundwater in Zimbabwe include:

- Shallow local low porosity crystalline aquifers dominate the country, and particularly the more populated regions;
- A semi-arid climate with limited and low groundwater recharge rates;
- Very high dependence on groundwater in the rural areas due to a lack of perennial surface water supplies;
- Increasing demand for groundwater in urban areas as municipal water supply services increasingly fail to meet demand; and
- Contamination of urban groundwater resources with the increasing incidence of water-borne diseases such as typhoid and cholera.

In order to monitor groundwater effectively, monitoring networks should be designed for a specific purpose and use. If such networks do not have a focused design, they may fail to monitor the most critical and important parameters in different settings. Furthermore, groundwater conditions are generally quite localized and do not have the extended upstream and downstream impacts that are a feature of surface water flows. This then raises the question of how groundwater monitoring networks should be designed for the conditions that exist in Zimbabwe. Figure 73 illustrates where the different types of monitoring would be applicable.

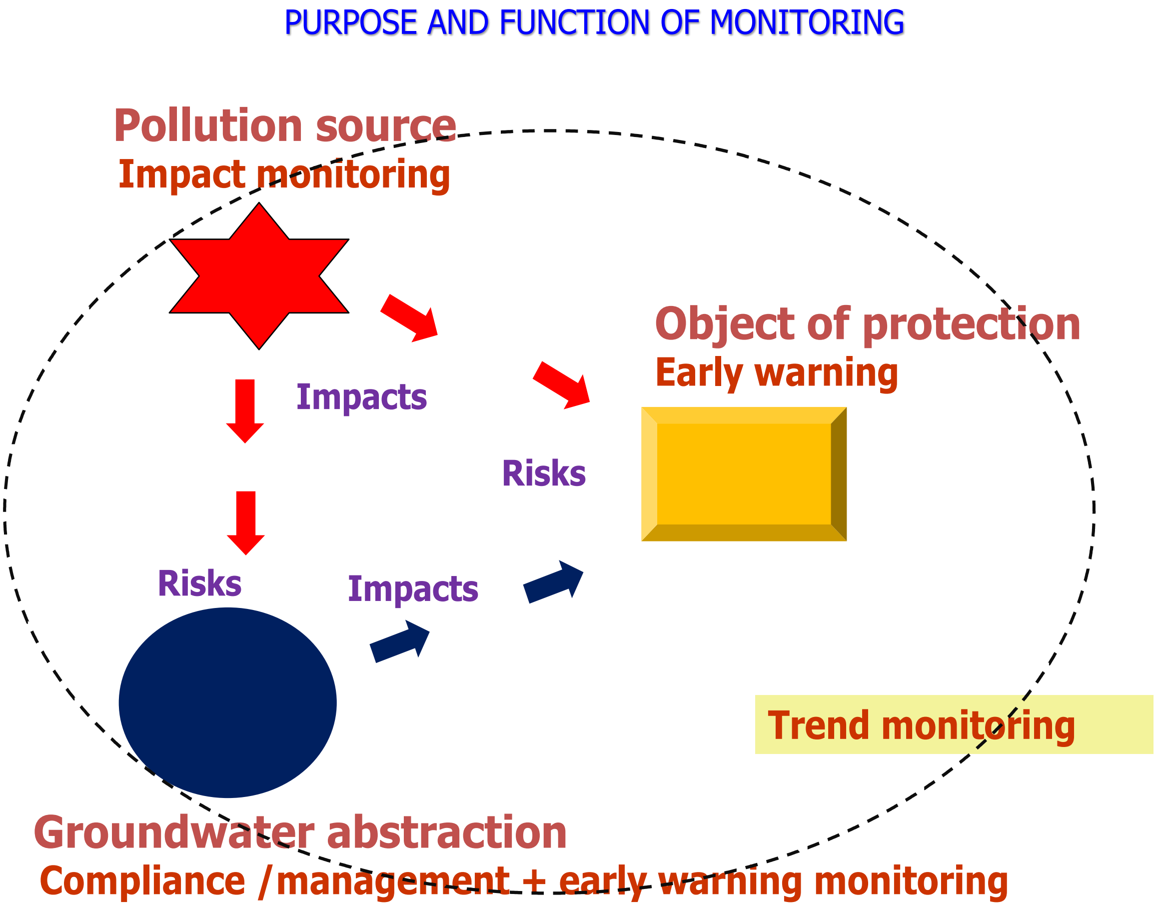


Figure 73: Field layout of monitoring systems.

5.1.3 What parameters are monitored?

Monitoring may include one or more of the different activities listed below: -

i. Monitoring groundwater levels in one or more dedicated monitoring boreholes. These boreholes must not be used for pumping. Monitoring boreholes need to be distributed wisely to adequately capture the groundwater conditions.
ii. Boreholes that are recharged by direct rainfall are most useful for groundwater resources monitoring. However, some boreholes are recharged by focused recharge via e.g. a fissure or fault zone, or by infiltration from a nearby stream. It is important to understand the recharge mechanisms of each monitoring boreholes in order to interpret the information sensibly.
iii. Surveying the position (x,y,z) of monitoring boreholes. This is essential to obtain groundwater flow patterns and draw groundwater contour levels.
iv. Monitoring groundwater quality (different parameters will be measured depending on the specific purpose/threat) in one or more boreholes. Groundwater quality may be monitored in pumping boreholes and it is not required that dedicated monitoring boreholes be used.
v. Monitoring abstraction of groundwater from boreholes. A variety of methods may be used to monitor abstraction ranging from water meters to, for example, the extent of irrigated area, or simple estimates based on the type of pump and hours in use daily. User participation in groundwater abstraction monitoring is helpful, but metering is recommended for very large scale and commercial users. If abstraction is not monitored, then the groundwater hydrographs may be misinterpreted.
vi. Monitoring groundwater piezometric head levels at different depths in multi-level boreholes to obtain the vertical distribution of the groundwater resources. When there are impermeable or low permeability strata inter-bedded with aquifer layers, then the hydraulic head distribution in the subsurface can be complex. Multi-level piezometry is typically used in layered aquifer systems in sedimentary

environments, and to assess if there focussed recharge via fissure flow. For multi-level borehole monitoring, proper borehole design and construction is essential to ensure that the different layers are hydraulically separate, and conditions and samples in different aquifer layers are measured correctly.

vii. Additional measurements/samplings may be carried out at selected boreholes in order to provide ancillary data that will allow for groundwater recharge estimations. Such measurements should always include rainfall on a daily time-step and temperature. Other measurements may include once-off pumping tests to estimate physical properties such as porosity, specific yield, and hydraulic conductivity. Additionally, groundwater chemistry (e.g. chloride) or isotopes (3H - tritium; 2H – deuterium; and d18O – oxygen-18; 36 C – chlorine 36) may be monitored to assess the source of recharge, the groundwater age, and other parameters. Such additional measurements should only be undertaken at specifically selected boreholes, for a specifically identified purpose, and should be carried out under the supervision of a trained scientific officer.

5.1.4 Where to monitor and how to set up groundwater monitoring networks

This section provides a simplified outline of how the groundwater trends may be monitored at a catchment and sub-catchment basis. In addition to providing a general outline for trend monitoring that may be used as a guide by the catchment/sub-catchment groundwater managers, we will also prepare a "draft design" for one catchment.

The term "draft design" is very deliberately used. There are certainly groundwater conditions within every catchment and sub-catchment that are known and considered either problematic or favourable by the local groundwater users and managers. As such, monitoring of such localities will likely be a priority for the groundwater users/managers. It is generally unwise and seldom helpful for an external person to locate the exact positions of monitoring boreholes in a catchment.

In particular, the catchment authorities are best placed in terms of determining whether and where there is need for any impact monitoring, early warning defensive monitoring and compliance management monitoring. These types of monitoring are all in response to local specific conditions and hence the identification of the local need for monitoring will be best placed with the local water management authority. It is envisaged that catchment authorities will submit their trend/impact/early warning/compliance groundwater monitoring needs to ZINWA.

Many online publications help set up a groundwater monitoring network. Perhaps the most widely accepted is the manual produced for the World Bank by the Groundwater Management Advisory Team (GWMate)
https://www.researchgate.net/publication/287202382_Groundwater_Monitoring_Requirements_-_for_managing_aquifer_response_and_quality_threats
Some general guidelines include the following: -

- Try to place monitoring holes within the grounds of public institutions where they can be protected against vandalism. Seal the top of the borehole with a lockable cover if possible. Where possible, monitoring boreholes should be easily accessible by road to encourage and facilitate monitoring.
- Schools may be suitable places for groundwater monitoring and the data can be shared with the schoolteachers and children to increase their awareness of groundwater.
- Where possible, drill or case the borehole at a smaller diameter (e.g. 75mm) so that people are not tempted to install a pump. Fix a permanent borehole ID label on every monitoring well.
- Groundwater level data are always measured from the same height, usually the top of the casing. The borehole id number should always be recorded.
- Data are handled in a way that preserves data integrity. In other words, record the data on pre-formatted sheets that are the same as the data recording sheets in the computer. Universal software such as EXCEL is fine for data capture. Enter the data into the computer database immediately. Back-up your groundwater database and make sure that you always send the monitoring data to the National Groundwater Database.
- Use pumping boreholes to monitor water quality. It is not necessary nor advisable to use un-pumped boreholes for water quality monitoring since you will be monitoring the water in the borehole rather than the water in the aquifer.
- Keep a copy of monitoring protocols on hand, especially for water quality sampling. For example, bacteriological water quality samples must be collected in sterile glass bottles, stored in a refrigerator and

analysed within 24 hours of collection. Parameters such as O2, pH, EC, T and alkalinity should be measured in the field if possible. Storage of water samples for different types of analyses are very specific.

- Always keep monitoring equipment and sample bottles in a safe clean place and test these before carrying out any monitoring.

5.1.5 Institutional Responsibility for Groundwater Monitoring in Zimbabwe.

- The ZINWA Groundwater Branch is the national authority that has the official responsibility for national groundwater resources management, and the ZINWA catchment councils and sub-catchment councils have the responsibility for groundwater allocation and groundwater management at catchment and sub-catchment level.

- Furthermore, ZINWA Groundwater Branch already holds a national groundwater database with approximately 18,000 borehole records. It holds monthly water level monitoring data for the well fields at the Nyamandlovu aquifer from 1989, the Save aquifer from 1997 and for the Lomagundi aquifer from 1984. Unfortunatley almost no abstraction data has been recorded. Hwange National Park (HNP) has an extensive game watering network based on approx. 100 boreholes and irregular and infrequent groundwater level monitoring has been carried out. HNP have also investigated the option of establishing an automated dedicated monitoring network.

- As the national water authority, it makes sense that the responsibility for installing and maintaining the monitoring network, and interpreting the data and using that to guide groundwater management, should lie with ZINWA and the catchment councils.

5.1.6 Data capture, recording, management and use

Typically monitoring may either be manual or by automatic water level recorders. For manual monitoring, the field officer visits each borehole on a regular pre-determined schedule and inserts a dip-meter tape (Figure 74) into the casing and lowers the tip until it reaches the water table. At the water table, electrical contact is made, and a buzzer and a light will come on at the cable reel. The reading on the tape records the depth in meters below ground level or mbgl. It is vital to ensure that this depth, mbgl, is always measured from the same point, usually the casing top.

Figure 74: Dip meter. Dip meters come with different length of tape, typically 30m, 50m and 100m. It is also possible to get manual dip-meters that have EC (electrical conductivity) and T (temperature) sensors. The tape on dippers can become snagged down the borehole quite easily and it is recommended to insert a 25mm PVC tube down the borehole as a dipper access tube.

These days automatic water level recorders are becoming much more common (Figure 75). Although the initial cost may be high, these devices quickly pay for themselves in terms of saved mileage and man-days. These devices are installed in boreholes and set to record data, usually the water pressure or head above the sensor, at set intervals. The intervals may range from seconds to months or longer. Ideally, the measurement interval is set to capture significant changes in the groundwater levels in the borehole. In the rainy season, when groundwater recharge is expected to take place, the measurement interval may be hourly or daily, while in the dry season, measurement intervals of weekly may be more appropriate. The user needs to visit the borehole only annually or bi-annually to download the data onto a laptop.

Figure 75: Automatic water-level recorder. These devices work with a pressure transducer that senses the height/head of the overlying water column. They also may have other sensors such as EC and T.

Which data needs to be recorded for effective monitoring in respect of national groundwater databases? It is advisable to separate the "monitoring network" boreholes from a general borehole register. This section discusses the monitoring network database.

Borehole data may be quite voluminous and there are software programmes (e.g. HydroGeoanalyst https://www.waterloohydrogeologic.com/hydro-geoanalyst/) that can guide the storage of groundwater data. Some of the data/information may not be rendered readily as a numeric value or a single word or phrase. There may be a requirement for maps and diagrams. Therefore, comprehensive databases may need to provide links and make reference to linked documents.

Nevertheless, there is always a demand for "key" data in some sort of tabulated format that can be readily accessed in a simple spreadsheet or table. A spreadsheet will be inadequate for a comprehensive groundwater database. One solution may be to create a suite of separate spreadsheet databases that cover different fields, for example, groundwater quality data, groundwater monitoring data, borehole location and yield.

Data may be divided into 'static' data and 'dynamic' data. Static data such as borehole construction and pump details need only be recorded once since it does not change, whereas dynamic data needs to be collected regularly since it reflects changes such as the borehole water level, pumping rates and water quality.

With respect to an unpumped borehole monitoring network, some of the key data are indicated below.

Static data may include the followings: -

- Borehole ID and co-ordinates. Catchment and sub-catchment names. (Ideally, a borehole will carry an identification tag in the field so that it can be positively identified. These days with the advent of GPS devices, this is becoming less critical. Nevertheless, it is still recommended that every borehole be given a permanent ID tag. Such ID tags should be part of a national borehole database identification system so that they provide information related to the locality of the borehole.)
- Borehole construction details: (date drilled, depths and diameters, casing lengths and diameters, materials used).
- Hydrogeological Unit/Aquifer Productivity/Aquifer Recharge Potential.
- No pump fitted ideally: (where fitted: Pump Type: type of pump fitted, rising main type and diameter; power source).
- Ownership/Responsibility. (This may include information on who owns the hole, the institutional responsibility for maintenance).

Dynamic data may include the followings: -

- Pumping test data (date of the test, yield, drawdown, specific capacity plus calculated hydraulic conductivity K, transmissivity T, specific yield, and storage coefficient. Date of tests);
- Well hydrograph data (date, water level mbgl; date2, water level);
- Water quality data (date, parameter 1, 2, 3; date 2, parameter 1, 2, 3); and
- Information on nearby local abstractions (where the cone of depression may affect water level readings).

5.1.7 Data use

A vital part of a monitoring network is that the data be put to use. If data is collected but not used, it will not long before data collection efforts start to decline, and maintenance of the monitoring network will fall away leading to an ever-decreasing number of monitoring stations. This type of decrease and decline has been already observed with the river flow gauging stations.

The use of groundwater monitoring data can be highly sophisticated and complex and provide a significant amount of real data on the groundwater resources in storage, the groundwater recharge volumes as well as trends in both quantity and quality.

An example hydrograph from a private borehole in Harare shows both rainfall and groundwater level fluctuations for the past eight seasons from 2010 to 2018 (see Figure 38). The hydrograph shows the annual recharge in the rainy season and highlights the link between consecutive wet days and groundwater recharge (Figures 39 and 40). In addition, trends can be discerned in terms of peaks and troughs for high and low groundwater levels.

If the local abstraction data and the aquifer properties (K and S) are also known, then much more information can be determined by a detailed study of such hydrographs.

If all the catchments and sub-catchments record this type of data in a moderate number of monitoring wells, then it will become possible to have a much more detailed understanding of Zimbabwe's national and local groundwater resources base.

5.1.8 Summary

The purpose of groundwater level and quality monitoring is to provide the catchment managers with information on the performance of the groundwater resources. Such information may initially be relative; water levels are declining or rising; water quality is deteriorating. However, over time, the groundwater monitoring data can be linked to, for instance, rainfall, abstractions or wastewater discharges and thereby provide the catchment groundwater managers with an effective tool for sustainable management of the catchment groundwater resources and evidence-based data for decision making.

Ideally, the monitoring network database will be linked with a general register of all the boreholes in each catchment to place the monitoring data more fully within the framework of groundwater demand and use in each catchment.

In the chapter on groundwater projects, a national groundwater trend monitoring network is proposed in detail with a suite of catchment maps that show suggested monitoring borehole locations located on the catchment groundwater development potential maps.

6. GROUNDWATER PROJECT PROPOSALS

As part of the NWRMP, an outline of project proposals is prepared for works that may be carried out as part of the outputs. For the groundwater component, the following project proposals are made.

i. Development and Installation of a National Groundwater Trend Monitoring Network.
ii. Development and implementation of legislation for the Registration and Annual Licensing of Water Drilling Companies.
iii. Rationalization of Groundwater Data Management Systems and upgrading of the National Hydrogeological Database System.
iv. Preparation of Groundwater Models (e.g. USGS MODFLOW) for the three major aquifer systems: Lomagundi, Nyamandlovu and Save aquifers.
v. Project Name: Upgrading of existing high yielding boreholes with solar power for pumping.

6.1 DESCRIPTION OF THE PROPOSED PROJECTS

i. Project name: Development of a National Groundwater Trend Monitoring Network

This is considered to be the most important and vital step for groundwater management and development in Zimbabwe. Zimbabwe is considered to be a nation with a very high groundwater drought risk status (Villholth et al., 2013). 29% of boreholes in the RWIMS database are already indicated as seasonal. Climate change further threatens the sustainability of groundwater use. In high demand areas such as Harare, boreholes are drying up earlier each year, and there is little doubt that the underlying aquifer units are already over-stressed. Furthermore, groundwater quality, particularly in the high-density suburbs, is declining due to high loads of waste from pit latrines and burst sewers, with typhoid now endemic and an ever-present risk of cholera. Groundwater drought is already a present condition, signalled by an ever-increasing number of bulk water delivery trucks plying the suburban roads of the nation's capital.

Yet the annual trend of groundwater level fluctuations is hardly monitored. Groundwater resource managers only hear of boreholes that have already dried up, without any data on how the groundwater levels have been fluctuating over the years. This is akin to flying an aeroplane with a blindfold over your eyes.

Distribution of monitoring wells: The proposal is for a total of 125 groundwater level monitoring boreholes to be established nationwide, spread across all catchments, and to monitor these with automatic data loggers. The distribution of the monitoring boreholes is not yet fixed and will require direct input from the individual catchments. However, the initial distribution is shown in Table 26.

Table 26: Groundwater trend monitoring network

Catchment	Number of monitoring boreholes
Gwayi	18
Manyame	17
Mazowe	24
Mzingwane	14
Runde	15
Sanyati	17
Save	20
Total	125

Quantitative catchment maps for Aquifer Productivity (groundwater volume in storage) and Aquifer Recharge Potential (annual groundwater recharge) are presented below for every catchment (Figures 77-83). These maps show the distribution of the groundwater resources in every catchment and provide a spatially explicit estimate of the volume of groundwater held in storage (ML) and a spatially explicit estimate of the volume of annual groundwater recharge (ML/year).

Catchment maps depicting the groundwater development potential are also appended, with the monitoring wells shown. The groundwater development potential maps are a qualitative assessment of the groundwater development potential and have been created by adding the aquifer productivity and the groundwater recharge potential maps together. They should be used in conjunction with the quantitative Aquifer Productivity, and Aquifer Recharge Potential maps.

We propose an initial distribution of the monitoring wells in the groundwater development potential maps. It should be noted that this distribution of monitoring wells needs to be ratified and accepted or changed at catchment and sub-catchment level, in line with local knowledge and local priorities. These catchment groundwater maps provide a basis by which groundwater monitoring and groundwater quantification can commence in the catchments.

The monitoring wells have been placed in order to cover areas of different groundwater development potential and also to give a fair spatial cover for each catchment. It must be appreciated that these are approximate localities. The final selection of the position of monitoring wells must be done with the catchment authorities. Monitoring wells will ideally be placed in the grounds of an institution, such as a clinic, school, local RDC office, police post or similar. This can help to provide some level of protection against vandalism.

It may be appropriate that a monitoring well is placed in the grounds of the catchment council or sub-catchment council offices at the start of the exercise of establishing groundwater monitoring. This may well have a motivational impact and allow catchment personnel to monitor water levels easily and thus start to get an understanding of the process itself and the value of the process. Wherever possible, it is helpful if daily rainfall can also be measured and recorded at the monitoring locality.

In addition, there will certainly be some local areas of concern or interest in the groundwater condition, for example, where the groundwater is abundant or where it is drying up or where the demand is very high or where the quality is poor or where there is an anthropogenic pollution threat. Such local information will guide the placement of the monitoring wells, and the recommended locations of monitoring wells may be changed in light of local conditions or new monitoring wells may be added as required.

It should be noted that this monitoring network does not cover the urban areas, which have become areas of very high demand. The Upper Manyame sub-catchment council has 20,945 registered boreholes for Harare, and the actual figure may be significantly higher. Anecdotal information from drilling companies is that in certain parts of Harare, groundwater levels have declined by 10 to 15 m, and drilling depths have increased from 40 to 60 m average to 80 to 150 m average in the Borrowdale area, where municipal water is rarely available. Given the scale of the urban groundwater challenge, this is flagged as an urgent priority. However, it is identified as a separate project from a national groundwater trend monitoring network.

For the national groundwater trend monitoring network, it is vital that each monitoring well has a unique ID and that the x, y and z coordinates are all captured accurately.

Design of monitoring wells: Trend monitoring wells should differ in construction from regular pumping wells. They are not pumping wells and they must not be pumped. They do not need to be drilled to depth to achieve high yields. They should end approximately 10m below the wet season rest water level (RWL) and 5 m below the late dry season rest water level. For granitic areas in the higher rainfall eastern parts of the country, 15m is often enough for monitoring well. A slightly deeper well around 20 m will be preferred if groundwater demand is high locally.

Obviously, in formations with deeper groundwater rest water levels, such as the sedimentary basins, the calcareous dolomite/limestone sequences and the metavolcanics, deeper monitoring boreholes will be required.

The finished borehole casing diameter should also be smaller, preferably less than 100mm, or even less than 75 mm. This will make it difficult for anyone to fit a pump, and thus preserve to the borehole for water level monitoring only. Water level monitoring boreholes should never be pumped. In addition to the smaller diameter, monitoring wells need to be constructed such that no water can flow down the sides of the casing into the borehole, thus giving a false picture of groundwater recharge. It is desirable if the top of the borehole is a little elevated (20 cms) above the surrounding ground so that run-off does not pond around the casing top. There should be a lockable lid to reduce tampering and theft of the data loggers that will be installed in the borehole. A bentonite seal is recommended from one meter below the surface down to about 3 m below the surface, which should ensure that there is no “false” recharge along the outside edge of the casing. In the illustration below, the screen is well below the RWL (Figure 76). Often for a monitoring well, the screen may be placed from the RWL down to the End Cap, one meter from the bottom of the hole.

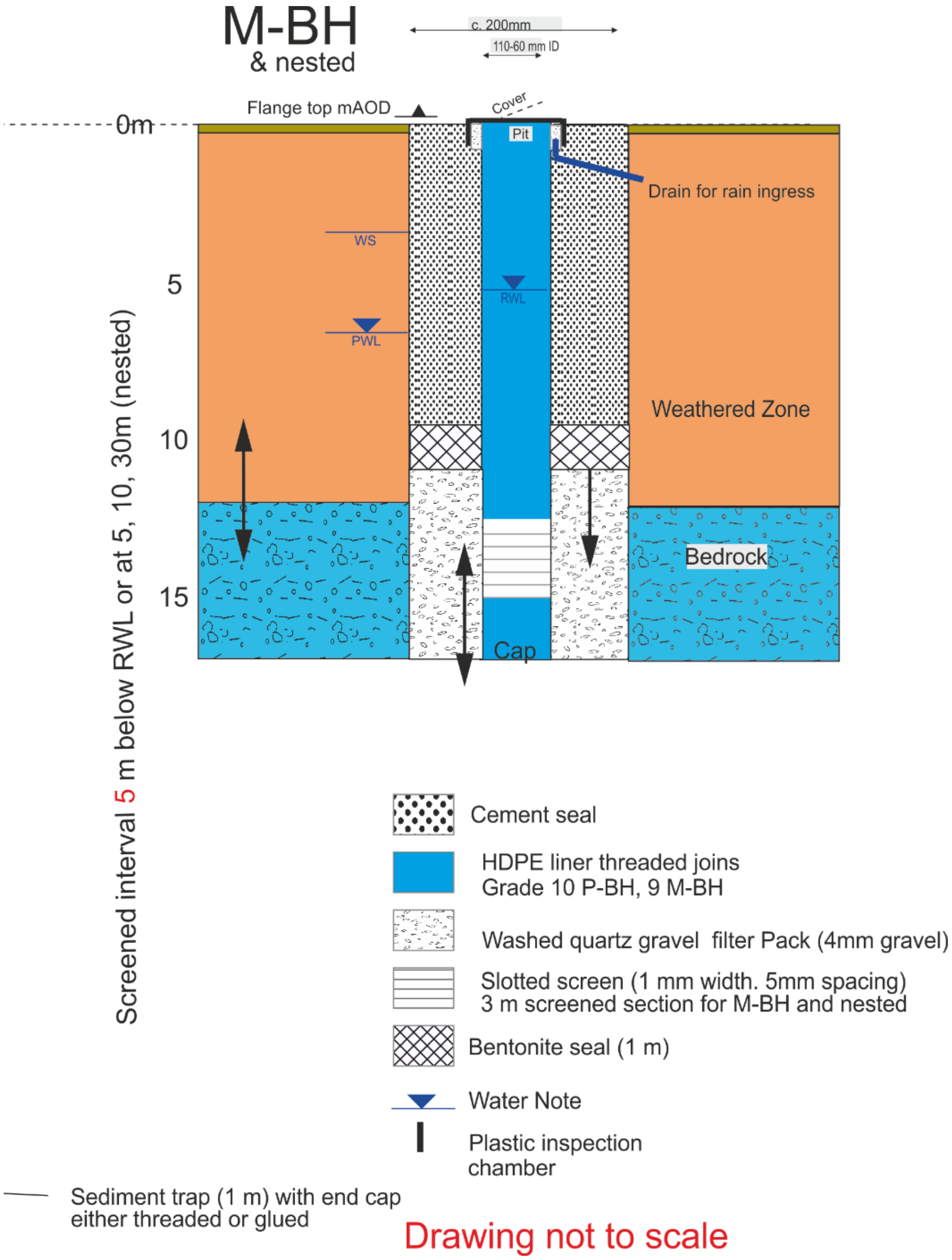


Figure 76: Typical design of a monitoring borehole

Groundwater level monitoring and data capture, storage, and use: Water level monitoring boreholes may be monitored manually using a dip-meter, but it is recommended that they be equipped with a data logger suspended in the borehole near the bottom of the well. Such data loggers may be set to record data on any time interval, but a daily or even weekly time-step will be appropriate for a national trend monitoring network.

Modern logging systems have loggers that allow the data to be downloaded remotely, but these are expensive, and it is anyway advisable to visit the monitoring stations annually and to dip the borehole with a manual dip-meter as a check. Modern loggers advertise that they can last for a million readings, but it will be safer to assume a 5-year lifespan.

The water level data needs to be captured in a properly designed database linked to a 3D spatial platform. This will allow the drawing of groundwater contours with time and also the calculation of volumetric recharge and discharge to the aquifer. The design of such a database and the linked 3D spatial platform is a specialized IT task that forms part of the process of developing a national trend monitoring network. Database development should be undertaken in conjunction with ZINWA Groundwater Division and with RWIMS to a) ensure compatibility with the existing systems and b) ensure that the relevant data fields are captured without overloading the database and making it unwieldy and difficult to use.

It is vital that groundwater levels be monitored, that the data be recorded and that it be stored safely in an appropriately designed database. However, all this work does not bear fruit until the data is processed and analysed and then disseminated, both to the technical-scientific community and to groundwater users and society in general.

The purpose of groundwater monitoring is to make groundwater visible to all users and society in general. Groundwater is a common pool resource and its effective management requires all users to be aware of threats to the resource and to participate in the management of the resource.

The database authority needs to make use of the incoming data to develop maps and time-series groundwater hydrographs showing the changes to the groundwater condition at the monitoring wells, to identify trends, and to propose management solutions.

Groundwater quality monitoring: It is not necessary, or even advisable to have a specific groundwater quality monitoring network, or even to use the water-level monitoring network, but rather to use existing pumped boreholes. The selection of such pumped boreholes should be done with care, and these boreholes upgraded where necessary, to avoid monitoring wells where there is ponding of water around the well, cracked and broken run-off aprons that will lead to well-head contamination. It is important that the aquifer water quality and contamination is monitored, rather than monitoring the effects of a local poorly constructed well.

By using pumped wells for groundwater quality monitoring, one is able to capture the ambient water quality, rather than locally stagnant water that may have accumulated around unpumped monitoring well.

The cost of a full water quality analysis can be high, and it is recommended that fewer boreholes be monitored for water quality trend monitoring. The focus should be on defensive and impact quality monitoring. It is preferable if a full water quality analysis can be carried out initially on all groundwater quality monitoring sites to provide a baseline and also to identify areas of concern for future monitoring. Thereafter, it should not be necessary to always carry out a full water quality analysis, but to rather focus on some field indicator tests, such as temperature (T), electrical conductivity (EC), pH, dissolved O_2 and turbidity.

In cases where there are bacteriological concerns, such as faecal coliforms and bacteria such as salmonella typhi and vibrio cholera, then such boreholes need to be either reserved for non-consumptive use, or water treatment infrastructure installed. Bacteriological water quality analysis always requires time, usually 24 hours, and laboratory conditions, to allow the bacteria colonies to multiply for analytical counting.

Below Figure 77 contains three Gwayi catchment groundwater maps: -

a. aquifer recharge potential,
b. aquifer productivity, and
c. development potential

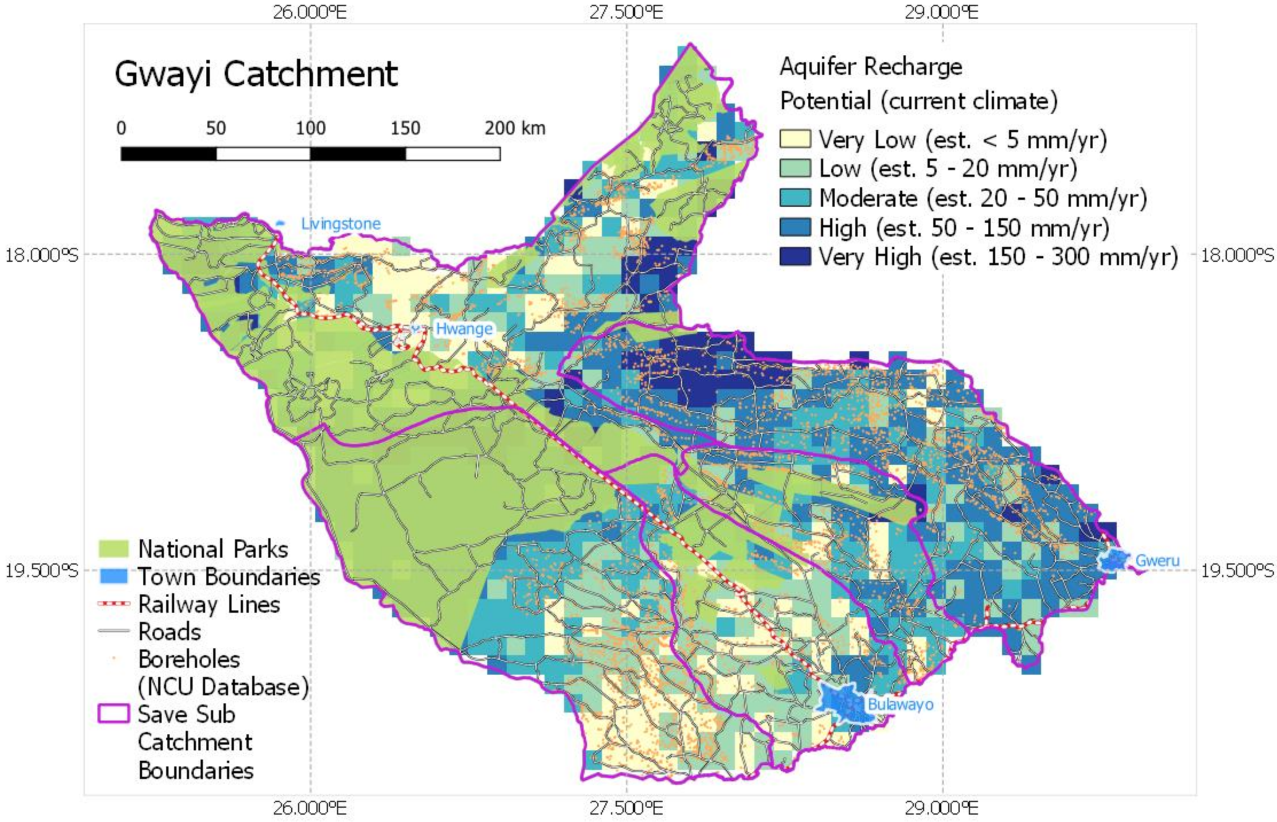


Figure 77 (a): Aquifer Recharge Potential

Note: Aquifer recharge has been estimated for direct recharge via rainfall. In all the catchments, and especially in Mzingwane and Runde catchments, there is significant "focused" recharge to alluvial channel sediments via annual streamflow – these are the so-called "sand rivers". Such recharge has not been captured in these maps but can be significant.

Table 27: Gwayi catchment aquifer recharge potential

Catchment	Category mm/year	Vol (ML) per km2/year	GW Recharge Volume (ML per km2/year)
Gwayi	Very Low (est. < 5mm/year)	5	63,111
	Low (est. 5 - 20mm/year)	5-20	230,015
	Moderate (est. 20 - 50mm/year)	20-50	719,161
	High (est. 50 - 150mm/year)	50-150	3,127,858
	Very High (est. 150 - 300mm/year)	150-300	1,545,677

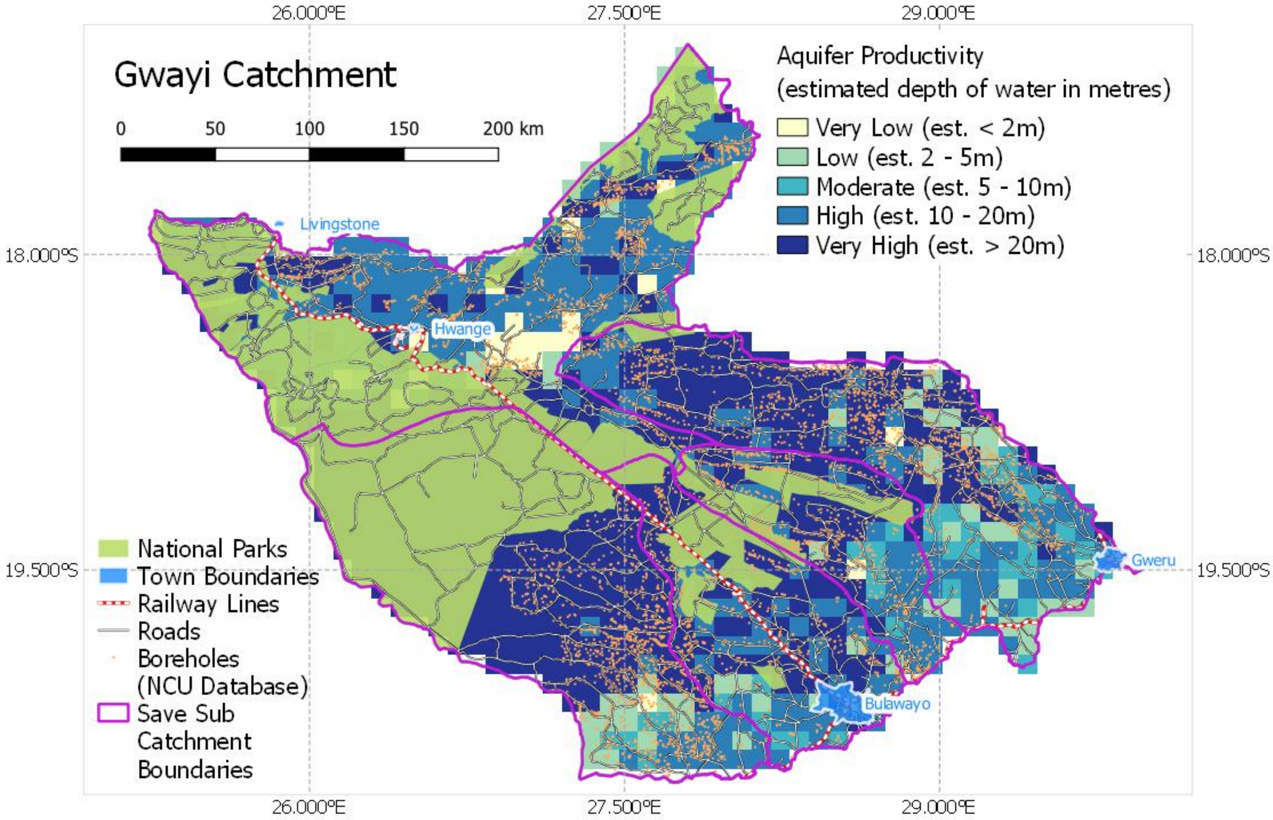


Figure 77 (b): Groundwater Volume in Storage

Table 28: Gwayi catchment groundwater Volume in Storage

Catchment	Category	Vol ML/km2	GW Storage Volume (ML)
Gwayi	Very Low (est. < 2m)	2,000	4,257,264
	Low (est. 2 - 5m)	2,000-5,000	18,841,032
	Moderate (est. 5 - 10m)	5,000-10,000	28,828,890
	High (est. 10 - 20m)	10,000-20,000	430,256,340
	Very High (est. > 20m)	>20,000	958,412,160

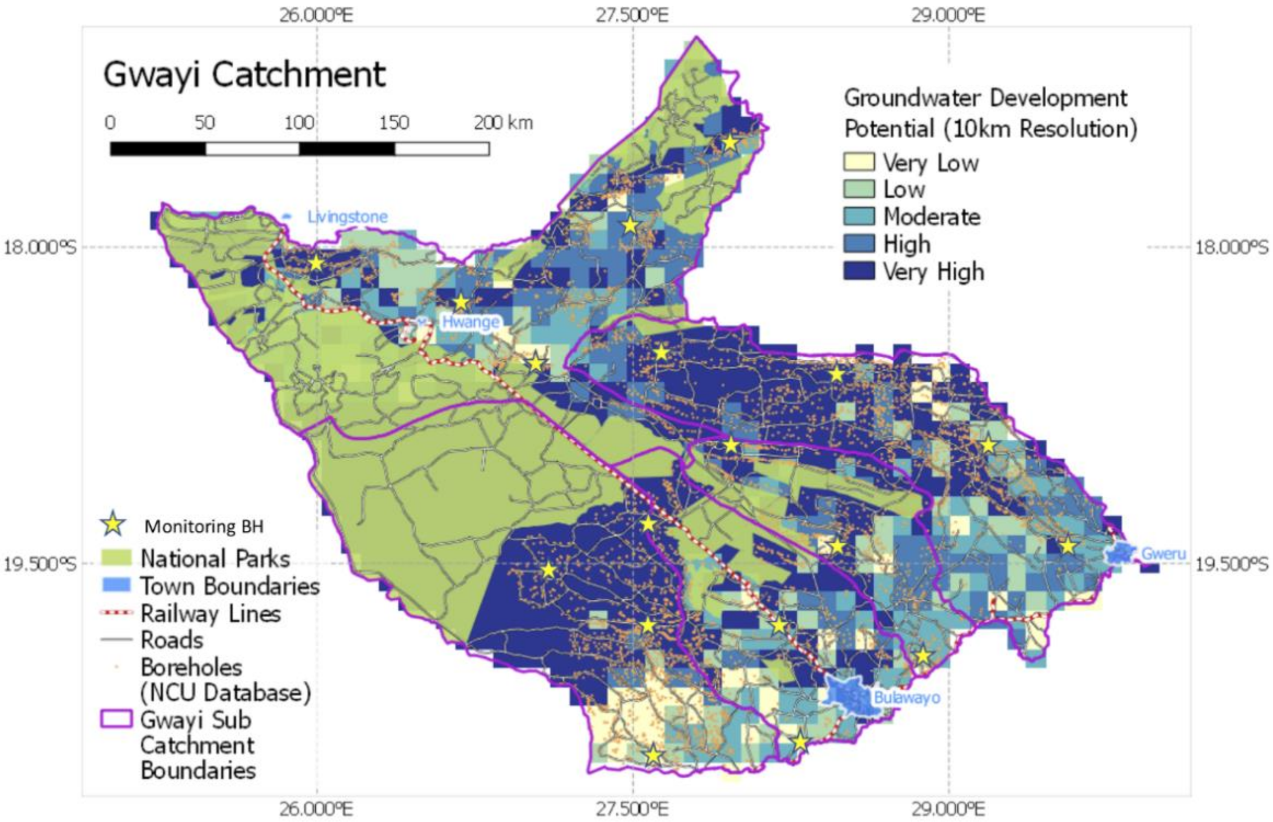


Figure 77 (c): Development potential

Figure 77: Gwayi catchment groundwater maps - (a) aquifer recharge potential, (b) aquifer productivity and (c) development potential

Figure 78: Manyame catchment groundwater maps - (a) aquifer recharge potential, (b) aquifer productivity and (c) development potential

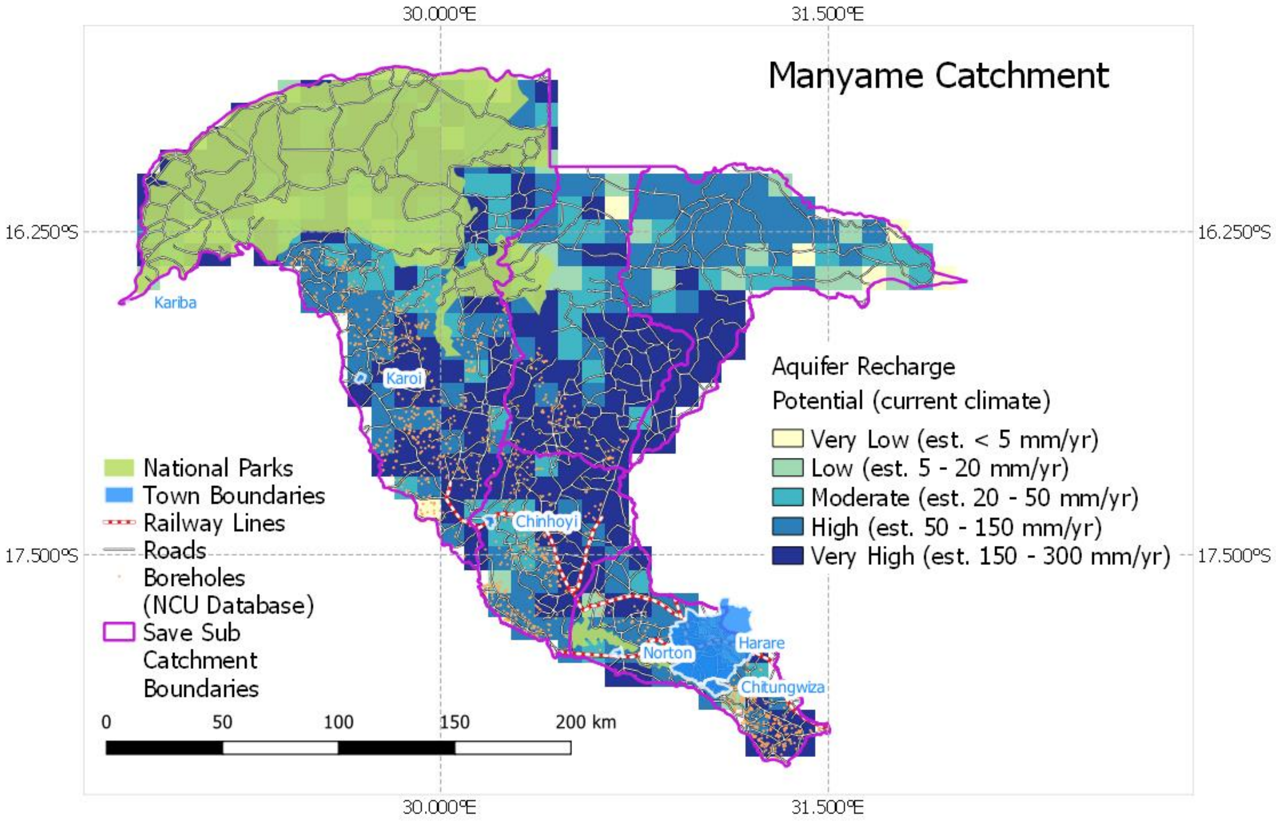


Figure 78 (a): Groundwater Volume in Storage

Table 29: Manyame catchment aquifer recharge potential

Catchment	Category	GW Recharge Volume (ML per km2/year)
Manyame	Very Low (est. < 5mm/year)	3,402
	Low (est. 5 - 20mm/year)	37,662
	Moderate (est. 20 - 50mm/year)	200,561
	High (est. 50 - 150mm/year)	1,320,607
	Very High (est. 150 - 300mm/year)	4,020,137

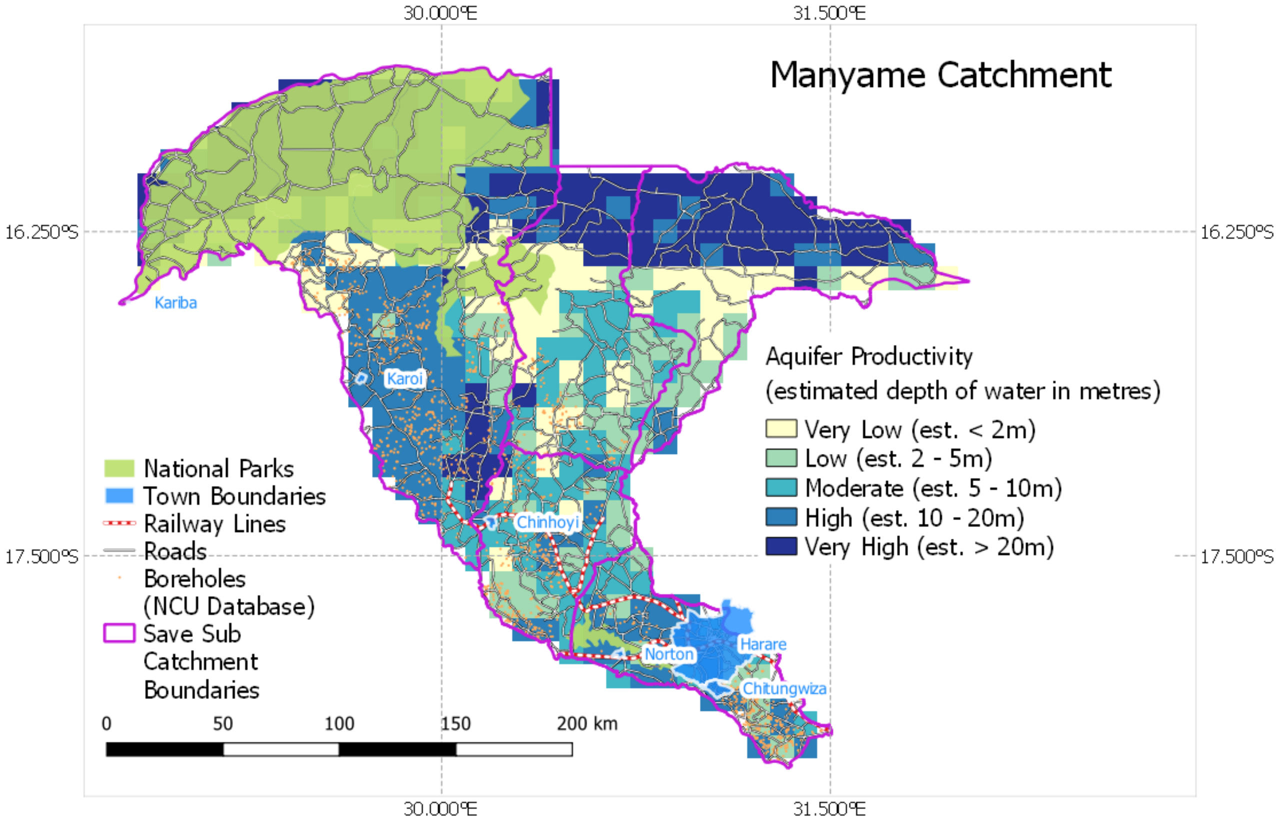


Figure 78 (c): Groundwater Volume in Storage

Table 30: Manyame catchment groundwater volume in storage

Catchment	Category	GW Storage Volume (ML)
Manyame	Very Low (est. < 2m)	14,352,137
	Low (est. 2 - 5m)	17,249,697
	Moderate (est. 5 - 10m)	44,222,724
	High (est. 10 - 20m)	177,194,624
	Very High (est. > 20m)	213,662,172

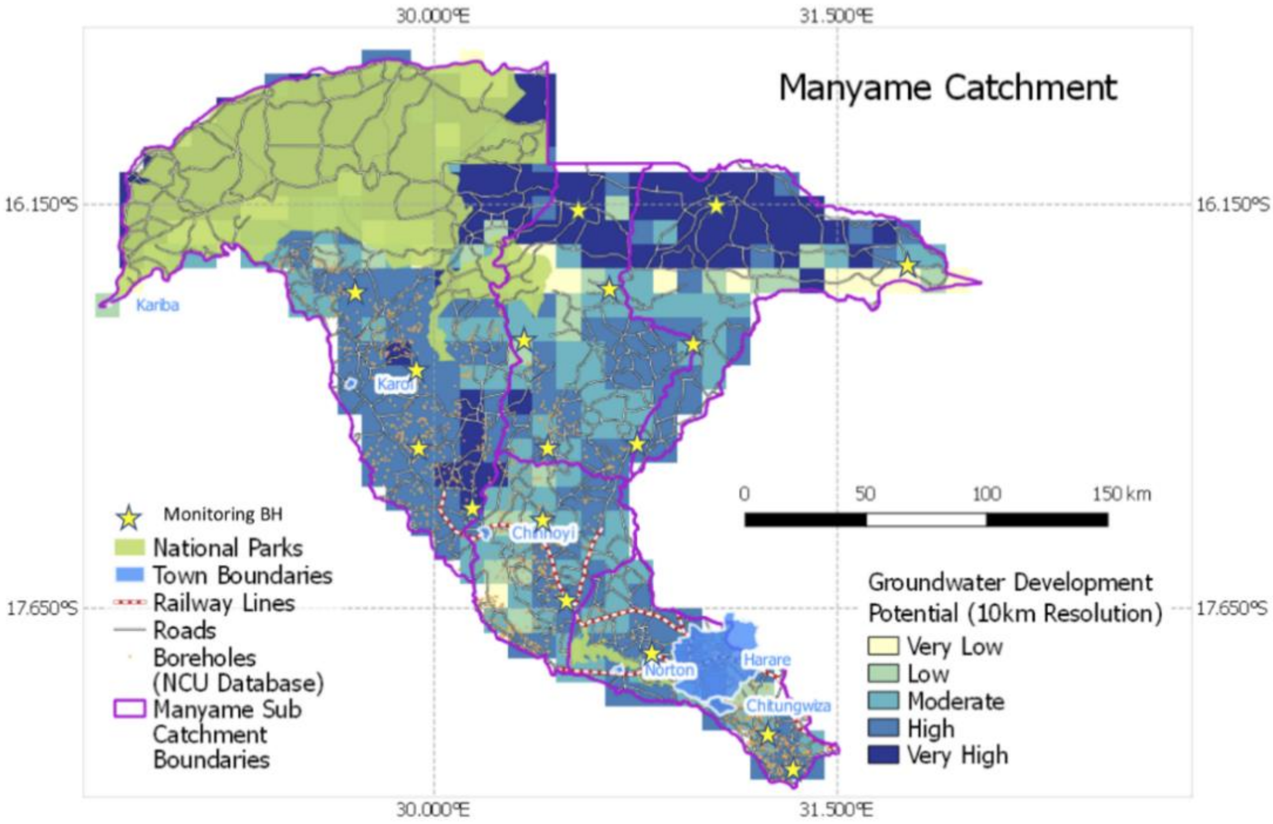


Figure 78 (c): Development Potential

Figure 79: Manyame catchment groundwater maps - (a) aquifer recharge potential, (b) aquifer productivity and (c) development potential

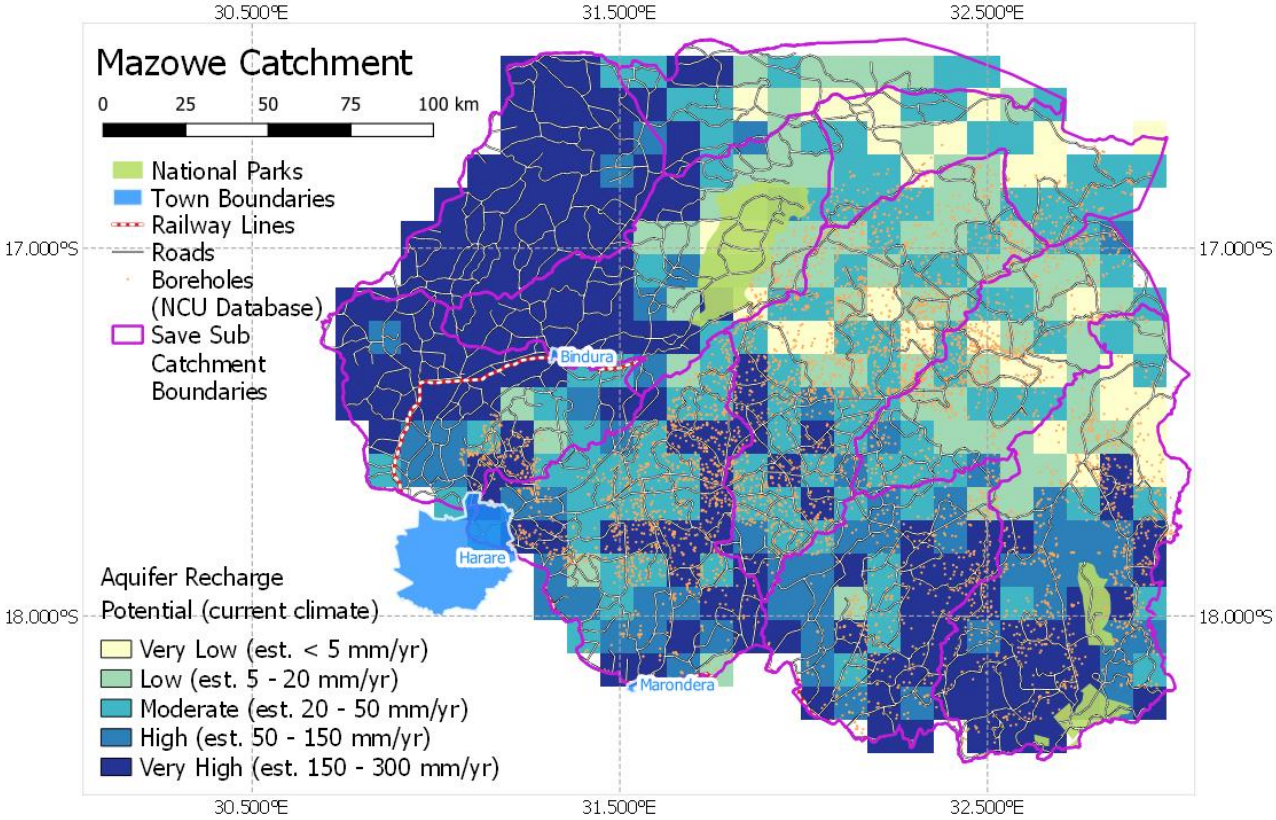


Figure 79 (a): Mazowe catchment aquifer recharge potential

Table 31: Mazowe catchment aquifer recharge potential

Catchment	Category	GW Recharge Volume (ML per km2/year)
Mazowe	Very Low (est. < 5mm/year)	13,628
	Low (est. 5 - 20mm/year)	79,870
	Moderate (est. 20 - 50mm/year)	361,413
	High (est. 50 - 150mm/year)	552,516
	Very High (est. 150 - 300mm/year)	3,144,260

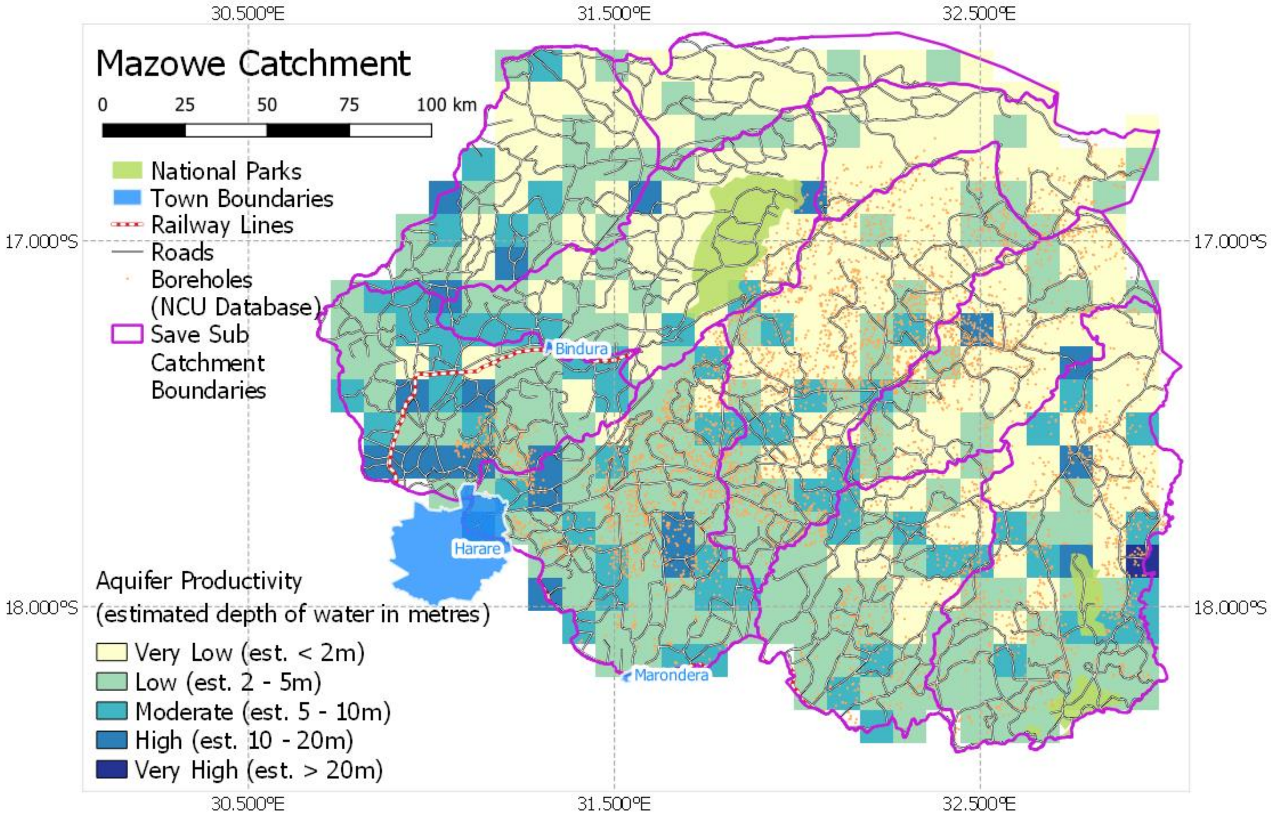


Figure 79 (b): Mazowe catchment groundwater volume in storage

Table 32: Mazowe catchment groundwater volume in storage

Catchment	Category	GW Storage Volume (ML)
Mazowe	Very Low (est. < 2m)	32,504,608
	Low (est. 2 - 5m)	51,500,023
	Moderate (est. 5 - 10m)	43,570,503
	High (est. 10 - 20m)	30,954,915
	Very High (est. > 20m)	1,868,976

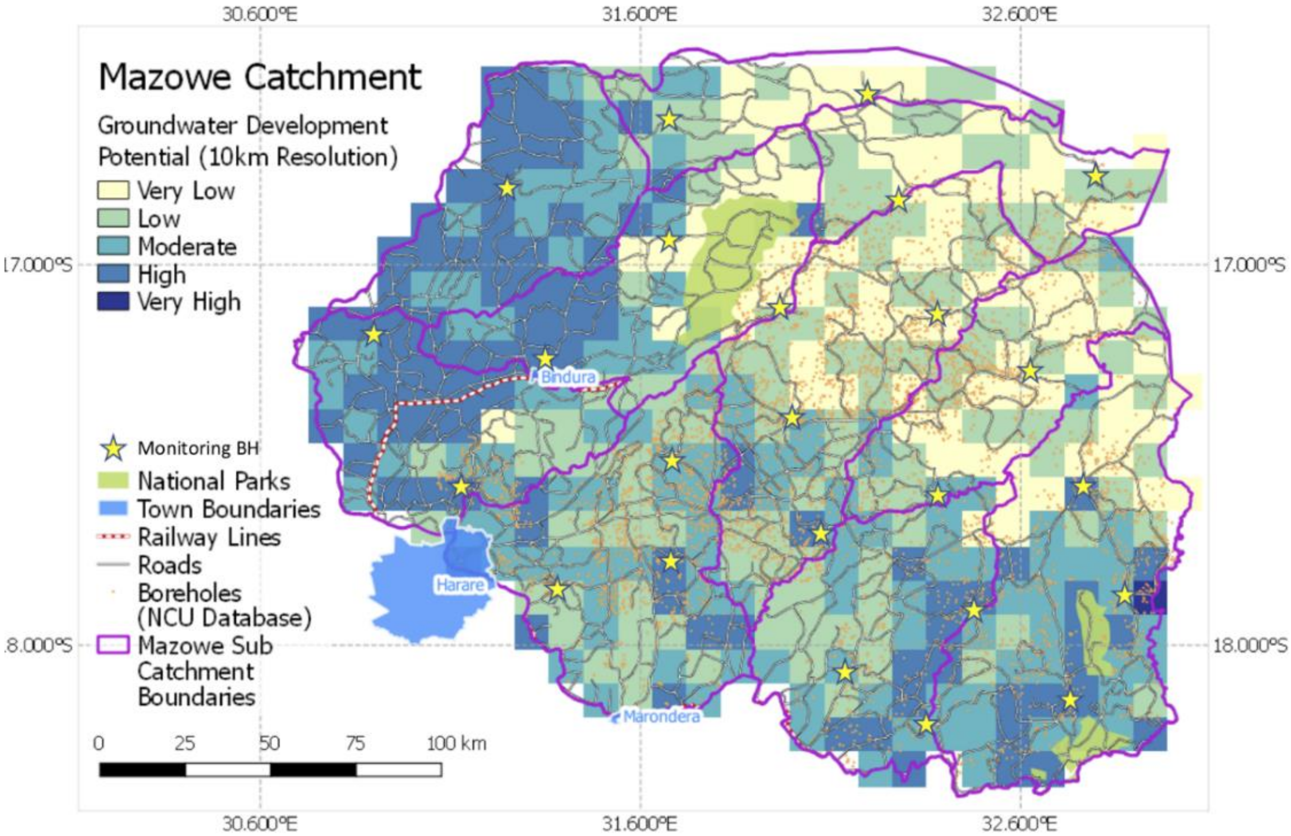


Figure 79 (c): Mazowe catchment Development Potential

Figure 80: Mazowe catchment groundwater maps - (a) aquifer recharge potential, (b) aquifer productivity and (c) development potential

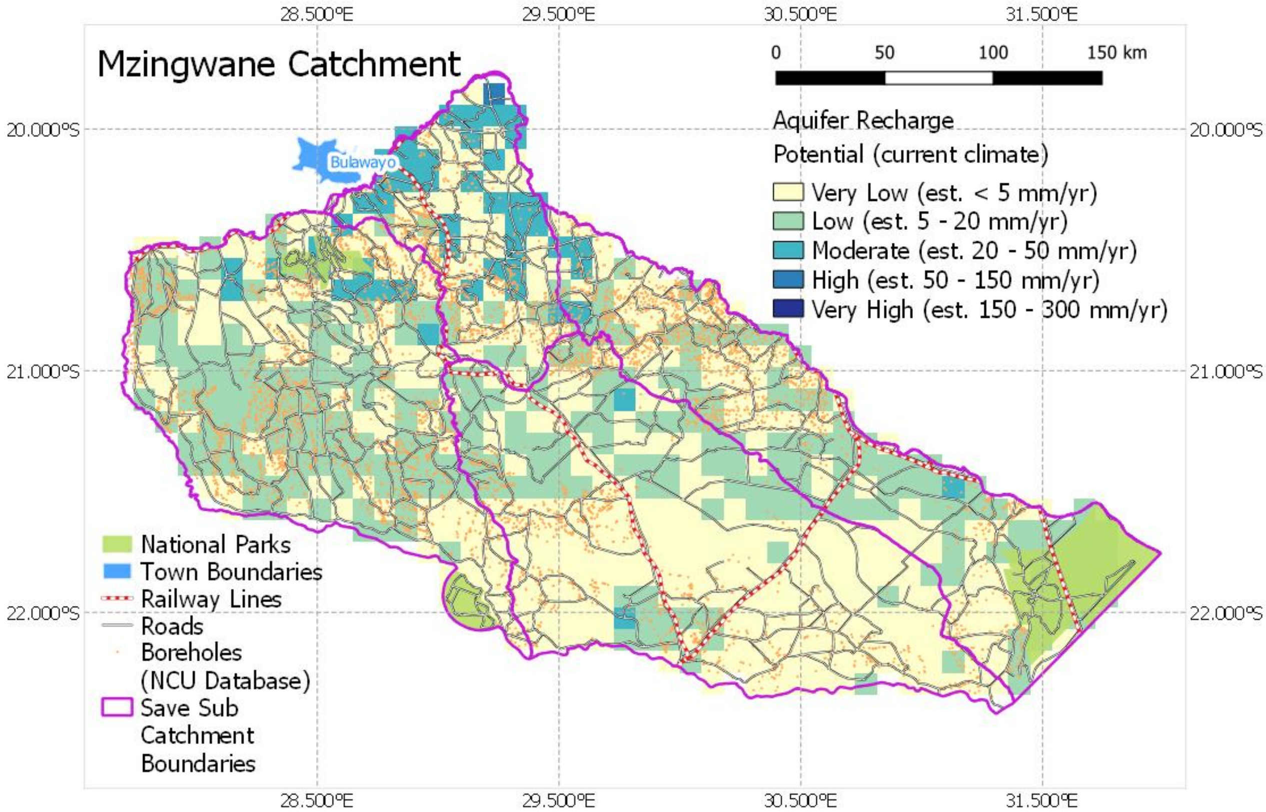


Figure 80 (a): Mzingwane catchment aquifer recharge potential

Table 33: Mzingwane catchment aquifer recharge potential

Catchment	Category	GW Recharge Volume (ML per km2/year)
Mzingwane	Very Low (est. < 5mm/year)	170,100
	Low (est. 5 - 20mm/year)	301,770
	Moderate (est. 20 - 50mm/year)	162,729
	High (est. 50 - 150mm/year)	18,900
	Very High (est. 150 - 300mm/year)	-

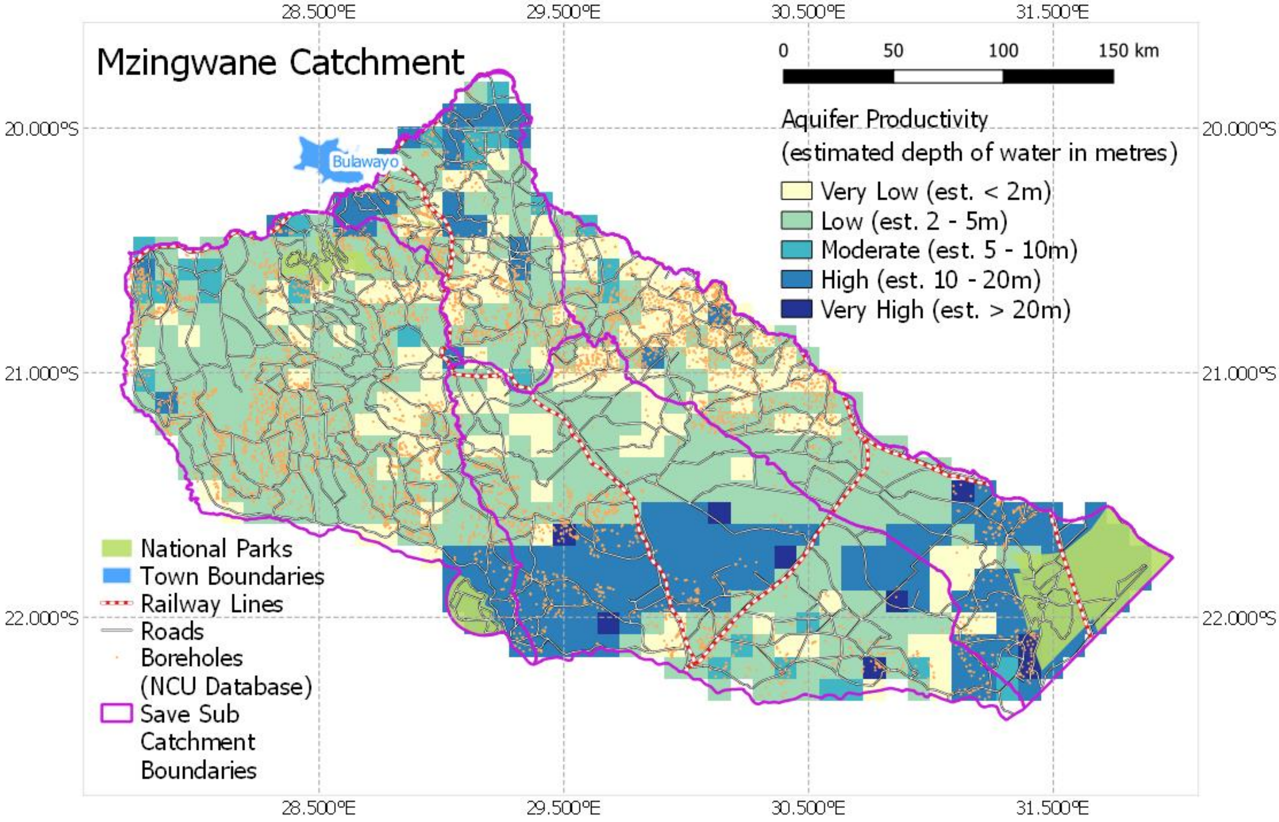


Figure 80 (b): Mzingwane catchment groundwater volume in storage

Table 34: Mzingwane catchment groundwater volume in storage

Catchment	Category	GW Storage Volume (ML)
Mzingwane	Very Low (est. < 2m)	24,330,600
	Low (est. 2 - 5m)	113,116,500
	Moderate (est. 5 - 10m)	19,797,750
	High (est. 10 - 20m)	225,571,500
	Very High (est. > 20m)	16,884,000

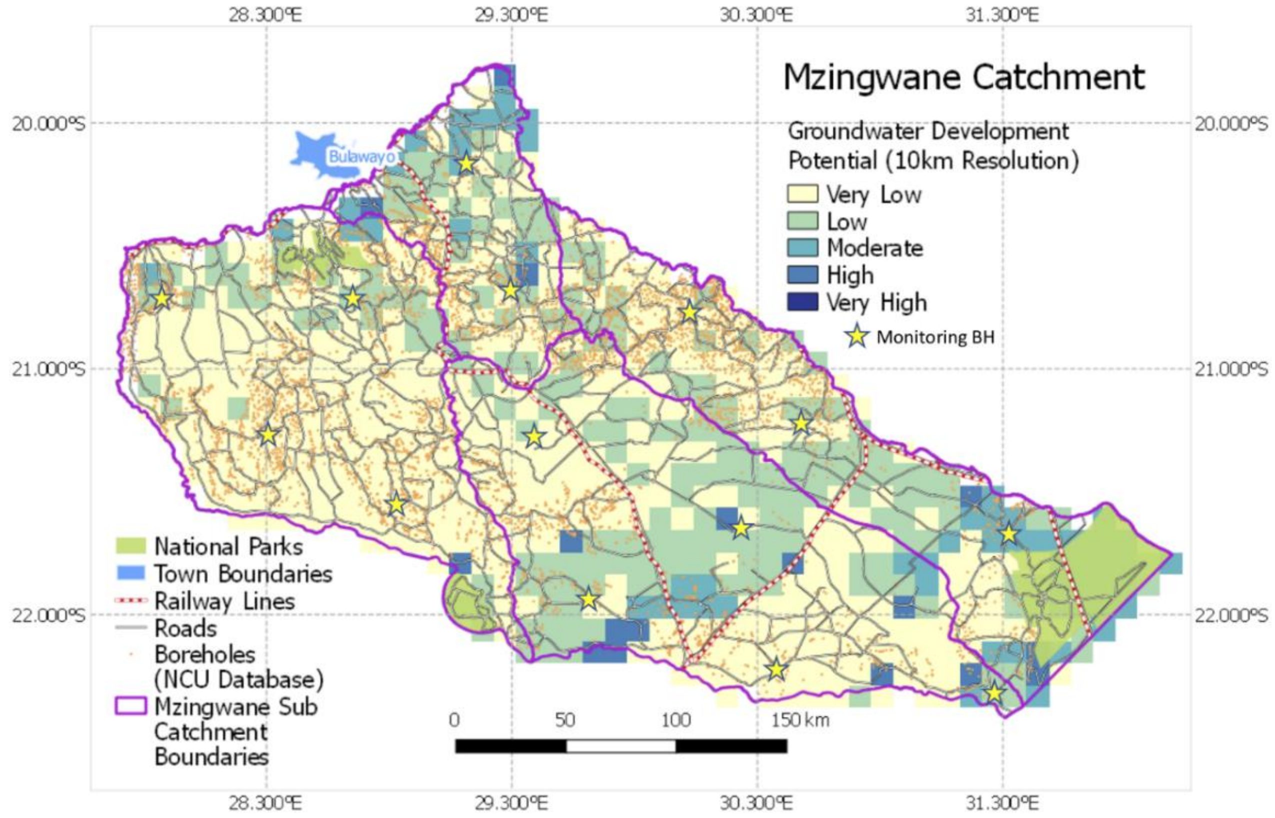


Figure 80 (c): Mzingwane catchment development potential

Figure 81: Mzingwane catchment groundwater maps - (a) aquifer recharge potential, (b) aquifer productivity and (c) development potential

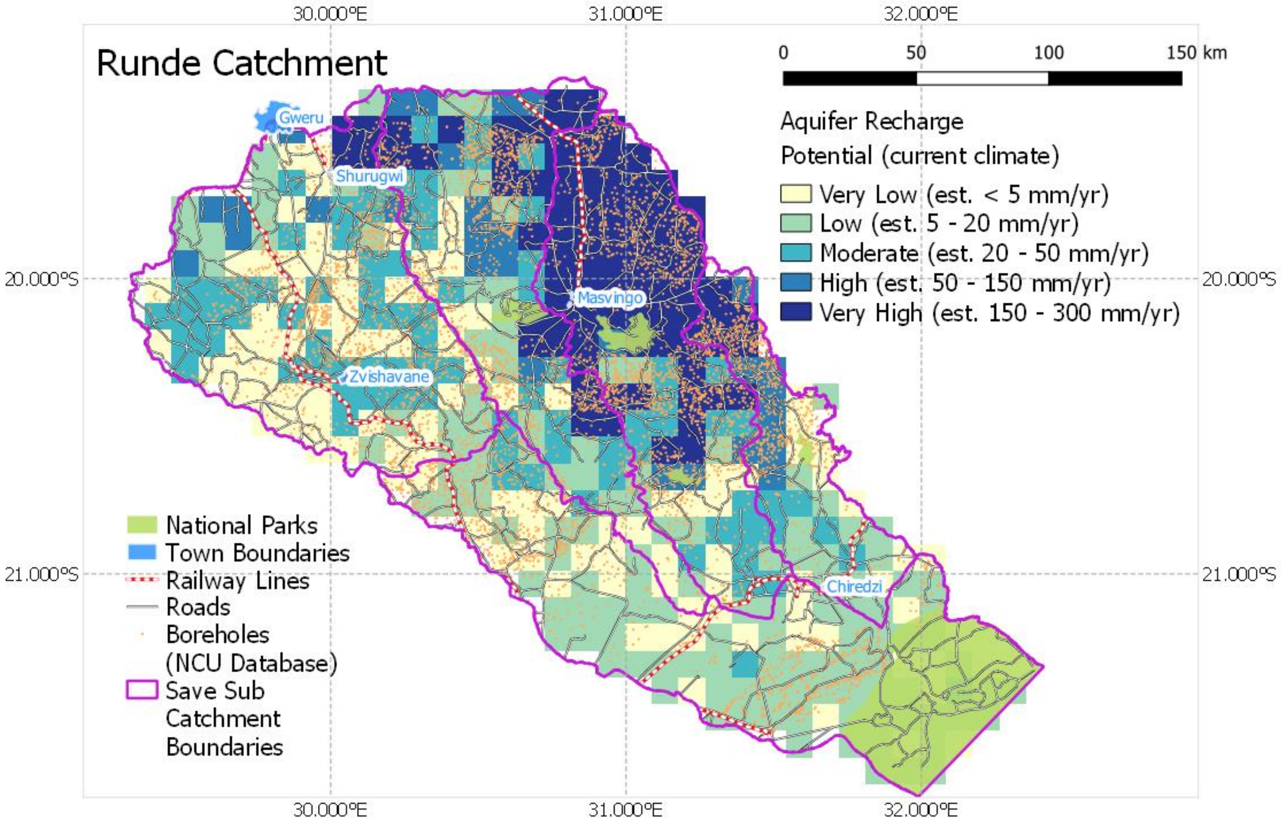


Figure 81 (a): Runde catchment aquifer recharge potential

Table 35: Runde catchment aquifer recharge potential

Catchment	Category	GW Recharge Volume (ML per km2/year)
Runde	Very Low (est. < 5mm/year)	52,172
	Low (est. 5 - 20mm/year)	151,503
	Moderate (est. 20 - 50mm/year)	279,360
	High (est. 50 - 150mm/year)	276,038
	Very High (est. 150 - 300mm/year)	1,735,900

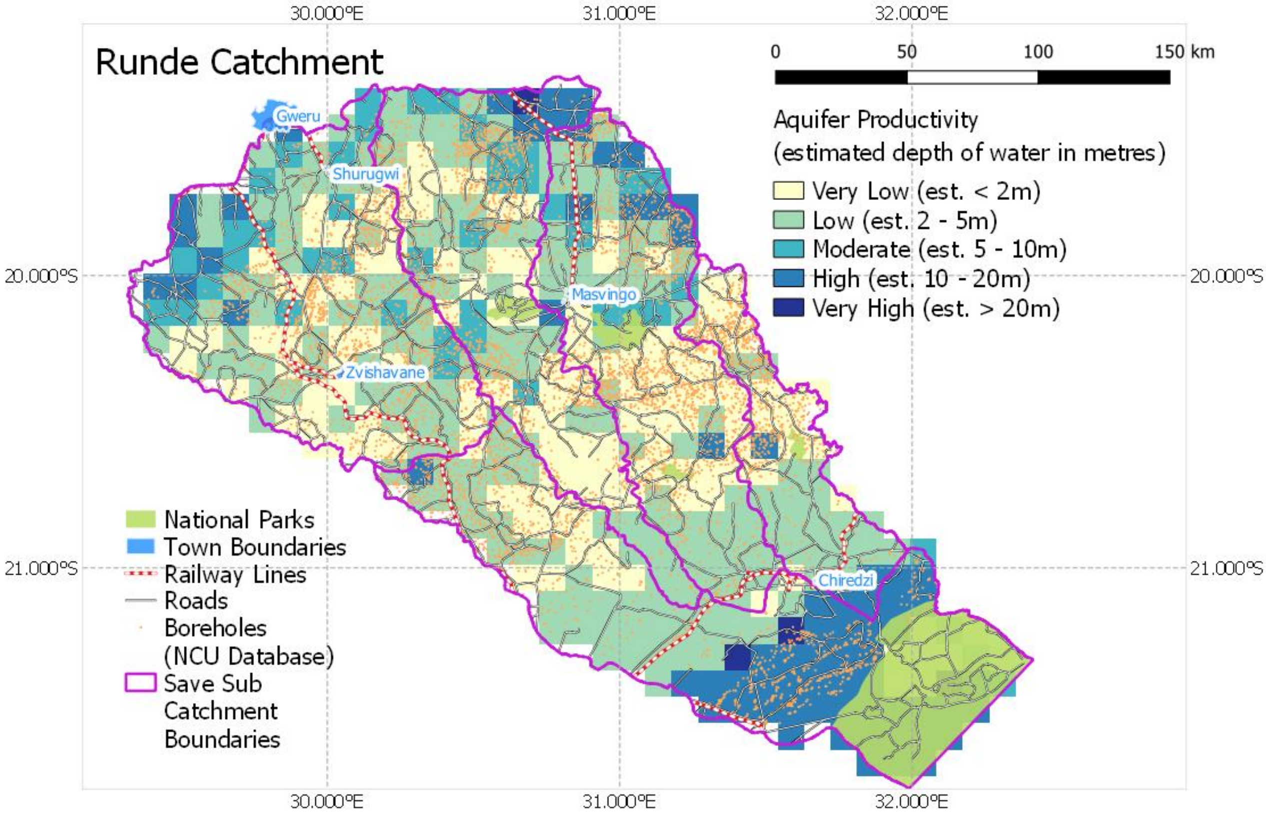


Figure 81 (b): Runde catchment groundwater volume in storage

Table 36: Runde catchment groundwater volume in storage

Catchment	Category	GW Storage Volume (ML)
Runde	Very Low (est. < 2m)	25,831,877
	Low (est. 2 - 5m)	60,149,964
	Moderate (est. 5 - 10m)	29,285,424
	High (est. 10 - 20m)	99,422,784
	Very High (est. > 20m)	7,546,944

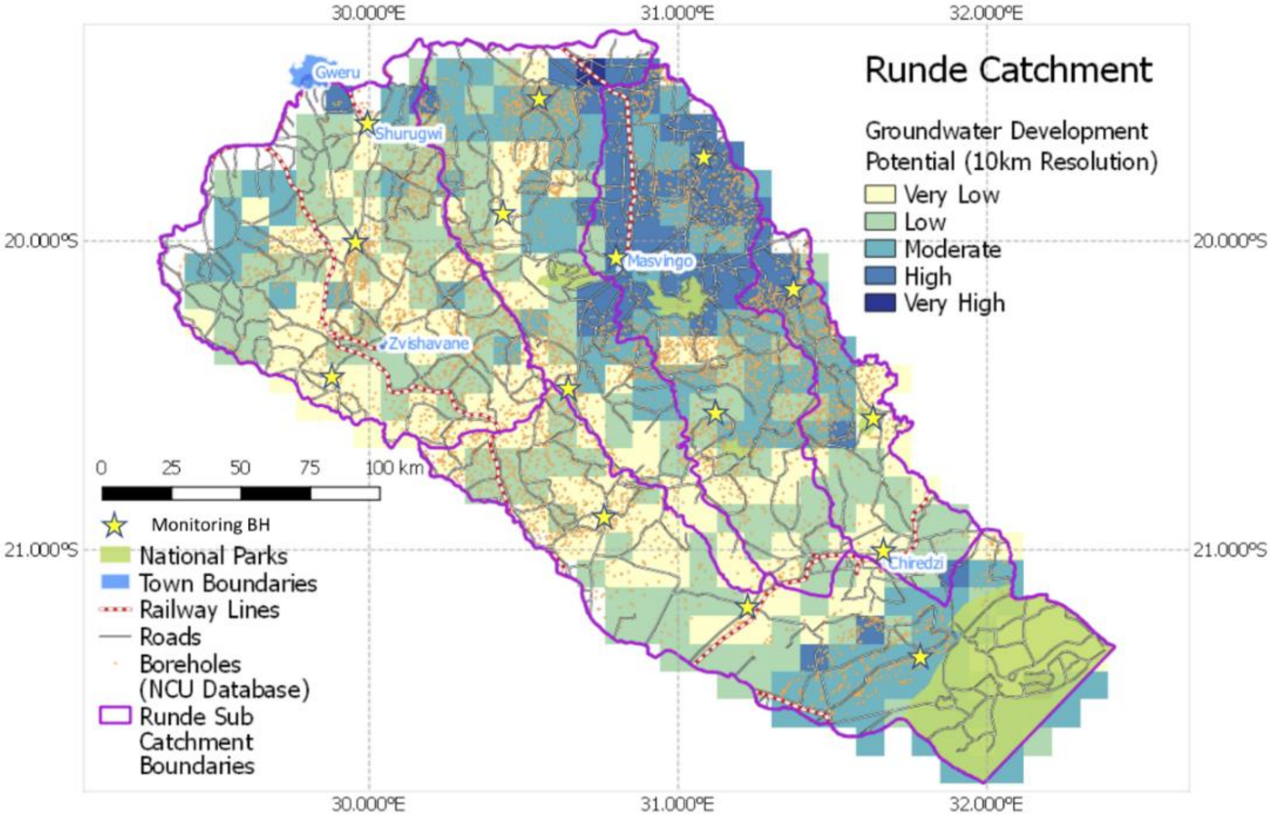


Figure 81 (c): Runde catchment development potential

Figure 82: Runde catchment groundwater maps - (a) aquifer recharge potential, (b) aquifer productivity and (c) development potential

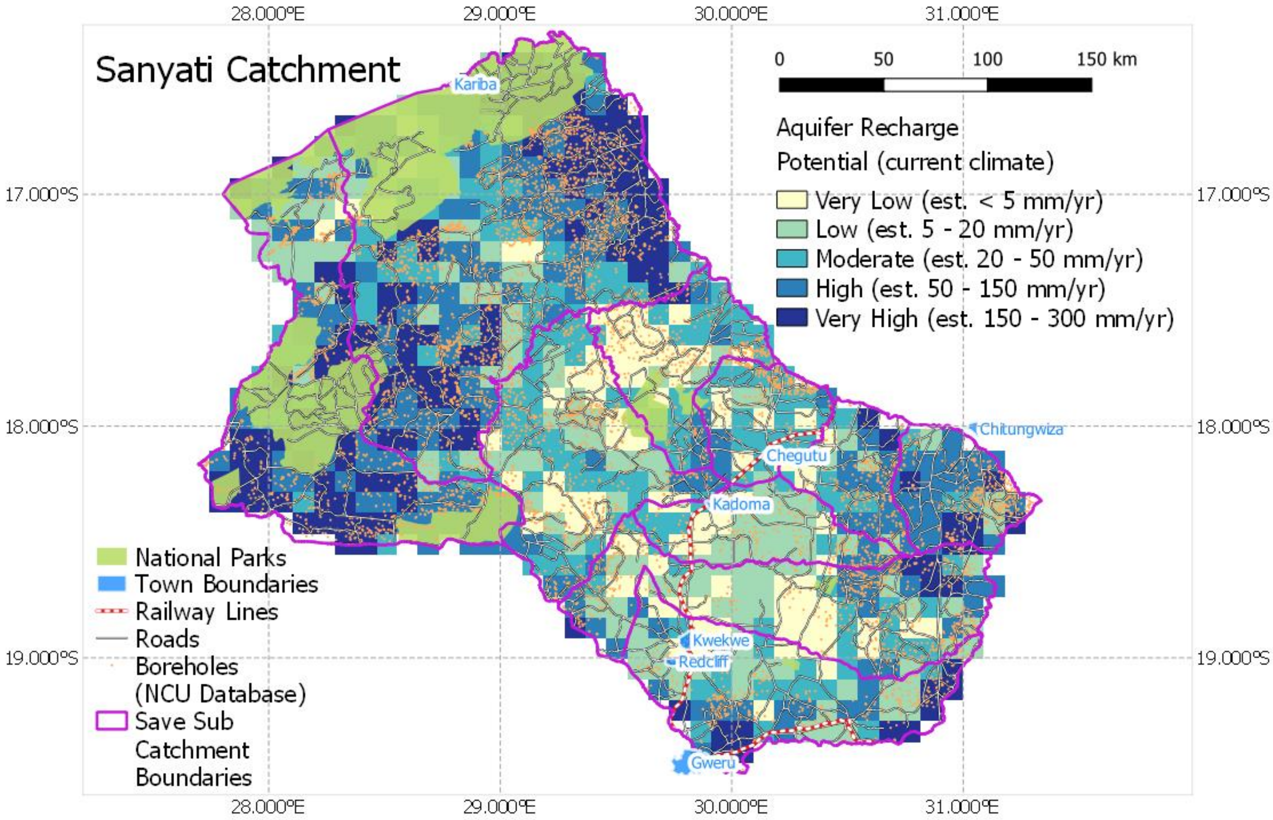


Figure 82 (a): Sanyati catchment aquifer recharge potential

Table 37: Sanyati catchment aquifer recharge potential

Catchment	Category	GW Recharge Volume (ML per km2/year)
Sanyati	Very Low (est. < 5mm/year)	43,145
	Low (est. 5 - 20mm/year)	173,834
	Moderate (est. 20 - 50mm/year)	527,480
	High (est. 50 - 150mm/year)	1,853,519
	Very High (est. 150 - 300mm/year)	3,243,306

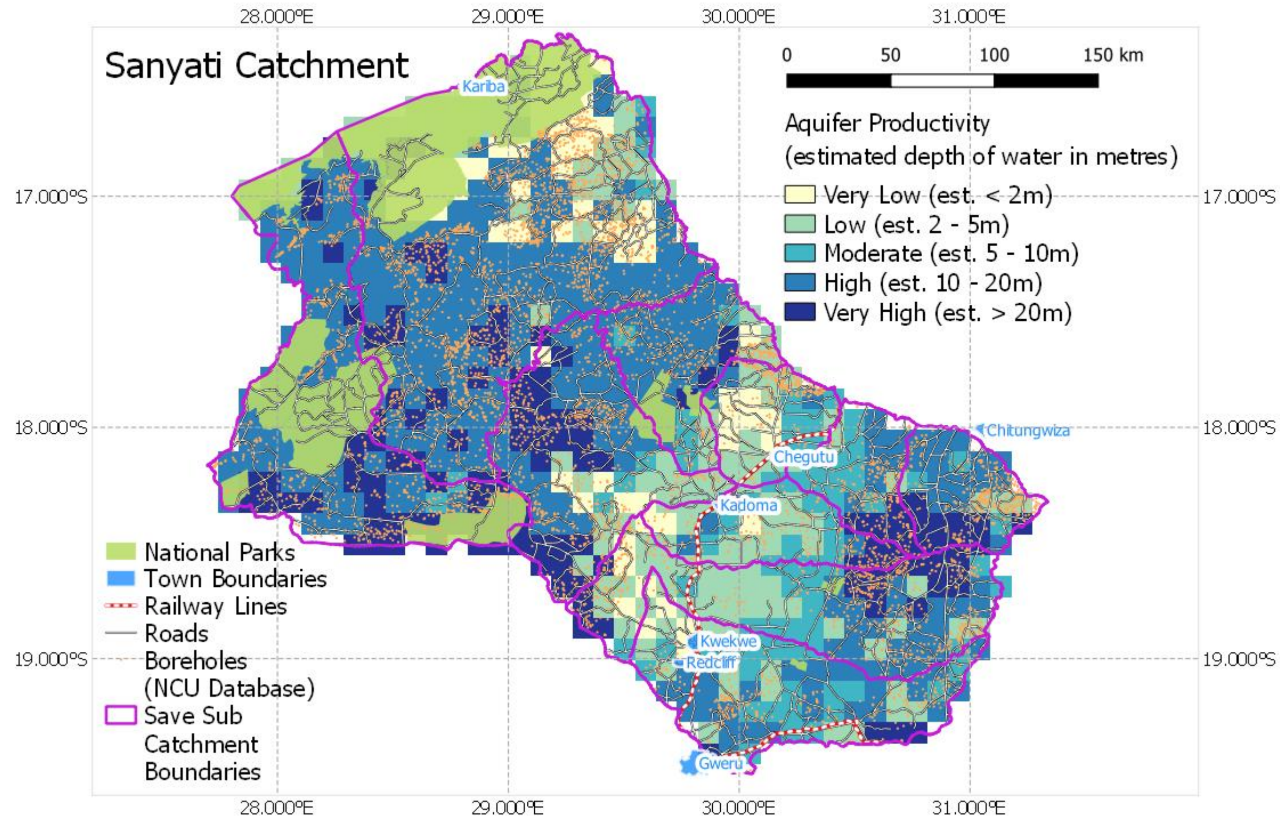


Figure 82 (b): Sanyati catchment groundwater volume in storage

Table 38: Sanyati catchment groundwater volume in storage

Catchment	Category	GW Storage Volume (ML)
Sanyati	Very Low (est. < 2m)	13,490,405
	Low (est. 2 - 5m)	44,672,854
	Moderate (est. 5 - 10m)	55,245,747
	High (est. 10 - 20m)	466,837,143
	Very High (est. > 20m)	251,181,173

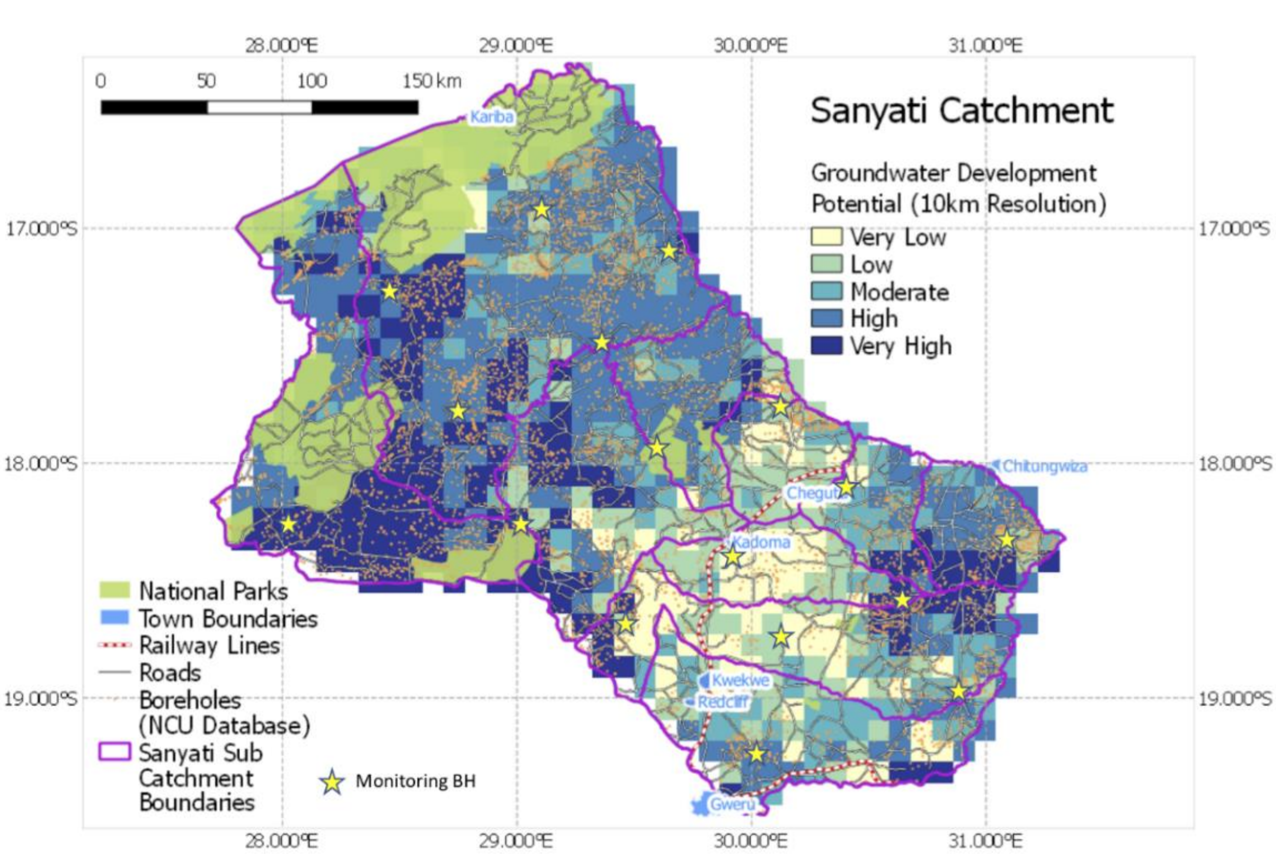


Figure 82 (c): Sanyati catchment development potential

Figure 83: Sanyati catchment groundwater maps - (a) aquifer recharge potential, (b) aquifer productivity and (c) development potential

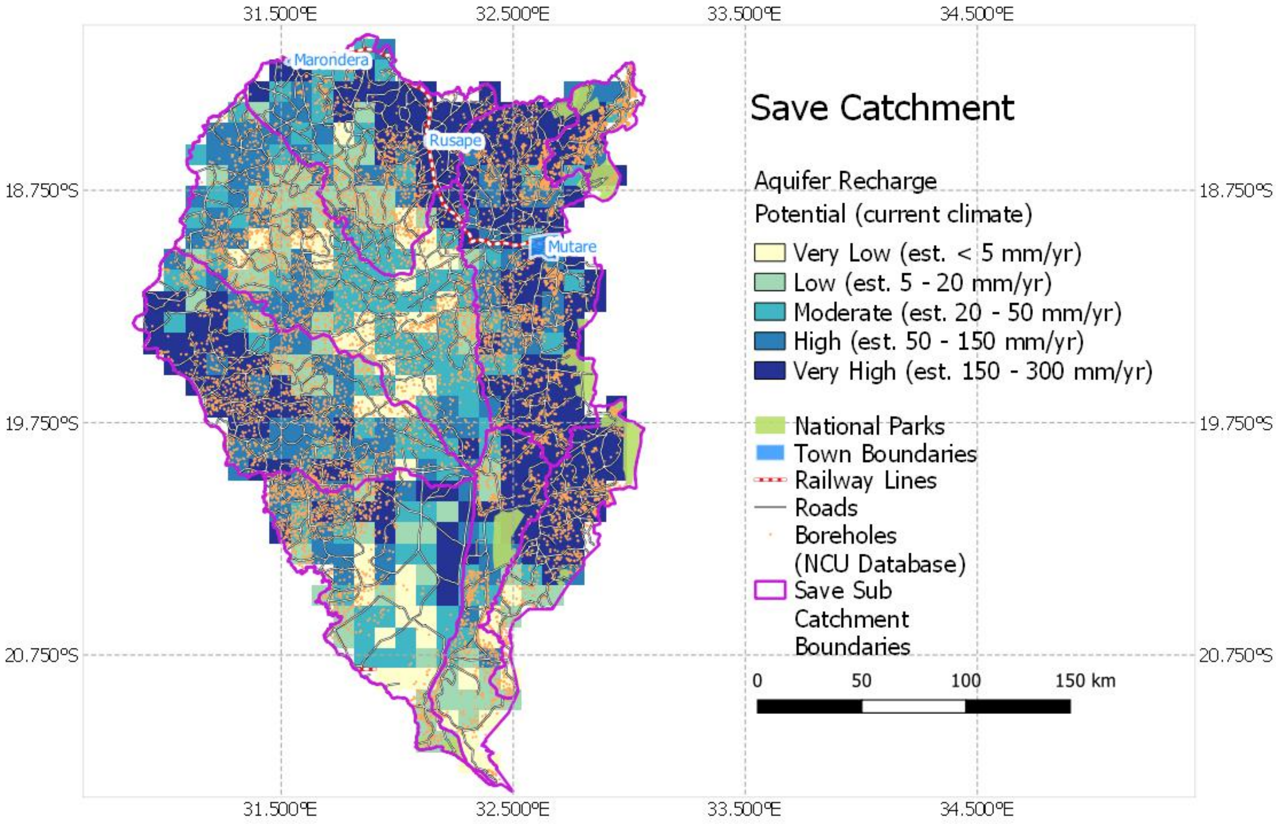


Figure 83 (a): Save catchment aquifer recharge potential

Table 39: Save catchment aquifer recharge potential

Catchment	Category	GW Recharge Volume (ML per km2/year)
Save	Very Low (est. < 5mm/year)	22,932
	Low (est. 5 - 20mm/year)	82,578
	Moderate (est. 20 - 50mm/year)	362,367
	High (est. 50 - 150mm/year)	1,055,338
	Very High (est. 150 - 300mm/year)	3,755,526

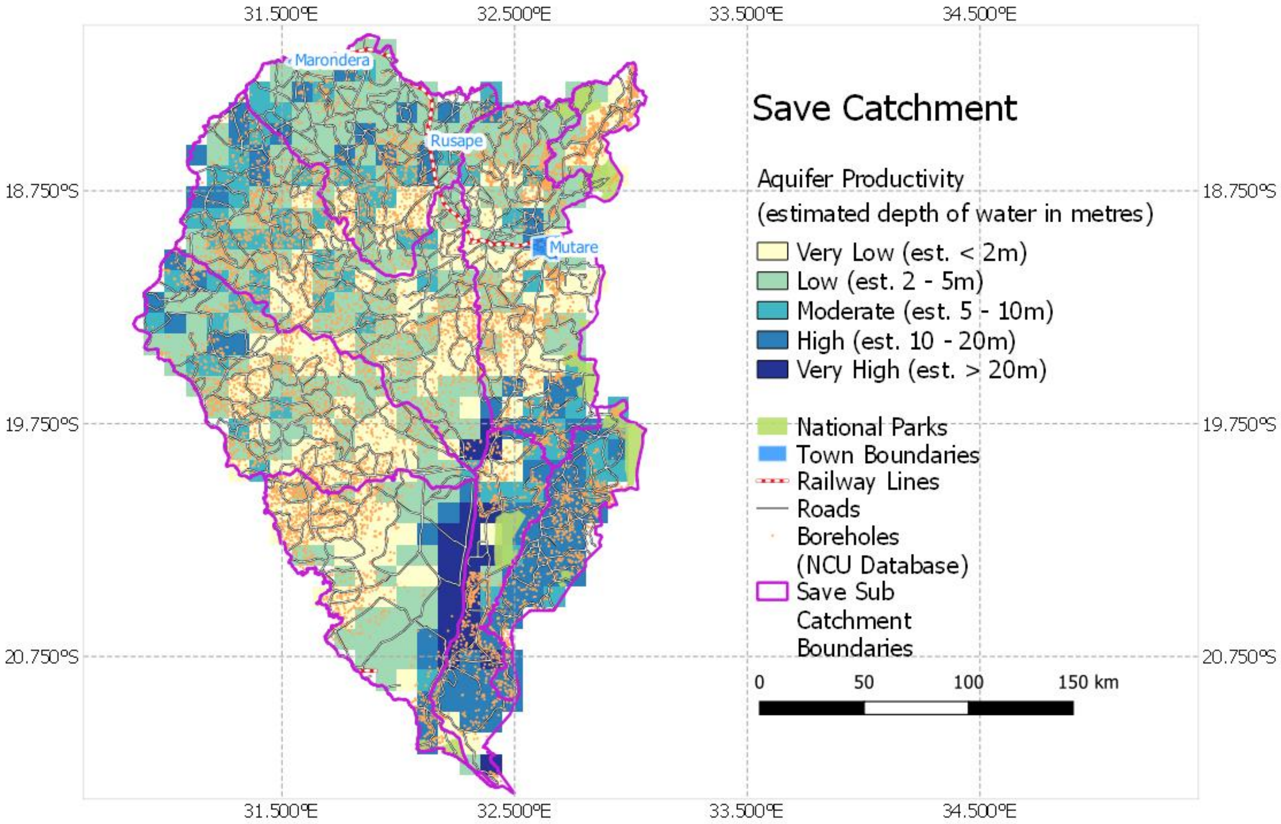


Figure 83 (b): Save catchment groundwater volume in storage

Table 40: Save catchment groundwater volume in storage

Catchment	Category	GW Storage Volume (ML)
Save	Very Low (est. < 2m)	26,581,059
	Low (est. 2 - 5m)	64,379,053
	Moderate (est. 5 - 10m)	51,742,315
	High (est. 10 - 20m)	121,707,879
	Very High (est. > 20m)	41,862,241

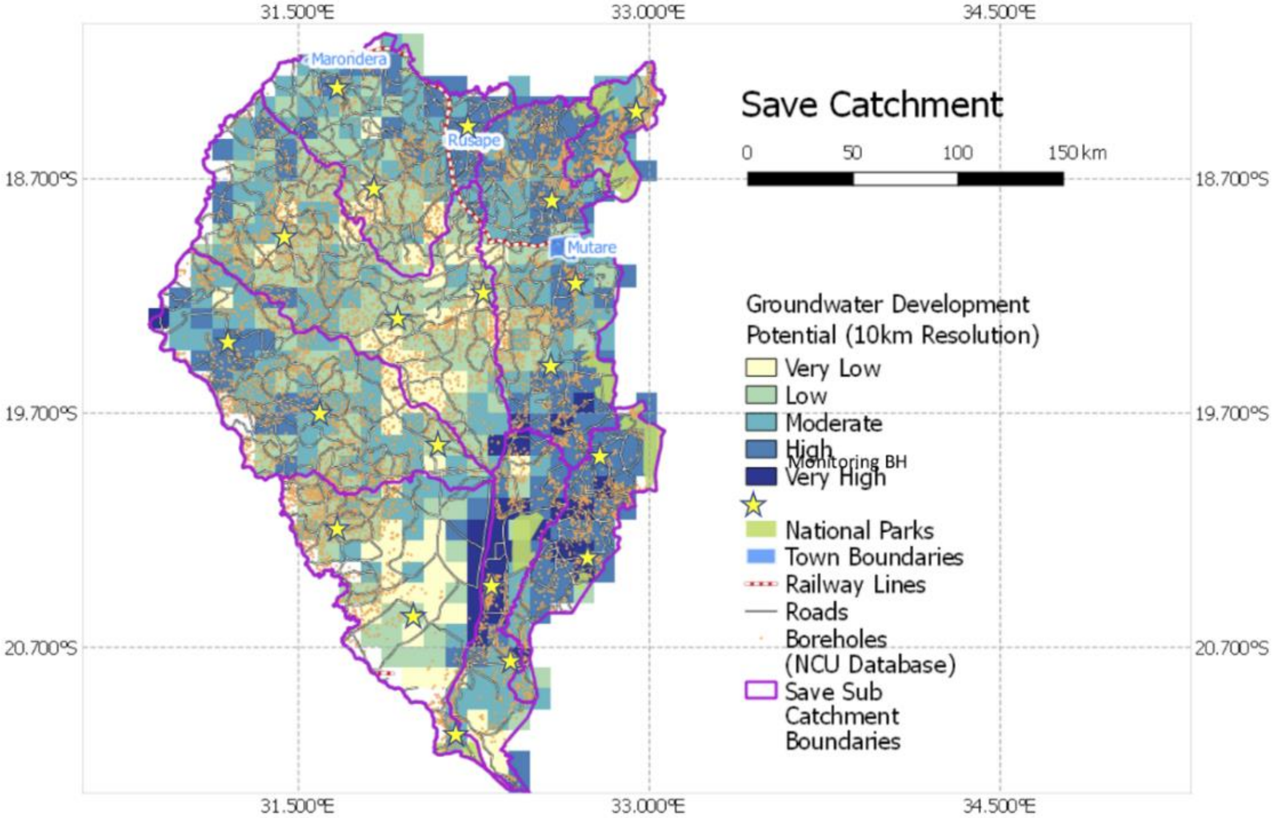


Figure 83 (c): Save catchment development potential

Figure 84: Save catchment groundwater maps - (a) aquifer recharge potential, (b) aquifer productivity and (c) development potential

ii. Project name: Develop and Implement Legislation for the Registration and Annual Licensing of Water Drilling Companies.

In recent times, a major problem identified in the groundwater sector in Zimbabwe is the very limited lifespan of many boreholes. Well drilled and constructed boreholes may be expected to have a lifespan of 30 to 50 years or more. This is particularly the case in hard rock areas where there is limited degradation and siltation from the borehole walls. However, the NCU has indicated that many boreholes have a far more limited lifespan, with many lasting less than five years. This represents a huge loss of infrastructure capital.

Various responses have been discussed and these fall into two categories:

a) Capacity building: Based on the Rural Water Supply Network (RWSN) training materials. Two courses, “Drilling Supervision” and “Cost-Effective Drilling”, have been identified and developed by SADC Groundwater Management Institute (GMI) and Africa Groundwater Network for delivery in the SADC region, including Zimbabwe. A pilot course on Drilling Supervision has already been delivered in Bloemfontein, South Africa, in April 2018. There appears to be a high demand for these courses.

b) Regulation: At present, drillers are not required to register with any authority. As a result, there is no legal instrument that the water sector can apply to ensure that drilling companies comply with the various guidelines and requirements of the sector. Many other countries have found that compulsory registration of drilling companies, with a requirement for annual renewal of registration, has provided a legal framework to regulate the drilling industry and to enforce compliance with a variety of reporting and drilling standards.

The combination of the availability of capacity development short courses together with the requirement for annual registration of drillers has been proposed as a potentially effective means of improving the quality and performance of the drilling sector, resulting in increased borehole lifespan.

If these short capacity development courses were to be officially recognized by the relevant authorities, then this would provide an incentive to both drilling companies and to drilling supervisors to undertake the training.

iii. Project name: Rationalization of Groundwater Data Management Systems and Creation of a National Hydrogeological Database System.

There are two groundwater data storage and management systems operating in Zimbabwe.

Rural Wash Information Management System (RWIMS) that is hosted by the National Coordination Unit (NCU). This database has approximately 60,000 boreholes and is directed towards borehole maintenance. Records can be viewed by district, by province and nationally. They may be displayed in a table, as statistics or in map view. The map view offers a view of functionality state, seasonality, water point committee or yield. In fact, there are almost no yield data. The tabulated data have a large number of fields that are useful in terms of borehole maintenance, such as pump type, water point committee contact details, ownership but have little data of hydrogeological significance. This is a functional and useful database for infrastructure maintenance.

a) ZINWA – Groundwater Database. By contrast, the ZINWA groundwater database does focus on more hydro geologically significant data such as well yield, rest water level, water strikes, specific capacity, geological formation. ZINWA also has databases for the three well fields: Nyamandlovu, Lomagundi, and Save. These databases have water level vs time data, but no abstraction data.

The ZINWA groundwater database consists of excel spreadsheets. The data has not been interpreted nor is it linked to any maps or hydrographs or any other interpreted hydrogeological information.

The development of a fully functional groundwater database is not a trivial undertaking. If carried out properly, such a database can provide a wealth of information about the formations drilled, well yields, groundwater recharge rates, water quality, abstraction rates, among other details. It can provide a platform for comprehensive integrated management of the groundwater resources. With foresight, a system can be developed that is compatible with the databases in neighbouring countries.

There is so much data that should be collected for a national groundwater database that it is important to structure it in such a way that it is user-friendly. Data for a national groundwater database will/should include the following:

- Borehole ID and x, y, and z location data;
- Borehole construction and completion data (depth, diameter, casing size, screens, sand filters depths, sanitary seal data, pump type, intake depth, rising main, headworks information, maintenance responsibility);
- Hydrogeological data (water strikes, rest water level, geological formations intersected with photos, blowing yield);
- Pumping test data (time/drawdown data, pumping water level, graphs of pumping test, specific capacity, hydraulic conductivity, specific yield/storativity, porosity, and recommended pumping rate);
- Geophysical data;
- Ownership and permit data;
- Hydraulic data (water levels over time, abstraction rates, rainfall data, hydrographs);
- Water quality data (physical, chemical and microbiological data); and
- Links to graphics, maps, borehole logs, hydrographs, geophysical profiles.

Clearly, such a volume of information can become confusing if it is not stored and presented in a well-structured way. It is recommended that separate sub-files be created and linked for each borehole identity and that a suite of key search information be identified. In this way, the database users can access the specific sections that are relevant to their information needs at that time.

Given the importance and the complexity of a complete groundwater database, it is recommended that a professional exercise be carried out to develop a functional groundwater database, to identify the various data fields required for the different aspects of groundwater management and resource protection, to develop management instruments for the acquisition of such data, to ensure compatibility with neighbouring database systems, to create routines for the automated generation of groundwater level hydrographs, groundwater contours, abstraction maps, and other useful hydrogeological information.

Such a database, if well managed, maintained and used proactively, will provide the platform for the management of the national groundwater resource.

iv. Project Name: Preparation of Groundwater Models for the Three Major Aquifer Systems (Lomagundi, Nyamandlovu and Save)

ZINWA manages three well fields: Lomagundi (dolomite/limestone), Nyamandlovu (Forest Sandstone) and Save (alluvial sands). These well fields are primarily developed for irrigation, although the Nyamandlovu well field is intermittently used for Bulawayo urban water supply in drought periods.

All three well fields are under high groundwater demand and they provide water for major irrigation developments. In light of the investments that have been and are being made based on these groundwater supplies, it is wise to investigate the capacity of these well-fields to sustainably supply the required water.

3D - Groundwater flow modelling is the recommended method for detailed aquifer investigations. It allows the spatial details of the hydrogeological units to be modelled together with the aquifer properties, hydraulic boundaries, inflows and outflows (including pumping) to the aquifer system and can be calibrated by comparing measured water levels with model water levels.

An active model that is updated regularly will allow the aquifer managers to track the aquifer performance against the water demand. Some areas of the aquifer may be underutilized, while others may be over-pumped. A model allows observation of such features. It can simulate the impact of different pumping regimes; it can be run under different climatic scenarios and predict the impact of climate change on aquifer water levels.

The initial model can provide a great deal of data about aquifer performance and its resilience under different abstraction rates and climatic conditions. However, it is important to regularly update the model and run it again to confirm that it is still simulating and converges with the actual measured data. In this way, it provides a long-term useful management tool. It is recommended that groundwater flow and water balance models be constructed for the three well-fields.

v) Project Name: Upgrading of existing high yielding boreholes with solar power for pumping.

There are approx 1500 boreholes in the Zinwa groundwater database that have blowing yields greater than 3 litres/sec (10.8 m^3/hour) – see Table 4 page 42. It is proposed as a national project that many of these boreholes can be upgraded with solar pumping systems.

The requirements would be to first determine if there is a demand and also an economic benefit for additional water supplies at each of these wells. If there is, then each well must be pumped for a 5-hour basic yield test to determine if it still has sufficient yield, > 3 litres/sec, to warrant being upgraded to solar pumping. Those wells that meet these two requirements may be upgraded, thus providing a site for local economic activity such as gardening, brick making, livestock fattening etc.

The costs of such upgrading per site would consist of a pumping test and then installation of the solar pumping system including protection from vandalism and theft. Costs are given in the economic analysis in the next section.

6.2 OTHER GROUNDWATER DEVELOPMENT ACTIVITIES

The activities listed below are not defined as specific "projects" and may. be more considered as possible areas of focus that arise out of the NWRMP.

i. Family wells

In the crystalline basement rock areas, and particularly in the extensive granite and granitic gneiss areas, the groundwater levels are relatively shallow, generally less than 10 m below the surface. These shallow water tables are more predominant in the higher rainfall north-eastern parts of the country. Such shallow water tables make it quite feasible to develop groundwater by the construction of hand-dug wells. Such hand-dug wells are traditional practice in these areas of shallow groundwater. The upgraded family wells program was designed to support these existing traditional practices, through a self-help scheme of upgrading these family wells to reduce their susceptibility to bacterial contamination.

The following description is taken from the British Geological Survey website: http://earthwise.bgs.ac.uk/index.php/Case_Study_Zimbabwe_Family_Well_Upgrading.

In the late 1980s, the Zimbabwe Government's National Institute of Health Research (NIHR) showed that improving existing family wells could indeed reduce the risk of well water contamination. They showed that bacterial load in well water could be reduced if the following changes were made compared to traditional hand-dug wells:

- Brick-lined wells;
- Narrower wells;
- Use of covers;
- Raising buckets and ropes off the ground;
- Guiding rainfall-runoff away from the well opening; and
- Installing robust sanitary aprons around the wells to prevent any seepage of contaminated water through cracks into the well.

In 1988, the NIHR started a demonstration scheme for the rigorous upgrading of existing family wells, with the backing of the Environmental Health Department and showed that not only did these improvements increase the safety of well water, but that improving existing wells was cheaper than constructing new ones. Families had to fund the digging and lining of the well shaft themselves, but they were supported by a subsidy from the Government (with donor funding) to cover the costs of cement, tin well covers and a windlass (commercially made at the time).

The NIHR/Mvuramanzi Trust alone upgraded over 38,000 family wells in the first part of the 1990s, and the efforts of other agencies may have brought the total to nearly 50,000. Morgan et al. (1996) estimated that the cost to government of providing water to a family had been cheaper using this method than any other. Moreover, the maintenance burden of family wells is entirely carried by the user family. Family wells are a traditional water resource development strategy and supporting the upgrading of such wells has already been proven as acceptable to the community and successful at providing both domestic water and water for home nutrition gardens (Morgan et al. 1996) (Figure 84).

Figure 85: An upgraded family well

It is recommended that ZINWA/Government of Zimbabwe review the Upgraded Family Well programme of the NIHR/Mvuramanzi Trust and revive it in areas where it is appropriate and welcomed by the user communities.

ii. NGADI gardens

The Nutrition Gardens and Groundwater Development (NGADI) Project was developed in the mid-1990s based on experimental work done by the United Kingdom's Overseas Development Administration (ODA) from 1992-1996 in southern Zimbabwe. The project focused on the development of groundwater resources from the crystalline basement aquifer using collector well technology with a view to providing sustainable irrigation water for community nutrition gardens (Lovell et al., 1996).

The NGADI pilot project was carried out in the Romwe area and successfully showed that with careful site selection and monitoring, there are localities in the crystalline basement aquifer that can support small scale nutrition gardens. The Romwe garden provided not only nutritional support to the Romwe villagers, but also provided a cash surplus generated from sales of fresh produce from the garden to neighbouring communities.

Other communities in the area expressed interest in similar developments within their areas and, as a result, the NGADI project proposals were developed. NGADI proposed that initially 100 similar gardens, based on widely distributed groundwater sources to avoid aquifer depletion, be developed at favourable groundwater localities. These groundwater localities may be existing high yield boreholes or newly developed sites. NGADI envisaged technical support with regards to groundwater development and community input with regards to the development of the nutrition gardens, supported by institutional guidance from, e.g. AGRITEX.

In the recommendations section of the final project report (Lovell et al., 1996), it states:

> "The pilot project reported here has shown the enormous potential for wide-scale implementation of community gardens in crystalline basement areas and the wide range of social, economic and

> environmental benefits that can accrue from such gardens. As part of the pilot project, a proposal has been prepared for a much larger project that will build capacity within departments of the Government of Zimbabwe and implement a further one hundred community gardens over a period of four years. This larger project, which is called the NGADI (Nutrition Gardens And Groundwater Development In Zimbabwe) Project, will use and develop further the guidelines produced during the pilot project. It is strongly recommended that the NGADI Project be funded and started as soon as possible."

The NGADI project was never fully implemented. However, it is still considered a viable project that holds hope for sustainable development in the communal areas of Zimbabwe, where the majority of the population reside. In some ways, the NGADI project proposes self-help development in much the same way that the Upgraded Family Wells is based on self-help with modest external support.

iii. (Village Level Operation and Maintenance (VLOM) – Zimbabwe Bush-Pump modifications

The Zimbabwe Model B Bush Pump is not considered a VLOM pump. The most common point of regular maintenance and failure in the bush pump occurs in the down-hole components of the pump, i.e. the seals (leather cups or rubber nitrile seals) on the piston. To bring these components to the surface, heavy lifting devices, such as a tripod and a block and tackle, are required to lift the rising main with the cylinder and piston so that repairs to/replacements of the seals can be carried out.

Thus all down-hole repairs require the presence of a professional maintenance crew, normally provided by the District Development Fund (DDF). In recent years, due to a decline in the Zimbabwean economy, the percentage of (bush) pumps that are fully functional in the rural areas has declined quite significantly. According to the RWIMS database, rural water point functionality now lies at approximately 50% nationwide.

Since water is an absolute essential for life, the rural water-point non-functionality rate of 50% should be considered unacceptable. One response can be to continue to work on design modifications to the most widely installed hand-pump, the Model B Bush Pump, to try and achieve VLOM status.

Many different hand-pumps have been developed and used in different parts of the world. There is no single answer to the question: Which is the best hand-pump? It depends on a wide variety of conditions, such as the depth to water, water quality, number of users, discharge demand, availability of spare parts or community acceptance. The Zimbabwe Model B Bush Pump has become widely accepted and appreciated in Zimbabwe for a number of reasons.

It is, therefore, recommended that funds be allocated so that work on the Bush Pump, particularly the down-hole components can continue so that down-hole maintenance requirements become less demanding and, for the most common down-hole repairs, fall within the capabilities of village communities and village level pump minders.

If such work, adequately supported, delivers a VLOM Bush Bump, then there is little doubt that this, by itself, will be very instrumental in improving the 50% rural water-point functionality figure, and thereby bring much-needed improvements to the quality of rural life for many water-stressed communities in Zimbabwe. Finally, it is noted that the original designer of the Model B Zimbabwe Bush Pump, Dr Peter Morgan, remains active in working, unsupported, on the Bush Pump in order to improve the ease of down-hole repairs (Morgan, 2017).

7. ECONOMIC ANALYSIS OF PROPOSED PROJECTS

The following projects have been proposed for implementation under the groundwater resources management component of the Master Plan 2020-2040:

Project 1: Development and installation of a national groundwater trend monitoring network.

Project 2: Development and implementation of legislation for the registration and annual licensing of water drilling companies.

Project 3: Rationalization of groundwater data management systems and upgrading of the national hydrogeological database system.

Project 4: Preparation of groundwater models (e.g. USGS's MODFLOW) for the three major aquifer systems: Lomagundi, Nyamandlovu and Save aquifers.

Project 5: Upgrading of existing high yielding boreholes with solar power for pumping.

7.1 ESTIMATED COSTS OF THE INTERVENTIONS

The costing assumptions and cost estimates for these projects are presented in Tables 41-.45

Table 41: General assumptions for cost estimation for Project 1 - Development and installation of a national groundwater trend monitoring network

Particulars	Description
Capex	• USD 7,830 for one borehole for groundwater water monitoring.
Implementation Period	• 3 years
O & M Cost	• O & M costs were assumed as a fixed rate of the percentage to the project costs, namely 2.50% per annum.
The economic life of the Projects	• The economic life of the projects was set at 30 years.

Table 42: General assumptions for cost estimation for Project 2 - Development and implementation of legislation for the registration and annual licensing of water drilling companies

Particulars	Description
Capex	In the preliminary assessment, it is found that • 6 man-months are required to complete the assignment. • USD 450,000 is undertaken as the economic cost of the assignment.
Implementation Period	• 4 years

Table 43: General assumptions for cost estimation for Project 3 - Rationalization of groundwater data management systems and upgrading of national hydrogeological database system

Particulars	Description
Cape x	In the preliminary assessment, it is found that • 12 man-months are required to complete the assignment. • USD 600,000 is undertaken as the economic cost of the assignment.
Implementation Period	• 2 years

Table 44: General assumptions for cost estimation for Project 4 - Preparation of groundwater models (e.g. USGS's MODFLOW) for the three major aquifer systems (Lomagundi, Nyamandlovu and Save aquifers)

Particulars	Description
Capex	In the preliminary assessment, it is found that • 20 man-months are required to complete the assignment. • USD 770,000 is undertaken as the economic cost of the assignment.
Implementation Period	• 2 years

Table 45: Gerneral assumptions for cost estimation for Project 5 – Upgrading of existing high yielding wells to solar pumping.

Particulars	Description
Capex	In the preliminary assessment, it is found that • 1000 boreholes may be upgraded to solar pumping. • Pumping tests to confirm yield sufficiency to sustain solar pumping. $250 ea. • Installation of submersible pump together with solar panels on an elevated tower to protect against vandalism / theft. $5750 ea. • USD 6,000,000 is undertaken as the economic cost of the assignment.
Implementation Period	• 3 years

Table 46: Cost estimation for groundwater resources management and development Projects 1-5

Description	Amount (USD)
Project 1: Development and installation of a national groundwater trend monitoring network.	978,550
Project 2: Development and implementation of legislation for the registration and annual licensing of water drilling companies.	450,000
Project 3: Rationalization of groundwater data management systems and upgrading of the national hydrogeological database system.	600,000
Project 4: Preparation of groundwater models (e.g. USGS's MODFLOW) for the three major aquifer systems: Lomagundi, Nyamandlovu, and Save aquifers.	770,000
Project 5: Upgrading of existing high yielding boreholes with solar power for pumping.	6,000,000

7.2 ECONOMIC EVALUATION AND BENEFITS OF THE PROPOSED INTERVENTIONS

The proposed interventions will be complementary to the hardware projects to be implemented under the NWRMP 2020-2040.

Installation of national groundwater trend monitoring network: Monitoring secures the effectiveness of management measures and as such avoid mitigation costs. For example, excessive groundwater abstraction from deep wells for irrigation impacts on the water level of shallower wells that are usually owned by small farmers, who may then be faced with the need to drill new, deeper wells. Economic benefits due to groundwater trend monitoring include but is not limited to: -

- Monitoring of commercial groundwater abstraction can provide income to the regulator as it supplies evidence for charges and penalties that are included in the regulations such as progressive rates for groundwater abstraction and penalties under the polluter-pays principle.

- Data collected by monitoring activities can be used in several possible ways, such as management of groundwater abstraction and providing information to the national groundwater database in order to develop a more comprehensive understanding of the national groundwater resources.
- Once the authority has accurate data about the water balance, it can then set rational water tariffs (full/partial cost recovery for groundwater management) which will benefit the financial health of the utilities.
- The relevant authority can set high tariffs for higher users. This will encourage households and other consumers to use water rationally.
- Monitoring will provide an overview of the national groundwater network and will be useful to raise awareness for the rational use of groundwater.
- It will generate opportunities to work with a single consistent dataset for shared inter-catchment groundwater resources and increase collaboration between the national authority (ZINWA) and the catchments.
- Groundwater monitoring is advantageous in economic and environmental respects in comparison with the costs expended on the rehabilitation of anthropogenic damage to the groundwater system when a monitoring network is not in operation and when warning signals are lacking that aquifer depletion or pollution is setting in.

Development of legislation for the registration and annual licensing of water drilling companies: Economic benefits due to the development of legislation for the registration and annual licensing of water drilling companies include but not limited to: -

- The combination of capacity development short courses together with the requirement for annual registration of drillers will become a potentially effective means of improving the quality and performance of the drilling sector, resulting in increased borehole lifespan.
- Making mandatory registration and annual licensing of water drilling by legislation will help to regulate the drillers and only registered drillers will operate.
- Registered companies will have to follow the standards and codes of practice as a result quality of digging and other related work will be improved that will increase the lifespan of the borehole.
- Following the standards and codes of practice will become necessary, and those who do not follow them will risk having their registration withdrawn.
- Groundwater users will benefit since the cost and quality of drilling will be optimised on account of drilling companies adhering to a code of practice.

Rationalization of groundwater data management systems and upgrading of a national hydrogeological database system: Data availability is essential to develop approaches that allow integrated water resources management for monitoring freshwater resource changes. Lack of data often prevents the application of integrated water management methodologies.

Preparation of groundwater models for the three major aquifer systems: Groundwater flow modelling is a fundamental step to understanding groundwater flow regimes, water budget, recharge estimation, risk assessment and stream depletion assessment. The benefits from groundwater modelling include, but are not limited to: -

- Enables simulating the behaviour of complex aquifers including the effects of irregular boundaries;
- heterogeneity and different processes such as groundwater flow and solute transport;
- Evaluating well systems and water resources (yield, drawdown, interference, etc.); and
- Defining capture zones/wellhead protection areas.

8 SUMMARY IMPLEMENTATION PLANS

The implementation plan for the five groundwater resources management and development are presented in table 47.

Table 47: Summary of implementation plans

Description	Amount (USD)
Project 1: Development and installation of a national groundwater trend monitoring network. Implementation Plans: Activity 1: Purchase of loggers and field computers Activity 2: Training at catchment and sub-catchment level – including identification of monitoring localities. Activity 3. Drilling of monitoring boreholes Activity 3: Installation of loggers by Zinwa catchment staff. Activity 4: Collection, archiving and publication of groundwater level data. Monitoring and Evaluation Indicators to be completed as per time-line specified: Short Term: Purchase of loggers and field computers; Training of catchment staff. Yr 1 Medium Term: Drilling of monitoring boreholes; Installation of loggers. Yrs 2-4. Long Term: Collection, archiving and publication of groundwater level data. Yrs 4-7.	978,550
Project 2: Development and implementation of legislation for the registration and annual licensing of water drilling companies. Implementation Plans: Activity 1: Development of appropriate legislation. Yrs 1 -2. Activity 2: Enactment of Legislation: Yr 3 Activity 3: Registration and annual licensing of drilling companies: Yrs 4- Monitoring and Evaluation Indicators to be completed as per time-line specified: Short Term: Legislation developed and approved by stakeholders Yr 2 Medium Term: Legislation enacted. Yrs 3. Long Term: Drilling companies registered and licenced. Yrs 4- and beyond.	450,000
Project 3: Rationalization of groundwater data management systems and upgrading of the national hydrogeological database system. Implementation Plans: Activity 1: Rationalization of appropriate groundwater data requirements and identification of suitable open source database and visualization software. Yrs 1 Activity 2: Transfer of existing data to new system: Yrs 2 - 3 Activity 3: Implementation of data collection to new standards and data submission to Zinwa implemented by drilling companies: Yrs 4- and beyond Monitoring and Evaluation Indicators to be completed as per time-line specified: Short Term: New database system in place. Yr 1 Medium Term: Existing data transferred to new system. System functional. Yr 3.	600,000

Long Term: Drilling companies submitting data as per legal requirements. Yrs 4- and beyond.	
Project 4: Preparation of groundwater models (e.g. USGS's MODFLOW) for the three major aquifer systems: Lomagundi, Nyamandlovu, and Save aquifers. Implementation Plans: Activity 1: Identification and purchase of suitable open source modelling software and contract signed with professional groundwater modelling consulants. Yr 1 Activity 2: Conceptual models developed for all three well-fields and approved by Zinwa: Yr 2 Activity 3: Field work – drilling and equipping observation wells as required; Pumping tests to determine aquifer properties: Yrs 3 and 4. Activity 4: Model creation, development and calibration. Future planning for well fields and report production. Training Zinwa staff. Yrs 5 and 6. Monitoring and Evaluation Indicators to be completed as per time-line specified: Short Term: Purchase of model software and contracting of modellers: Yr 1 Medium Term: Drilling and pumping tests completed: Yr 4. Long Term: Model completed and functional. Zinwa staff trained. Yr 6.	1,500,000
Project 5: Upgrading of existing high yield boreholes to solar pumping. Implementation Plans: Activity 1: Field identification and GPS mapping of high yield boreholes: Yrs 1-2. Activity 2: Community engagement to determine demand for additional water Yrs 3-4 Activity 3: Pumping tests and solar installations: Yrs 5 - 10 Monitoring and Evaluation Indicators to be completed as per time-line specified: Short Term: All existing high yield boreholes identified and mapped. Yr 2 Medium Term:. Community approvals completed Yr 4. Long Term: Test pumping completed yr 5: Solar pumping installations underway: Yrs 6 and beyond.	6,000,000

9 SUMMARY AND CONCLUSIONS

In summary, this groundwater report has presented an overview of the groundwater resources in Zimbabwe at the present time, and it addresses the issue of groundwater in the future under a climate change scenario (CSIRO RCP 4.5) to 2040. Priority aquifers and critical groundwater threats are addressed and groundwater development potentials and threat mitigation strategies are identified.

Most aquifers in Zimbabwe are weathered crystalline basement (WCB) systems, limited in extent (2-10 km) and with low storage (200 – 500 mm). There are areas with large sedimentary aquifers, both consolidated (Karoo system) and unconsolidated (Kalahari sands). These are large productive aquifers with flow systems from 2 -100 km, and storage from 1000 – 20,000 mm. In Zimbabwe, these large-scale groundwater resources are largely in the peripheral areas of the country where demand is low. Small Alluvial Formations (SAF) are found in existing river channels, mostly in the southern low-veld parts of the country. They are quite limited in extent (2 – 20 km), but do store reasonable volumes of water (800 – 4000 mm). In addition, they are generally annually recharged (see Figure 85)

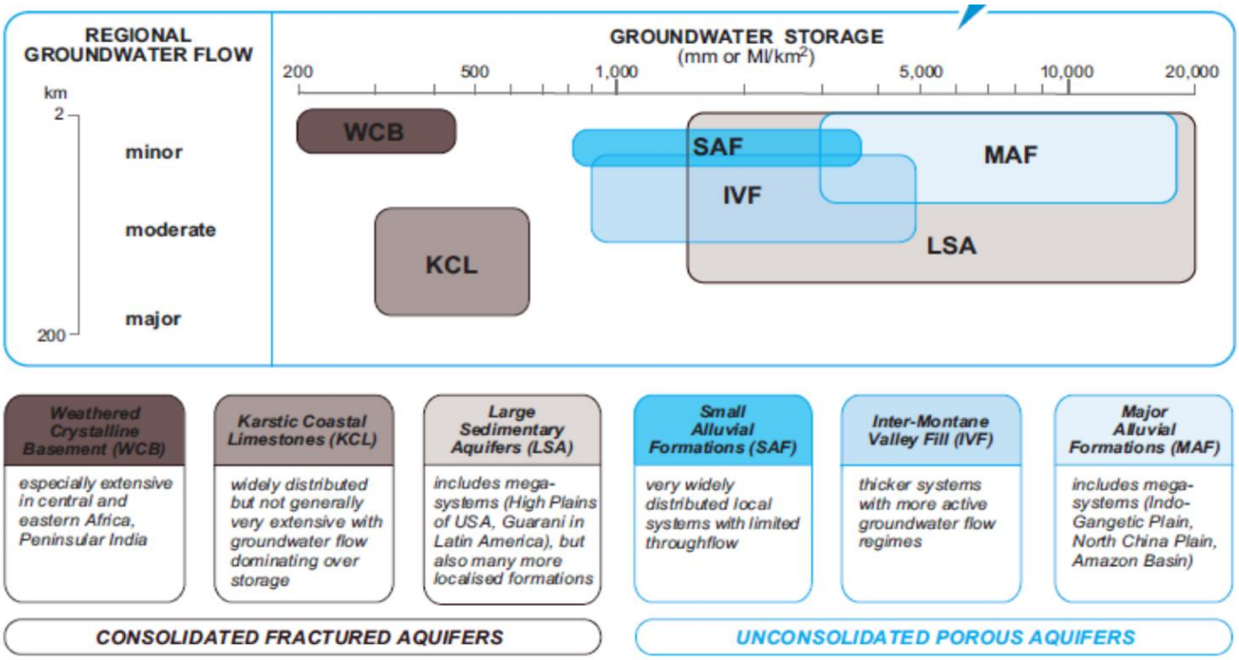


Figure 86: Most common aquifer types and their management dimensions.

The recommended strategy for groundwater management is focussed less on additional development and more on sustainability for the WCB aquifers, with local medium-scale development at high yield wells, combined with monitoring and management. Excess abstraction will lead to aquifer depletion, as already witnessed in Harare.

The larger aquifers can be developed further, where there is demand. These aquifers can provide for significant new developments where they occur. Groundwater monitoring is required to ensure sustainable development.

In order to manage, protect and develop the groundwater in a spatially distributed manner, the study has developed a suite of groundwater maps that provide a new view of groundwater resources and their status throughout the country. These maps include aquifer productivity, groundwater recharge potential, groundwater development potential, groundwater vulnerability to pollution, geogenic groundwater quality and groundwater drought risk.

It proposes that groundwater management be devolved, as far as is possible, to the local catchment authorities and it further proposes that these authorities be provided with the technical tools to put into effect a sustainable groundwater management strategy. These tools include the groundwater maps (including interactive online versions), and the development of catchment groundwater monitoring networks.

Zimbabwe is a country that faces serious groundwater drought risk. Therefore, it is essential that groundwater monitoring be included in our framework for groundwater resources management.

The issues of borehole drilling and groundwater pumping technology are discussed. The critical issues facing these sectors are presented and various opportunities and threats are identified.

In conclusion, groundwater resources are a vital water resource widely used throughout the country, both in the rural areas and, more and more, in the urban areas. They must be treasured and protected from both aquifer depletion and quality deterioration.

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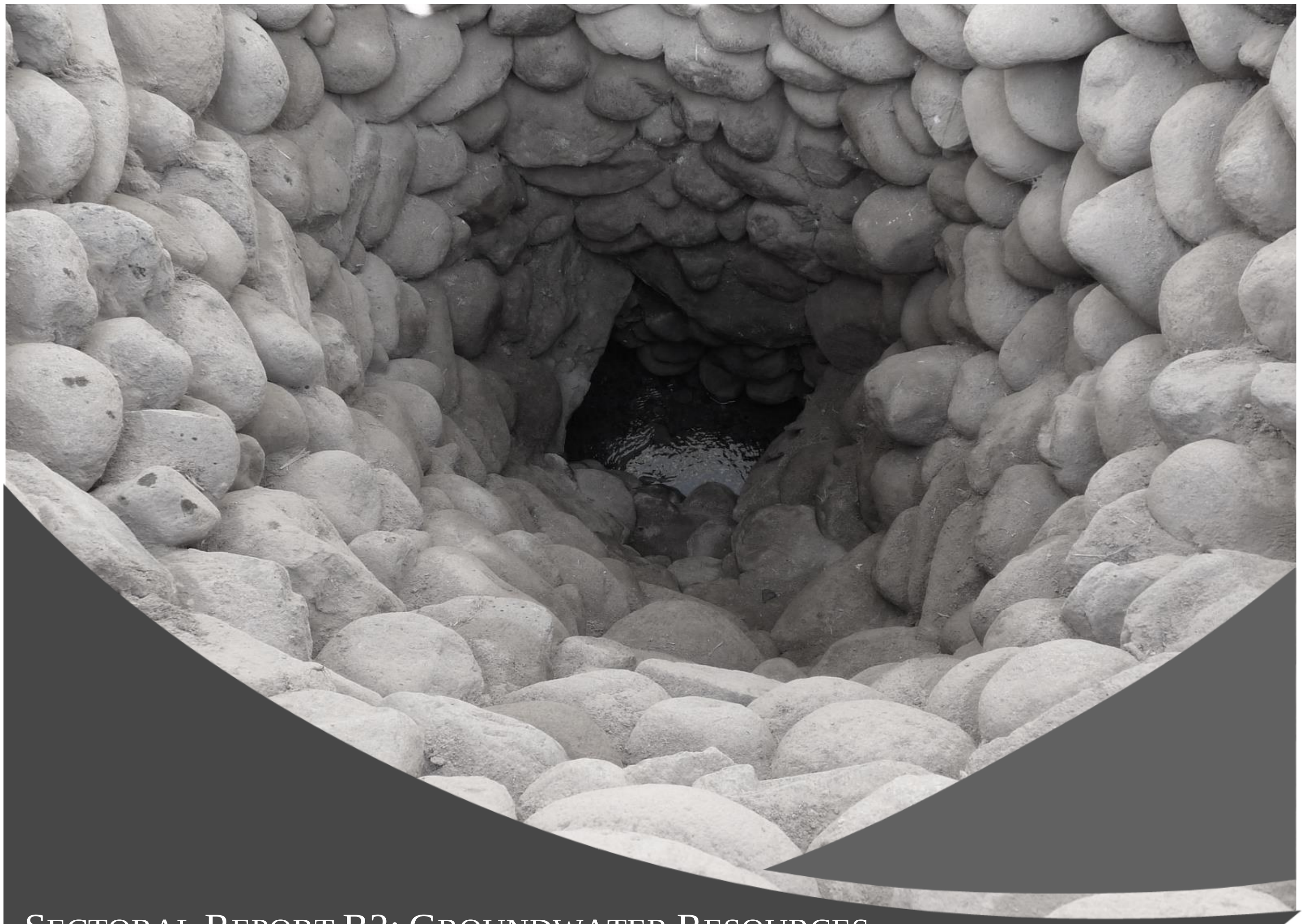

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