WITS
UNIVERSITY

Optimisation of national groundwater monitoring network of Lesotho

By: Mpoetsi Nketsi

A research report submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Hydrogeology

Supervisor: Prof. Tamiru Abiye

Co-Supervisor: Dr. Teboho Shakhane (Senior Scientist, Inkomati-Usuthu Catchment Management Agency)

Johannesburg, 2021

DECLARATION

I, Mpoetsi Nketsi, declare that this research report is my own work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

_____

(Signature of Candidate)

02 Day of November 2021 at Johannesburg

Abstract

Groundwater resources are a major source of water supply in Lesotho, particularly for the rural communities that rely on them for drinking, irrigation and domestic uses. However, Lesotho has been failing to meet its water demand due to an increase in demand and low supply caused by variations in climatic conditions. Furthermore, the emergence of textile industries, increasing urbanisation, and mining activities seem to be affecting groundwater resources negatively as well. Therefore, regular, systematic monitoring of groundwater resources is necessary to establish effective management.

The aim of the study was to review and evaluate how optimised the groundwater monitoring network was on the basis of the geological and hydrogeological status.. The present national groundwater monitoring network was evaluated based on its geological and hydrogeological status. Through delineation of catchments using HECGEO-RAS and Global Mapper, results showed that the country is predominantly covered by basalts from the Drakensberg Group and has four major aquifers: sedimentary (fractured aquifers), basaltic aquifers, dyke-related and alluvial aquifers. Water levels range between 5 and 42 metres below ground level. Groundwater recharge is 4.24% of Mean Annual Precipitation (MAP) in the lowlands (Maseru) and 9.04% of MAP in the highlands (Mohale's Hoek). A review process was then followed to identify gaps in the existing network. It was noted that amongst all limitations, the biggest one was data management and storage.

On the basis of these findings, it is recommended that to optimise the network, the national groundwater monitoring network should increase its monitoring points in areas that were less prioritised, carefully select parameters to be monitored, increase monitoring frequency, and make use of a centralised database. Furthermore, to meet the set Quality Assurance/Quality Control (QA/QC) standards, institutional frameworks should invest in training and capacity development.

Acknowledgements

This research was conducted as part of the Lesotho's Ministry of Water Affairs (DWA) project through GCS-Lesotho. As such, I would like to thank (DWA) for the provision of information and Dr Shakhane (Co-supervisor, GCS-Lesotho) for his patience and unwavering support provided throughout the research.

Many thanks to my Supervisor, Professor T. Abiye for his encouragement and guidance throughout my MSc period. This work would not have been completed if he did not share his extensive knowledge with me.

A big appreciation to National Research Fund (NRF) for funding me.

To my family and friends, thank you for always being by my side and cheering me on when the going got tough. Your love and understanding pushed me to reach this level.

Table of Contents

List of figures

List of tables

Acronyms and Abbreviations

AMS:	American Meteorological Society
AGW-NET:	Africa Groundwater Network
CoW:	Commissioner of Water
DWA:	Department of Water Affairs
DWAF:	Department of Water Affairs and Forestry
DWRS:	Department of Rural Water Supplies
EDF:	European Development Fund
EEA:	European Environment Agency
EC:	Electrical Conductivity
EU:	European Union
FAO:	Food and Agricultural organization
GIS:	Geographic Information Systems
GMI-PLI:	Groundwater Management Institute- Policy, Legal and Institutional development
ICM:	Integrated Catchment Management
IGRAC:	International Groundwater Resources Assessment Centre
Km^2:	Square Kilometre
LHDA:	Lesotho Highlands Development Authority
LP:	Lerotholi Polytechnic
LLWSU:	Lesotho Lowlands Water Supply Unit
MAP:	Mean Annual Precipitation
masl:	Metres above sea level
mbgl:	Metres below ground level
ms/m:	MilliSiemnes per metre
MoNR:	Ministry of Natural Resources
NUL:	National University of Lesotho
ORASECOM:	Orange-Senqu River Basin Commission
ORP:	Oxidation-reduction potential
pH:	Potential of hydrogen
PWRAs:	Prescribed Water Resource Areas

QA:	Quality Assurance
QC:	Quality Control
SADC-GMI:	Southern African Development Community- Groundwater Management Institute
SC:	Sub-Catchment
TDS:	Total Dissolved Solids
UN/ECE:	United Nations/ Economic Commission for Europe
UNICEF:	United Nations Children's Fund
US-EPA:	The United States Environment Protection Agency
WASA:	Water and Sewage Authority
WASCO:	Water and Sewage Company
WHO:	World Health Organization
WISH:	Windows Interpretation Systems for Hydrogeologists
Yr:	Year

CHAPTER 1: Introduction

1.1 General Introduction

Lesotho is a highland country with an area of 30 355 km^2 landlocked in the Republic of South Africa. Its groundwater forms an important resource that provides safe and reliable water supplies for both rural and peri-urban communities (*Figure* 1) (Davies, 2003; Mare, 2007 and IGRAC, 2013). Groundwater is accessed through springs and boreholes that are distributed throughout the entire country. It is used to sustain livelihood by fulfilling domestic needs as well as playing a role in the irrigation of crops within rural parts of Lesotho (Davies, 2003). Mare (2007) highlights that, previously, Lesotho relied on springs to supply its rural population and surface water to supply towns. However, both urban and peri-urban areas are beginning to use groundwater due to frequent droughts that have since been attributed to the emerging climate change. In fact, throughout the world, groundwater is increasingly becoming a preferred resource whose demands are expected to rise while supplies will be limited by emerging shortfalls in precipitation due to the emerging climate change (IGM, 2016).

The American Meteorological Society (AMS) Glossary (2017) defines climate change as "any systematic change in the long-term statistics of climate elements (such as temperature, pressure, or winds) sustained over several decades or longer". An increase in temperature, consequently, increases the rate of evaporation and causes surface drying. This process plays a major role in elongating the duration of drought such that some regions like southern Africa may not see a noticeable increase in heavy precipitation (Hausfather, 2018). Major hot spots of these strains are more inevitable in arid and semiarid parts of the world, mainly resulting from substantial dependence on groundwater coupled with little and highly variable rainfall (Giorgi, 2006). The 2014/2015 and 2015/2016 drought in the summer rainfall areas are testimony to the emerging impacts of climate change on water resource availability in Southern Africa (Monyela, 2017). This has led to more dependency on groundwater with correspondingly excessive withdrawals while the lack of rainfall and drying rivers will mean less or no recharge. Due to the lack of rainfall and drying rivers, Lesotho has

seen an exponential increase in the number of boreholes drilled for domestic water supply.

The emerging increase in the dependence on groundwater resources, coupled with increasing population, and climate change has resulted in groundwater resources being subjected to huge pressure (Mare, 2007; IGRAC, 2013). Additionally, mismanagement of this resource has contributed to poor water quality and overexploitation of aquifers in several areas. This could potentially add to the already existing water supply problems as well as deteriorate groundwater-dependent ecosystems (IGRAC, 2013). To address the increasing concerns on groundwater over-abstraction and contamination, groundwater level and quality monitoring are vital to managing the above-mentioned issues (Yang et al., 2008). However, groundwater monitoring cannot be determined by basic once-off snapshot surveys alone as it requires more elaborate monitoring networks and data interpretation (Tuinhof et al. 2006).

In Lesotho, the institution with direct responsibility for groundwater monitoring, assessment, and allocation of water resources is the Department of Water Affairs (DWA) (https://www.water.org.ls). Basically, DWA regulates groundwater development in Lesotho (Mare, 2007). The priority for the DWA is to establish itself as a reliable and independent source of information for water resources for any development and related activities needing data for their course. However, the DWA has struggled to maintain a consistent monitoring schedule. In addition to the lack of consistency in monitoring, the current monitoring network is not spatially representative of the entire country i.e. the monitoring boreholes are mainly only located in the lowlands and therefore, do not depict a true picture of the groundwater level fluctuations over the entire country. The individual boreholes are also not strategically positioned to allow monitoring of the various stresses/impacts on groundwater e.g. drought, flood, pollution-prone areas, and various lithologies (https://www.dwa.org.ls). Consequently, the spatial impacts of climate and land use/cover on groundwater and over-exploitation are not well understood. Baalousha (2010) justifies that improper distribution and limited monitoring stations do not indicate the entire state of the environment. Moreover, the effectiveness of the network is related to the accuracy of spatial estimation (Yang et al., 2008).

Overall, the steps followed for data collection in Lesotho seem to be flawed. In 1996 only 4% to 5% of the borehole records contained yield data and only 1% to 3% had transmissivity and storativity data (TAMS, 1996). The situation does not seem to have changed since then and, poor monitoring persists. This poor monitoring data collection has negatively affected the annual reporting on the groundwater status of the country. The performance in terms of groundwater monitoring in Lesotho has declined and resulted in poor monitoring data collection. Suggestively, Lesotho needs public awareness on the value of groundwater as the nation seems not to comprehend the importance of observation wells among local communities.

The existing network was established not with the intention of designing a groundwater monitoring network as such, but it was a product of the various groundwater exploration projects by the Department in the early ‘90s (Davies, 2003) Since then, limited efforts were done to expand the coverage of the network, instead, their number has decreased over the years, mainly due to borehole collapse and conversion into water supply boreholes. Finally, as evidence of the need for comprehensive and reliable groundwater information, the Department is often requested to supply data and relevant information on the status of groundwater quality and quantity to other government agencies or private individuals. Many of these requests cannot be answered specifically or with a high level of precision due to the inadequacy of the current groundwater monitoring program. This is especially true with respect to data on borehole water quality which is not routinely analysed as part of the present data collection program.

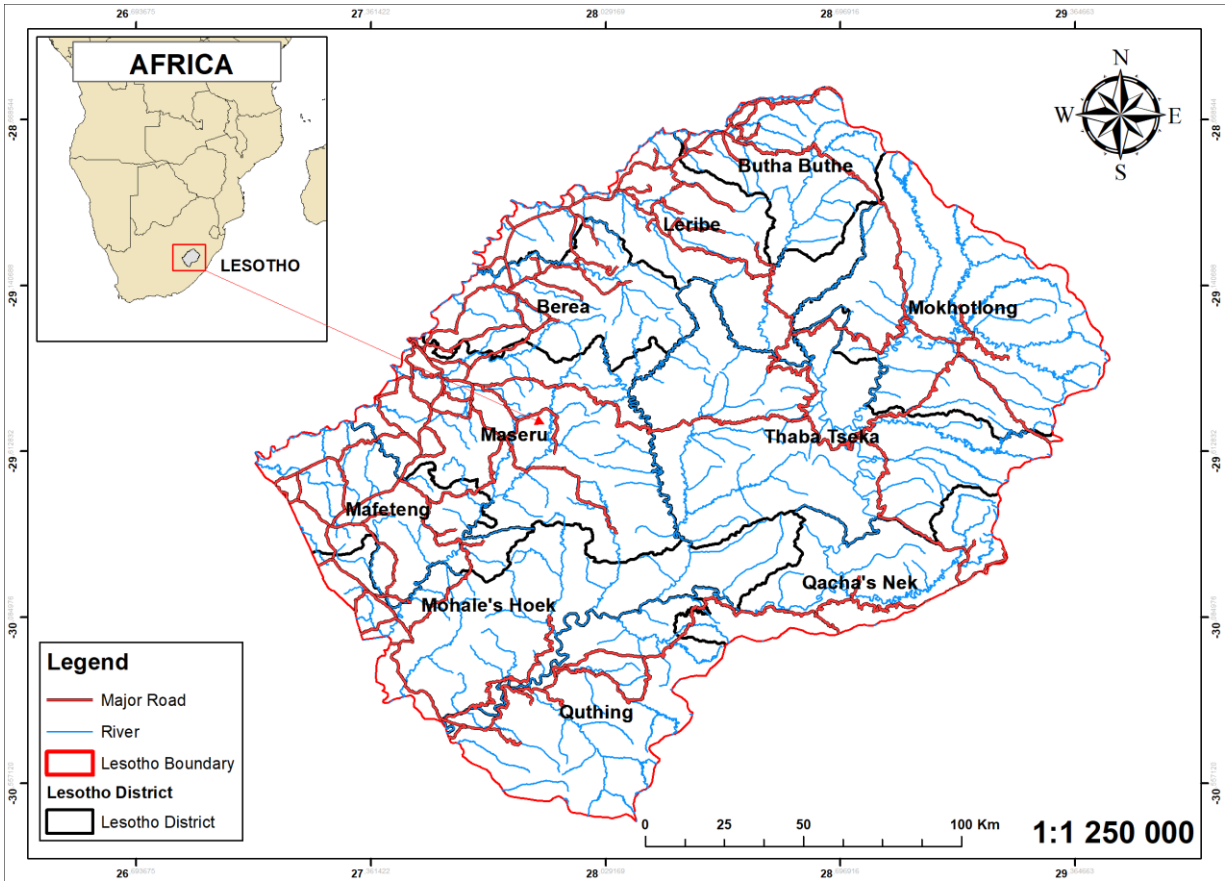

Figure 1: Location of the study area

1.2 Motivation for the study

Groundwater is a valuable resource that needs to be monitored consistently. Groundwater monitoring remains one of the important aspects in the field of hydrogeology because data generated from monitoring activities are used for various interpretations about groundwater levels and quality. There is a tremendous need, therefore, to carry out this research in order to identify gaps in the current network and later optimise it. This will help make information readily available to end-users for informed decisions. Consequently, maximising optimisation for water uses for both the private sector and the public at large, as well as making them aware of the significance of this resource. Furthermore, monitoring our groundwater resources is crucial for the assessment, prediction, and sound groundwater management. Optimising the national groundwater monitoring network will facilitate reliable and long term hydrogeological information, groundwater quality and quantity data that may be used for land-

subsidence mitigation plans in certain instances as well as to make informed decisions regarding an area or country where conducted (Hsu, 1998).

1.3 Aim and objectives

1.3.1 Aim

To review and assess the groundwater monitoring network for Lesotho

1.3.2 Objectives:

The objectives of the study were:

- to investigate the hydrogeological, and geological situation of Lesotho,
- evaluate groundwater quality and level variations so as to identify areas that need inclusion into the monitoring network,
- investigating factors that have the potential to affect groundwater systems so as to determine areas with high or low monitoring priority,
- to evaluate how representative the existing network is
- to propose a detailed design of the national groundwater monitoring network.

CHAPTER 2: Literature Review

Background on Groundwater monitoring

2.1 Introduction

Groundwater monitoring is an essential tool used to manage groundwater resources sustainably (Quevauviller et al., 2009). Both observational data and climate predictions show that water resources are strongly being affected by climate change (Green et al., 2011). As such, groundwater is increasingly becoming a preferred resource whose demands are continuously rising, while supply is constrained by shortfalls from precipitation due to the emerging climate change impacts. Monitoring groundwater is, therefore, considered the entry point to management because, based upon groundwater monitoring data, workable information could be derived. A groundwater monitoring network is classified as an information collection system because its main objective is to collate information efficiently (Mogheir and Singh, 2002). It usually arises due to gaps in data and collection of long-term hydrogeological information such as groundwater quality and quantity data (Hsu, 1998; IGRAC, 2013). According to IGRAC (2013) groundwater is monitored for various reasons such as to depict spatial and temporal trends that aid in comprehending the cause-effect relationship of groundwater resources as well as to spread awareness on groundwater resources and their usage. A good monitoring network represents the entire groundwater system. An improper distribution and limited monitoring stations do not represent the entire state of the environment (Baalousha, 2010). Moreover, the effectiveness of the network is related to the accuracy of spatial estimation (Yang et al., 2008).

2.1.1 Background on monitoring in Lesotho

Groundwater monitoring in Lesotho started early in the 1990s, at a very small scale with 72 observation boreholes across the country. Initially, the boreholes were drilled for the compilation of the Lesotho Hydrogeological map, but later 48 of them became the groundwater monitoring network (IGRAC, 2019). With time, the network expanded and more boreholes were drilled and are now being monitored. At the start of the monitoring, the aim was to conduct monitoring every three months, recording the spring yields as well as the physical parameters of the groundwater (IGRAC, 2013).

The purpose of this chapter is twofold, namely 1) reviews mandates and the capacity of institutional and legal frameworks to efficiently monitor the network and 2) assesses spatial representativity, quality assurance, and quality control measures against consistency with approved protocols and standards and further establishes the status quo and gaps or strengths in the existing network.

2.1.1.1 Institutional Framework of the national groundwater monitoring network

An institutional framework oversees and coordinates the monitoring process by implementing monitoring policies, strategies, and methodologies (UN/ECE, 2000). The institutional framework of the national groundwater monitoring network in Lesotho is shown in Figure *2*, where the key institutions are: The Ministry of water, the Commissioner of water (CoW), the Department of Water Affairs (DWA), the Department of Rural Water Supply (DRWS), Water and Sewage Company (WASCO), Lesotho Highlands Development Authority (LHDA), and Lesotho Lowlands Water Supply Unit (LLWSU).

As a sector leader in this framework, the office of the Prime Minister has the sole purpose of providing water services to the nation. As such, it delegates the task of developing policies, legislation and institutional frameworks to the Ministry of Natural Resources (MoNR) to deliver on the national policy. Through the principal secretary, the Commissioner of Water (CoW) then plans and coordinates all water sector institutions, with key responsibilities of each sector listed below.

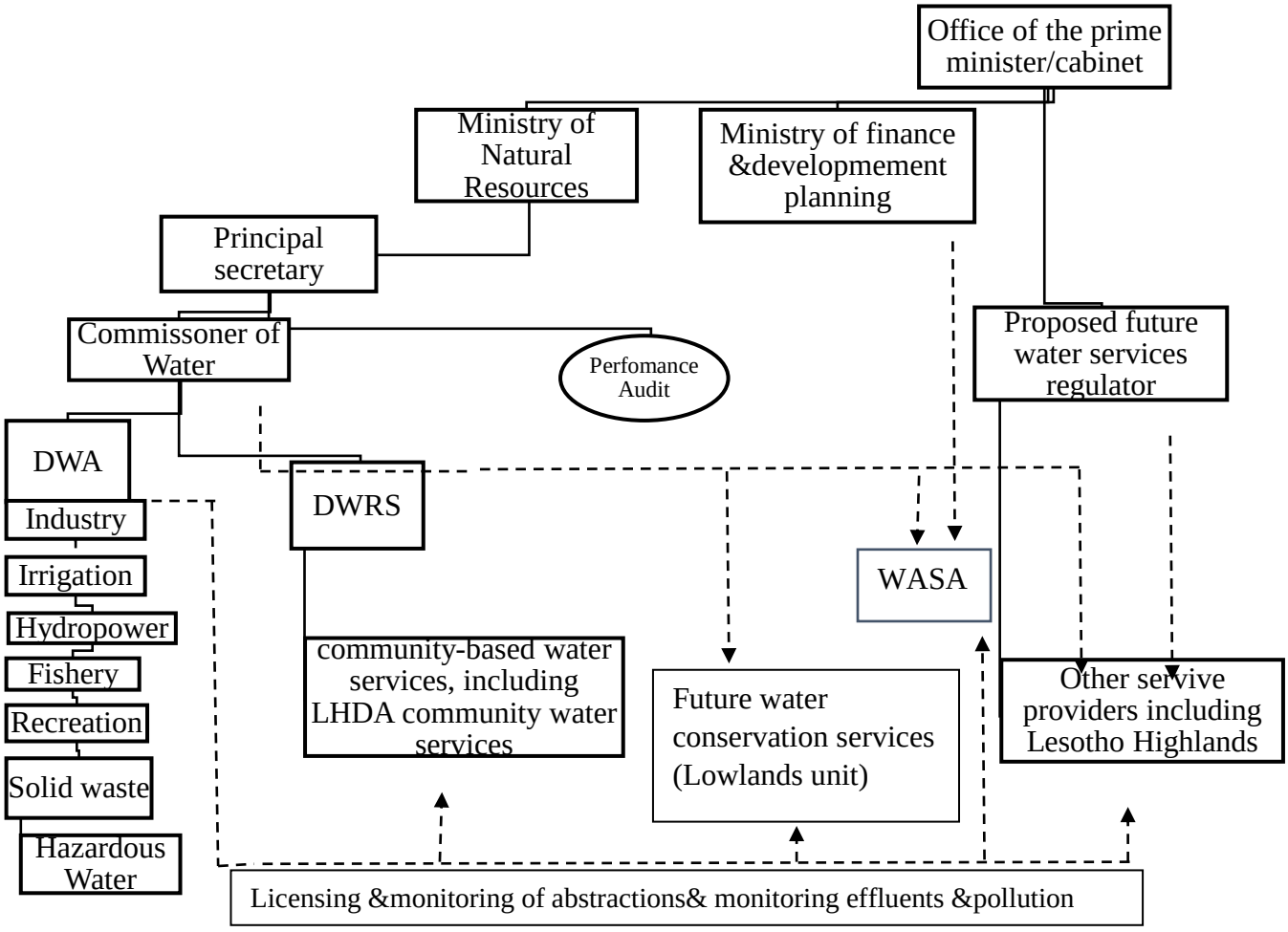

Figure 2: Organizational structure of the water sector in Lesotho (Source: Ministry of Natural Resources, 2007)

2.1.1.1.1 Department of Water Affairs (DWA)

DWA is the main executing department for the national groundwater monitoring network of Lesotho (IGRAC, 2013). The mandate of this department is to manage the quality and quantity of water resources in the country as defined by the Water Resources act of 1978 (Davies, 2003). The key functions of DWA are:

- to assess and develop water resources across the country through exploration, construction of boreholes, conducting aquifer tests as well as monitoring spring yields and boreholes water levels
- to conserve and rehabilitate wetlands through its water resource division.
- to strictly manage water use within the country, and

- through its division of water rights, it puts into place the water act. This is done to protect and manage water resources by ensuring the use of water use permits and construction permits.

2.1.1.1.2 Department of Rural Water Supply (DRWS)

Through community-managed water schemes and sanitation facilities, the Department of Rural Water Supply (DRWS) provides sustainable and adequate water to the rural population. Two-thirds of the water supplied by the DRWS comes from springs supplied through gravity-fed schemes and a third from boreholes equipped with hand or submersible pumps (Davies, 2003). Their goal is to build and expand capacity in operating and maintaining water supply systems (Https://www.dwa.org.ls). In 1996, DWRS changed its status from being an implementer to being a facilitator hence during 1998-2002 it implemented a more demand response approach that ensures community ownership of water supply systems (ORASECOM, 2007).

2.1.1.1.3 Water and Sewage Authority (WASA)

WASA, is now known as WASCO, provides safe drinking water for urban communities. Its role is to provide water treatment and distribution services to the community at large.

2.1.1.1.4 Lesotho Highlands Development Authority (LHDA)

LHDA is responsible for the planning, implementing and operating water activities in the highlands of Lesotho and dealing with bulk water transfers.

2.1.1.1.5 Lesotho lowlands Water Supply Unit (LLWSU)

LLWSU designs bulk water transfers in the lowlands of Lesotho.

2.1.1.2 The strength of the institutional framework

Through the Ministry of Natural Resources and Ministry of Finance, the water sectors are able to build relationships with international donors to embark on various water projects. For example, DWA has previously partnered with the European Development Fund on the International Catchment Management (ICM) project.

2.1.1.3 The limitations of the institutional framework

- Limited capacity building within the water sectors
- Lack of hydrogeologists in the designated water departments
- There is a lack of data management, there is no central database for different departments to share information

2.1.1.4 Legislative and policy framework of the national groundwater monitoring network

Regulation of groundwater development was established by the Water Resource act 1978, which was revised and the water management policy of 1998 was enacted focusing on groundwater abstraction, water quality monitoring by the DWA, and groundwater exploration, etc. (Davies, 2003). In accordance with the water act of 2008, the office of the water commission was established to develop, update and monitor the implementation of the water policy.

Since Lesotho falls within the Orange-Senqu Basin, its policy framework is somewhat similar to that of the ORASECOM member states that include South Africa, Botswana and Namibia. The legislative framework was established after King Letsie III signed the Water Act in 2008 (Government of Lesotho Gazette, 2008). This framework is in place to support the Integrated Water Resource Management (IWRM) principles. A brief overview of policies related to the water sector in terms of monitoring are:

- Lesotho Water Act, 2008 (No.15 of 2008)
- Lesotho Water and Sanitation Policy, 2007

The National Water Act of 2008. Stipulates that "*the act will provide for the management, protection, conservation development and sustainable utilization of water resources"*. The objectives of the National Water Act with the implications for groundwater monitoring are (Government of Lesotho, 2008):

- Duties and functions performed under this act will account for effective management and protection of water sources. This will be achieved through sustainable usage of water sources, intergenerational equity, integrated water resources management, equitable distribution of water, and a public participatory approach.
- Introducing a water bill to make provisions for the conservation and protection of water from pollution. It further makes provisions for permits (abstraction and construction permits) so that no individual engages in water activities without a permit.

The Lesotho water and sanitation policy is "based on a need for a holistic and sustainable water resources management and development approach". This policy is consistent with the Dublin principles Helsinki rules, SADC declaration, and Southern African Vision for water management. Its objectives in regards to groundwater monitoring are to promote (MONR, 2007):

- *the proper management of the country's water resources and its sustainable utilisation*
- *an adequate and sustainable supply of potable water and sanitation services to all of the population of Lesotho*
- *coordination and coherence in the management and development of water and other related natural resources, to maximize the resultant socio-economic benefits without compromising the sustainability of vital ecosystems*
- *harmonisation of processes and procedures followed by different development partners and other stakeholders in order to optimise available internal and external resources as well as ensure timely implementation of sector programs.*

2.1.1.5 Quality Assurance/ Quality Control (QA/QC) protocol

Quality assurance deals with principles and procedures which ensure that reliable data have been collected whereas quality control deals with ensuring that groundwater data collected meets the standards put in place.

In terms of quality control, it is not quite clear if there are any formalised procedures. As noted by (IGRAC, 2019) boreholes are in different coordinate systems. This, therefore, increases inconsistency issues within the network. Also, the fact that borehole data is stored in spreadsheets, not readily accessible databases proves that there is no backup plan in place to avoid national groundwater monitoring data loss. Furthermore, quality control protocols are not well developed.

2.2 Groundwater quantity monitoring

Groundwater level monitoring indicates the oscillation of groundwater in an aquifer. Information on groundwater fluctuations aids in understanding the aquifer condition in both static and pumping conditions. Abiye et al. (2018) state that groundwater fluctuations are attributed to both human-driven activities and natural processes. Therefore, a significant decline in groundwater levels may be due to exploitation of the resource and reduction of recharge (Zhou et al., 2013) and rising groundwater levels may be due to the absence of abstractions and high rainfall conditions (Abiye et al., 2018). According to Abiye et al. (2018), previous work across the world has shown that in the Ozark aquifer (USA) and Bangladesh groundwater fluctuations were associated with over-pumping of groundwater resources. In Pakistan, the water level drop was caused by the rapid growth of the population in that area. To this effect, monitoring of groundwater level is important for successful groundwater management such as in the quantification of groundwater abstraction rates, estimating recharge and assessing the impact on the environment. Taylor and Alley (2001) suggested that groundwater level monitoring provides data needed to evaluate changes that occur in groundwater resources over time, forecast trends, and monitor groundwater management strategies. It is also essential to avoid disputes over groundwater use (Abiye et al., 2018). Groundwater level monitoring network may be optimised by proposing a groundwater regime zone mapping method. This method delineates

different water level variations and may be used in locating groundwater monitoring wells (Zhou et al., 2013)

2.3 Groundwater quality monitoring

Groundwater in unconfined aquifers is inherently vulnerable to human impacts due to susceptibility to contamination wherein it can contain substances that may be harmful to human health. Consequently, groundwater quality monitoring is vital to collect, process, and analyse data on water quality as a basis for assessing the current state, changes, and trends of the hydrogeological system due to natural and anthropogenic processes in space and time. Adequate and reliable data on groundwater quality monitoring thus maximizes human knowledge on environmental processes that affect water quality, reducing uncertainties (Harmancioglu et al., 1998). Against this background, Baalousha (2010) highlights that groundwater quality monitoring is vital for characterising groundwater systems. This may be achieved by identifying groundwater quality with contribution from humans or by focusing on the extent of contamination around the impacted site.

The main objective of groundwater quality monitoring is to give a complete overview of the hydrochemical status at different spatial and time scales (Quevauviller et al., 2009). To optimise a groundwater monitoring network, a hydrogeological approach represented by vulnerability mapping is used to identify areas susceptible to contamination.

2.4 Monitoring cycle

UN/ECE (2000) provided a framework for a monitoring cycle as shown in (Figure *3*). The monitoring cycle indicates that water management constitutes a first step in the cycle. Water management is made up of three core elements: Functions/Uses, issues, and measures (UN/ECE, 2000). The functions/ uses aspect focuses on maintaining groundwater quality for various uses, whereas the issues element addresses problems related to declining water tables and pollution. Lastly, the measures element focuses on remediation strategies as well as limit abstraction rates.

The information need plays a significant role in the groundwater monitoring cycle. Monitoring networks for groundwater management should match the information demands of water management (Mogheir and Singh, 2002). Once the information

needs have been established, the next step is to look into the monitoring strategies. These strategies ensure that all monitoring objectives are implemented. This may be achieved by screening the existing information and ensuring that the groundwater system is well understood in order to design an efficient monitoring system. Furthermore, the types of monitoring and monitoring techniques must be decided upon. (UN/ECE, 2000).

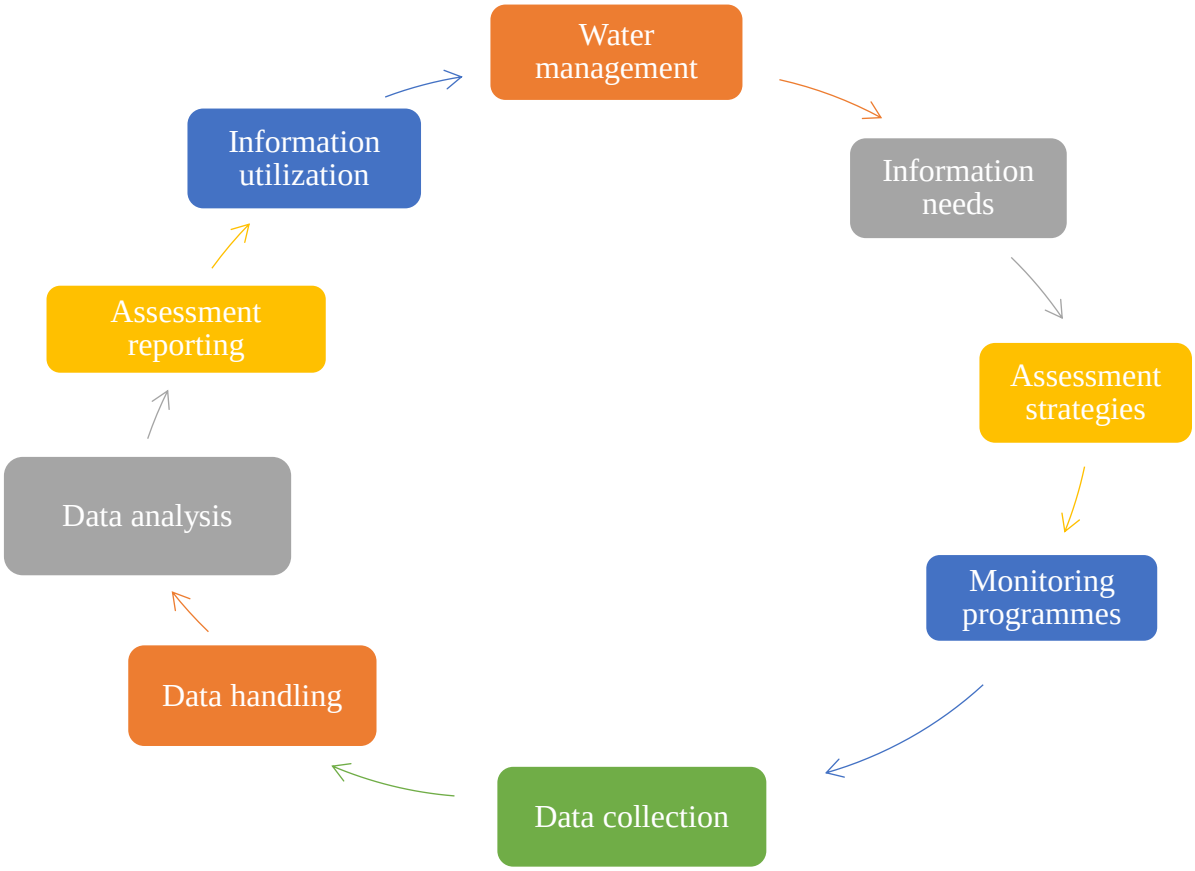

Figure 3: The monitoring cycle (Source: UN/ECE, 2000)

Once groundwater management objectives have been agreed upon, the information needs identified and the strategies provided for gathering the necessary information, the monitoring network design takes place (UN/ECE, 2000). The monitoring network design takes into account the network density, location of monitoring points, monitoring parameters, sampling procedures, the measuring and sampling frequency, and lastly the statistical versus the hydrogeological approach (UN/ECE, 1999). According to (Harmancioglu et al., 1999), basic factors such as; sampling sites,

sampling frequencies, and time intervals constitute a coordinated monitoring network. A monitoring network design is defined by a selection of borehole locations (Loaiciga, 2008). For an effective monitoring network, environmental conditions (e.g. groundwater resource use such as aquifers affected by intensive exploitation) and human activities (e.g. so-called diffuse and point source pollution sources related to anthropogenic activities such as agriculture, landfills, abandoned municipal or industrial sites) should be understood clearly. Nixon (1997) suggests that when addressing the network density, the strategy adopted to differentiate the diffuse and point sources of pollution, as well as the differences between different types of networks, play a crucial role.

A properly designed monitoring network aids in understanding the hydrogeological (e.g. quality and quantity) state of the monitored area. Therefore, the ideal monitoring network is representative of the groundwater system with the least number of monitoring points (Baalousha, 2010). It is suggested that two approaches be utilised in optimising a monitoring network design: the geostatistical approach and the hydrogeological approach. Nunes et al. (2007) suggest that the widely used statistical approach for a monitoring network design is based on Kriging. The Kriging variance method highlights points of high variance as potential points for monitoring, however, this approach does not consider the hydrogeology of the system but focuses on the spatial distribution of monitoring points (Baalosha, 2010). The hydrogeological approach relies on hydrostratigraphic conditions that regulate groundwater system and is applied where there is insufficient data to assess the monitoring density and frequency.

Once the network design has been established, data management has to be taken into consideration. Data management deals with the conversion of data into information required and meets the objectives of the monitoring program. Quality control, correct data analysis, and timely reporting constitute good data management. In addition, data must be validated before being made available and stored in such a way that it may be interpretable and reported frequently for policymakers (UN/ECE, 2000).

2.5 Monitoring Objectives

A monitoring network describes a system where the level and quality records of groundwater are generated, become available, and are evaluated (Taylor and Alley, 2001). These data records provide fundamental information to understand the water quantity and quality. According to the European Environment Agency (1996); European Environment Agency (2008) and Vaessen and Brentführer (2015) the records are further useful as a base to predict water management actions related, but not limited to

- General surveillance purposes for early warning systems of the impacts of pollution and over-exploitation,
- How large-scale processes like climate change affect groundwater,
- Data assimilation for research,
- Information assimilation for different uses, need-oriented groundwater management and development programs,
- Assessment compliance with national legislation,
- Forecasting the impact of possible pollution sources and water quality changes caused by these sources.

2.6 Types of monitoring networks

A monitoring network provides levels and quality data that can be used to answer different questions about groundwater resources on a variety of scales. The following scale-based type of monitoring networks are distinguished (European Environment Agency, 2008; Jousma, 2008):

- Basic networks,
- Specific networks, and
- Temporary networks.

The **basic network** works for large scale regional or national monitoring networks. It covers the entire country to deliver long-term general representative information about the groundwater. The monitoring program usually has a permanent character over a long time wherein the objectives are threefold: (1) providing data for characterising the

groundwater regime, (2) providing data for detecting long-term trends in groundwater levels (quantity) or groundwater quality, and (3) serving as a reference network for the specific purpose networks (UN/ECE, 2000).

The **specific networks** are regional or local scale monitoring networks that focus on local problems and are constructed for monitoring selected areas such as point sources. Therefore, they act as impact stations (Zhou et al., 2013). The stations can form a separate network, or they can be an extension of the basic network (Nixon, 1997). The specific network can be permanent or be operational as long as there are needs for information at that specific place. This could be during the period of an envisaged or emerging impact and for a period after the target activity has ceased (European Environment Agency, 2008). Typical examples here are compliance monitoring networks operated by mining operations such as one operated by the Lets'eng Diamond Mine monitoring network.

The **temporary network** stations are established for data collection related to specific groundwater projects and are normally impact stations (Nixon, 1997). The network will often be very dense and normally operational during the project period after which they are decommissioned. However, it is often recommendable to transfer monitoring points for these networks to the basic or specific network instead of being decommissioned.

2.7 Cases studies on groundwater monitoring network optimisation

According to Zhou et al. (2013) there has been an urgent need to optimise the groundwater level monitoring network in Beijing plain, China, where a hydrogeological approach for network design was used. Groundwater regime zone mapping methodology was proposed, delineating the study area into the geology, hydrogeology, land use activities and precipitation. Through this methodology, different observation wells were located and the network optimised.

In Japan, Chaiwopu basin, a geostatistical approach was used for optimisation of the groundwater monitoring network. The Basin's monitoring network had 18 observation wells and was assessed using Kriging. By trial and error of this methodology, a network density of 55 wells with a suitable standard deviation of interpolation error was considered (Yang et al., 2008). This, therefore, suggests that the kriging

methodology optimises the groundwater network density, giving the spatial distribution of the monitoring points.

For this particular study, both the statistical and hydrogeological approaches for optimisation have been applied to aid the study meets its objectives. The hydrogeological approach gives a conceptual understanding of the hydrogeological system of the study area. It takes into consideration all physical factors and anthropogenic influences. On the other hand, the geostatistical approach optimises the network density, taking into account the variation of the spatial distribution of groundwater monitoring wells.

CHAPTER 3: Methodology

This study was undertaken as part of the Department of Water Affairs (DWA) (project number GOL-DWA-2 of 2019/202) through GCS-Lesotho. To this effect, all the project resources (data) were made available by DWA and relevant institutions. As such, different methodologies were used to address the following:

- Initial Characterisation (Characterisation of the geological, and hydrogeological situation of Lesotho)
- Review of the existing national groundwater monitoring network
- Optimisation of the national groundwater network

3.1 Initial characterisation

The initial characterisation was based on the existing static and dynamic data (e.g. geological and hydrogeological) provided by DWA, as well as identifying pressures that affect groundwater bodies.

In order to characterise the study, a semi-distribution concept was adopted by breaking the study area into smaller catchments (sub-catchments). The sub-catchments were made using the catchment delineation tool using ArcGIS's HecGeo-Ras and Global Mapper's: Watershed Tool. These software were deemed suitable for carrying out the task because of their ability to decompose larger terrains into smaller tiles, therefore, modelling results for a larger study area (Https://www.esri.com), making it easy for analysis compared to other software. The catchment delineation was further followed by a baseline hydrogeological characterisation to establish the following:

- the status of water quality in a basin,
- long-term trends in groundwater levels,
- the contributing sources of diffuse or regional groundwater contamination (mining activities, and industries.), and
- Recharge source in the catchments

ArcGIS was used to produce map (s) of each of the Prescribed Water Resources Areas (PWRAs) showing locations of monitoring points, groundwater abstraction points (wellfields), surface water resources (wetlands, rivers, and streams), diffuse-source/and or point-source and etcetera in accordance with the study's objectives

3.2 Review of the current monitoring network

The existing monitoring network was reviewed in order to establish the status quo of the network as well as to identify its gaps and strengths.

The review addressed:

- Spatial representativeness of monitoring points (boreholes and springs),
- Data quality management
- Data storage and information management

3.2.1 Spatial representativeness

The representativeness of monitoring points in each of the sub-catchments was assessed using the calculated representativity index (R_u), using the representativity indices empirical formulae below (Rentier et al 2006). This methodology seems to show good performance in describing how well represented an area is because it takes into account the different parameters (distance between points, number of points and the size of an area) that play a role in estimating the homogeneity of a groundwater monitoring network (Dabrowska et al., 2016).

$$Ru = \frac{37.7}{dav\sqrt{\frac{n}{A}}}(\%) \quad (1)$$

Where;

R_u is a representativity index,

d_{av} is an average distance to the nearest monitoring point (m),

n is a number of monitoring points, and

A is the delineated catchment area (m^2)

For a homogenous groundwater monitoring network, locations of monitoring points are chosen in a way that the distance from any point in the area to the nearest monitoring point is small relative to the area of the test site wherein the monitoring network is considered spatially representative if $R_u \geq 80\%$ (Rentier et al., 2006).

3.2.2 Data quality management

The review of the data quality management was undertaken covering aspects such as:

- quality control measures against consistency with locally and internationally approved protocols and standards,
- data quality (e.g., accuracy and completeness) of the monitoring data,
- monitoring parameters,
- documentation and records (electronic data deliverables, archival requirements)

3.2.3 Data storage and information management

This exercise reviewed elements of groundwater monitoring data management system such as:

- information storage and processing (e.g., processing methods),
- information sharing and dissemination

3.3 Design or optimisation of monitoring network

In the sub-catchments where $R_u < 80\%$, the spatial optimisation was undertaken using Kriging. This is because this statistical technique generates an estimated surface from a set of points with *z*-values, assuming that the distance from the sample points reflects a spatial correlation that can be used to explain the variation in the surface as follows (Journel and Huijbregts, 1978):

$$z\,(So) = \sum_{i=1}^{N} \lambda i\; z\,(Si) \qquad (2)$$

Where:

Z (S_o) is the prediction location

N is the number of the measured values

λi is the unknown weight for the measured value at the *i*th location. This weight (λi) is based on the distance between the measured points, predicted location, and the overall spatial arrangement of the measured points. The unknown weight was calculated using ArcGIS Spatial Analyst

Z (S_i) is the measured value at the *i*th location

To this effect, monitoring points were formulated using this statistical technique, considering a distance of (1point/ 100 km^2) for non-pressured water resources. The EU working group suggests that, where groundwater is under pressure, a distance of (1 point/ 50 km^2) should be considered (Jousma and Willems, 1996). So given that Lesotho's water resources are not under pressure yet, (1 point/ 100 km^2) was found to be appropriate.

CHAPTER 4: Initial characterisation

This chapter seeks to provide a conceptual description of the groundwater situation in Lesotho. Characterisation is essential before commencing a monitoring program, simply because characterising an area helps identify representative monitoring points for optimising the network (UN/ECE, 1999).

4.1 Study Area

4.1.1 Geology

Lesotho is generally divided into three geographical regions, namely the lowlands (1400 mamsl-1750 mamsl), Mountain foothills (1750 mamsl-2000 mamsl) and basaltic highlands (≥2000 mamsl) (Figure *4*). It is covered by different rock units of the Triassic and Jurassic age belonging to the Karoo Supergroup (Schmitz and Rooyani, 1987; Grauso et al., 2020). The chronostratigraphic succession of the Karoo Supergroup shows that the lowlands and valley bottoms of the country are predominantly underlain by sediments of the 1) Molteno Formation, 2) Elliot Formation transitioning into the Clarens Formation interspersed in places by the dolerite intrusions and 3) the Quaternary deposits (recent alluvial) (*Figure 5*) (Eriksson, 1994). The highlands, on the other hand, are predominantly characterised by Drakensberg basalts of the Lesotho Formation, interspersed in places by other formations (i.e., Molteno, Elliot, Burgersdorp) and intruded by diamond-bearing kimberlite pipes and dolerite dykes.

The oldest sedimentary unit represented in Lesotho is the Burgersdorp Formation belonging to the Beaufort Group (Schluter, 2006; Grauso, 2020). The 200 m thick Burgersdorp Formation mainly consists of low permeability mudstones, siltstones, coal seams, and fine-grained sandstones intruded by dolerite ring dykes (Davies, 2003 and Abiye, 2012). The Burgersdorp Formation is then overlain by the Molteno Formation (Schluter, 2006) *(*Figure *6*). The contact between the two is marked by a basal conglomerate made up of quartzite pebbles and boulders (Grauso, 2020). Molteno Formation is 250 m thick in the south and less than 50m in the north. It consists of medium to coarse-grained buff feldspathic sandstones alternating with mudstones and siltstones (Davies, 2003; Grauso, 2020). Lying conformably above the Molteno Formation is the 100 m – 200 m thick Elliot Formation (Figure *7*). This formation

consists of red mudstones, red shales, fine to medium-grained yellow-white sandstones, and weathered clays (Schluter, 2006). The Clarens Formation then closes the sedimentary succession of the Stomberg Group. According to Davies (2003), the Clarens Formation consists of brown fine to medium-grained bedded sandstones, siltstones, and shales often cross-bedded with thin bands of chert. Amygdale-rich lava flows then constitute the Lesotho formation of the Drakensberg Group (Schluter, 2006) (Figure *8*).

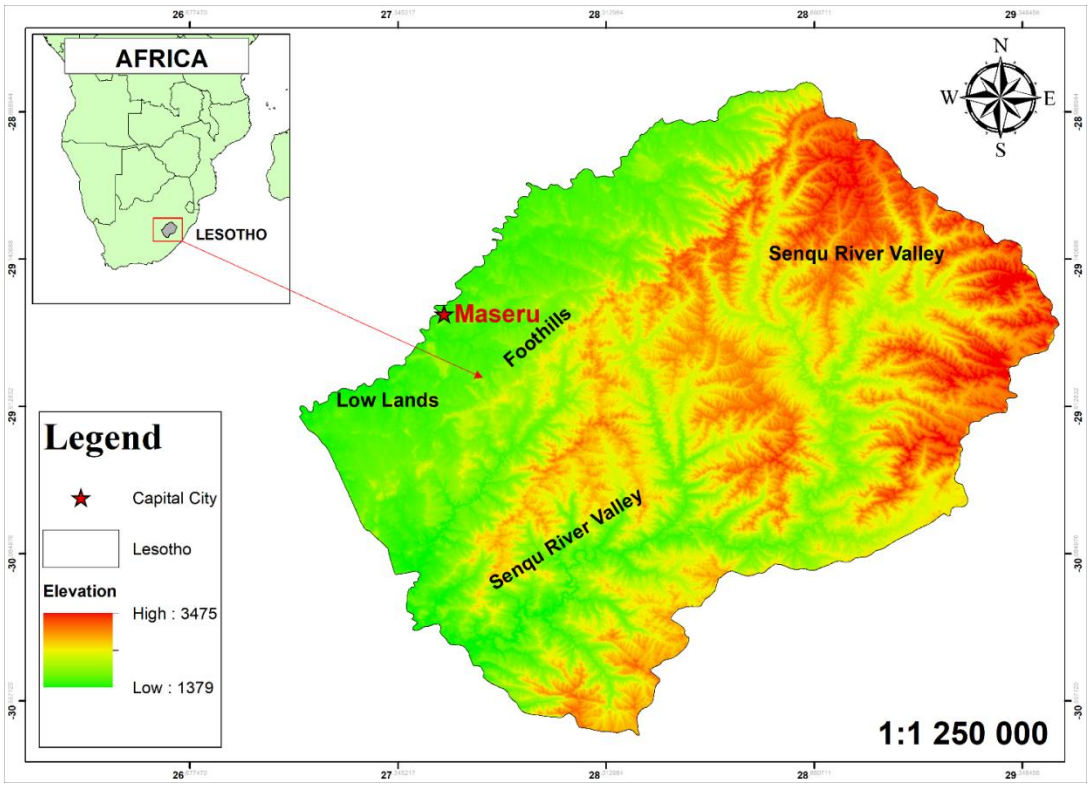

Figure 4: Digital Elevation Map for Lesotho

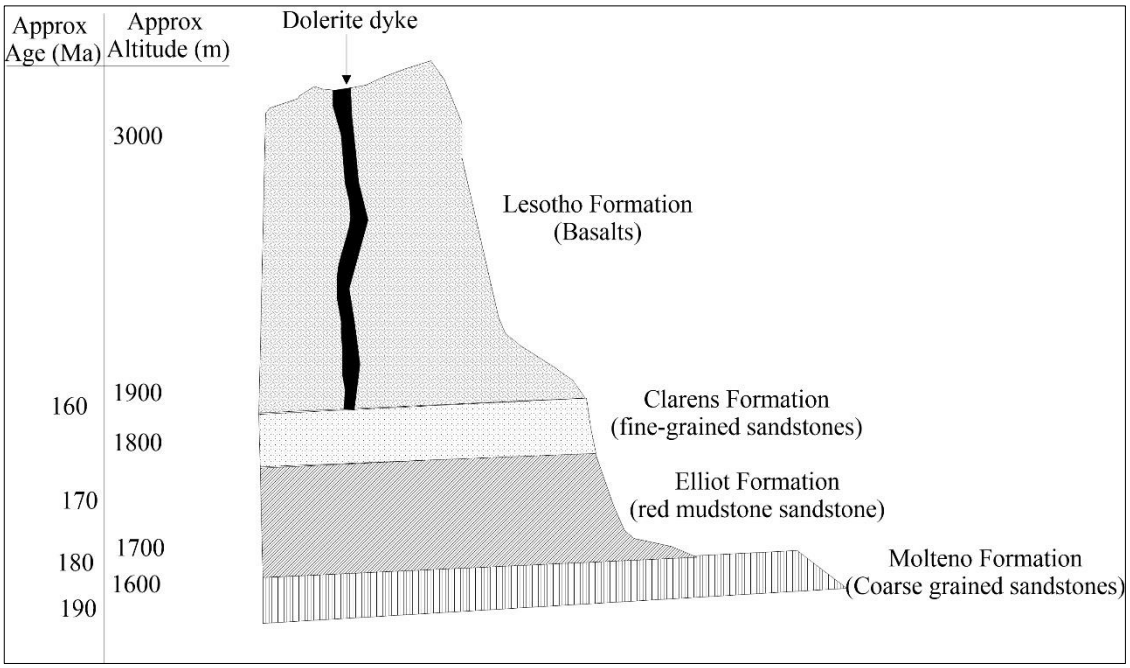

Figure 5: The geological succession on an east-west transect *through the escarpment (*Source: *Eriksson, 1994)*

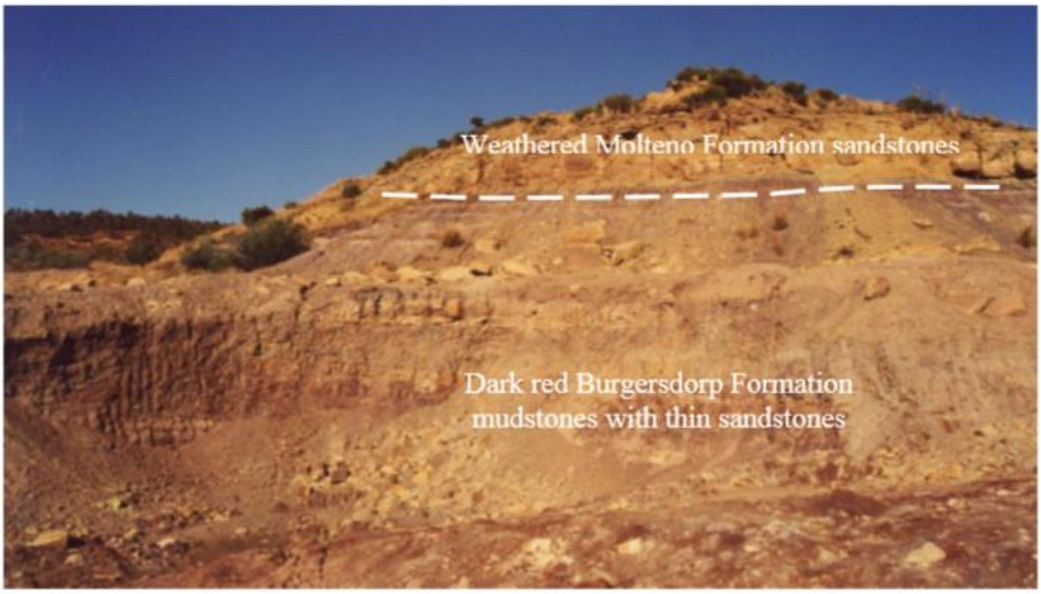

Figure 6: Molteno Formation overlying the Bugersdorp Formation east of Mazenod in Maseru (Source: Davies, 2003)

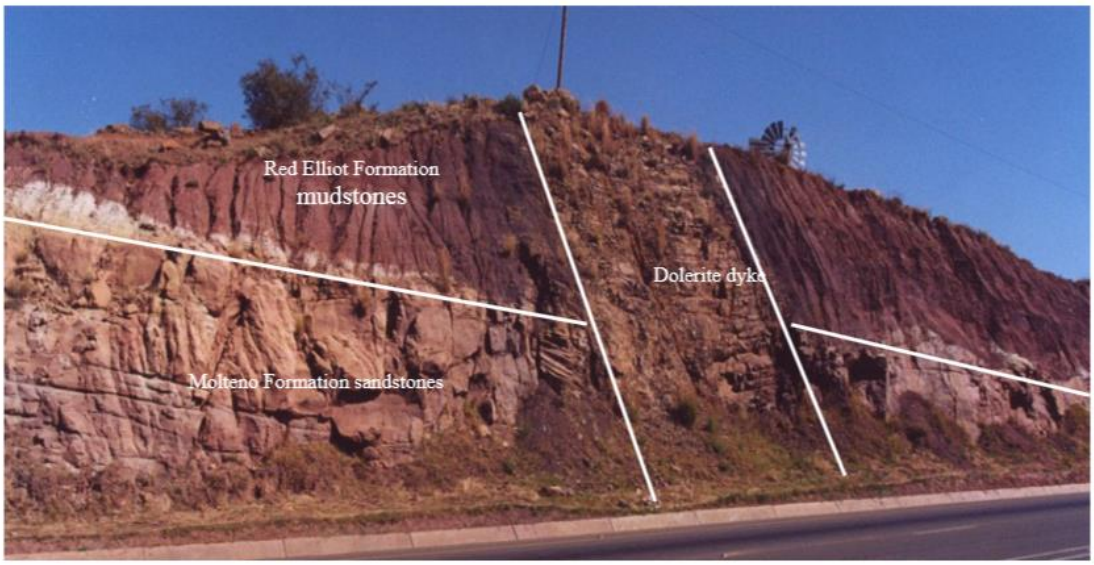

Figure 7: Elliot Formation overlying the Molteno Formation, north of Ha Maja in the Maseru district (Source: Davies, 2003)

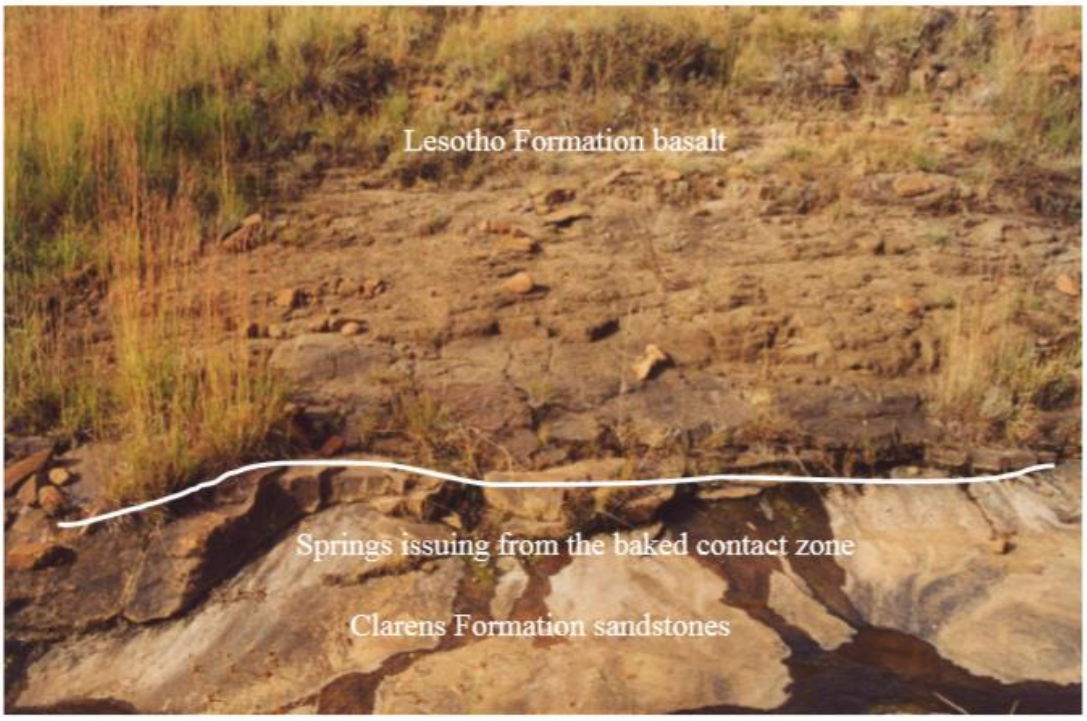

Figure 8: Lesotho Formation basalts overlying the Clarens Formation at Metolong in Maseru (Source: Davies, 2003)

4.1.2 Hydrogeology

4.1.2.1Catchments

Lesotho has three major sub-basin river systems: the Mohokare, Makhaleng, and Senqu (FAO, 2016) (Figure *9*). These three catchments are further divided into 20 Sub-

catchments across the country (Figure *10*) of which sub-catchment 1 to 12 are found in the lowlands whereas sub-catchment 13 to 20 are in the highlands. All three rivers are characterised by a well-developed network of tributaries with high runoff during rainfall periods (SSI, 2009). The rivers do not depend on one source, instead, different sources: rain, snow, and groundwater play a crucial role in feeding them. During (October-March), 80% of the rainfall occurs, making those months high flow periods, further characterising rainfall as a primary source for those rivers (SSI, 2009). The mean annual rainfall in the Senqu catchment is 749 mm/yr, in Makhaleng 844 mm/yr and 824 mm/yr for the Mohokare catchment (Del Sette and Arduino, 1994)

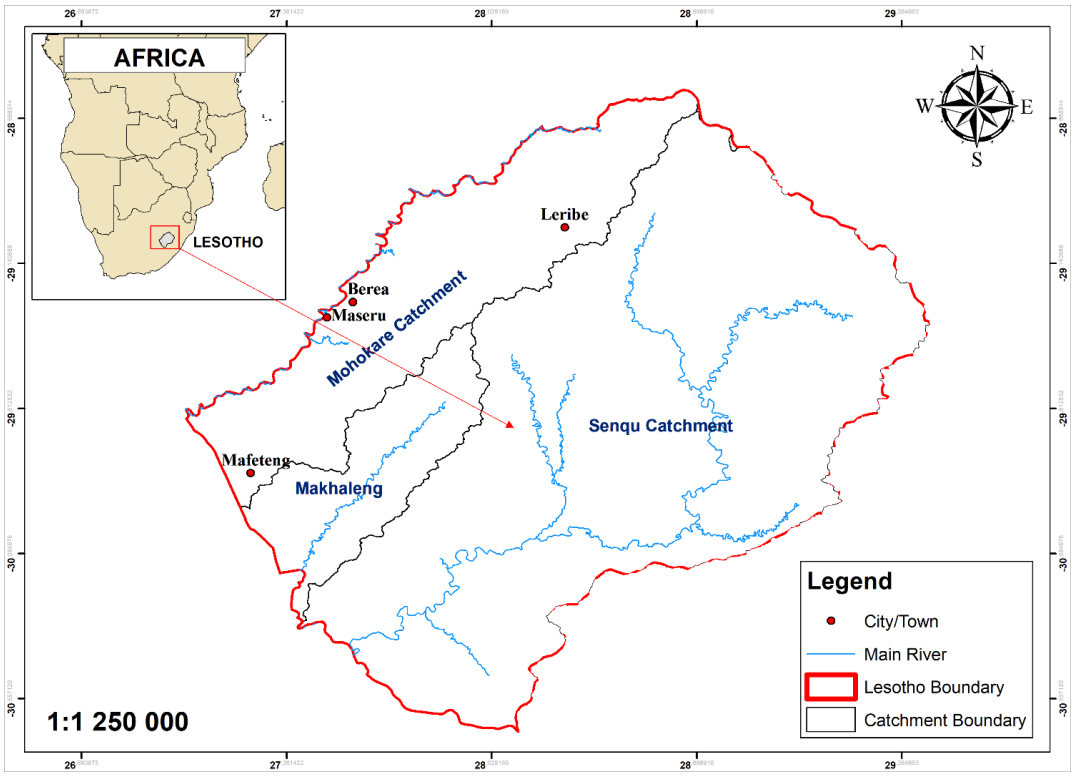

Figure 9: Major catchments in Lesotho

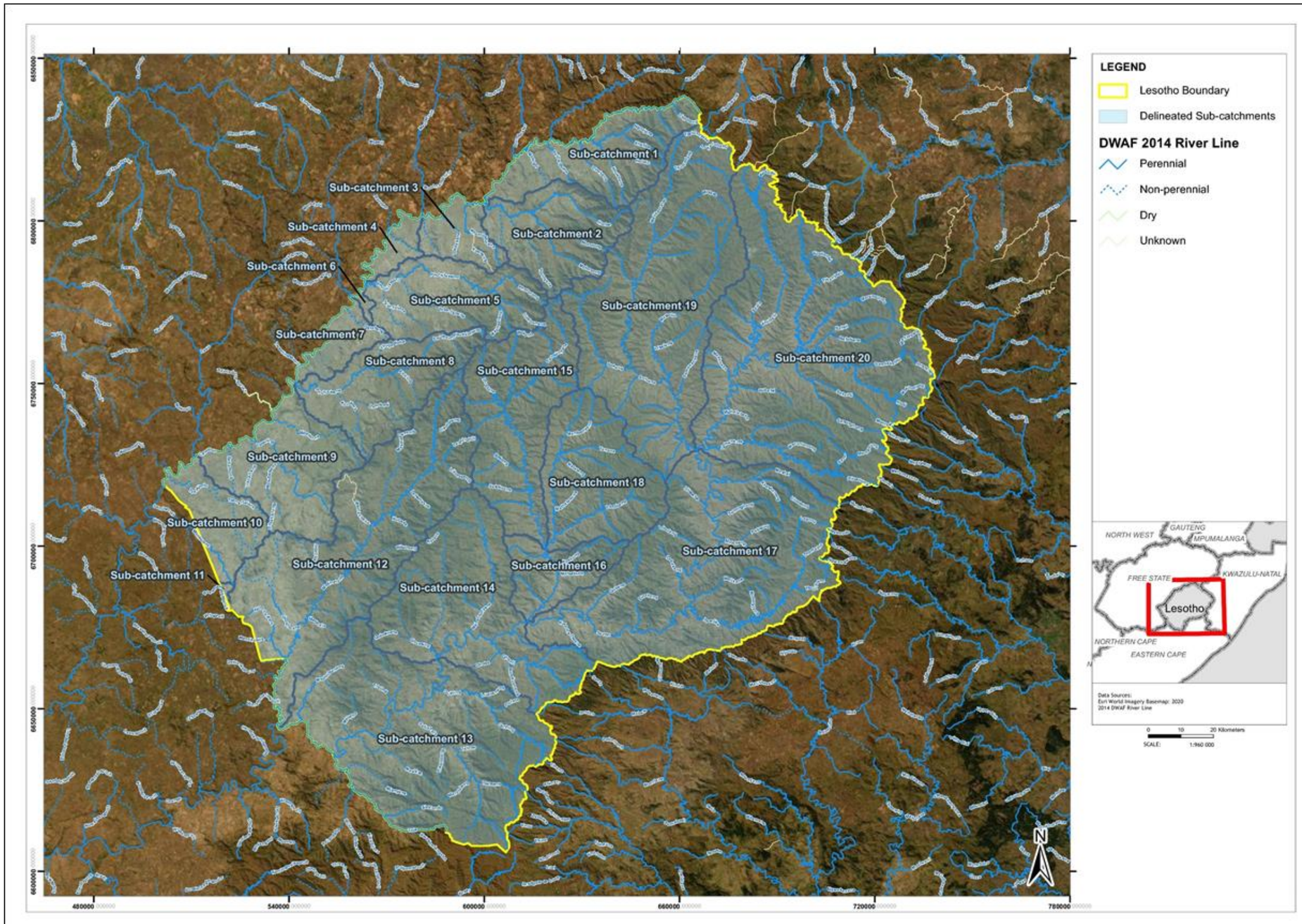

Figure 10: Map of delineated sub-catchments across Lesotho

4.1.2.1.1 Mohokare Catchment

This catchment consists of sub-catchment 1 to 10. According to (Chatanga et al., 2019) the Mohokare, also known as the Caledon River is a major tributary of the Senqu-Orange River, flowing through Leribe, Berea, Maseru, and Mafeteng (Figure *9*). Mohokare River originates from Mont-aux sources, flowing in a south-west direction where it joins the Orange Senqu River in Free State, South Africa at the Gariep reservoir (ORASECOM, 2007). It, therefore, becomes a transboundary river, forming a western border between Lesotho and South Africa. It is suggested that it has a catchment area of about 22 127.73 km^2, where, 6890 km^2 covering the northern part of the country and 15 237.73km^2 the southeast of Free State (TAMS consultant, 1996; FAO, 2016). As such, it forms the border between South Africa and Lesotho. Given that the capital city, Maseru, stands on the Mohokare River, the river then acts as the main supply of water for the city.

4.1.2.1.2 Makhaleng Catchment

The Makhaleng River rises in the Maluti ranges, in Mount Machache covering an area of 2911km^2 (FAO, 2016). This river system flows in a southwesterly direction across the highlands of Lesotho and later exits the country near Mohale's Hoek to join the Orange River (Vanden Bossche and Bernacsek, 1990). It consists of sub-catchment 11 and 12.

4.1.2.1.3 Senqu Catchment

The Senqu River is the largest river system in the country, originating north of Cathedral Dome peak (Vanden Bossche and Bernacsek, 1990). FAO (2016) states that the river then runs south, flowing out of Lesotho at the Southwestern border. It has a catchment area of 24485km^2. This catchment consists of sub-catchment 13 to 20.

4.1.3 Aquifer Properties

The occurrence and movement of groundwater are solely dependent on the hydrogeological characteristics of the sub-surface formations which vary in lithology, texture, and structure (Singhal and Gupta, 2010). Groundwater occurrence in Lesotho is, therefore, limited to fractured sedimentary and basaltic rock aquifers of the Karoo Supergroup as well as the dolerite intrusion zones with variable productivity Figure *11*- (ORASECOM, 2007):

- Sedimentary rock (fractured) aquifers (of Clarens- 0.1 l/s, Elliot- 0.1-0.2 l/s, Molteno- 0-1.6 l/s and Burgersdorp Formation- 1.16 l/s) with generally low productivity (sometimes higher),
- Basalt aquifers (of the Lesotho Formation) with generally moderate productivity (1.5 l/s)
- Alluvial aquifers with generally high to very high productivity (10- 40 l/s).
- Dolerite dyke-related aquifers with low to moderate productivity (4 l/s for boreholes and 2 l/s for springs) (Arduino et al., 1994)

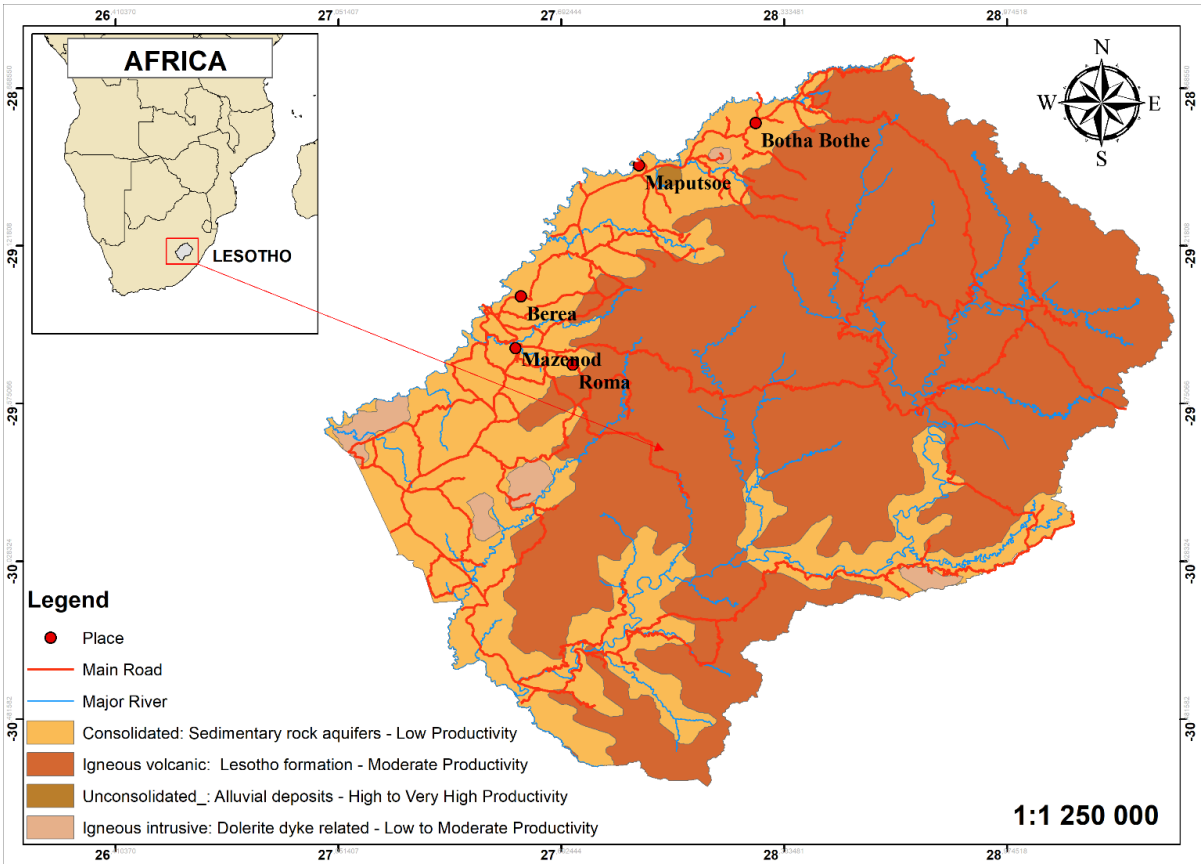

Figure 11: Aquifer Map of Lesotho

The argillaceous units in the Burgersdorp Formation yield 1.6 L/sec, Sandstones from the Molteno Formation yield 1.58 L/sec, interbedded sandstone from the Elliot Formation yields 1.34 L/sec, compact sandstones from the Elliot Formation yield 0.9 L/sec, and the weathered basalts or dyke contacts from the Lesotho Formation yield 2.55 L/sec (Davies, 2003). These low

borehole yields suggest that groundwater abstraction is likely to be small (Cobbing et al., 2008). However, it could depend on the pump capacity used for the measurement. Furthermore, the country does have exploitable alluvial aquifers with good hydraulic characteristics in Leribe (maputsoe), Botha Bothe, North of Berea and Mazenod (Figure *11*) (ORASECOM, 2007).

Burgersdorp aquifer systems are characterised by low transmissivity of 20 m^2/day and storativity of 0.00117 portraying characteristics of low permeability aquifer under semi-confined to confined groundwater conditions (ORASECOM, 2007). Boreholes yield less than 0.5 L/sec except in areas adjacent to dolerite intrusions that have high yields (Davies, 2003). Within this formation, dolerite ring dykes and sediment contacts play a role in supplying water (Cobbing et al., 2008).

The Molteno aquifer systems are characterised by low permeability semi-confined sandstones. It has both intergranular and fracture permeability that yields greater than 3 L/sec at wellfields installed in Roma and Berea (Figure *11*) (Davies, 2003; ORASECOM, 2007). The dolerite dykes further enhance the productivity of this aquifer, as secondary permeability has been enhanced by the jointing of the rocks during contact metamorphism (Davies, 2003). More productive boreholes are found in well-developed fracture zones.

The Elliot Aquifer is connected with the underlying Molteno sandstone aquifer, this is evident from water strikes found at the contact between the two (ORASECOM, 2007). According to Davies (2003), this aquifer has low permeability and is characterised by confined sandstones. Due to its compact nature, it is regarded as a poor aquifer and has less development potential. This characteristic is the same for the Clarens aquifer which is made up of compact sandstones with yields of about 0.9 L/sec (Davies, 2003).

The weathered basalt horizons and adjacent dolerite dykes in the highlands of Lesotho give rise to numerous highly productive springs (ORASECOM, 2007). A number of boreholes record high yields with water strikes occurring in the weathered mantle, dykes as well as fracture zones. Sometimes, boreholes yield more than 10 L/sec.

Evidently, the presence of dykes in these formations is paramount as they enhance hydraulic conductivity both for the circulation and storage of groundwater. However, their storage

capacities are very low due to limited thickness, as such the storage potential of the country-rock must be used as a proxy for borehole productivity (Davies, 2003).

Alluvial aquifers are present and have excellent hydraulic characteristics (boreholes can yield up to 40 l/s) compared to other aquifers that yield above 1 l/s.

Average transmissivity values for Burgersdorp and Molteno Formation are 20 m^2/day while they are 24 m^2/day, 5 m^2/day, and 106 m^2/day for Elliot Formation, Clarens Formation, and alluvial sediments, respectively. The Burgersdorp and Elliot Formations are generally considered as a semi-confined to confined due to the low storativity (0.0005-0.00117) compared to a semi-confined Molteno Formation with storativity of 0.001 and semi-confined to unconfined alluvial sediments with storativity of 0.04 (Davies (2003).

CHAPTER 5: Reviewing the existing monitoring network

5.1 Groundwater Level Dynamics

The groundwater level time series data and aquifer lithologies of selected boreholes in Leribe, Maseru, Mafeteng, and Mohale's Hoek districts are shown below.

Figure *12* show that water levels range between <5 mbgl in Maputsoe 29 and about 16 mbgl in Maputsoe 12, this suggests two zones of groundwater level fluctuations. Boreholes located in Matukeng 7 reflect very shallow groundwater fluctuations that may be caused by induced recharge, whereas the shallow groundwater fluctuations in Maputsoe 29 could be caused by effluent from the textile industries. Furthermore, the boreholes are located on the Elliot Formation (Figure *13*), so the semi-confined sandstones allow for surface water interaction, increasing the water level. Whereas boreholes located in Maputsoe 12 show deeper groundwater levels. The fluctuations in Maputsoe 12 may be attributed to over-abstraction as the area is highly industrialized, therefore, the water demand is high.

Figure *15* shows that groundwater level in Morija 14a, Morija 14c, and Mapholo 4 is increasing. From 2001 to 2015, the water level for the Morija 14a borehole increased by 1.85 m, 3.89 m for the Morija 14c borehole and 1.97 m for the Mapholo 4 borehole. This increase may be driven by human activities in these areas or the good hydraulic properties of the Molteno Formation as indicated in Figure 14 that the boreholes are located on the Formation. On Contrary, the Likotsi 1 and Likotsi 14 boreholes show a decrease in water level. This means that these two boreholes are over-pumped, decreasing the water level.

Figure *17* shows that groundwater level fluctuations in Mafeteng are characterised by an increase from 1999 to 2016. This increase may be caused by induced recharge from effluent caused by industries in those areas. However, there are sharp declines noted in the Lempetje 4 borehole in 1999, Lempetje 3 borehole in 1999 and Ngoae 4 borehole in 2003. These declines should have been caused by dry conditions during those years. Figure *16*, therefore, highlights that all these boreholes are located on the Elliot Formation. The presence of sandstones in these formations could play a role in increasing the water level because of their high permeable nature.

Figure *19* suggests that the MH Meriting and Maseruoe boreholes portray shallow groundwater level time series, while the Braakfontein 1 and Holy cross 2 boreholes show deep groundwater level time series. However, the MH meriting borehole shows an increase in water level from 8.46 mbgl in 1990 to 6.73 mbgl in 2015. This increase may be attributed to high rates of recharge. On the other hand, the Maseruoe, Braakfontein1 and Holy cross 2 boreholes show declining water levels. This may suggest that those boreholes are under a lot of pressure due to over-pumping. Figure *18* also suggests that all boreholes are located on the Elliot Formation. The presence of sandstones in the Formation may aid explain the shallow groundwater level time series, as the high permeability may increase the rate of infiltration where the boreholes are located.

Although the long-term patterns do not show similar characteristics, the following blanket remarks are made:

- Water levels are as shallow as ≤5 metres below ground level (mbgl) in some of the boreholes while some are as deep as 42 mbgl wherein the shallower water levels may be attributed to a high level of groundwater–surface water interaction. The nearby surface water bodies like rivers influence groundwater level by maintaining an 'artificially' high minimum groundwater level. On occasions when the river runs dry, the groundwater level drops significantly from the normal minimum level.

- Groundwater fluctuates with varying amplitudes, some of which are up to 42.4 m within the aquifers

- The general trend of the hydrographs is characterised by intermittent anomalies while the decadal trend does not exhibit any recession.

- All hydrographs are characterised by a reactive decline (inter-annual groundwater level variations) due to recent reduction in rainfall (dry periods and/or draught) and seasonal responsiveness.

- After dry periods, the groundwater recharges sufficiently for groundwater levels to rebound such that there is no display of little evidence of decadal declines.

- absence of any progressive long-term decline in the hydrographs is indicative that emerging groundwater developments and climate change have not placed stress on regional groundwater resource

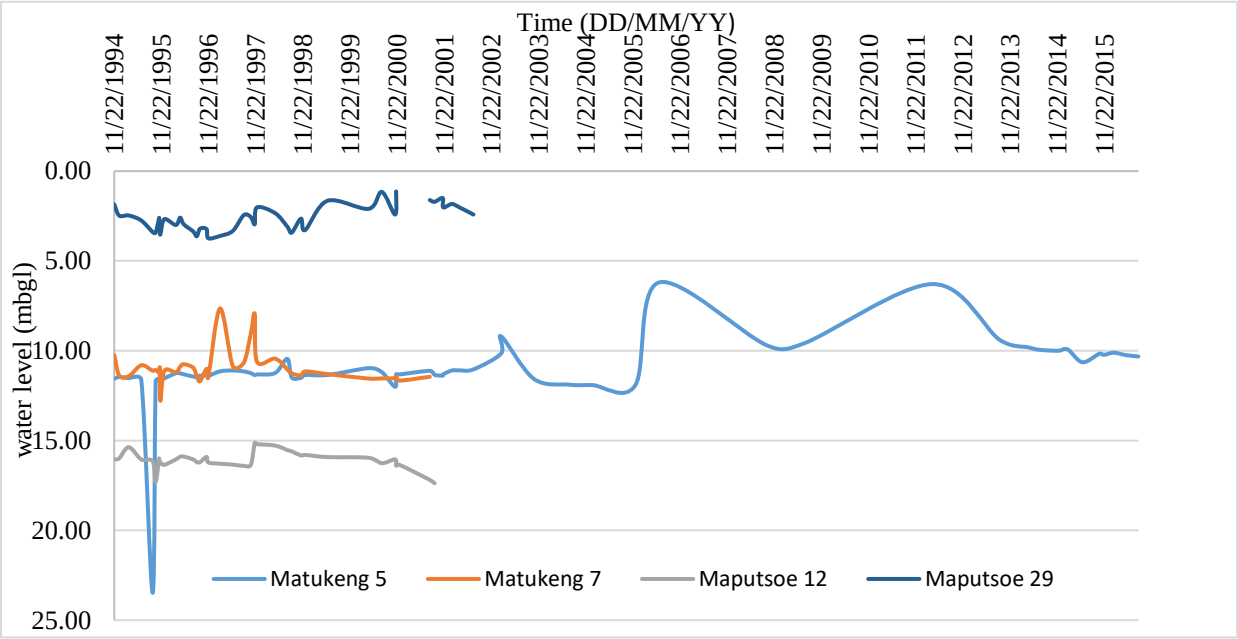

Figure 12: Groundwater level fluctuations for the selected boreholes in Leribe catchment

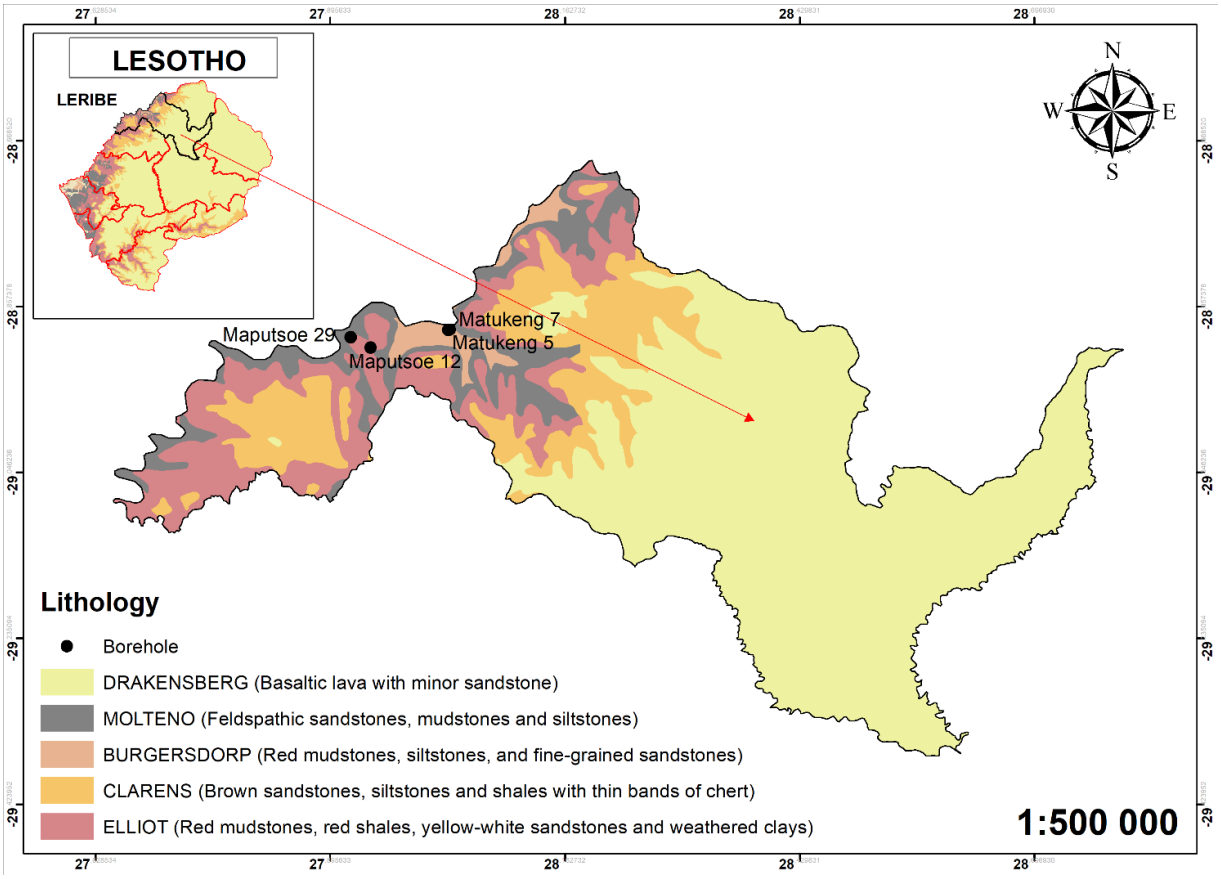

Figure 13: Aquifer lithology Map for the selected boreholes in Leribe catchment

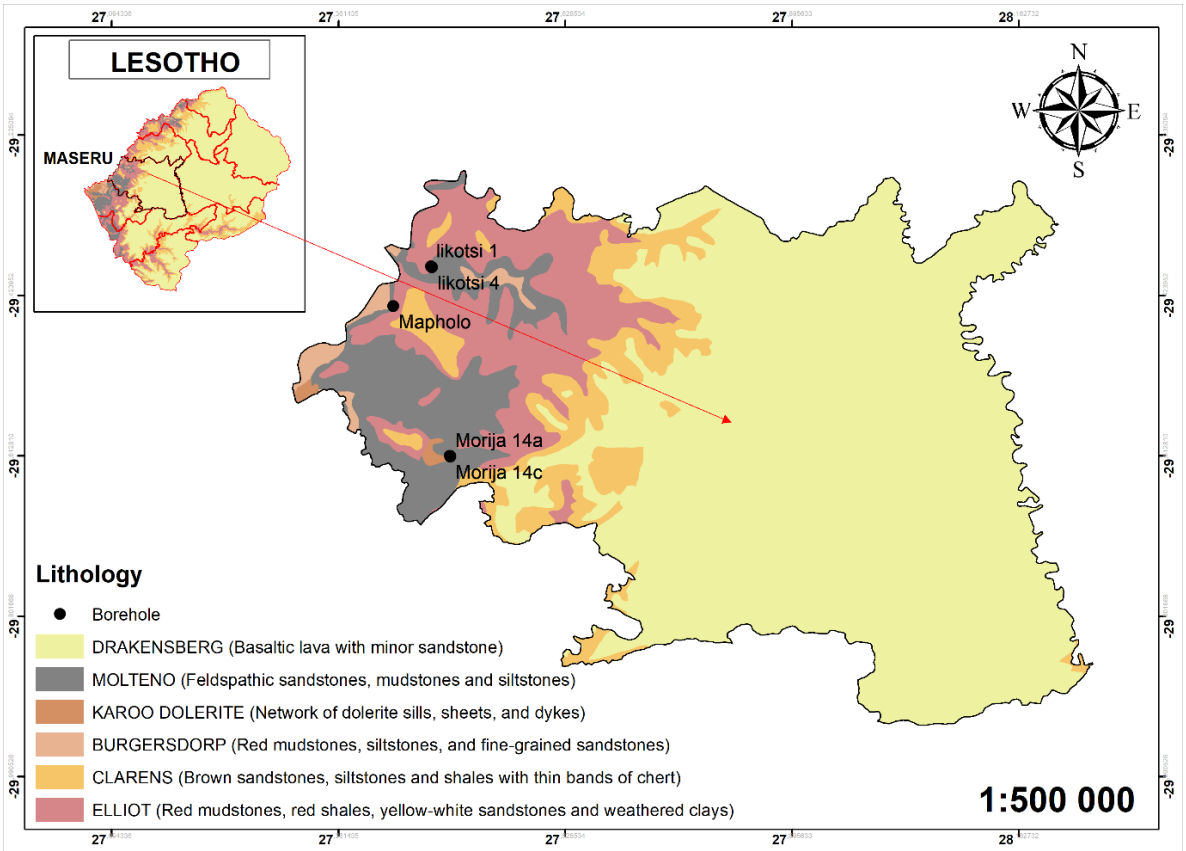

Figure 14: Aquifer lithology map for selected boreholes in Maseru catchment

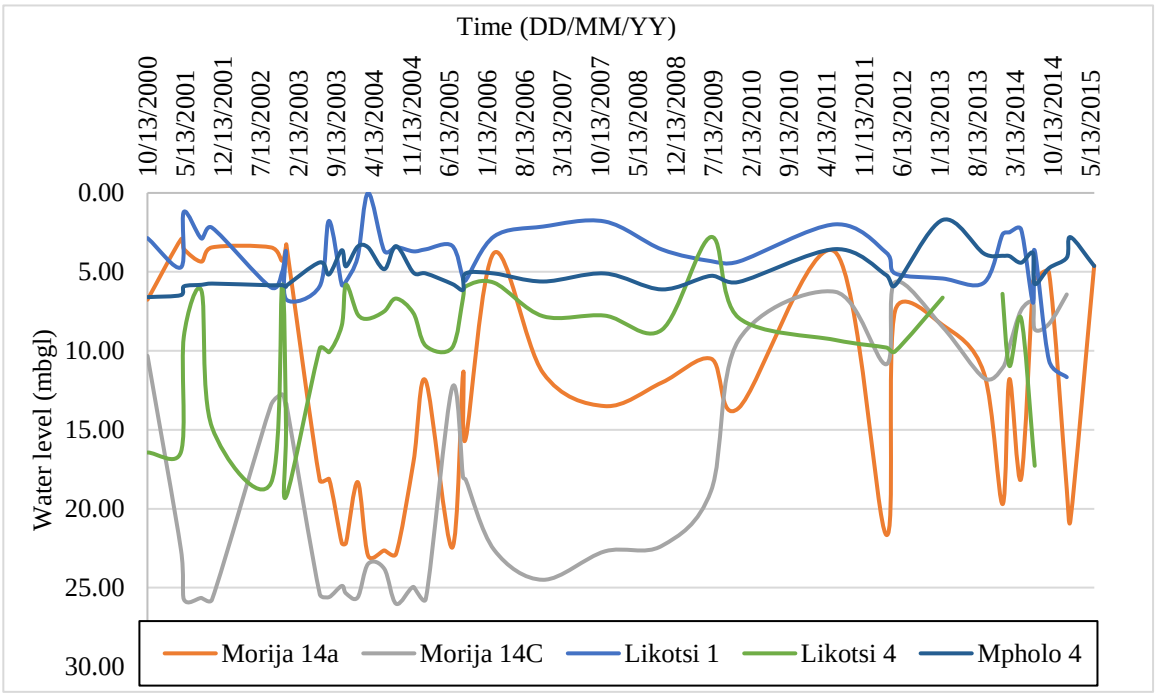

Figure 15: Groundwater level fluctuations for the selected boreholes in Maseru catchment

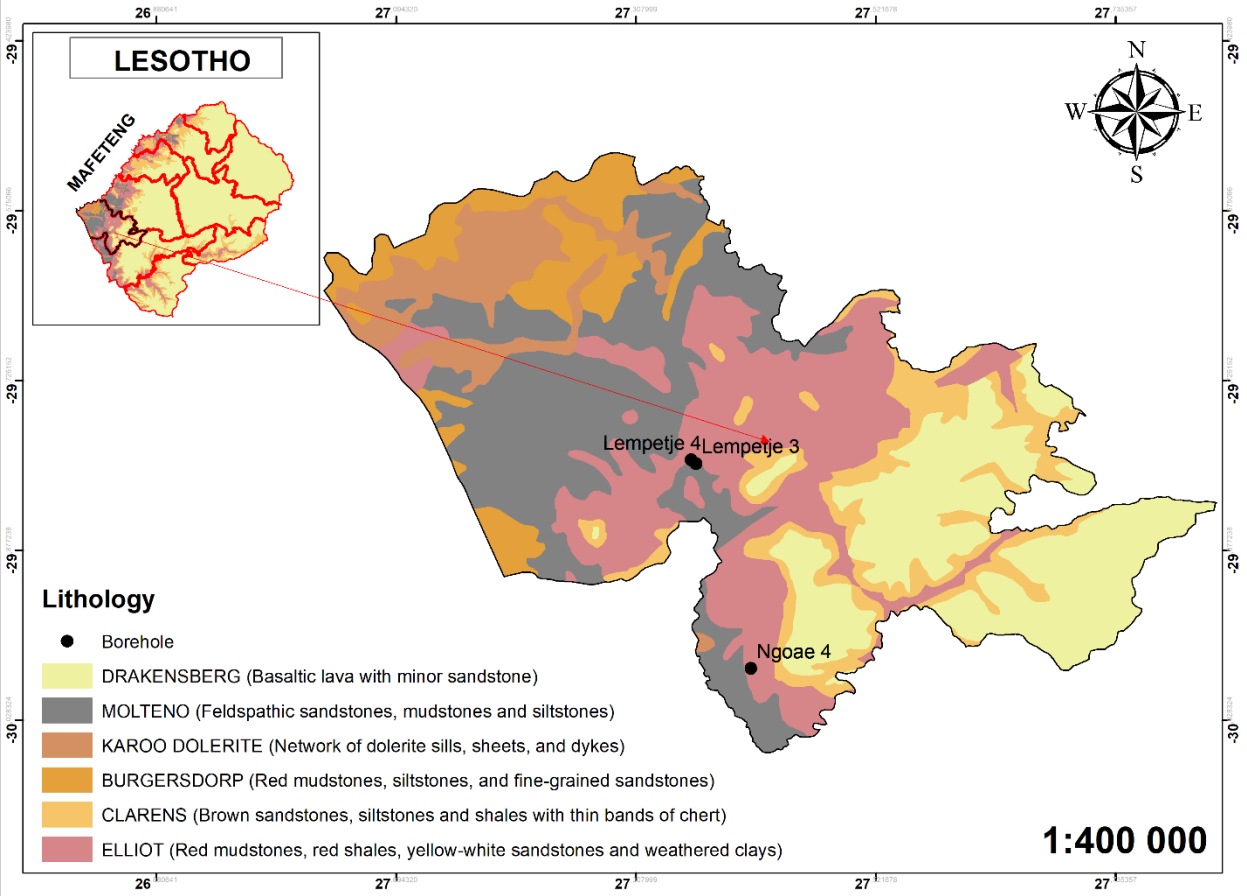

Figure 16: Aquifer lithology map for selected boreholes in Mafeteng catchment

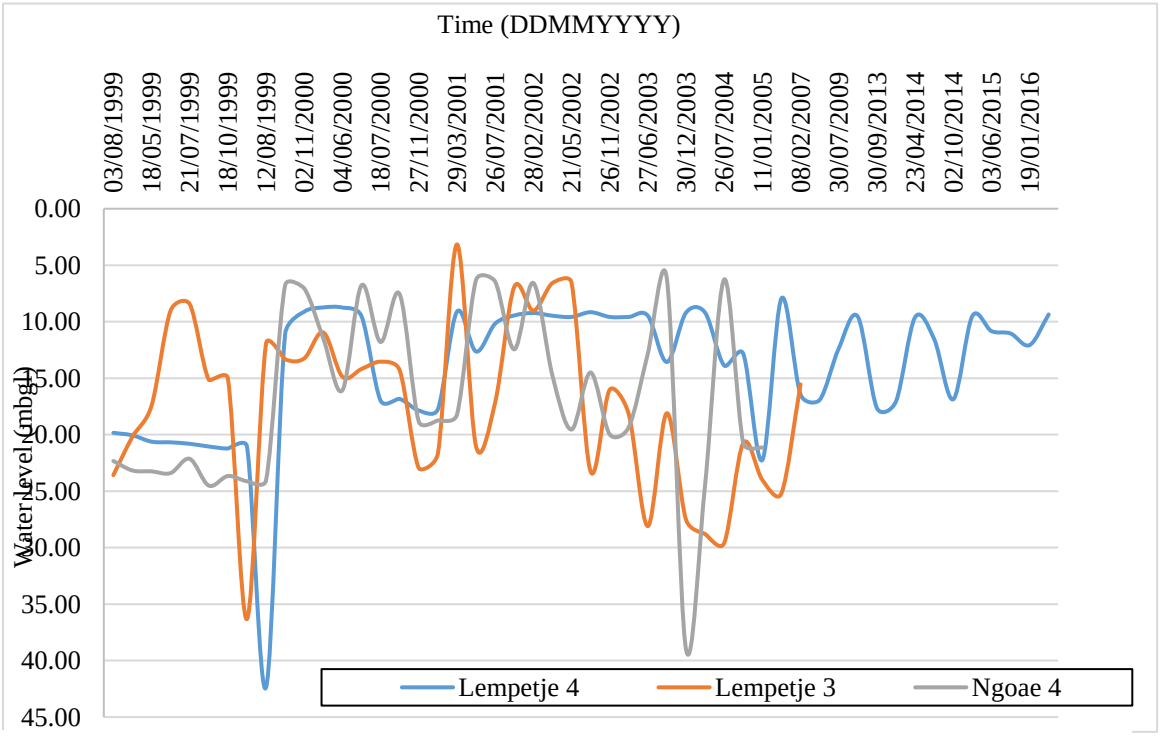

Figure 17: Groundwater level fluctuations for selected boreholes in Mafeteng

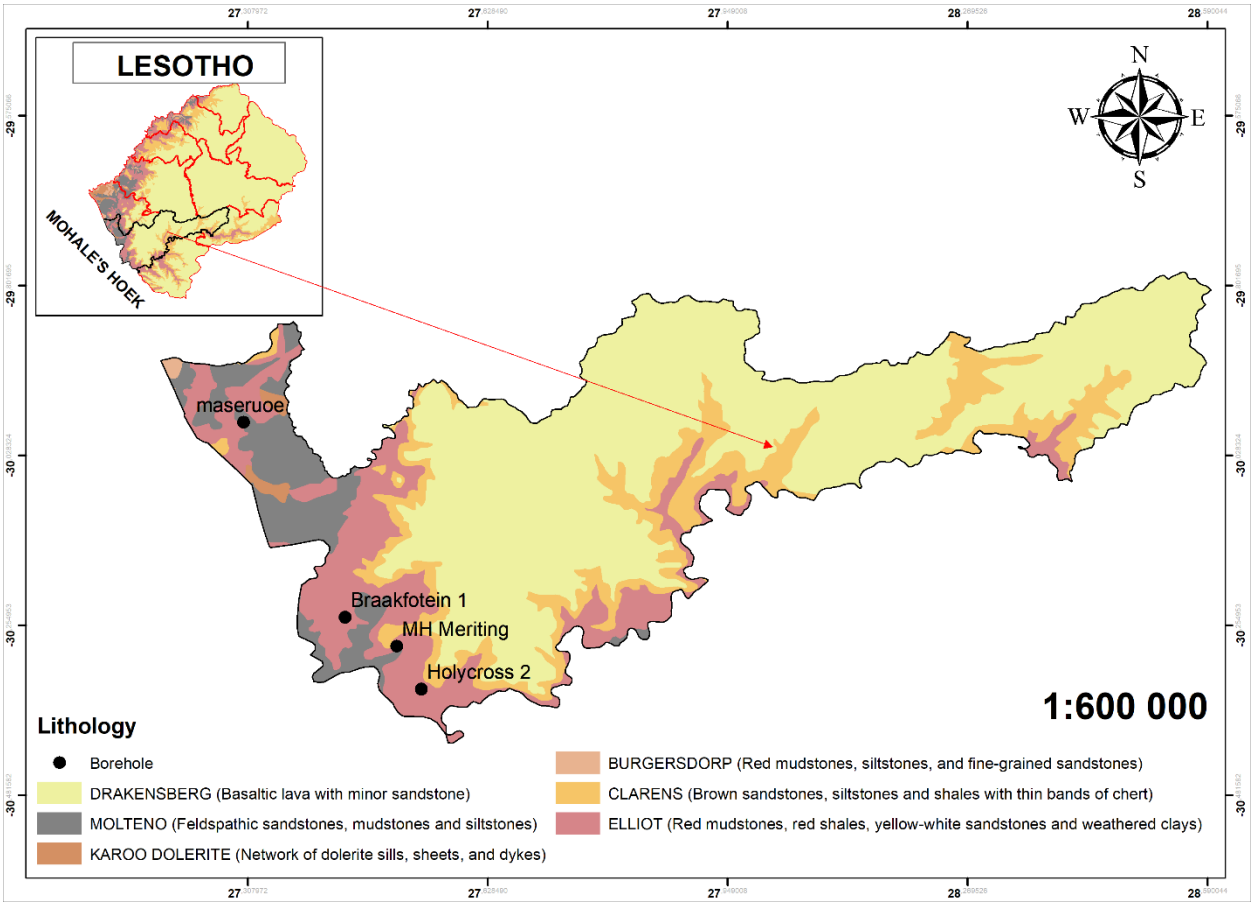

Figure 18: Aquifer lithology map for selected boreholes in Mohale's Hoek catchment

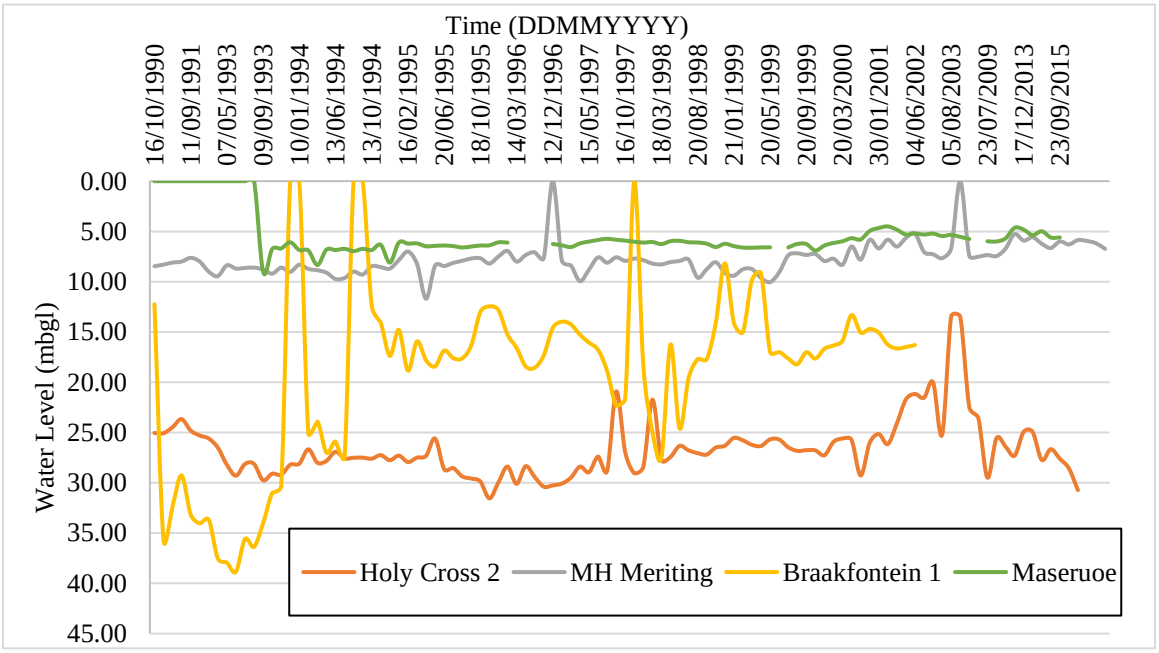

Figure 19: Groundwater level fluctuations for selected boreholes in Mohale's Hoek catchment

5.2 Groundwater Recharge

Using groundwater level fluctuations to estimate rates of recharge through the unconfined aquifer systems, TAMS (1996) reported a recharge of 2.5% of rainfall for the Lowlands region. However, Davies (2003) disputed these findings, indicating that there was no water-level data to support these estimates. Since then, there have been some developments in accumulating time series data. These data were used to tentatively affirm recharge estimates. The data used was from selected two (2) boreholes that abstained from the DWA.

The baseline and indicative recharge of the Lowlands and Highlands were estimated using the following formulation (Healy and Cook, 2002):

$$R = Sy\ \frac{\Delta h}{\Delta t} \quad (3)$$

Where:

$\frac{\Delta h}{\Delta t}$ is the average rate of the water level recession or upturn (Δh is the change in the water table (m) elevation during a given time period Δt (years) between any two measurement times. The specific yield was determined by applying the following equation on the experimental groundwater hydrographs (Raghavendran, 2013):

$$Sy = \frac{\alpha t}{d} \quad (4)$$

Where:

d is the total drawdown (m),

t is the time period (years) and

α is the recession or upturn constant for the groundwater system depleting or gaining under natural conditions (m/day). Using the experimental groundwater hydrographs, the recession/upturn constant was calculated from (Hannula *et al*., 2003):

$$a = [\ln(h1/h2)/(t2 - t1)] \quad (5)$$

Where:

h_1 is the groundwater level (m) at time t_1 (days)

h_2 is the groundwater level (m) at time t_2 (days).

Table 1: Recharge calculations for the Maseru and Mohale's Hoek districts

Recharge calculations for the Boreholes in Maseru and Mohale's Hoek		
	Ts'osane 3 Borehole (Maseru)	**Sephapho 7 Borehole (Mohale's Hoek)**
H1	23	14
H2	4	6.1
T1	2004	1995
T2	2011	2006
t	1	1
d	16	0.6
ΔH	19	7.9
ΔT	7	11
Recession constant (a)	0.249886	0.075524
Specific yield (sy)	0.015618	0.125874
Recharge	**4.24%**	**9.04%**

Using the hydrograph of a borehole (Ts'osane 3) located in Maseru catchment, recharge was calculated as 4.24% of MAP while 9.04% of MAP was calculated from the Sephapho 7 borehole located in Mohale's Hoek catchment. The 4.24% in the lowlands indicates low rainfall patterns and dry conditions. This may be driven by rising temperatures caused by pollution (global warming), or high evapotranspiration processes in the lowlands. Moreover, the low permeability rocks in the lowlands may be inhibiting groundwater infiltration. The high values in the highlands indicate high rainfall patterns or suggest that the permeability enhanced by fracturing and dykes in the highlands may cause high infiltration rates. Additionally, the effluent from mines and pit latrines artificially recharges these areas. Therefore, induced recharge is at play.

Rainfall varies from less than 300 mm in the lowlands to 1 600 mm in the highlands (FAO 2005). Consequently, a tentative groundwater recharge of 296 mm is estimated in the highlands compared to the 6 mm in the lowlands. Against this background, Abiye et al. (2018) state that increased rates of rainfalls contribute to water that reaches deep aquifers. As such, the recharge in the highlands circulates at depth through the bedrock system and discharges to surface water and/or shallow groundwater at stream valleys especially situated in the lowlands. Aquifers wherein the boreholes are located for Mohale's Hoek are more sensitive to surface contamination than those located in Maseru. The hypothesis is that near-surface contaminants are more likely to migrate downward in areas of increased groundwater recharge (IGS 2015).

5.3 Physicochemical parameters

A good water status for all groundwater bodies ensures that such resources are sustained for future generations. Quevauviller (2009) explains a good water status as the condition when groundwater is free from pollution, salinity, and other interferences that compromise its quality for different uses and does not exceed applicable water quality standards in place. Thus, groundwater quality is a major constraint on groundwater utilisation. Table *2* presents average values of physical parameters measured in all 10 districts, as well as their ranges in those districts. There is a huge variation between the parameters, and this may be attributed to land use activities in the districts or the heterogeneity of the geology.

Table 2: Water quality parameters in all 10 districts (https://water.org.ls.dwa/)

District	EC(µs/cm)		TDS(mg/l)		pH		Temp(°C)		DO(mg/l)		ORP(mV)	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
Botha Bothe	102	0.01-466	140	22.4-315	9.3	7.1-10.8	19.5	9.6-24.6	1.5	0-12	-63.7	-148 – 14
Leribe	73.5	0.02-363	82.6	29.1-260	7.2	6.1-11.9	18.7	11.5-25			31.8	-17 - 234
Berea	33	0.01-253	108	34-193.6	8.5	6.09-12.4	19	17-21.7	0.03	0.03-0.03	60.6	-7 - 173
Maseru	35.2	0.01-440	106	20-265	7.8	5.87-9.25	18.3	15-29.5	0.11	0.08-0.14	-7.85	-139 – 150
Mafeteng	260	0-602	167	95.2-252	8.4	7.25-10.8	18.6	11.4-25.8	2.3	1.24-5.1	-20	-53.3 – 22
Mohales Hoek	306.3	248-450	148.4	128.7-195.7	7.6	6.89-8.03	19	17.6-21.1	0.9	0.72-1.6	-30.5	-64 – 9
Quthing	40.8	0.21-404	135	30.1-209	7.6	6.48-8.2	16.5	13.4-20.4	39	39-39	20	-34.5 - 63
Qachas Nek	152.4	0.13-673	154	52.2-338	8.6	7.13-11.8	17.4	12.3-20.4			-4.5	-150 – 87.2
Thaba Tseka	83	0.23-370	167	97.3-23	7.7	7.1-8.48	15.7	12.5-20.7			-45.3	-99 – 38.3
Mokhotlong	110	0.21-480	110	11.1-240	8.1	7.13-9.52	16.8	11.1-28.3	1.7	1.7-1.7	-36.7	-152 - 18
Min	33		82.6		7.2		15.7		0.03		-63.7	
Max	306.3		167		9.3		19.5		39		60.6	
Average	119.5		131.8		8.08		17.95		6.51		-9.62	

EC= Electrical conductivity; TDS= Total Dissolved Solids; Temp=Temperature; DO= Dissolved Oxygen; ORP= Oxidation reduction potential

5.3.1 Electrical conductivity

Electrical conductivity is the ability of water to conduct electricity which is controlled by the concentration of charged ions. The EC of groundwater for the entire area varies from 33 µs/cm recorded in the Berea district to 306.3 µS/cm recorded in Mohale's Hoek with a mean value of 119.53 µS/cm (Table *2*). The high EC value recorded in Mohale's Hoek suggests that more nutrients from leaching soils are dissolved in the water.

5.3.2 Total Dissolved Solids

The total dissolved solids in groundwater are representative of the amount of dissolved inorganic salts. Most of these salts are products of chemical reactions such as dissolution (DWAF, 1999). In Lesotho the TDS value varies between a minimum of 82.6 mg/l and a maximum of 167 mg/l (Table *2*), indicating that the groundwater in the study area lies within the desirable limit of 450 mg/l as stated by (DWAF, 1999). To this effect, groundwater in Lesotho is classified as freshwater (<1000 mg/l) (Davies and De Wiest, 1966). The high TDS values are usually attributed to the leaching of salts from soils and excess untreated wastewater. The latter may be the case in the Mafeteng, this district has an industrial site (Table *2*) that contributes to the maximum value of 167 mg/l. However, this scenario does not apply in Thaba tseka since it records the same value. The high TDS value in Thaba Tseka may be caused by effluent flowing from mines (Lets'eng, Liqhobong, and Kao) in the neighbouring district, Mokhotlong. Another reason for this may be that evaporative enrichment occurred. Given that Basotho residing in the highlands (Thaba Tseka) depend on farming for survival, the application of fertilizers and manure could increase the concentration of dissolved salts. It could be that irrigation water was removed via evaporation leaving behind increased levels of salts or the uptake of water by plants may have been at play as well. The high concentration of TDS in Thaba Tseka and Mafeteng, therefore, poses a threat for downstream users.

5.3.3 pH

pH measures the balance between the concentration of hydrogen ions and hydroxyl ions in water. This concentration is influenced by the extent to which water molecules dissociate (Metcalf and Eddy, 2004). The pH of water thus provides information in geochemical equilibria (Hem, 1985). Raw waters are usually expected to fall within the range of 6.5-8.5 (WHO, 1996). Lesotho records pH values ranging from 7.2 to 9.3 (Table *2*). This, therefore, means that 90% of the country falls within the specified range of raw waters. It is also worthy to note that the average

value of pH value recorded show that water in the study area is alkaline in nature. The alkalinity of water may come from the geology of the catchment area as stated earlier. Igneous and sedimentary rocks often undergo slow weathering of silicate minerals, releasing concentrations of calcium, magnesium as well as sodium which have a tendency to cause alkalinity (Selinus et al., 2013). Alkalinity in itself does not have adverse effects on human beings, but in large quantities, alkalinity imparts a bitter taste to water and may result in skin and eye irritations (WHO, 1996).

5.3.4 Temperature

Groundwater temperature in Lesotho ranges between 15.7 °C and 19.5 °C, with an average value of 18 °C (Table *2*). These temperature values suggest that groundwater in the study area is preferably cool and this may be attributed to the altitude of the country. It may further, be classified as of good quality because temperature affects the rate of biological, chemical, and physical reactions occurring in water (Yilmaz and Koc, 2014). High temperatures promote the growth of Microorganisms altering the colour, odour, and taste of water (UNICEF, 2008). An optimum temperature range of 25 °C to 35 °C enhances microbial activity, whereas a temperature of 15 °C inhibits the activity of some methane-producing bacteria as well as nitrifying bacteria. Moreover, high temperatures also increase the toxicity of metals (Metcalf and Eddy, 2004).

5.3.5 Dissolved Oxygen

Dissolved oxygen concentration regulates water quality by controlling the microbial metabolism of dissolved organic species (Rose and Long, 1988). The concentration of dissolved oxygen in groundwater is usually associated with temperature and atmospheric pressure. At a high temperature of 19 °C, DO concentration is 0.03 mg/l and at a low temperature of 16.5 °C, DO concentration is 39 mg/l (Table *2*). This observation is similar to that of (Tchobanoglous et al., 2004) that suggested an inverse relationship between the two. This is because high temperatures increase metabolic rates and thus oxygen demand for aquatic systems, as the oxygen demand increases the dissolved oxygen supply decreases (DWAF, 1996).

US EPA (2012) suggests that DO is related to altitude, that at high altitude the DO concentration lowers due to decreasing atmospheric pressure. However, this is not the case as shown in (Table

2). It could be that at our low altitude area (Berea) there is presence of more oxidisable organic matter leading to the low DO concentration of 0.03 mg/l and atmospheric pressure does not come into play.

5.3.6 Redox

Redox potential measures the oxidizing and reducing potential of the water. The minimum value recorded in Lesotho is -63.7 mV and the maximum 60.6 mV (Table *2*). This suggests Botha Bothe has a reducing water system, releasing its electrons, therefore, toxicity of metals increases. Berea has an oxidizing system suggesting that there is a lot of oxygen present, allowing bacteria to efficiently break down contaminants but this is not the case given the DO concentration is 0.03 mg/l. The low DO concentration suggests that this was taken towards the bottom of the water body.

5.3.7 Nitrate

Figure *20* shows that nitrate concentrations of (≤6 mg/l) are largely concentrated in the lowlands, with concentrations ranging between 6-10 mg/l and ≥20 mg/l concentrated in areas where industrial sites are located as shown in (Figure *22*). The low nitrate concentrations of ≤6 mg/l may be due to the denitrification process and biogenic assimilation (Kiirikki et al., 2006). Elevated nitrate concentrations in groundwater are usually a result of human activities. These usually come from septic systems and sanitary-sewer effluents in urban areas (Chatanga et al., 2019). It is, therefore, safe to conclude that the elevated nitrate concentrations in the Leribe, Maseru, Mafeteng, and Mohale's Hoek districts come from the textile industries in those areas. However, nitrate concentrations may also be caused by domestic animal wastes, agricultural runoff and fertilizers, and atmospheric deposition.

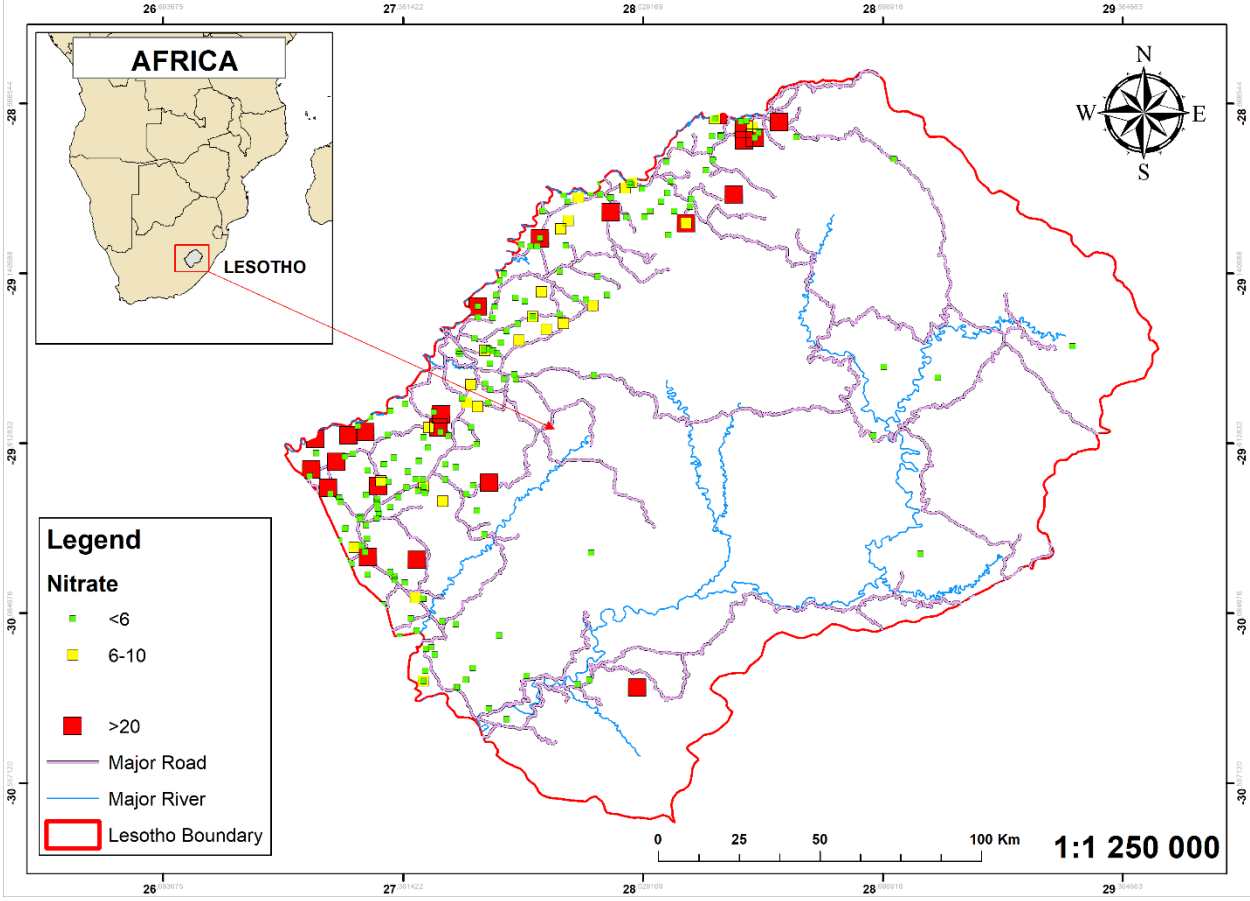

Figure 20: Map showing the Nitrate concentration in Lesotho (Shakhane, 2009)

5.3.8 Fluoride

Figure *21* indicates that the lowlands of Lesotho are dominated by <0.7 mg/l of fluoride concentrations. However, higher values of >1.5 mg/l of fluoride are observed in isolated occasions in the Leribe, Berea, Maseru, and Mafeteng districts where concentrations of up to 15mg/l were recorded in some boreholes. According to WHO (1996), the permissible drinking water limit is 1.5 mg/l, any concentration >1.5 mg/l can lead to health problems, specifically, fluorosis. Against this background, the high concentrations in the above-mentioned districts are dangerous and may be attributed to geological conditions of the districts, where leaching or weathering of fluoride-bearing minerals.

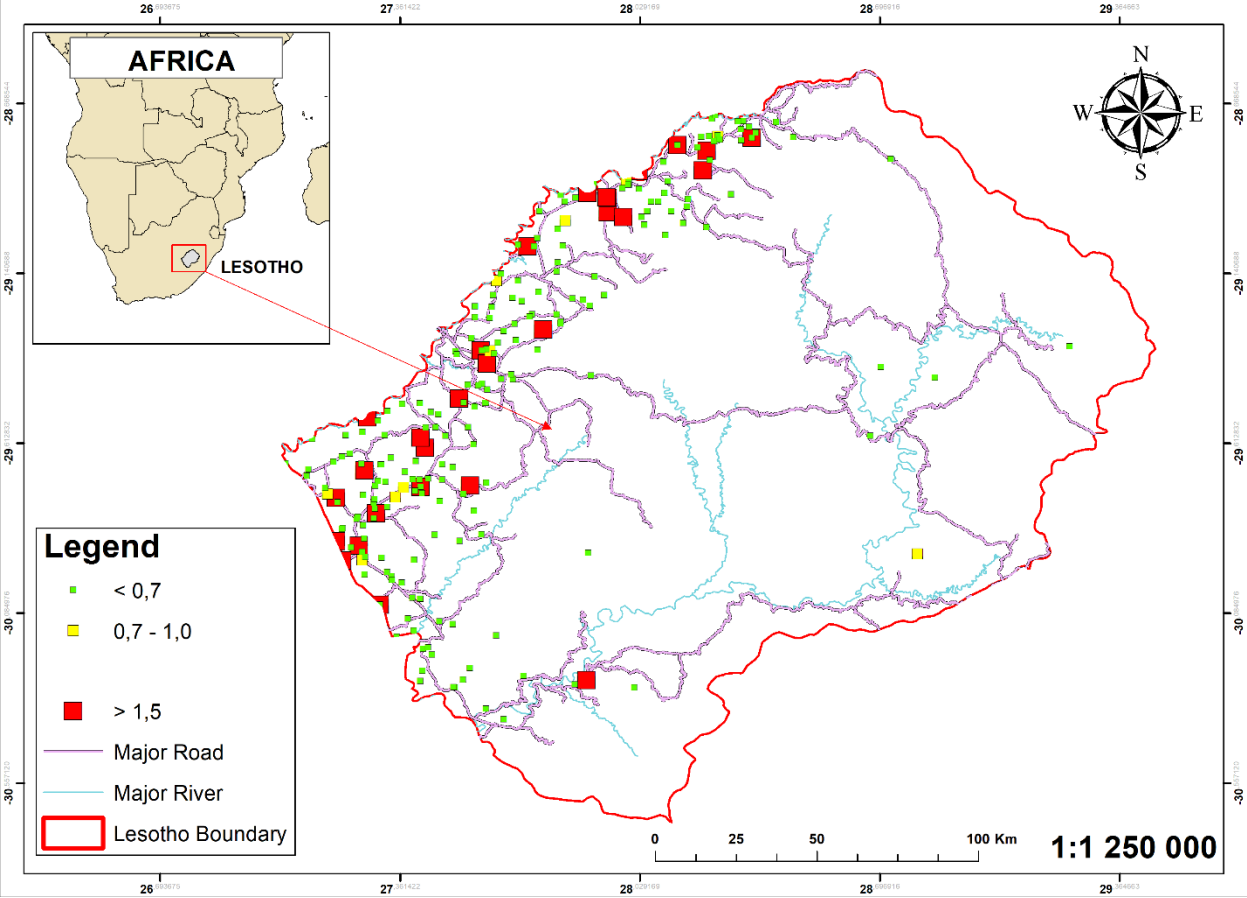

Figure 21: Map showing the fluoride concentration in Lesotho (Source: Shakhane, 2009)

5.4 National groundwater pollution sources

In Lesotho, the national key pollution sources include industrial and mining sites (Figure *22* and Figure *23*). In the past decade Lesotho has established several industries (Gibbs and Gibbs, 2003). However, these industries cause water pollution. Chatanga et al. (2019) state that these industries generate roughly 960 m^3 of wastewater per day. As shown in Figure *22* the Maseru district has a substantial amount of industries. Mining activities are also taking place in the country (Figure *23*), this is seen in the Mokhotlong district where most diamond mining takes place. Rahm et al. (2006) highlight that wastewater produced by these activities tends to contain elevated concentrations of salts, which when discharged onto the ground causes pollution and ends up compromising the water quality.

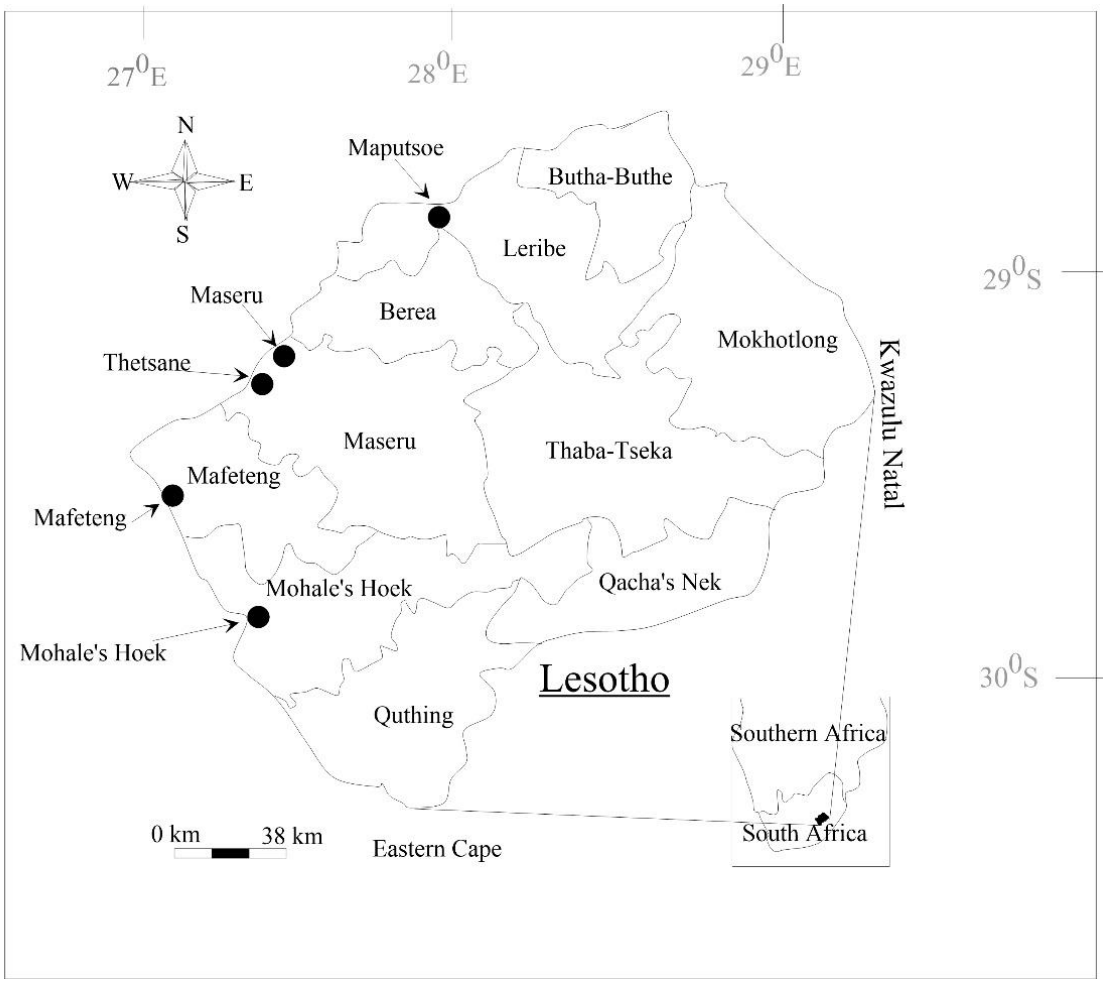

Figure 22: Map showing the location of industries in Lesotho

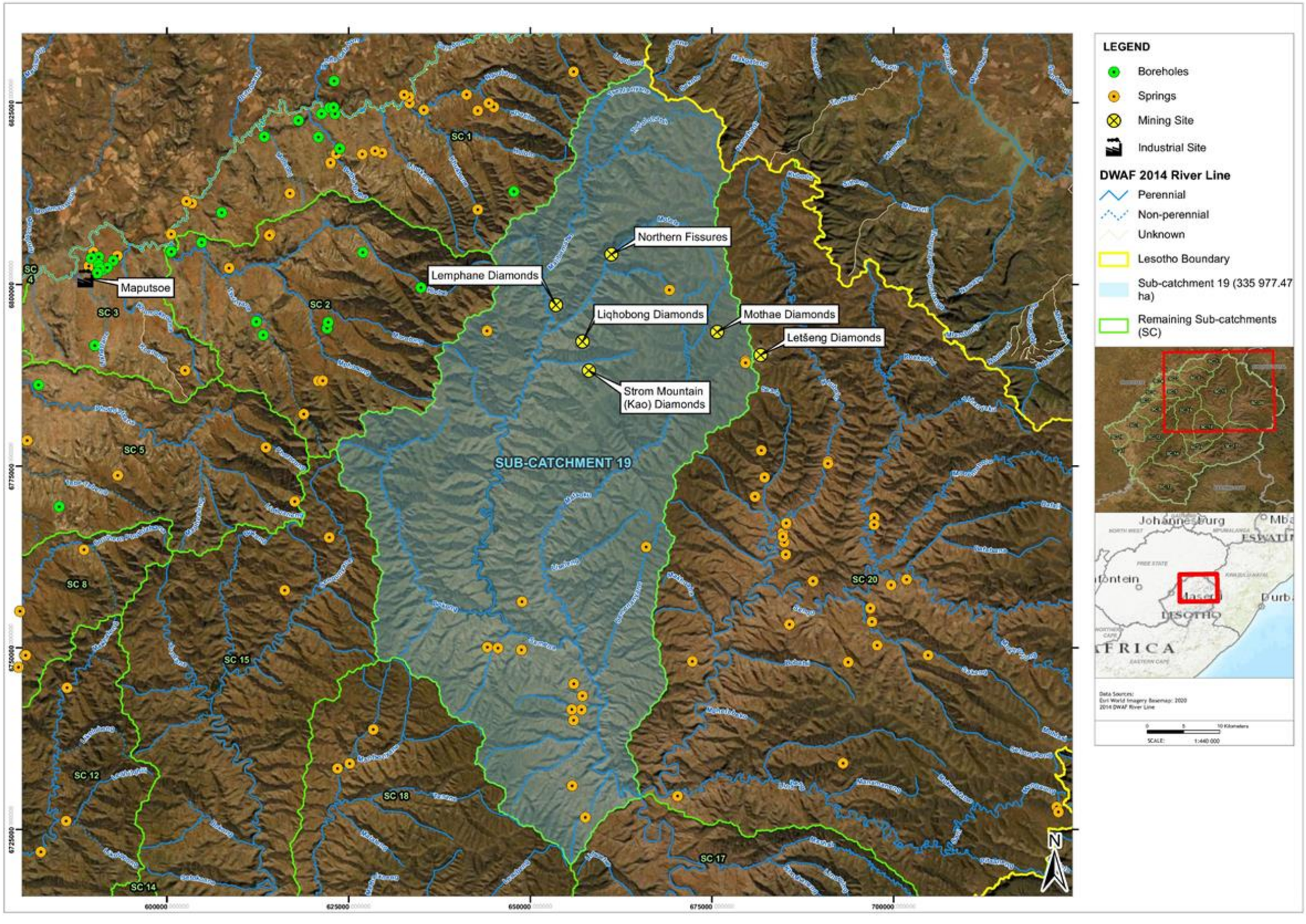

Figure 23: Map showing the location of mines in Lesoth

5.5 Status of groundwater monitoring in Lesotho

5.5.1Monitoring points representativeness

As per the recommendation by Chilton et al. (2013), the review of monitoring points representativeness was undertaken based on the following key constraints: the complexity of the hydrogeology, aquifer distribution in relation to geology, land use, groundwater contamination, and statistical considerations.

As shown in Table *3* and Figure *24*

- More monitoring points are located within the combined Burgersdorp, Clarens and Alluvial formations (34.9%) followed by Elliot (27.5%), Lesotho (22%), and Molteno (15.5%) Formations in the lowlands.
- With Burgersdorp-Clarens-Alluvial and Elliot formation occupying the most parts of the lowlands and forming the most productive aquifer systems in Lesotho, the monitoring network is found to be well represented.
- In the highlands, most of the monitoring points are represented by the Lesotho Formation, which is quite representative in many instances.
- Geologically, other formations (Elliot and Clarens) have been identified in the Highlands; within sub-catchments 13-18 which are not monitored.

The representativity index (R_u) with a three-tier rating for each of the sub-catchments (SCs) is presented in (Table *4*), and these SCs vary in size, ranging from 13.82 km^2 to 4514.47 km^2. Of these 20 SCs, only 20% have a $R_u \geq$ 80% (Table *4*). Given that finances may constrain the representativity of the network in Lesotho, a R_u of 50% seems to be a reasonable benchmark to use. Besides, Lesotho has not yet reached a stage of overexploitation of groundwater resources and industrialisation, therefore, using a R_u of 80% could be considered a luxury. Against this recommendation, 65% of the SCs have a $R_u \geq 50\%$. As highlighted that the representative index is predominantly ≥50%, the monitoring network is represented in this regard.

In terms of the national pollution sources in Lesotho, it has been established that there are no monitoring points upstream of the Maputsoe and Mafeteng factories, there are no monitoring points around the Mohale's Hoek factories yet some wells are located upstream, and lastly, there are no sufficient monitoring points around the 6 operational mines in sub-catchment 19 (Figure *23*). Now given that communities in the highlands depend on water supply from the springs, yet mining sites are also located there, more monitoring points are required in this area. With both

boreholes and textile industries located in the lowlands, it is safe to conclude that the lowlands may be under pressure, as such more monitoring points should be introduced to attain a representative index of ≥80%.

Table 3: Percentage distribution of monitoring points (springs and boreholes) in the current national monitoring network of Lesotho

Geomorphological regions	Sub-catchment ID	Lithological Formations & % coverage	Monitoring points distribution (%)			
			Lesotho	Elliot	Burgersdorp+ Clarens +Alluvial	Molteno
Lowlands and Foothills	1	Lesotho (60%), Elliot (20%), Clarens + Molteno+ Alluvial (20%)	21	38	38	4
	2	Lesotho (60%), Elliot (20%), Clarens + Molteno+ Alluvial (20%)	47	0	20	33
	3	Lesotho (5%), Elliot (70%), Clarens + Molteno + Alluvial (25%)	7	47	47	0
	4	Lesotho (3%), Elliot (80%), Clarens + Molteno + Alluvial (20)	0	33	33	33
	5	Lesotho (40%), Elliot (35), Clarens + Molteno + Alluvial (25%)	14	47	33	5
	6 & 7	Lesotho (1%), Elliot (69%), Clarens + Molteno + Alluvial (30%)	0	61	39	0
	8	Lesotho (50%), Elliot (20%), Clarens + Molteno + Alluvial (30%)	48	11	28	13
	9	Lesotho (10%), Elliot (20%), Clarens + Molteno + Alluvial (70%)	0	5	84	11
	10 & 11	Lesotho (10%), Elliot (10%), Clarens + Molteno + Alluvial (80%)	52	5	19	23
	12	Lesotho (70%), Elliot (15%), Clarens + Molteno + Alluvial (15%)	31	28	8	33
Average			**22**	**27.5**	**34.9**	**15.5**
Basaltic Highlands	13	Lesotho (60%), Elliot (25%), Clarens + Molteno + Alluvial (15%)	24	52	10	14
	14	Lesotho (80%), Elliot (5%), Clarens + Molteno + Alluvial	100	0	0	0

		(15%)				
	15	Lesotho (100%)	100	0	0	0
	16	Lesotho (90%), Elliot (2.5), Clarens + Molteno + Alluvial (6.5%)	75	0	25	0
	17	Lesotho (80%), Elliot (15%), Clarens + Molteno + Alluvial (5%)	100	0	0	0
	18	Lesotho	100	0	0	0
	19	Lesotho (100%)	100	0	0	0
	20	Lesotho (100%)	100	0	0	0
Average (%)			**87.4**	**6.5**	**4.4**	**1.8**

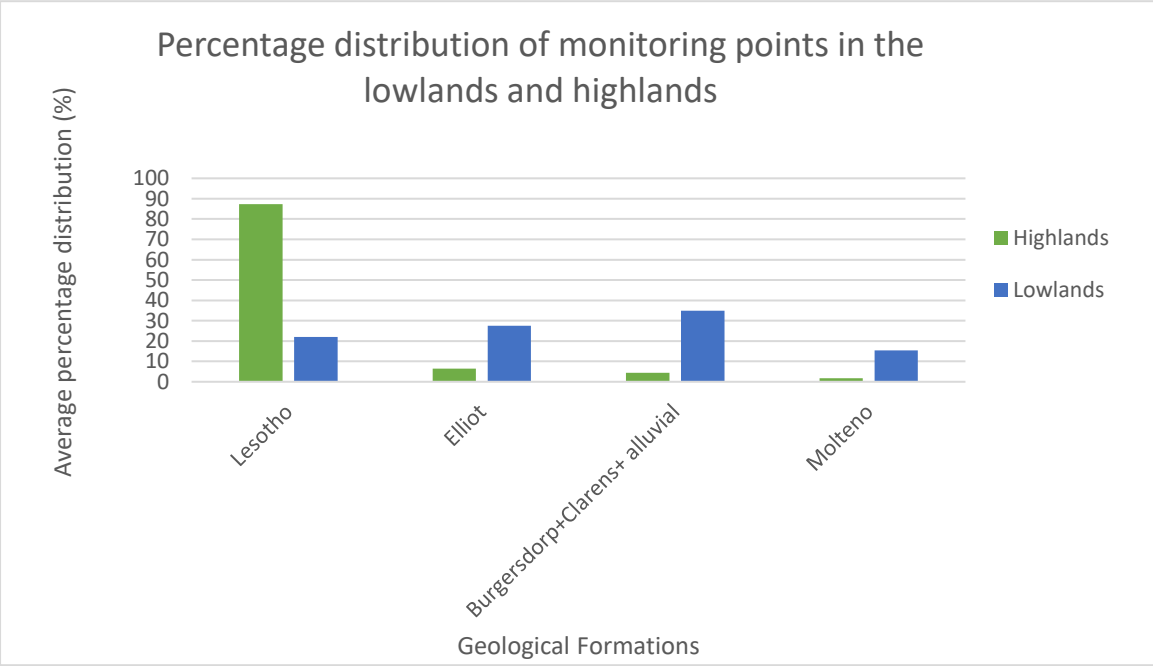

Figure 24: Monitoring points distribution in the lowlands and the highlands

Table 4: The current representativity index and rating for each of the SCs

SC ID	Area(km^2)	D_{av} (Km^2) **	R_u (%)	Rating
1	1057.0763	4	88	
2	1011.2621	10	62	
3	378.0666	10	56	
4	181.8339	10	32	
5&6	1111.592	4	34	
7	300.3648	4	70	
8	1115.3624	3	86	
9	1223.3298	6	61	
10&11	587.8459	4	55	
12	2970.2545	4	84	
13	3331.2526	4	45	
14	2771.2066	10	56	
15	1610.5985	10	36	
16	570.976	15	11	
17	3636.6358	20	31	
18	1345.8029	30	27	
19	3359.7747	20	55	
20	4514.468	20	90	
Rating				
Very Good to Excellent				$R_u \geq 80\%$
Fair to Good				$80\% \geq R_u \geq 50\%$
Poor				$R_u \leq 50\%$

** Approximated distance

5.5.2 Location and type of monitoring points

Groundwater quality, water levels and discharge data for 540 boreholes and 274 springs were received from the Department of Water Affairs (DWA). According to these data, there are approximately 636 monitoring points in Lesotho which include- 400 Boreholes, and 236 springs. About 140 boreholes and 38 springs have incorrect or missing coordinates (Table *5*) and as such plot out of Lesotho's boundaries (Figure *25*). Spatially, all the boreholes and only a few springs are largely concentrated in the lowlands whereas a greater percentage of springs are in the highlands (Figure *25*)

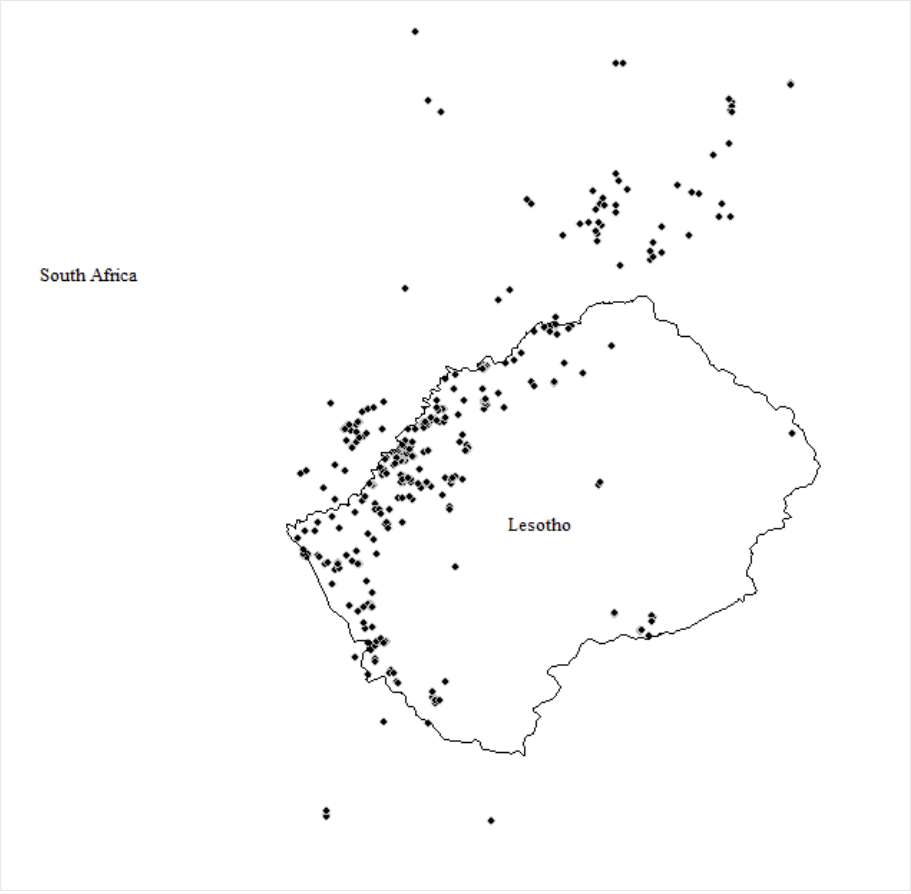

Figure 25: Location of monitoring points in the current network, wherein most points have incorrect coordinates and plot outside Lesotho's boundaries

Table 5: Example of springs with incorrect or missing coordinates in the current network

Location	Coordinates		District	Comments
	Latitude	Longitude		
Makeneng 2	28°41′07.5″	28°21′26.7″	Botha Bothe	This point lies outside and west of Lesotho
Nkhoaneng	28°49′40.1″	27°03′26.4″	Leribe	This point lies outside and north of Lesotho
London	35J059786	6748000	Maseru	This point lies far west of Lesotho
Mount Olivet			Mafeteng	No coordinates
Rakhoboko			Mafeteng	No coordinates
Masiu 1			Quthing	No coordinates
Masiu 2			Quthing	No coordinates
Kete 1			Berea	No coordinates
Kete 2			Berea	No coordinates
Kete 3			Berea	No coordinates
Ntloana-tsoana			Berea	No coordinates
Oetho			Berea	No coordinates
Maqoala			Mohale’s Hoek	No coordinates
Mosae 1			Mohale’s Hoek	No coordinates
Mosae 2			Mohale’s Hoek	No coordinates
Tsepo 1			Mohale’s Hoek	No coordinates

5.5.3 Monitoring frequency

When groundwater monitoring first started, the aim was to monitor every three months for an effective and efficiently run monitoring network. This seems to have occurred in earlier years of monitoring, however, as time went on, the department slacked a bit. The Lesotho lowlands Water Supply feasibility study by Davies (2003) suggested that from as early as 1994, DWA monitored discharge rates once a month for 84 springs and water samples were analysed for chemistry twice a year during the wet and dry seasons. The water level was monitored at a two-month interval starting in 1992. It could be that when they started, they had the capacity to monitor frequently due to the fewer number of monitoring points, but things changed with an increase in the monitoring points. The department, therefore, could not carry out the monitoring tasks, particularly water quality monitoring procedures frequently. For example, this is evident in Table *6*, which shows the spring dataset where parameters like EC, pH, and TDS were last recorded in 2014. Table *7* shows that there is a fair frequency of water level monitoring, however, there is no record of groundwater chemistry data. Table *7* is an example of one of the 370 boreholes without water chemistry data. Also, in 2003, water quality monitoring was constrained by a limited number of water samples that could be analysed in the DWA laboratory due to lack of capacity. The DWA staff could not operate an atomic absorption spectrophotometer. Laboratories capable of producing full information on the hydrochemical analysis of water samples are located in South Africa (Davies, 2003).

Table 6: Dataset of the Ha-Rapoulo spring (Mafeteng district) as stored in the data management system of the current network (https://water.org.ls.dwa/)

Ha Rapoulo 29º 42' 23.6" S , 27º 04' 24.4" E, Elvn 1596 masl							
date	**Yield (l/s)**	**Temp (ºc)**	**EC (mS/m)**	**Sal (ppt)**	**DO (mg/l)**	**pH**	**Remarks**
16/08/2013	no flow	10.1	0.30	0.42		7.83	near Tsupane functioning hand pump
30/10/2013	0.01	24.1	0.51	0.39		7.65	
16/12/2013	0.01	22.3	0.66	0.33		8.15	
26/02/2014	0.02	25.8	0.45	0.23			
15/07/2014	0.03						
22/12/2014	0.03						
17/02/2015	0.02						
18/03/2015	0.03						
16/06/2015	0.02						
19/08/2015	0.02	13.1	602.00		1.41	7.74	
17/11/2015	**No overflow**						
24/02/2016	**no flow**						
8/6/2016	**no flow**						

Table 7: An example of one of the Datasets (Sephapho 1 borehole, Mohale's Hoek district) with no groundwater chemistry data as stored in the data management system of the current network (Https://water.org.ls/dwa/)

Sephapho 1 29°56'35.0" S & 27°12'51.7"E

Date	**Water Level dry(m)**	**Water Level wet(m)**	**Water Level dry & wet(m)**	**Elevation (m)**	**Remarks**
30/09/2013	1.01		1.01	1639	near dyke on gravel RHS to the border gate
23/04/2014	0.45		0.45		
25/07/2014	0.77		0.77		
03/10/2014		0.85	0.85		
15/01/2015		0.64	0.64		
03/06/2015	0.73		0.73		
23/09/2015	0.93		0.93		
24/11/2015		0.99	0.99		
11/05/2016	0.85		0.85		
10/10/2019					

5.5.4 Monitoring parameters

The DWA has been monitoring both water quality and quantity parameters in the country. The monitoring points are limited to the water level, spring yields, rainfall, temperature, pH, EC, TDS, DO, and Redox (Table *8*). There is less data on volumes of water abstracted, turbidity, hardness, and major ion and metal concentrations, therefore, it is safe to conclude that the DWA rarely measures those parameters. Meanwhile, these parameters are essential for planning sustainable groundwater development. Their monitoring seems to be partial given they do not produce full data for the interpretation of the network, as well as to give information regarding water chemistry or groundwater evolution. However, it is also important to note that they could be monitoring only those parameters based on their monitoring objectives, which are not quite clear or they basically do not have the capacity to conduct the task.

Table 8: Dataset of the Mphenyeke borehole as stored in the data management system of the current network (https://water.org.ls/dwa/)

MPHENYEKE - LERIBE									
Date	**Yield (l/s)**		**Temp (°C)**	**EC (mS/m)**	**pH**	**DO**	**Rainfall (mm)**	**Redox (mV)**	**TDS (mg/l)**
12/01/2000	0.99	99.00	20.9	112.6	6.29		225.9	41.0	56.0
16/02/2000	0.93	93.00	22.2	141.7	6.60			23.0	71.2
16/03/2000	0.62	62.00	20.5	148.4	6.99			5.0	74.7
12/04/2000	1.12	112.00	20.6	160.4	6.45			76.0	79.4
10/05/2000	0.70	70.00	17.8	147.8	6.39			32.0	74.0
27/07/2000	0.54		18.5	262.0	6.95			4.0	134.0
14/11/2000	0.31		19.20	266.0	7.86			-38.0	134.0
10/01/2001	0.55		22.4	264.0	6.74			16.0	135.0
15/03/2001	0.12		25.6	264.0	6.83			11.0	136.0
11/07/2001	0.35		18.9	243	7.13			-4	124
15/09/2001	0.36		17.8	230	7.07			-1	119
15/11/2001	0.53		19.1	242	6.94			7	125
				Captured					

5.5.5 Data storage

In terms of data management, institutional bodies governing the groundwater monitoring network store their raw data in hardcopy data sheets as well as databases established within their respective departments as shown in Table *6* to Table *8*. The DWA makes use of an inaccessible database that was since established by the Italian groundwater program in 1982. Thereafter, the DWA database was modified by TAMS in 1996 by georeferencing the water point, but it has not been utilised nor updated for easy recording. The DRWS uses the National Database, however, this database has shortcomings such as lack of test pumping data and hydrochemical data (ORASEOM, 2007). Furthermore, data is found in technical reports produced by consultants during their execution of various projects in the country. Davies (2003) states that although data collected by consultants meet the set standards, project reports only show worked data as raw data and is not shared with DWA, hence, there is insufficient data for hydrogeologists to use.

DWA further owns a fully licensed Windows Interpretation Systems for Hydrogeologists (WISH), a graphic user interface used by hydrogeologists to execute day to day data management and reporting. However, the Microsoft excel sheet-based data file used for WISH does not show any ongoing data input or update currently taking place. WISH alone does not allow remote real-time access and querying of data.It is important that any database system is controlled and accessible, viewable, editable, and data entering controls implemented. In this regard, the setback with the WISH excel data input file is that it does not log users and changes made, which is detrimental to quality assurance measures especially given that no dedicated professional is responsible for the coding, entry, and quality control of the data input.

5.6 Summary

Based on the review made above, conclusions were drawn coincide with the TAMS (1996) report, followed by (Davies, 2003) feasibility study that both established the baseline scorecard (Table *9*) of the groundwater monitoring network, which suggest no improvement in the groundwater monitoring network. The scorecard was generated on a range scale of 0-10. Where 0-4 represents negligible, 5-6 is incomplete or insufficient, 7-8 fair, and 9-10 good. As per the scorecard the highest score is achieved by the spatial representativeness of the national groundwater monitoring locations whereas all other elements are rated poor.

Table 9: Baseline Scorecard of Lesotho's national groundwater monitoring network (Source: Tams, 1996; Davies, 2003)

Baseline Scorecard		
Elements	Determinant	Score
Spatial Representativeness	Monitoring points (Boreholes & Springs)	8
Data (Baseline, metadata& time-variant)	Spatial coordinates, Groundwater level, groundwater quality, climatic data, land-use inventories, geological maps, national key pollution sources, Hydrogeological data	4
Data management (Quality control, storage & archiving)	Data quality control (collection, validation& processing, data management (E.g. storage, archiving, process, analyzing, interpretation & analyzing)	2

CHAPTER 6: Optimisation of the network

This chapter focuses on optimising the groundwater monitoring network of Lesotho based on the review done in chapter 4. The optimisation aims to propose how the country can achieve a suitably designed and operational groundwater monitoring network. The chapter further deals with 1) monitoring objectives 2) monitoring strategies 3) it deals with recommendations for the existing data management system.

6.1 Monitoring objectives to be adopted

The DWA documents state that monitoring objectives in Lesotho are unclear. As such, Van Lanen and Carrillo-Rivera (1998) suggest that before any groundwater monitoring commences, monitoring objectives must be outlined. Sanders et al. (1987) echo this by stating that formalising an objective statement is the first and most important step in designing any monitoring network. The following are the fundamental monitoring objectives to be adopted by DWA:

6.1.1 Groundwater level monitoring objectives

DWA should measure both seasonal and long-term systematic water level measurements. This objective will provide sufficient information that will be used to evaluate how the resource changes over time as well as develop groundwater forecast trends.

6.1.2 Groundwater quality monitoring objectives

DWA should characterise groundwater quality with respect to existing water bodies. This objective will give an insight into the existing physical, biological, and chemical nature of present groundwater bodies, assisting different decision-makers to determine the potential use of the resource.

Groundwater quality monitoring objectives lay a foundation for a better understanding of environmental processes taking place, which then help water users reduce any present uncertainties pertaining to groundwater quality and allow for good management of the resource (Harmancioglu et al., 1992). Water quality data and information thus play a role in managing a country's water resources efficiently (Geldenhuys et al., 1991).

6.2 Monitoring Strategies for groundwater quality and quantity monitoring

Monitoring strategies outline the overall plan by specifying tasks to be undertaken.

- **Preliminary surveys-** DWA should conduct preliminary surveys for purposes of screening of the existing data or new information. Preliminary surveys give an insight on lithologic, hydrogeological, and aquifer characteristics information used to make conceptual models that formulate principles and guidelines to be considered when designing a monitoring network (Zhou et al., 2013). This tends to minimise duplication issues in case the same information may be retrieved from different sources. Once this is done, an understanding of groundwater systems is established thus, an effective and efficient groundwater monitoring network will be designed.
- **Selection of parameters**- for general monitoring of groundwater quality, field measurements (pH, temperature, and EC) and laboratory analysis of major ions are essential to classify water types, predict the origin of water and give an insight into indications of contamination. Groundwater level fluctuations and discharge rates should be used for groundwater level monitoring.
- **Selection of priority areas**- given that most monitoring points are clustered in the lowlands, this, therefore, suggests that spatial variability of the groundwater quality and quantity is limited. The monitoring network in place does not truly represent the existing water status. Lesotho's national groundwater monitoring network should, therefore, prioritise areas not covered by the current network (the highlands, where the representative indices are <50%) and areas in the lowlands where industrial sites are located with fewer to no monitoring points in place.

- **Aquifer vulnerability mapping**- measures the aquifer's susceptibility to contamination (Parsons, 1995). It serves as a base for prioritising monitoring, thereof, aquifers deemed to be more vulnerable require intense monitoring as an impact is most likely to occur.
- **Implementation of departmental monitor committees-** these committees will facilitate monitoring by creating monitoring guidelines, identifying information needs, and making sure that groundwater data collection is done efficiently.

6.3 Network Design

Harmancioglu et al. (1999) stated that an operational monitoring network is defined by a selection of basic factors: sampling sites, sampling frequencies, and parameters to be monitored. Sampling sites act as pathways for identifying groundwater resources, therefore, allowing detection of groundwater level fluctuations and trends in groundwater quality (Tuinhof et al., 2006). This is because monitoring points should reflect the importance of the aquifers in terms of their usage (Davies, 2003). On the other hand, sampling frequencies in network design help to regularly understand groundwater systems due to gradual changes that take place. UN/ECE (2000) highlighted that monitoring parameters define the functions of a groundwater system, so for different issues faced, a set of parameters are selected. For example, to address issues of water supply, water level and discharge rates will be monitored. To tackle pollution, major ions and minor ions will be analysed.

6.3.1 Sampling sites

The review in chapter 5 indicated that the highest representative indices ranged between 80% and 50% in the lowlands whereas, the lowest indices (≤50%) were calculated for SCs located in the highlands. As such, more monitoring points were formulated for the optimisation of this network (Figure *26*). Where new points overlap with the existing points in the current network, these points will be ignored if the existing monitoring points are still functional, otherwise, Table *10* may be considered. Taking into consideration this approach, coupled with the geological

knowledge of the study area, the land use of the study area, groundwater usage, and anthropogenic impacts affecting the aquifers and funding, these points will be considered for the network design. For example, SADC-GMI (Https://www.sadc-gmi.org) states that 86% of the country is underlain by low permeability rocks, this, therefore, means that DWA should target areas where permeability is enhanced by fracturing, dolerite dyke intrusions as well as secondary metamorphism.

Table 10: Factors to consider to retain or remove a monitoring point from a monitoring network (Source: Nobel et al, 2004)

Reasons for retaining a well in a monitoring network	**Reasons for removing a well from a monitoring network**
Well is needed to further characterise the site or monitor changes in contaminant concentrations through time	Well provides spatially redundant information with a neighboring well (e.g. same constituents, and or a short distance between wells)
Well is important for defining the lateral or vertical extent of contaminants	Well has been dry for more than two years
Well is needed to monitor water quality at a compliance or receptor exposure(e.g. water supply well)	Contaminant concentrations are consistently below laboratory detection limits or clean-up goals
Well is important for defining background water quality	Well is completed in the same water-bearing zone as nearby well(s)

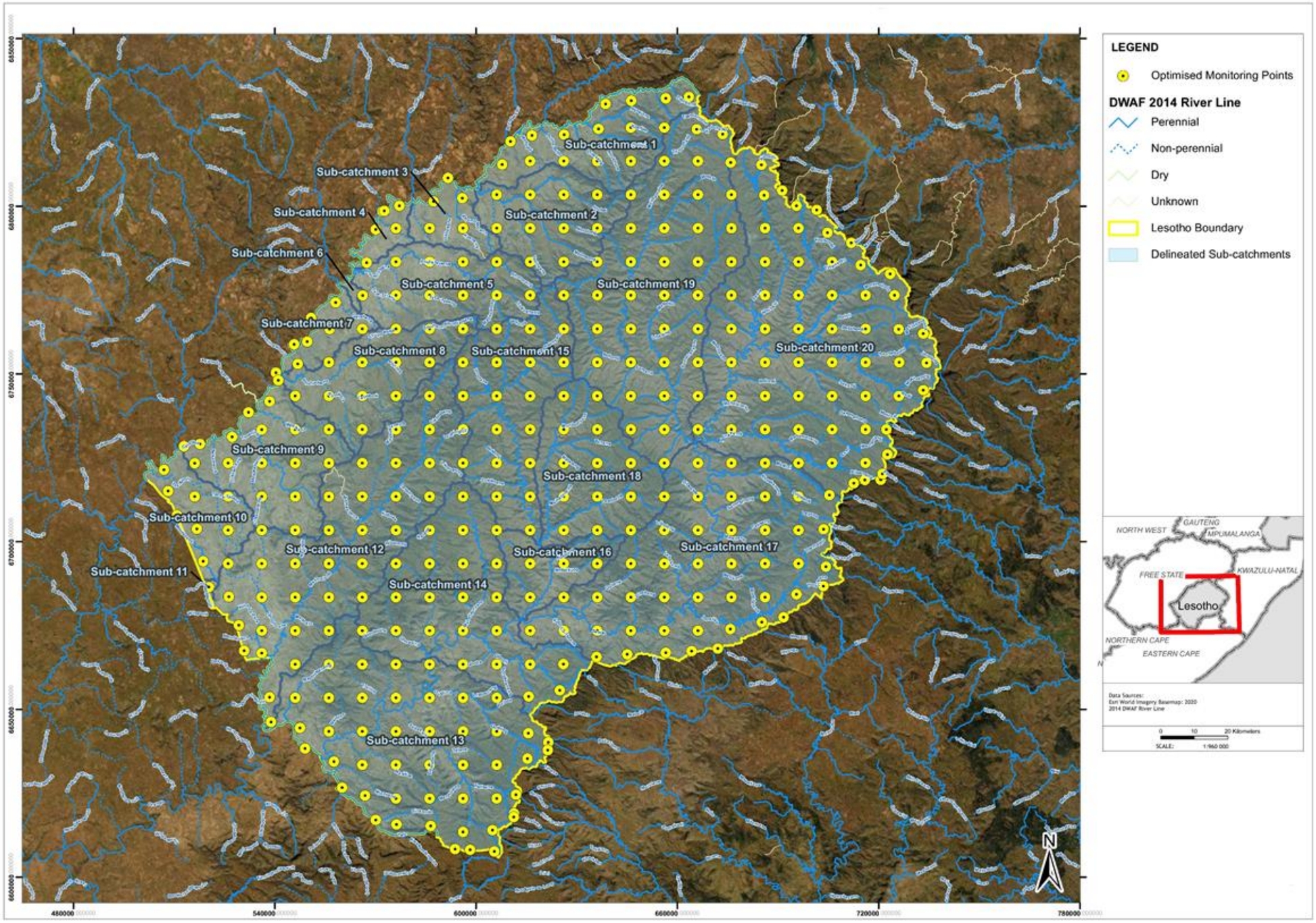

Figure 26: The optimised monitoring network showing the predetermined set of N locations based on (1 point/ 100km criterion

6.3.2 Type of monitoring points

In the existing network, both springs and boreholes are used as monitoring points. For optimisation, more springs should be considered because representative data will be obtained more easily. Moreover, data collected from springs tend to show more aggregated information compared to monitoring wells that only show well-related data (UN/ECE, 2000). Consideration may also be given to production boreholes given that they are the only wells of interest in the study area, with dynamic water level data as per long-term measurements conducted.

6.3.3 Sampling frequency

EEA (2016) suggests that for groundwater level monitoring, sampling should be conducted at least twice a year, during a period of high groundwater level and at a period of low groundwater level. However, in semi-arid regions like Lesotho, seasonal fluctuations corresponding to wet and dry seasons are dominant, as such higher frequencies of about 4 times a year are considered reasonable (IGRAC, 2008). Additionally, for production boreholes, water level measurements should be taken a few times during the period of recovery, till stability is reached (Jousma and Roelofsen, 2003). For groundwater quality monitoring, low sampling frequencies are expected in deep groundwater systems that are only affected by the natural evolution process (IGRAC, 2008). However, this is not the case in Lesotho, groundwater systems are shallow and affected by anthropogenic effects. Therefore, the sampling frequency for groundwater monitoring should be increased each year as opposed to the five-year interval for deep groundwater systems. Sampling frequencies may also be attributed to factors such as infiltration rates and velocity of groundwater. Areas with high infiltration rates should be monitored more intensively. Furthermore, in places where groundwater is relatively slow, the sampling frequency should be increased because abstraction rates are likely to cause faster changes in the groundwater system (IGRAC, 2008).

6.4 Data management

Data management deals with managing data from the point of collection up to a point where it's reported to different stakeholders and users (Figure *27*). The aim of a data management system is to enhance the effective and efficient use of data while ensuring that it is fully trusted and providing a centralised repository for storage (IGRAC, 2008). Data is converted into information that meets specific objectives of the monitoring plan (UN/ECE, 2000).

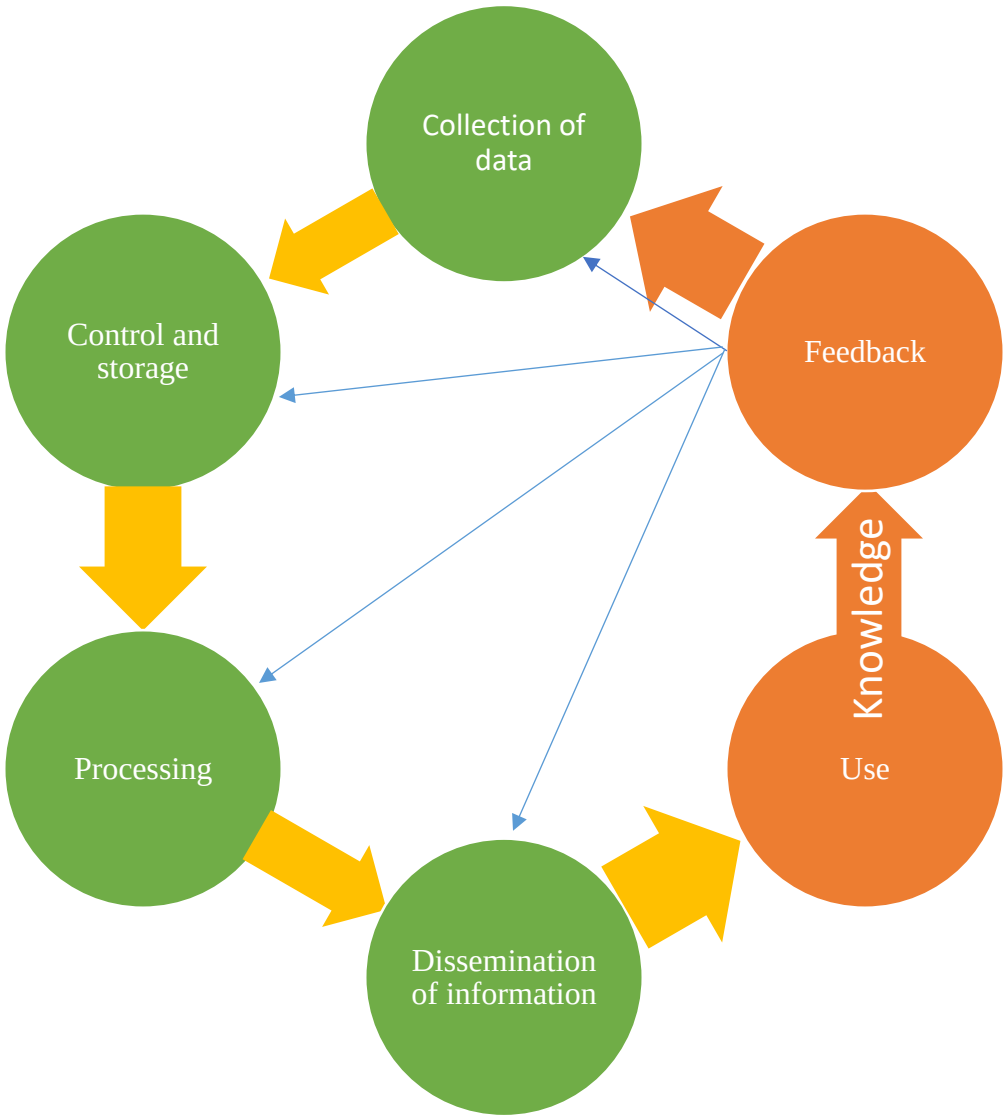

Figure 27: Data management cycle (Source: IGRAC, 2005)

6.4.1 Data collection

As indicated in the review, DWA struggles to acquire reliable information. To ensure that reliable data is collected during monitoring, a set of operating guidelines and procedures (QA/QC) must be put into place. This helps prevent or minimise the number of errors that may occur during the data collection process (SADC-GMI, 2019). Inconsistent data collection methods have proven to lead to biased data. Furthermore, UN/ECE (2000) suggests that a good budget and adequate resources must be available for high-quality data collection.

It is, therefore, advisable that the staff at DWA involved in data collection adopts and makes use of such guidelines. SDADC-GMI (2019) suggested a more general procedure to follow:

- DWA should organise short courses or workshops to ensure the technical competence of their staff, as well as sharpen their knowledge in groundwater science. This will help the staff to be in a better position to interpret any hydrogeological data and be more involved.
- Field technicians involved in groundwater data collection should be well trained. Vocational training programs should be developed to enhance capacity building for field technicians, as this will improve the quality and efficiency of the data collected.
- DWA should ensure supervision of field procedures and activities
- Field technicians tasked with the duty of collecting data should make use of data collection forms. The forms usually contain mandatory fields, which will help ensure the reliability and consistency of the data.
- Data collectors should ensure that the equipment used is always calibrated and utilised according to the guidelines put in place.
- Clearly defined communication structures should be put in place to avoid lax monitoring and limitations to detect errors.
- Field procedures must be reviewed from time to time because such procedures are revised over time and new policies introduced.

Loaiciga (2008) states that for data collection, a sufficient amount of data (Geological maps, Climatic data, Land use inventories, pollution sources, etc.) should be collected. This creates a

better understanding of the subsurface environment, giving insight into potential threats of contamination and monitoring costs to be incurred.

The following is the standard additional data required:

- The borehole/ spring should have a unique name or conventional numbering.
- The longitude and latitude coordinates and elevation should be clearly stated.
- The type (Borehole, spring, river, etc.) of the monitoring point should be stated.
- The status (in use, destroyed, abandoned) of the monitoring point should be stated.
- Information regarding the site owner should be made available
- Topographic setting should be stated

Moreover, as part of the database, lithological logs and pump test data should also be captured. After data has been entered into the database, it should then be verified against the original field forms by a third party. Furthermore, a method that involves private drillers or borehole owners should be used to supply information about the well they drilled.

6.4.2 Data validation

Data validation ensures that errors are limited throughout all stages of data management, producing high-quality data. Data must be checked and approved before it becomes accessible. Therefore, quality control procedures must be undertaken once data collected in the field gets to the DWA offices. Jousma and Roelofsen (2003) suggest that data must be cross-checked through internal and external controls to ensure that it is well assessed and processed before storage. Before capturing the data into the database, a visual inspection of the data should be carried out. DWA staff should check for outliers and missing values in the data collected. Field technicians would have to capture the data collected from the field into the database, this procedure will be done by the same individuals to minimise chances of capturing the data incorrectly. Furthermore, supervisors in the department should develop checks to trace any data that may be labelled as suspicious. This should be added as a required tool to the groundwater databases (SADC-GMI, 2019).

6.4.3 Data Storage

As established in the review chapter, Lesotho does not have any centralised database for data storage. As such, it is strongly recommended that database systems used at a national level should have the functionality to enter new data, store multiple data types in a logical manner, export data incompatible formats, as well as to establish data security, and validate data to protect it against loss or being altered by users. Lastly, it should allow multi-user options, with different user authorizations to allow multiple users to access data simultaneously.

Though cost-effective, it requires available human capacity and skills, relational databases (Figure *28*) such as MS SQL-server or Oracle databases may be opted for.

A relational database has vast advantages. It allows for large amounts of data to be stored. It has the ability to link data records, which in turn ensures functionality and flexibility when generating reports. Moreover, its data structure is set up in a way that no standard user may disrupt or corrupt it. With the mere fact that they can create index files, it becomes easier to navigate through large data sets (SADC-GMI, 2019). Relational databases such as (MS SQL) have the ability to record actions and changes made to the database by users.

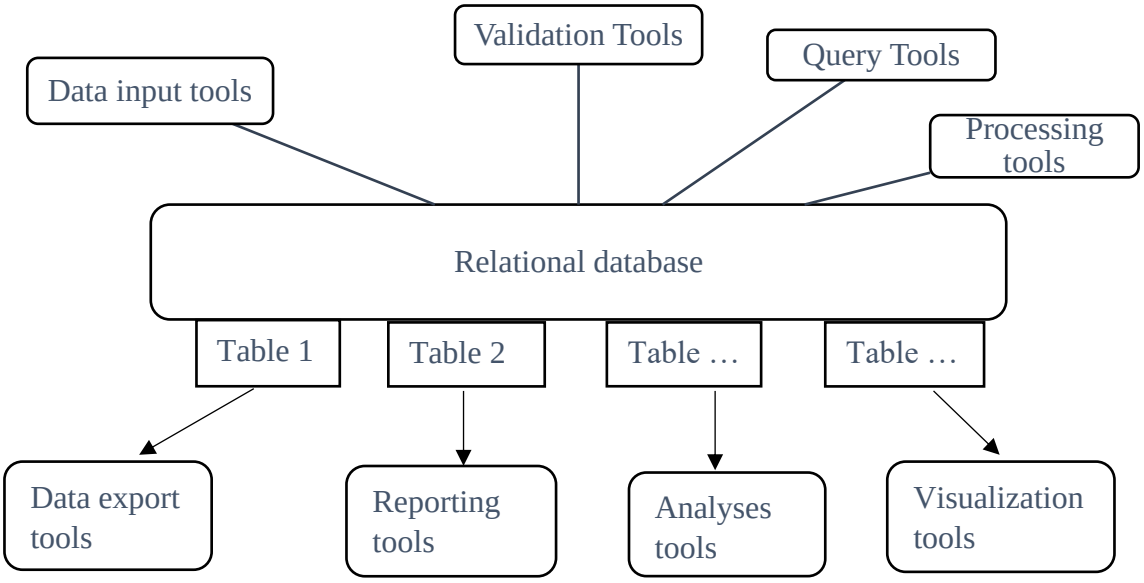

Figure 28: Relational database with tools to centralise information (Source: Fitch et al., 2016)

6.4.4 Data processing

This step involves transforming point data (water levels, hydrochemistry, borehole logs, etc.) into spatial information (Hydrogeological maps, hydrochemical distribution maps, etc.), time-series data, or statistical data (IGRAC, 2008). Data processing tools also make it easier to detect outliers and missing information in the data.

Examples of data processing methods to be adopted as per (IGRAC, 2008):

- Groundwater level should be represented in a form of contour maps in order to show the elevation of groundwater level with respect to the mean sea level. Or, it could be represented in hydrographs
- Groundwater chemistry may be represented in water quality diagrams. For example, a piper or stiff diagram may be used for the graphical representation of major ion chemistry, further making the classification and evaluation of water much easier.

6.4.5 Data Sharing and Access

The following information management tools could be explored:

- **Data reports-** Information sharing in Lesotho could be facilitated by producing quarterly or yearly data reports on groundwater quality and water level observations. These reports make the distribution of data to interested parties much easier, as they contain detailed information regarding monitoring points.

- **Open data-** Lesotho could adopt South Africa's open data sharing strategy. South Africa uses a National Groundwater Archive to share its data (SADC-GMI, 2019), and this is advantageous in the sense that it makes data accessible to anybody and does not limit sharing by imposing a nominal fee or requiring permission for usage.

- **Sharing information with the general public-** DWA should actively involve general groundwater users and other stakeholders to access all data and information regarding groundwater resources. This may be achieved by allowing groundwater users to contribute to the collection of groundwater data.

- **Open Geospatial Consortium-** for sharing geo-spatial data and geo-referenced images (map of monitoring boreholes) between geospatial data systems and users, an open geospatial consortium is a viable option to consider given a stable internet connection is established. It has applications that support the visualisation of data in any browser and downloading of data SADC-GMI (Https://www.sadc-gmi.org). Furthermore, making use of GIS-based tools help display all data linked to databases. Thus, when databases are constantly updated, updated maps are made available to stakeholders

6.5 Discussion

Optimisation must be undertaken to improve the scorecard of the groundwater monitoring network. To achieve this, spatial representativeness and data management issues should be addressed once there is funding.. By way of background, during the monitoring network review, the highest indices (R_u>50%) were calculated in the lowlands, and the lowest representative indices (R_u<50%) were calculated in the highlands. This can be enhanced by additional

monitoring points. The target areas in the lowlands must be where the major textile industries are located, mainly because in these areas, aquifers are affected by extensive exploitation and are deemed to be under a lot of pressure. Secondly, additional monitoring points should be in the highlands where there is a growing number of pit latrines and waste disposal from the mining sites. Furthermore, communities in the highlands largely depend on springs for domestic, irrigation, and drinking purposes, increasing the water demand in the area. For SC 4, 5, 6, and 18 (Table *4*), the Lesotho Formation should be targeted and for SC 16 and 17, the Molteno and Clarens Formations are ideal. This is because the geological features present in these Formations are likely to transmit groundwater. The Lesotho Formation has shown the presence of weathered basalt horizons at inter-basalt flow zones and adjacent to dolerite dykes (ORASECOM, 2007), as such, because of the basaltic weathered mantle, inter-flow zones, dykes, and fracture zones, it is likely to yield considerable amounts of groundwater.

To ensure that the drilling of these points is successful, the national groundwater monitoring network should include the private sector (drillers) and make them accountable. To this effect, drilling must be undertaken under the supervision of a qualified hydrogeologist who will be responsible for designing the borehole construction and ensuring that drillers adhere to the best drilling standard guidelines. The inclusion of drillers will enhance accountability and provide a mechanism for all stakeholders to raise their concerns about the network. As such, there are several ways in which drillers may be held accountable for the network: 1) introducing a professional drillers association that will ensure that the groundwater development industry is mandatory and technical excellence is promoted. Moreover, a database of qualified drillers will be compiled and DWA will utilise professionals from those databases. 2) Drillers should clearly outline the drilling methods and equipment used, the accurate locations of boreholes drilled, the geological formations and their depths, as well as the date on which the job was done. This will help collate and digitise the information, in turn populating the database. Furthermore, for guidelines on installation of groundwater monitoring boreholes, reference should be made to the following published paper:

- ✓ *Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells* by Aller et al (1989).

In addition to spatial representativeness, accurate data collection is essential to efficiently and effectively manage the national groundwater monitoring network. To improve data quality collected, suitably qualified and trained human resources must be implored. Having noted that there is a shortage of skilled hydrogeological expertise within the DWA, there is a tremendous need to strengthen technical capacity and involve skilled people for optimising the groundwater monitoring network. This will be achieved if DWA collaborates with geological surveys and systematic incentives for groundwater professionals as suggested by (Abiye, 2012). Ongoing training of the staff through workshops and seminars will introduce interventions that provide hands-on technical support (Davies et al., 2002). Furthermore, training at all levels will enforce that QA/QC protocols are followed, technically optimising the current groundwater monitoring network.

To ensure that DWA staff successfully implement their tasks and maintain continuity, compliance, and enforcement should be established. DWA should see to it that it implements systems and procedures that will promote effective compliance monitoring. Sound approaches DWA could look into are 1) ensuring that the staff maintains all records of groundwater quality, groundwater levels, and water use. DWA should undertake localised actions such as establishing water user associations (WUAs) within communities. These associations (WUAs) aid with the maintenance of the groundwater database by providing water use records as well as providing support to develop capacity within institutions such as DWA, 2) Regulating drillers, 3) issuing directives to correct non-compliance, and 4) establishing a regulatory framework for groundwater abstractions and monitoring wherein groundwater development and potential groundwater polluters apply for water use licenses.

Data collected should be validated and approved before it is made accessible to any user. This will be achieved by instituting random reviews of field practices to assure that data is collected according to the specifications documented. Furthermore, data quality must be checked through internal and external controls, making sure that the data has been assessed and processed before archiving and storing. Lastly, DWA must adopt a monitoring database that can keep a detailed log of actions and changes made by individual users.

To ensure that the optimised monitoring network is efficiently implemented, it is important that DWA delivers on its mandates and policies. Taking accountability for the deliverance of those

mandates will ensure that the monitoring network will be successfully governed. DWA must carry out periodic reviews of its procedures, as new policies are added or revised over time.

Additionally, involving academic institutions in the monitoring program will help implement an effective groundwater monitoring network. The engagement of academic institutions is essential to improve the level of research into the groundwater monitoring network (SADC-GMI-PLI, 2009). For this monitoring network to work effectively and efficiently, the National University of Lesotho (NUL) and Lerotholi Polytechnic (LP) should be included. Both institutions already offer courses with a component on water, but there is limited coordination between the disciplines. Therefore, they should build water institutes that will coordinate research on groundwater resources and promote the exchange of knowledge. Moreover, high-quality laboratories should be built within these institutions to help with the testing of major ion chemistry in groundwater samples.

Although funding remains a core challenge in resource-limited countries like Lesotho, the operational cost of running a monitoring program must be taken into consideration. Adequate funding is essential for the successful implementation of the groundwater monitoring network, as such, the SADC-GMI has offered funds for this current project. Consequently, aid donors such as the World Bank, African Development Bank, EU development fund and the German Federal Ministry for Economic Cooperation and Development (BMZ) should be approached to chip in funds as done for previous projects such as the integrated catchment management (ICM) undertaken in Lesotho in 2018 (EDF, 2018). In addition, DWA may fund the monitoring program by introducing a pollution tax and fees on water usage.

To establish a cost-effective monitoring network, existing monitoring points in the current network and publicly owned boreholes should be included to ensure continuity. Furthermore, DWA should consider using springs in the highlands as observation wells because no drilling will take place.

Lastly, to monitor the performance of the monitoring network, a strong and efficient monitoring unit within DWA needs to be set up. This unit will be responsible for organising annual performance audits within the department. Similarly, regular progress reports stating the achievements or challenges encountered by the monitoring network should be produced

quarterly or annually. Furthermore, evaluation reports must be shared with all stakeholders to jointly monitor the performance of the network.

CHAPTER 7: Conclusion and recommendations

7.1 Conclusion

In conclusion, the current monitoring network in place is classified as a specific network as it only focuses on local problems and deals with specific objectives set., For an optimised groundwater monitoring network, DWA should consider basic or reference monitoring to address changes in groundwater levels and quality to develop its water resources. Basic monitoring will establish long-term trends from land use changes, groundwater flow and establish anthropogenic or natural impacts affecting groundwater systems. Literature information shows that this type of monitoring supports groundwater management policies at a national scale as it generally gives a true picture of the groundwater quantity and quality of the present groundwater systems. Moreover, information collected from a basic or primary network provides a starting point for water resources planning, management, and other hydrogeological studies that may be of interest (Yangxiao, 1994). It is, therefore, befitting that, taking into consideration the information needs of Lesotho, this type of monitoring is adopted. Furthermore, specific monitoring must be included in the general monitoring plan. Individual mines such as Lets'eng already run specific monitoring networks that are not reflected in the existing network. Therefore, observing groundwater effects from pollution sources would be beneficial. This would map out the development, extent, and concentration levels of the pollution plumes (IGRAC, 2008), ensuring that efficient remediation plans are implemented. The inclusion of specific monitoring networks will further enhance spatial representativeness around groundwater resources under pressure of any sort.

The methodology proposed to account for Lesotho's national groundwater monitoring network, initial characterisation showed that the geology in the lowlands is significantly different from that of the highlands and as such plays a role in groundwater occurrence. It further reveals that groundwater occurs within fractured sedimentary and basaltic rocks, as well as fractured dolerite intrusions. The evaluation of the groundwater quantity indicated that the water level ranges between 5 and 42 metres mbgl wherein shallow water levels may be attributed to a high level of groundwater-surface interaction and deep water levels are associated with over-abstraction of the resource. This suggests that all areas with deep water levels need to be included in the

monitoring network. While the evaluation of the water quality suggested thatthe key groundwater quality issues in Lesotho are human-driven. In the highlands, the vulnerability of groundwater to pollution comes from an emerging number of pit latrines, and mining operations, whereas, in the lowlands, effluent from textile factories play a major role. In this regard, all areas prone to pollution need to be prioritised in the monitoring network. Reviewing the current network has shown that Lesotho does not have clear monitoring objectives in place, as such, the network is not properly monitored, highlightingissues such as: lack of institutional responsibilities, fair spatial representativity, poor data collection, and management. It is quite clear that no efforts have been made to improve the national groundwater monitoring network because past studies also picked up the same issues. Therefore, as a way to propose a detailed groundwater monitoring network, additional monitoring points have been formulated for optimisation in all sub-catchments with representative indices less than 50 %. A suggestion about what parameters to measure and their frequency has been made. Furthermore, ways of improving data collection and management have been stipulated in chapter 6.

7.2 Recommendations

- Clear monitoring objectives should be stated.
- Highly stressed areas and those prone to pollution should be included in the monitoring network.
- Existing specific networks at national pollution sources should be included in the current monitoring network. This will enhance spatial representativity especially around pressure and impact areas such as wellfields, industries and mining areas.
- Additional monitoring points should be added in the highlands to give a true representation of the existing water status.
- DWA should reform its guidelines for the current monitoring program. Some of the identified problems were found by previous studies but with no record of subsequent improvements
- DWA should invest more in capacity building programs aimed at minimising poor data collection, handling and storage.
- A centralised database should be used for the dissemination and sharing of information.

References

Abiye, T.A. 2012. Groundwater Needs Assessment, ORASECOM.AGW-NET

Abiye, T., Masindi, K., Mengistu, H. and Demlie, M., 2018. Understanding the groundwater-level fluctuations for better management of groundwater resource: A case in the Johannesburg region. *Groundwater for sustainable development*, *7*, pp.1-7.

Aller, L., Bennett, T.W., Hackett, G., Petty, R.J., Lehr, J.H., Sedoris, H., Nielsen, D.M. and Denne, J.E., 1989. *Handbook of Suggested Practices for the Design and Installation of Ground Water Monitoring Wells. US Environmental Protection Agency*. EPA 600/4-89/034. Dublin, Ohio.

American Meteorological Society. 2017. *Atmospheric River Glossary of Meteorology*. [Online].Available: https://glossary.ametsoc.org [Accessed on the 29th May 2020]

Arduino, G., Bono, P. and Del Sette, P., 1994. Hydrogeological Map of Lesotho, Scale: 1:300 000. Government of Italy General Directorate of Development Cooperation MOLISVGroundwater Project and Government of Lesotho Ministry of Natural Resources Department of Water Affairs, Groundwater Division.

Baalousha, H., 2010. Assessment of a groundwater quality monitoring network using vulnerability mapping and geostatistics: a case study from Heretaunga Plains, New Zealand. *Agricultural water management*, *97*(2), pp.240-246..;

Cobbing, J. E. Hobbs, P. J. Meyer, R. Davies J. 2008. A critical overview of Transboundary aquifers shared by South Africa. Hydrogeology Journal 16: 1207–1214

Chatanga, P., Ntuli, V., Mugomeri, E., Keketsi, T. and Chikowore, N.V., 2019. Situational analysis of physico-chemical, biochemical and microbiological quality of water along Mohokare River, Lesotho. *The Egyptian Journal of Aquatic Research*, *45*(1), pp.45-51.

Davis, S. & De Wiest, R. (1966) Hydrogeology (Vol. 463).

Davies, J., Lesotho Lowlands water supply feasibility study–Hydrogeology. *British Geological Survey Report CR/03 C*, *176*, p.2003.

DWAF. (1999). South African Water Quality Guidelines. Volume 1 Domestic Use

Dąbrowska, D., Kucharski, R. and Witkowski, A.J., 2016. The representativity index of a simple monitoring network with regular theoretical shapes and its practical application for the existing groundwater monitoring network of the Tychy-Urbanowice landfills, Poland. *Environmental Earth Sciences*, *75*(9), p.749.

Eriksson, P.G., McCourt, S., and Snyman, C.P., 1994. A note on the petrography of upper Karoo sandstones in the Natal Drakensberg: implications for the Clarens Formation palaeoenvironment. S. Afr J. Geol. 97: 101-103

European Development Fund, 2018. Support to Integrated Catchment Management in Lesotho.

European Environment Agency, 2008. European Freshwater Monitoring Network design. European Topic Centre on Inland Waters, Topic report no 10/96

FAO, 2005. AQUASTAT country profile-Lesotho. Food and Agriculture Organization of the United Nations. Rome, Italy. Available: https://www.fao.org/NR/Water/Aquastat/countries_regions/profile_segments/LSO . Accessed on 16th August 2020

FAO, 2016. AQUASTAT country profile-Lesotho.a Food and Agriculture Organization of the United Nations (FAO). Available: https://fao.org/NR/Water/aquastat/countries_regions/Profile_segments/LSO-WR_eng.stm Accessed 16th August 2020

Fitch. P., Brodaric, B., Stenson, M., Booth, N., 2016. Integrated Groundwater Data Management. In: Jakeman A.J., Barreteau O., Hunt R.J., Rinaudo JD., Ross A.(eds) Integrated Groundwater Management. Springer, Cham. [Online] Available: https://doi.org/10.1007/978-3319-23576-9_26 [Accessed 4th November 2020]

Foster, S., Chilton, J., Nijsten, G-J. and Richts, A., 2013. Groundwater—a global focus on the ‘‘local resource.’’ Current Opinion in Environmental Sustainability 5: 685–695

Geldenhuys, W., Nell, U. and van VEELEN, M., 1991. Surface water quality of South Africa 1978- 1988 Volume 5: drainage region J, K, L, M, N, P, Q, R and S; Technical Report TR 145, Department of Water Affairs and Forestry

Gibbs, A., Gibbs, T., 2003. A Water Supply and Poluution crisis in Lesotho’s Textile Factories: The Problems of Footloos Investment. University of Natal, South Africa, pp. 3-10

Giorgi, F., 2006. *Regional climate modelling: status and perspectives.* In Journal de Physique IV (Proceedings) vol.139, pp 101-118. EDP sciences

Grauso, S., Pasanisi, F. and Tebano, C., 2020. Modeling the suspended sediment yield in Lesotho rivers. Modeling Earth Systems and Environment, pp.1-10.

Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM, Hiscock KM, Treidel H, Aureli A (2011) Beneath the surface of global change: Impacts of climate change on groundwater. J Hydrol 405(3–4):532–560.

Hannula SR, Esposito KJ, Chermak JA, Runnells D, Keith DC (2003) Estimating groundwater discharge by hydrograph separation. Groundwater 41: 368-375.

Harmancioglu, N.B.; Alpaslan, N. and Singh, V.P., 1992. Design of water quality monitoring networks, in R. N. Chowdhury (ed.), Geomechanics and Water Engineering in Environmental Management, chp. 8, pp. 267-296.

Harmancioglu, N.B. and Alpaslan, N., 1998. Water quality monitoring network design: a problem of multi-objective decision making 1. *JAWRA Journal of the American Water Resources Association, 28*(1), pp.179-192.

Harmancioglu, N.B, Fistikoglu, O., Ozkul, S.D., Singh, V.P., and Alapaslan, M.N., 1999. Water Quality Monitoring Network Design. Springer Science+ Business Media Dordrecht

Hausfather, Z., 2018. *Explainer: What Climate Models Tell Us About Future Rainfall.* Carbon Brief

Healy, R.W. and Cook, P.G. 2002. Using ground-water levels to estimate recharge. Hydrogeology Journal, 10: 91-109.

Hsu, S.K., 1998. Plan for a groundwater monitoring network in Taiwan. *Hydrogeology Journal*, *6*(3), pp.405-415.

IGRAC, 2005. Sharing Information and Knowledge on Water: Groundwater examples. [Online]. Available: https://www.igrac.nl [Accessed on 5th November 2020]

IGRAC, 2008. Guideline on: Groundwater monitoring for general reference purposes. [Online]. Available: https://www.un-igrac.org>files>files . Accessed [27th September, 2020]

IGRAC, 2013. Groundwater monitoring in the SADC region. [Online]. Available: https://www.oieau.org/eaudoc/system/files/documents/45/226147/226147_doc.pdf igrac 2013 [accessed on the 20Th May 2020]

IGS. 2015. Aquifer Sensitivity (Near Surface). Bloomington, India

Journel, A.G. and Huijbregts, C.J., 1978. *Mining geostatistics* (Vol. 600). London: Academic press.

Jousma, G. and Willems, W.J., 1996. Groundwater monitoring networks. *European Water Pollution Control*, *5*(6), pp.52-62.

Jousma, G., and Roelofsen., F.J., 2003. Inventory of existing guidelines and protocols for groundwater assessment and monitoring. International Groundwater Resources Assessment Centre (IGRAC), Utrecht, the Netherlands

Jousma, G., 2008.Guideline on: Groundwater monitoring for general reference purposes. International Groundwater Resources Assessment Centre (IGRAC), Utrecht, the Netherlands

Kiirikki, M., Lehtoranta, J., Inkala, A., Pitkanen, H., Hietanen, S., Hall, P.O.J., Tengberg, A., Koponen, J., Sarkkula, J., 2006. A simple sediment process description suitable for 3D-ecosystem modelling- development and testing in the Gulf of Finland. J. Mar.Syst. 61 (1), pp. 55-66

Lesotho Government, 2008. Lesotho government gazette. Available: https://www.water.org.ls/download/lesotho-water-act-no-15-of-2008/?wpdmdl=5860&refresh=5f770608ca7f81601635848. Accessed [1st October, 2020]

Loaiciga, H.A., 2008. Groundwater Monitoring Network Design. Developments in Water Science Volume 36: 371-376

Mare, H., 2007. Review of surface hydrology in the Orange River catchment. *Centurion: ORASECOM/GiZ by WRP Consulting Engineers, Jeffares & Green, Sechaba Consulting, WCE Pty. Ltd. & Water Surveys Botswana Pty. Ltd. ORASECOM*.

Metcalf, L. and Eddy, H.P., 2004. *Wastewater Engineering.* Fourth Edition, McGraw-Hill Publishers, New York

Meybeck, M., Green, P. and Vorosmarty, C., 2001. A new typology for mountainous and other relief classes. *Mountain Research and Development,* 21 (1), pp. 34-45

Mogheir, Y. and Singh, V.P., 2002. Application of information theory to groundwater quality monitoring networks. *Water Resources Management,* 16(1), pp.37-49

Monyela, B.M., 2017. *A two-year-long drought in summer 2014/2015 and 2015/2016 over South Africa* (Doctoral Dissertation, University of Cape Town)

Ministry of Natural Resource, 2007. Lesotho Water and Sanitation Policy. Available: http://extwprlegs1.fao.org/docs/pdf/les180046.pdf . Accessed [22nd September, 2020)

Ministry of Water-Lesotho government. Available: https://www.water.org.ls .Accessed [16th may 2020]

Nixon, S.C.ed., 1997. *European freshwater monitoring network design.* European environment agency

Nobel, C. and Anthony, J.W., 2004. A three-tiered approach to the long-term monitoring optimization. *Bioremediation journal*, 8(3-4), pp 147-165

Nunes, L.M., Paralta, E., Cunha, M.C. and Ribeiro, L., 2007. Comparison of variance-reduction and space-filling approaches for the design of environmental monitoring networks. *Computer-Aided Civil and Infrastructure Engineering*, *22*(7), pp.489-498.

ORASECOM. 2007. Orange River Integrated Water Resources Management Plan: Review of Existing Infrastructure in the Orange River Catchment

Parsons, R.P., 1995. A South African aquifer system management classification. Water Research Commission, Pretoria. WRC report no. KV 77/95

Quevauviller, P., Fouillac, A., Grath, J., and Ward, R., 2009. Groundwater Monitoring. John Wiley & Sons, Ltd, Publication

Rahm, D., Swatuk., and Matheny, E., 2006. Water Resource Management in Botswana: Balancing Sustainability and Economic Development. *Environment, Development and Sustainability,* 8, pp. 157-183

Raghavendran, S., 2013.Estimation of changes in groundwater storage using recession curve method. Karnataka, Surathkal: National Institute of Technology.

Rentier, C., Delloye, F., Brouyère, S. and Dassargues, A. 2006. A framework for an optimized groundwater monitoring network and aggregated indicators. Environmental Geology, 50: 194-201

Rose, S. and Long, A., 1988. Monitoring dissolved oxygen in ground water: Some basic considerations. *Ground Water Monit. Rev.*, *8*(1), pp.93-97.

Sanders, T.G., Ward, R.C., Loftis, J.C., Steel, T.D., Adrian, D.D .and Yeyjevich, V., 1987: Design of networks for monitoring water quality; Water Resources Publications, Colorado.

SADC-GMI, IGRAC, IGS (2019) SADC Framework for Groundwater Data Collection and Data Management. SADC-GMI report: Bloemfontein, South Africa.

SADC-GMI. Groundwater Management in the Southern African Development Community

SADC-GMI. 2019. Framework for Institutionalising Groundwater Management in the SADC Region. SADC GMI report: Bloemfontein, South Africa.

Schmitz, G. and Rooyani, F., 1987. *Lesotho geology, geomorphology, soils*. National University of Lesotho.

Schluter, T. 2006. *Geological Atlas of Africa*. Springer, Berlin, Heidelberg

Selinus, O., Alloway, B., Centeno, J.A., Finkelman, R.B., Fuge, R., Lindh, U. and Smedley, P., 2013. *Essemtials of Medical Geology.* Springer Publishers, New York.

Shakhane, T., 2009. Mapping Fluoride and Nitrates concentration in Groundwater of Lesotho. Honus Research, Natural and Agricultural Sciences, Institute of Groundwater Studies (IGS), University of the Free State, Bloemfontein.

Singhal, B.B.S. and Gupta, R.P., 2010. *Applied Hydrogeology of fractured rocks.* Springer Science & Business Media

SSI, 2009. Lesotho Power Generation Master Plan Project # LEC/GEN/1-2009. FINAL MILESTONES REPORT (1). *Hydropower Generation Option*

TAMS, 1996b. Water Resources Management: Policy and Strategies, Annex D, Water Resources Inventory, Volume 1 (Draft). TAMS Consultants, Inc. New York with Sechaba Consultants, Maseru and BeePee Groundwater Consultants, Maseru, for Department of Water Affairs, Ministry of Natural Resources, Lesotho. (2.4.10), Groundwater Resources (pp 30-70).

Taylor, C.J. and Alley, W.M., 2001. Groundwater level monitoring and the importance Of long-term waterlevel data. USGS circular 1217. USGS, Denver

Tchobanoglous, G., Burton, F.I., Stensel, H.D., 2004. Wastewater Engineering Treatment and Reuse. Mcgraw-Hill Companies, New York.

Tuinhof A, Foster A, Kemper K, Garduno H, and Nanni M., 2006. *Groundwater Monitoring Requirements for managing Aquifer Response and Quality Threats.* Briefing Note series Note, The World Bank

UN/ECE, 1999. Problem-orientated approach and the use of indicators. UN/ECE Task Force on Monitoring and Assessment. UNE/ECE, Lelystad

UN/ECE, 2000. Task Force on Monitoring and Assessment, Guidelines on Monitoring and Assessment of Transboundary Groundwaters

UNICEF, 2008. UNICEF Handbook on Water Quality. United Nations Children's Fund (UNICEF), New York, USA. Pages: 179.

US-EPA, 2012. Dissolved Oxygen and Biochemical Oxygen demand. Washington DC. [Online] Available: https://water.epa.gov/type/rsl/monitoring/vms52.cfm . [Accessed on 20 September 2020]

WHO, 1996. Guidelines for drinking water quality. World Health Organisation, Geneva

Vaessen, V., and Brentführer, R., 2015. Module 5: GROUNDWATER MONITORING AND INFORMATION MANAGEMENT.

Vanden Bossche, J.P and Bernacsek, G.M. 1990. Source book for the inland fishery resources of Africa: 1 CIFA Tech. Pap. No. 18.1.411p

Van Lanen, H.A.J. and CARILLO-RIVERA, J.J., 1998. Framework for groundwater Monitoring in (semi-) arid regions. In: HENNY IR and VAN LANEN HAJ (eds.) Monitoring for groundwater management in (semi-) arid regions. UNESCO, Paris

Yang, F.G., Cao, S.Y., Liu, X.N., and Yang, K.J., 2008. Design of groundwater level monitoring network with ordinary kriging. *Journal of Hydrodynamics*, *20*(3), pp.339-346.

Yangxiao, Z., 1994. Objectives, criteria and methodologies for the design of primary groundwater monitoring networks. *IAHS Publications- Series of Proceedings and Reports-Intern Assoc Hydrological Science*, *222*, pp. 285-296

Yilmaz, E. and C. Koc, 2014. Physically and chemically evaluation for the water quality criteria in a farm on Akcay. J. Water Resource. Prot., 6: 63-67.

Zhou, Y., Dong, D., Liu, J., and Li, W., 2013. Upgrading a regional groundwater level monitoring network for Beijing Plain, China. *Geoscience Frontiers*, *4*(1), pp.127-138.