# THE INFLUENCE OF GROUNDWATER MANAGEMENT STRATEGIES ON GROUNDWATER LEVELS OF NAMIBIAN SAVANNAH AQUIFERS

A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF

MASTER OF SCIENCE (APPLIED GEOLOGY)

OF

THE UNIVERSITY OF NAMIBIA

BY

ESTER MWHADHINA NDAHAFA NUUNYANGO

200419421

APRIL 2019

SUPERVISOR: Dr. Heike Wanke (University of Namibia)

CO - SUPERVISOR: Ms. Shoopala Uugulu (University of Namibia)

## ABSTRACT

Namibia has been known as water scarce, attributing mostly to its geographic location and primarily because of the limited surface water as well as the high potential evaporation rates beyond 2000 mm/year. Groundwater therefore quickly becomes crucial, most of which is located in aquifers in the savannah biome which covers a large part of the country. This is also where most industrialization as well as most farming is practiced. It is however unknown how these savannah aquifers are managed on a local scale and how the management strategies influence the long term groundwater levels of the aquifers. To understand these strategies, three research sites along a rainfall gradient, namely Tsumeb area, Waterberg and Kuzikus area were studied. Through means of a self-developed questionnaire tailored for the government officials and farmers, five (5) interviews were conducted with government officials at DWAF. Across all three research sites a total of seventeen (17) farmers were interviewed. For the scientific groundwater management strategy, the sustainable yield was calculated using the catchment area and the recharge of the area. The short-term volume available was calculated for each research site using the formula $Vol_{bal} = G*S_y (\phi_{ave} - \phi_{min})$. The quantitative data from these four strategies were modeled using the Processing MODFLOW modelling software. The results show that the government strategy employed makes use of the Water Act no 54 of 1956. In comparison with the regulatory guidelines such as carrying capacity, many farmers abstract greater volumes per Small and Large livestock unit per hectare. However they have a similar influence on the groundwater levels over time when compared to the government policy guided strategy. The influence on groundwater levels by the farmer and policy guided strategies are well within the scientific sustainable yield strategy.

LIST OF CONFERENCE(S) PROCEEDINGS

1. Nuunyango. E. & Wanke H. (2017) ‘Water Management Impacts. *OPTIMASS Conference*. Windhoek, Namibia, July 2017.
2. Nuunyango. E. & Wanke, H. (2017) ‘Groundwater Management Options in Namibian Savannah Aquifers. 5$^{th}$ Science Research Conference of the *University of Namibia*. Windhoek, Namibia. November 2017.

**Table of Contents**

## LIST OF FIGURES

## LIST OF TABLES



## LIST OF APPENDICES

## LIST OF ACRONYMS

| Acronym/Abbreviation | |
|---|---|
| AR | Artificial Recharge |
| Ave | Average |
| BMC | Basin Management Committee |
| 1D | One Dimensional |
| 3D | Three Dimensional |
| cm/sec | centimeter per second |
| DWA | Department of Water Affairs |
| DWAF | Department of Water , Agriculture and Forestry |
| Eq. | Equation |
| GROWAS | National Groundwater Database |
| Ha | Hectare |
| hh | Hydraulic head |
| ISOE | Institut für sozial-ökologische Forschung |
| JICA | Japan International Cooperation Agency |
| K | Hydraulic conductivity |
| Kg | Kilogram |
| $Km^2$ | Kilometer squared |
| LSU | Large Stock Unit |
| M | Meter |
| m/day | meters per day |
| $m^2$/day | meter squared per day |
| $m^3$ | Cubic meter |
| MAP | Mean Annual Precipitation |
| MAR | Managed Aquifer Recharge |
| Max | Maximum |
| Min | Minimum |
| mm | Millimeters |
| mm/a | millimeters per annum |
| $Mm^3$/a | Million cubic meters per annum |
| MT3D | Mass Transport Three Dimensional |
| MWAF | Ministry of Water Agriculture and Forestry |
| n.d. | Not dated |
| NamWater | Namibia Water Cooperation Ltd |
| NWR | Namibia Wildlife Resort |
| OML | Otavi Mountain Land |
| OPTIMASS | Options for sustainable geo-biosphere feedback management in savannah systems under regional climate change |
| PMPATH | The Advective Transport Model |

| | |
|---|---|
| PMWIN | Processing Modflow for Windows |
| pp | Pages |
| SAB | Stampriet Aquifer Basin |
| SLR | SLR Environmental Consulting Namibia (PTY) Ltd |
| SSU | Small Stock Unit |
| STAS | Stampriet Transboundary Aquifer System |
| T | Transmissivity |
| TGWS | Tsumeb Groundwater Study |
| UNESCO | United Nations Educational, Scientific and Cultural Organisation |
| WCA | Water Controlled Area |

## ACKNOWLEDGEMENTS

Your eyes saw my substance, being yet unformed, and in Your book they were written, the days fashioned for me, when as yet there were none of them, Ps. 139v 16. Thank You Almighty God for the journey set before me. Thank You for the right people you have placed in my academic journey, Thank You for hope, faith, strength, an increase in knowledge and understanding. You are awesome!

In the words of Ever Garrison, paraphrased, a supervisor is a compass that activates the magnets of curiosity, knowledge and wisdom in the students. I would love to express my gratitude to my Supervisor, Dr. Heike Wanke for being my compass. Thank you for your guidance, corrections and training to think beyond the obvious. I would also like to thank my Co-Supervisor Ms. Shoopala Uugulu for always being available and willing to assist when needed.

Many thanks to the joint German-Namibia research project OPTIMASS (Options for sustainable geo-biosphere feedback management in savannah systems under regional climate change) for providing funds to carry out the project, not forgetting the help of the Staff from the Institut für Sozial-Ökologische Forschung (ISOE) in Frankfurt, Germany. Petra Hansen, Stefan Liehr, Oliver Schulz, and Jenny Bischofberger, thank you for your support and guidance in bringing the holistic view of the project.

To the Department of Water Affairs, thank you for your insight, for the clarity you brought through the interviews. Thank you for the information you made available.

A special thank you goes to my family and friends, especially Ndinelago Heita, for praying and encouraging me, especially when there were obstacles and the going got tough. Thank you all.

## DEDICATION

I gratefully dedicate this thesis to my uncle Jesaya Valombola who from the time since I could read was a great motivator, always reminding me that there is more to be learned and that I am not to get comfortable with the minimal knowledge of any subject. Alongside him is my guardian angel of a mother, Mirjam Valombola, who supported me through thick and thin, you understood that you couldn't spent time with me as often as you would've liked to because of my academic obligations. Thank you for praying, advising and understanding. I also dedicate this thesis to my dearest best friend and husband Julio Gustavo, my cheerleader, and support. Thank you Love.

**DECLARATION**

I Ester Mwadhina Ndahafa Nuunyango, declare that this study on The Influence of Groundwater Management Strategies on Groundwater Levels of Namibian Savannah Aquifers is my own work. The work has not been submitted before for any degree or examination in any other university, and that all the primary and secondary sources that I have used or quoted have been indicated and acknowledged correctly.

________________ April 2019

# 1 INTRODUCTION

## 1.1 Orientation of the study

Degradation of groundwater resources is an on-going threat to dry land systems, not only in Namibia, but also in the rest of the world. Aims of enhancing the understanding of how management of water can mitigate such degradation processes and bring about sustainable stabilisation of the system cannot go unfulfilled (Jeltsch & Wanke, 2013).

When evaluating the water supply sources of Namibia, 45% of that water is abstracted from groundwater, leaving 55% to be divided from other water sources. Surface water is expected to be less available in future due to anticipated increase in evaporation due to climate change and this will without a doubt increase the demand for groundwater (MAWF, 2010).

The management of groundwater has two major components, namely the management of groundwater quality and that of the groundwater quantity, the latter is the focus in this study. In Namibia the groundwater is considered a public resource regulated by the state through the Department of Water, Agriculture and Forestry (DWAF) in the Ministry of Agriculture Water and Forestry (MAWF), they further receive regulatory assistance from the Namibia Water Cooperation (NamWater), which is a parastatal or commercial entity which supplies bulk water to municipalities, industries and to the Directorate of Rural Water Supply of DWAF.

The Namibian government has groundwater management strategies that it has put in place to manage and hence protect the resource. It is however currently unknown how aquifers in Namibian savannah systems are managed at the local scale and how this fits with governmental plans as well as with the standard sustainable yield approach. This leaves a knowledge gap of how the aquifers react to these different management approaches in terms of sustainability of the water resource. It is therefore the reason for embarking on this research. The study is set to bring about an understanding of the groundwater aquifers in the three study sites, with the aim to explore the influence of groundwater abstractions on the hydraulic heads in borehole catchments and on a larger scale, groundwater levels in the different aquifers across the three research sites.

This research study is part of the joint German-Namibia research project OPTIMASS (Options for sustainable geo-biosphere feedback management in savannah systems under regional climate change). Special attention of the subproject on water management was given to government approach based on policy, scientific approach based on sustainable yield approach and other existing management options the farmers apply. The stakeholders involved are the farmers at the OPTIMASS field sites and government officials relevant to groundwater management.

The research was carried out in the years 2016-2018. Three sites made up the study area as indicated in the Figure 1 below. The overarching objective of this study is to compare and contrast how different management strategies at the different study sites influence the groundwater system and its long term sustainability.

## 1.2 Study areas

The study was carried out along a precipitation gradient within the savannahs ecosystems of Namibia (Figure 2). Research site 1, includes farms situated in the vicinity of Tsumeb, with a mean annual precipitation of 550 mm/a. Research Site 2 includes farms around the Waterberg National Park, with a mean annual precipitation of 450 mm/a, and Research Site 3 includes the surroundings of farms of Uhlenhorst southeast of Windhoek with 250 mm/a mean annual rainfall.

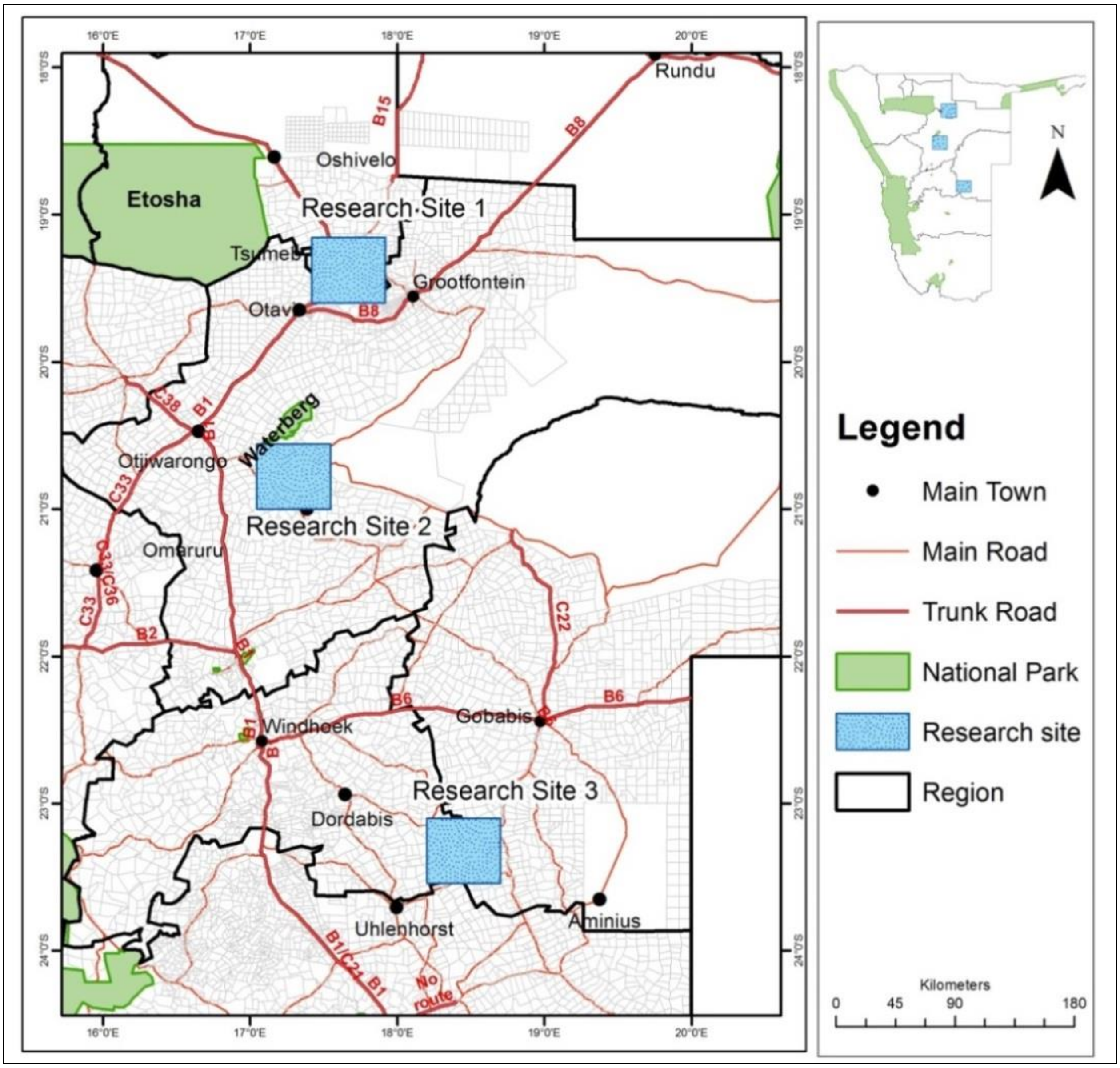



Figure 1: Location of the three research sites. (Map prepared with ArcGIS version 10.2 using data from GROWAS).

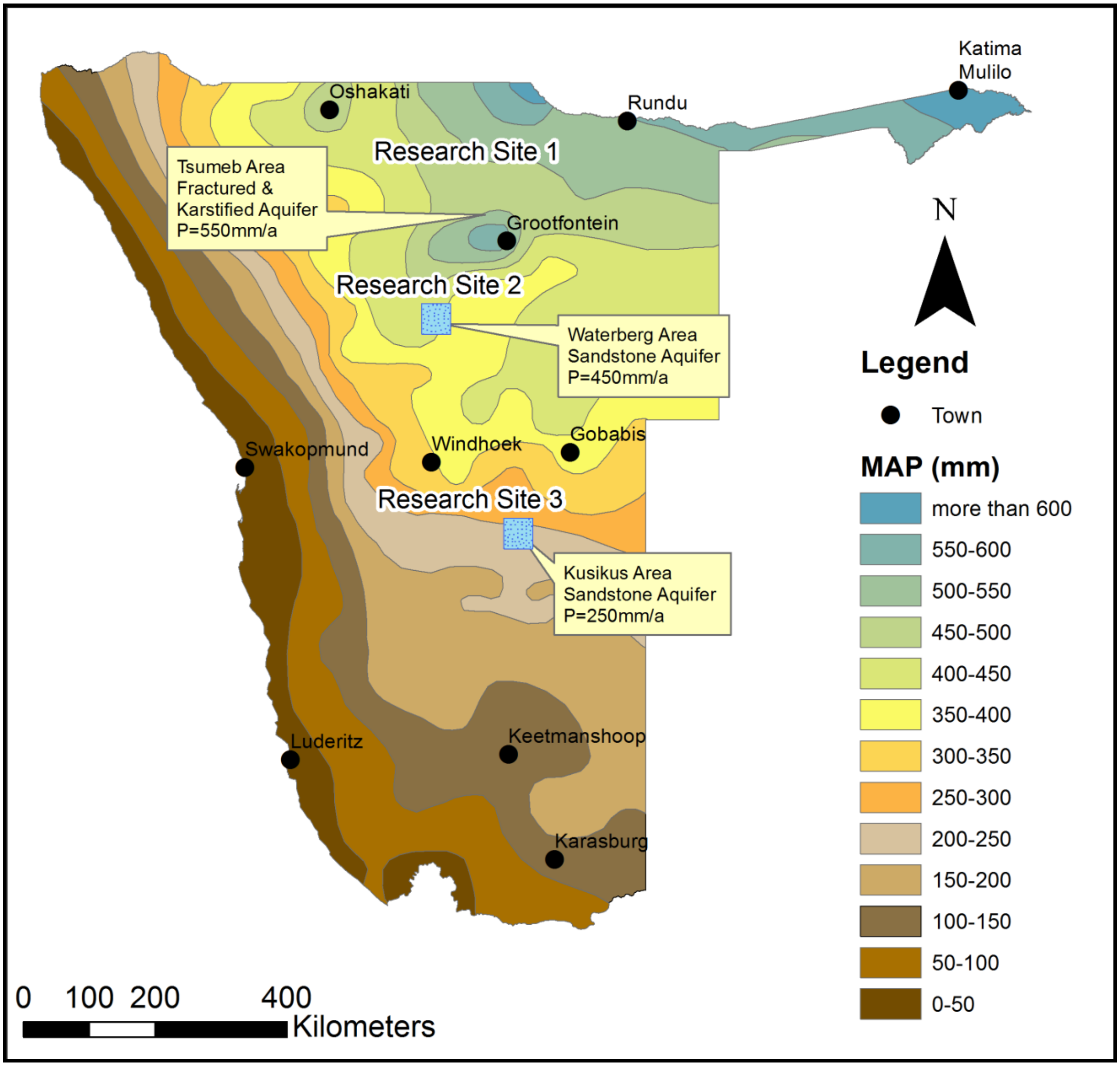



Figure 2: Map of study sites and mean annual Precipitation (Map prepared with ArcGIS version 10.2 using data from GROWAS).

# 2 LITERATURE REVIEW

## 2.1 Groundwater management

There are certain characteristics of groundwater that need to be clarified from the onset and which distinguishes it from its counterpart in the hydrological cycle. One being the fact that groundwater refers to the water beneath the land surface in the saturated zone – which is the portion of rock or soil with pores and fractures that are filled with water (Fitts, 2002; Campana, 2007). This water is stored in what is referred to as aquifers which are earth materials made of sediments or hard rocks. The aquifers then both store and transmit the groundwater. The other very important aspect of groundwater is its recharge and discharge. The former refers to water that bridge the water table and replenishes the aquifer. This process occurs as stipulated by Campana (2007) and Poehls & Smith (2009) through means of percolation of precipitation which moves through the soil and thence across the water table, or via seepage from a stream or other surface water body. The inverse is the discharging of water that leaves the saturated zone and exiting at the land surface or to a surface-water body. Groundwater can discharge naturally via springs and seeps, seepage to surface water, evaporation and transpiration (evapotranspiration). Common water discharge is also the artificial groundwater discharge that occurs by wells and boreholes.

A fundamental aspect of groundwater management is the water budget (Nonner, 2010). This is brought about in undeveloped basins that groundwater recharge equals groundwater discharge. The matter may be further complicated only by introducing a pumping rate to the system. This leads to the matter of groundwater over-drafting and its consequences. The over-drafting poses a threat to any ecosystem dependent on water. This essentially has been overlooked when allocating water resources. Campana (2007) reports that few people are aware of the effects of over-drafting on ecosystems. The mentioned concern doesn't stop with the ecosystem, but rolls further to land subsidence and sinkhole formations, potential seawater intrusion and changes to groundwater quality- factors to be considered by groundwater managers and policy makers and to be integrated in policy and decision making. Steenbergen (2008) introduces that groundwater management takes on many forms. It is applied in areas of abundant water as well as areas where the resource is limited. In either set ups, the resource requires management. He outlines that knowing where the groundwater exists is good and well, even though it may be invisible, but management of this resource requires the appreciation of aquifer systems, basic hydrogeology, the flow systems of groundwater, the depths to groundwater and the sustainable capacity of the aquifers. He highlights that the understanding of the aquifer systems should be coupled with information sharing, thereby ensuring joint management in our case between the different stakeholders, highlighting the farmers and the policy regulators.

## 2.2 Groundwater Management in Namibia

Within the borders of Namibia, surface water contributes a smaller percentage to the country's water demands in comparison to the percentage that comes from groundwater. This is firstly due to that only 8% of the country is calculated to receive rainfall above 500 mm per year, which is the north-eastern region of the country, while the other extreme is in the west where the mean annual precipitation (MAP) is less than 100 m (Braune et al. 2013). The second reason for the surface water contributing minimally is the lack of perennial rivers, with the exception of the northern and southern boundary rivers which are shared between neighbouring countries. Ephemeral rivers in Namibia are a function of the unreliable and unpredictable rainfall pattern across most parts of the country. These facts translate to the country's high dependence on groundwater, especially when drought periods are prolonged. High evaporation from surface water of as much as 2000 mm/a has accelerated the drying up of the surface waters, further minimising water from these sources (Braune et al. 2013)

Groundwater is finite and its potential is limited depending on its management. Heyns (2008) exemplifies the action by Namibian Government to manage water, with the case of Otavi Mountain Land (OML) when after the discovery of base metals in 1915 occurred; there was a rise in mining operations, such that local stock farmers had to find new sources for their livestock because the rainfall was not sufficient. This resulted in the increase of water demand by the 1970s, raising red flags to the Government of Namibia. The government's concerns were focused on the uncontrolled abstraction of groundwater and the feared unsustainable abstractions. The Government therefore started putting management strategies in place to ensure sustainable abstraction of groundwater. Those groundwater management strategies put in place to manage and hence protect the resource are outlined by Heyns (2008) and acknowledged by BIWAC (2004), *inter alia*, as the, declaration of water control areas as the case in OML; The setting up of basin management committees (BMC); Preliminary permit system and for each catchment a permissible abstraction allocation was derived from a conservative estimate of the annual recharge as well as groundwater monitoring activities.

Alley (2007) emphasises that groundwater monitoring is an essential element of any effort to integrate groundwater science with water-management decisions. This is based on the notion that monitoring provides important data that serve as a key input into the decision-making process.

What monitoring offers is:

a) A track record of the groundwater levels which helps validate or disqualify issues regarding long-term sustainability of an aquifer as a primary water source, consequently helping decision makers to make appropriate policies.

b) Monitoring further helps identify whether flow patterns have changed, which could have been brought upon by prevailing abstraction regimes. This is especially helpful to policy makers when it regards areas where salt water/brackish water intrusion is a potential threat.

c) lastly the effects of climate change can be assessed using groundwater level monitoring records, thereby enabling the policy makers to issue timely drought warnings and declarations so that befitting mitigation measures may be enacted.

If long-term monitoring is done, many complex water resources related issues can be resolved. This type of monitoring should include but is not limited to monitoring aquifers substantially affected by groundwater abstraction for various sectors, including industries and farming. The monitoring should also include areas planned for future groundwater development and monitoring of areas that serve as major areas of groundwater recharge.

Periodic evaluations of monitoring programmes are to be carried out to ensure that adequate data is collected for the current situation and for the envisaged future scenarios. The data should represent the full range of topographical, hydrogeological climatic, and land environments.  it is cautioned that data storage, access and availability to scientists, decision makers and the public must be taken into consideration (Alley, 2007).

Campana (2007) adds to Alley (2007) that groundwater monitoring is not the only important facet to this subject. Other disciplines are involved and dependent on this very matter, which include economics of a country, law, engineering, ecology and chemistry to name a few. This only implies that management of groundwater resources in this present day and age will demand more managers than yesteryears.

## 2.3 Particular Importance of Groundwater Management in Namibia

The sentiments of the Convention Ramsar Secretariat (2010) are echoed that particularly in arid areas, groundwater is vital to the livelihoods and health of the majority of the people, not only because it provides almost the entire water resource for domestic and agricultural use, but also because the industrial sectors heavily depended on it. As in the Namibian context, where groundwater dominates the hydrological regime, the most appropriate management unit will be the aquifer unit. Most of the productive aquifers in Namibia underlie the savannahs.

By scientific definition savannahs Skarpe (1992)are areas of grassland with a layer of shrubs and trees. It is also referred to as a rolling grassland scattered with shrubs and isolated trees, which can be found between a tropical rainforest and desert biome. There is not enough rain that falls on a savannah to support forests. They may also be known as tropical grasslands

It is the most prominent biome in Namibia. Nationally there are nine (9) distinct savannah biomes Mendelsohn et al. (2002) and they cover mostly the central part of the country stretching in a linear formation from north-west to south –east. These savannah biomes are named Central Kalahari which is located to the central and eastern part of the country. It is home to Acacia woodlands. There is the Cuvelai Drainage located in the central north of the country and hosts floodplain grassland and woodlands in some areas. The Highland Shrubland can be found around the areas of Windhoek, Okahandja and Rehoboth also known as the Khomas Hochland Plateau. The Karstveld biome is located in the Otavi Mountain Land area stretching west to the Kamanjab and Khorixas area and mostly contains a mix of woodland. The Mopane Shrubland biome comprising Mopane shrubs and woodland is located to the north-west of the country, just north of Kamanjab. The Southern Kalahari biome covers the areas of Stampriet, Mariental, further stretching towards south of Rehoboth where mostly open Acacia shrublands are found. Covering areas north of Okahandja, west of Omaruru and Karibib, stretching all the way past Otjiwarongo and reaching the south of Otavi, is the Thornbush Shrubland biome which also is home to the Acacia woodlands. West of Opuwo is where the Western Kalahari biome is located, flanked between the Mopane Shrubland biome and the Western Highlands and hosts the broadleaved woodlands. The latter biome linearly covers the largest areas of all the biomes, stretching from south-west of Windhoek, past Karibib, Khorixas, Kamanjab, past Opuwo reaching to the Kunene River in the north-east of the country and this Western Highlands biome consists of grassland and scattered trees. For exact demarcations of the biomes, refer to Figure 3 below (Shaw, n.d.).

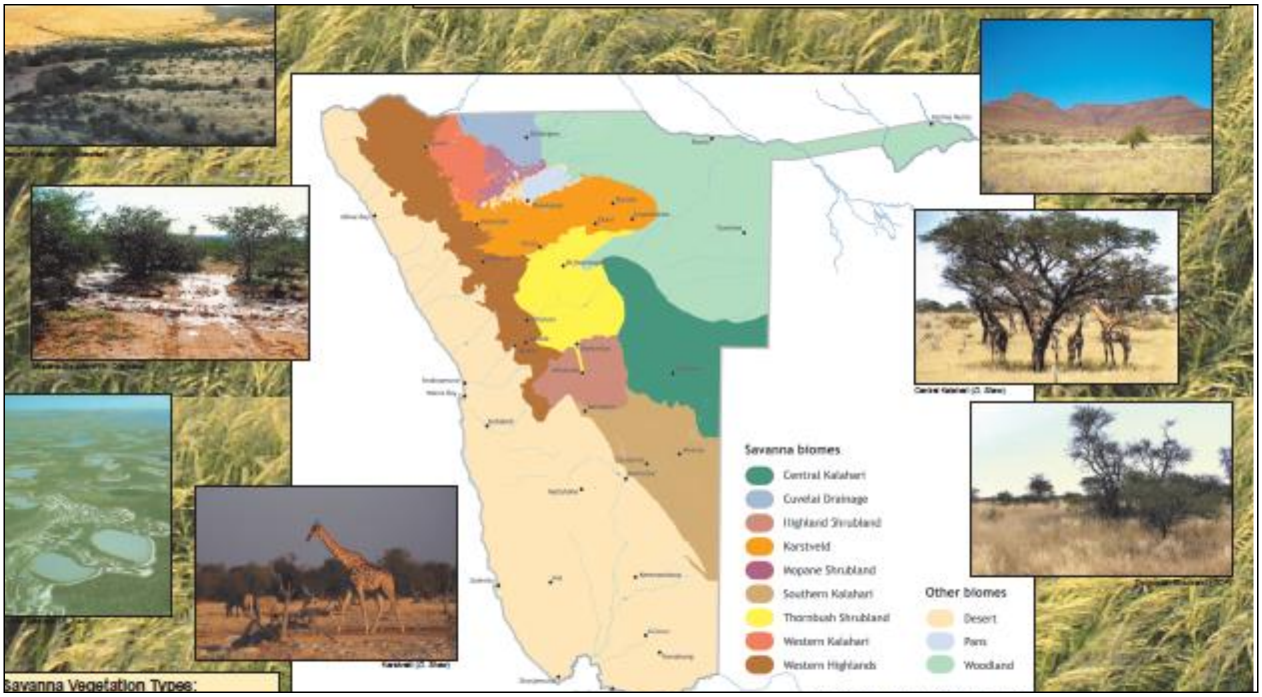



Figure 3: Savannah Biomes of Namibia (Source: Shaw, EEMC).

Safeguarding and management of the Namibian savannahs requires and understanding of the importance of this section of the country. In the Namibian context, we stand to lose a lot if these savannahs are neglected. Two major components of this biome are the rich biodiversity and the land use within the biome. (Shaw, n.d.) alludes to facts about the Namibian savannah specifically that they support high concentration of various species which are endemic to the semi- arid region and have up to 40% of their world population in Namibia. A large number of game, both herds and predators roam on the plains of the savannahs. Headwaters and catchments of most ephemeral rivers are contained in the savannahs, whereby linear corridors are formed to provide food, shelter, water for both wildlife and livestock, even for people. Indigenous farming knowledge and practices, domestic stock breeds and selected crops are all supported by the different forms of savannahs.

Additional to biodiversity in animal and crops, the savannahs are economically important in terms of their land use. Rangeland farming for communal, freehold and small to large stock farming occurs here; agriculture both subsistence and commercial crop and livestock and even irrigation are thriving in these locations.

Other economic activities occurring in these areas include trophy and sport hunting of wild life. This extends further into harvesting of meat for production, live capture and eventual sales of wild life on both communal and freehold areas.

One other economic activity practiced in these areas is the nationally highly regarded activities of conservation, whereby national parks extend up to 5% into savannah biomes, freehold conservancies take up 13%, communal conservancies take up 11%, concluding that 30% of the conservancies are on the aforementioned biome.

The author continues to stipulate other economic activities including tourism, recreation, mining and prospecting of economic minerals. Mines such as the B2Gold Mine, Kombat Mine, Tschudi Mine, Dundee Precious Metals, Lofdal Rare Earth Elements, Otjihase, Oamites (though no longer in operation) are all located in the biome, and the national has grossly benefitted from these since yesteryears.

Harvesting of veld products such as food, medicinal plants, construction material including wood, charcoal from clearing bush encroachment all come from this biome.

Urban development and infrastructure, research, training and education as well the aforementioned activities are expected to increase in importance in the future. At this juncture, it is appropriate to point out that these abovementioned activities all depend on water, and with limited surface water in the form of rivers and dams, groundwater quickly becomes the priority resource and emphasis is placed on the undisputable fact that there is much to be lost if management groundwater resources (aquifers) in this biome goes unattended with the highest primacy.

The above is a pressing concern because the Namibian Savannahs are particularly vulnerable to the impacts of climate change and to land degradations because the rainfall is so variable and it has been declining. Wilhelm (2012) supports Shaw (n.d.) in stating that climate change will severely affect water availability, rainfall patterns and agricultural production in future. Shaw ( n.d.) reports that the central savannahs are predicted to experience the greatest rainfall decline in the coming 40-70 years up to 15-20% less rain which is to be attributed to climate change. Climate variability will not be uncommon. For rangeland farming the issue of grass availability will hit hard. Grasses are the main vegetation in the biome and unpredictable rainfall (far below average in the one year and twice the annual amount in the next) has huge impacts on productivity, mainly because grasses do not have the adaptation mechanisms that their counterparts (shrubs and trees) have which help the to survive in dry periods. As grasses respond very fast to good rains but decimate just as fast in dry spells, the boom and bust type of response to rainfall makes the savannahs extremely vulnerable to more than one form of land degradation.

Shaw ( n.d.) and Campana (2007) agree that management of the savannah aquifers will require collaborative and integrated planning and management on all levels because it is such an interdependent and integrated subject. One of the strategies highlighted and supported by Alley (2007) is the developing and implementing of monitoring systems which can detect change early. But detection is not enough; it should be followed by immediate response to ensure that the biome does not collapse. Awareness and capacity must be built on all levels depending on the groundwater resource, especially because the human s struggle to manage when rainfall is unpredictable or when climate change hits, but this does not have to be a life sentence, the impacts on the natural resource must be studied and thereafter preparedness will influence the management of the impact.

## 2.4 Groundwater management laws in Namibia

Measures to manage and protect the groundwater resources are in place, more as legislation, but execution of the legislations is tardy, potentially due to lack of executing capacity or as a result of lack of funds.

Nonetheless, legislation such as the Water Resources Management Act 11 of 2013 has been gazetted, but is not in effect yet. DWAF has revealed through interviews conducted in December 2016 that the department cannot enforce the Act yet, because there are regulations that were under revision, but positively, the regulations are in the final stages of being completed.

Currently the water management is still governed by the Water Resources Act 54 of 1956, but in future the Water Resources Management Act 11 of 2013 will override the current Act. There are two major components to groundwater management, i.e. the quantity and quality of groundwater. The Act is there to provide for the management, protection, development, use and conservation of water resources; to provide for the regulation and monitoring of water services and to provide for incidental matters in terms of both quality and quantity of the resource. The Water Act No.54 of 1956 covered the following components of groundwater. Surface water was covered by the Act, but that is outside the scope of this study.

The minister is ultimately the power that enforces the Act and the powers and functions of the minister are also outlined in the Act. Further to this, the components (relevant to this study) of the Act currently governing groundwater in Namibia cover the following:

- "CHAPTER II: Control and use of private and public water
- CHAPTER III: Control and use of subterranean water and water found underground
- CHAPTER IV: Water courts
- CHAPTER V: Government works
- CHAPTER VIII: Servitudes
- CHAPTER IX: Water sport control areas and Irrigation loans, liabilities and subsidies"

Details of the Chapters may be found in the complete Water Act No.54 of 1956 at the Legal Assistance Centre, Windhoek.

Chapters III of the above mentioned Act played a particular role in the governing of the groundwater resources. Two of the study sites are classified as subterranean Water Control Areas (WCA). In this chapter the Act describes the term subterranean water as water which exists naturally underground and that which is contained in an area declared as a subterranean water control area.

The declaration is given under section 28(1) that the Minister may proclaim an area as subterranean WCA if that area is dolomitic or if it is geologically artesian or if the abstraction of groundwater may in some way result in undue depletion of the groundwater resource.

The Act distinguishes the use of these areas and in section 30 (1) and (2) it defines that owners of land have authority to abstract and withdraw from any subterranean water under his land for the use of any purpose on such land. However, the cabinet may make regulations and has made regulations pertaining to the exercising of control over the drilling of boreholes for the purpose of locating the subterranean water, or pertaining to sinking of wells and pumping, for the protection against pollution and for the preservation of the said water. These regulations may further limit the number of boreholes or wells which may be drilled and sunk in these areas and even limit the amount of water which may be pumped or abstracted from the boreholes and wells located in area of concern. This applies to all boreholes and wells drilled or sunk before or after the commencement of the abovementioned Act. The conditions set by the cabinet are to be followed as specified. These conditions include the right that subject to notification in writing to the land owner, the minister may "make such adjustments or repairs to such water work, or construct or erect such additional works, or in writing direct any such owner to make such adjustments or repairs or construct or erect such additional works, within a period stipulated by the Minister and at his own expense, as may, in the opinion of the Minister, be necessary for the proper measurement and regulation of any subterranean water abstracted or conveyed by, or flowing over, such works."

The Act did not only address farmers but also industries such as mines. Section 30; subsection 5(a) refers to that owners of mines may apply to the minister and the minister may permit such an owner to use, sell, give or exchange or otherwise dispose subterranean water that is removed from the mine.

In addition to applying for a permit to drill a borehole or sink a well, and even abstracting of water in a WCA, the Act also stipulates that any driller sinking a borehole by means of a water boring machine or other apparatus for the purpose of locating water has to furnish his details to the secretary of the minister.

This chapter in summary highlights the management strategy that is employed by the government. Since the Water Act No.54 of 1956 was initially made drawn up for the Republic of South Africa and adopted to Namibia, then known as South West Africa, the Act has some sections that did not apply to Namibia. The Namibia cabinet has since drawn up a Water Resources Management Act No.11 of 2013 which as mentioned before will supersede the Water Act No.54 of 1956.

The Water Resources Management Act No.11 of 2013 is further an amendment of Water Resources Act No.24 of 2004, and it addresses a lot more aspects and the following parameters that ultimately are the backbone of the resource's management. The parameters include;

- Part 3: Establishment of Water Advisory Council
- Part 4: Establishment of Water Regulator
- Part 5: Establishment of Basin Management Committees
- Part 6: Management of Internationally Shared Water Resource
- Part 7: Management of Rural Water Supply
- Part 8: Development of Integrated Water Resources Management Plan
- Part 9: Water Supply, Abstraction and Use
- Part 10: Licensing of Water Services Providers
- Part 11: License to Abstract and Use Water

- Part 12: Control and Protection of Groundwater
- Part 13: Water Pollution Control
- Part 14: Declaration of Water Protection Area
- Part 15: Emergency Powers to Control Pollution
- Part 16:Water Services Plans and Efficient Water Management Practices

## 2.5 Carrying Capacity for Namibia

Other management strategies closely linked to groundwater management that are employed by the MAWF include the development of the carrying capacity map of Namibia. Carrying capacity is in brief described as the number of animals a management unit such as a hectare is able to support without depleting rangeland vegetation or soil resources. **Figure 4** below shows the carrying capacity map for Namibia, from which estimation of allowable LSU/SSU can be made. The figure in particular depicts the measures of how many kilograms live mass of livestock can be supported on one hectare (ha), or the number of hectares required for each large stock unit (LSU, each equivalent to cattle of 360 kilograms) or small stock unit (SSU, a sheep or goat weighing an average of 60 kilograms).

For the purpose of this study, this strategy is beneficial because it assists in calculating the groundwater volume that may be abstracted over a measurement of farming land, which may be compared to the actual application and abstraction done by farmers.

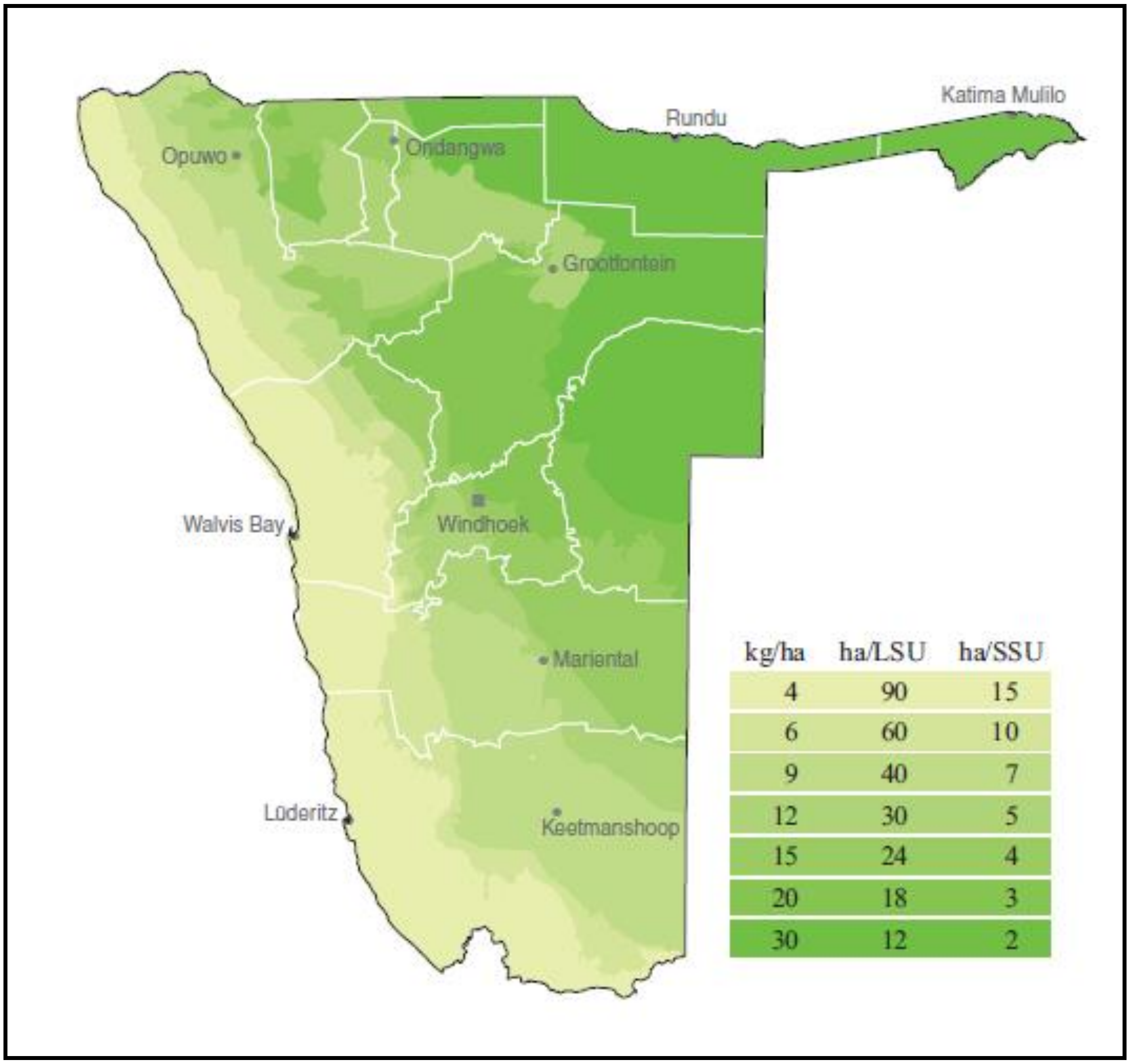



Figure 4: Carrying Capacity Map of Namibia. (Source: Mendelsohn, 2006; Lubbe and Espach 2006).

The trading economics website sites that in Namibia, there is 38 809 000 ha of agricultural land. It has also estimated that the human population living on agricultural and is 931 000. This equates to 42 ha/person. These values are relevant in calculating the estimated volume that could be abstracted per hectare. (www.TradingEconmics.com).

## 2.6 Groundwater availability assessments through safe yield

The term safe yield has undergone an evolution of definition from as early 1915. It has progressed from simple definitions stating that safe yield refers to when the abstraction rate does not exceed the rate of infiltration or natural recharge (Zhou, 2009), to more fuller definitions after defining that safe yield must take into account the outcomes such as depletion of groundwater reserves, the possibility of intrusion of water that has substandard quality and the infringement of water rights that are in place, not excluding the deterioration of the economic advantage of pumping. Additional outcomes by (Freeze & Cherry, 1979) are that land subsidence and induced infiltration are also points that need to be considered when addressing the term 'safe yield'. Although still common to some hydrogeologist to date, the term safe yield was abandoned due to its misleading definition and the term sustainable yield emerged as a better term. This term now was observed in light of the complete hydrological system and the long term management of groundwater resources. (Alley & Leake, 2004) sustained that the evolution in the understanding of the terms safe yield to sustainability brought about the enlightenment of the dynamic nature of groundwater and how it incorporates the biosphere and the human activities. As an end result it is today recognized that groundwater abstraction can influence the surface water supply for potable water and at the same time influence the maintenance of stream flow for aquatic life and other environmental needs including a healthy riparian and wetland ecosystems, therefore concluding that the amount of groundwater available depends on the effect that recharge and discharge has on the surrounding environment and the acceptable trade-off between the groundwater utilization and the changes experienced. .

$P_s = R_0 + \Delta R_0 - D_R$………………………………………………………………….. (1)

Where Ps =Sustainable pumping rate

$D_R =$ Residual discharge

$R_0 =$ Natural recharge

$\Delta R_0 =$ Induced recharge

Eq. (1) states that the sustainable pumping rate Ps and residual discharge $D_R$ are balanced by natural recharge $R_0$ and induced recharge $\Delta R_0$. In circumstances where there is no induced recharge $\Delta R_0$, the sustainable pumping rate and residual discharge are balanced only by natural recharge:

$P_s = R_0 - D_R$ ………………………………………………………………….. (2)

Where Ps =Sustainable pumping rate
$R_0 =$ Natural recharge
$D_R =$ Residual discharge

The above equations illustrate that surely natural recharge is imperative in determining a sustainable pumping rate, and the higher the natural recharge, the higher the sustainable pumping rate for the basin. For the calculation of the basin sustainable yield to be comprehensive there are conditions outlined by (Zhou, 2009) and validated by (Yin et al., 2012) that must be satisfied:

1. As much as sustainable yield is determined by the water balance in Eq. (1) there are further conditions that must be attached to attaining the sustainability. These include:
2. Environmental constraints such as pumping captures that should not result in the exorbitant depletion of surface water and groundwater to springs, rivers and wetlands and that the cone of depression caused should not trigger the infiltration

of substandard water quality, land subsidence and destroy ecosystems that depend on the groundwater resource.

3. Irrigation and industrial use of groundwater has economic constraints, therefore pumping should be considered to the point that it does not deplete the groundwater and make pumping a more costly affair due to deep cone of depression.
4. The water must be equally accessible to all and of good quality both to upstream, downstream, urban or rural inhabitants.

After realizing that the basin sustainable yield cannot be simply calculated as single value using the water balance Eq. (1), and that it also requires assessing the capture and the cone of depression brought about by pumping and the consequent response of the environment and society. All stakeholders then must agree on reasonable tradeoffs and a negotiated groundwater development plan could be reached. Groundwater modeling with access to field data as stated by Yin et al. (2012) then come into play, although they are as good as the data provided they are able to simulate and predict certain outcomes. The effects of different scenarios on the environment and to society are assessed by hydrogeologists through means of numerical groundwater modeling and these scenarios outcomes should be clearly presented to stakeholders and used as a basis for reaching a compromised development plan.

The investigation into the sustainability of yield continues to expand and encompass more practical approaches as sited by (Yin et al. 2012). The author further quotes Maimone (2004) and highlights that those spatial and temporal aspects, conceptual water balance, influence of boundaries, water demand and supply, and the stakeholder involvement must be considered.

And therefore by (Nonner, 2010) the sustainable yield encompasses all above components to calculate it by means of the volume balance:

$$V_{bal} = GS_y (\phi_{ave}-\phi_{min}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where $V_{bal}$ = volume of groundwater available from storage

$G$ = Surface area ($m^2$)

$Sy$ = Specific yield (dimensionless)

$\Phi_{ave}$ = Average groundwater table elevation (m)

$\Phi_{min}$ = Minimum groundwater table elevation (m)

## 2.7 Aquifer properties

The term aquifer is used to refer to an underground rock layer which is saturated with groundwater. Aquifers have many distinguishing characters which mainly depend on the type of lithology that the aquifer is made up of. Some aquifers are porous and permeable such as those made up of sand, gravel or silt, others are fractured and fissured, such as those made up of dolomites, quartzites or columnar basalts the latter tend to have secondary porosity brought on by fracturing and fissuring, see Figure 5. Some aquifers are referred to as saturated and others as unsaturated. The difference is that the saturated rock layer is within the zone where rock spaces are filled with water, where the water pressure exceeds the atmospheric pressure. The unsaturated aquifer is found in the zone where there are pockets of air and only some these pockets are filled with water. These aquifers may be further categorised into confined and unconfined aquifers. The aquifer that is exposed at the surface and has no confining layer above it is termed by hydrogeologist as an unconfined aquifer (Earle, 2006). This type has the water table as its upper limit of the saturated zone. The aquifer with a geological layer covering it is referred to as a confined aquifer. The covering layer typically has low permeability.

Within confined and unconfined aquifers the classification goes broader to primary and secondary aquifers, consolidated and unconsolidated aquifers and even as far as low potential to high potential aquifers. Geologically, there are consolidated and unconsolidated geologic materials which both make important aquifers. As mentioned in the categorising above, there are different levels of value attached to them. Those made up of sedimentary rocks for instance have higher importance because they tend to have porosities and permeabilities in magnitudes far greater than aquifer of other rock types. This is not to say that other rocks are useless as aquifers, but they are usually just not as good.

Earle (2006) adds to the classification of aquifers that due to the permeability of an aquifer and its volume, a rock body may be classified as an aquifer or non-aquifer, whereby non aquifers may be those rock bodies such as confining layers, aquitards, aquicludes and aquifuges. These rocks are typically made of clay deposits, mudstones or unfractured igneous and metamorphic rocks. There are however confining layers that may be permeable which are consequently termed leaky aquifers.

And on this basis of different origin, one can easily understand why aquifers are unique and behave significantly different. There are numerous aquifer properties that must be understood in order to conceptualise the reaction of the aquifer. The major ones are effective porosity, permeability, transmissivity, specific yield /storativity and hydraulic conductivity.

Porosity

The empty spaces between grains that make up a rock are known as the porosity of the rock. And it refers to the rock's ability to hold water. It is therefore the measure of how much water a rock body can hold and it is expressed as a percentage of the rock's volume. There is intergranular and fracture porosity, which refer to the spaces between the grains or crystals of s rock and the fractures within the rock respectively (Earle, 2006).


Figure 5: Sand aquifer with primary porosity and bedrock aquifer with secondary porosity (Source: www.gsi.ie).

Porosity is defined as:

$n=V_v/V_t$…………………………………………………………………….. Eq (4)

Where n = porosity
$V_v$ = the volume of voids and
$V_t$= is the total volume

Table 1 shows the representative porosity values of unconsolidated sedimentary, sedimentary rocks and crystalline materials given by Duffield (2016) after Morris and Johnson (1967).

Table 1: Representative porosity values for different geologic materials Duffield (2016) after Morris and Johnson (1967)

| **Unconsolidated Sedimentary Materials** | **Porosity (%)** |
|---|---|
| Gravel, coarse | 24 - 37 |
| Gravel, medium | 24 - 44 |
| Gravel, fine | 25 - 39 |
| Sand, coarse | 31 - 46 |
| Sand, medium | 29 - 49 |
| Sand, fine | 26 - 53 |
| Silt | 34 - 61 |
| Clay | 34 - 57 |
| **Sedimentary Rocks** | |
| Sandstone | 14 - 49 |
| Siltstone | 21 - 41 |
| Claystone | 41 - 45 |
| Shale | 1-10 |
| Limestone | 7-56 |
| Dolomite | 19 - 33 |
| **Crystalline Rocks** | |
| Basalt | 3-35 |
| Weathered granite | 34 - 57 |
| Weathered gabbro | 42 - 45 |

Effective porosity is however the most important measure of porosity as it takes into account the ratio of the connected pore volume to the total volume. This is vital as explained by Glover (2013) because rocks may have the same porosity, but vary significantly in other physical properties such that one rock type due to the un-connectivity of the pores will result in a much lower permeability than that of a different rock, with same porosity but its pores are well connected. This parameter is controlled by three main structural settings at micro level, namely the grain size, the manner of packing and the shapes of the grains.

Regarding grain size and its influence on porosity the author dictates that in sedimentary rocks the rule of thumb is that porosity only becomes significant at grain sizes lower than 100 µm. It is qualified that as gran sizes reach above 100 µm, fictional forces decrease and the porosity decreases until a limit is reached that represents random frictionless packing with porosity as given in Table 2. The relationship between grain size and porosity for sedimentary rocks is given in the Figure 6 below.

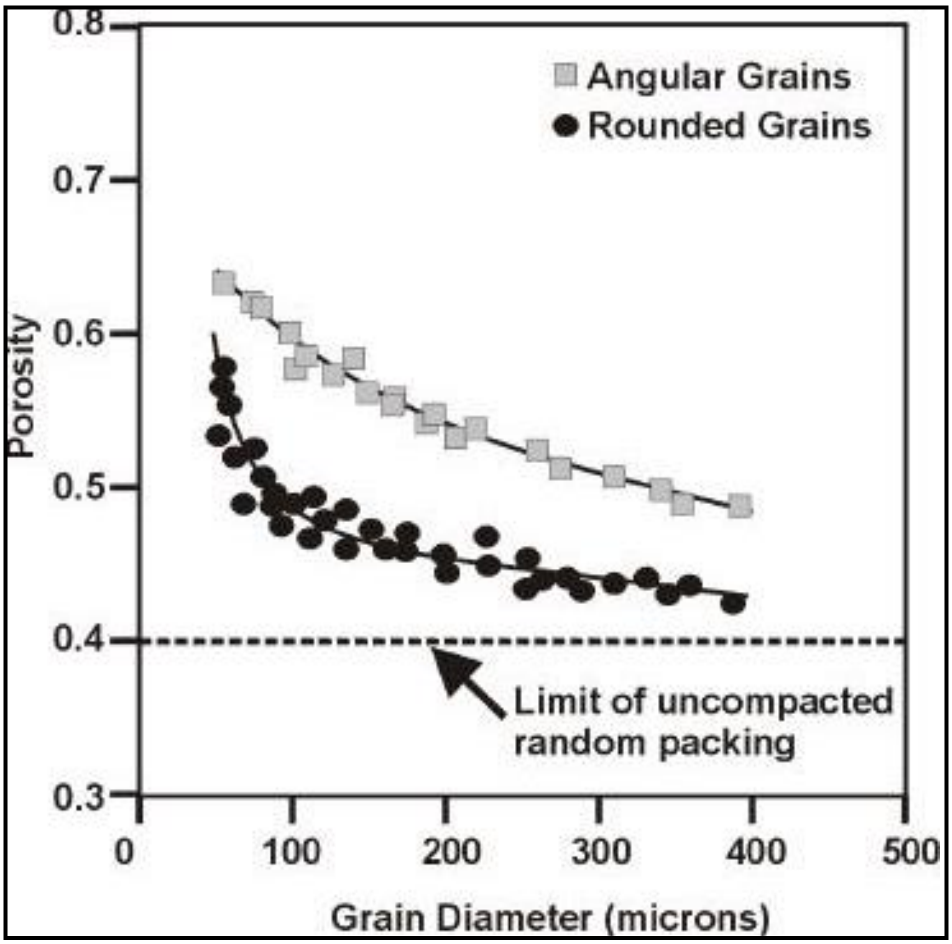



Figure 6: Relationship between porosity and grain size according to Glover (2013).

Theoretical porosities of various grain packing arrangements can be computed. And below is an example of how influential grain packing can be. Table 2 for comparison shows the influence of packing arrangements as given by Glover (2013) .

Table 2: Maximum calculated porosity for different packing arrangements according to Glover (2013)

| **Packing** | **Maximum Porosity (fractional)** |
|---|---|
| Random | ≥0.399 (dependent on grain size) |
| Cubic | 0.476 |
| Orthorhombic | 0.395 |
| Rhombohedral | 0.26 |
| Tetragonal | 0.302 |

Porosity based on grain shape has been confirmed in several studies that angular grains have a larger porosity than those of sub-spherical. This is depicted in the Table 3 .

Table 3: The influence of grain shape on porosity according to Glover (2013).

| **Grain Shape** | **Maximum Porosity (fractional)** |
|---|---|
| Sphere | ≥0.399 (dependent on grain size) |
| Cube | 0.425 |
| Cylinder | 0.429 |
| Disk | 0.453 |

<u>Hydraulic conductivity</u>

This parameter is specific to flow of water through a medium. And it is the measure of the ease with which a medium transmits water. Earle (2006) adds to this definition that hydraulic conductivity may also be referred to as permeability. He elaborates that this parameter is dependent on intergranular porosity, the extent and the nature of the fractures as well as the development of bedding planes. Fitts (2002) agrees with Earle (2006) that the saturated hydraulic conductivity (-K) is a function of the size and distribution of the pores in the rock layer. For instance, in granular rock layers, there exists a positive correlation between the particle sizes and the K. This parameter is measured in length per time (cm/sec).

Earle (2006) further qualifies that hydraulic conductivity is in itself not velocity and that the movement of the water is aided by a gravitation force and a gradient is needed. Real subsurface materials always have a complex and irregular distribution of hydraulic conductivity, to the extent that rock layers may be qualified as aquifers or non-aquifers based on their hydraulic conductivity values, and also the volume of water they hold. Hydraulic conductivity distribution is often described using the terms heterogeneity and anisotropy. In a heterogeneous material the value of hydraulic conductivity varies spatially, and in a homogeneous material the K is does not dependent on the location. Anisotropy implies that the value of hydraulic conductivity at a given location depends on direction. If $K_x \neq K_y$, where Kx is the conductivity in the x direction and Ky is the conductivity in the y direction, the medium is anisotropic.

Isotropy implies that hydraulic conductivity is not different for each direction at a given location. In a perfectly isotropic material, $K_x = K_y = K_z$. Although real geologic materials are never perfectly homogeneous or isotropic, it's often reasonable to assume that they are for the purpose of calculations (Fitts, 2002).

Table 4 gives a list of horizontal and vertical hydraulic conductivity values for a selected range of rocks (Duffield, 2016 after Domenico & Schwartz, 1990).

Table 4: Representative Hydraulic Conductivity values for different geologic materials after (Duffield, 2016)

| Material | Horizontal Hydraulic Conductivity (m/sec) | Vertical Hydraulic Conductivity (m/sec) |
|---|---|---|
| Anhydrite | $10^{-14}$ to $10^{-12}$ | $10^{-15}$ to $10^{-13}$ |
| Chalk | $10^{-10}$ to $10^{-8}$ | $5\times10^{-11}$ to $5\times10^{-9}$ |
| Limestone | $10^{-9}$ to $10^{-7}$ | $5\times10^{-10}$ to $5\times10^{-8}$ |
| Dolomite | | |
| Sandstone | $5\times10^{-13}$ to $10^{-10}$ | $2.5\times10^{-13}$ to $5\times10^{-11}$ |
| Shale | $10^{-14}$ to $10^{-12}$ | $10^{-15}$ to $10^{-13}$ |
| Salt | $10^{-14}$ | $10^{-14}$ |

Table 5: Representative Values of hydraulic conductivity for various material (Duffield, 2016)

| **Sedimentary Rocks** | **Hydraulic Conductivity** |
|---|---|
| **Rock Type** | **(m/sec)** |
| Karst and reef limestone | 1×10-6 to 2×10-2 |
| Limestone, dolomite | 1×10-9 to 6×10-6 |
| Sandstone | 3×10-10 to 6×10-6 |
| Siltstone | 1×10-11 to 1.4×10-8 |
| Salt | 1×10-12 to 1×10-10 |
| Anhydrite | 4×10-13 to 2×10-8 |
| Shale | 1×10-13 to 2×10-9 |
| **Crystalline Rocks** | |
| Permeable basalt | 4×10-7 to 2×10-2 |
| Fractured igneous and metamorphic rock | 8×10-9 to 3×10-4 |
| Weathered granite | 3.3×10-6 to 5.2×10-5 |
| Weathered gabbro | 5.5×10-7 to 3.8×10-6 |
| Basalt | 2×10-11 to 4.2×10-7 |
| Unfractured igneous and metamorphic rock | 3×10-14 to 2×10-10 |
| **Unconsolidated Sedimentary Materials** | |
| Gravel | 3×10-4 to 3×10-2 |
| Coarse sand | 9×10-7 to 6×10-3 |
| Medium sand | 9×10-7 to 5×10-4 |
| Fine sand | 2×10-7 to 2×10-4 |
| Silt, loess | 1×10-9 to 2×10-5 |
| Till | 1×10-12 to 2×10-6 |
| Clay | 1×10-11 to 4.7×10-9 |
| Unweathered marine clay | 8×10-13 to 2×10-9 |

Transmissivity

Rushton (2003) specifies that mathematically transmissivity (T) can be calculated as the product of the hydraulic conductivity and the saturated thickness. Fitts (2002) clearer defines this parameter that it is the measure of how easily a layer transmits water. He concurs with Rushton (2003) that transmissivity is deduced from the constant hydraulic conductivity tangential to a layer over a thickness of the layer. He elaborates that if a certain layer is composed of a specific geology and has a particular thickness, and then the transmissivity of the layer is its thickness multiplied with its constant hydraulic conductivity. Below in is a list of representative values of T for various geologic materials as given by Duffield (2016) after Domenico and Schwartz (1990).

Storativity and Specific yield

Storativity of a confined aquifer refers to the volume of water that is released from storage per unit surface area of the aquifer or aquitard and it is controlled by the unit decline in hydraulic head (Kruseman & de Ridder, 2000). It is also alternatively referred to as the storage coefficient. Mathematically it is derived from the formula:

$S= S_s*b$……………………………………………………………………..Eq (5)

In this equation:

S = Storativity which is dimensionless
Ss = Specific storage ($m^{-1}$)
b = is the aquifer thickness (m).

The specific storage in the above equation depicts the volume of water that a unit volume of aquifer would release from its storage when there is a unit decline in head, further relating to the compressibility of water and the aquifer. It therefore takes into consideration the following parameters giving rise to the formula:

$Ss= \rho*g\ (\alpha+n_e\beta)$……………………………………………………………… Eq (6:

Where Ss = Specific storage ($m^{-1}$)
$\rho$ = Mass density of water ($g/m^3$)
g = Gravitational acceleration ($m/s^2$)
$\alpha$ = Aquifer compressibility

$n_{e,}$= Effective porosity and
$\beta$ = Water compressibility

The representative specific storage values for selected materials are given in Table 6 as given by Duffield, (2016) after Domenico and Mifflin (1965).

Table 6: Representative Specific storage values for selected material (Fitts, 2002)

| **Material** | **$S_s(m^{-1})$** |
|---|---|
| Plastic clay | 2.6E-03 to 2.0E-02 |
| Stiff clay | 1.3E-03 to 2.6E-03 |
| Medium hard clay | 9.2E-04 to 1.3E-03 |
| Loose sand | 4.9E-04 to 1.0E-03 |
| Dense sand | 1.3E-04 to 2.0E-04 |
| Dense sandy gravel | 4.9E-05 to 1.0E-04 |
| Rock, fissured | 3.3E-06 to 6.9E-05 |
| Rock, sound | <3.3E-06 |

The same concept in unconfined aquifers is that of specific yield (Sy) or simply put, "the drainable porosity). $S_y$ is therefore derived from $S=S_y+S_s\, b$ whereby $S_y$ becomes $S- S_s b$.

$S_y$ can therefore be related to total porosity as $n= S_y + S_r$………………………..Eq (7)

Whereby n = Porosity (dimensionless)
Sr = Specific retention (dimensionless)
Sy = Specific yield (dimensionless)

$S_r$ is the amount of water retained by capillary forces during the gravitational drainage in an unconfined aquifer).

The discrepancies from various authors exist of the representative specific yield values of certain materials, however they are within the same order of magnitude. See

Table 7 for the $S_y$ for some materials as given by (Duffield, 2016).

Table 7: Representative Specific yield values for selected materials (Duffield, 2016).

| Material | Porosity | Specific Yield | Specific Retention |
|---|---|---|---|
| | **(%)** | **(%)** | **(%)** |
| Soil | 55 | 40 | 15 |
| Clay | 50 | 2 | 48 |
| Sand | 25 | 22 | 3 |
| Gravel | 20 | 19 | 1 |
| Limestone | 20 | 18 | 2 |
| Sandstone (unconsolidated) | 11 | 6 | 5 |
| Granite | 0.10 | 0.09 | 0.01 |
| Basalt (young) | 11 | 8 | 3 |

## 2.8 Groundwater modelling

With the ever growing tension between growth and limited water supplies, there is a need for increasingly sophisticated numeric models such as “Modflow, to analyze the relationships between surface water and groundwater in basins where rapid growth is occurring. Hydrogeologists across the world rely heavily on the numerical groundwater modelling for groundwater flow and it has therefore gained approval by many to be the preferred tool for analysing and simulating the active behaviour of the aquifers” (Gehrels & Gieske, 2003). The authors further state that analysis of the effects of groundwater abstractions provides more insight to the impact of these measures. Comparing stochastic models based on time series analysis to physically based models, the authors differentiate the two types of models and conclude that the former is especially useful in the initial phase of reconnaissance of water management, it is easy to formulate and not much input data is required. In contrast, physically based 1D or 3D models are useful in the subsequent phases of water management where comprehensive spatially distributed information and scenario calculations are required. They caution that, if the objective is merely simulating groundwater levels, then this type of model is rather complex than is strictly required and depending on the data required, it is worthwhile to consider other possible models that may answer the research questions with a simpler approach.

With regard to modelling, certain parameters are imperative to understand and conceptualize the model area. These are presented in the Table 12 for the three study sites.

During the process of modeling, all available data must be taken into account. These data additional to the aquifer parameters given in the above table include water table elevations, the stratigraphy and determination of fracture density and pumping abstraction rates. The data in Table 12 have been obtained from previous literature which initially has been determined by aquifer tests conducted in the areas of interest. It is reported by Barnett et al. (2012) that the collection of data for the model cannot go without the assessing of the spatial distribution and the validation of the data. A model project database must be produced. The data used to produce groundwater head maps is originally obtained from water levels measured in monitoring wells. They emphasize that the reliability in data obtained from designated observation boreholes is above water level data obtained from an abstraction borehole.

*Conceptual model development* is a critical step in groundwater modeling. This step involves the determining of the hydrogeological domain which in turn provides the set-up of the conceptual model with the aquifer properties. These help in considering the physical processes operating within the domain. When defining the hydrogeological domain, the aquifer of the study area is addressed, the hydraulic properties of the hydrogeological units as well as the boundaries and the stresses are also considered (Barnett et al. 2012).

These authors give guidelines that when defining the extent or limits of the conceptual model, it is wise to follow natural boundaries like topography, the geology and the surface water features like lakes and rivers. To complete the hydrogeological domain, one has to:

- Describe the components of the system, emphasizing their relevance to the problem. These components are such as aquifer units and the aquifer properties.
- Describe the interaction of these components with the system and the vice versa, not excluding the broader environment outside the hydrogeological unit.
- Define then the specific processes that cause water to move from the source to the sink though the aquifer materials
- The spatial scale whether regional or local and the timescale whether steady state or transient state is also defined, because they assist in the water balance of the area.
- It is always a good strategy to making a simplified assumption that reduces the complexity of the system to a level befitting the system, this must in the end be able to be simulated quantitatively. These assumptions must be documented and justifications thereof must be presented.

These authors elaborate on the type of data that is fed in to the development of a conceptual model. As mentioned before that hydrostratigraphic info is needed, it is important to understand what this data comprise which is:

- Stratigraphy, structural and geomorphological features such as faults, fractures, sink holes.
- It also includes lateral and vertical extent of the hydrostratigraphic units i.e. length and thickness of the units
- The units must be classified into aquifers or aquitards, and further defined as confined and unconfined
- Not excluding maps of the lateral (length) and vertical (depth) of the aquifers.

The aquifer properties are the next important feature to building a conceptual model, and these have been described in detail in the above sections. In this step the questions of the heterogeneity of the properties is asked, the question of isotropism of the hydraulic conductivity is asked, and the quantification of the different parameters as well.

The conceptual boundaries are just as important as the aquifer properties in the conceptualisation stage (Barnett et al. 2012) because they establish the groundwater flow of the system.

Typical boundaries are the impermeable base of the aquifer which may be inferred or known geologic layers also known as aquitards. The other boundaries are constant head boundaries, and no flow boundary other than the base of the model.

It is also typically assumed that the groundwater and its solutes must enter and leave the groundwater system somehow; it is also assumed that there is a spatial extent or geometry to the boundary and that there are processes taking place at the boundary, whether it be recharge or discharge; and finally it is assumed that there is a magnitude and a temporal variability of the processes occurring at the boundaries.

The last component to conceptualization of the model is determining the stresses imposed on to the system. Pumping or abstraction is the most common human originating stress, but climate through evapotranspiration and recharge also contributes as an input to stresses.

Assessments or consideration about the stresses are directed to whether the stresses are constant or changing in time, whether they occur in cycles or not. The volumes abstracted rates and the distributions of these stresses are also to be assessed and determined if they are localized or widespread.

Essential to this kind of model is identifying the recharge and discharge processes and the flow of groundwater between the recharge and discharge locations.

It is good practice to perform a form of checking for the model which can involve peers or stakeholders or otherwise produce a variety of experimental numerical conceptual models to compare how well they reproduce reality and choose a preferred conceptualization accordingly.

## 2.9 Background of the Research Areas

### 2.9.1 Overview of Research Area 1

#### 2.9.1.1 Physiography

Research Site 1 falls in the Otavi Mountain Land hydrogeological region which falls in the Cuvelai Etosha Basin which is described by (Christelis and Struckmeier, 2011) as stretching from the Otavi-Grootfontein-Tsumeb triangle east bound and runs along the southern rim of the Etosha basin. To the west it stretches up to 70 km beyond Outjo. This basin represents a watershed that drains into the Ugab Catchment to the west and towards the Etosha Pan in the north, while south and eastwards the drainage is into the Omatako Omuramba. The mean annual rainfall in the area increases from Outjo (450 mm/a) to Tsumeb (540 mm/a). A mean potential evaporation rate of 2800 mm - 3000 mm/a can be expected.

The basin is fractured in some locations such as in the dolomites of the Otavi Mountain Land and these fractures facilitate the replenishing/recharge of the groundwater

#### 2.9.1.2 Geology

Geologically, the Research Site 1 is primarily made up of quaternary Kalahari sediments and the dolomite and limestone of the Damara Sequence. It is part of the Otavi Mountain Land (OML), which stretches from Otavi in the south, to Grootfontein in the east and is bounded by Tsumeb in the north. The Damara sequence is of the Proterozoic age, and comprises the lower most aranaceous Nosib Group, the middle carbonate Otavi Group with the clastic Mulden Group most recent of the three units, view Figure 7. The sediments which partially make up the Etosha Limestone Member are mostly calcrete, dolcrete and unconsolidated calcareous sand and gravel (Bufler et al. 2000)

The Nosib group as stated above is the most basal Group of the three. In the Otavi Mountain Land this unit is further divided into two units. The lower, much thicker Nabis Formation and the upper thinner unit called the Varianto Formation. The lower Nabis Formation consists of basal fanglomerate, pebbly sandstone, and feldspathic sandstones. When one comes across the conglomerates, quartzitic cobbles set in greenish grey to maroon feldspathic grit matrix that is rich in muscovite can be expected. Granite, schist and muscovite quartzite from minor fractions are also part of this unit. The cross-bedded K –feldspar dominated fluvial sandstones that may appear to be reddish due to weathering overly the basal conglomeratic fractions. The Nabis Formation can be as thick as 1200m in the area, but is also recorded to be variable in thickness (Miller, 2008).

Deposited over the Nosib group is the middle carbonaceous Otavi group, which is further comprising Chuos Formation (ferruginous, black, magnetic, siliceous iron formation, granitic and gneissic clasts), and Ghaub Formation (carbonaceous and granitic clasts). These two formations that make up the Otavi group are cap carbonates that resulted from glaciation.  Miller (2008) clarifies that the Varianto Formation formerly attributed to the

Nosib Group was later revised and has been moved stratigraphically from the top of the Nosib group to near the base of the Otavi Group. These cap carbonates may be identified by their typical lamination, whitish, and buff, light grey or pinkish colour. The dolostones may be up to 40m thick and plump stromatolites may be encountered in some places

Miller (2008) differentiates that the Mulden Group unconformably to paraconformably overlies the Otavi Group. These rocks are confined to the northern part of the Damara orogeny and make up the third Neoproterozoic succession of the Northern Platform (NP). Formations making up the Mulden group are the Lower and Upper Tschudi Formations, the Lower and Upper Kombat Formation as well as the Owambo Formation which are ultimately covered by the Kalahari and Karoo successions a large extent in the Owambo basin. The Group forms intra-mountain deposits in synclinal structures. The Mulden Group may contain quartzites and sub-arkoses, some folded, silvery, chlorite-muscovite phyllites.

The Lower Tschudi Formation consists of dark, grey shales that are up to 30m, slates, feldspathic greywackes, marls, quartzites and to interbedded conglomerate layers. The conglomerate layers have sericitic and marly sandstone matrix with the clasts being light grey and of dolomitic nature. Uncharacteristic to the Lower Tscudi Formation is that the sandstones do not contain carbonate grains, but rather lithic grains of chert, schist, siltstones and quartzite.

The upper Tschusi Formation which is better exposed than the Lower, has an upward fining succession and is made up of light grey arkoses, feldspathic sandstones and feldspathic greywackes. They can reach up to 800 m in the Otavi Mountain Land.

Overlying the Upper Tschudi formation is the Kombat Formation primarily comprising grey to black shale, sandstone, siltstone and phyllite, while the Owambo Formation youngest of the formations has red and grey shale, sandstone, siltstone with minor limestone and dolomite (Miller, 2008; Külls, 2000).

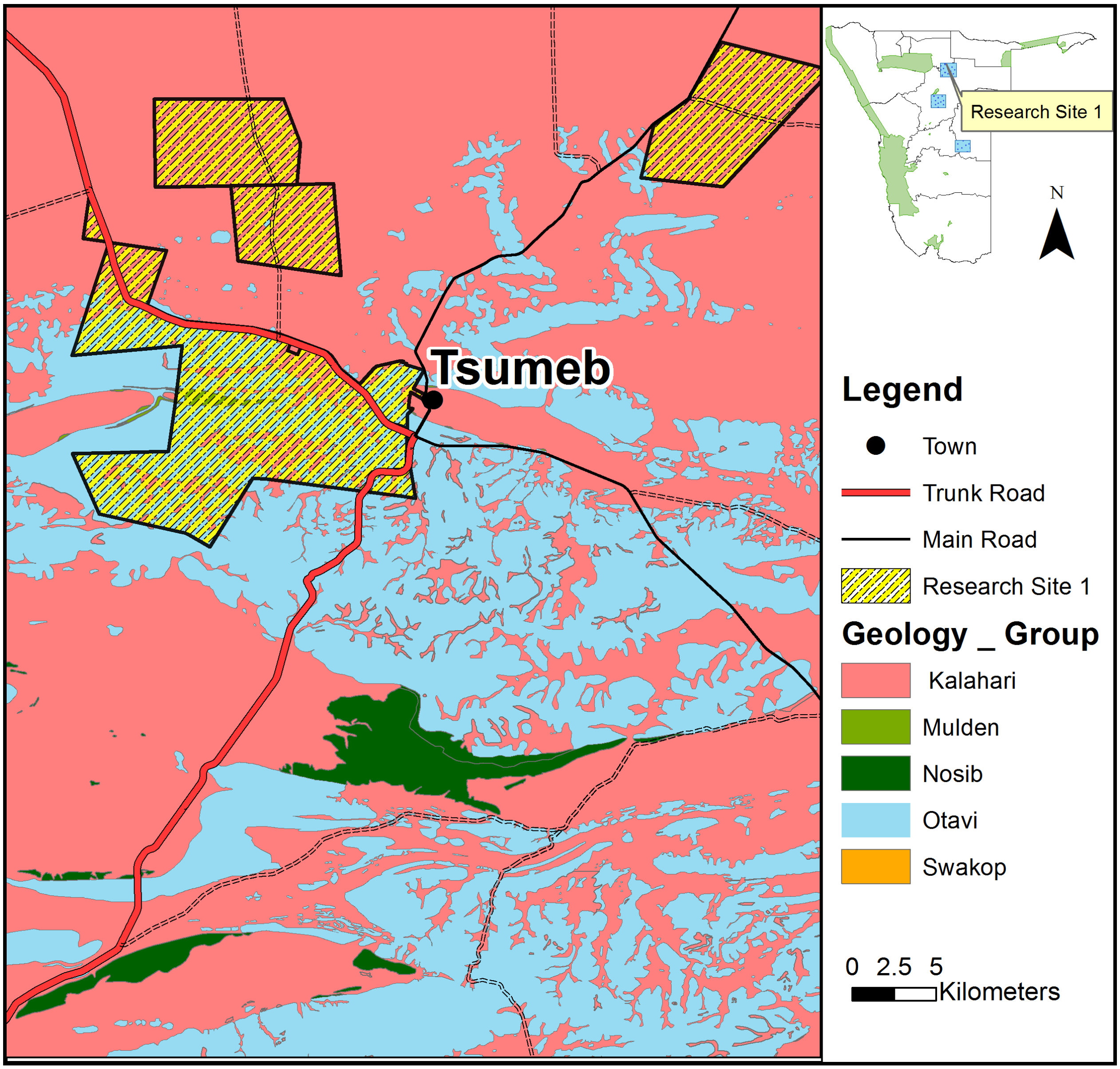



Figure 7: Geology Map of the Otjikoto Area, Research Site 1 (Map produced using Arc GIS 10.2 based on data from GROWAS, 2009).

#### 2.9.1.3 Hydrogeology

Generally, there are two aquifers in the area, but the target aquifer for this study area is the Karst aquifer, also referred to as the dolomite aquifer and hosts the most important groundwater source of the Oshikoto region. Its groundwater is autochthonous as all the groundwater is directly recharged from rainfall in the area. Although the aquifer's fractured rock has little primary porosity, the permeability is enhanced through the intense fracturing and dissolution of the carbonate rocks (karstification). Transmissivity of the heterogeneous rocks can range between 10 $m^2$/d to several 100 $m^2$/d, and locally, it can reach to 1000 $m^2$/d. The Karst aquifer is further divided by the E-W trending Nosib anticline into north and south portion, namely Tsumeb and Grootfontein-Otavi aquifers respectively.

The natural groundwater flow from Tsumeb is in a northerly direction as established by (GKW Consultants and BICON Namibia, 2003). From the Tsumeb groundwater study conducted by the author, it was noted that north of Tsumeb the groundwater flowing northward from the Tsumeb Karst Area (TKA) and is assumed to mix with locally recharged groundwater of the shallow Kalahari calcrete aquifer (Etosha Limestone Member). The flow within the Kalahari sediments is mainly directed towards the Etosha Pan, which is located northwest of the study area. SLR, (2017) however disputes this notion and suggests that groundwater flow is only happening within the Tsumeb subgroup but not in the Kalahari calcrete and sand.

There is a consensus between (GKW Consultants and BICON Namibia, 2003) that the dolomite of the Hüttenberg Formation has high transmissivity, although secondary fracture flow in the area may result in localised acceleration of the groundwater flow rates. Further to the north the flow lines widen within the Elandshoek and Hüttenberg Formations due to increased permeability values of the dolomite rocks, resulting in a flow-gradient of 0.003 (GKW Consultants and BICON Namibia, 2003).

Within the Tsumeb Aquifer, the groundwater flow is generally south to north as mentioned earlier and this is attributed to its north dipping rocks, dipping underneath the Kalahari sediments north of Tsumeb, the Tsumeb aquifer is source of groundwater to the Kalahari aquifer.

Over 500 boreholes have been monitored by DWAF since 1970s. Some boreholes however have either become dry or have been abandoned due to various reasons such as collapsing, or vandalism. This groundwater monitoring plan has been revised and currently 158 sites are being monitored over the Water Control Area (WCA).

Between 1980 to 2000 groundwater levels had decreased due to drought, and some springs have either disappeared completely or have a drastically reduced yield (Christelis and Struckmeier. 2011).

##### *2.9.1.3.1 Groundwater recharge, porosity, specific yield and Transmissivity*

Dolomite outcrops are showing relatively high groundwater recharge, whereas basement sub outcrops are significantly lower. Wherever dolomite and/or other rock types are overlain by Kalahari calcrete or sandy layers, lower recharge values have been observed (SLR Namibia, 2017).

(Uugulu and Wanke, 2018) summarise that the Tsumeb study area overall has recharge rates ranging from 21.1 mm/a, to 48.5 mm/a (3.5% - 8.71% of annual precipitation).

Table 8: Hydraulic Properties taken from the Tsumeb Groundwater Study (SLR, 2017)

| Hydrostratigraphical Unit | k [m/d] | Storage Coefficient [-] | Porosity [%] | Characterisation | Description | Recharge [%] |
|---|---|---|---|---|---|---|
| Tschudi-Formation (Mulden-Group) | 0.032 | $3.0 \cdot 10^{-04}$ | 1 | Aquitard | Fractured aquitard. Fault zone acting as a vertical conduit within low permeable fractured rock. Evaluation suggests bilinear rather than linear flow field indicating a finite conductive vertical fracture zone. | Less than 0.1% of the annual precipitation |
| Huettenberg-Formation (Tsumeb-Subgroup) | 55.65 | $1.6 \cdot 10^{-03}$ | 8 | Aquifer | Homogeneously fractured aquifer | 10% of the mean annual precipitation at the central and eastern ranges and 6% of the mean annual precipitation towards the west |
| Elandshoek-Formation (Tsumeb-Subgroup) | 12.60 | $7.0 \cdot 10^{-04}$ | 6 | Aquifer | Homogeneously fractured aquifer | 10% of the mean annual precipitation at the central and eastern ranges and 6% of the mean annual precipitation towards the west |

| Hydrostratigraphical Unit | k [m/d] | Storage Coefficient [-] | Porosity [%] | Characterisation | Description | Recharge [%] |
|---|---|---|---|---|---|---|
| Maieberg-Formation (Tsumeb-Formation) | 1.23 | $9.0 \cdot 10^{-05}$ | 2.8 | Aquitard or Aquifer | Fractured aquifer. Fault zone acts as a vertical conduit. Length of hydraulically active zone appears to be much smaller than the length of the lineament determined from geophysical data. | 10% of the mean annual precipitation at the central and eastern ranges and 6% of the mean annual precipitation towards the west |
| Gauss-Formation (Abenab-Subgroup) | 4.66 | $6.0 \cdot 10^{-04}$ | 3.8 | Aquifer | Fractured aquifer. Either homogeneously fractured rock or finite conductive fracture zone with considerable storage properties | 10% of the mean annual precipitation at the central and eastern ranges and 6% of the mean annual precipitation towards the west |
| Basement-Complex | 0.002 | 0 | 0.1 | Aquiclude | Virtually impermeable rock | 0.01 |

The Karst aquifer is in an area with annual rainfall of 550 mm/a and 2% of this contributes to recharge in the carbonate rocks. In total, a volume of 60 $Mm^3$/a recharge has been calculated for the whole Karst area by (DWA, 1992) of which 32 $Mm^3$/a makes up for the Tsumeb aquifer only. In comparison to the Tsumeb Groundwater Study (TGWS) 2003, a 43 $Mm^3$/a recharge is calculated for the Tsumeb aquifer. A sustainable yield of 18 $Mm^3$/a was calculated during the TGWS of 2003. These values have been suspected to be underestimation, or rather conservative (personal comm. Aina Mutota)

Christelis and Struckmeier (2011) categorized the principal aquifer formations of Namibia into two main hydrogeological rock types, that is, unconsolidated rock deposits and hard rock terrains. They further categorized the aquifers into three different aquifer types as porous, fractured and aquitard/aquiclude (Figure 8), and into 12 Hydrogeological Regions as presented in Figure 9.

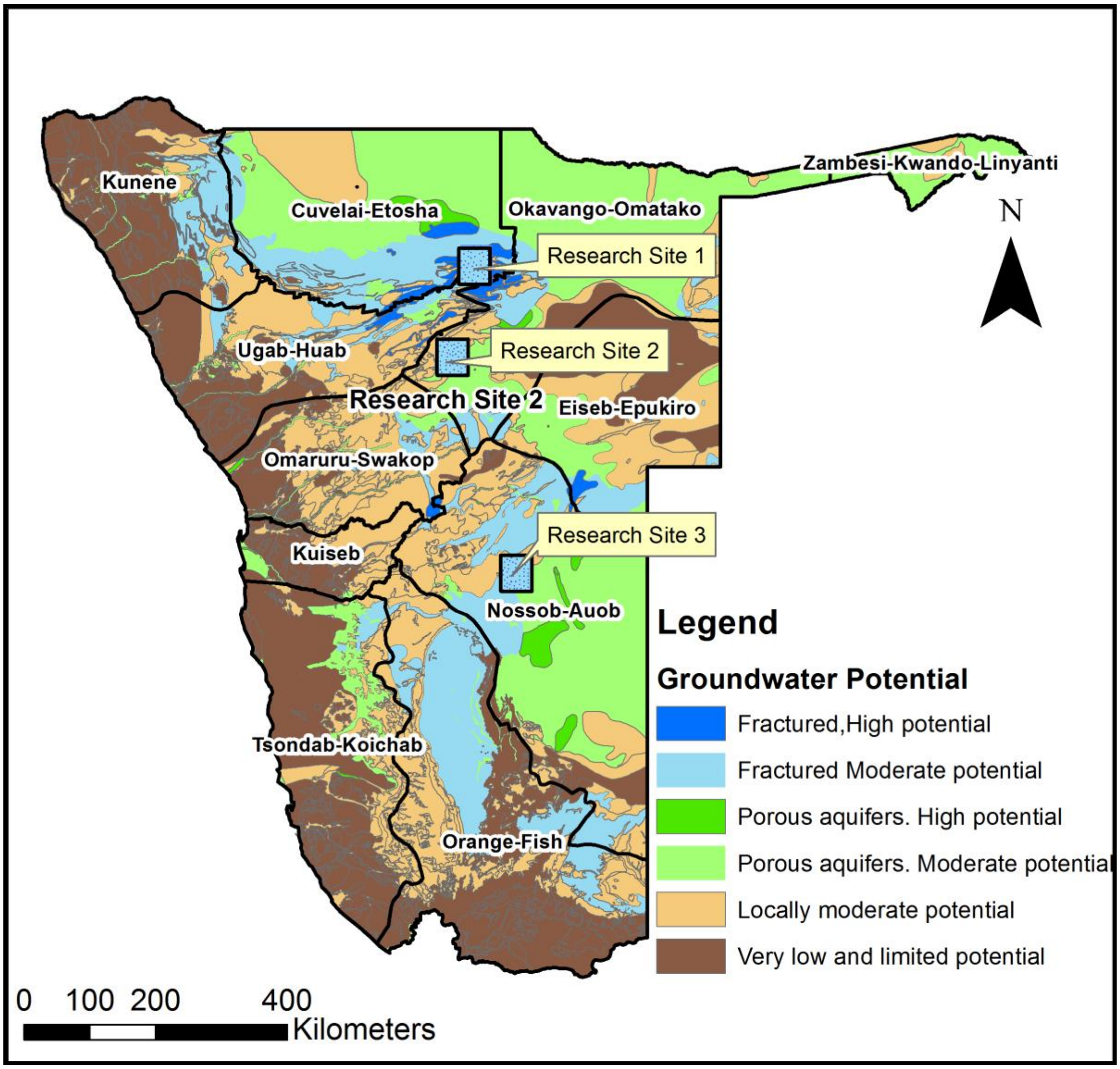



Figure 8: Principal aquifer formations and aquifer types of Namibia (Map prepared with ArcGIS 10.2 using data from GROWAS).

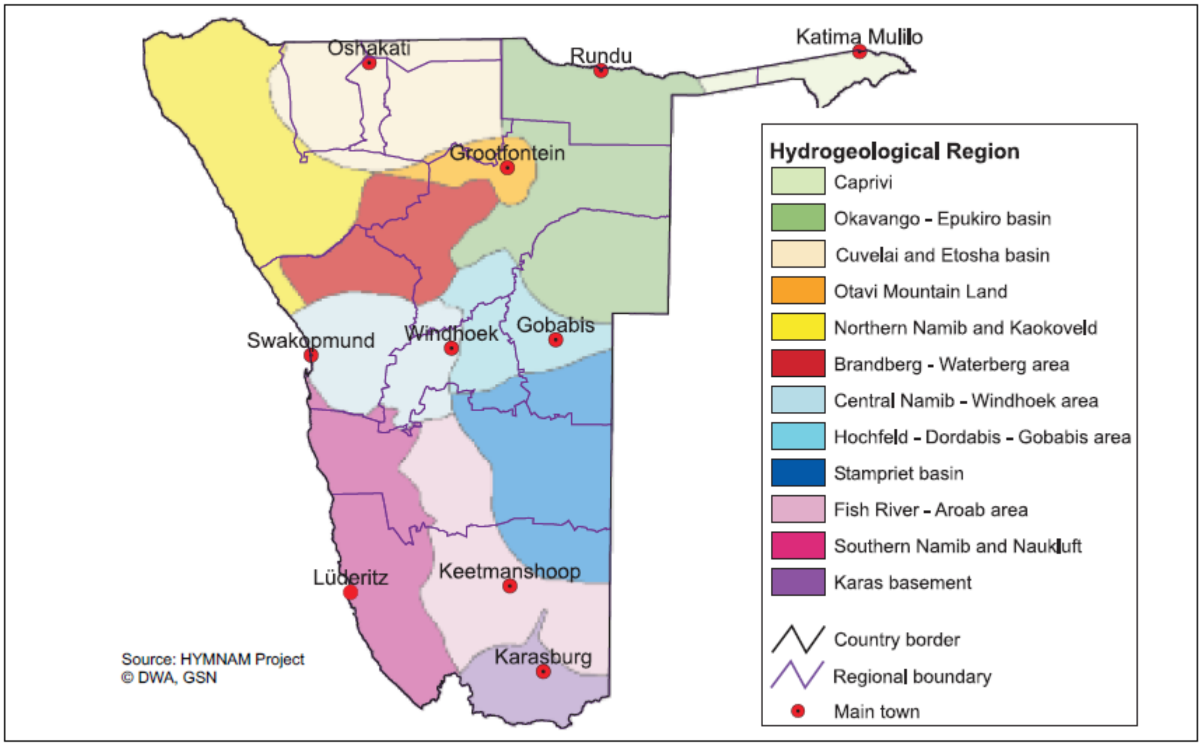



Figure 9: Hydrogeological Regions of Namibia (Christelis & Struckmeier, 2011).

### 2.9.2 Overview of Research Site 2

#### 2.9.2.1 Physiography

Falling within the Brandberg, Erongo and Waterberg hydrogeological region within the Omatako Basin, the Research Site 2 is about 1300 m above mean sea level. The Waterberg is a flat plateau type of mountain similar to Mount Etjo. Annual rainfall ranges between 50 mm/a in the west of the basin to 450 mm/a around the study site. The average temperatures are between are between 20-22°C and the potential evaporation rate vary between 2100 mm and 2400 mm/a (Mendelsohn et al. 2002)

#### 2.9.2.2 Geology

Forming the central part of the Damara trough in geological setting the area is characterised by north east striking faults and thrusts as well as north striking faults in the younger rocks represented by the Aeolian sandstones of the Etjo Formation (Stormberg Group) which makes up the Waterberg Plateau and Mount Etjo. Sandstones are the characteristic rock type and subsequently main aquifer and they overlie some argillaceous sediments of the Omingonde formation (Ecca Group). View Figure 10 for overview of the geology of the site as given by (GROWAS, 2009). As illustrated by Miller (2008) the sandstones of the Etjo Formation are feldspathic, fine to medium-grained and Aeolian. They are creamish to pink to brick red in colour. These build the cliffs that cap the Waterberg and Klein Waterberg Mountains. The formation is 60 m thick at Klein Waterberg and is 150 m thick at Waterberg.  The formation is further divided into three units, lower, middle and upper unit.

The lower unit is made up of interbedded layers of bedded pebbly sandstones; some sandstones are laminated with massive fine-medium grains. It also has thin bioturbated purple mudstones.

The middle unit is typically mainly made up of massive, well sorted, fine grained sandstones. The sandstone beds are thickly to very thick, and form the orange –brown cliffs of the Waterberg. The unit is 15 m thick on the northern edge of the Waterberg.

The upper unit which is at least 100 m to the north-west of the Waterberg and consists of fine-medium grained, aeolian cross-bedded sandstone facies which is the majority of this upper unit. Some minor mudstone facies and sand and pebble lags facies also exist. The individual layers of aeolian origin range between 1-4 m at the base but 30 m thickness has been encountered towards the north of the unit. (Miller, 2008)

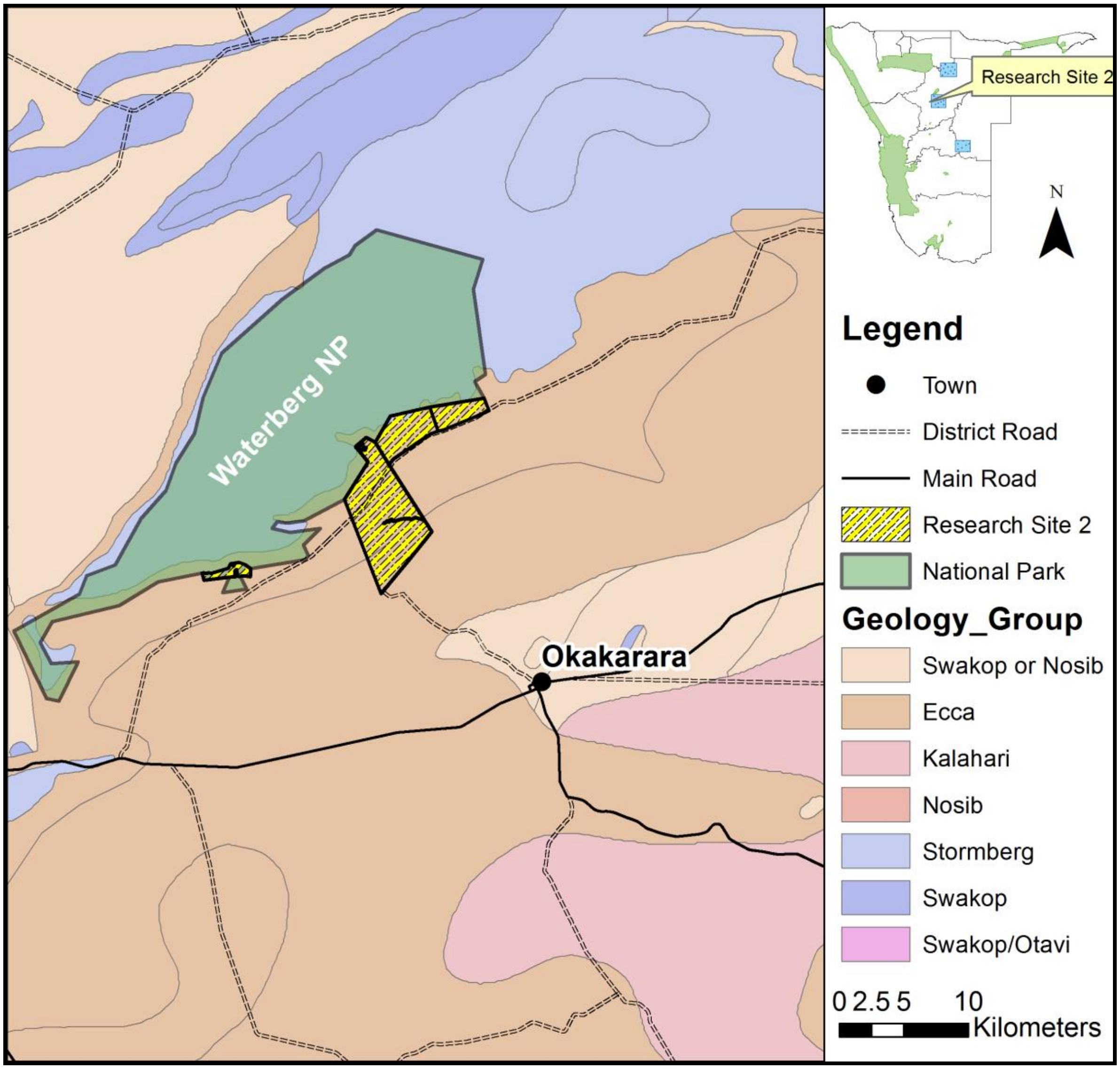



Figure 10: Geology Map of Waterberg Area, Research site 2 (Map prepared with AcrGIS 10.2 with data from GROWAS, 2009).

#### 2.9.2.3 Hydrogeology

The Waterberg Park falls into the Brandberg, Erongo and Waterberg hydrogeological region of which the Otjozondjupa and Erongo regions form a major part. The Waterberg Park depends majorly on groundwater from this basin. The authors have identified that the plateau forms a major hydrogeological feature. The Etjo sandstone rests with an unconformity on the underlying Omingonde argillites, which in turn have given rise to what are called contact fountains which tap water from the porous sandstone. Contrary to what may be deduced by the presence of many springs and fountains found in the area, the area actually only has moderate to low groundwater potential. This low potential can be elevated to moderate potential in areas where there are contact zones, karstified zones and faults. In these areas, the marble aquifer is the most significantly utilized aquifer and it lies north, north east of Otjiwarongo. Water in this aquifer generally is of good water quality and it is tapped from the fractured and slightly karstified Karibib marble (Christelis and Struckmeier, 2011)

##### *2.9.2.3.1 Groundwater recharge, porosity, specific yield and Transmissivity*

A study conducted by Klock (2001) outlined the hydraulic conductivities of the Etjo Aquifer to vary between $7.2x10^{-6}$ m/s and $1.3x10^{-5}$ m/s, and an average of $1x10^{-5}$ m/s while for the Omingonde Aquifer, hydraulic conductivities range between $1.1x10^{-9}$ m/s and $1.6 \times 10^{-7}$ m/s, with an average of $1 \times 10^{-7}$ m/s. The effective porosity of the Etjo sandstone are reported as 0.13 to 0.21 based on the (carbon tetrachloride method and 0.11 to 0.12 based on the Darcy's apparatus. Total porosity is given to be as 0.13 to 0.30. Where porosity data is limited in literature, data from similar lithologies were reviewed and estimates were given based on these values. Recharge values calculated by Uugulu and Wanke (2018) for this study area are given to be between 8.7 and 11.4% of the MAP or as 39.1 mm to 51.1 mm per annum. High recharge rates in Waterberg could be related to fast infiltration and absence of evaporation.

### 2.9.3 Overview of Research Site 3

#### 2.9.3.1 Physiography

This study area is found in the Dordabis - Gobabis district, and falls under the Hochfeld-Dordabis-Gobabis Hydrogeological area within the Nosob Auob water Basin. This hydrogeological unit covers the area from east of Windhoek to the eastern national boundary of Namibia. On a regional scale, the study site falls within the Stampriet Transboundary Aquifer System (STAS). The STAS stretches from Central Namibia into Western Botswana and South Africa's Northern Cape Province, and lies within the Orange River basin. It covers a total area of 86 647 km², of which 73% is in Namibia, 19% in Botswana, and 8% in South Africa.

The STAS was delineated based on the occurrence of geological formations belonging to the Ecca Group within the Auob and Nossob River basins. Within the Namibian Borders, the section of the STAS is referred to as the Aranos or Stampriet Basin (Alker, 2008). The area has two major ephemeral rivers, i.e. the Nossob River and the Auob River flowing from Namibia and joining the Molopo River in Botswana. Elevations are reported to be 1450 m – 900 m above mean sea level, where the north-west is at the higher elevation decreasing towards the south –east. The groundwater level follows the surface slope from high to low. Characteristic to the area are the dunes which cover a large area extending south-east into the Republic of South Africa.

Other than dunes, the landscape of the study area consists of pans, occasional thick bushes, calcrete/ sandy surfaces. Figure 11 below shows the delineation of the STAS covering the Namibian, South African and Botswana extend, while Figure 12 displays the SAB which is within the Namibian Borders.

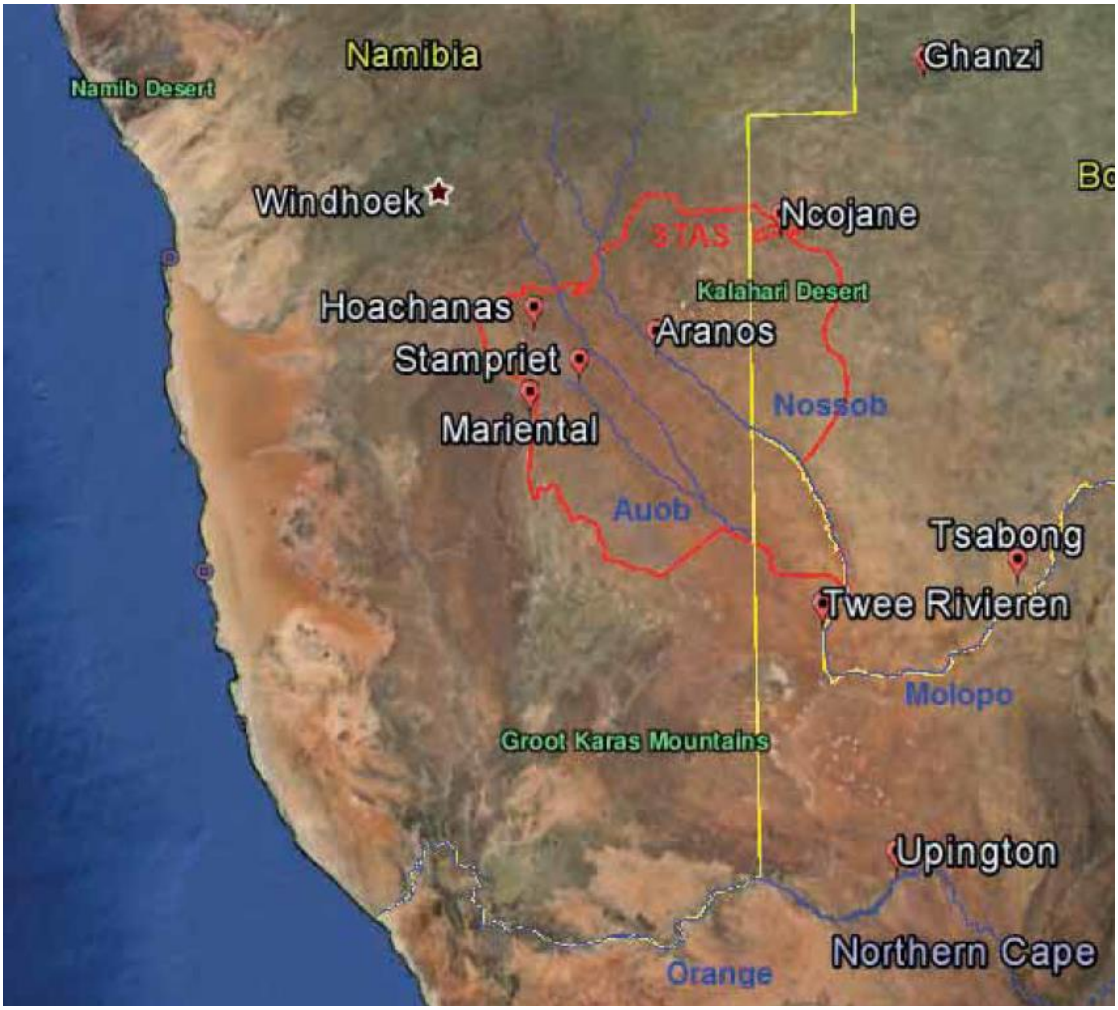


Figure 11: Delineation of the SAB. (Source: **UNESCO, 2016)**.

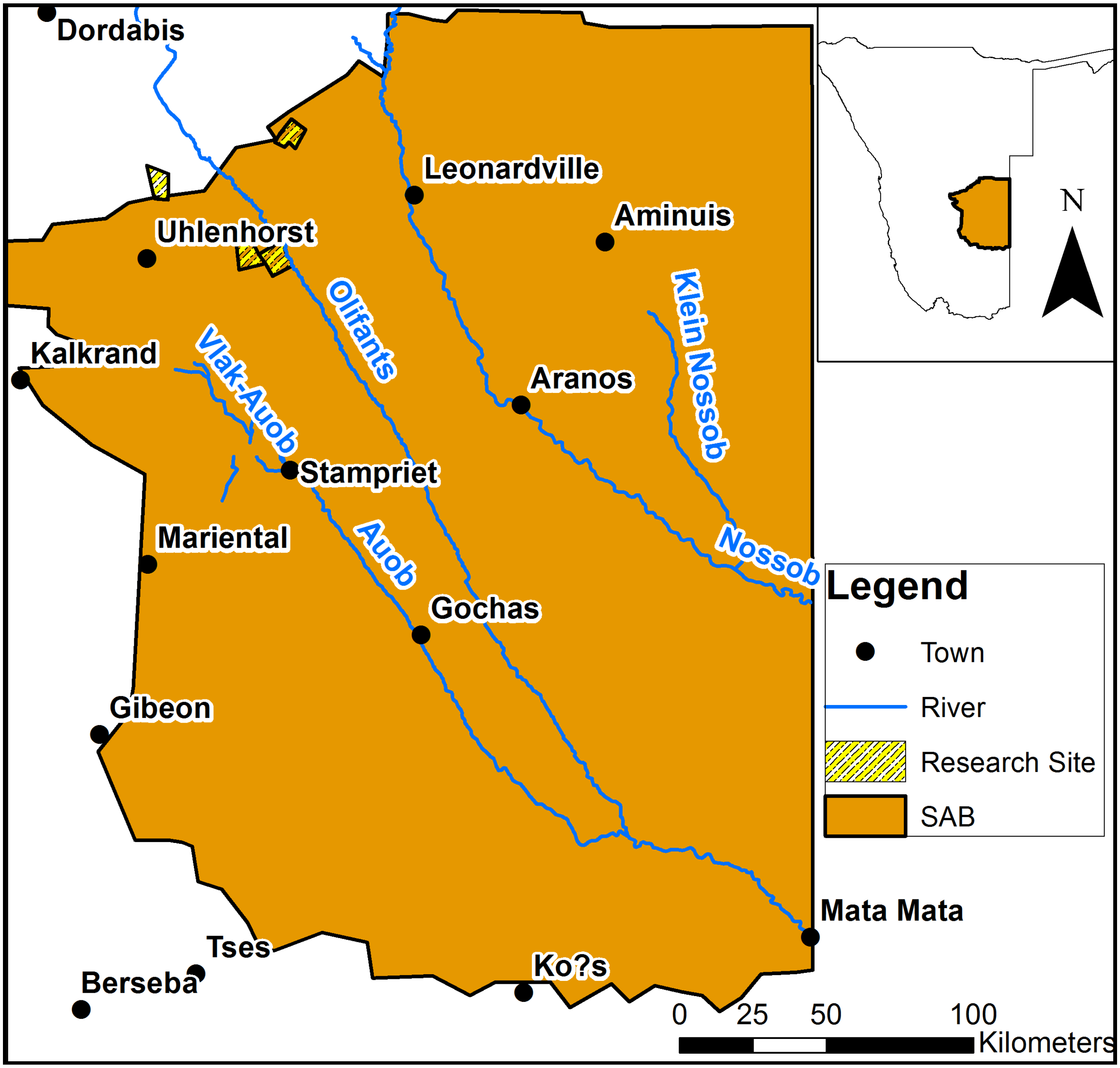



Figure 12: Boundary of the SAB (Map Produced with ArcGIS 10.2 with data sourced from GROWAS and Alker, 2008).

*Temperatures* are influenced by the semi-arid condition, and are without high annual mean variations. The mean annual temperatures range between 19 - 22 °C. The southern part of the area is much warmer than the central and northern parts. In January the mean maximum temperatures in the west, south and east range from 26 to 36°C and in winter they vary from 1-12°C (UNESCO, 2016).

*Rainfall* for the most part is intense and of short duration, it occurs heavier between January and March and decreases in frequency during most of the winter months. An average annual rainfall of 240 mm/year is common for the southern and western segment of the SAB (See Figure 2). The MAP for the general STAS is depicted in Figure 13. Sporadic heavy rainfall events that record much higher precipitation than expected have occurred in 1960, mid - 1970’s, 2000, 2006 and 2011.

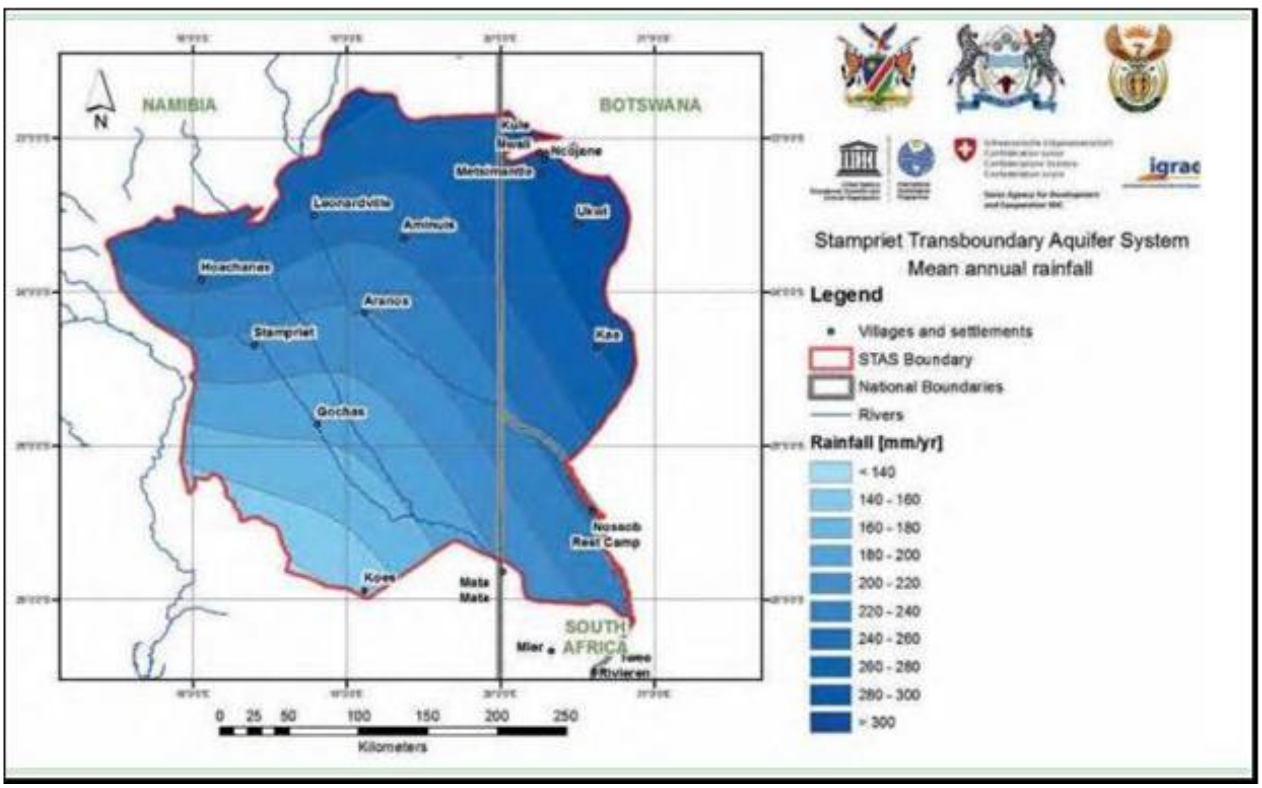



Figure 13: The MAP across the STAS (Source: JICA, 2002).

*Groundwater utilisation* has been described by Braune et al. (2013) to be the most relied on source of water supply to the inhabitants of this study area. It is observed that the water is mainly used for irrigation, domestic and stock watering purposes. Although 37%

of the population in the STAS is served with improved water supply, there remains a large percentage of the rural population that has no access to improved water sources and they rely primarily on primitive, undeveloped sources such as hand-dug wells and springs.

### 2.9.3.2 Geology

A good conceptualisation of the geology of the study area is paramount to the understanding of the hydrogeology and groundwater conditions of the study site. Therefore, geological description of the area as described by (JICA, 2002) was reviewed to better conceptualise the area.

Generally, the area is a huge sedimentary basin, which consists of sandstone, siltstone, limestone, shale and mudstones which are collectively known as the Karoo Supergroup deposits see Figure 14 for an overview of the geological set up of Research Site 3. The figure also shows the farms were the study was conducted; these areas are highlighted in yellow, and indicated in the legend as farm. The Supergroup is overlain by younger Tertiary to Quaternary aged Kalahari Group Sediments (UNESCO, 2016).

It has been summarised by (JICA, 2002) that the area is geologically made up of basement rocks comprising the Damara Sequence, Dwyka Group and Nama Group. The Damara Sequence and Nama Group are a result of the Pan –African Orogeny, and the Dwyka Group is made up of glacial sediments of the late Carboniferous to early Permian geological period.

The Dwyka Group is overlain by the Prince Albert Formation, Rietmond Member and the Whitehill Member. The Prince Albert Formations hosts the Nossob and Auob Members, characterised be non-marine sediments deposited in the early Permian Period. The Prince Albert Formation hosts numerous faults, dolerite dykes and sills.

*The Kalahari Beds* on the other hands are the most recent geological layers, deposition occurred between the late Cretaceous to recent geologic periods, on what is known as the African surface- an erosional landscape. Most part of the Namibia is covered by the Kalahari Beds of unsorted, fluviatile Aeolian sands. Its most bottom layers are made up of poorly sorted, small pebbles, partly imbricated conglomeratic fan deposits that are held together by calcrete. Karstic topography is a common result when the calcrete is exposed over large extends. Above these Karstings are the younger Kalahari deposits, which are for the most part, poorly sorted sands that are of fluvial origin and the Aeolian sands are better sorted. Gritty zones, and calcrete cementations as well as silcretes may be found across the Kalahari deposits.

The *Auob Member* underlies the Kalahari Beds. This member has five (5) detailed units to it.

The bottom layer is sandstone, called the Lower Sandstone (A1). It has been described by (JICA, 2002) to have some cross bedding, be medium to coarse grained and can be as thick as 30 m.

On top of the (A1) is the (A2) - Lower Bituminous shale and coal Layer. Not much is known about this layer, other than that the swampy conditions may have been developed abruptly. This layer consists of shale and coal also comprises fine grained sandstones, siltstones and often dark, carbonaceous shales.

The Middle Sandstone layer (A3) however, is discovered to be well bedded, fine to medium grained, and it hosts biotite as accessory mineral. Along with clay pellets, petrified wood is often encountered in Iron rich sandstone layers.

The (A4) Upper Auob Bituminous shale and coal layer overlies the above mentioned sandstone layer.  This layer is evidence of the second event of swamp, marsh and possibly lagoon deposition which was associated with coal. The coal layers vary in thickness, up to 36 m. The layers co-exist with beach sandstones; splay sandstones that have been bioturbated and are generally fine grained, but feature an upward coarsening.

The most top layer (A5) is recognised by coarse grained channels of sandstones, often with lag deposits. Splay deposits that are fining upwards and black bituminous shale layers, not thicker than 4 m, are also found in this unit. The A5 has a general thickness varying from 0-61 m, but due to the intrusion of the thick Karoo sills, and the pre Kalahari erosion cutting through it, the preserved thickness did not remain unaffected.

The most bottom layer of the Prince Albert Formation is the *Nossob Member* divided in to Lower Sandstone, Middle Shale and Upper Sandstone layer.  The Lower sandstone unit marks the regional unconformity, which is also detected as the most upper Dwyka Group layer. The transition from Dwyka to Nossob is believed to have been sudden, as suggested by the scouring surface at the base of the Nossob, on to which pebbly sandstone is found deposited (JICA, 2002).

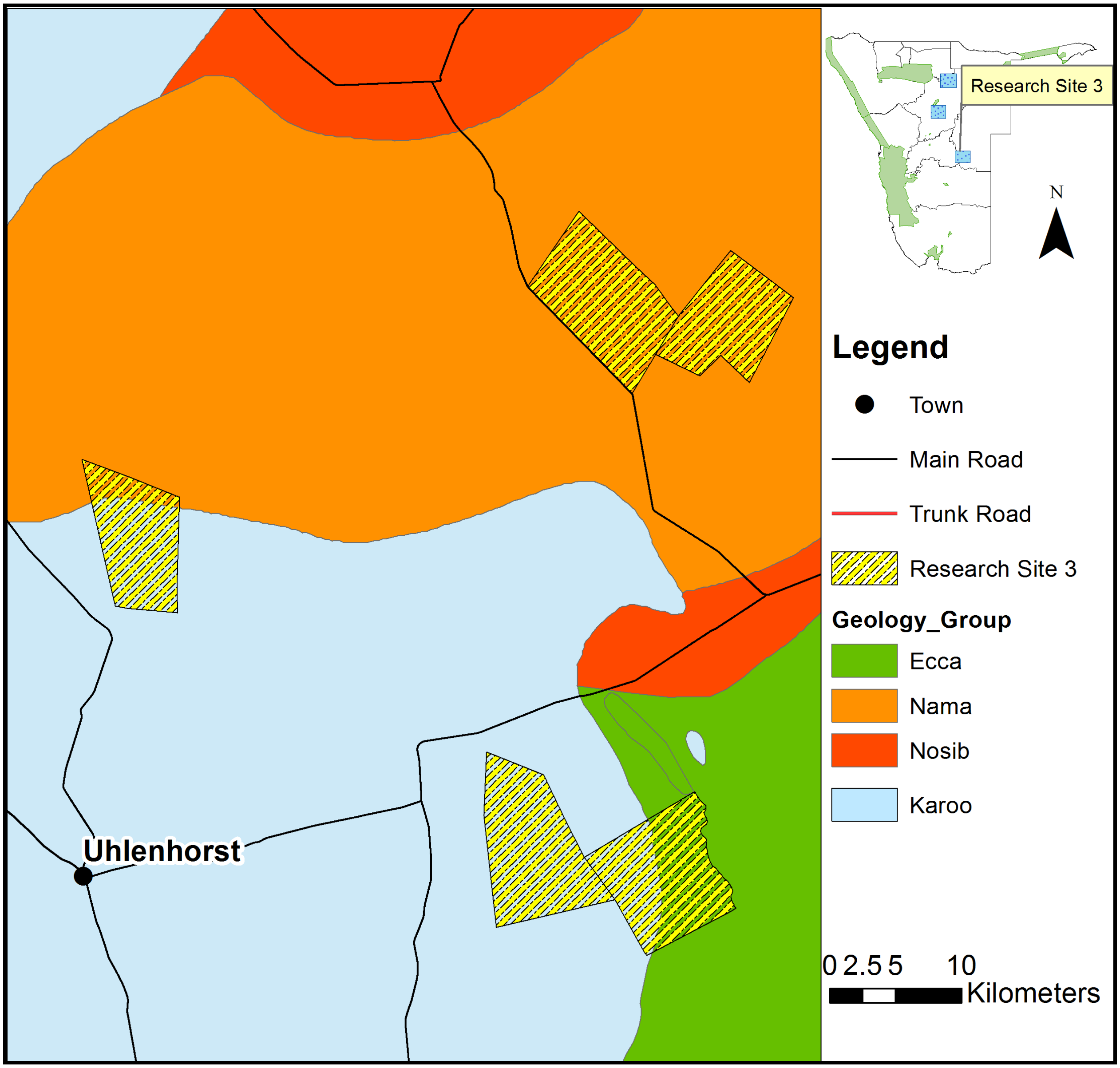



Figure 14: Geology Map of Research Site 3 ( Map Produced with ArcGIS 10.2 with data sourced from GROWAS, 2009).

### 2.9.3.3 Hydrogeology

The SAB consists of superimposed unconfined and confined aquifers, formed by a succession of sedimentary rocks deposited in a basin of the Nama System bedrock.

The basin is made of different geological Supergroups/Groups/Formations/Members and contains three major aquifer systems: two confined aquifers in the Lower Karoo Supergroup sediments (Auob and Nossob), and a discontinuous aquifer system in the overlying Kalahari Group and Upper Karoo Supergroup sediments. The Auob and Nossob aquifers produce truly artesian conditions in some zones of the depressed valleys of the Auob and Nossob Rivers, which prompted the name Aranos Basin or Stampriet Artesian Basin (SAB). The Dwyka and Nama Groups can be regarded as the hydrogeological basement rocks of the study area (UNESCO, 2016).

The Kalahari beds, the Kalkrand Basalt and partially also the Upper Rietmond Formation in some parts make up the unconfined aquifer system. In the Upper Rietmond Formation is made up of sandstone and subordinate shale bands, whose water-bearing properties can vary significantly and some of the lower layers can even serve as an aquiclude for the underlying Auob aquifer (See Table 9). The distribution of each of the three aquifer units is not the same across the basin, in some areas two of the aquifers may be present while in other areas; all three units may be hosted. Although the chemical nature of the host rock and the groundwater may differ, the groundwater in these unconfined aquifers is essentially considered as one hydrological "type" of groundwater. However, the water bodies are not connected and may be absent in some parts or only a perched water table may have been formed.

The confined aquifers in most parts of the STAS are made up of the sediments of the Nossob, Mukorob and Auob. The discharge is along the surface water drainage system which is south easterly. Recharge to these confined units happens in the northern, northwestern and western parts of the SAB (Kirchner et al. 2002).

Table 9: Stratigraphy of the SAB (Source: JICA, 2002)

| GEOLOGY | | | | | | | | HYDRO-GEOLOGY | |
|---|---|---|---|---|---|---|---|---|---|
| Age | Super group | Group | Formation/Member | | | | Lithology | | |
| | | | Botswana (Smith, 1984) | Namibia (Miller, 2008) | S. Africa (SACS, 1980) | This report | (simplified) | STAS | |
| Tertiary to Quaternary | Kalahari | Kalahari | | | | Kalahari beds | Sand, silcrete, calcrete (duricrust), gravel, sandstone, marls, clayey gravels | Unsaturated zone | |
| Jurassic | Karoo | Stormberg-lava (B) Kalkrand (N) Drakensberg (SA) | | Neu Loore | | Kalkrand | Basalt and dolerite | Kalahari aquifers | |
| Triassic | | Lebung (B) Etjo (N) Clarens (SA) | Ntane | | | Ntane | Sandstone | | |
| | | | Mosolotsane | | | | | | |
| Permian | | Ecca[16] | Kule | Whitehill | Whitehill | Whitehill | Shale and limestone | | |
| | | | Rietmond | Rietmond | Prince Albert | Rietmond | Shale and sandstone | Aquitard/ aquiclude | |
| | | | Otshe | Auob | | Auob | Sandstone, interbedded with shale and coal horizons | Auob aquifer | Stampriet Artesian Basin |
| | | | Kobe | Mukorob | | Mukorob | Shale, mudstone, siltstone | Aquitard/ aquiclude | |
| | | | Ncojane | Nossob | | Nossob | Sandstone | Nossob aquifer | |
| Carboni-ferous | | Dwyka | | | | | Glacial sediments | Aquitard/ aquiclude | |
| Cambrian | Pre-Karoo | Nama | | | | | | | |

### *2.9.3.3.1 Groundwater Recharge, Porosity, Specific Yield and Transmissivity*

Rainfall has been documented to be between 120-240 mm per year, with an annual evaporation greater than 3000 mm. From isotopes studies of $^{14}C$ the Kalahari aquifer has old water, although some younger water was detected in the northwest part of the basin close to the study area. Recharge is noticed to occur mostly after heavy rainfall event, and it believed to be positively influenced by the existing calcritic sinkholes northwest of the basin. The Auob aquifer is indirectly recharged by the overlying Kalahari aquifer and major lineaments across the basin enhance the recharge in the basin. The Chloride Mass Balance Method has been used in previous studies and a recharge value between 0.1 and 1 mm/a has been deduced Braune et al. (2013).

Taapopi (2015) with the CMB method has calculated the recharge of a farm Ebenhaezer which falls within this Research site 3. The author presents the recharge values to be 0.44% of the average annual precipitation of 240 mm/a, which translates to 1.6 mm/a (Uugulu and Wanke, 2018) have calculated a slightly higher recharge in the same area of 3.24 mm/a to 17.5 mm/a (1.34% - 7.3% of annual precipitation).

Braune et al. (2013) further reports that the three aquifers are deduced to have porosity ranging between 25 and 27%. It was further concluded that the distribution of the specific yields in the three aquifers is broad. However, it was narrowed down to Auob aquifer being the most superior aquifer and the Nossob being the inferior aquifer based on specific yields. The values are between 0.01 and 1.5 in the Auob aquifer while they range from 0.001 to 0.01 for the Nossob and Kalahari aquifers.

The Auob aquifer has the greatest transmissivity values of up to 194 $m^2$/d from the JICA study. Closer to the area of interest, transmissivity values between 2.5 and 25 $m^2$/d may be expected (JICA, 2002).

# 3 STATEMENT OF THE RESEARCH PROBLEM

It is currently unknown how aquifers in Namibian savannah systems are managed at the local scale and how this fits with governmental plans as well as with the standard sustainable yield approach. This leaves a knowledge gap of how the aquifers react to these different management approaches or strategies in terms of sustainability of the water resource.

## 3.1 Limitations of the study

Ideally, the sustainable yield approach needs input observations for at least 30 years. With shorter observations that are currently available, the results have larger uncertainty. For this study, it will be overcome by using and relying on long term observations from existing databases such as that of Namibia Water Cooperation (NAMWATER), Bittner Water Consult (BIWAC) and Department of Water, Agriculture and Forestry Affairs (DWAF) where monitoring data is at least 30 years coming. Also, many interviews have been conducted in an around the farms for different projects and therefore, some farmers have been unwilling to undergo more interviews, however, they have been approached concerning the project.

# 4 OBJECTIVES

The overarching objective of this study is to compare and contrast how different management strategies at the different study sites influence the groundwater system and its long term sustainability. To achieve this, there are specific objectives for each management strategy that must be considered, and these objectives are:

1. To assess how groundwater management strategies employed by the local farmers influence the long term sustainability of the savannah aquifers in Namibia.
2. To assess how groundwater management strategies suggested by the governing bodies influence the long term sustainability of the savannah aquifers in Namibia.
3. To assess how groundwater management strategies as per standard sustainable yield approach influence the long term sustainability of the savannah aquifers in Namibia.

4. To assess how groundwater management strategies as per short - term available volume approach influence the long-term sustainability of the savannah aquifers in Namibia

# 5. HYPOTHESIS OF THE STUDY

The groundwater management strategy of the local farmers, the government, the sustainable yield and that of the short - term volume available, have a significant influence on the long term groundwater levels of the Namibian savannah aquifers.

# 6. MATERIALS AND METHODOLOGY

## 6.1 General research design

To obtain all the data necessary to complete the study, the methodology included the following tasks as presented in Figure 15.

Permission to carry out the research and ensuring ethical standards were adhered to where granted by the University of Namibia's School of Post Graduate Studies. The permission letter and ethical clearance certificate are attached as Appendix 1 and Appendix 2.

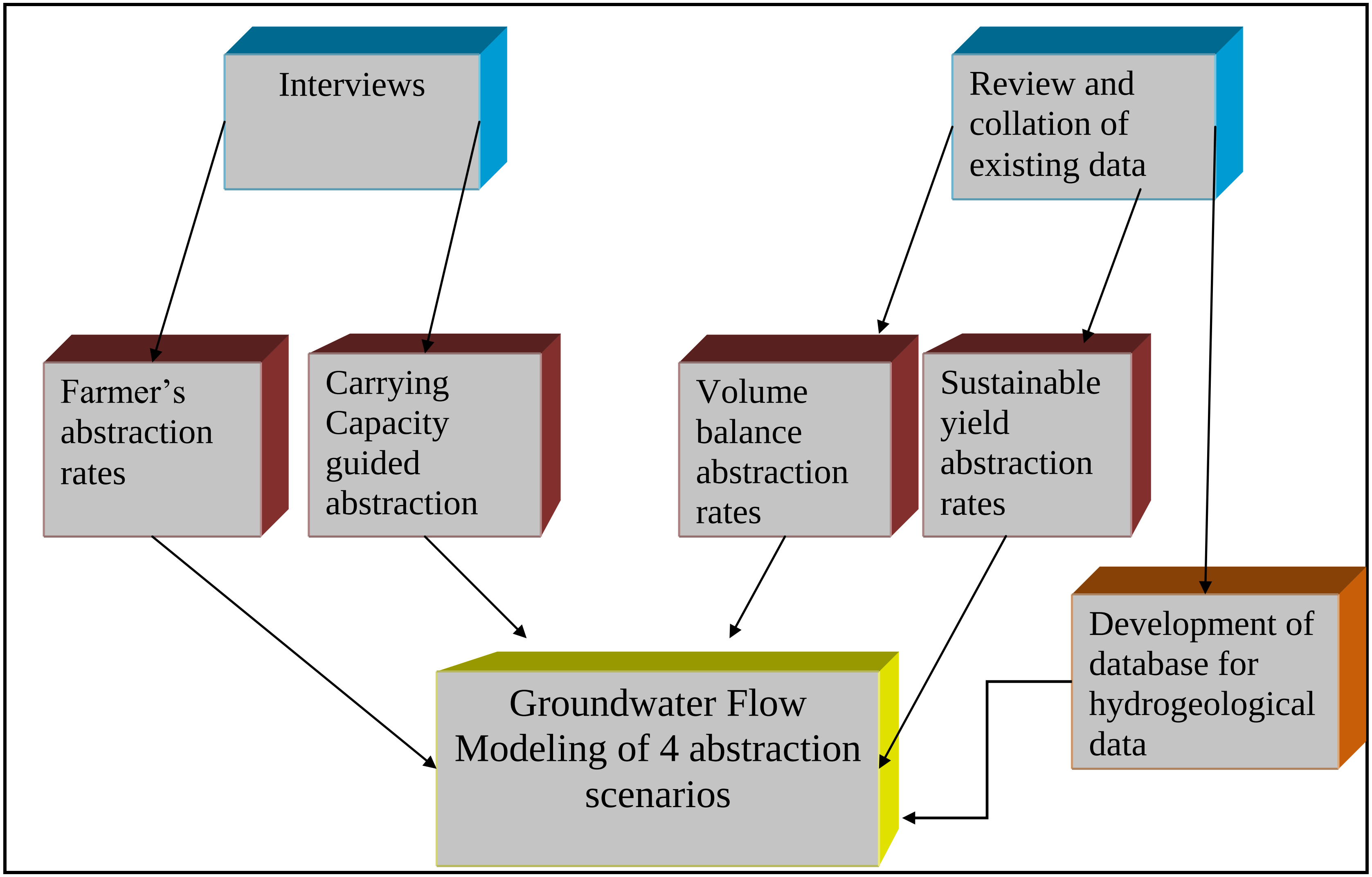



Figure 15: Flow diagram for the research methodology.

### 6.1.1 Interviews

#### 6.1.1.1 Questionnaire Development

Two different questionnaires were developed for this research. One targeted to acquire the management strategies that the farmers put into effect at the local scale and the other to acquire the management strategies employed by government. The questionnaires addressed both qualitative and quantitative measures. For the farmers, specific questions addressed the livestock count on the farm, the number of boreholes on the farm highlighting the ones being utilized and what management options they the farmers currently practise.

The second questionnaire was as mentioned above tailored for the government officials who work at DWAF. This questionnaire aimed at finding out what management strategies the government employs in order to manage groundwater in the country.

Once the questionnaires were ready, appointments with the farmers and government officials were set with those available.

#### 6.1.1.2 Conducting of Interviews

For the local farmers a field trip to the research sites was conducted and the farmers who were willing to participate were interviewed. Coordinates of the farms and set up of water infrastructure were captured. Some farmers, who were not onsite, were interviewed telephonically, while yet other farmers answered the questionnaire via electronic mail.

At the Research Site 1 (Otjikoto site), six (6) farmers were interviewed on the following farms; Farm Driefontein, Pasedina, Research Center portion 1 and portion 2, Farm Tshiguuo, Farm Muteka (the latter two are part of consolidated farm Tsumore).

At the Research Site 2 (Waterberg area), five (5) farmers were interviewed at Farm Onjoka, Okatjikona, Okomumbonde, Namibia Wildlife Resort and Waterberg Plateau Lodge. Finally in the Research Site 3 (Kuzikus area), Five (5) farmers were interviewed. In order to obtain the cooperation of some farmers, a list of farmers with their contact details in the Research Site 3 area was obtained from a willing farmer and thereafter, emails were forwarded requesting for their assistance. The cooperating farms in this research site were from farms Rice, Olifantswater, Kuwinamab, Gomnab, and Tivoli.

Five (5) government officials have been interviewed two (2) of who were employees of DWAF but are no longer serving in that capacity, however their knowledge of management in the department is still useful. The remaining three (3) interviewees include the Chief Hydrogeologist, the Deputy Director, and a hydrogeologist of the Division Geohydrology in the MAWF.

### 6.1.2 Compilation of Existing Data

In the process of compiling relevant data for the study, existing information was collected and reviewed. The information was gathered from existing reports compiled by various institutions such as DWAF, NamWater, SLR Namibia, Namib Hydrosearch, journals and online sources. All the information received from  DWAF were legally obtained through a request form addressed and submitted to the Permanent Secretary of MWAF as required by the Ministry. The same applied for the information gathered from NAMWATER, where a permission to use the information was granted by the Chief Executive Officer of NAMWATER. These consent letters are attached in the Appendix 3 and Appendix 4.

For the governmental strategy, the existing Water Act No. (54) of 1956 and the yet to be enacted Water Resources Management Act of 2013 were reviewed to understand the strategies in place.

From DWAF and NAMWATER data pertaining to monitoring of water levels, borehole completion reports, elevations and locations of boreholes in the study area were collated and the relevant information to the study was retrieved. From DWAF only information for Research Site 1 and Research Site 3 was requested , while that of Research Site 2 was obtained from NAMWATER because DWAF reported to not have monitoring occurring in this region, due to reasons that the Research Site 2 does not fall under what is classified as a Sub-terrainean Water Controlled Area as dictated by the Water Act. No variability in the monitoring data is expected because the hydrogeological monitoring framework is given by DWAF to the bulk water supplying parastatal NAMWATER and this framework is followed almost effortlessly for reasons such as manual monitoring of waterlevels at boreholes is not a dynamic or versatile activity and standard operating preocedures are followed. It has also been noted that the same template is used for information logging by the two entities, further eliminating discrepancies.

Additionally, the setting up of the groundwater model requires initial hydrogeologic input values of the aquifers in the study areas. These input parameters include the hydraulic conductivity, porosity, initial hydraulic heads, aquifer thickness and recharge values. These parameters were thereafter stored in a excel sheets where further calculations were conducted.

Lastly, literature of the study areas were collected and processed in order to widen and deepen the understanding of the physical geology of the areas. This literature included, the physiological, hydrogeological, geological, topographical information of the research areas as well as general groundwater management case studies in Namibia and around the world.

### 6.1.3 Estimation of the Abstraction Strategies

There are four groundwater management strategies under study. The first strategy is based on the farmer's abstraction volumes on the farms. The second strategy is the carrying capacity guided abstraction volume which is also referred to as the government strategy. Thirdly is the sustainable yield strategy and the fourth strategy is the short-term volume available strategy

#### 6.1.3.1 Farmer's Abstraction Strategy

Using the quantitative information gathered from the interviews conducted with the farmers at all the research sites. The annual groundwater abstraction volumes of farmers were computed. The quantitative data includes the consumable groundwater volumes for small stock unit (SSU) and large livestock units (LSU) per day. For these abstraction rates the actual numbers of SSU and LSU kept on each farm, obtained through farmer's interview was multiplied with the water consumption quota per SSU and LSU per day given by DWAF, and this value gave a calculated estimation of the actual volume of water abstracted from that farm per day, and ultimately the volume abstracted per annum. A daily consumption of water for SSU is 12 litre/head/day and for the LSU 45 litre/head/day. The department of water affairs and forestry does not have actual livestock consumption figures for different areas across the country. Therefore only the available averages could be used to for all consumption calculations. Also to maintain a level of comparability, these values served the right purpose.

#### 6.1.3.2 .Government guided Abstraction Strategy

There exists a carrying capacity map referred to by Mendelsohn (2006) (see Figure 4). The map illustrates the capacity of SSU and LSU permitted sustainably per hectare of farming land. From the interviews conducted with DWAF it was revealed that there exist estimation for stock water requirements and allowances which is produced by the Research and Training Directorate in the MAWF. These are essentially allocated water consumption quota estimated to be sufficient per head of small stock per day as well as per large stock.

Using the carrying capacity map together with the daily consumption quotas per head of livestock as given by DWAF, the subsequent sustainable volume to be abstracted from that size of a farm was obtained. And this was used as the policy guided abstraction volume. This was achieved by dividing the factored size of the farm by the carrying capacity of that area to observe how many SSU and LSU are supposed to be on that size of farm. The SSU and LSU for each farm were multiplied by the water consumption quotas per SSU/LSU per day to obtain the volume of water that should be abstracted from this farm as by the policy guided values. This daily volume abstracted was then converted to an annual consumption.

#### 6.1.3.3 Sustainable Yield Abstraction Strategy

The sustainable yield abstraction volume as per scientific approach was calculated per selected borehole and per selected farm which will be modelled. The sustainable yield considered the size of the area being modelled, (in this case the borehole catchments at first and then again for the farm size) and the annual recharge values of the area. The recharge values per research area were derived from existing literature along with existing data in the GROWAS database and from calculations using the Chlorine Mass Balance (CMB) method. The CBM is derived from the equation below (Klock et al. 2001):

$R=P*Cl_P / Cl_{GW}$........................................................................................ (8)

$R$= Recharge (mm)

$P$= Precipitation (mm)

$Cl_p$ = Chloride concentration in precipitation (mg/l)

$Cl_{GW}$ = Chloride concentration in groundwater

#### 6.1.3.4 Volume Balance/ Short-term available volume Abstraction Strategy

The fourth strategy includes the short-term management strategy of calculating the volume balance based on the Eq (3), $Vol_{bal} = G*S_y (\phi_{ave} - \phi_{min})$ as given by Nonner (2010). In order to calculate the volume balance, the constituents of the equation had to be satisfied. Therefore, groundwater monitoring data from DWAF and NAMWATER for the three research areas dating back to as early as 1985 up until 2016 was sourced. With the use of Microsoft Excel the average ($\phi_{ave}$) and minimum ($\phi_{min}$) rest water levels/ elevation heads were computed for each relevant borehole within the research area. The other components of the formula are the surface area of the well catchment (G) and the specific yield ($S_y$) of the aquifer. Surface area was computed while the specific yield was obtained from previous work done in the research areas.

The (G) in the formula was revised to fit the local conditions. The G was therefore redefined to cover only the borehole influenced aquifer area. This was obtained by the following formula:

$$G^* = A/n \qquad (9)$$

Where $G^*$ = Borehole influenced aquifer area,

A= Size of the farm and
n = Number of boreholes on that exact farm.

This computed area ($G^*$) was then applied to the Equation (3) to produce the volume of water available from storage using the fluctuations of rest water levels in the monitoring boreholes in the respective research sites. A database for the boreholes across the three research areas was managed with all the parameters needed to satisfy the equation.

The strategy was not only applied to individual boreholes, but also to a larger area, i.e. entire farms. When calculating the short-term available volume from the entire farm, the area of the farm was used for ($G^*$).

### 6.1.4 Groundwater modelling

#### 6.1.4.1 Model Objective

The groundwater modelling was done in order to estimate the influence that the above mentioned abstraction strategies have on the groundwater levels/hydraulic heads at the research sites. The modelling was conducted using the tool Processing MODFLOW, also known as the PMWIN or Processing Modflow for Windows. Produced by the US Geological Survey PMWIN is a simulation system for modelling groundwater flow and transport processes with the modular three-dimensional finite-difference groundwater model MODFLOW. There were two types of models created.

#### 6.1.4.2 Model Set up

In general, as part of model construction, the first step undertaken to construct the model was to define the model domain. This was decided to be the borehole catchment area. Thereafter, a mesh was created to provide spatial discretisation in each model layer. This is followed by the creation of model layers. For each borehole, the layers were of different thicknesses. Then, the defining the distribution of model parameters was done and this gave a representation of the hydrogeological properties these parameters have first been collated as in Table 12.

The boundary conditions were set for each model, followed by the initial conditions. And finally time stepping options, appropriate numerical solvers were selected and the convergence criteria were finally set. The abstraction borehole was placed in the middle of the model area which represents the borehole catchment, and it was assumed that the catchment is a perfect square.

Once the model was setup the four scenarios modelled for two boreholes at each research site. Only two boreholes were modelled at each site because the lack of monitoring data presented a difficulty that can only be overcome by more monitoring data which was not available from DWAF or NAMWATER. Monitoring data for research site 2 for instance was limited in that only 5 boreholes were monitored by NAMWATER in this area and there exists no other long-term monitoring data for other proximal areas. These boreholes were drilled in a similar calcrete and sandstone formation. This situation therefore limited the modelling to two boreholes because variability was not expected in such similar geohydrological setting and because the area under study is similar modelling two boreholes of the area was representative enough.

A similar challenge was experienced at research sites 1 and 3. The long term monitoring data available was localised, and in order to maintain comparability of the scenarios, only boreholes that had sufficient information could be used, limiting the number of boreholes that could give a good enough representation of the area of similar geohydrological setup. The scenarios included the annual abstraction by farmers at each borehole as scenario 1, scenario 2 was the annual volume that should be abstracted when the carrying capacity as stipulated by policy is considered, the scenario 3 was the sustainable yield calculated from the borehole catchment and the recharge of the area, while scenario 4 is the short-term volume available from storage. These scenarios were modelled using a steady state model. The model elevation was obtained from drill logs and water level monitoring data from DWAF, and it was verified with a Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) data from NASA was used to compile a ground elevation map for the study areas

#### 6.1.4.3 The Single Borehole Models

Two boreholes were selected per research site. The boreholes modeled were from farms where sufficient and long term monitoring data exists.

A model was set up for each borehole using the inforamtion gathered in section 6.1.2 Compilation of Existing Data. The abstratcion strategies decribed in the section of Estimation of the Abstraction Strategies were used as modelling scenarios, where all four scenarios were modelled and their influence on each of the boreholes at the research site was investigated and recorded. These influence of the scenarios were then compared and contrasted between the the research sites.

Specifically, each borehole modelled had its own model set up. This was aided with borehole completion reports containing drill logs that were obtained from DWAF. The respective borehole completion reports are given in Appendix 7.

**WW 30897**:

<u>Conceptual Model</u>

Located in the Karst area, the borehole intersects a 50 m layer of calcrete and intersects a further 24 m of dolomite. The two layers are modeled as one hydrogeological unit. The borehole catchment is calculated as $7.5*10^6$ $m^2$, with a hydraulic gradient towards the north. Although the elevation is generally high above mean sea level (1202), the terrain is flat and uniform, i.e. not mountainous.

The borehole catchment extends over an area of 2700 m by 2700 m ($7.5*10^6$ $m^2$) but it was rounded off to the nearest 1000 m to give 3000 m x 3000 m. The model consists of one layer and the pumped borehole is located approximately in the centre of the model. The model was divided into 30 rows x 30 columns representing a 100 m each.

**WW 9736:**

<u>Conceptual model</u>

Hydrogeologically located in the Karstic aquifer, the borehole is drilled through 3 m of surface limestone and further intersected 71 m of Dolomite. The borehole catchment is calculated to be about $2.9*10^9$ $m^2$. The topographic elevation is at 1257 mamsl. Groundwater hydraulic gradient is towards the north. The initial hydraulic head was set at 1210 mamsl at the southern boundary, and a fixed head boundary at 1208 mamsl was applied at the northern model boundary.

The borehole catchment extends over an area of 1703 m by 1703 m ($2.9*10^6$ $m^2$) but it was rounded off to the nearest 1000 m to give 2000 m x 2000 m for simplifying the model procedure. The model consists of one layer and the pumped borehole is located approximately in the centre of the model. The model was divided into 20 rows x 20 columns representing a 100 m each.

**WW 35852:**

Conceptual Model

Research site 2 is located in the Etjo Sandstone aquifer. The borehole catchment calculated is $9.2*10^6 m^2$. The borehole log indicates that the borehole was drilled through 30 m of calcrete and followed by 83 m of red sandstone. The gradient for groundwater is from west to east and the topographic elevation is at 1240 mamsl. The initial hydraulic heads was 1204 masl. The abstraction borehole is located in the centre of the model domain.

The borehole catchment extends over an area of 3033 m by 3033 m ($9.2*10^6$ $m^2$) but it was rounded off to the nearest 1000 m to give 3000 m x 3000 m for simplifying the model procedure. The model consists of one layer and the pumped borehole is located approximately in the centre of the model. The model was divided into 30 rows x 30 columns representing a 100 m each.

**WW 35853:**

Conceptual Model

Research site 2 is located in the Etjo Sandstone aquifer. The borehole log indicates that the borehole was drilled through 42 m of calcrete and followed by 54 m of red sandstone. The borehole has a catchment area of $9.2*10^6 m^2$. The gradient for groundwater is from west to east and the topographic elevation is at 1245 m. The initial hydraulic heads was 1204 mamsl. The abstraction well is centered in the model domain.

The borehole catchment extends over an area of 3033 m by 3033 m ($9.2*10^6$ $m^2$) but it was rounded off to the nearest 1000 m to give 3000 m x 3000 m for simplifying the model procedure. The model consists of one layer and the pumped borehole is located approximately in the centre of the model. The model was divided into 30 rows x 30 columns representing a 100m each.

**WW 21784**:

Conceptual Model

Borehole WW 21814 is within the Research Site 3 and it is located in the Auob Sandstone aquifer, and as per borehole log, it is indicated that the borehole was drilled through 30 m of calcrete and followed by 25 m of Auob sandstone. The borehole catchment is calculated to be $6.24*10^6$ $m^2$.The gradient for groundwater is from west to east and the topographic elevation is at 1269mamsl, while the initial hydraulic head is 1245.51 m The borehole catchment extends over an area of 2497 m by 2497 m ($6.24*10^6$ $m^2$) but it was rounded off to the nearest 1000 m to give 25000 m x 2500 m for simplifying the model procedure. The model consists of one layer and the pumped borehole is located approximately in the centre of the model. The model was divided into 25 rows x 25 columns representing a 100 m each.

**WW 21814**:

<u>Conceptual Model</u>

Borehole WW 27184 is within the Research Site 3 and it is located in the Auob Sandstone aquifer and as per borehole log, it is indicated that the borehole was drilled through 30 m of calcrete and followed by 26 m of Auob sandstone, 41 m shale and 60 m of intercalated sandstone and shale. The borehole catchment is calculated as $6.24*10^6 m^2$. The gradient for groundwater flow is from west to east and the topographic elevation is at 1269 mamsl

The borehole catchment extends over an area of 2501 m by 2501 m ($6.24*10^6$ $m^2$) but it was rounded off to the nearest 1000 m to give 2500 m x 2500 m for simplifying the model procedure. The model consists of one layer and the pumped borehole is located approximately in the centre of the model. The model was divided into 25 rows x 25 columns representing a 100 m each

### 6.1.4.4 The Entire Farm Models

One farm was modeled from each research site. A model was set up for each farm using the information gathered in section 6.1.2 Compilation of Existing Data. The abstraction strategies described in the section Estimation of the Abstraction Strategies were used as modeling scenarios, where all four scenarios were modeled and their influence on each of the farms at the research site was investigated and recorded. Modelling only one farm per research site was sufficient because although various farms were investigated, when it came to complete and comprehensive information sufficient for model setup, the lack of data reduced the number of farms that could be modeled. However, the areas with monitoring data are homogenous in setup therefore a good representation is achieved. These influences of the scenarios were then compared and contrasted between the three research sites.

Conceptual model for Farm 1

The farm is geologically located on Quaternary sediments. The boreholes drilled on the farm intersect the calcrete and dolomite of the Elandshoek formation of the Otavi Group. The farm has a calculated are of $4.3*10^7$ $m^2$. The farmer has indicated that the farm has four boreholes that are in use. The four boreholes are as per GROWAS located to the east of the farm. For this model, the boreholes were allocated the same abstraction rate. The topographical elevation is 1202 mamsl with an initial hydraulic of 1195 mamsl. A groundwater gradient exists where groundwater naturally flows from the south the north. To the north east corner are inactive cells, representing the boundary of the neighboring farm. The locations of the boreholes are given in Figure 47.

Conceptual model for Farm 10

The farm is geologically located on the sandstone of the Etjo formation. The boreholes drilled on the farm intersect the calcrete and red sandstone of the aforementioned formation. The farm has a calculated area of $4.6*10^7$ $m^2$. There are five boreholes that are in use. The five boreholes are as per GROWAS located in the center of the farm. The topographical elevation is 1243 mamsl with an initial hydraulic of 1206 mamsl. A groundwater gradient exists where groundwater naturally flows from the west to the east. The locations of the boreholes are given in Figure 52.

For this model, three boreholes were allocated the same abstraction rate as they show to pump equal in the field and the remainder two were allocated equal abstraction volumes but less, almost half of the previous three.

Conceptual model for Farm 18

The farm is geologically located on the sandstone of the Auob Aquifer. The boreholes drilled on the farm intersect the calcrete and Auob sandstone of the Prince Albert Formation. Although the boreholes were drilled deeper, the interest lies within the first Kalahari and Auob aquifers. The farm has a calculated area of $6.5*10^7$ $m^2$. There are thirteen boreholes on the farm and eleven of those boreholes are in use. The eleven boreholes are not known where exactly they are located, but as per GROWAS database, the successfully drilled boreholes are located scattered across the east of the farm. The topographical elevation is 1269 mamsl with an initial hydraulic of 1254 mamsl. A groundwater gradient exists where groundwater naturally flows from the west to the east. The locations of the boreholes are given in Figure 57 below. For this model, all 11 boreholes were allocated the same abstraction rate as GROWAS indicated that most boreholes yield about the same volume per hour, and because the abstraction rates of each of the borehole on this farm are not know, an equal abstraction rate was assumed.

### 6.1.4.5 Model Software

The model software is described as on of the most complete simulation system in the world which comes complete with a professional graphical pre-processor and post-processor, the 3-D finite-difference ground-water models MODFLOW-88, MODFLOW-96, and MODFLOW 2000; the solute transport models MT3D, MT3DMS, RT3D and

MOC3D; the particle tracking model PMPATH 99; and the inverse models UCODE and PEST-ASP for automatic calibration. A 3D visualization and animation package, 3D Groundwater Explorer, is also included (Chiang and Kinzelbach, 1998)

#### 6.1.4.6 Model Calibration

It has been noted by various researchers that validating a model is a very challenging task and maybe even impossible. However, this issue was addressed through model calibration by fitting model results to field/measured data at the starting point or current situation. Model calibration may be viewed as an evolutionary process in which successive adjustments and modifications to the model are based on the results of previous simulations. When finally the modeller has decided on the sufficient adjustments made to the representation of parameters and processes, the model can thereafter be accepted as being adequately calibrated. This may be based on a mix of subjective and objective criteria (Khadri and Pande, 2016). Unfortunately the models could not be calibrated, due to lack of data to calibrate it against

#### 6.1.4.7 Model Verification/Validation

For the peace of mind of the entities setting up the model and making decisions based on the model, it is imperative to know that the model is valid. Validation of the model is achieved much similar to the process of calibration in that it is also achieved by comparing calculations with field or laboratory measurements. It must be taken into account that though a good comparison may be achieved during validation, model solutions are not unique, and thereby comparisons could be achieved with an erroneous model. It was later recommended that the term validation not be used in groundwater models, because it is subjective and there is very little that can be done to prove the validation (Khadri and Pande, 2016). The two institutions from which monitoring data was obtained failed to conduct further monitoring in the subsequent years to the data collected. It was therefore difficult to validate the model with present day field data. However the input data is was consistent and reliable.

#### 6.1.4.8 Interpretation of results

Changes in groundwater levels over time under the four different scenarios computed with MODFLOW were contrasted for 2 boreholes per study site and again for one farm at each research site.

Overall groundwater level distribution one year period was used to visualise the spatial variations under the four scenarios. Results computed were examined and the influence of each management strategy was interpreted, discussed and finally conclusion and recommendation of the sustainable management strategy are provided in the sections below.

# 7 RESULTS

## 7.1 Interviews

The results from the questionnaires conducted with farmers are given in the Table 10. The answered questionnaires are attached Appendix 6. The results from the questionnaires conducted with the government officials are given in Table 11 and the individual questionnaires are presented in Appendix 5.

From Table 10 it is observed that most farmers are practicing some form of groundwater management. Only two farmers (5 and 17) have not indicated any groundwater management activities. Moreover, Research site 3 has lesser management activities compared to Research Site 1 and Research Site 2. These managing activities cover a broad spectrum of options which include, de-bushing, rainwater harvesting, earth dams, flow meters, pump and level switch, camp rotation, *inter alia* complete list of local management activities are given in Table 10.

From Table 11, it is observed that as many management strategies as there are, the government encounters various shortcomings that prohibit the officials from fulfilling their mandate. Top priority management activity revealed is drilling and abstraction permits accompanied by groundwater level monitoring, abstraction returns, and groundwater level monitoring through quarterly compliance visit. The crucial shortcoming is the lack of quantification of strategic aquifers due to lack of data, funds and human capacity.

Table 10: Management strategies employed by farmers

| Management Activity | Research Site 1 | | | | | | | Research Site 2 | | | | | Research Site 3 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| **De-bushing** | | ✓ | | | | | ✓ | | ✓ | | | ✓ | | | ✓ | | | |
| **Mix spring and borehole water** | | | | | | | | | ✓ | ✓ | | | | | | | | |
| **Rainwater harvesting** | | | | | | | | | | ✓ | | | | ✓ | | | | ✓ |
| **Camp rotation** | ✓ | | ✓ | | | | | | | | | | | | | | | |
| **Pump switch** | | | | ✓ | | | ✓ | | | | | | | | | | | |
| **Earth dam** | | ✓ | | | | | | | | ✓ | | | | | | | | |
| **Level switch** | | | ✓ | | | | | | | | | | | | | | | |
| **Ties windmill when dam full** | ✓ | | ✓ | | | | | | | | | | | | | | | |
| **Livestock drink from streams in rainy season** | ✓ | | ✓ | | | | | | | | | | | | | | | |
| **Harvest Spring water** | | | | | | | | ✓ | | ✓ | ✓ | | | | | | | |
| **Connected to eastern water carrier canal** | | | | | | | | | | | | ✓ | | | | | | |
| **Pre determined diesel intake for pump, pump switches off when diesel is finished** | | | ✓ | | | | | | | | | | | | | | | |
| **Replace open reserviors with closed 10m3 tanks** | | | | | | | | | | ✓ | | | | | | | | |
| **Limited abstraction during rainy season** | | | | | | ✓ | | | | ✓ | | | | | | | | |
| **Use drip irrigation instead of Pivot system** | | | | | | ✓ | | | | | | | | | | | | ✓ |
| **Cover tank to reduce evaporation and treat water with microfil** | | | | | | | | | | | | ✓ | | ✓ | | | | |
| **Water level indicators** | | | | | | | | | | | | | | | | | | |
| **Flow meter installation** | | | | | | | | | | | | | ✓ | | | ✓ | | |


Figure 16: Farmers management strategies: a) Trough switch b) Rainwater harvesting c) Connecting to water canal d) Combining spring and borehole water

Table 11: Summary of Management Activities through Policy and Short Coming Encountered

| |
|---|
| **Government management Activities** |
| Drilling and abstraction permits in Water Controlled Areas |
| Abstraction returns |
| Periodic compliance visits for groundwater modeling |
| Buffering systems and Managed Aquifer Recharge (MAR) |
| NamWater Act 1997 (Act 12 of 1997) |
| Water Act No.54 of 1956 |
| Lessening of abstraction permits validity from 5 years to 2 years in specific circumstances |
| Conservative abstraction amounts based on 2003 Groundwater model |
| Minimum groundwater level detection ensued to allow greater restrictions on farmers |
| Basin Management Committees exist |
| Permit conditions require the installation of flow meter, to be quartely available to government officials |
| Letters regarding the revoking of permits are send via Law Admind Division to non-complying farmers |
| |
| **Shortcomings encountered** |
| Not all the aquifers have been quantified |
| Only the Karst Aqifers are quantified and have sub-catchments abstracion allocations |
| Lack of numerical groundwater models |
| Limited MAR across the country |
| Only commercial farmers posses abstraction permits |
| Farmers adhere to abstraction quotas depending on climatic conditions |
| Limits for abstraction is loosely adopted for 10,000m³/ha/a for lucerne irrigation |
| There is limited knowledge of the aquifers to manage appropriately |
| De-bushing, drip irrigation is not enforced |
| There's a lack of data prohibitting the quantification of several strategic aquifers |
| Limited adherence from farmers to abstraction limits |
| Farmer and regulator interactions are limited leading to a lack of ownership |
| Several citations exist where farmers record inconsistent abstraction volumes to the flowmeter readings |
| The new Water Resource Management Act No. 11 of 2013 is not yet enacted |
| Limited funds to update the groundwater model |

## 7.2 Compilation of Existing Data

### 7.2.1. Hydrogeologic Parameters

Table 12 represents the data compiled from existing reports from various institutions, and online sources. The table reflects the major hydraulic parameters required for a model set up for different aquifers systems. A few outliers from the results are visible in the table. Research Site 1 has the complex stratigraphy compared to the other sites, which also reflects the largest range of recharge values compared to the other research sites. The Research Site 2 has the highest storativity between the research sites. Research Site 3 has the highest porosity values. Transmissivity values in Research Site 1 have a high variability and also the highest recharge values are observed in Research Site 1. Lowest hydraulic conductivities are observed at Research Site 1.

Table 12: Summary of hydraulic parameter for different aquifers as obtained from various sources

| | **Formation** | **Aquifer thickness [m]** | **Transmissivity [$m^2$/day]** | **Recharge [mm/a]** | **Porosity [%]** | **Permeability [m/day]** | **Storativity [-]** | **Hydraulic conductivity [m/s]** |
|---|---|---|---|---|---|---|---|---|
| **Research Site 1** | Tschudi-Formation | 10 - 1000 [a] | 10 - 1000[a, f] | 1 - 55 [a]<br>20 - 46 [d]<br>7-28 [f] | 1 [a] | 0.032 [a] | $3.0 \cdot 10^{-04}$ [a] | |
| | Huettenberg-Formation | | | | 8 [a] | 55.65 [a] | $1.6 \cdot 10^{-03}$ [a] | $5*10^{-6}$ [a] |
| | Elandshoek-Formation | | | | 6 [a] | 12.6 [a] | $7.0 \cdot 10^{-04}$ [a] | $5*10^{-6}$ [a] |
| | Maieberg-Formation | | | | 2.8 [a] | 1.23 [a] | $9.0 \cdot 10^{-05}$ [a] | $5*10^{-6}$ [a] |
| | Gauss-Formation | | | | 3.8 [a] | 4.66 [a] | $6.0 \cdot 10^{-04}$ [a] | $5*10^{-6}$ [a] |
| | Basement-Complex | | | | 0.1 [a] | 0.002 [a] | | |
| | | | | | | | | |
| **Research Site 2** | Etjo Sandstone | 60 - 150 | | 39 - 51 [d] | 0.13 - 0.21 [b] | $8.6*10^{-1}$ [b] | 0.15 [b] | $1*10^{-5}$ [b] |
| **Research Site 3** | Kalahari | 100 [c] | 6 | 1.06 [e]<br>18 [d] | 25 27 [c]. | 0.00864 | 0.001-0.01 [c] | $2.1*10^{-4}$ [e]<br>$3.9*10^{-4}$ [e] |
| | Auob | 100 [c] | 3.42 | | | 0.28512 | 0.0001-0.01 [c] | |
| | Nossob | 30 [c] | 2.94 | | | $7.6*10^{-4}$ | 0.001-0.01 [c] | |

a) SLR, 2017 b) Klock et al., 2001 c) JICA , 2002 d) Uugulu & Wanke, 2018 e) Taapopi, 2015 f) Schmidt and Ploethner, 2000

### 7.2.2 Computed Volume balance

The potentially available amount of groundwater storage in a groundwater system can be defined as volume balance given by $V_{bal}= G*S_y (\phi_{ave} - \phi_{min})$ as described in (Eq 3). This volume takes into consideration the water levels of the boreholes over a long time, it considers the specific yield, the size of the borehole catchment and thereby calculating short-term volume available that can be abstracted from storage such that the aquifer can still recover. These parameters for numerous boreholes in the research areas are given in the Table 13. The boreholes are selected based on their proximity to farms where interviews were conducted. The table reveals a range of volumes calculated in ($m^3$).

At Research Site 1, the greatest volume is calculated in the order of 2.6 $Mm^3/a$, in borehole WW 30897, and the least volume of 6,705 $m^3/a$, is calculated in borehole WW 9734.

At Research Site 2, the greatest volume was in the order of 49.9 $Mm^3/a$ in borehole WW 35851, while the least volume was calculated to be 11.2 $Mm^3/a$ in borehole WW 35855.

Research Site 3 shows the highest volume calculated in WW 22545 drilled into the Nossob aquifer with a volume of 7861 $m^3/a$, while the least volume of 337 $m^3/a$, was calculated in the Auob Aquifer borehole WW 21814.

Table 13: Calculated volume balance (short-term volume available) per Research Site

| | WW | ϕAve (masl) | ϕmin (masl) | Sy | Farm size (ha) | Bh catchment ($m^2$) | Vol bal. (m) | Vol bal.(mm) | Vol bal ($m^3$) | Period of measurement | Sub/Group | Formation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research Site 1 | 9734 | 1210.71 | 1205.1 | 0.0004 | 2,610 | 2,900,000 | 0.002 | 2.2 | 6,508 | 1991-2016 | | Huttenberg |
| | 9736 | 1209.02 | 1202.95 | 0.0006 | 2,610 | 2,900,000 | 0.004 | 3.6 | 10,562 | 1990-2016 | | Huttenberg |
| | 25919 | 1552.15 | 1525.85 | 0.0004 | 3,920 | 6,330,000 | 0.011 | 10.5 | 66,592 | 1983-2016 | Tsumeb | Huttenberg |
| | 25922 | 1541.93 | 1529.67 | 0.0004 | 3,920 | 6,330,000 | 0.005 | 4.9 | 31,042 | 1982-2016 | | |
| | 25929 | 1540.95 | 1521.24 | 0.0004 | 3,920 | 6,330,000 | 0.008 | 7.9 | 49,906 | 1982-2015 | Mulden | Huttenberg |
| | 25930 | 1548.52 | 1522.25 | 0.0006 | 3,920 | 6,330,000 | 0.016 | 15.8 | 99,773 | 1983-2014 | Abenab | Aurob |
| | 25932 | 1550.34 | 1523.8 | 0.0006 | 3,920 | 6,330,000 | 0.016 | 15.9 | 100,799 | 1983-2016 | Abenab | Aurob |
| | 26991 | 1546.68 | 1521.05 | 0.0003 | 3,920 | 6,330,000 | 0.008 | 7.7 | 48,671 | 1983-2013 | Mulden | Huttenberg |
| | 26993 | 1535.56 | 1524.63 | 0.0006 | 3,920 | 6,330,000 | 0.007 | 6.6 | 41,512 | 1983-2016 | Abenab | Aurob |
| | 27000 | 1559.75 | 1536.69 | 0.0004 | 3,920 | 6,330,000 | 0.009 | 9.2 | 58,388 | 1983-2016 | Tsumeb | Huttenberg |
| | 27001 | 1541.22 | 1521.86 | 0.0004 | 3,920 | 6,330,000 | 0.008 | 7.7 | 49,020 | 1983-2016 | Mulden | Huttenberg |
| | 27002 | 1545.22 | 1517.54 | 0.0004 | 3,920 | 6,330,000 | 0.011 | 11.1 | 70,086 | 1983-2016 | Mulden | Huttenberg |
| | 27039 | 1544.83 | 1523.1 | 0.0004 | 3,920 | 6,330,000 | 0.009 | 8.7 | 55,020 | 1983-2016 | Mulden | Huttenberg |
| | 28216 | 1359.06 | 1350.42 | 0.0006 | 3,920 | 6,330,000 | 0.005 | 5.2 | 32,815 | 1983-2016 | | Aurob |
| | 30708 | 1137.96 | 1136.45 | 0.0500 | 3,920 | 6,330,000 | 0.075 | 75.5 | 477,915 | 1990-2015 | | |
| | 30897 | 1194.15 | 1190.54 | 0.0500 | 3,000 | 7,500,000 | 0.181 | 180.5 | 1,353,750 | 1989-2016 | | |
| | 31487 | 1195.67 | 1191.99 | 0.0004 | 5,000 | 6,250,000 | 0.001 | 1.5 | 9,200 | 1988-2016 | | Huttenberg |
| | 31488 | 1194.74 | 1191.43 | 0.0004 | 5,000 | 6,250,000 | 0.001 | 1.3 | 8,275 | 1990-2016 | | Huttenberg |
| | 31490 | 1200.56 | 1198.06 | 0.0004 | 5,000 | 10,000,000 | 0.001 | 1.0 | 10,000 | 1989-2007 | | Huttenberg |
| | 31495 | 1197.16 | 1194.36 | 0.0004 | 5,000 | 6,250,000 | 0.001 | 1.1 | 7,000 | 1989-2006 | | Huttenberg |
| | | | | | | | | | | | | |
| Research Site 2 | 35851 | 1212.59 | 1176.4 | 0.1500 | 4,600 | 9,200,000 | 5.428 | 5428.5 | 49,942,200 | 1998-2017 | Stormberg | Etjo |
| | 35852 | 1204.1 | 1188.7 | 0.1500 | 4,600 | 9,200,000 | 2.310 | 2310.0 | 21,252,000 | 1998-2017 | Stormberg | Etjo |
| | 35853 | 1212.84 | 1194.12 | 0.1500 | 4,600 | 9,200,000 | 2.808 | 2808.0 | 25,833,600 | 1998-2017 | Stormberg | Etjo |
| | 35854 | 1212.96 | 1197.67 | 0.1500 | 4,600 | 9,200,000 | 2.293 | 2293.5 | 21,100,200 | 1998-2017 | Stormberg | Etjo |
| | 35855 | 1216.72 | 1208.54 | 0.1500 | 4,600 | 9,200,000 | 1.227 | 1227.0 | 11,288,400 | 1998-2017 | Stormberg | Etjo |
| | | | | | | | | | | | | |
| Research Site 3 | 22546 K | 1255.17 | 1254.56 | 0.0010 | 6,863 | 6,239,091 | 0.001 | 0.6 | 3,806 | 1985-2016 | Ecca | Prince Albert |
| | 22546 A | 1255.24 | 1254.68 | 0.0001 | 6,863 | 6,239,091 | 0.000 | 0.1 | 349 | 1985-2016 | Ecca | Prince Albert |
| | 22546 N | 1245.87 | 1244.67 | 0.0010 | 6,863 | 6,239,091 | 0.001 | 1.2 | 7,487 | 1985-2016 | Ecca | Prince Albert |
| | 22545 K | 1254.21 | 1253.29 | 0.0010 | 6,863 | 6,239,091 | 0.001 | 0.9 | 5,740 | 1985-2016 | Ecca | Prince Albert |
| | 22545 A | 1254.17 | 1253.43 | 0.0001 | 6,863 | 6,239,091 | 0.000 | 0.1 | 462 | 1985-2016 | Ecca | Prince Albert |
| | 22545 N | 1248.45 | 1247.19 | 0.0010 | 6,863 | 6,239,091 | 0.001 | 1.3 | 7,861 | 1985-2016 | Ecca | Prince Albert |
| | 21815K | 1253.65 | 1252.96 | 0.0010 | 6,863 | 6,239,091 | 0.001 | 0.7 | 4,305 | 1985-2016 | Ecca | Prince Albert |
| | 21814A | 1253.67 | 1253.13 | 0.0001 | 6,863 | 6,239,091 | 0.000 | 0.1 | 337 | 1985-2016 | Ecca | Prince Albert |
| | 21784 N | 1247.63 | 1246.31 | 0.0010 | 6,863 | 6,239,091 | 0.001 | 1.3 | 8,236 | 1985-2016 | Ecca | Prince Albert |

## 7.3 Estimation of Abstraction Strategies

### 7.3.1 Farmer's Abstraction

Table 14 presents the volumes abstracted at the farms across the three research sites. For the farmers and government's abstraction the values are differentiated between SSU and LSU. For the farmers, the highest abstraction for SSU occurs at Farm 17 located in the Research Site 3, while the lowest occurs at Farm 4 in the Research Site 1. Looking at the abstraction for LSU by farmers, the highest is on Farm 11 in Research Site 2 while the lowest is at Farm 2 in Research Site 1.

### 7.3.2 Government Guided Abstractions

For the carrying capacity guided abstraction represented as "GOV" in the table, the abstraction for SSU is highest at Farm 16 in Research Site 3 and lowest at Farm 5 from Research Site 1. The abstraction for the LSU for the "GOV" is highest at Farm 7 in Research Site 1 and lowest is calculated at Farm 5 from the Research Site 1.

There is only one general trend observed in the results and that is that the farmers in the Research Site 3 abstract the highest combined volumes for SSU and LSU compared to the other two research sites combined. An outlier is observed at the Farm 11 with the highest abstraction rate amongst all farms of 28,530 $m^3/a$.

### 7.3.3 Comparison of Annual Abstraction Volume between Government Guided Abstraction and Farmers Abstraction for SSU and LSU

Figure 17 depicts the comparison between volume abstracted by the farmers and the calculated volume recommended/allowed as per carrying capacity at Research Site 1. Comparing these, the farmers generally abstract more water than what is allowed per carrying capacity, except at farm 1 and farm 7 where the framers abstract less than the carrying capacity guided abstraction.

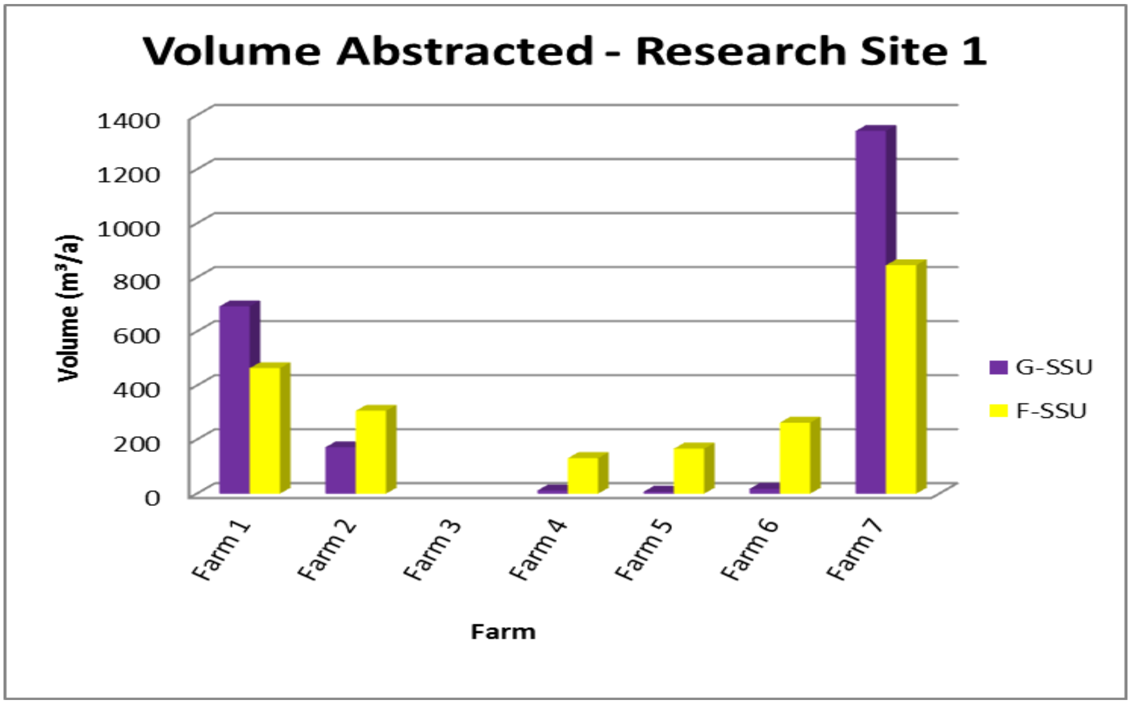



Figure 17: Annual Volume Abstracted for Small Stock Unit as per Government Policy (G-SSU) and per Individual Farms (F-SSU) at Research Site 1.

Figure 18 depicts the comparison between volume abstracted by the farmers and the calculated volume recommended/allowed as per carrying capacity at Research Site 2. From the farms interviewed, only farms 10 and 11 have SSU. Two of the farms are research stations, and one farm was reluctant to give details. At farm 10, the farmer's annual abstraction is below that which would be allowed based on carrying capacity for the area.

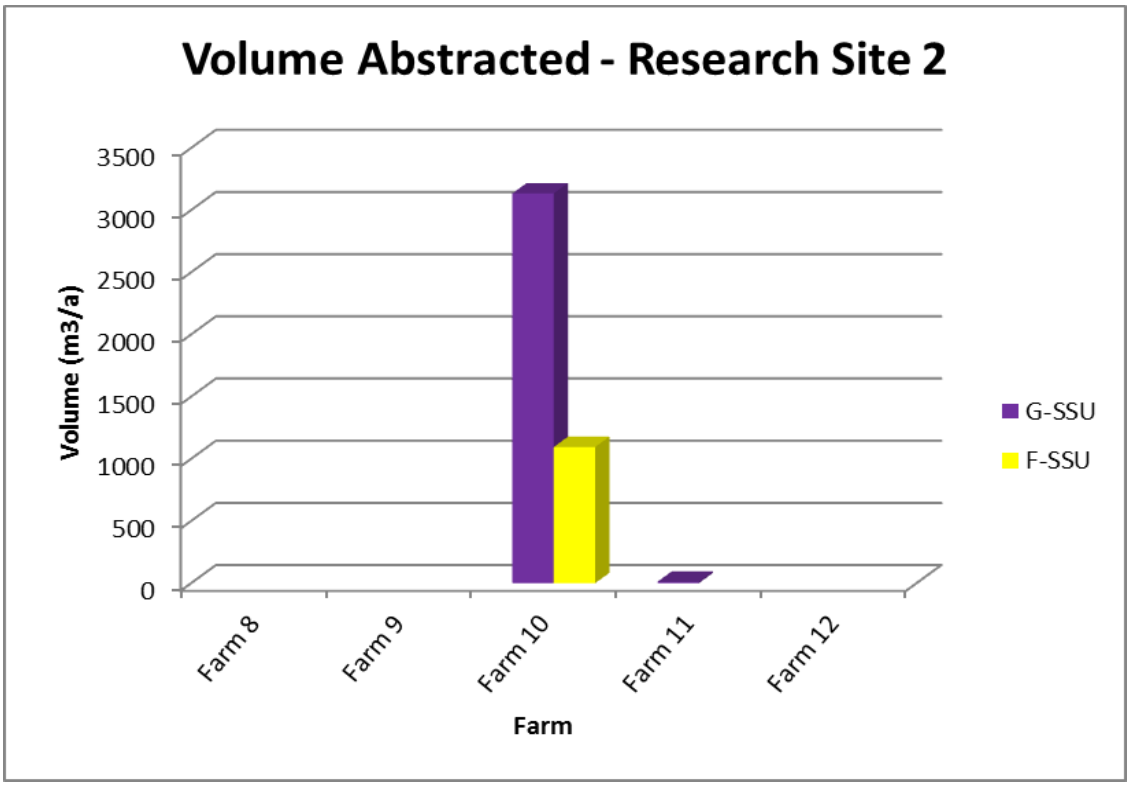



Figure 18: Annual Volume Abstracted for Small Stock Unit as per Government Policy (G-SSU) and per Individual Farms (F-SSU) at Research Site 2.

Figure 19 depicts the comparison between volume abstracted by the farmers and the calculated volume recommended/allowed as per carrying capacity at Research Site 3. At the third research site, most farmers, except at farm 18, abstract more groundwater annually than what is allowable as per carrying capacity of the area. The farmers in the third research site have more small stock than the other two sites.

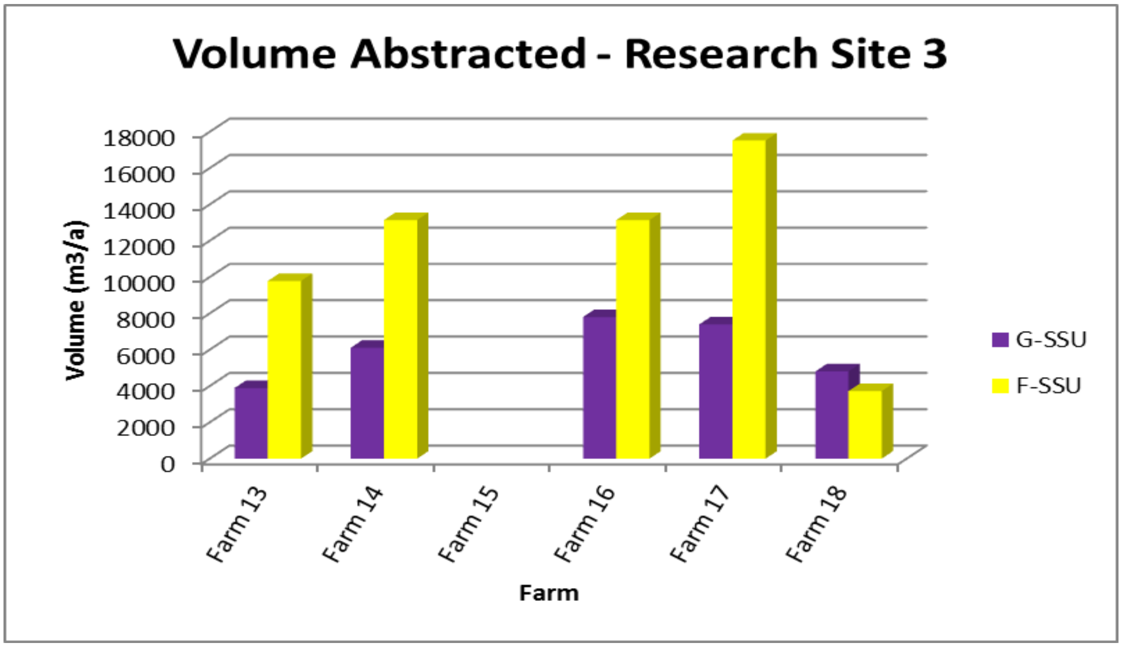



Figure 19: Annual Volume Abstracted for Small Stock Unit as per Government Policy (G-SSU) and per Individual Farms (F-SSU) at Research Site 3.

Figure 20 depicts the comparison between volume abstracted by the farmers and the calculated volume recommended/allowed as per carrying capacity at Research Site 1. For the volume abstracted for the supply to large stock units, farm 1, 3, and 7 have a much higher abstraction volume than that calculated based on carrying capacity. Farms 2, and 5, do not show a large difference in the abstraction volumes, whilst farms 4 and 6 had no LSU.

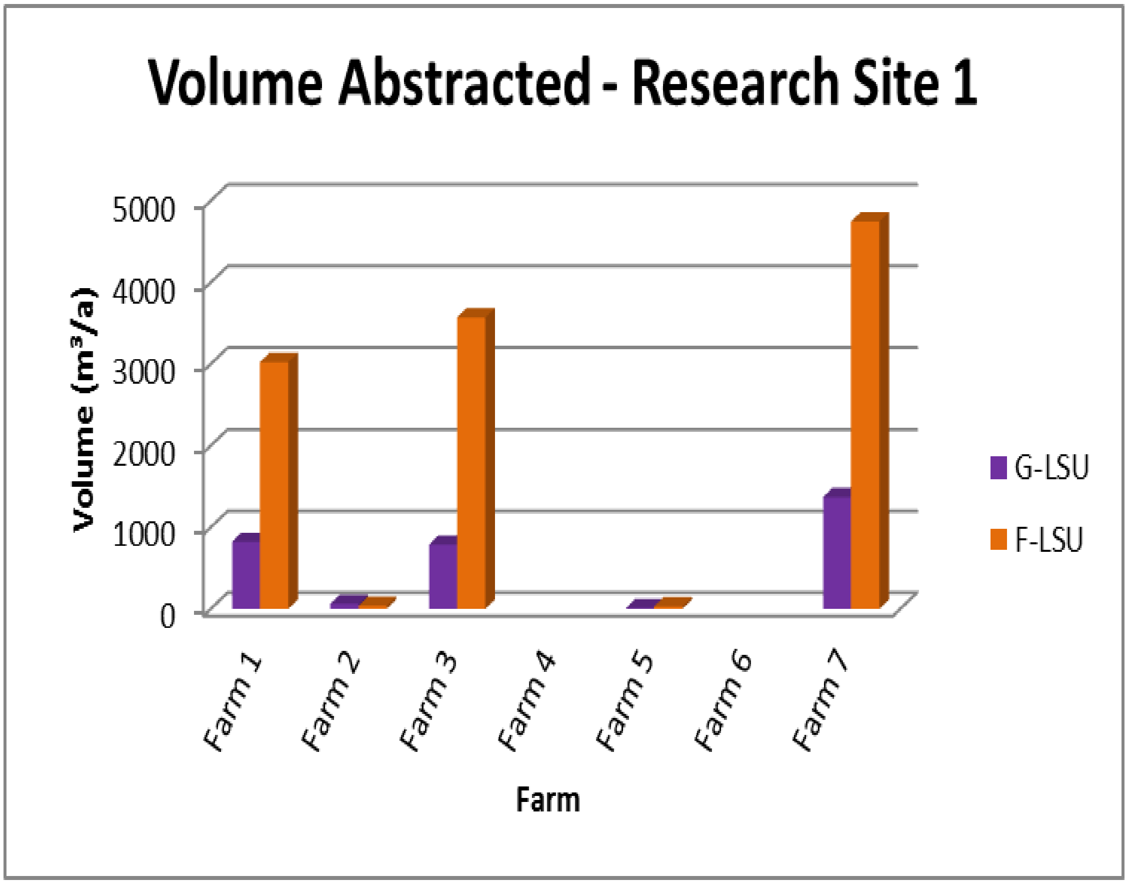



Figure 20: Annual Volume Abstracted for Large Stock Unit as per Government Policy (G-LSU) and per Individual Farms (F-LSU) at Research Site 1.

Figure 21 depicts the comparison between volume abstracted by the farmers and the calculated volume recommended/allowed as per carrying capacity at Research Site 2. There is more large stock at farm 11 than any other farm. And at this farm, the farmer's annual abstraction is much higher than that allowed by the carrying capacity. Farm 8 has no LSU.

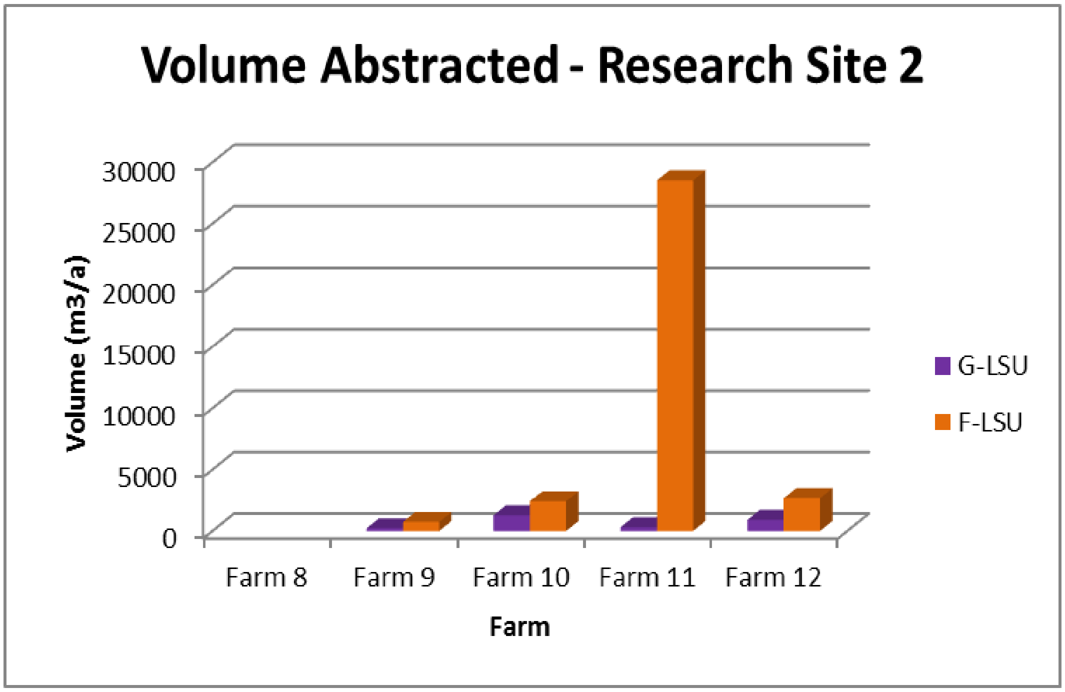



Figure 21: Annual Volume Abstracted for Large Stock Unit as per Government Policy (G-LSU) and per Individual Farms (F-LSU) at Research Site 2.

Figure 22 depicts the comparison between volume abstracted by the farmers and the calculated volume recommended/allowed as per carrying capacity at Research Site 3. The farmers abstract greater volumes than the suggested volume defined by the carrying capacity. Also, the farmers in the third research site abstract higher volumes that the other two research sites, indicative of larger amounts of livestock than the farmers in the counterpart research sites.

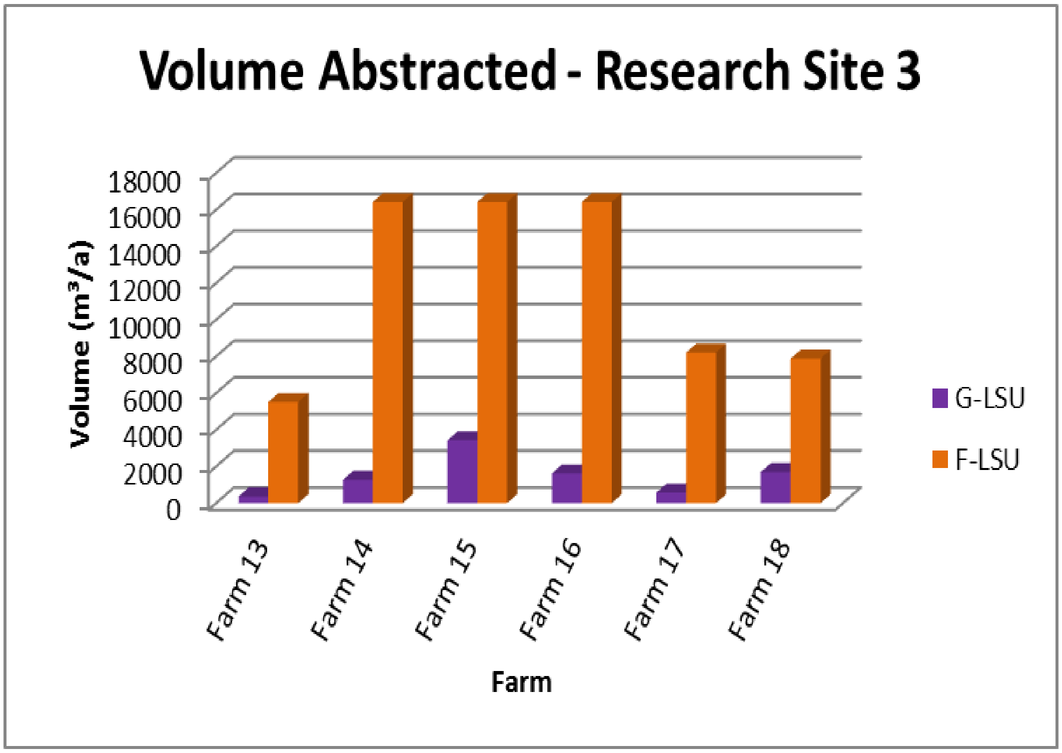



Figure 22: Annual Volume Abstracted for Large Stock Unit as per Government Policy (G-LSU) and per Individual Farms (F-LSU) at Research Site 3.

### 7.3.3 Sustainable yield Abstraction

Table 14 further displays the abstraction strategies of the sustainable yield calculated for selected farms. The selected farms are of interest because they have boreholes that have long term monitoring occurring on site, i.e at least 30 years of monitoring data. The greatest sustainable volume is calculated at Farm 10 and the lowest volume at Farm 3.

### 7.3.4 Short-term Volume Available

Table 14 also displays the short-term abstraction volumes available for selected farms with continuous long-term water level monitoring. The highest short term volume available is calculated at Farm 10 in the Research Site 2 and the lowest short-term available volume is calculated at Farm 3 in the Research Site 1. No particular trend is observed.

Table 14: Annual Abstraction Volume for the Four Abstraction Strategies

| | Farm No. | Farmers ($m^3/a$) | | GOV ($m^3/a$) | | Sustainable Yield | Short term volume availabe |
|---|---|---|---|---|---|---|---|
| | | SSU | LSU | SSU | LSU | ($m^3/a$) | ($m^3/a$) |
| Research Site 1 | Farm 1 | 464 | 4,862 | 693 | 3,024 | 780,000 | 5,857,500 |
| | Farm 2 | 307 | 164 | 172 | 38 | | |
| | Farm 3 | 0 | 3,285 | 0 | 3,572 | 678,600 | 17,069 |
| | Farm 4 | 131 | 0 | 12 | 0 | | |
| | Farm 5 | 166 | 1,577 | 7 | 29 | | |
| | Farm 6 | 263 | 0 | 18 | 0 | | |
| | Farm 7 | 845 | 7,178 | 1,342 | 4,747 | 1,300,000 | 30,425 |
| Research Site 2 | Farm 8 | 0 | 0 | | | | |
| | Farm 9 | 0 | 0 | 0 | 730 | | |
| | Farm 10 | 1,095 | 4,928 | 3,134 | 2,421 | 1,794,000 | 129,416,400 |
| | Farm 11 | | 28,530 | 11 | 303 | | |
| | Farm 12 | 0 | 2,677 | 0 | 903 | | |
| Research Site 3 | Farm 13 | 9,785 | 5,519 | 3,892 | 366 | | |
| | Farm 14 | 13,140 | 16,425 | 6,108 | 1,273 | | |
| | Farm 15 | 0 | 16,425 | 0 | 3,422 | | |
| | Farm 16 | 13,140 | 16,425 | 7,802 | 1,625 | | |
| | Farm 17 | 17,520 | 8,213 | 7,393 | 578 | | |
| | Farm 18 | 3,723 | 7,884 | 4,803 | 1,695 | 1,170,000 | 38,582 |

### 7.3.5 Comparison between annual abstraction volumes of farmers and of carrying capacity guided abstractions

Comparison of abstraction for SSU

Table 14 depicts the comparison between volume abstracted by the farmers and the calculated volume recommended/allowed as per carrying capacity. Comparing the abstraction for SSU, the farmers at Research Site 1 generally abstract more water than the carrying capacity defined abstraction volumes with the exception of Farm 1 and Farm 7 where the framers abstract less than the carrying capacity guided abstraction.

At Research Site 2, as presented in the Table 14, the farmers interviewed had less livestock. Two of the farms are research stations, and one farm was reluctant to give details. At Farm 10, it is observed that the farmer's annual abstraction is below that which would be allowed based on carrying capacity for the area.

From Table 14 further comparisons reveal that at Research Site 3, all the farmers, except at Farm 18, abstract more groundwater annually than what is allowable as per defined carrying capacity of the area. The farmers in the third research site have significantly more small stock than the other two sites.

Comparison of Abstraction for LSU

Table 14 also reveals the abstractions for LSU. Comparing the outcome at Research Site 1, Farm 1, Farm 3, and Farm 7 have a much higher abstraction volume than that calculated based on carrying capacity. Farm 2, Farm 4, Farm 5, and Farm 6, do not show a large difference in abstraction volumes.

At Research Site 2, Farm 11 has the most LSU than any other farm in research site, and overall the research sites. Consequently the farmer's annual abstraction is much higher than that suggested by the defined carrying capacity.

At Research Site 3, as it has been the trend at the aforementioned sites, the farmers abstract greater volumes than the suggested volume defined by the allocated carrying capacity. Also, the farmers in the third research site abstract significantly higher volumes that the other two research sites, indicative of larger amounts of livestock than the farmers in the counterpart research sites.

### 7.4 Modeling Results

Table 15 depicts the summary of the modeling results for the single borehole models. The table presents the borehole that was modeled, recharge value applied, the abstraction strategy pumped, the average hydraulic head across the borehole catchment and the hydraulic heads at the pumped wells. Further details on the results are presented in the model in Figure 27 to Figure 46.

Table 16 depicts the summary of the modeling results for the entire farm models. The table presents the recharge value applied, the abstraction strategy pumped, the initial hydraulic heads and the resulting hydraulic heads at the pumped wells. Further details on the results are presented in the model in Figure 48 to Figure 61. For the ease of interpretation, the abstraction strategies gave been categorized into scenarios as follows:

- Scenario 1 represents the farmer's abstraction,
- Scenario 2 represents the carrying capacity guided abstraction,
- Scenario 3 represents the sustainable yield and,
- Scenario 4 represents the volume balance/short-term volume available from storage.

Table 15: The Influence of Different Abstraction Scenarios on the Hydraulic Heads for the Single borehole models at the Research Sites

| Scenario | BH No. | Recharge (m/a) | Abstraction rate (m³/a) | Initial Hydraulic head (m) | Mean Hydraulic head (m) | Hydraulic head at modelled well (m) |
|---|---|---|---|---|---|---|
| **Research Site 1** | | | | | | |
| | WW 30897 | | | | | |
| Scenario 1 | | 0.026 | -1,332 | 1200.00 | 1192.007 | 1191.864 |
| Scenario 2 | | 0.026 | -929 | 1200.00 | 1192.012 | 1191.895 |
| Scenario 3 | | 0.026 | -195,000 | 1200.00 | 1189.610 | 1174.510 |
| Scenario 4 | | 0.026 | -477,915 | 1200.00 | Dry well | Dry Well |
| | | | | | | |
| | WW 9736 | | | | | |
| Scenario 1 | | 0.026 | -396 | 1210.00 | 1209.001 | 1208.915 |
| Scenario 2 | | 0.026 | -365 | 1210.00 | 1290.002 | 1208.918 |
| Scenario 3 | | 0.026 | -75,400 | 1210.00 | 1207.509 | 1198.797 |
| Scenario 4 | | 0.026 | -6,507 | 1210.00 | 1208.886 | 1208.203 |
| | | | | | | |
| Research Site 2 | | | | | | |
| | WW 35852 | | | | | |
| Scenario 1 | | 0.039 | -1,204 | 1204.00 | 1196.302 | 1196.709 |
| Scenario 2 | | 0.039 | -1,111 | 1204.00 | 1196.302 | 1196.713 |
| Scenario 3 | | 0.039 | -414,000 | 1204.00 | 1193.966 | 1180.230 |
| Scenario 4 | | 0.039 | -21,252,000 | 1204.00 | Dry Well | Dry Well |
| | | | | | | |
| Scenario 1 | WW 35853 | 0.039 | -1,204 | 1204.00 | 1203.451 | 1203.965 |
| Scenario 2 | | 0.039 | -1,111 | 1204.00 | 1203.451 | 1203.969 |
| Scenario 3 | | 0.039 | -358,800 | 1204.00 | 1201.066 | 1186.750 |
| Scenario 4 | | 0.039 | -25,833,600 | 1204.00 | Dry Well | Dry Well |
| | | | | | | |
| Research Site 3 | | | | | | |
| | WW 21814 | | | | | |
| Scenario 1 | | 0.018 | -1,055 | 1245.51 | 1255.005 | 1254.87 |
| Scenario 2 | | 0.018 | -590 | 1245.51 | 1255.018 | 1254.95 |
| Scenario 3 | | 0.018 | -112,320 | 1245.51 | 1253.477 | 1228.258 |
| Scenario 4 | | 0.018 | -337 | 1245.51 | 1256.586 | 1256.613 |
| | | | | | | |
| Scenario 1 | WW 21784 | 0.018 | -1,055 | 1245.51 | 1234.992 | 1236.578 |
| Scenario 2 | | 0.018 | -590 | 1245.51 | 1235.001 | 1236.628 |
| Scenario 3 | | 0.018 | -1,123,200 | 1245.51 | Dry well | Dry well |
| Scenario 4 | | 0.018 | -8,235 | 1245.51 | 1234.860 | 1235.811 |

Table 16: The Influence of Different Abstraction Scenarios on the Hydraulic Heads for the Entire Farm Models at the Research Sites

| Scenario | Recharge (m/a) | Abstraction rate per farm (m³/a) | Initial hydraulic head (m) | Hydraulic head at modelled well (1) (m) | Hydraulic head at modelled well (2) (m) | Hydraulic head at modelled well (3) (m) | Hydraulic head at modelled well (4) (m) | Hydraulic head at modelled well (5) (m) | Hydraulic head at modelled well (6) (m) | Hydraulic head at modelled well (7) (m) | Hydraulic head at modelled well (8) (m) | Hydraulic head at modelled well (9) (m) | Hydraulic head at modelled well (10) (m) | Hydraulic head at modelled well (11) (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Research Site 1** | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Scenario 1 | 0.026 | 5,326 | 1,195.60 | 1194.620 | 1195.535 | 1196.948 | 1196.059 | | | | | | | |
| Scenario 2 | 0.026 | 3,716 | 1,195.60 | 1194.673 | 1195.589 | 1196.988 | 1196.121 | | | | | | | |
| Scenario 3 | 0.026 | 780,000 | 1,195.60 | 1161.829 | 1162.174 | 1167.548 | 1155.710 | | | | | | | |
| Scenario 4 | 0.026 | 6,622,500 | 1,195.60 | Dry well | Dry well | Dry well | Dry well | | | | | | | |
| Research Site 2 | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Scenario 1 | 0.039 | 6,023 | 1,206.83 | 1196.336 | 1196.638 | 1202.948 | 1205.079 | 1207.206 | | | | | | |
| Scenario 2 | 0.039 | 5,555 | 1,206.83 | 1196.342 | 1196.644 | 1202.953 | 1205.085 | 1207.210 | | | | | | |
| Scenario 3 | 0.039 | 1,794,000 | 1,206.83 | 1166.000 | 1167.229 | 1180.205 | 1171.275 | 1190.488 | | | | | | |
| Scenario 4 | 0.039 | 129,416,400 | 1,206.83 | Dry well | Dry well | Dry well | Dry well | Dry well | | | | | | |
| Research Site 3 | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Scenario 1 | 0.018 | 7,884 | 1,254.76 | 1255.967 | 1253.583 | 1254.11 | 1253.588 | 1253.643 | 1253.282 | 1253.379 | 1253.246 | 1253.942 | 1253.7 | 1253.53 |
| Scenario 2 | 0.018 | 6,498 | 1,254.76 | 1256.004 | 1253.628 | 1254.165 | 1253.555 | 1253.709 | 1253.338 | 1253.45 | 1253.309 | 1254.016 | 1253.777 | 1253.605 |
| Scenario 3 | 0.018 | 1,188,000 | 1,254.76 | Dry well | Dry well | Dry well | Dry well | Dry well | Dry well | Dry well | Dry well | Dry well | Dry well | Dry well |
| Scenario 4 | 0.018 | 38,583 | 1,254.76 | 1255.512 | 1253.266 | 1253.486 | 1252.44 | 1251.503 | 1251.628 | 1250.163 | 1250.92 | 1250.685 | 1250.748 | 1250.555 |

### 7.4.1 Single Borehole Models

## 7.4.1.1 Research Site 1: Borehole WW 30897 and WW 9736

#### *7.4.1.1.1 Scenario 1*

The modeling results of scenario 1 at borehole WW 30897 can be visualized in Figure 23. The modeled scenario calculates the hydraulic heads to 1191.86 mamsl at the abstraction well.

The modeling results of scenario 1 at borehole WW 9736 can be visualized in Figure 27. The modeled scenario calculates the hydraulic heads to 1208.92 mamsl at the abstraction well.

#### *7.4.1.1.2 Scenario 2*

The modeling results of scenario 2 at borehole WW30897 can be visualized in Figure 24. The modeled scenario calculates the hydraulic head to 1191.90 mamsl at the abstraction well.

The modeling results of scenario 2 at borehole WW 9736 can be visualized in Figure 28. The modeled scenario calculates hydraulic head down to 1208.92 mamsl at the abstraction well.

#### *7.4.1.1.3 Scenario 3*

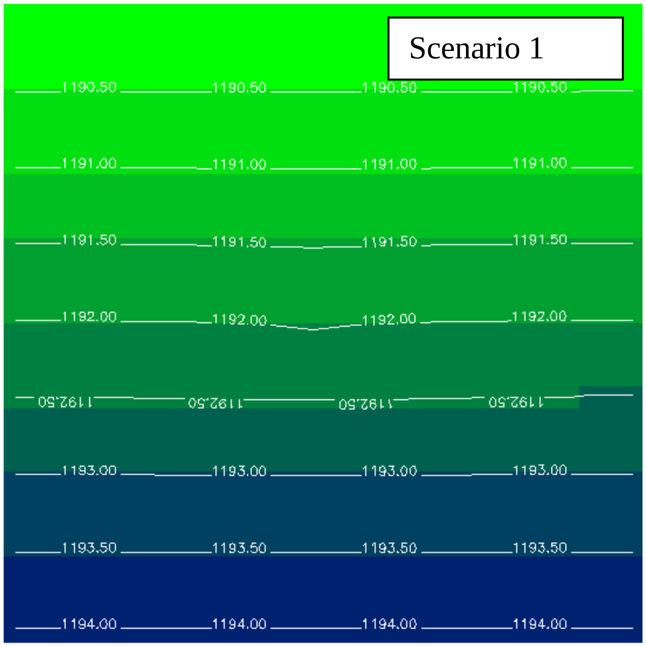
The modeling results of scenario 3 at borehole WW30897 can be visualized in Figure 25. The modeled scenario calculates the hydraulic head to 1174.51 mamsl at the abstraction well.

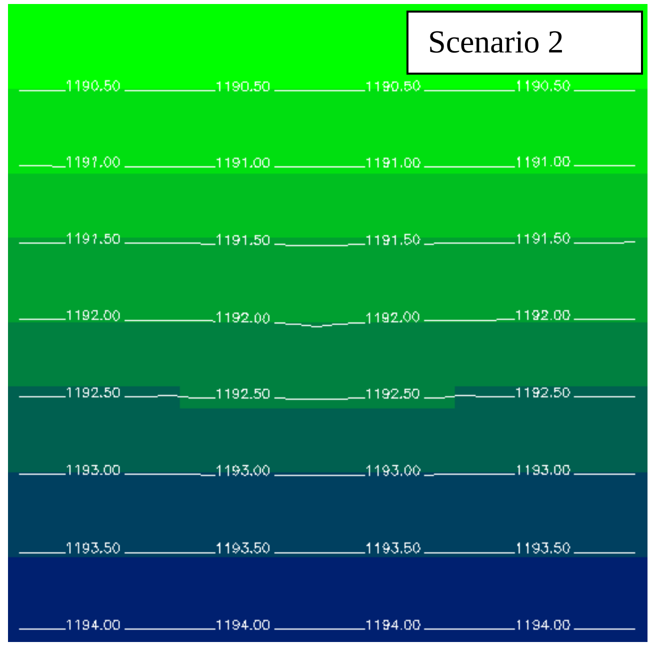
The modeling results of scenario 3 at borehole WW 9736 can be visualized in Figure 29. The modeled scenario calculates the hydraulic head down to 1198.80 mamsl at the abstraction well.

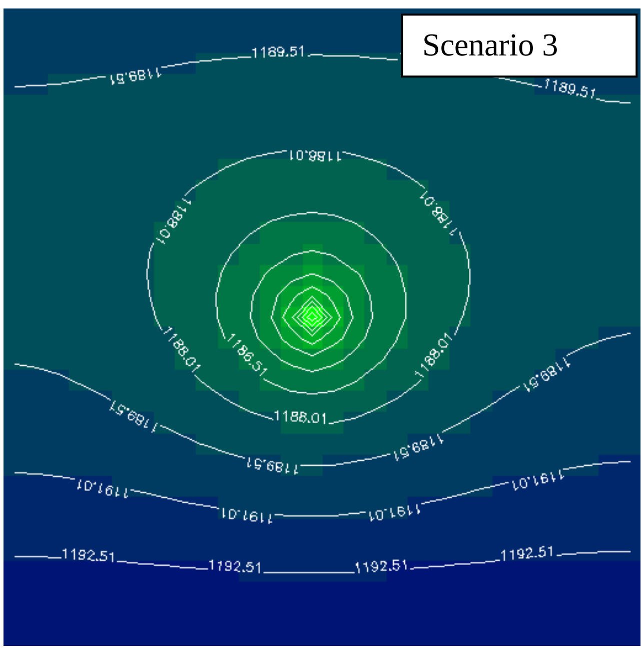
#### *7.4.1.1.4 Scenario 4*

The modeling results of scenario 4 at borehole WW30897 can be visualized in Figure 26. The modeled scenario resulted in drying up of the borehole.

The modeling results of scenario 4 at borehole WW 9736 can be visualized in Figure 30. The modeled scenario calculates the hydraulic head to 1207.72 mamsl at the abstraction well.



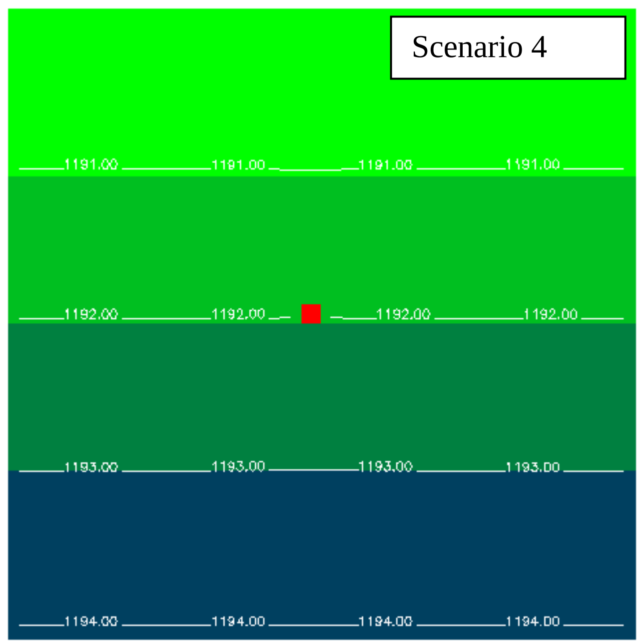
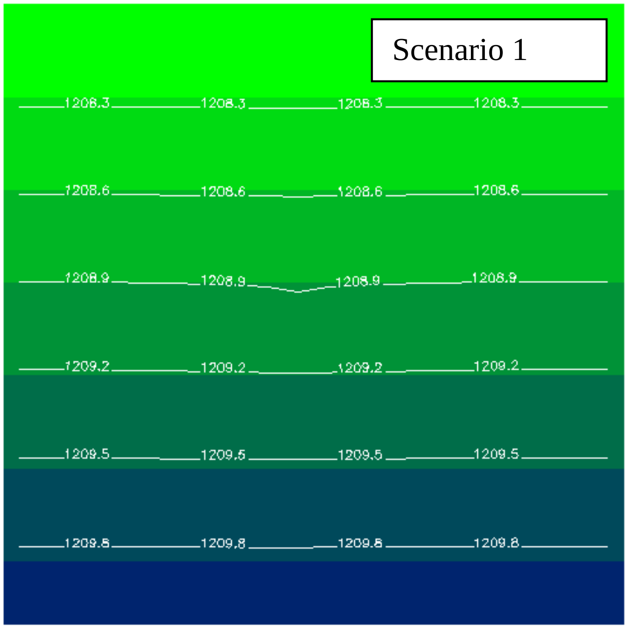
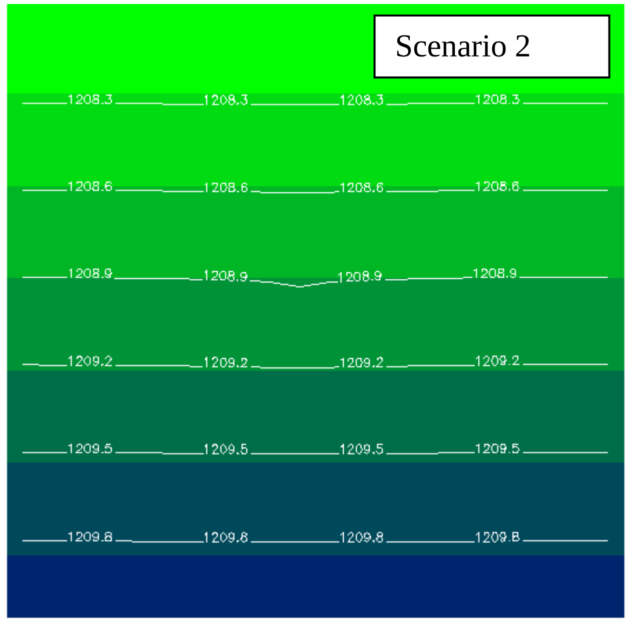
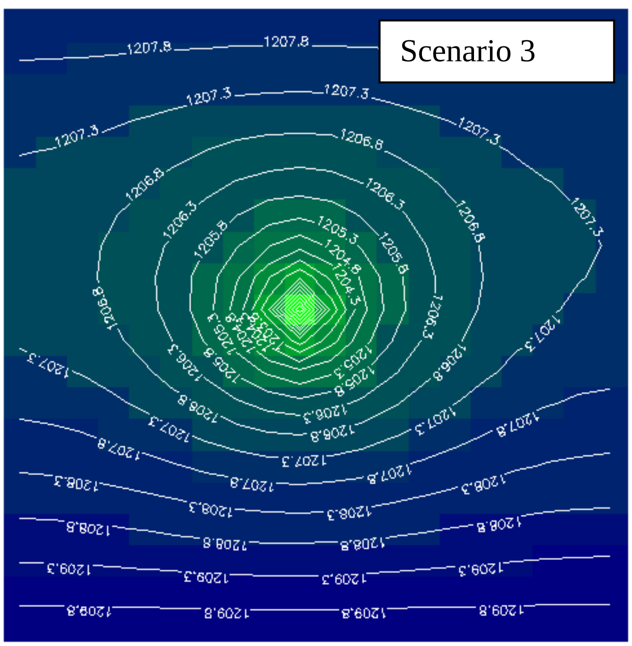




Figure 23: Scenario 1: Hydraulic Heads at WW 30897 as influenced by abstraction rate of 1332 $m^3$/a.
Figure 24: Scenario 2: Hydraulic Heads at WW 30897 as influenced by abstraction rate of 929 $m^3$/a.
Figure 25: Scenario 3: Hydraulic Heads at WW 30897 as influenced by abstraction rate of 195 000 $m^3$/a.
Figure 26: Scenario4: Hydraulic heads at WW 30897 as influenced by abstraction of scenario 4 at 13 $Mm^3$ /a.



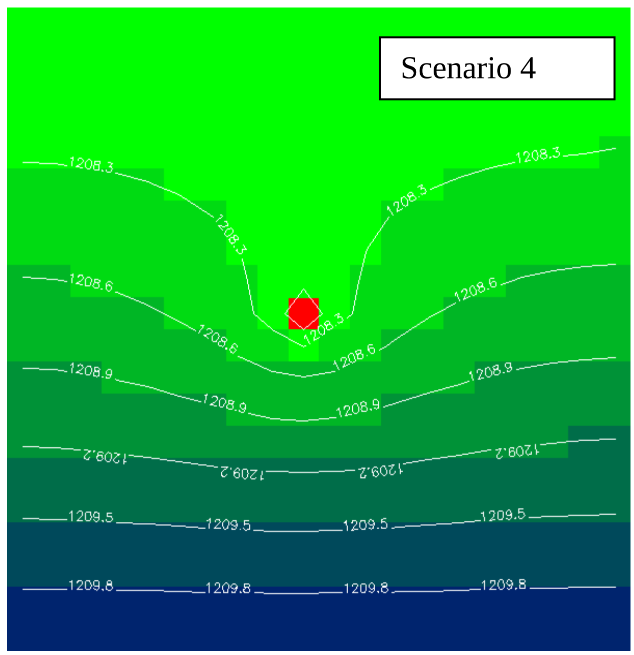




Figure 27: Scenario 1: Hydraulic Heads at WW 9736 as influenced by abstraction rate of 396 $m^3/a$.

Figure 28: Scenario 2: Hydraulic Heads at WW 9736 as influenced by abstraction rate of 365 $m^3/a$.

Figure 29: Scenario 3: Hydraulic Heads at WW 9736 as influenced by abstraction rate of 75,400 $m^3/a$.

Figure 30: Scenario 4: Hydraulic heads at WW 9736 as influenced by the 10561 $m^3/a$.

### 7.4.1.2 Research site 2: Boreholes WW 35852 and WW 35853

#### *7.4.1.2.1 Scenario 1*

The modeling results of scenario 1 at borehole WW 35852 can be visualized in Figure 31. The modeled scenario calculates the hydraulic head to 1196.71 mamsl at the abstraction well.

The modeling results of scenario 1 at borehole WW 35853 can be visualized in Figure 35. The modeled scenario calculates the hydraulic head to 1203.97 mamsl at the abstraction well.

#### *7.4.1.2.2 Scenario 2*

The modeling results of scenario 1 at borehole WW 35852 can be visualized in Figure 32. The modeled scenario calculates the hydraulic head to 1196.71 mamsl at the abstraction well.

The modeling results of scenario 2 at borehole WW 35853 can be visualized in Figure 36. The modeled scenario calculates the hydraulic head to 1203.97 mamsl at the abstraction well.

#### *7.4.1.2.3 Scenario 3*

The modeling results of scenario 3 at borehole WW 35852 can be visualized in Figure 33. The modeled scenario calculates the hydraulic head to 1180.23 mamsl at the abstraction well.

The modeling results of scenario 3 at borehole WW 35853 can be visualized in Figure 37. The modeled scenario calculates the hydraulic head to 1186.75 mamsl at the abstraction well.

#### *7.4.1.2.4 Scenario 4*

The modeling results of scenario 4 at borehole WW 35852 can be visualized in Figure 34. The modeled scenario resulted in the drying up the borehole.

The modeling results of scenario 3 at borehole WW 35853 can be visualized in Figure 38. The modeled scenario resulted in the drying up of the borehole.

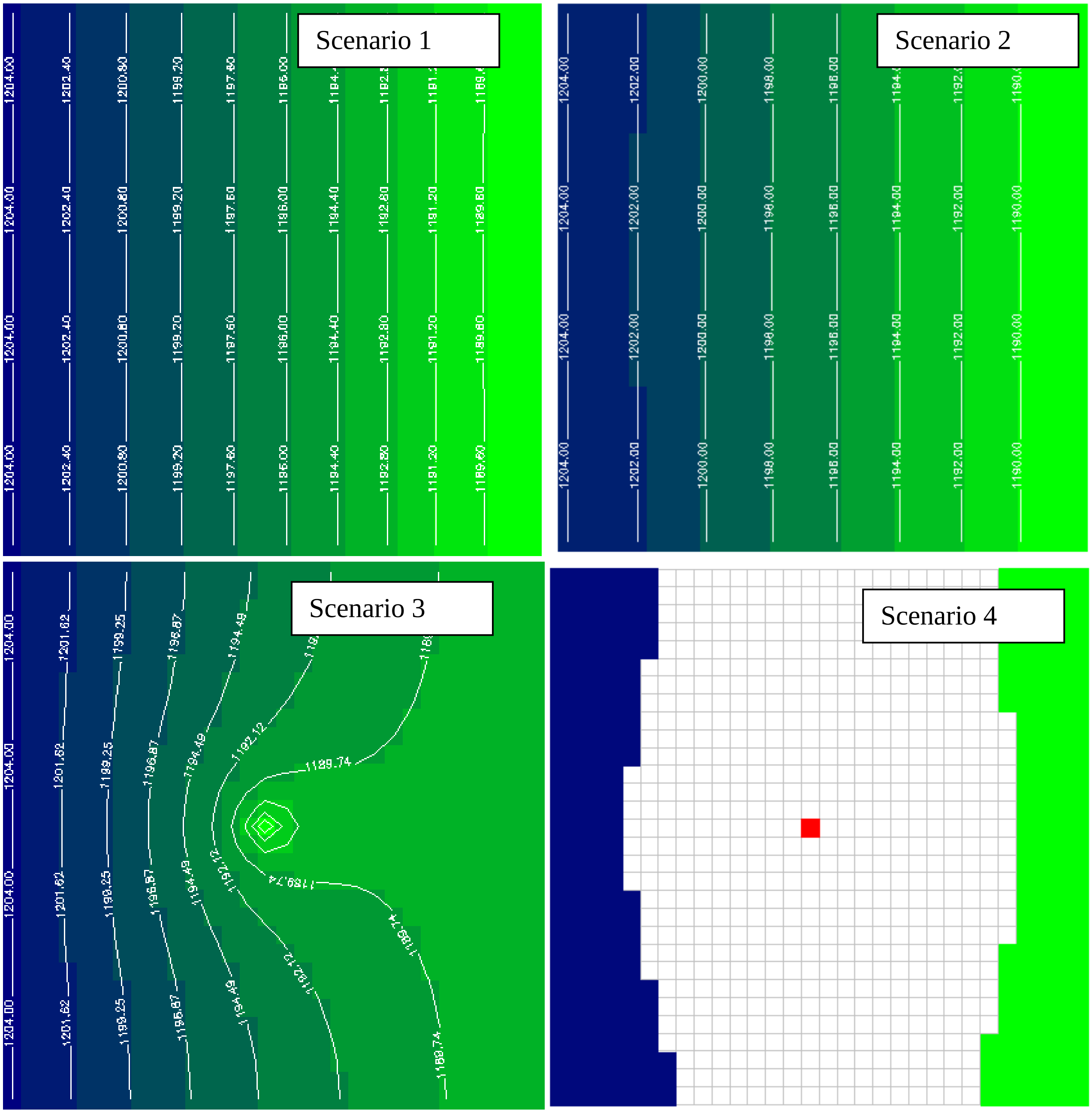



Figure 31: Scenario 1: Hydraulic Heads at WW 35852 as influenced by abstraction rate of 1204 $m^3$/a.
Figure 32: Scenario 2: Hydraulic Heads at WW 35852 as influenced by abstraction rate of 1111 $m^3$/a.
Figure 33: Scenario 3: Hydraulic Heads at WW 35852 as influenced by abstraction rate of 414 000 $m^3$/a.
Figure 34: Scenario 4: Hydraulic Heads at WW 35852 as influenced by abstraction rate of 21.2 $Mm^3$/a.

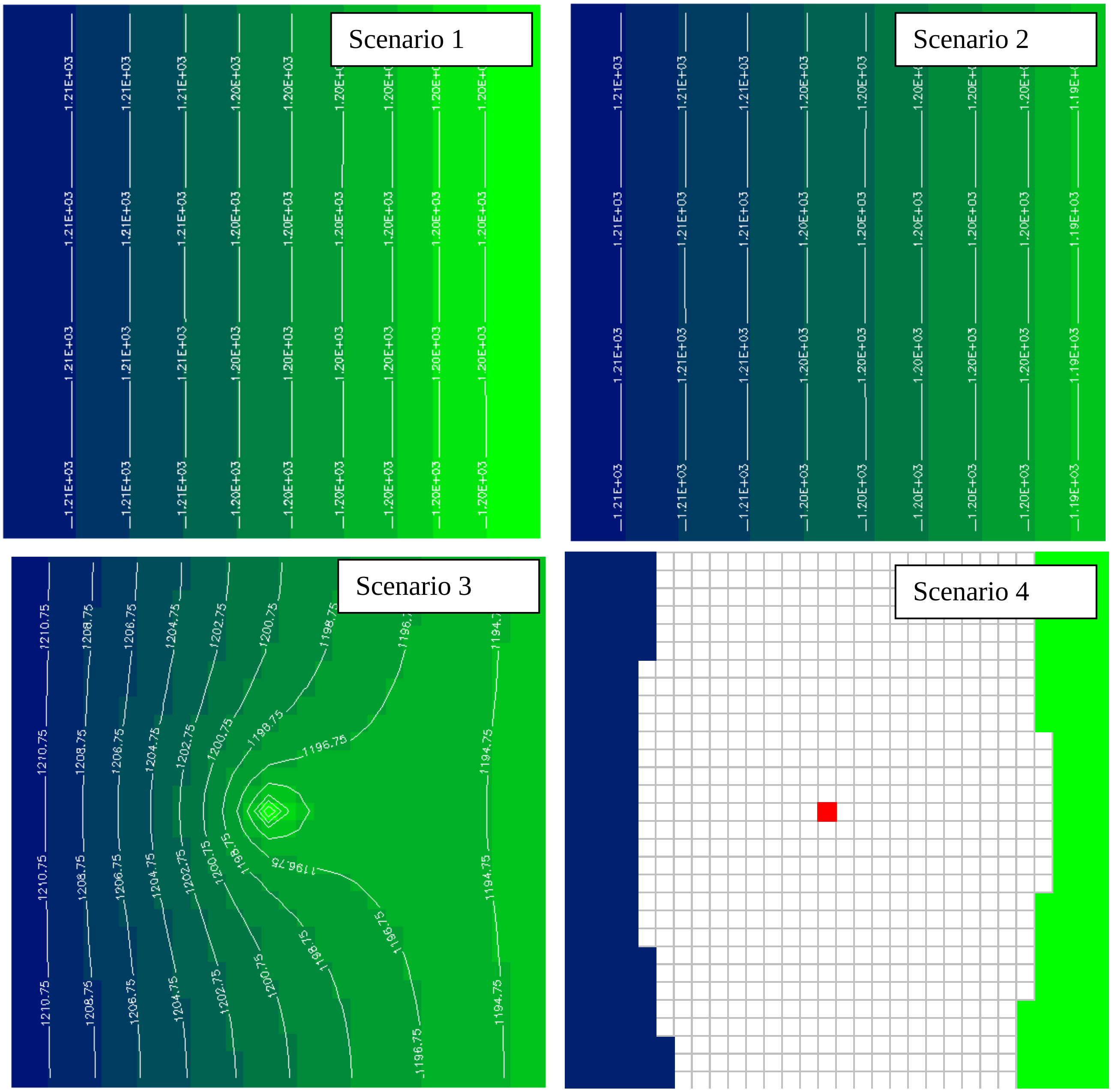



Figure 35: Scenario 1: Hydraulic Heads at WW 35853 as influenced by abstraction rate of 1204 $m^3$/a.

Figure 36: Scenario 2: Hydraulic Heads at WW 35853 as influenced by abstraction rate of 1111 $m^3$/a.

Figure 37: Scenario 3: Hydraulic Heads at WW 35853 as influenced by abstraction rate of 358,800 $m^3$/a.

Figure 38: Scenario 4: Hydraulic Heads at WW 35853 as influenced by abstraction rate of 25.8M $m^3$/a.

### 7.4.1.3 Research Site 3: Boreholes WW 21814 and WW 21784

#### *7.4.1.3.1 Scenario 1*

The modeling results of scenario 1 at borehole WW 21814 can be visualized in Figure 39. The modeled scenario calculates the hydraulic head to 1254.87 mamsl at the abstraction well.

The modeling results of scenario 1 at borehole WW 21784 can be visualized in Figure 43. The modeled scenario calculates the hydraulic head to 1236.58 mamsl at the abstraction well.

#### *7.4.1.3.2 Scenario 2*

The modeling results of scenario 2 at borehole WW 21814 can be visualized in Figure 40. The modeled scenario calculates the hydraulic head to 1254.95 mamsl at the abstraction well.

The modeling results of scenario 2 at borehole WW 21784 can be visualized in Figure 44. The modeled scenario calculates the hydraulic head to 1236.63 mamsl at the abstraction well.

#### *7.4.1.3.3 Scenario 3*

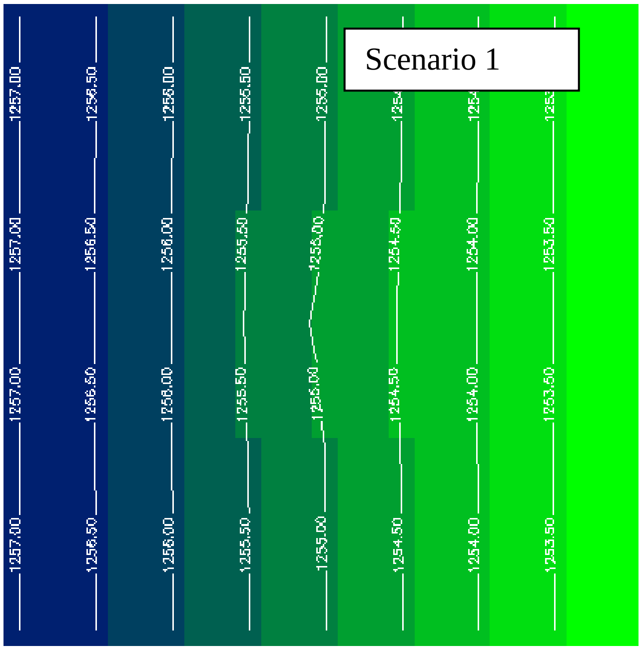
The modeling results of scenario 3 at borehole WW 21814 can be visualized in Figure 41. The modeled scenario calculates the hydraulic head to 1228.26 mamsl at the abstraction well.

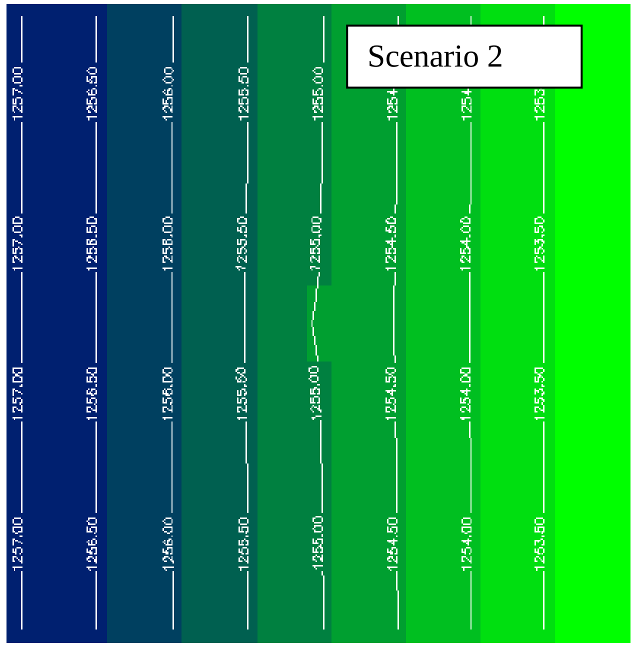
The modeling results of scenario 3 at borehole WW 21784 can be visualized in Figure 45. The modeled scenario resulted in the drying up at the abstraction well.

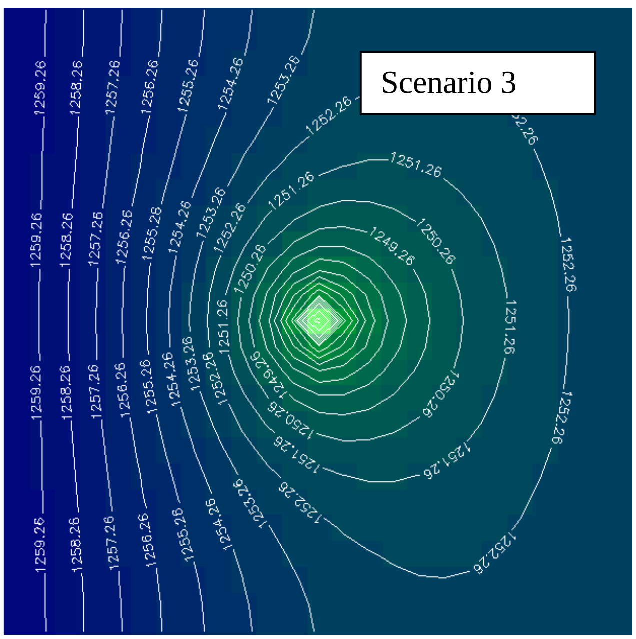
#### *7.4.1.3.4 Scenario 4*

The modeling results of scenario 4 at borehole WW 21814 can be visualized in Figure 42. The modeled scenario calculates the hydraulic head to 1256.61 mamsl at the abstraction well.

The modeling results of scenario 4 at borehole WW 21784 can be visualized in Figure 46. The modeled scenario calculates the hydraulic head to 1235.81 mamsl at the abstraction well.



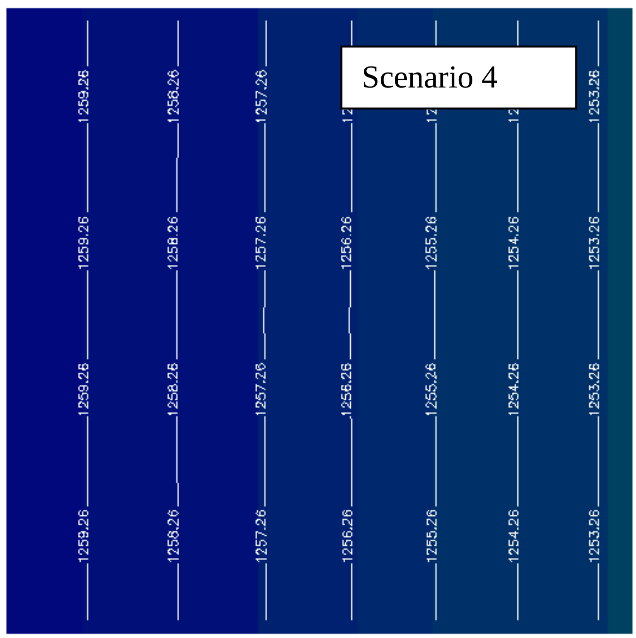
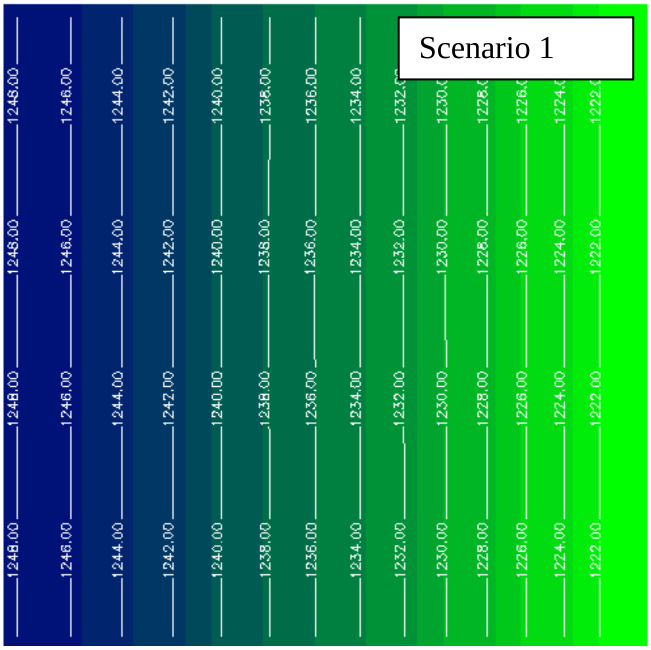
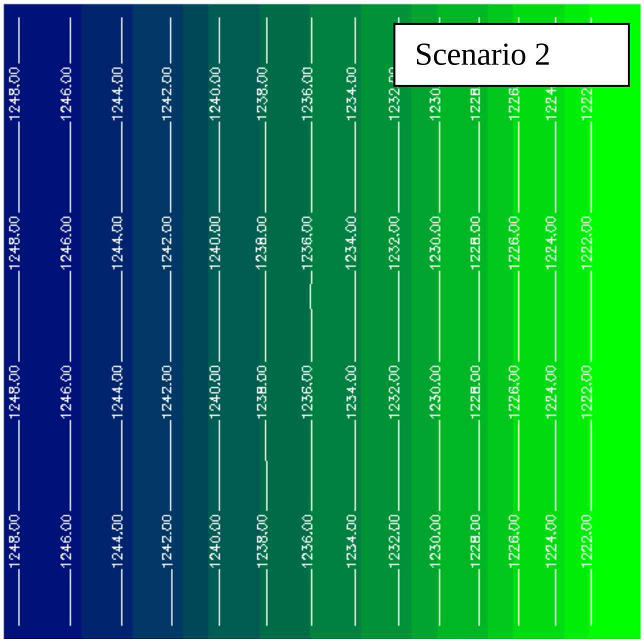
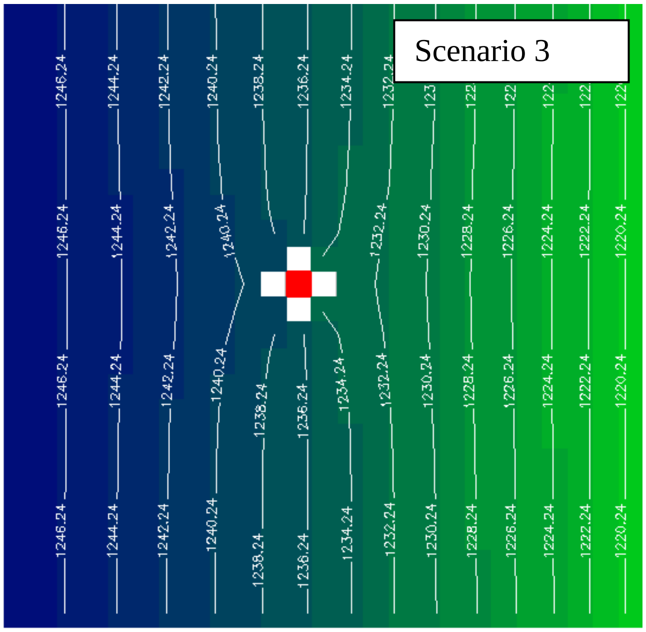




Figure 39: Scenario 1: Hydraulic Heads at WW 21814 as influenced by abstraction rate of 1055 $m^3$/a.
Figure 40: Scenario 2: Hydraulic Heads at WW 21814 as influenced by abstraction rate of at 590 $m^3$/a.
Figure 41: Scenario 3: Hydraulic Heads at WW 21814 as influenced by abstraction rate of 112,320 $m^3$/a.
Figure 42: Scenario 4: Hydraulic Heads at WW 21814 as influenced by abstraction rate of 337 $m^3$/a.



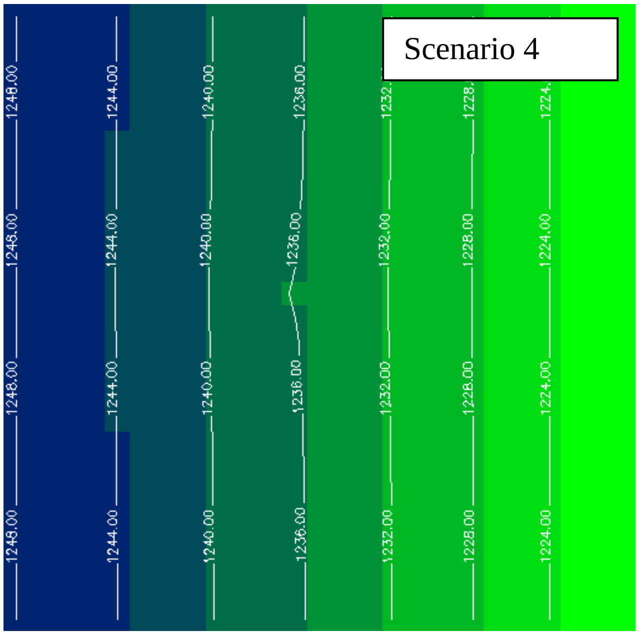




Figure 43: Scenario 1: Hydraulic Heads at WW 21784 as influenced by abstraction rate of 1055 $m^3$/a.

Figure 44: Scenario 2: Hydraulic Heads at WW 21784 as influenced by abstraction rate of 590 $m^3$/a.

Figure 45: Scenario 3: Hydraulic Heads at WW 21784 as influenced by abstraction rate of 1,123,200 $m^3$/a.

Figure 46: Scenario 4: Hydraulic Heads at WW 21784 as influenced by abstraction rate of 8235 $m^3$/a.

### 7.4.2 Entire Farm Models

## 7.4.2.1 The Influence of pumping from multiple boreholes on Farm 1 at Research Site 1

Additional to modeling the influence of the above four scenarios on the hydraulic heads within a borehole catchment, the four scenarios were furthermore modeled to evaluate their influence when pumping from the multiple active boreholes on the entire farm. One farm per research site was modeled. The results are given in the Figure 48 to Figure 51. The summary of the draw-down is given in Table 16. The approximate locations of the modeled boreholes (1, 2, 3, and 4) are given in Figure 47.

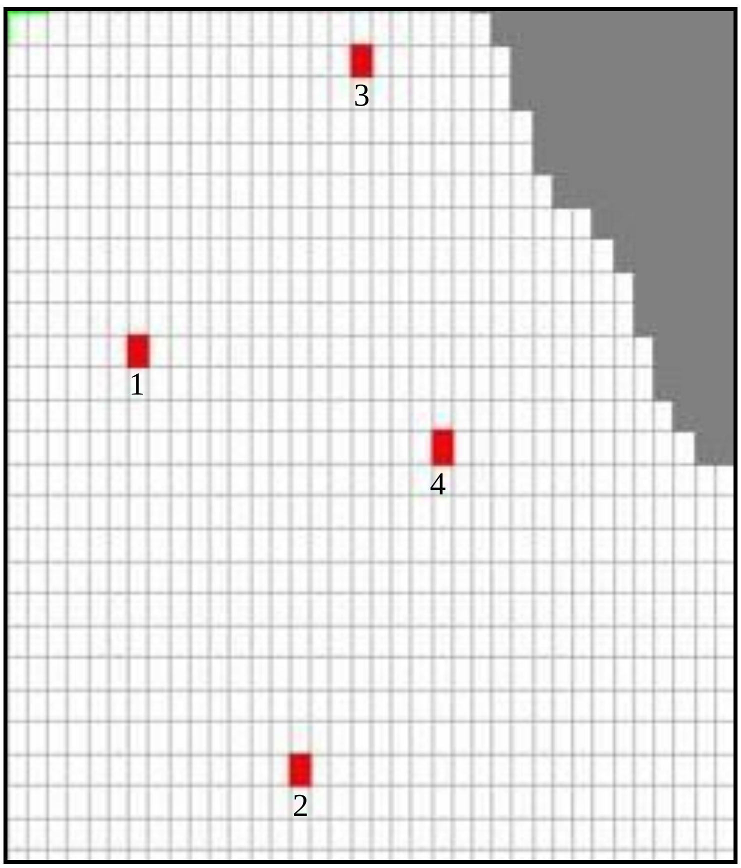



Figure 47: Locations of the Four Abstraction Boreholes at Farm 1.

##### *7.4.2.1.1 Scenario 1*

The modeling results of scenario 1 at Farm 1 can be visualized in Figure 48. The modeled scenario calculates the greatest influence on hydraulic heads to 1194.62 mamsl at borehole 3, while at borehole 2 and borehole 4 the model calculates the least influence on the hydraulic heads to1196.95 mamsl and 1196.06 mamsl respectively.

##### *7.4.2.1.2 Scenario 2*

The modeling results of scenario 2 at Farm 1 can be visualized in Figure 49. The modeled scenario calculates the greatest influence on hydraulic heads to 1194.67 mamsl at borehole 3, while at borehole 2 and borehole 4 the model calculates the least influence on the hydraulic heads to1196.99 mamsl and 1196.12 mamsl respectively.

##### *7.4.2.1.3 Scenario 3*

The modeling results of scenario 3 at Farm 1 can be visualized in Figure 50. The modeled scenario calculates the greatest influence on hydraulic heads to 1155.71 mamsl at borehole 4, while at borehole 2 the model calculates the least influence on the hydraulic heads to 1167.55 mamsl.

##### *7.4.2.1.4 Scenario 4*

The modeling results of scenario 4 at Farm 1 can be visualized in Figure 51. The abstraction regime has resulted in the drying up of the boreholes and their immediate surroundings.

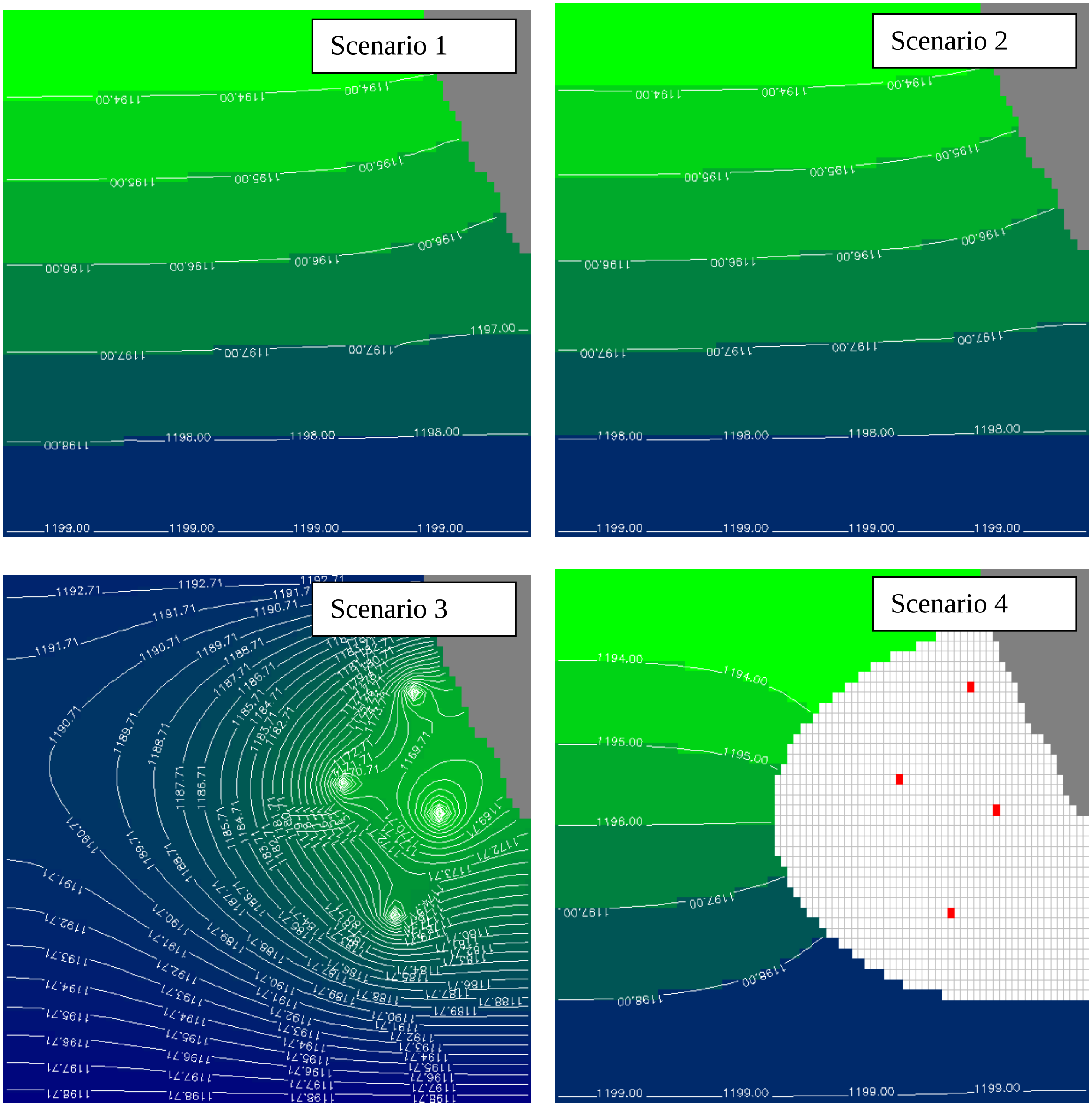



Figure 48: Scenario 1: Hydraulic heads at Farm 1 as influenced by the abstraction rate of 5326 $m/^3a$.

Figure 49: Scenario 2: Hydraulic head at Farm 1 as influenced by abstraction rate of 3716 $m^3/a$.

Figure 50: Scenario 3: Hydraulic head at Farm 1 as influenced by abstraction rate of 780,000 $m^3/a$.

Figure 51: Scenario 4: Hydraulic head at Farm 1 as influenced by abstraction rate of 6.6 $Mm^3/a$.

#### 7.4.2.2 The Influence of Pumping from Multiple Boreholes on Farm 10 at Research Site 2

Modeling of the four scenarios for the entire Farm 10 in Research Site 2 produced the hydraulic heads as summarized in Table 16. The model results are given in Figure 53 to Figure 56. The locations of the boreholes are given in Figure 52.

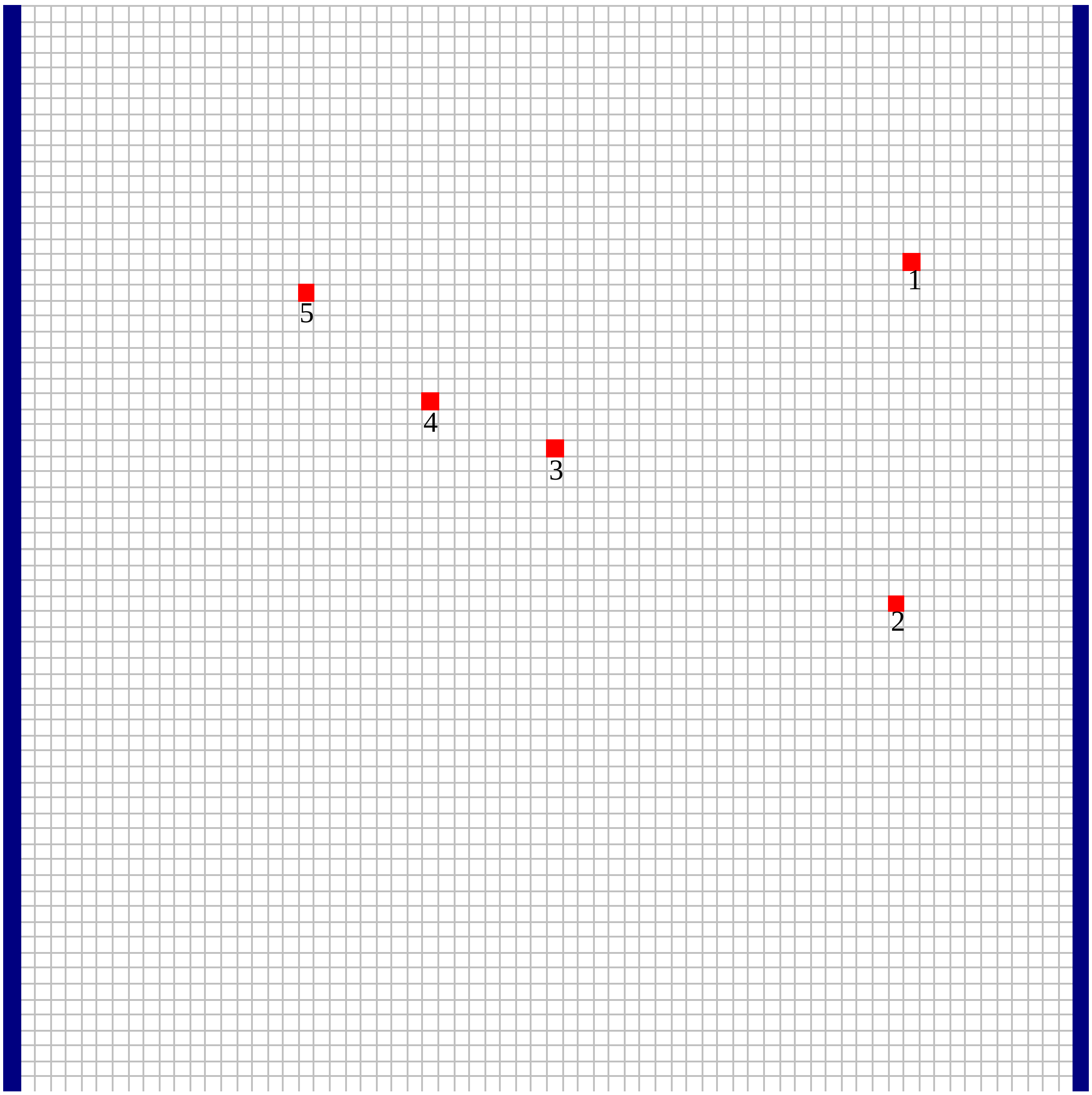



Figure 52: Locations of Five Abstraction boreholes at Farm 10.

#### *7.4.2.2.1 Scenario 1*

The modeling results of scenario 1 at Farm 10 can be visualized in Figure 53. The modeled scenario calculates the greatest influence on hydraulic heads at four of the five boreholes (1, 2, 3 and 4), 1196.34 mamsl, 1196.64 mamsl, 1202.95 mamsl, and 1205.08 mamsl respectively, while at borehole 5 the model calculates the least influence on the hydraulic heads to1207.21 mamsl.

#### *7.4.2.2.2 Scenario 2*

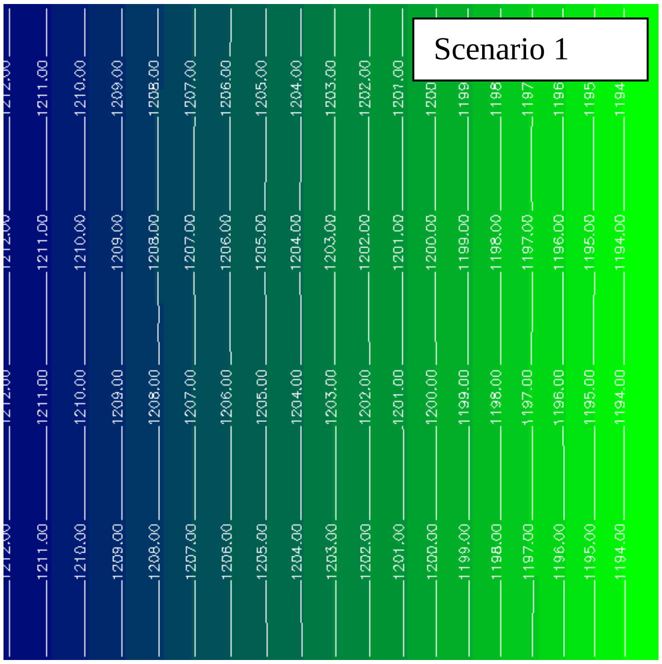
The modeling results of scenario 2 at Farm 10 can be visualized in Figure 54. The modeled scenario calculates the greatest influence on hydraulic heads at four of the five boreholes (1, 2, 3 and 4), 1196.34 mamsl, 1196.64 mamsl, 1202.95 mamsl, and 1205.09 mamsl respectively, while at borehole 5 the model calculates the least influence on the hydraulic heads to1207.21 mamsl.

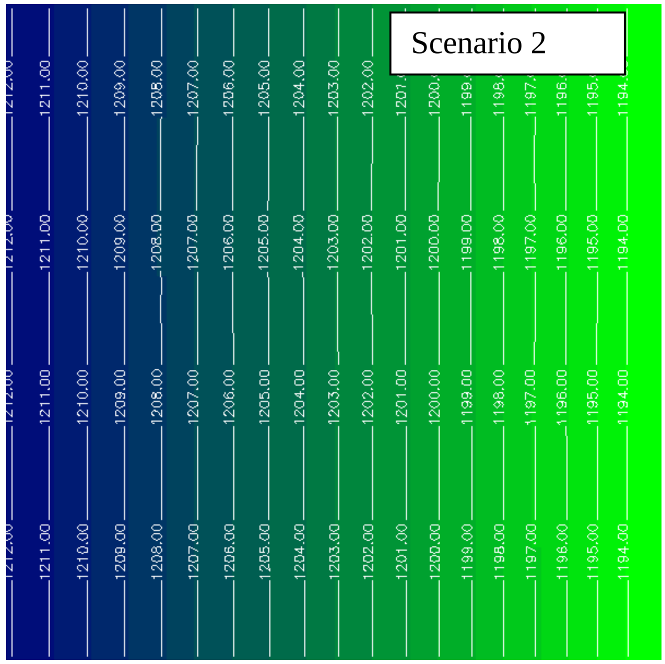
#### *7.4.2.2.3 Scenario 3*

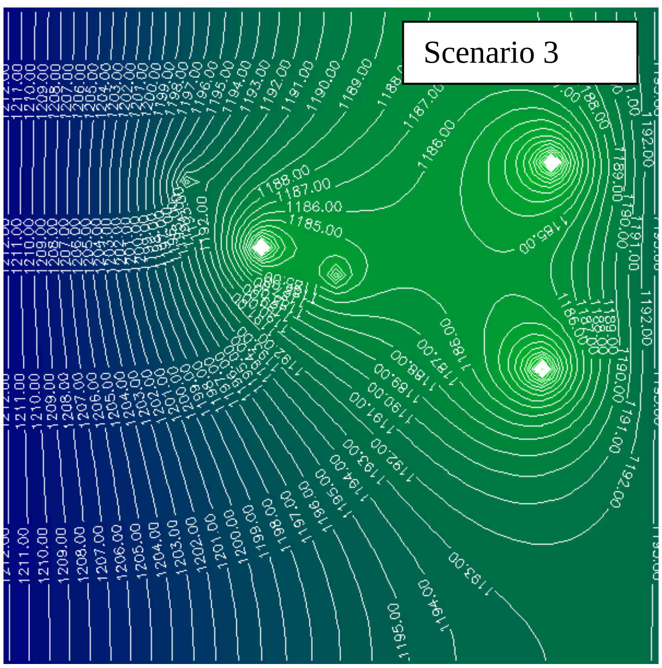
The modeling results of scenario 3 at Farm 10 can be visualized in Figure 55. The modeled scenario calculates the influence on hydraulic heads at boreholes (1, 2, 3, 4 and 5), to 1166 mamsl, 1167.23 mamsl, 1180.21 mamsl, 1171.28 mamsl and 1190.50 mamsl respectively. The modeled scenario calculates the greatest influence on hydraulic heads at borehole 1 to 1166 mamsl.

#### *7.4.2.2.4 Scenario 4*

The modeling results of scenario 4 at Farm 10 can be visualized in Figure 56. The modeled scenario resulted in the drying up of the boreholes and their immediate surroundings.



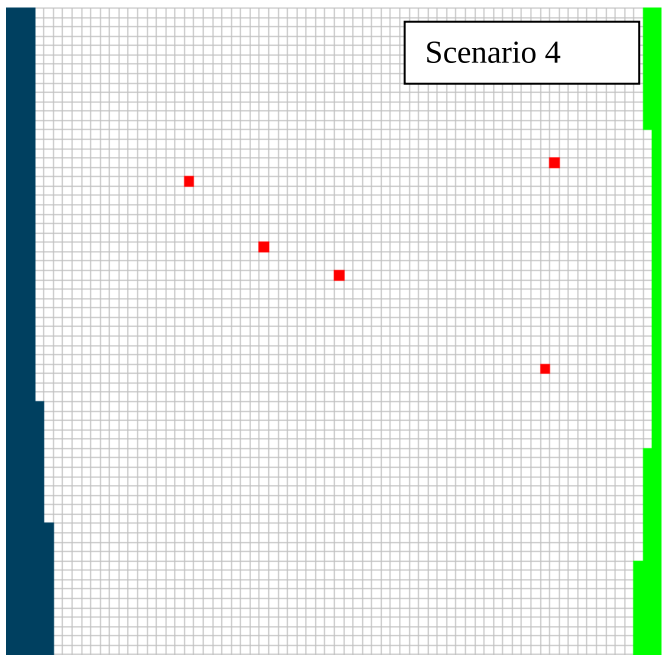




Figure 53: Scenario 1: Hydraulic head at Farm 10 as influenced by abstraction rate of 6023 $m^3$/a.
Figure 54: Scenario 2: Hydraulic head at Farm 10 as influenced by abstraction rate of 5555 $m^3$/a.
Figure 55: Scenario 3: Hydraulic head at Farm 10 as influenced by abstraction rate of $1.7*10^6$ $m^3$/a.
Figure 56: Scenario 4: Hydraulic head at Farm 10 as influenced by abstraction rate of $1.3*10^8$ $m^3$/a.

### 7.4.2.3 The Influence of Pumping from Multiple Boreholes on the Farm 18 at Research Site 3

Modeling of the four scenarios for the entire farm in Research Site 3 produced the hydraulic heads as summarized in Table 16, the model results are given in the following Figure 58 to Figure 61. The locations of the boreholes are given in Figure 57.

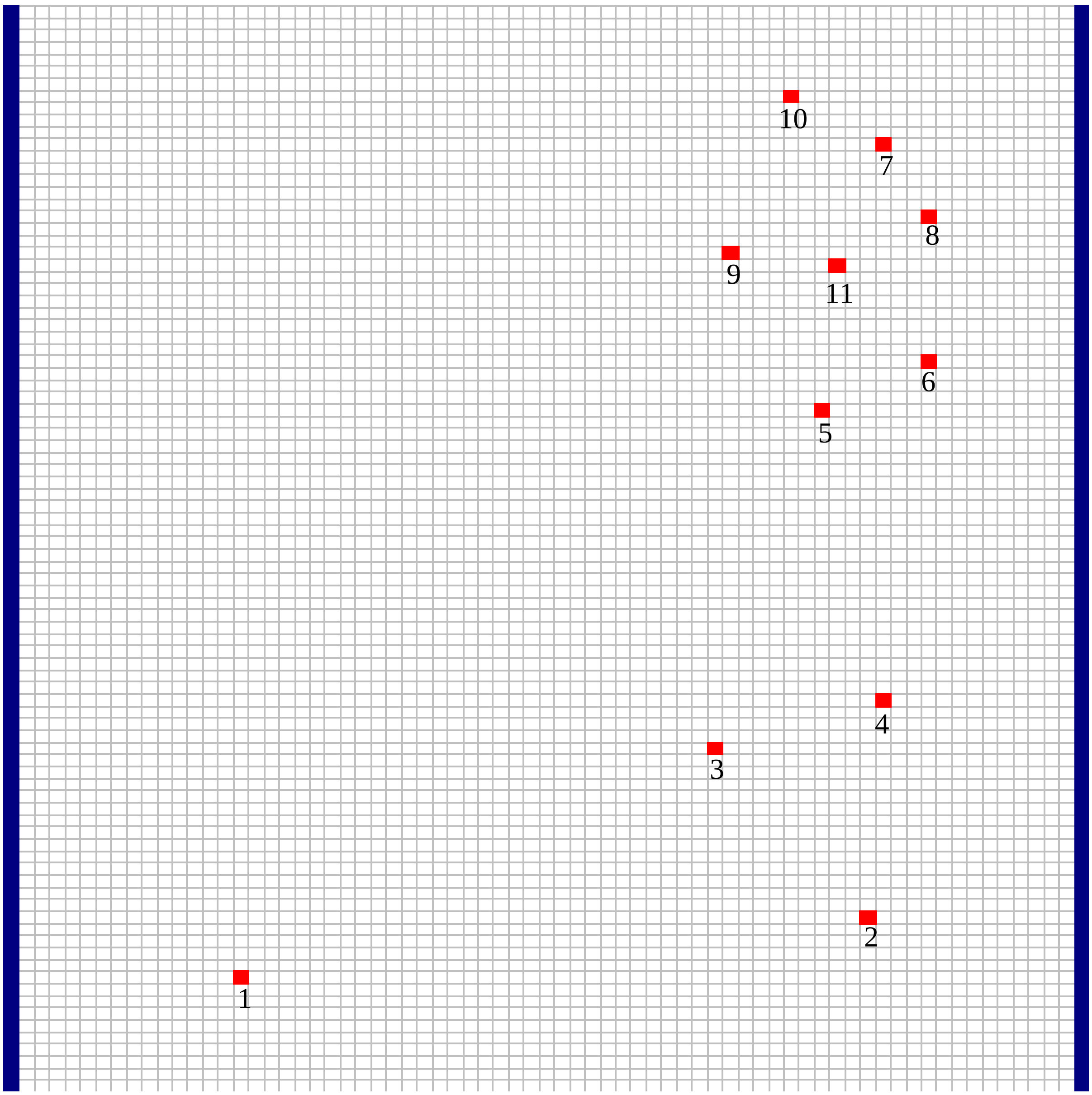



Figure 57: Locations of 11 Abstraction Boreholes at Farm 18.

#### *7.4.2.3.1 Scenario 1*

The modeling results of scenario 1 at Farm 18 can be visualized in Figure 58. The modeled scenario calculates the least influence on the hydraulic heads at borehole 3 to 1254.11 mamsl and the greatest influence was observed at borehole 8 to hydraulic heads of 1253.25 mamsl.

#### *7.4.2.3.2 Scenario 2*

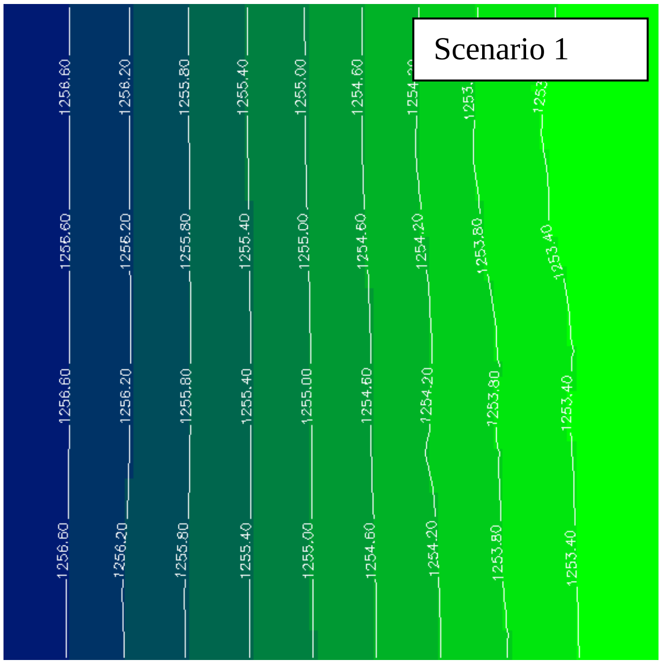
The modeling results of scenario 1 at Farm 18 can be visualized in Figure 59. The modeled scenario calculates the least influence on the hydraulic heads at borehole 3 to 1254.17 mamsl and the greatest influence was calculated at borehole 8 to hydraulic heads of 1253.31 mamsl.

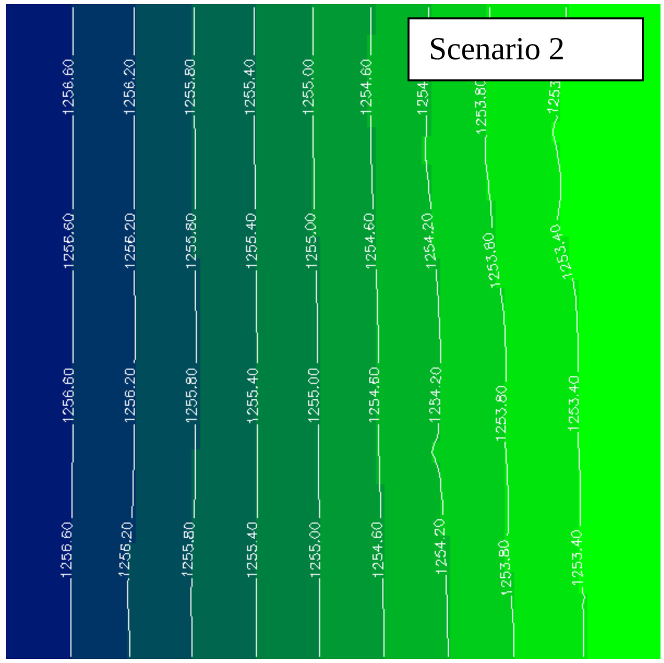
#### *7.4.2.2.3 Scenario 3*

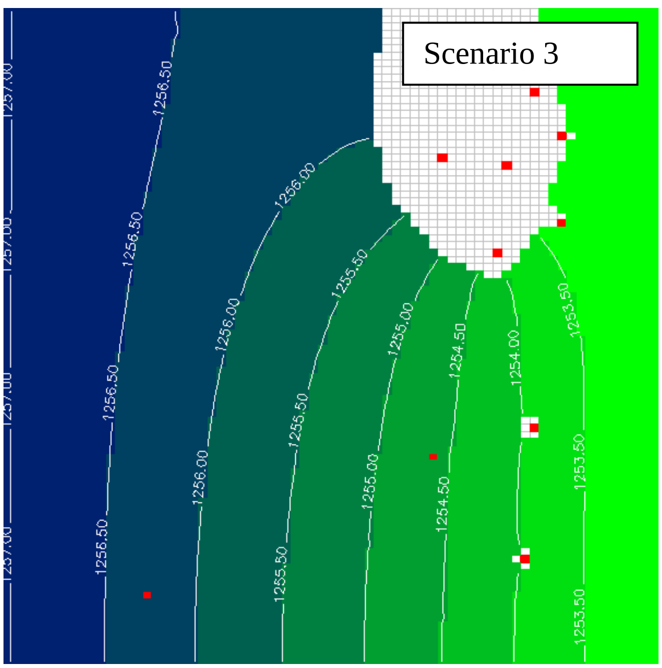
The modeling results of scenario 3 at Farm 18 can be visualized in Figure 60. The modeled scenario resulted in the drying up of the boreholes and their immediate surroundings. Also noticeable is the greater drying up at the northeast cluster of boreholes.

#### *7.4.2.3.4 Scenario 4*

The modeling results of scenario 4 at Farm 18 can be visualized in Figure 61. The modeled scenario calculates the least influence on the hydraulic heads at borehole 3 to 1253.45 mamsl and the greatest influence was calculated at borehole 7 to hydraulic heads of 1250.16 mamsl./a.



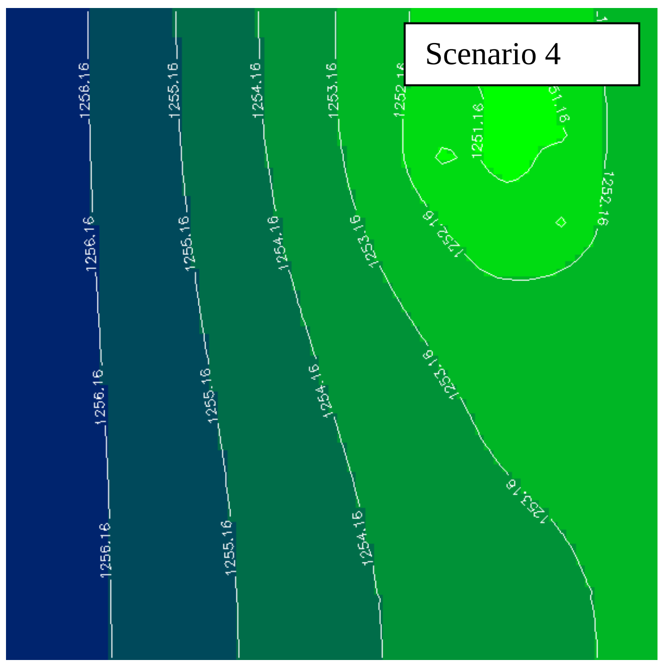




Figure 58: Scenario 1: Hydraulic head at Farm 18 as influenced by abstraction rate of 7884 $m^3$/a.

Figure 59: Scenario 2: Hydraulic head at Farm 18 as influenced by abstraction rate of 6498 $m^3$/a.

Figure 60: Scenario 3: Hydraulic head at Farm 18 as influenced by abstraction rate of 1.2 $Mm^3$/a.

Figure 61: Scenario 4: Hydraulic head at Farm 18 as influenced by abstraction rate of 38582 $m^3$/a.

### 7.4.3 Comparison of the Modeled Influence of the Four Scenarios on Hydraulic Heads

## 7.4.3.1 Single Borehole Models

Comparing scenario1 and scenario 2 for the modeled boreholes, the volume abstracted in scenario 1 was always higher than of scenario 2 across all three research sites. However, their influence on the hydraulic heads was nearly similar, with the exception at a research Site 3, where the difference in hydraulic heads between scenario 1 and scenario 2 was significant.

The influence of scenario 1 and scenario 2 was always lower than that of scenario 3. Similarly, the influence of scenario 3 was always lower than that of scenario 4 with the exception of the boreholes in Research Site 3, where the influence of scenario 4 is lower than that of scenario 3.

Scenario 4's influence at Research Site 1 and Research Site 2 has in all the boreholes modeled resulted in the drying up of the borehole and the surrounding areas. But, at Research Site 3, the influence of the scenario as mentioned being lower than the others does not result in the drying up of the boreholes. Compared to the abstraction rates of scenarios 1, 2, 3, at research site 3, the abstraction rate is at least two orders of magnitude smaller.

The modeled borehole's abstraction regimes for scenario 1 and scenario 2 are not vastly different, in most of the boreholes the volumes are almost 1:1, except in research site 3, where the ratio of the two scenarios is close to 1:2.

### 7.4.3.2 Entire Farm Models

The influence of scenario 1 and scenario 2 for the bigger models validates the trends observed in the smaller single borehole models. The two scenarios albeit having different abstraction rates, have a near equal influence on the hydraulic heads, noting that their abstraction rates are not immensely different. The influence of scenarios 1 and 2 are below the influence of scenario 3 across all three research sites.

Scenario 3's influence has a greater but manageable influence at Research Sites 1 and Research Site 2, but at Research Site 3, the abstraction regime results in the drying up of the boreholes and even to the northeastern part of the model. Its influence is generally less than that of the scenario 4, except at the third Research Site.

Scenario 4 has a far reaching negative consequence on the groundwater levels compared to the other three scenarios and as observed previously, it catapults into the drying up of the farm's aquifer at Research Site 1 and Research Site 2, but not at Research Site 3. The Figure 62 below summarizes the influence of the modeled scenarios.

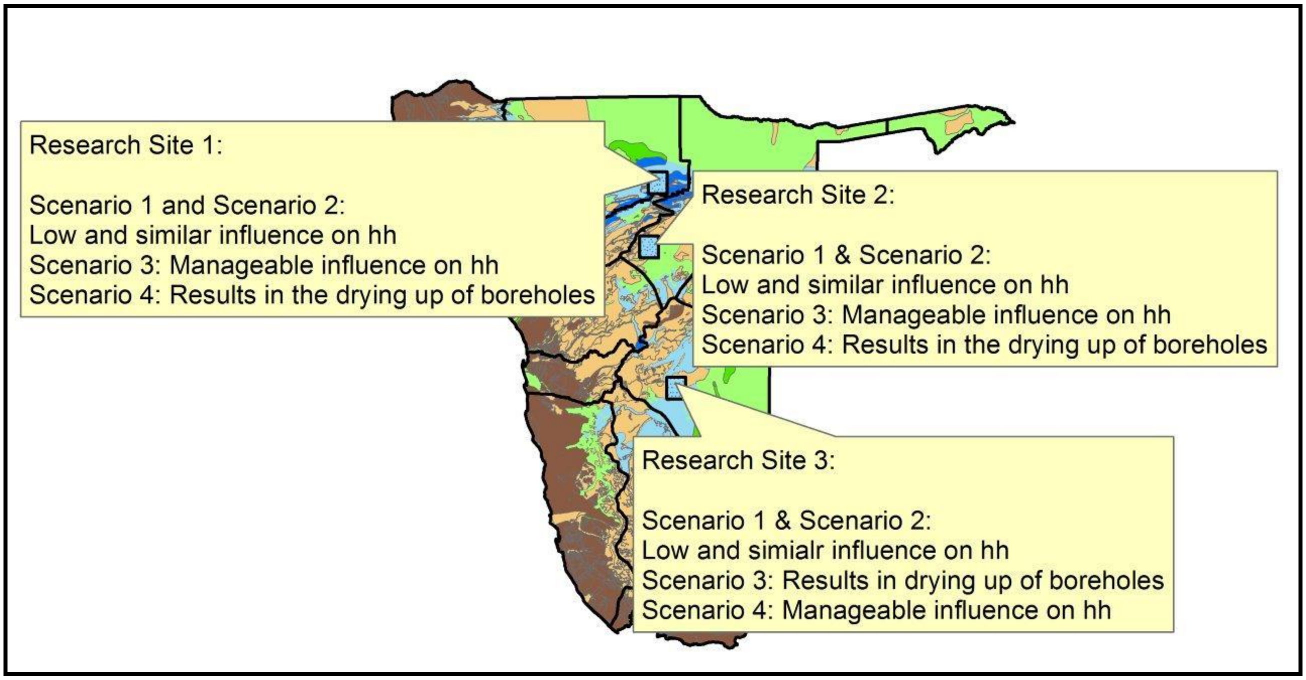



Figure 62: Summary of Entire Farm Model (Map created with ArcGIS 10.2 with data from GROWAS).

# 8 DATA ANALYSIS

The Box –Whisker plots for the farmer's and the carrying capacity guided abstraction for the SSU and LSU for the research sites are given in Figure 63, Figure 64 and Figure 65.

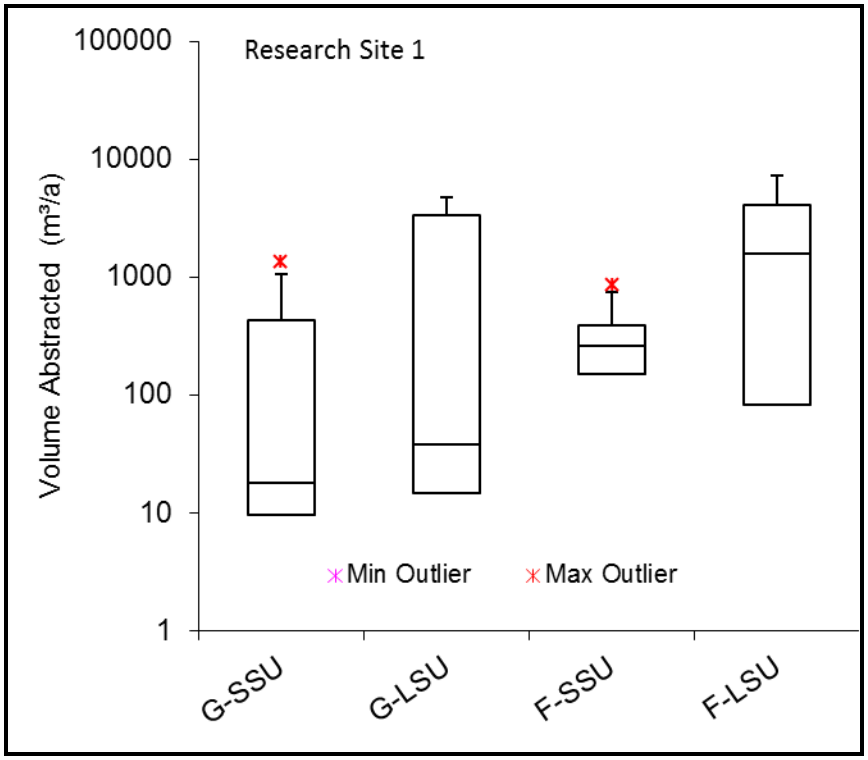



Figure 63: Box-Whisker Plot for the comparison of annual abstraction volumes by farmers and the government guided abstractions at Research Site 1.

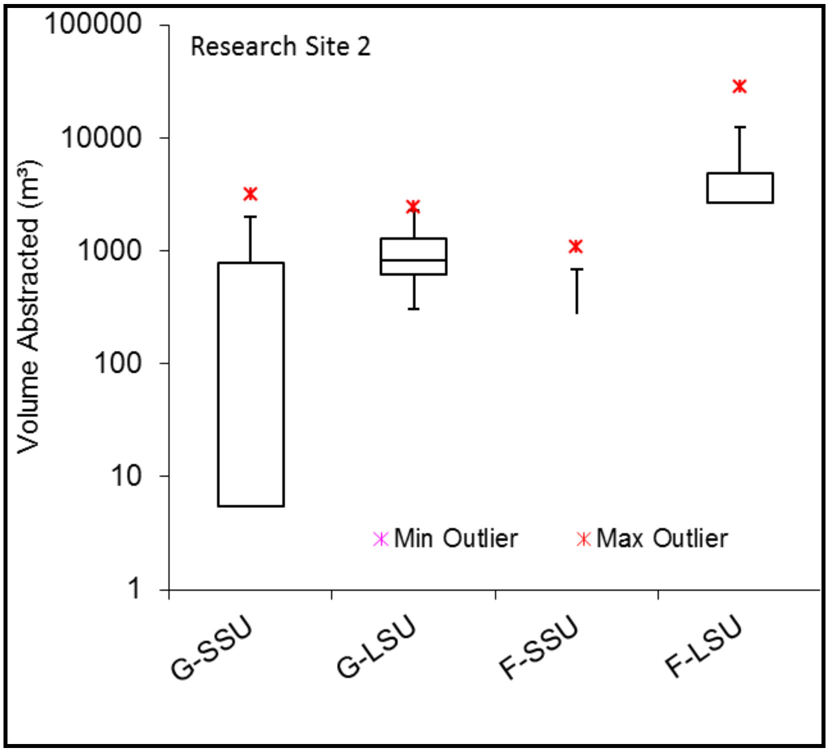



Figure 64: Box- Whisker Plot for the comparison of annual abstraction volumes by farmers and the government guided abstractions at Research Site 2.

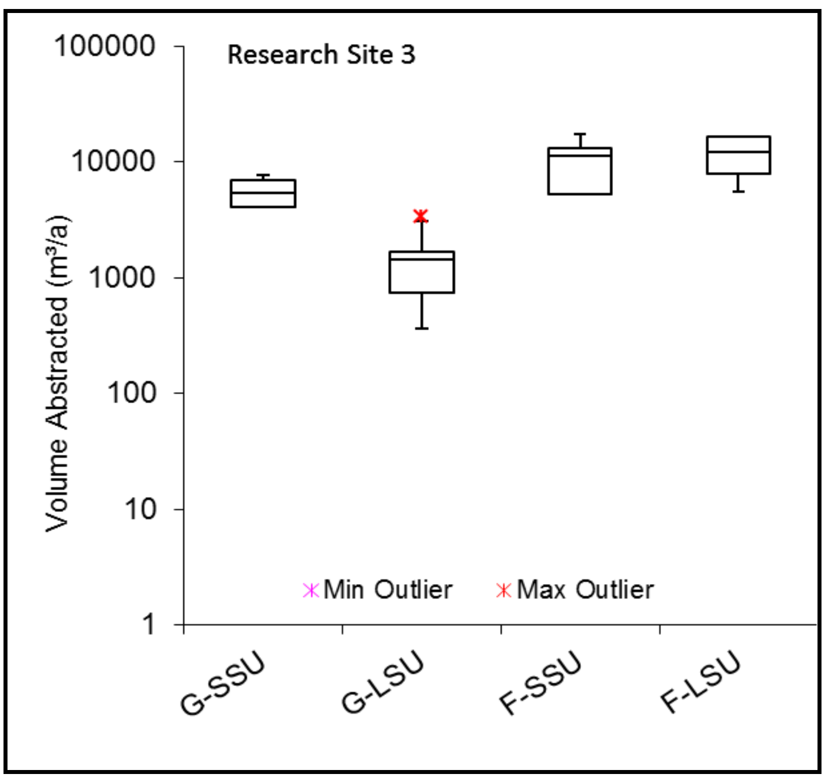



Figure 65: Box- Whisker Plot for the comparison of annual abstraction volumes by farmers and the government guided abstractions at Research Site 3.

In Table 17 the data analysis pertaining to the minimum, maximum, average, and standard deviation are presented. The data analyzed is for the calculation of the volume balance which included the recorded long-term average water level per borehole; the minimum recorded water level per borehole, the specific yield of the aquifers, the farm and borehole size, as well as the volume balance for each borehole.

From the three sites, one can highlight that Research Site 1 has the lowest average water level measurement, as well as the lowest minimum water levels recorded. The standard deviation for the average and minimum water levels is largest at Research Site 1, and lowest at Research 2 indicating that most of the values are close to the average. It is also observed that the farm sizes in Research Site 1 vary greatly in size. There is no deviation from the mean at the Research Site 2 and Research Site 3. The same applies to the borehole catchment. Looking at the overall volume balance, Research Site 2 has the greatest variation and deduced from the standard deviation. While research Site 3 has the lowest standard deviation, although it is also a high deviation the average volume balance calculated.

Table 17: Statistical Analysis of monitored hydraulic heads and resulting volume balance for the three Research Sites

| Research Site | Analysis | ϕAve (masl) | ϕmin (masl) | Sy | Farm size (ha) | Bh catchment ($m^2$) | Vol bal. (m) | Vol bal.(mm) | Vol bal ($m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| Research Site 1 | | | | | | | | | |
| | Min | 1138 | 1136 | 0.000 | 2610 | 2900000 | 0.00 | 1.00 | 6508 |
| | Max | 1560 | 1537 | 0.050 | 5000 | 10000000 | 0.18 | 180.50 | 1353750 |
| | Ave | 1395 | 1381 | 0.005 | 3959 | 6217000 | 0.02 | 18.90 | 129342 |
| | STDev | 175 | 166 | 0.015 | 685 | 1416657 | 0.04 | 41.25 | 305548 |
| Research Site 2 | | | | | | | | | |
| | Min | 1204 | 1176 | 0.150 | 4600 | 9200000 | 1.23 | 1227.00 | 11288400 |
| | Max | 1217 | 1209 | 0.150 | 4600 | 9200000 | 5.43 | 5428.50 | 49942200 |
| | Ave | 1212 | 1193 | 0.150 | 4600 | 9200000 | 2.81 | 2813.40 | 25883280 |
| | STDev | 5 | 12 | 0.000 | 0 | 0 | 1.57 | 1571.56 | 14458313 |
| Research Site 3 | | | | | | | | | |
| | Min | 1166 | 1166 | 0.000 | 6863 | 6239091 | 0.00 | 0.01 | 83 |
| | Max | 1255 | 1255 | 0.001 | 6863 | 6239091 | 0.04 | 37.50 | 234031 |
| | Ave | 1221 | 1217 | 0.001 | 6863 | 6239091 | 0.00 | 3.51 | 21881 |
| | STDev | 35 | 38 | 0.000 | 0 | 0 | 0.01 | 9.27 | 57843 |

In Table 18, the data analysis pertaining to the minimum, maximum, average, and standard deviation are presented. The data analyzed is for the calculation of the volume abstracted for SSU, LSU by farmers and by the government determined carrying capacity, the sustainable yield and the short-term available volume for individual farms.

There are several farms where no abstraction for SSU and LSU was possible to calculate as livestock figures were not shared, hence the minimum abstraction of 0 $m^3$/a for these scenarios. The maximum volume abstracted across the research sites was in the Research Site 3. For both SSU and LSU abstraction the Research Site 3 has the greatest deviation.

The maximum sustainable volume was calculated for Research Site 2, and the Minimum at Research Site 1. The maximum short-term volume available was calculated at Research Site 2 and the minimum at Research Site 3.

Table 18: Statistical Analysis for the abstraction scenarios

| **Research Site** | **Analysis** | **Farmers (m³/a)** | | **GOV (m³/a)** | | **Sustainable Yield (m³/a)** | **Short term volume availabe (m³/a)** |
|---|---|---|---|---|---|---|---|
| | | **SSU** | **LSU** | **SSU** | **LSU** | | |
| Research Site 1 | | | | | | | |
| | Min | 0 | 0 | 0 | 0 | 678600 | 17069.4 |
| | Max | 845 | 7178 | 1342 | 4747 | 1300000 | 5857500 |
| | Ave | 311 | 2438 | 321 | 1630 | 919533 | 1968331 |
| | STDev | 277 | 2795 | 515 | 2075 | 333372 | 3368125 |
| Research Site 2 | | | | | | | |
| | Min | 0 | 0 | 0 | 303 | 1794000 | 129416400 |
| | Max | 1095 | 28530 | 3134 | 2421 | 1794000 | 129416400 |
| | Ave | 274 | 7227 | 786 | 1089 | 1794000 | 129416400 |
| | STDev | 548 | 12086 | 1565 | 923 | | |
| Research Site 3 | | | | | | | |
| | Min | 0 | 5519 | 0 | 366 | 1170000 | 38582 |
| | Max | 17520 | 16425 | 7802 | 3422 | 1170000 | 38582 |
| | Ave | 9551 | 11815 | 5000 | 1493 | 1170000 | 38582 |
| | STDev | 6550 | 5135 | 2866 | 1089 | | |

# 9 DISCUSSION

## 9.1 Interviews

One of the shortfalls from the farmer's management strategies is lack of groundwater monitoring. This is a major shortfall in groundwater management because one of the important aspects of managing this resource is assessing the water level's behavior and quantifying its fluctuations. This gives an idea of what fluctuations can be tolerated in an aquifer so that a bench mark may be set to ensure that the groundwater levels remain above this, because otherwise the levels reach a critical level where after continued pumping can cause harmful and even irreversible effects to the aquifer (Bredenkamp, *et al.*, 1995). Amongst all the activities that farmers engaged in, the activity of groundwater level monitoring was omitted. This is potentially a direct result from lack of or limited involvement of Basin Management Committees (BMC), some of the farmers interviewed had no idea of their existence. Referencing the Water Resources Management Act No. 11 of 2013 section 5(23) (b), two major functions of these BMC's are: "to promote community participation in the protection, use, development, conservation, management and control of water resources in its water management area;" and secondly "to monitor and report on the effectiveness of policies and measures in achieving sustainable management of water resources and resource quality in its water management area." It is unfortunate that these BMC's are not part of the current legally binding Water Act no.54 of 1956 (Water Act No. 54 of 1956, 1985). Although an entire chapter is dedicated to BMC's in the pending Act, they cannot be enforced. This therefore culminates to the limited fulfillment of their function and subsequently the public are uninformed and major management tools such as the groundwater level monitoring are not practiced. It is acknowledged that the BMC's do exist and are functional in some areas.

In the same breath, it is observed that the farmers across the three Research Sites apply a maximum of three of these management activities with the exception of farm 3 and farm 10 where five (5) activities have been recorded. The interviews reveal that mostly the farmers in the Research Site 3 belong to farmer union, but even then, only one farmer admitted that they converse about water issues at their farmer's union meeting. If water and the management thereof was discussed more frequently and placed in high regard amongst farmers, then a whole lot more management activities would be employed by the farmers, thus greater level of groundwater management would be had.

Fundamentally, water issues are omitted in discussions possibly because the water supply in quality or quantity is currently not a threat in these areas, and the situation may change if a threat arises to the water.

The government carries out the management of water resources and enforces management from users with the backing of the Namibian constitution, Article 100 that states that the land, water and natural resources below and above the surface of the land shall belong to the State. Many of the management activities employed by the government are underlain and supported by the particularly practical activity of delineating the Water Controlled Areas (WCA) which covers the most highly productive aquifers. The government is further backed by the Water Act No 54 of 1956 (sections of South African Water Act made applicable to Namibia) as well as the Namibia Water Corporation Act, Act No 12 of 1997 (Christelis et al. 2018).

From the long list of achieved management activities by the government of Namibia, there remains still a longer list of management activities to be implemented. Echoing the cries of the government officials, Cobbing and Davies (2008) recognizes that the plight facing many African countries is the lack of capacity for the centralized and organized collection, storing and dissemination of groundwater data and the lack of human capital to carry out the necessary work, which as in the case of Namibia includes the further quantification of the rest of the aquifers.

One of the shortcomings encountered is that, because farmers are reluctant to share their water usage information, only a limited number of farms could be studied. Nonetheless, the outcome may be used as a guide in gauging the sustainability of the farmer's abstractions, and because it is done for individual farms, the results can be applied to farms of similar sizes and set up to assess their sustainability or to request them to destock and reduce their abstraction volumes.

## 9.2 Compilation of Existing Data

Research Site 1 has highest range of transmissivity due to the complex and highly variable stratigraphy. Bufler et al. (2000) agrees that there exists heterogeneity amongst the carbonate rocks of the Otavi Group because of the karstic features and related structural nature of the rocks. The sedimentology of the Kalahari group is also highly variable and this leads to a lateral and vertical variability in the transmissivity values. The same applies to the storativity and permeability values. It also has the highest recharge values observed compared to the other research areas and this is attributed by the higher rainfall of 550 mm/a, versus the 250 mm/a, at Research Site 3. Schmidt, and Ploethner (2000) support this explanation that higher recharge is attributed to higher rainfall as most recharge is detected in relation to greater rainfall.

The lowest hydraulic conductivities are observed in Research Site 1 which is typical for fractured and locally karstified dolomites (Schmidt and Ploethner, 2000)

## 9.3 Estimations of Abstraction Strategies

A comparison between the volume abstracted daily by farmers with the volume as calculated based on the carrying capacity that can be abstracted by the farms gives rise to one major observation. That is, the farmers abstract greater volumes than that which is defined by carrying capacity of each farm studied. This unequal abstraction by the farmers is brought about by two factors. Firstly, the farmers overstock on SSU and LSU above the carrying capacity developed for their areas and secondly due to a lack of patrolling on the stocking by the relevant Ministry. Consequently more groundwater is abstracted by farmers than is fitting for the carrying capacity and this is driven by economics of livestock farming which is categorized by Espach et al. (2006) that livestock farming is the main income generating farming system.

Overall the Research Site 3 has the highest animal count of all the sites, and this is merely a matter of farm sizes in the area being larger than those at the other research sites.

The sustainable yield varies across research areas and the primary reason is the rainfall in the area, which has an effect on the recharge used to calculate the sustainable yield. The relationship between recharge and rainfall has been backed up by Schmidt and Ploethner, (2000) in the earlier sections.

The short –term available volumes also differ across the study areas, and it is very dependent on the long term groundwater monitoring which enables the determination of the volume. Although dependent on the aquifer characteristics as those highlighted in previous sections, the short term available water is heavily reliant on technical, social and economic constraints. These constraints may reduce the volume available from optimum to potential depending on ability to abstract it (Nonner, 2010).

## 9.4 Modeling

The challenge faced of converting the questionnaire answers into a format that can be input into a model was overcome and the results shed light on the influence that the management strategies employed by farmers, government, scientific sustainable yield and the short-term yield have on the hydraulic heads. These four options were used as model scenarios.

### 9.4.1 Modeling of Single Boreholes

The overarching result from the modeling of the single borehole catchments is that although scenario 1 which was the volume that the farmers abstracted from a borehole for stock watering was always higher than scenario 2, which was the volume calculated using the carrying capacity, these two scenario's influence on the hydraulic heads of the borehole catchments were similar, in that the scenarios drew the hydraulic heads down by an equal or almost equal amount with a difference of millimeters. This is attributed to the fact that from the studied sites, the counts of SSU and LSU per farm is not much higher than that calculated with carrying capacity. This result implies that there is a margin in which farmers can exceed their live-stocking to a point where the influence of stock watering is the same as that of the carrying capacity. Although the upper limit for this margin is not produced in this study, at least the discovery thereof is made and further studies can be conducted to refine the upper and lower limit of stocking above the carrying capacity.

At Research Site 3, the difference in the two scenarios was higher, between 0.5 m and 0.8 m. The contributing factor is that the farmer's abstraction strategy at Research Site 3 was almost double the volume of the government guided abstraction strategy.

Scenario 3 was modeling the sustainable yield strategy. The effect on the hydraulic heads as outlined in the results was much higher than that of the farmer's and government guided abstraction strategies. This sustainable yield was obtained using the recharge into the system; otherwise the term sustainable would not apply, and instead be replaced by the term groundwater mining. The implication is that the effects of the sustainable yield abstraction strategy are the bench mark for abstraction. The farmer's and government guided abstraction strategies are well within this benchmark, and therefore the farmers would be within their limits if they continue with the current pumping regimes.

Both the farmer and the government abstraction strategies are largely below the calculated sustainable volume's influence on hydraulic heads which indicates that the farmers in the studied farms are underutilizing their borehole, and is well within the sustainable abstraction volume. This result supports the claim by DWAF in the Research Site 1 specifically, that the allocation of water quotas done by division of Geohydrology as based on the 2003 Karst model is very conservative (DWA, 1992).

The short-term available volume abstraction strategy (scenario 4), refers to the volumes that can be abstracted in emergency cases such as droughts. Nonner (2010) defines the short term groundwater strategy to be one that only permits a temporal reduction in groundwater storage during dry periods. The Research Area 2 has the largest short-term storage available owing to its mostly low specific yield of the area, and the difference of average hydraulic heads and minimum hydraulic heads as calculated by (Eq.3).

These short term volumes were modeled at each borehole, and the result is that at the abstraction well was pumped dry at Research Sites 1 and 2. These are relatively large volumes and that is why, as the term suggests, the volumes are not for prolonged abstraction. Such abstraction would be unsustainable and if extended in duration, then it would be declared as groundwater mining.

In contrast however, Research Site 3 which has been different throughout the study, the study site has a much lower short-term availability compared to the two other research sites which is the reason why this scenario did not dry up the boreholes at Research Site 3. The fluctuations of the water level over the past three decades at the Research Site 3 have not been as high as the other sites, owing much to the unconfined nature of the aquifer where response to pumping is not rapid.

### 9.4.2 Modeling the Entire Farm

Modeling all the boreholes used on the studied farms has as expected a cumulative impact on the hydraulic heads. As already established the farmer’s abstraction at all three research sites is higher than the carrying capacity guided abstraction. Firstly this results from lack of capacity from government officials to enforce the standard and so the farmers are still under the notion that small quantities abstracted by the farmers re inherently sustainable (Cobbing and Davies, 2008).

At all three research sites, the farmer’s and the government guided abstraction strategies have a similar influence on the hydraulic heads validating the results observed in the modeling the borehole catchment.

The sustainable yield abstraction strategy has a greater effect on the water levels than the farmer’s and the government guided abstraction strategies, but it once again acts as a bench mark for the farmers. This is across Research site 1 and 2 with the exclusion of Research Site 3, where the sustainable yield abstraction strategy has caused the drying up of the abstraction wells.

Ultimately this value is to be considered with caution and more studies to quantify the sustainable yield are pending. With the changes in climate predicting more floods but also longer droughts, it is expected that these figure calculated in this study will change.

As expected, the scenario 4 in the Research Site 1 and 2 is drying up of the wells, and this is again showing that such as abstraction regime is not feasible in the long run. This will be further aggravated by climate change that is predicted when seasons of prolonged droughts are experienced. Kumar (2012) explains how climate change influences surface water first before it ultimately influences the groundwater through the climate change crippled recharge. In Research Site 3, the short term is very small compared to the other scenarios, and that is the reason for the lower effect on the hydraulic heads. The low short-term is explained in the above section of modeling single boreholes.

Finally, across the three research sites, along the rainfall gradient, there is no threat of over abstraction from the farmers. The threat may be of concern in times of drought when the short –term available volumes will be targeted as the only water supply for domestic, irrigation, industrial and livestock watering.

It is also acknowledged that these abstraction volumes were computed for livestock watering only, and that is the probable cause for the acceptable effect that these abstraction scenarios have on the hydraulic heads. It is expected that if water used for irrigation had to be included in the modeling, then different and possibly more adverse effects may have been discovered.

Based on the finding of the study, it can be noted, as pointed out by Hogeboom et al. (2015) that what the modeling of the strategies has achieved is the preventing of unsubstantiated claims about savannah systems' behavior when the different management strategies have been applied.

Comparing the stocking capacity along the rainfall gradient, the Research Site 3 has larger farms in size than the other two sites and also stocks in general more livestock than the two sites. Higher stocking capacity affects the volume abstracted which is higher in Research Site 3.

With the discussion of the results of the study, the hypothesis that different management strategies have a significant influence on the long term groundwater levels of the savannah aquifers in Namibia is accepted.

# 10 CONCLUSION

## 10.1 Interviews

The main concern that led to the study was that it was unknown how aquifers in Namibian savannah systems are managed at the local farmer's scale and how this compares with government guidelines, sustainable yield guidelines and the short term available volumes guidelines and how individually these strategies affect ground water levels in the savannah aquifers of Namibia. In an attempt to resolve the concern, data pertaining to farmers' groundwater management strategies and government groundwater management strategies was collected through means of questionnaires. It was done along a rainfall gradient across three Research Sites in savannah covered areas of Namibia. The savannah aquifers were of particular interest because they cover more than 64% of the country's land surface, and they are home to numerous economically important sectors having mining and agriculture at the top of the list, and these sectors all make use of the underlying aquifers, magnifying the value of the biome to the country.

The results revealed that farmers employ many groundwater management activities that are not stipulated in the Water Act, however these activities are not widely practised and it is concluded that minimal application of these activities is due to a limited involvement of government with the local farmers, which is something that is expected to be done through BMC's. The farmers also tend to believe that small abstraction amounts are inherently sustainable, therefore extraordinary or scientific methods of groundwater management are disregarded.

It is further concluded that although the government is tirelessly working on regulations to manage the water, they are subdued in their efforts by lack of funds, lack of human capital to fulfil management activities such as quantifications of all the strategic aquifers. This begs the question, is it not time to encourage partnerships between the government and the private sector or between the non-governmental agencies, local communities and the government, where it may prove beneficial to converge these ideas to strengthen the efforts of community funded and managed systems where the non-governmental agencies and the private sectors hook efforts to bring it about, and the country can finally depart from the models of advocating centrally funded systems run by the national governments?

## 10.2 Compilation of Existing Data

The compilation and summary of the existing data exhibits the variability of the study sites and highlighted the physiological, hydrogeological, geological, topographical information of the research areas as well as general groundwater management case studies in Namibia and around the world. The majority of the existing data was obtained from DWAF, NamWater, SLR Consulting Namibia, Namib Hydrosearch, journals, previous work done in the areas and online sources.

## 10.3 Estimations of Abstraction Strategies

A comparison between the volume abstracted daily by farmers with the volume as calculated based on the carrying capacity that can be abstracted by the farmers leads to the conclusion that the farmers abstract greater volumes than that which is defined by carrying capacity of each farm studied. It was further concluded that this unequal abstraction by the farmers is brought about by the farmers overstocking on LSU and SSU above the carrying capacity and also due to a lack of patrolling on the stocking. There however exists a margin by which farmers can stock above the recommended carrying capacity without evoking a groundwater response greater than what is ideally expected when within the carrying capacity. The upper limit of this margin is yet to be defined.

The sustainable yield varies across research areas and the primary reason is the distinguishable rainfall in the area, which has an effect on the recharge used to calculate the sustainable yield.

The short –term available volumes also differ across the study areas. It is dependent on the aquifer characteristics and it is accessible only if technical, social and economic constraints are eliminated which would otherwise alter the status of this volume from optimum volume available to merely potential volume available depending on ability to abstract it. The short-term volume available in essence only get considered in cases of emergency water shortages and it is not to be relied on for extended periods of time, because abstracting at these volumes will deplete the aquifer and transcend into aquifer mining.

## 10.4 Modelling

Models for single boreholes on farms where 30 years or more of groundwater level monitoring data exists were set up and run. Two boreholes per site were modelled. Due to lack of spatially widespread and reliable data at the research sites, boreholes of similar geological and hydrogeological settings were used. This validated the results and with continuous groundwater monitoring, the models could be updated to include more boreholes from the network.

The modelling of individual farms with numerous boreholes also allowed for the validation of the single borehole results. The areas with monitoring data are homogenous in geological and hydrogeological setup therefore a good representation of other farms with similar settings is achieved.

The fundamental conclusion is that all the four abstraction scenarios do have an effect on the groundwater levels.

Each research site's groundwater levels/hydraulic heads have a different response to different abstraction volumes modelled, but the farmer's abstraction and government guided abstraction have a similar effect on the groundwater levels even though the farmer's abstractions are higher than those of the government's. Furthermore it is concluded that the farmer's and the government's guided abstractions influences are lower than the sustainable yield volume's influence on the hydraulic head, therefore the farmers are currently abstracting water conservatively and are within the governments guidelines.

Groundwater must be managed in times of groundwater abundance just as much as in groundwater scarce times. As a result, despite the absence of a water crisis, the farmer's abstraction rates should remain as it is now and this will contribute to good management practises which reduce the risk of water crises.

Finally, along the rainfall gradient there is no threat of over abstraction from farmers, except when in times of drought when the short-term available volume will be the targeted. In such climatic conditions the values for short-term availability are expected to dwindle. The modelling has shown that this abstraction scenario is not to be dependent on over a long-term as it leads to drying up of the aquifer on the farms and it is concluded that this scenario is not sustainable, and that its abstraction is limited to months.

There still exists a gap between farmers and the government and the efforts to collectively manage groundwater. It is foreseen that bridging the gap would see the local management activities adopted by the farmers implemented into regulations and practised countrywide and possibly beyond the national borders, because whether there is an abundance of water or a scarcity, management should remain a priority.

# 11 RECOMMENDATIONS

From the study, the following recommendations are made:

- The greatest manner of managing savannah aquifers is controlling and monitoring that the carrying capacity of the savannah biome in Namibia is not significantly exceeded through livestock stocking and that the responsible Ministry enforces appropriate stocking and patrols it.
- The Ministry of Agriculture Water and Forestry should continue and enforce stricter groundwater monitoring at irrigation farms, livestock farms and industries such as mining.
- Savannah biomes are primarily made up of trees and shrubs which also compete for groundwater, therefore an increase in Artificial Recharge (AR) or Managed Aquifer Recharge (MAR) strategies such at the one at the Omaruru Delta and the one in the Windhoek South Aquifer should be developed, not only to store water for drought years, but to be proactive against the potentially high evaporation rates in the savannahs.
- Basin Management Committees that are existing must get more involved, because presently many farmers are not aware that they exist and this would bring a rise in management activities.
- Water management should be a principal issue being addressed at farmer's union meetings and emphasizing the importance of long-term data collection and storage.
- Interactions between the farmer and the regulating bodies must be strengthened and scientific knowledge should be offered to the farmers.

- In order to prohibit harmful environmental problems, groundwater trends of exploitation across the country should be observed continuously by means of groundwater models that get updated every 5years with the added information or at every sign of noticeable climatic change.
- A series of data such as discharge, water quality, hydraulic heads and water temperature, etc. should be collected in order to construct groundwater management models. This will act as a scientific basis to be used for reasonable development of groundwater resources.
- Different hydrogeological settings require unique management strategies, especially with regards to groundwater pollution, therefore, in addition to groundwater level monitoring, groundwater samples must also be included in the management of this resource to keep a record of water quality patterns and to ensure early pollution detection if any.
- Some of the managing activities employed by farmers are quite good and can preserve water for future use. Therefore the selected activities can be included in the by - laws of the Resource Management Act. These may be including but are not limited to:
    - Install flow meters to monitor monthly abstraction per borehole
    - Create earth dams possibly covered with shade balls to be used in rainy season instead of pumping from the groundwater
    - Use earth dams to assist in infiltration and percolation of surface water to keep it from being lost due to evaporation and thereby carrying out artificial recharge into the aquifer

- Convert open reservoirs to closed 10 $m^3$ tanks to reduce evaporation
- Install pump and trough water level switches for indication of sufficient water pumped
- Keep a record of monthly water level measurements in the farm boreholes.
- Furthermore managed/artificial aquifer recharge with rainwater could be a good option. It however must be conducted in the utmost care and knowledge to prohibit the contamination of groundwater.

## 11.1 SUGGESTIONS FOR FURTHER RESEARCH

It was discovered that there exists a margin of overstocking that allows the farmer's abstraction influence on the hydraulic heads to be similar to that suggested by government, this upper limit of the overstocking has not been determined in this study and it is suggested that further studies can be conducted to refine the upper limit of stocking above the carrying capacity, that produces acceptable influence on groundwater levels.

It is expected that if water abstracted for irrigation had to be included in this modeling study, then different and possibly adverse effects may be discovered. The suggestion is to conduct further studies by modeling the influence of stock watering together with irrigation quotas.

In addition to the above, modeling the effect of mining and/or other industrial activities on groundwater in the savannah aquifer, and finally modeling the collective influence of groundwater abstraction by mining and/or other industrial activities, livestock farming and irrigation would give a holistic influence of groundwater abstraction from the aforementioned sites.

Finally, the modelling simulation period could be increased to run and predict the influence of the management strategies over a period exceeding one year. The influence can be predicted over 5, 10 and 15 years.

## 12 REFERENCES

Alker, M., 2008. The Stampriet Artesian Aquifer Basin A case study for the research project ”Transboundary groundwater management in Africa”.

Alley, W.M and Leake, S.A., 2004. Journey from Safe Yield to Sustainable Yield. Groundwater 42, 12–16.

Alley, W., 2007. The Importance of Monitoring To Groundwater Management, in: Sustainable Management of Groundwater in Mexico. National Academies Press. https://doi.org/10.17226/11875

Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, a. D., Knapton, a., Boronkay, a., 2012. Australian groundwater modelling guidelines, Waterlines Report Series.

BIWAC, 2004. Criteria for the Demarcation of the 11 Water Basins. In Demarcation of Water Basins on National Level. Windhoek.

Braune, E.; Christelis, G.; Kenathabo, P., 2013. Preliminary Evaluation of Kalahari-Karoo Aquifer Conditions; Groundwater Resources Governance in Transboundary Aquifers.

Bredenkamp, D., Botha, L., van Tonder, G., van Rensburg, H., 1995. Manual on Quanititative Estimation of Groundwater Recharge and Aquifer Storativity. Water Research Commission, Pretoria.

Bufler, R., Ambs, P., Himmelsbach, T., Tordiffe, E., Baumle, R., 2000. Groundwater: Past Achievements and Future Challenges. Rotterdam.

Campana, M., 2007. A Primer on Groundwater Management, in: Sustainable Management of Groundwater in Mexico. National Academies Press. https://doi.org/10.17226/11875

Chiang, W.H., Kinzelbach, W., 1998. Processing Modflow. A simulation program for modelling groundwater flow and pollution. User manual.

Christelis, G., and Struckmeier, W., 2011. Groundwater in Namibia. Formset (PTY) Ltd, Cape Town.

Christelis G, Dierkes K, Quinger M, Matengu B, Lohe C, Bittner A, Upton K, Ó Dochartaigh BÉ and Bellwood-Howard, I., 2018. Africa Groundwater Atlas: Hydrogeology of Namibia. [WWW Document]. British Geological Survey.

Cobbing, J.E., and Davies, J., 2008. Applied Groundwater Studies in Africa. CRC Press/ Balkema, Leiden.

Convention Ramsar Secretariat, 2010. Managing groundwater, 4th ed. Ramsar Convention Secretariat, Gland.

Duffield, G., 2016. Representative Values of Hydraulic Properties [WWW Document]. unpublished. URL www.aqtesolve.com

Department of Water Affairs at the Ministry of Agriculture, Water and Rural Development Namibia (DWA). (1992). Criteria to be considered when allocating permits for he abstraction of groundwater for irrigation purposes in Karst area. Unpublished Geohydrology Division Report File no.12/1/B; pp3-5.

Earle, S., 2006. Properties of Aquifers (No. Geo-304), Hydrogeology, Unpublished, Malaspina.

Espach, C., Lubbe, L.G., Ganzin, N., 2006. Determining Grazing Capacity In Namibia :

Approaches and Methodologies. pp. 28–39.

Fitts, C.., 2002. Groundwater Science. Academic Press.

Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice Hall In., Englewood Cliffs, N.J., New Jersey.

Gehrels, H. and Gieske, S.M.A (2003).Aquifer Dynamics (I Simmers, Ed.), Tokyo, Japan: Balkema Publishers

GKW Consultants and BICON Namibia, 2003. Hydrogeological Investigations to Determine the Groundwater Potential of the Tsumeb Aquifers in Northern Namibia (Tsumeb Groundwater Study).

Glover, P., 2013. Pore scale study of flow in porous media : Scale dependency , REV , and statistical REV Dongxiao Lattice-Boltzmann. Advances in Water Resources 51, 1734. https://doi.org/10.1103/PhysRevE.54.1734

GROWAS, 2009. National groundwater Database.

Heyns, P., 2008. Application of Basin Management Approach to Groundwater Utilisation in the Otavi Mountain Land, Namibia. Physicss and Chemistry of the Earth 33, 913–918.

Hogeboom, R.H.J., Oel, P.R. Van, Krol, M.S., Booij, M.J., 2015. Modelling the Influence of Groundwater Abstractions on the Water Level of Lake Naivasha , Kenya Under Data-Scarce Conditions 4447–4463. https://doi.org/10.1007/s11269-015-1069-9.

Jeltsch, F., and Wanke, H. (2013) Options for Sustainable Geo-Biosphere Feedback Management in Savannah Systems. Unpublished Manuscript.

JICA, 2002. The Study on the Groundwater Potential Evaluation and Management Plan in the Southeast Kalahari (Stampriet) Artesian Basin in the Republic of Namibia.

Khadri, S.F.R., Pande, C., 2016. Ground water flow modeling for calibrating steady state using MODFLOW software: a case study of Mahesh River basin, India. Modeling Earth Systems and Environment 2, 39. https://doi.org/10.1007/s40808-015-0049-7

Kirchner, J., G. Tredoux, A. Wierenga, G. Christelis & J. Wrabel., 2002. Sustainable Development Of Groundwater Resources In The Africa Region – Technical Report: Namibia: Assessment Of The Recharge To The Stampriet Artesian Basin To Formulate A Groundwater Management Plan For Sustainable Use Of The Resource In The Southeast Kalahari.

Klock, H., 2001. Hydrogeology of the Kalahari in north-eastern Namibia with special emphasis on groundwater recharge, flow modelling and hydrochemistry. Julius Maximilians-University of Wurzburg.

Klock, H., Kuells, C., Udluft, P., Kulls, C., Udluft, P., 2001. Estimating recharge values using hydrochemical and geological data: a case study from the semiarid Kalahari catchment of northern Namibia. Impact of Human Activity on Groundwater Dynamics 269, 25–32.

Kruseman, G.P. and N.A. de Ridder., 2000. Analysis and Evaluation of Pumping Test Data, 2nd ed. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Külls, C., 2000. Groundwater of the North-Western Kalahari, Namibia: Abschätzung der Neubildung und Quantifizierung der Fließsysteme. Julius-Maximilian University of Würzburg.

Kumar, C.P., 2012. Climate Change and Its Impact on Groundwater Resources. International Journal of Engineering and Science 1, 43–60.

Lubbe, L., Espach, C., 2006. Spotlight on Agriculture. Directorate of Research and Training.

Maimone, M., 2004. Defining and managing sustainable yield. Ground Water 42, 809–814. https://doi.org/10.1111/j.1745-6584.2004.tb02739.x

MAWF, 2010. Groundwater Monitoring and Control. In Development of an Integrated Water resources Management Plan for Namibia. Windhoek.

Mendelsohn, J., Jarvis, A., Robert, C., Robertson, T., 2002. Atlas Of Namibia: A Portrait of the Land and its People. David Philip Publishers, Cape Town.

Mendelsohn, J., 2006. Fa r m i n g S y s t e m s in Namibia, Farming Systems in Namibia. RAISON.

Miller, R., 2008. The Geology of Namibia. Volume 3: Palaeozoic to Cenozoic. Geological Society of Namibia.

Nonner, J.., 2010. Introduction to Hydrogeology, 2nd ed. Taylor & Francis Group plc., London.

Poehls, D.J and Smith, G.J., 2009. Encyclopedic Dictionary of Hydrogeology, Ground Water. Academic Press. https://doi.org/10.1111/j.1745-6584.2010.00723.x

Rushton, K.., 2003. Groundwater hydrology. John Wiley and Sons Ltd.

Schmidt, G., Ploethner, D., 2000. Hydrogeological Invetigations in the Otavi Mountain Land, in: Sililo, O., et al (Ed.), Groundwater: Past Achievements and Future Challenges. Balkema Publishers, Rotterdam, pp. 419–421. https://doi.org/9058091597

Shaw, D., n.d. Savanna Vegetation Types [WWW Document]. URL www.the-eis.com (accessed 9.12.18).

Skarpe, C., 1992. Dynamics of Savannah Ecosystems. Journal of Vegetation Sciences 293.

SLR Namibia, 2017. Dundee Precious Metals Tsumeb Groundwater Flow and Transport Model. Windhoek.

Steenbergen, S.C., 2008. Ideas for groundwater management. Meta.Meta and IUCN.

Taapopi, J., 2015. Application of the Chloride Mass Balance Method To Determine Groundwater Recharge in the Area of Farm Ebenhaezer. University of Namibia.

WWW.TradingEconmics.com. Retrieved 14 August 2018

WWW.gsi.ie. Retrieved 29 September 2018

UNESCO, 2016. Stampriet Governance of Groundwater Resources.

Uugulu, S., and Wanke, H., 2018. Use of isotopic composition and chloride mass balance method to estimate groundwater recharge along a precipitation gradient, Namibia .

Water Act No. 54 of 1956, 1985. Water Act 54 of 1956 ( SA ). South Africa.

Wilhelm, M., 2012. The Impact of Climate Change in Namibia- A Case Study of Omusati Region. The Polytechnic of Namibia.

Yin, D., Shu, L., Xu, C., Wang, Z., Appiah-Adjei, E.K., 2012. An approach for estimating sustainable yield of karst water in data sparse regions. Environmental Earth Sciences 66, 399–407. https://doi.org/10.1007/s12665-011-1247-x

Zhou, Y., 2009. A critical review of groundwater budget myth, safe yield and sustainability. Journal of Hydrology 370, 207–213. https://doi.org/10.1016/j.jhydrol.2009.03.009

# 13 APPENDICES

## Appendix 1: Ethical Clearance

UNAM
UNIVERSITY OF NAMIBIA

ETHICAL CLEARANCE CERTIFICATE

**Ethical Clearance Reference Number: FOS/130/2016** **Date: 5 December, 2016**

This Ethical Clearance Certificate is issued by the University of Namibia Research Ethics Committee (UREC) in accordance with the University of Namibia's Research Ethics Policy and Guidelines. Ethical approval is given in respect of undertakings contained in the Research Project outlined below. This Certificate is issued on the recommendations of the ethical evaluation done by the Faculty/Centre/Campus Research & Publications Committee sitting with the Postgraduate Studies Committee.

**Title of Project**: Groundwater Management Options In Namibian Savannah Aquifers

**Nature/Level of Project**: Masters

**Researcher**: E. M.N. Nuunyango

**Student Number:** 200419421

**Faculty**: Faculty of Science

**Supervisor** : Dr. H. Wanke

Take note of the following:

(a) Any significant changes in the conditions or undertakings outlined in the approved Proposal must be communicated to the UREC. An application to make amendments may be necessary.
(b) Any breaches of ethical undertakings or practices that have an impact on ethical conduct of the research must be reported to the UREC.
(c) The Principal Researcher must report issues of ethical compliance to the UREC (through the Chairperson of the Faculty/Centre/Campus Research & Publications Committee) at the end of the Project or as may be requested by UREC.
(d) The UREC retains the right to:
(i). Withdraw or amend this Ethical Clearance if any unethical practices (as outlined in the Research Ethics Policy) have been detected or suspected,
(ii). Request for an ethical compliance report at any point during the course of the research.

UREC wishes you the best in your research.

Prof. P. Odonkor: UREC Chairperson

Ms. P. Claassen: UREC Secretary

## Appendix 2: Research Permission Letter

**CENTRE FOR POSTGRADUATE STUDIES**

University of Namibia, Private Bag 13301, Windhoek, Namibia
340 Mandume Ndemufayo Avenue, Pioneers Park
☎ +264 61 206 3275/4662; Fax +264 61 206 3290; URL.: http//www.unam.edu.na

UNAM
UNIVERSITY OF NAMIBIA

**RESEARCH PERMISSION LETTER**

**Student Name: Ester Nuunyango**

**Student number: 200419421**

**Programme: MSc Geology (by thesis)**

**Approved research title: GROUNDWATER MANAGEMENT OPTIONS IN NAMIBIA SAVANNAH AQUIFERS**

**TO WHOM IT MAY CONCERN**

I hereby confirm that the above mentioned student is registered at the University of Namibia for the programme indicated. The proposed study met all the requirements as stipulated in the University guidelines and has been approved by the relevant committees.

The proposal adheres to ethical principles as per attached Ethical Clearance Certificate. Permission is hereby granted to carry out the research as described in the approved proposal.

Best Regards

**Dr Marius Hedimbi**
**Director: Centre for Postgraduate Studies**
**Tel:** +264 61 2063275
**E-mail:** mhedimbi@unam.na

Centre for Postgraduate Studies
Office of the Director
2017 -03- 15
University of Namibia
UNAM

## Appendix 3: DWAF Permission to use Data

REPUBLIC OF NAMIBIA

**MINISTRY OF AGRICULTURE, WATER AND FORESTRY**


**Telephone: (061) 208 7089**
**Fax: (061) 208 7149**
**Enquiries: B. Swartz**
**Reference: 12/13/3/14**

**Department of Water Affairs & Forestry**
**Private Bag 13193**
**WINDHOEK**

11 October 2017
ester.nuunyango@yahoo.com

Ester Nuunyango
P.O.Box 87206
Eros
Windhoek


Dear Madam,

FOR ATTENTION: Ms. M Mahoto

**<u>Letter of Agreement: Request for data of the Tsumeb-Otavi-Grootfontein Water Control Area</u>**

1. This letter of agreement is between the Directorate of Water Resource Management of the Ministry of Agriculture, Water and Forestry and Ester Nuunyango.

2. The Geohydrology Division herewith acknowledges the request to supply:
   *Data pertaining to Groundwater legislation
   *Groundwater abstraction allocations
   *Abstraction returns
   *Allocation for livestock and irrigation
   *Groundwater levels
   *Past Modelling report/s

Of the area bounded by The Tsumeb-Otavi-Grootfontein Water Control Area and its 8 sub-catchments. **The information will be used for a Master's of Science Research Project.**

3. The Geohydrology Division is mandated to collect groundwater data both quality and quantity respectively

4. The collected data is then stored in the Geohydrology Division's database GROWAS II

5. In order for Requestor to use these data, the following conditions apply:

**For Approved and released data:**

- Rights (including any copyright) in any data, data set or database made available through data servers and archives belong to MAWF.
- Unless otherwise stated, all data, metadata and related materials are considered to satisfy the quality standards relative to the purpose for which the data were collected.
- Although these data and associated metadata have been reviewed for accuracy and completeness and approved for release by the Ministry of Agriculture, Water and Forestry (MAWF), no warranty expressed or implied is made regarding the display or utility of the data on any other system or for general or scientific purposes, nor shall the act of distribution constitute any such warranty.

**For copyrighted materials:**

- Although this information is in the public domain, it also may contain copyrighted materials as noted in the texts. Permission to reproduce copyrighted items must be secured from the copyright owner.

**Use of information for publications:**

- In accordance with scientific standards, appropriate acknowledgment of the Ministry of Agriculture, Water and Forestry (MAWF), should be made in any publications or other disclosures concerning data or information made available by Ministry of Agriculture, Water and Forestry (MAWF).
- If results using preliminary sequence data are to be published, MAWF recommends reference in a manuscript as follows:

"*The Ministry of Agriculture, Water and Forestry (MAWF), personal communication" or "The Ministry of Agriculture, Water and Forestry (MAWF), Project "Name of the project."*

**For acknowledgments, the following is recommended**:

- *"Data for [project name] was obtained from the Ministry of Agriculture, Water and Forestry (MAWF, Directorate, Subdivision, Project name). Also include following text if applicable: Sequencing of [project name] was accomplished with support from [name of funding agency]. "*

**Citations**

- A report, article, paper and presentation that refers to, or draws, information from a data set should cite the data set or unpublished interim-results of ongoing projects.

1. A signed copy of this agreement should be returned to the Ministry of Agriculture, Water and Forestry (Geohydrology Division, for Attention the Deputy Director Geohydrology).

[signature]

**ACKNOWLEDGEMENT BY THE REQUESTOR**

23.10.2017

**DATE:**

pp [signature]

**PERMANENT SECRETARY**

MINISTRY OF AGRICULTURE, WATER AND FORESTRY
PRIVATE BAG 13184
2017 -10- 11
WINDHOEK
REPUBLIC OF NAMIBIA

**DATE:**

## Appendix 4: NAMWATER Permission to use Data

NON-DISCLOSURE AGREEMENT

BETWEEN:
*Mrs Ester Gustavo Ne' Nuunyango .*

On the one hand

and,

**Namibia Water Corporation Ltd**, a company established in terms of the Namibia Water Corporations Act, 12 of 1997 and registered as a public company in terms of the Companies Act, 61 of 1973, with its registered office at 176 Iscor Street, Northern Industrial Area, Windhoek Namibia (Postal Address: Private Bag 13389, Windhoek – Namibia), herein represented by Dr. Vaino P Shivute, in his capacity as the Chief Executive Officer, (Hereinafter referred to as **"NAMWATER")**.

On the other hand

Hereinafter referred to individually or collectively as "**Party**" or "**Parties**", as the case may be.

PREAMBLE

WHEREAS the **Recipient** requested data and/or information for the following reason: ( MSc Programme with the University of Namibia"); and

WHEREAS the release to third parties or to the public of such data and or information could be detrimental to the disclosing Party's interests;

Now, therefore, in consideration of the undertakings as set forth in this Agreement, the Parties agree as follows:

ARTICLE 1 – RESTRICTED INFORMATION

For the purpose of this Agreement, "Restricted Information" shall mean any and all information and data, disclosed directly or indirectly by or on behalf of a Party ("Disclosing Party") to the other Party ("**Recipient**"), in whatever form (particularly orally, electronically or in written form) whether furnished or learned before or after the date of signature of this Agreement, in connection with or related to the Assignment.

The term "Restricted Information" shall include particularly any information or data of scientific, technical, technological, social, commercial, financial, legal nature or of any other nature whatsoever, whether protected by



E G   JPS

intellectual property rights or not, such as but not limited to plans, drawings, specifications, processes, know-how, design, methods, studies, all trade secrets, designs, reports and information related to or regarding the Disclosing Party's financial results, performance metrics, business plans, business methodologies, strategies, software, billing records, pricing information, all notes, analyses or names of clients or partners.

Without prejudice to the generality of the foregoing, Parties will endeavour to restate the restricted nature of the Restricted Information through any means (particularly by marking as "Restricted" or any other proprietary legend) at the time of their disclosure each document or other tangible materials, together with the date of the disclosure and the reference to this Agreement.

Restricted Information disclosed orally or visually, for example during site visits or meetings, shall be identified verbally as "restricted" at the time of disclosure by the Disclosing Party. In addition, the restricted nature of the Restricted Information shall be (i) either confirmed in the meeting minutes co-signed between the Parties at the end of the visit or the meeting, or (ii) reduce in writing in a document summarizing the Restricted Information disclosed delivered to the **Recipient** within fifteen (15) days of the oral or visual disclosure.

Notwithstanding the above, failure to mark such documents or materials or to reduce in writing in case of oral disclosure shall neither affect the restricted nature of the Restricted Information nor Parties' rights and obligations under this Agreement.

## ARTICLE 2 – USE AND NON DISCLOSURE OF RESTRICTED INFORMATION

**Recipient** commits to preserve at all times the restricted nature of the Restricted Information. Particularly, **Recipient** commits to comply with the following:

I. Not disclose in whole or in part, directly or indirectly, Restricted Information to any third party other than (i) its Affiliates or (ii) non-conflicted professional advisors sworn in under professional confidentiality rules without Disclosing Party's prior written consent, subject always to point II below.

   For the purposes of this Agreement,

   - "Affiliates" shall mean:
     - With respect to the **Recipient**, any existing or future legal entity directly or indirectly Controlled by, or under the common Control of the **Recipient**, provided that such entity does not hold activities directly or indirectly competing to those of NamWater of its Affiliates,
     - With respect to NamWater, any existing or future legal entity directly or indirectly Controlled by NamWater, provided that such entity does not hold activities directly or indirectly competing to those of the **Recipient** or of its Affiliates.



VPS EG

- "Control" shall mean:
  - the possession, directly or indirectly, of more than 50% of the equity of the relevant legal entity, or
  - the power to appoint more than 50% of the management bodies of such legal entity.

The **Recipient** shall only disclose Restricted Information to third parties listed above, (other than its Affiliates but including its professional advisors) who specifically agreed in advance and in writing to comply with the provisions of this Agreement or to be bound by similar, but no less stringent, obligations.

**The Recipient** shall in any case remain responsible towards the Disclosing Party for the compliance of such third parties with all obligations deriving from this Agreement.

II. Not to circulate Restricted Information to any of its employees, professional advisors, Affiliates or other authorized third parties as defined here-above other than on a strict "need-to-know" basis and for the purposes of the Assignment only. Pursuant to their antitrust obligations, Parties undertake, where they are competitors, not to communicate any commercially sensitive Restricted Information which they would need to exchange for the sole purpose of the Assignment (such as information relating to Parties' prices, volumes or costs) to the **Recipient** employees (or those of its Affiliates) who could use such Restricted Information to develop or influence the **Recipient**'s (or it's Affiliate's) present or future commercial activities or strategy.

III. Not use or copy any of the Restricted Information for any other purpose than the Assignment. The **Recipient** particularly undertakes not to use Restricted Information for any purposes contrary to Disclosing Party's interest, including, without limitation, to contact, directly or indirectly, customers, suppliers or other present or future commercial partners of the Disclosing Party, or inducing them to terminate their relation with the Disclosing Party.

IV. Keep on all the Restricted Information provided in written form all the confidential or proprietary marking, if any, including, if any, on all authorized copies thereof.

V. Treat Restricted Information in the same manner, and with at least the same degree of care, as it treats its own restricted information, but in any event with no less care than a reasonable standard of care so as to prevent any unauthorized access to, or use or disclosure or copy of, the Restricted Information.

VI. At any time, upon written request from the Disclosing Party:



EG VPS

- Return without delay all or part of the Restricted Information provided by the Disclosing Party; together with a detailed list of the returned Restricted Information;
- Destroy, and certify in writing the destruction of, all the documentation that includes Restricted Information and send to the Disclosing Party the detailed list of the destroyed documentation.

**ARTICLE 3 – EXCEPTIONS**

The obligations of the **Recipient** under Article 2 above shall not apply to any portion of Restricted Information, where the **Recipient** is able to provide written evidence that such specific portion of Restricted Information:

(i) Is now, or subsequently becomes, generally available to the public by publication or otherwise through no act or failure to act on the part of **Recipient** in accordance with the provisions of this Agreement or with any other confidentiality agreement entered with any third party;

(ii) Is lawfully received from a third party who is not, directly or indirectly, bound by restricted obligations towards the Disclosing Party; or

(iii) Was independently developed by the **Recipient** without any use of Restricted Information provided by the Disclosing Party

For avoidance of doubt, the fact that only part or a combination of individual characteristics of Restricted Information is embedded in broader information available to the public or in possession of the **Recipient** is not sufficient so as to consider that such Restricted Information falls under one of the exceptions referred hereinabove.

**The Recipient** will notify Disclosing Party in writing, as much in advance as is reasonably possible, of its need to make any disclosure of Restricted Information as may be (i) required by law, (ii) in response to a valid order by a court or other governmental body. Such notification shall specify the nature and the extent of the requested Restricted Information.

**The Recipient** shall make its best efforts and shall cooperate with Disclosing Party, to the extent feasible, in order to prevent such disclosure or limit the content and the quantity of Restricted Information disclosed; the **Recipient** shall support Disclosing Party's efforts to seek such protective orders or similar protections with respect to such disclosure as Disclosing Party may elect to pursue.

**ARTICLE 4 – WARRANTY – LIABILITY**



VPS EG

4.1 Disclosing Party does not make any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the Restricted Information.

**The Recipient** shall be exclusively responsible and liable for, and shall indemnify and hold harmless Disclosing Party and its suppliers and subcontractors of any tier for any liabilities or damages resulting from any use or misuse of any Restricted Information furnished hereunder.

4.2. The **Recipient** acknowledges that any breach of this Agreement may cause Disclosing Party irreparable harm for which money damages would be both incalculable and an insufficient remedy. Accordingly, the **Recipient** agrees that in the event of any breach or threatened breach of this Agreement, Disclosing Party, in addition to any other remedies at law or in equity it may have, shall be entitled to seek equitable relief, including injunctive relief, specific performance, recovery of its reasonable attorney's fees incurred in connection with such legal action, and other equitable remedies without proof of monetary damages or the inadequacy of other remedies. The **Recipient** shall not be required to post a bond or other security to do so.

## ARTICLE 5 – OWNERSHIP OF RESTRICTED INFORMATION

Subject to third parties rights, all Restricted Information furnished to the **Recipient** by Disclosing Party shall remain the property of Disclosing Party.

The disclosure of Restricted Information under this Agreement shall not be construed as granting the **Recipient** any rights, either express or implied, under any patent or any other rights in the Restricted Information.

Nothing in this Agreement shall be construed as a waiver by Disclosing Party to protect its Restricted Information through patents or any other intellectual property rights.

**The Recipient** commits particularly not to file any intellectual property rights' application(s) in any country whatsoever containing all or part of all the restricted information received under this Agreement.

## ARTICLE 6 – EXPORT CONTROL

The Parties agree to abide by such export control laws and regulations that may be applicable to the disclosure or receipt or re-exportation of Restricted Information and/or of information or equipment developed with the Restricted Information.



EG VPS

## ARTICLE 7 – TERM

This Agreement shall enter into force at the date of signature of this Agreement by the last Party to sign the Agreement and shall remain valid up to the signature of an agreement in relation to the Assignment or for two (2) years, whichever is the longer.

Notwithstanding the foregoing, the confidentiality obligations under this Agreement shall survive for a period of five (5) years following its term.

## ARTICLE 8 – MISCELLANEOUS

8.1 This Agreement shall not be construed to create an obligation by either Party to enter into a contract, subcontract or other business relationship.

8.2 No amendment or assignment of this Agreement shall be valid or of any force and effect unless reduced to writing and signed by a duly authorized representative of the Parties.

8.3 Each provision of this Agreement is severable and if any provision is determined to be invalid, unenforceable or illegal under any existing or future law by a court or an arbitrator having jurisdiction, or by operation of any applicable law, this invalidity, unenforceability or illegality does not impair the operation of or affect those portions of this Agreement that are valid, enforceable and legal.

8.4 This Agreement constitutes the entire agreement and understanding between the Parties with respect to the Restricted Information in connection with the Assignment and all prior discussions, negotiations, and understandings are merged herein and superseded.

8.5 Nothing herein shall be construed to require the Disclosing Party to disclose any specific Restricted Information to the **Recipient**.

## ARTICLE 9 – GOVERNING LAW – SETTLEMENT OF DISPUTE

This Agreement shall be governed, and construed in accordance, with the laws of the Republic of Namibia without application of any conflict of law provision that would apply the law of another jurisdiction.



HS EG

Any dispute arising out of or related to the validity, interpretation, performance, discharge, excuse, waiver, breach, or termination of this Agreement, including any dispute as to its arbitrability, shall first be referred to the respective chief executive officers of the Disclosing Party and the **Recipient** for determination, who shall attempt to resolve such dispute expeditiously and in good faith. Failing resolution of such dispute by no later than thirty (30) days after its first arising, shall be exclusively and finally settled under the Rules of Arbitration of the Namibian Law Society or by one or more arbitrators appointed in accordance with the said Rules. The Seat of Arbitration shall be Windhoek, Namibia. The language of arbitration shall be English.

**(The Recipient)**

By ____________

Name Ester Cristavo ne Mwangayo

Title Hydrogeologist

NAMWATER

By ____________

Name V. P. Shivute

Title CEO

20/03/2018

# Appendix 5: Questionnaires for Government Officials

**Official 1: Questionnaire for government officials _**

1. Are there specific volumes and quantities allocated to specific catchments or basins?

Only the Karst area has allocations made to sub compartments

2. If so, what were the deciding factors for these allocations? Area, livestock, rainfall, recharge, GW modelling?

Allocations are based on Rainfall, the allocations are as follows

**Summary of irrigation permit status in the GTO Karst area updated July 2016**

| Area | No. of Irr. farms | Historical value in m³/a, allocated | Permitted m³/a | Remaining m³/a |
|---|---|---|---|---|
| A | 11 | 500,000 | 1,185,000 | -685,000 |
| | | | | |
| B1 | 10 | 2,400,000 | 2,050,000 | 350,000 |
| | | | | 0 |
| B2 | 64 | 6,200,000 | 7,670,000 | -1,470,000 |
| | | | | 0 |
| C | 7 | 500,000 | 770,000 | -270,000 |
| | | | | 0 |
| D | 7 | 200,000 | 1,600,000 | -1,400,000 |
| | | | | 0 |
| E + F | 7 | 500,000 | 880,000 | -380,000 |
| | | | | 0 |
| G | 22 | 1,500,000 | 2,220,000 | -720,000 |
| | | | | |
| Total | 128 | 11,800,000 | 16,375,000 | -4,575,000 |

3. If there are farmers in these areas, are the farmers notified of the allocations and given guidelines for utilisation?

Yes the farmers are notified, especially those in commercial and water controlled areas where they are required to obtain permits for abstraction in which their allocation per farm is allocated. Attached to the permit is a condition to compulsory install a water meter which should be accessible to Government officials quarterly.

Government has a system of decreasing the allocations of farmers, who underutilise their allocations,

Farmers who over utilise above their allocations, their limits were also decreased. To this threat, the farmers were reluctant to give their abstraction returns.

4. Do the guidelines include abstraction limits if so what are these limits and how are they determined?

Yes, limits exists for every crop or livestock has been assigned, i.e. Lucerne grass – 10 000m3/ha/a

Grapes, and other fruits – 8000m3/ha/a

Cows – 45l/head/day

Humans- 25l/head/day

Horses and donkeys – 20l/head/day

Small livestock (goats and sheep) - 12l/head/day

5. Are the farmers adhering to these management guidelines

   Not always, several citations have been made where farmer's abstraction returns were reporting volumes different from the volumes recorded by the flow meters

6. How do you make sure of this?

   DWAF has quarterly compliance visits,

   DWAF request by law the abstraction returns

   DWAF compares the flow meter readings to that of the abstraction returns

   DWAF sends warnings through the Law Administration Department, of revoking farmer's abstraction permits if they are not adhering to the permit conditions.

7. Have your allocations changed over the years to suit varying climatic differences i.e., has the allocation increased or decreased during drought or abundant rainfall years.

Yes, they have changed, the old allocation have been increased over the years, to see if the increase will have a change in the groundwater levels over time

The old allocations were based on the safe yield, which was most often a conservative amount.

The abstraction is generally between 3-5 years, some farmers have water saving measures, such as rainwater harvesting, building of earth dams in rainy seasons where the abstraction returns may be lower than allocations.

DWAF may increase the allocations during droughts as some farmers need a certain quantity to maintain profit.

The allocations are not cut during periods of high rainfall, as lower abstraction rates may be due to water saving measures, and also there is no decrease in the allocations rainy season so that DWAF can monitor any influence

The allocations may be changed for user's whose utilisation is above permit allocation; therefore they are forced to comply since permit allocation will be cut until compliance is reached.

8. How do you verify that your strategies are working sustainably and that you won't find yourself in high water deficit due to over abstraction?

   First attempt is monitoring,

   For new farmers, no new allocations are given; farmers who extend boundaries will still be operating with volumes as allocated before the extension, until new modelling is done

   Verification is difficult as there are no funds to upgrade the modelling

9. Do the management strategies include buffering systems such as, artificial recharge, de-bushing of encroaching bushes, rainwater harvesting, installing of switch pumps?

   Rainwater harvesting, earth dams and automatic switch DWAF encourages, but the farmers help and do it themselves.

   De-bushing is mostly done by the veterinary or livestock division, and not particularly by DWAF

10. What other government policies are in place regarding groundwater management?

    There is the Namibia Water Resources Act, 2013, which has not been enforced yet, because it needs policies and regulations which at this point are reported that the policies and regulations are in the final stages of finalisation.

11. How are these management strategies executed?

    Compliance visits,

    Workshops and awareness campaigns

**Official 2: Questionnaire for government officials_**

1. Are there specific volumes and quantities allocated to specific catchments or basins?

   Yes, but these are limited to strategic aquifers, such as Karst, Omdel, Kuiseb. There are other aquifers also classified as strategic, but they are not quantifies due to challenges with regard to input data for quantification.

2. If so, what were the deciding factors for these allocations? Area, livestock, rainfall, recharge, GW modelling?

   Allocations are per aquifer. Because the areas as mentioned in (1) have been quantified through modelling, Groundwater users are limited to their allocations based on whether the aquifer has been quantified. The allocations are thereafter prioritised according to the use, such as domestic, livestock, irrigation and industrial

3. If there are farmers in these areas, are the farmers notified of the allocations and given guidelines for utilisation?

   The farmers are informed of the allocation during basin management meetings. Information shared include amount of allowable resources for the specific aquifer, remaining resources that can still be allocated, and users complying with the permit requirements. This generally is limited to aquifers where resources are quantified.

   The farmers are only given basic data on groundwater resources in the case where resources are not fully quantified due to data gaps, such as the Stampriet Artesian Aquifer system.

4. Do the guidelines include abstraction limits if so what are these limits and how are they determined?

Again, this is applicable only where groundwater resources have been quantified, during the modelling process, there are limitations set for the entire aquifer which in-turn is broken down into limitation for domestic users, stock farming, irrigation and industrial users or applicants. The limits are based on the population at the time of modelling. The domestic uses are then predicted for the future based on population growth for that area. This amount is then set aside, noting that domestic supply is the primary use. The available amount is subdivided amongst the other sectors (irrigation, livestock and industry) based on the dominance of the sector in the area. E.g. livestock farming and irrigation are more dominant in the northern parts of the Karst Area, while industrial (mining) received a larger allocation of the available groundwater in the southern parts.

5. Are the farmers adhering to these management guidelines

   The official was unable to answer this question as he no longer works in the division, but says, during the time he served as manager of the Karst area, there was a 70% adherence from irrigation farmers, while the bulk users (mines and municipalities) did not comply at all.

   No details were available to him concerning other management areas. Such as Stampriet, Kuiseb, and Omdel)

6. How do you make sure of this?

   The key is communication and involvement. If there is constant communication between the users and the regulator, ensuring transparency, then the users are more inclined to share. Additionally, if users are involved in management of the resource, having a shared input in the decision making then they will also share returns and adhere to allocated quotas for groundwater use.

7. Have your allocations changed over the years to suit varying climatic differences i.e., has the allocation increased or decreased during drought or abundant rainfall years.

   The baseline allocations haven't change due to data gaps and limited human resources to re-model the aquifers. The individual allocations have been increased based on environmental factors ad changes in uses. E.g. the sub-catchments have been increased with 20% after good rainy seasons, while the allocations to irrigation farmers were increased after the mine closure. I.e. reduced allocations in a sector. These allocations were recently limited due to reduced rainfall (recharge) while no new permits were issued.

8. How do you verify that your strategies are working sustainably and that you won't find yourself in high water deficit due to over abstraction?

   Most of the strategic aquifers are being monitored either through automatic water level loggers or through manual dip meter measurements. Any significant changes in the water levels are logged and an investigation is done. These water levels represent the lowest levels and are therefore used to guide the management of the aquifer.

9. Do the management strategies include buffering systems such as, artificial recharge, de-bushing of encroaching bushes, rainwater harvesting, installing of switch pumps?

   Yes, the central areas (Windhoek Aquifer) and the Omdel Aquifer employs the principal of artificial recharge, while the de-bushing is encouraged by the Ministry and the farmers unions. A separate section was done during the Platveld study 2004-2007 to investigate the influence of de-bushing n groundwater levels, proving that the ministry is taking note of the concern to inform the farmers

10. What other government policies are in place regarding groundwater management?

National Development plan (NDP 5)

Namibia Water corporation Act, 1997 (Act 12 of 1997)

Water Resources Management Act, 2013(Act No.11 of 2013

Water Supply and Sanitation Policy, 2008

11. How are these management strategies executed?

Official 3: Questionnaire for government officials_

1. Are there specific volumes and quantities allocated to specific catchments or basins? You would have to run through this with someone from the Hydrology Division as I am not sure to what extent those are quantified (surface water amounts in the rivers). We have calculated specific volumes in the Otavi-Grootfontein- Tsumeb karst area based on sub-basin amounts for which the recharge figures could be calculated and these were used to determine the sustainable volumes.
2. If so, what were the deciding factors for these allocations? Area, livestock, rainfall, recharge, GW modelling? The deciding factor is the volume of water available and the crop type considered. We did not introduce bonus points for matters such as bush removal etc. – although that would be a good practice to follow.
3. If there are farmers in these areas, are the farmers notified of the allocations and given guidelines for utilisation? In the Karst area we used to make use of a water management committee that was selected by the farmers. All applications were processed and then sent to the committee to support or not support the allocation.
4. Do the guidelines include abstraction limits if so what are these limits and how are they determined? Limits are determined rather loosely at the moment for around 10 000 $m^3$ /ha regardless of crop type. It should be re-visited as the matter needs to be given more thought with regard to the criteria used.
5. Are the farmers adhering to these management guidelines? In the Karst area where it was controlled together with the committee it was well run but left alone some comply and others not – not too sure how well it is monitored by the Institute
6. How do you make sure of this? This would be confirmed by the readings we obtain and from time to time this should be confirmed through a filed inspection.
7. Have your allocations changed over the years to suit varying climatic differences i.e., has the allocation increased or decreased during drought or abundant rainfall years. They have changed normally with the increase in knowledge. In the Karst area we were able to detect the lowest water level experienced and if this is reached again then restrictions should be applied. However we are limited in knowledge to apply this process in other areas. From a surface water perspective this is easier to determine.
8. How do you verify that your strategies are working sustainably and that you won't find yourself in high water deficit due to over abstraction? This is normally

done in conjunction with the monitoring results. A permit for irrigation must be renewed every 45 years and this can then be managed according to the conditions.

9. Do the management strategies include buffering systems such as, artificial recharge, de-bushing of encroaching bushes, rainwater harvesting, installing of switch pumps? De-bushing should be promoted with credits in the allocation amounts – not yet applied. All buffering systems should be explored and applied – in theory at the moment. Irrigation methods should also receive credits towards promoting drip irrigation.
10. What other government policies are in place regarding groundwater management? The Water supply and sanitation policy, the Water Resources Management Act of 2013, the IWRM plan (for which I am not too sure how well this is covered).
11. How are these management strategies executed? These management strategies should be executed through DWAF – that is ailing at the moment due to poor leadership and a lack of vision.

**Official 4: Questionnaire for government officials_**

1. Are there specific volumes and quantities allocated to specific catchments or basins?

Yes, specific catchments and sub-catchments within a basin have volumes allocated to them. The allocation of major aquifers and water control areas are based on numerical modelling and historical allocations.

2. If so, what were the deciding factors for these allocations? Area, livestock, rainfall, recharge, GW modelling?

When evaluating allocations, the initial allocation of the sub-catchment area/aquifer is considered and what can sustainably be abstracted from the source. The use of the water is considered, if for irrigation purposes. The area intended for irrigation is considered as well as the type of crop and the method of irrigation. Within areas where large volumes of bulk water are being abstracted GW modelling of the resource is done in order to obtain a more reliable quota for sustainable abstraction.

3. If there are farmers in these areas, are the farmers notified of the allocations and given guidelines for utilisation?

Communication to farmers and other stakeholders on the allocation and quota of the area is important, and is done through the basin management committee meetings and/or through compliance visits to the farmers. Guidelines for the utilization of the quota are guided by the regulations and the permit conditions for the water users.

4. Do the guidelines include abstraction limits if so what are these limits and how are they determined?

Yes, the guidelines and permit conditions include abstraction limits and quota for water use.

5. Are the farmers adhering to these management guidelines

The non-complying farmers/water users are numerous and many over abstract on the allocated quota. There is however a lot of users that have always been on the correct side of the law, concerning permit conditions and the abstraction of water.

6. How do you make sure of this?

Compliance of permit conditions is monitored through monthly readings submitted quarterly by the users. When returns from the user have not been received this negatively impacts their renewal of the permit and users are aware of this conditions. Renewal of the permits also allow for the assessment of water usage and the adherence. Periodical compliance visits are also conducted to verify the groundwater use and adherence to permit conditions.

7. Have your allocations changed over the years to suit varying climatic differences i.e., has the allocation increased or decreased during drought or abundant rainfall years.

No, there has not been a consideration for the normal abstraction volumes, but we do take cognisance of the fact that during drier/drought periods the volume of abstraction will generally increase and during periods of surface water and rainfall abundance the abstraction volumes decrease.

8. How do you verify that your strategies are working sustainably and that you won't find yourself in high water deficit due to over abstraction?

The plans that are in place with the regulation of abstraction of groundwater pertain to approach of constant evaluation of the abstractable volume of groundwater. This is an ever changing and dynamic process. As not all the groundwater reserves have been ideally quantified and have operational models where various scenarios of abstractions are projected and the predictions incorporated into strategies.

9. Do the management strategies include buffering systems such as, artificial recharge, de-bushing of encroaching bushes, rainwater harvesting, installing of switch pumps?

The strategies for major groundwater systems do involve some of these buffering systems, artificial recharge for Omdel aquifer and Windhoek Managed Aquifer Recharge system. But on a smaller scale there is not a lot being included.

10. What other government policies are in place regarding groundwater management?

The use of groundwater in urban areas are dictated by not only the Water Act but the Act for Urban and Rural development, and through this Act the development and management of the groundwater resources are as well put into strategies and management procedures.

The NamWater Act makes provision for the management of water resources.

11. How are these management strategies executed?

Strategies are enacted through the development of policies and acts, regulations guide water users and the regulator on the use of and modalities of what is set out in the act. And these strategies become operational tasks which are brought in to the strategic and operational plans of the Ministry and the Department respectively.

**Official 5: Questionnaire for government officials_**

1. Are there specific volumes and quantities allocated to specific catchments or basins?

   - Yes, this is the case.

2. If so, what were the deciding factors for these allocations? Area, livestock, rainfall, recharge, GW modelling?

   The deciding factors for the allocation is basically; recharge related, the aquifer extend and parameters that influence groundwater availability in that area.

3. If there are farmers in these areas, are the farmers notified of the allocations and given guidelines for utilisation?

   - Most farmers are aware, especially the ones actively involved in irrigation activities, and posses' groundwater permits. Farmers that are not given guidelines for utilisation, they themselves try to adopt best practices that are economically viable within the region they doing their irrigation/farming activities for high quality yield and return. Nevertheless, the ministry encourages farmers to adopt water saving methods for them not to over abstract and waste water.

4. Do the guidelines include abstraction limits if so what are these limits and how are they determined?

   - A limit of a specific quota is determined by the estimated available groundwater of the sustainable yield of the specific catchment and also the number of permit holders that are not active but have been allocated abstraction quota.

5. Are the farmers adhering to these management guidelines

   - Not necessary, mainly because of the change in the weather patterns.

6. How do you make sure of this?

   - Permits are regularly checked, to see which permit holder is complying with their permit conditions and which ones are not. As result the validity period of permits has been re-adjusted from 3, 4 and 5 years to 2years to closely monitor permits.

7. Have your allocations changed over the years to suit varying climatic differences i.e., has the allocation increased or decreased during drought or abundant rainfall years.

   - No they have not changed. We are still using the groundwater model of 2002 recommended abstraction rate, which is somewhat conservative because, between 2002 and 2016, there has been significant recharge events that led to water levels

# Appendix 6: Questionnaire for farmers

**Farm 1: Questionnaire for farmers regarding groundwater management**

:

1. Where does your water come from?
   (a) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells
   Borehole and streams during rainy season
2. How many boreholes do you have, how many do you use?
   Five boreholes, four boreholes are in use.

3. How much small livestock and cattle do you have? How many people live on the farm?
   296 Cows, 70 goats, 36 sheep,
   1 lemon tree, 5 orange trees
   The farm is 300 ha
4. How has your water usage changed over the years?
   In rainy season, water tastes like manure, but otherwise, boreholes have always been the source..
5. How do you manage your water different from other farmers?
   One of the pos/camp has a windmill. The windmill gets tied up when dam s full to prohibit overflow. During rainy season
   Livestock drinks from the streams, and there less pumping
6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?
   Was part of the Tsumeb boerevireniging, and emerging farmer's assistance- but focussed on agriculture excluding water.
7. Do you use a pump switch to regulate amount abstracted per day
   The windmill gets tie to not over pump at one of the pos
8. How much water do you abstract per day (tank filling up rate)
   Klein pos 80m³ dam is filled weekly, takes two days to fill dam
   Blou pos 80m³ dam is windmill – no data on pumping duration
   Fruit trees get watered Monday and Friday .
9. Do you use a solar pump or windmill, diesel pump, electric pump and why?
   1 windmill at Blou pos
   2 diesel at Klein pos
   1 solar at homestead
10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000litres do you have?
    No rainwater harvesting done, there are 80 m³ dams, 1 x1 m³ tank, 1x1.5 m³ tank, 1x60 m³ dam,
11. Do you carry out any de bushing activity to combat bush encroachment
    No de-bushing
12. What was the deepest and shallowest groundwater level ever recorded on your farm?
    No details
13. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? None

**Farm 2: Questionnaire for farmers regarding groundwater management**

: S-19.14952 E 17.53246

1. Where does your water come from?
2. Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells
   Borehole
3. How many boreholes do you have, how many do you use?
   One borehole
4. How much small livestock and cattle do you have? How many people live on the farm?
   10 Cows, 70 goats, there is a bar, and a 25 m x 25 m.
5. How has your water usage changed over the years?
   Has only been there three years, has always the borehole..
6. How do you manage your water different from other farmers?
   None that the farmer knows of.
7. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?
   No
8. Do you use a pump switch to regulate amount abstracted per day
   No.
9. How much water do you abstract per day (tank filling up rate)
   Fill up 2x 2500 l in two hours. 2.5 $m^3/h$
10. Do you use a solar pump or windmill, diesel pump, electric pump and y?
    Diesel
11. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000litres do you have?
    No rainwater harvesting done, there are three dams,
12. Do you carry out any de bushing activity to combat bush encroachment
    De-bushing happens three times a year
13. What was the deepest and shallowest groundwater level ever recorded on your farm?
    No details
14. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? It's always been diesel

**Farm 3: Questionnaire for farmers regarding groundwater management**

1. Where does your water come from?
   (b) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells
   Boreholes
2. How many boreholes do you have, how many do you use?
   Nine boreholes, 9 boreholes are in use with one alternating.
3. How much small livestock and cattle do you have? How many people live on the farm?
   200Cows, 15 people
4. How has your water usage changed over the years?
   No details,
5. How do you manage your water different from other farmers?
   The windmill gets tied up when dam s full to prohibit overflow. During rainy season
   Livestock drinks from the streams, and there less pumping, the are 9 camps but only 8 have cattle on, and cattle gets rotated between the camps.
   Put enough diesel to fill the dams, ones diesel is up, pumping stops
   There is a level switch at the troughs
6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?
   No details.
7. Do you use a pump switch to regulate amount abstracted per day
   The windmill gets tie to not over pump at one of the pos, there is a level switch at the troughs
8. How much water do you abstract per day (tank filling up rate)
   They pump once a week, no idea of how much they pump or how long, because it varies..
9. Do you use a solar pump or windmill, diesel pump, electric pump and y?
   3 windmill
   4 diesel
   1 solar at homestead
10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000litres do you have?
    No rainwater harvesting done, there are 8 80 m³ dams, 2 x 10 m³
11. Do you carry out any de bushing activity to combat bush encroachment
    No de-bushing
12. What was the deepest and shallowest groundwater level ever recorded on your farm?
    No details
13. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? None

**Farm 4: Questionnaire for farmers regarding groundwater management**

Working borehole: S-19.20608 E17.58206, Old bh: S-19.20596 E17.58161

1

1. Where does your water come from?

   (c) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells

   Boreholes

2. How many boreholes do you have, how many do you use?

   2 boreholes, only use one.

3. How much small livestock and cattle do you have? How many people live on the farm?

   30 goats, 5 people

4. How has your water usage changed over the years?

   Water usage has increased over the years with introduction of garden trees.

5. How do you manage your water different from other farmers?

   No details

6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?

   No details.

7. Do you use a pump switch to regulate amount abstracted per day

   Yes, there are pump switch.

8. How much water do you abstract per day (tank filling up rate)

   There are 2 tanks , but no control as to how much is pumped per hour.

9. Do you use a solar pump or windmill, diesel pump, electric pump and y?

   Electrical and Diesel, they alternate when electricity is off, then diesel is used.

10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000litres do you have?

    Used to harvest, but not anymore. 3x 10 $m^3$

11. Do you carry out any de bushing activity to combat bush encroachment

    No de-bushing, only for cleanliness..

12. What was the deepest and shallowest groundwater level ever recorded on your farm?

    No details,.

13. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? None, but changes from electricity to diesel in case of power failure.

**Farm 5: Questionnaire for farmers regarding groundwater management**

Coordinates to be obtained: Aubrey January

1. Where does your water come from?

   (d) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells

   Boreholes

2. How many boreholes do you have, how many do you use?

   1 borehole, only use one.

3. How much small livestock and cattle do you have? How many people live on the farm?

   96 cows, 29 goats, 9 sheep, 4 people

4. How has your water usage changed over the years?

   11 years, water usage is the same.

5. How do you manage your water different from other farmers?

   No details

6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?

   No details.

7. Do you use a pump switch to regulate amount abstracted per day

   No,

8. How much water do you abstract per day (tank filling up rate)

   There are 2 tanks and two shallow dams, and it takes two hours to fill four tanks/dams

9. Do you use a solar pump or windmill, diesel pump, electric pump and y?

   Diesel, it has always been diesel

10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000 litres do you have?

    No rainwater harvesting done. 2x 2500 l

11. Do you carry out any de bushing activity to combat bush encroachment

    No de-bushing, only for cows to move freely.

12. What was the deepest and shallowest groundwater level ever recorded on your farm?

    No details,.

13. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? None, only changed machines as the previous machine consumed too much fuel.

**Farm 6: Questionnaire for farmers regarding groundwater management**

BH 1: S-19.19367 E 17.54682

1. Where does your water come from?
   (e) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells
   Boreholes for domestic use, Otjikoto Lake water
2. How many boreholes do you have, how many do you use?
   One borehole. The rest of the water for the crop fields comes from the lake
3. How much small livestock and cattle do you have? How many people live on the farm?
   60 livestock need to confirm with DWAF.
4. How has your water usage changed over the years?
   Since 2009 only used borehole water and increased later from the lake.
5. How do you manage your water different from other farmers?
   No abstraction during rainy season, abstraction returns are given to DWAF, abstraction has always been lower than permit allocation, they use drip line for the vegetable garden at home instead of the pivot system.
6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?
   Yes the Karst water committee, but hasn't met them for the past two years
7. Do you use a pump switch to regulate amount abstracted per day
   No switch pump.
8. How much water do you abstract per day (tank filling up rate)
   2500l tank by the house gets filled with water from the borehole so does 5.2 ha. The rest of the 7.5ha gets water from the lake
   An amount of 200 000 m³/a has been allocated
9. Do you use a solar pump or windmill, diesel pump, electric pump and y?
   Electric pump
10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000litres do you have?
    No rainwater harvesting done,
    There was a dam, not in use any longer,
    1x 2500 l tank
11. Do you carry out any de bushing activity to combat bush encroachment
    No de bushing
12. What was the deepest and shallowest groundwater level ever recorded on your farm?
    None recorded by this farmer,
13. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? None

**Farm 7: Questionnaire for farmers regarding groundwater management**

1. Where does your water come from?
   (f) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells
   ANSWER: (b) borehole(s)
2. What is the size of the farm in hectares?
   ANSWER: 5000 hectares
3. How many boreholes do you have, how many do you use?
   ANSWER: 11 boreholes only 8 boreholes are in operation
4. How much small livestock and cattle do you have?
   ANSWER: 136 Goats, Sheep 67 and Cattle 437
5. How many people live on the farm?
   ANSWER: 915 people
6. How has your water usage changed over the years?
   ANSWER: water usage has increased due to an increase in the population of people living on the farm
7. How do you manage your water different from other farmers?
   ANSWER: at this stage there's no water management as there are no water recycling facilities where sewage water can be utilized as night manure or something similar.
8. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?
   ANSWER: No.
9. Do you use a pump switch to regulate amount abstracted per day
   ANSWER: Yes
10. How much water do you abstract per day (how many dams and tanks do you fill up in a day)
    ANSWER: 545 $m^3$ per day (five dams)
11. Do you use a solar pump or windmill, diesel pump, electric pump and y?
    ANSWER: Electric pump
12. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole
    ANSWER: No we just use underground borehole water
13. How many 10,000litres tanks do you have?
    ANSWER: Five
14. Do you carry out any de-bushing activity to combat bush encroachment
    ANSWER: Yes – the method used is the mechanical removal of bushes using offenders to cut the trees/bushes using axes and pangas.
15. What was the deepest and shallowest groundwater level ever recorded on your farm?
    ANSWER: deepest was 11m and shallowest 10 m
    Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these water levels as indicators of adjusting your water use?
    ANSWER: No.

**Farm 8: Questionnaire for farmers regarding groundwater management**

: Tank of the Spring: no Cordinates taken, telephonic interview Cosmos Mata

1. Where does your water come from?

   (g) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells

   Spring

2. How many boreholes do you have, how many do you use?

   No boreholes.

3. How much small livestock and cattle do you have? How many people live on the farm?

   Could not be confirmed

4. How has your water usage changed over the years?

   No details, the spring has never dried up, it has always been full.

5. How do you manage your water different from other farmers?

   Connected a pipe to the spring and harvests the water from the spring into tanks

6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?

   No details.

7. Do you use a pump switch to regulate amount abstracted per day

   No, when tank is full water just runs on the grounds

8. How much water do you abstract per day (tank filling up rate)

   The spring is artesian, it flows all day, but they collect in 12 x 10 $m^3$ tanks

9. Do you use a solar pump or windmill, diesel pump, electric pump and y?

   No pumps needed, spring flows via Pipeline

10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000litres do you have?

    No rainwater harvesting done, only collecting spring water in tanks.

11. Do you carry out any de bushing activity to combat bush encroachment

    No de-bushing, only along the road for cars.

12. What was the deepest and shallowest groundwater level ever recorded on your farm?

    No details, it's a spring.

13. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? None, only when pipes are broken

**Farm 9: Questionnaire for farmers regarding groundwater management**

Okat Bh1: S-20.39649 E 17.39906; WB Spring S-20.39582 E 17.39889

1. Where does your water come from?

   (h) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells

   Spring, borehole and surface water dam for animals

2. How many boreholes do you have, how many do you use?

   One borehole, and is used. Water from the spring and borehole are mixed into the tanks

3. How much small livestock and cattle do you have? How many people live on the farm?

   No domestic livestock, but wildlife.

   Mostly three people at the centre

4. How has your water usage changed over the years?

   There is an alternating between the borehole and spring depending on the rainfall.

5. How do you manage your water different from other farmers?

   None that the farmer knows of.

6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?

   No

7. Do you use a pump switch to regulate amount abstracted per day

   No, only use the borehole when the spring is dry, there used to be a switch that shut the pump off when the tanks were full, but the switch is no longer functioning.

8. How much water do you abstract per day (tank filling up rate)

   Two tanks, 20 $m^3$ with irrigation of vegetable garden - Tomatoes, onions, cabbage

9. Do you use a solar pump or windmill, diesel pump, electric pump and y?

   Electric pump SP 3A- 25PUMP MET WATERBERG

10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000 litres do you have?

    No rainwater harvesting done, spring water is redirected to troughs for the wild animals, 4 x 10 $m^3$ tanks

11. Do you carry out any de bushing activity to combat bush encroachment

    Burning happens once in a while

12. What was the deepest and shallowest groundwater level ever recorded on your farm?

    None Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? There was diesel pump before

**Farm 10 Questionnaire for farmers regarding groundwater management**

OKOMU BH: S-20.42247 E 17.33047 OKOMU BH 2: S-20.42190 E17.33154

Spring: S-20.42181 E17.33032

1. Where does your water come from?
   (i) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells
   Spring, 2 boreholes and surface water dam for animals
   Bh 1 has about 8 pipes
2. How many boreholes do you have, how many do you use?
   Two boreholes for potable water and for livestock. There are two outlets from the spring to troughs in the field for animals.
3. How much small livestock and cattle do you have? How many people live on the farm?
   300 cattle, 150 small calves, 100 goats, 9 horses..
   There are fruit trees on the farm, 11 nectarine trees, 4 orange trees, 16 people
   There are two posts, and 13 camps.
4. How has your water usage changed over the years?
   No change in water usage, always had been two boreholes and the spring.
5. How do you manage your water different from other farmers?
   Instead of using the big reservoirs, they plan to upgrade to 10 $m^3$ tanks or alternatively close the reservoirs
   Water from bh and spring gets mixed
6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?
   None
7. Do you use a pump switch to regulate amount abstracted per day
   No switch pump. Pumping is done from 7a.m to 7p.m. but water is constantly running to the other outlets.
8. How much water do you abstract per day (tank filling up rate)
   2 x 10 $m^3$ when empty it takes 3.5 hours to fill. The tanks are empty after two days.
9. Do you use a solar pump or windmill, diesel pump, electric pump and y?
   Diesel on both pumps
10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000litres do you have?
    Yes, rainwater harvesting is done from the roof into a 10$m^3$ tank, namwater has a dam on the farm, but not in use.
    2 x 10 $m^3$ tanks
11. Do you carry out any de bushing activity to combat bush encroachment
    Yes de bushing is done
12. What was the deepest and shallowest groundwater level ever recorded on your farm?
    None recorded by this farmer,
13. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? Borehole was first installed with a windmill, now it's diesel

**Farm 11: Questionnaire for farmers regarding groundwater management**

: Tank of the Spring:S-20.50729 E17.24048

1. Where does your water come from?

   (j) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells

   Spring

2. How many boreholes do you have, how many do you use?

   No boreholes.

3. How much small livestock and cattle do you have? How many people live on the farm?

   Massen to confirm

4. How has your water usage changed over the years?

   No details, the spring has never dried up, it has always been full.

5. How do you manage your water different from other farmers?

   Connected a pipe to the spring and harvests the water from the spring into a huge tank from German time.

6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?

   No details.

7. Do you use a pump switch to regulate amount abstracted per day

   No, when tank is full water just runs on the grounds

8. How much water do you abstract per day (tank filling up rate)

   The spring is artesian, it flows all day.

9. Do you use a solar pump or windmill, diesel pump, electric pump and y?

   No pumps needed, spring flows via Pipeline

10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000litres do you have?

    No rainwater harvesting done, only collecting spring water in tank.

11. Do you carry out any de bushing activity to combat bush encroachment

    No de-bushing

12. What was the deepest and shallowest groundwater level ever recorded on your farm?

    No details, it's a spring.

13. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? None, only when pipes are broken

**Farm 12: Questionnaire for farmers regarding groundwater management**

Onjo Spring: S-20.41060 E 17.35369; Onjo BH1 S-20.41192 E 17. 35406;

Onjo BH2 -20.41232 E17.35454

1. Where does your water come from?

   (k) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells

   Boreholes for domestic use, canal water

2. How many boreholes do you have, how many do you use?

   Three boreholes and only two are used. One is broken. The rest of the water for the animals comes from the canal

3. How much small livestock and cattle do you have? How many people live on the farm?

   No domestic livestock, but wildlife.

   Sixty people at the farm

4. How has your water usage changed over the years?

   Borehole yield is dropping, it used to take 4hours to fill the dam now it takes 12 hours.

   There is a plan in place to rehabilitate the boreholes and install water meter.

5. How do you manage your water different from other farmers?

   One of the tanks for the animals is covered to reduce evaporation, it gets treated with microfil.

6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?

   No

7. Do you use a pump switch to regulate amount abstracted per day

   At the canal outlets are switch pumps, however the boreholes on the farm run 24hours.

   Boreholes believed to recover quickly.

8. How much water do you abstract per day (tank filling up rate)

   It takes about one week to fill the 60-80 $m^3$ dams, there are no meters to measure the abstraction

9. Do you use a solar pump or windmill, diesel pump, electric pump and y?

   Electric motor pump

10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole d) how many 10000litres do you have?

    No rainwater harvesting done,

    Twelve 10$m^3$ + three 60-80 $m^3$ reservoirs

11. Do you carry out any de bushing activity to combat bush encroachment

    Killing the sikkelbos with herbicides and removing them

12. What was the deepest and shallowest groundwater level ever recorded on your farm?

    None

13. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these levels as indicators of adjusting your management strategy? There was diesel pump before

**Farm 13: Questionnaire for farmers regarding groundwater management**

1. Where does your water come from?
   (I) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells
   B) boreholes
2. How many boreholes do you have, how many do you use?
   We have – 12
   We use - 6
3. How much small livestock and cattle do you have? How many people live on the farm?
   Small livestock - 2234
   Cattle - 336
   People - 12
4. How has your water usage changed over the years?
   Stayed the same, water usage depends on the number of cattle on the farm
5. How do you manage your water different from other farmers?
   Maintain the dams and water troughs to reduce leakages and try to minimise waste as far as possible. Not sure how other farmer manage there water
6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?
   Yes we are part of a farmers union and study group.
   We do not share ideas in the farmers union but may share ideas on water if it is a needed.
7. Do you use a pump switch to regulate amount abstracted per day
   No, it's not available as far as we are aware but we would love to have
8. How much water do you abstract per day (how many dams and tanks do you fill up in a day)
   Cattle per head drink 30-40 liters per day and we have cattle
   Sheep drink 2-3 liters per day and we have sheep
   Human useage per day is 2000 liters per day
9. Do you use a solar pump or windmill, diesel pump, electric pump and y?
   Solar pumps

10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole
    No
11. How many 10,000litres tanks do you have?
    None
12. Do you carry out any de-bushing activity to combat bush encroachment
    No
13. What was the deepest and shallowest groundwater level ever recorded on your farm?
    Deepest – 110 meters
    Shallowest – 20 meters
14. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these water levels as indicators of adjusting your water use?
    No

**Farm 14: Questionnaire for farmers regarding groundwater management**

1. Where does your water come from?

   (m) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells

   (n) boreholes

2. How many boreholes do you have, how many do you use?

   18, all

3. How much small livestock and cattle do you have? How many people live on the farm?

   1000 small stock, 600 cattle, 2000 springbok, 400 gemsbok, 20 people

4. How has your water usage changed over the years?

   Not at all

5. How do you manage your water different from other farmers?

   Only have wind pumps/solar pumps on when there's livestock there, otherwise just keep reservoirs full for game. Never use too much water at the houses, no waste of water in gardens

6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?

   Yes, part of farmers' association; never any talks about water

7. Do you use a pump switch to regulate amount abstracted per day

   No

8. How much water do you abstract per day (how many dams and tanks do you fill up in a day)?

   We keep water tanks full, so only little needed per day to top up

9. Do you use a solar pump or windmill, diesel pump, electric pump and y?

   Mostly windmills, couple solar pumps

10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole

    Yes we collect rainwater in tanks (run off from tin roofs) – would like to do more in future

11. How many 10,000litres tanks do you have?

    12

12. Do you carry out any de-bushing activity to combat bush encroachment

    Don't have a problem with that so far

13. What was the deepest and shallowest groundwater level ever recorded on your farm?

    Shallowest – 3m ; deepest – 15m

14. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these water levels as indicators of adjusting your water use?

    We use water levels as indicators, especially it tells us about how long it takes for rain water from a good rainy season to reach the underground water level.

    As we do not use / overuse water extensively in any case, we do not drastically change infrastructure just because water levels sink. But we always use water wisely.

**Farm 15: Questionnaire for farmers regarding groundwater management**

1. Where does your water come from?

   a)Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells boreholes

2. How many boreholes do you have, how many do you use?12 boreholes and I use 11
3. How much small livestock and cattle do you have? How many people live on the farm? Depending on rain we stock between 400 and 600 cattle and 300-400 game. Between 12 and 15 people stay on farm
4. How has your water usage changed over the years? unchanged
5. How do you manage your water different from other farmers? Probably similar to other farmers.
6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings? part of Dordabis Farmers Union
7. Do you use a pump switch to regulate amount abstracted per day. Only pump as much as we require for human and animal consumption
8. How much water do you abstract per day (how many dams and tanks do you fill up in a day)?about 20000 l per day
9. Do you use a solar pump or windmill, diesel pump, electric pump and y? Solar, wind and electric
10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole no, no rivers
11. How many 10,000litres tanks do you have?6
12. Do you carry out any de-bushing activity to combat bush encroachment yes
13. What was the deepest and shallowest groundwater level ever recorded on your farm?35 to 45m
14. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these water levels as indicators of adjusting your water use? The water level stays very constant. In very dry years the water table goes down by 2-3 m and the returns on good rains

**Farm 16: Questionnaire for farmers regarding groundwater management**

1. Where does your water come from?
   (o) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells
   b) and d)
2. How many boreholes do you have, how many do you use?
   On 9500 hectares: 11 boreholes, but only 9 in use. 2 hand dug wells, but only 1 in use
3. How much small livestock and cattle do you have? How many people live on the farm?
   3000 small livestock, 1000 cattle. 5 – 10 people live on the farm (during holidays up to 25)
4. How has your water usage changed over the years?
   Through sound rangeland management we produced more grazing over the years. With this stocking rates increased and so water usage for watering livestock also increased.
   Our general approach to water usage did not change as we always were conscious about saving and not wasting water and made sure we do not overuse boreholes.
   We see no change over the years in groundwater tables. Drought years let the water table sink slightly which always refilled during better rainy years.
5. How do you manage your water different from other farmers?
   I am not completely sure about other farmer's water management. Our aim is not to waste water (no leaking pipes, overflowing reservoirs, etc.), not to irrigate on large scale (other than our home garden for own fruit and vegetable consumption) in order for not to deplete the groundwater resource. We want to live sustainably and only use the available water for the livestock and people who live on the farm.
6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?
   I am member of Blumfelde Farmers Association which is affiliated to the Namibia Agricultural Union. Seldomly water issues are discussed at the meetings. If yes, mainly concerning the questionable borehole drilling for irrigation purposes in our area.
7. Do you use a pump switch to regulate amount abstracted per day
   No. We pump what we need for our animals which is far less than groundwater/boreholes could deliver. It is our aim to keeping it like that. At two boreholes I have installed flow meters to see how much water is consumed by livestock on a daily base.
8. How much water do you abstract per day (how many dams and tanks do you fill up in a day)?
   As much as livestock needs (we have indigenous cattle and sheep breeds, Nguni cattle and Damara sheep which are small framed and whose needs are less. On average I calculate 35liters / head of cattle / day = 35 000 litres for the cattle, plus average of 5 litres / head of sheep / day = 15 000 litres for the sheep.) plus supply for houses and gardens which will be between 1000 and 10000 litres daily depending if trees must be watered at that specific day. NB: these are estimations.
9. Do you use a solar pump or windmill, diesel pump, electric pump and why?
   Solar and windmill as it is renewable energies on the one hand and are adapted to the water quantities needed for our livestock on the other hand.
10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole
    No rain water harvesting is done. I believe in natural refill of groundwater through rains without harvesting and redirecting.
    Our groundwater table is very shallow. Unharvested water will very quickly end up in the groundwater resources. We are in an area with sub-artesian water. There is even a pan next to the house with a "spring". Seems to be the lowest point in the area. After a good rainy season water rises from underground and fills the pan.
    In addition, our rangeland management aims to foresee covered soils to keep the moisture in the ground. The way we work the soil with hoofs of our animals also helps to let the rainfall enter the ground without flow off. So yes, in this sense we do rainwater harvesting by applying sound

rangeland management and with this leading the rainwater directly into the groundwater resources.

11. How many 10,000litres tanks do you have?
    None. We have one 5000litre tank at the house. 10 000 litre tanks would be too small to supply the amount of water we need at a time to water the large herds we manage (we run all the animals on the farm in three herds. With this many water points and camps lie "empty" for many weeks whereas three water points on the farm at any given time, must supply water for all the animals. The herds are rotate over the whole property according to a grazing plan which includes water supply management.)
    The water points for livestock have open reservoirs, mostly corrugated iron: 2 x 100,000 litres, 3 x 60-80,000 litres, 12 x 30,000 litres, spread over the whole farm area.
12. Do you carry out any de-bushing activity to combat bush encroachment?
    We apply sound rangeland management practices (following principles of Holistic Management since decades) and thus experience no bush encroachment on the farm for the last 6 decades since the farm is owned by our family.
13. What was the deepest and shallowest groundwater level ever recorded on your farm?
    Am not completely sure as I am on the farm only for 15 years whereas my deceased husband grew up on the farm and his father was on the farm since 1960. Water levels are normally between 3 and 25 m, mostly lying around 5 to 10 metres, depending on the borehole. I assume the deepest could have been 30 m. shallowest groundwater level was above ground when the pan next to the house and the hand dug well were totally flooded!
14. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these water levels as indicators of adjusting your water use? `
    For us and our livestock we use much less water than is available. We monitor the groundwater levels but so far had no reason to react.

**Farm 17: Questionnaire for farmers regarding groundwater management**

1. Where does your water come from?
   (p) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells
   b) boreholes
2. How many boreholes do you have, how many do you use?
   13
3. How much small livestock and cattle do you have? How many people live on the farm?
   4000 small stock, 500 cattle, 20 people
4. How has your water usage changed over the years?
   Did not change significantly
5. How do you manage your water different from other farmers?
   I do not think, we manage it different from other farmers
6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?
   Yes, we are part of a farmer's union and discuss water issues regularly
7. Do you use a pump switch to regulate amount abstracted per day
   Only at the farm house, the cattle posts have windmills
8. How much water do you abstract per day (how many dams and tanks do you fill up in a day)?
   Appr. 45 l per large stock unit, 5 l per small stock unit, 10.000l for people and gardens on 7600 ha farm
9. Do you use a solar pump or windmill, diesel pump, electric pump and y?
   Solar pumps, electric pumps and windmills
10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole
    no
11. How many 10,000litres tanks do you have?
    3 at the main house, and 20 dams on the farm
12. Do you carry out any de-bushing activity to combat bush encroachment
    No, as bush encroachment is not a problem in our area
13. What was the deepest and shallowest groundwater level ever recorded on your farm?
    Deepest: 12 m shallowest: 4,2 m
14. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these water levels as indicators of adjusting your water use?
15. No, as it would not have any effect on groundwater levels

Explanation: we have an average annual rainfall of 230mm per year (measured since 1964)
The scientifically researched amount of rainwater reaching the groundwater is appr. 1% in our area (flat area with no rivers or mountains)
On a 7.600 ha farm, the amount of water reaching the groundwater would therefore be: 7.600ha x 10.000m² x 2.3 l/m² = 174.800.000 l.
This amount divided by 365 days, results in an amount of appr. 478.000 l/day which would be available for the farm without overexploitation.
Our farm uses an appr. amount of 55.000 l/day

**Farm 18: Questionnaire for farmers regarding groundwater management**

1. Where does your water come from?
   (q) Spring (b) borehole(s) (c) sand dam (d) surface water (dam, river) (d) hand dug wells
   B: Borehole
2. How many boreholes do you have, how many do you use?
   13 boreholes, 11 used
3. How much small livestock and cattle do you have? How many people live on the farm?
   Size of 6863 ha : Ca 850 small stock, ca 480 heads of cattle, 16 people permanent
4. How has your water usage changed over the years?
   Usage has slightly increased due to a horticulture operation
5. How do you manage your water different from other farmers?
   No significant differences, irrigation in the vegetable garden is done by drip-lines
6. Are you part of a farmer's union and do you share ideas on how to deal with water at these meetings?
   NAU member, water use / management is not a critical point of discussion in our area.
7. Do you use a pump switch to regulate amount abstracted per day
   No
8. How much water do you abstract per day (how many dams and tanks do you fill up in a day)?
   Ca 20 cubic meters for approximately 16 reservoirs
9. Do you use a solar pump or windmill, diesel pump, electric pump and y?
   1 solar pump, rest wind pumps
10. Do you harvest water from the rain, how (a) Dam upstream (b) collect in tanks (c) redirect into a borehole
    1 rain water tank at homestead
11. How many 10,000litres tanks do you have?
    n.a., Water is stored in galvanized steel reservoirs, total capacity about 320 cubic meters
12. Do you carry out any de-bushing activity to combat bush encroachment
    Only along public road for better visibility, to prevent road accidents with game and domestic animals
13. What was the deepest and shallowest groundwater level ever recorded on your farm?
    Groundwater levels fluctuate between a minimum of 2 metres on west side of the farm and up to 20 metres on the east side of the farm. Individual boreholes fluctuate by no more than 5 metres from minimum to maximum.
14. Do you change anything in your infrastructure or abstraction when reaching any of the levels in the above two questions, i.e. do you use these water levels as indicators of adjusting your water use?
    No changes are done except for additional marketing of animals during droughts. The water levels are considered to be highly stable by Namibian standards.

# Appendix 7: Borehole Completion Reports

S.W.A. 182

ADMINISTRASIE - S.W.A. - ADMINISTRATION
AFDELING WATERWESE / WATER AFFAIRS BRANCH

## BOORVERSLAG / BORING REPORT

(moet in triplikaat ingedien word / to be rendered in triplicate)

Plaas / Plek Farm / Place: TSUMEB DORPSGROND
Nr. No.: —
Distrik District: TSUMEB

Boorgat Nr. Borehole No.: 9736
Beskrywing van Boorplek Description of Site: 314 m * van B/G 9734

Boorgat aangewys deur Borehole selected by: G.23614
Boordery gestaak deur Boring stopped by: XXXXXXXX Mnr. Blom

Datum begin Date commenced:
Datum voltooi Date completed: 24/10/69

B. Moolman.
Kontrakteur / Contractor

| Diepte van-af Opperv. Depth from Surface | Section Seksie | Formasie Strata |
|---|---|---|
| 10 | 10 | Surface limestone |
| 256 | 236 | Grey dolomite. |
| | | [illegible] |
| | | [illegible] |
| | | 5/11/69 |
| | | Forada |

DEURSNY EN DIEPTE VAN BOORGAT
DIAMETER AND DEPTH OF BOREHOLE

10 duim vanaf oppervlakte tot / inches from surface to: 256 voet / feet

duim vanaf / inches from ___ voet tot / feet to ___ voet / feet

Totale diepte vanaf oppervlakte / Total depth from surface: 256 voet / feet ___ duim / inches

POMPPROEFNEMING
PUMPING TEST

Met *Pomp, *Bailer of *Suier / By *Pump, *Bailer or *Snatam:

Binnekste deursny van pompsilinder / Inside diameter of pump cylinder: Amarillo turbine pomp

Lengte van slag / Length of stroke:

Aantal slae per minuut / Number of strokes per minute:

Diepte waarin pompsilinder geplaas was / Depth to which pump cylinder was inserted: 230'

Begin van proefneming: Datum / Commencement of test: Date: 23/10/69 uur / hour 2 pm

Voltooiing van proefneming: Datum / Completion of test: Date: uur / hour 2 pm

Totale duur van proefneming / Total time testing: 12 ure / hours

WATER

Diepte vanaf oppervlakte waar water getref was / Depth from surface at which water was struck: 140 - 150 voet / feet

Diepte vanaf oppervlakte waartoe water styg / Depth from surface to which water rises: 140 voet / feet

Beraamde lewerbaarheid per ... uur / Estimated yield per ... hours: 2400 gelings / gallons

Is voorraad permanent of nie? / Is yield considered permanent?: Ja

Kwaliteit van water / Quality of water: Vars

Doel waarvoor die water gebruik sal word / Purpose for which water will be used: dorp

VOERING NAGELAAT IN BOORGAT NA VOLTOOIING
CASING LEFT IN BOREHOLE ON COMPLETION

Gewone / Plain — Lengte / Length: 9' — Deursny / Diameter: 10"

Deurgeboorde / Perforated — Lengte / Length: — Deursny / Diameter:

Ek sertifiseer dat bovermelde besonderhede korrek is en dat die boorgat ooreenkomstig die boorkontrak voltooi is.
I certify that the above particulars are correct and that the borehole has been completed in accordance with the boring contract.

J. G. Schoeman.
BOORINSPEKTEUR / BORING INSPECTOR

Datum / Date: 24/10/69

* Skrap ontoepaslike woorde / del... words inapplicable

12/4/2/21

BOORGATVOLTOOIINGSVERSLAG (Privaat Kontrakteur)

BOREHOLE COMPLETION REPORT (Private Contractor)

Dept Watersake

Geelhoutboom

30847

21-3-89

23-2-89

0 – 48 Kalkrust

48 – 72 Doleriet

72

72

Bleestaaks

25

72 K4B

Goed

Drink

3 m PL
6 m PF
6 m PL
6 m PF
3 m PL
3 m PF
4 m PL
6 m PF
6 m PL
6 m PF
3 m PL
6 m PF
9 m PL
3 m PF
3 m PL

8" x 72 m staining

TOTALE KOSTE
TOTAL COST

23-2-89

12/5/1/2.

# BOREHOLE COMPLETION REPORT

**A SEPARATE REPORT TO BE COMPLETED FOR EACH BOREHOLE**

| | | |
|---|---|---|
| **APPLICANT:** | | **BOREHOLE NUMBER: WW** 35852 |
| **FARM:** Kobleny **NUMBER:** | | **TOPO & WELL NUMBER:** 2018 AA / 135 |
| **DISTRICT:** Hereroland-West. | | **LATITUDE:** 20 , 1108 ° |
| **DATE COMMENCED:** 26-3-96 | | **LONGITUDE:** 19 , 2083 ° |
| **DATE COMPLETED:** 15-4-96. | | **COLLAR HEIGHT:** 1240 m |
| **GEOLOGY** | | **TOTAL DEPTH FROM SURFACE:** 113 m |
| **from - to in (m)** | **DESCRIPTION** | **DIAMETER OF BOREHOLE** |
| 0-30m | Calcrete. | 206 mm from 0 to 113m |
| 30-113m | Red Sandstone. | ……mm from…… to…… |
| | | ……mm from…… to…… |
| | | FIRST WATER STRIKE 52 m |
| | | SECOND WATER STRIKE 93to105 m |
| | | THIRD WATER STRIKE ……m |
| | | WATER LEVEL 38,50 m |
| | | YIELD m³/h ± 90m3 h. |
| | | APPARENT QUALITY OF WATER: Fresh. |
| | | TDS WHEN DRILLED: |
| | | **INITIAL CAPACITY TEST** |
| | | **AIRLIFT YIELD** * ☐ |
| | | **PUMP YIELD** * ☐ |
| | | **YIELD IN m³/h:** |
| | | **DATE:** |
| | | **DURATION** |

**DRILLING COSTS**

| ITEM | N$ |
|---|---|
| m drilled 113 N$ per m 192-02 | 21697-8 |
| testing of borehole: | |
| **CASING** | |
| plain length m N$ per m 113m X 206mm | 9605-0 |
| perforated length m N$ per m | |
| **TOTAL COST** N$ | 31302-8 |

**State whether borehole is:**

☒ successful * ☒ Casing left in borehole *

☐ unsuccessful * ☐ Casing recovered *

**DECLARATION BY DRILLER AND DRILLING INSPECTOR**

| I declare that the information supplied above is true and correct | I declare that the information supplied above is true and correct |
|---|---|
| Signature of driller: [signature] | Signature of drilling inspector [signature] |
| Rank Driller | Rank Chief Drill Foreman |
| Date: 15-4-96. | Date: 29-5-96 |
| Place: Kobleny. | Place: Okahandja. |

* mark applicable block

**Please indicate at reverse side the position of the borehole and draw a casing plan.**

**GEOHYDROLOGIST:** [signature] 10-6-96

**SIGNATURE** **DATE**

12/5/1/2.

# BOREHOLE COMPLETION REPORT

**A SEPARATE REPORT TO BE COMPLETED FOR EACH BOREHOLE**

| | |
|---|---|
| APPLICANT: | BOREHOLE NUMBER: WW 35853. |
| FARM: Bobleny. NUMBER: | TOPO & WELL NUMBER: 2018 AA /37 |
| DISTRICT: Hereroland-West. | LATITUDE: 20 , 1072 ° |
| DATE COMMENCED: 15-4-96 | LONGITUDE: 18 , 1672 ° |
| DATE COMPLETED: 20-4-96. | COLLAR HEIGHT: 1245 m |

**GEOLOGY**

| from - to in (m) | DESCRIPTION |
|---|---|
| 0-42m | balcrete. |
| 42-96m | Red Sandstone. |

TOTAL DEPTH FROM SURFACE: 96. m

DIAMETER OF BOREHOLE
206 mm from 0 to 96m.
.......mm from....... to.......
.......mm from....... to.......

FIRST WATER STRIKE 53+63 m
SECOND WATER STRIKE 76 m
THIRD WATER STRIKE 86 m
WATER LEVEL 35,50 m
YIELD m³/h ±90 m3h.
APPARENT QUALITY OF WATER: Fresh.
TDS WHEN DRILLED:.......

**INITIAL CAPACITY TEST**

AIRLIFT YIELD * ☐
PUMP YIELD * ☐
YIELD IN m³/h:.......
DATE:.......
DURATION.......

**DRILLING COSTS**

| ITEM | N$ |
|---|---|
| m drilled 96 N$ per m 216-07. | 20742-6 |
| testing of borehole: | |
| CASING | |
| plain length m<br>N$ per m 96mX206mm | 8160-00 |
| perforated length m<br>N$ per m | |
| TOTAL COST N$ | 28902-6 |

State whether borehole is:

☒ successful * ☒ Casing left in borehole *
☐ unsuccessful * ☐ Casing recovered *

**DECLARATION BY DRILLER AND DRILLING INSPECTOR**

| I declare that the information supplied above is true and correct | I declare that the information supplied above is true and correct |
|---|---|
| Signature of driller: [signature] | Signature of drilling inspector [signature] |
| Rank Driller | Rank Chief Drill Foreman |
| Date: 20-4-96. | Date: 29-5-96. |
| Place: bobleny. | Place: Okahandja. |

* mark applicable block

Please indicate at reverse side the position of the borehole and draw a casing plan.

GEOHYDROLOGIST: [signature] 10-6-96

SIGNATURE DATE

D/Kaart 21814 WW 20/12

DW 57

BOORGATVOLTOOIINGSVERSLAG (Privaat Kontrakteur)

BOREHOLE COMPLETION REPORT (Private Contractor)

A. Algemeen/General

1. Volle naam van applikant / Full name of applicant: WATERWESE
2. Plaas / Farm: OLIFANTSWATER
3. No.: 102
4. Distrik / District: MARIENTAL
5. Boorterrein aangewys deur / Boring site selected by: GO
6. Datum van begin van werk / Date of commencement of work: 28-7-76
7. Boorgat No. / Borehole No.: 21814
10. Datum van voltooiing van werk / Date of completion of work: 2-8-76
11. Boorwerk gestaak na goeddunke van / Boring stopped at discretion of: Applikant / Applicant: X
12. Gee 'n kort beskrywing van ligging van boorgat / Give a short description of site of borehole: Km 0,55 van woonhuis en 100 m suid van blomtuin/agter pad of sinkers gewer

B. Geologie/Geology

| Diepte van oppervlakte af / Depth from surface | Seksie / Section | Skaal / Scale |
|---|---|---|
| 29,60 | Kalk-Kalkreet | 59,60 |
| 3,00 | Riviersandsteen | 25,40 |

C. Diameter en diepte van boorgat / Diameter and depth of borehole

1. NX ... 55
3. Totale diepte van oppervlakte af / Total depth from surface: 55

D. Water

2. 14,30
3. NVT
4. Goed
5. Watervoorsiening / Water supply purposes

E. Pomptoets / Pumping test: NVT

F. Boorkoste / Drilling cost

TOTALE KOSTE / TOTAL COST: 185 | 03

G. Pyplening / Casing

H. Verklaring deur boorkontrakteur en boorinspekteur / Declaration by boring contractor and boring inspector

Handtekening van boorkontrakteur / Signature of boring contractor: J. H. Kotze
Datum / Date: 12-8-76
Adres / Address: Bloemhoek

Handtekening van boorinspekteur / Signature of boring inspector: [signature]
Datum / Date: 13-8-76
Inspeksieaan / Inspectorate: Windhoek

Streeksraamwerk Lias area [signature]

R/GAT 21784 WW 20/12

P.-S.12840—1973-74—25 000 (M-S)

DW 57

# BOORGATVOLTOOIINGSVERSLAG (Privaat Kontrakteur)
# BOREHOLE COMPLETION REPORT (Private Contractor)

A. Algemeen/General

1. Volle naam van applikant / Full name of applicant: WATERWOES
2. Plaas / Farm: OLIFANTSHUITSIK
3. No.: 106
4. Distrik / District: MARIENTHAL
5. Boorgat No. / Borehole No.: 21784
9. Datum van begin van werk / Date of commencement of work: 16-6-76
10. Datum van voltooiing van werk / Date of completion of work: 27-7-76

B. Geologiese/Geology

| Diepte van oppervlakte af / Depth from surface | Seksie / Section | Skaal |
| --- | --- | --- |
| 29,60 | KALKSI KALKREIT | 29,60 |
| 55,85 | ASOOB SANDSTEEN | 26,25 |
| [illegible] | SKALIE | 41,10 |
| [illegible] | [illegible] | 34,50 |
| [illegible] | SKALIE | 2,05 |
| [illegible] | SANDSTEEN SKALIE | 1,00 |
| [illegible] | SANDSTEEN | 8,10 |
| [illegible] | [illegible] SKALIE | 10,68 |
| [illegible] | [illegible] | 8,25 |
| 168,55 | SANDSTEEN SKALIE | 6,05 |

C. Diepte: NA / DX — 61 — 168,55

Totale diepte / Total depth from surface: 168,55

D. Water: 54,12 — NUT — GEEN — Purpose for which water will be used: WATERGEHALTE INGEWING

E. Pompe/Pumping: NVT

TOTALE KOSTE / TOTAL COST: 1274 57

J.A. KOTZE
15-8-76
BOORMEESTER

12-8-76