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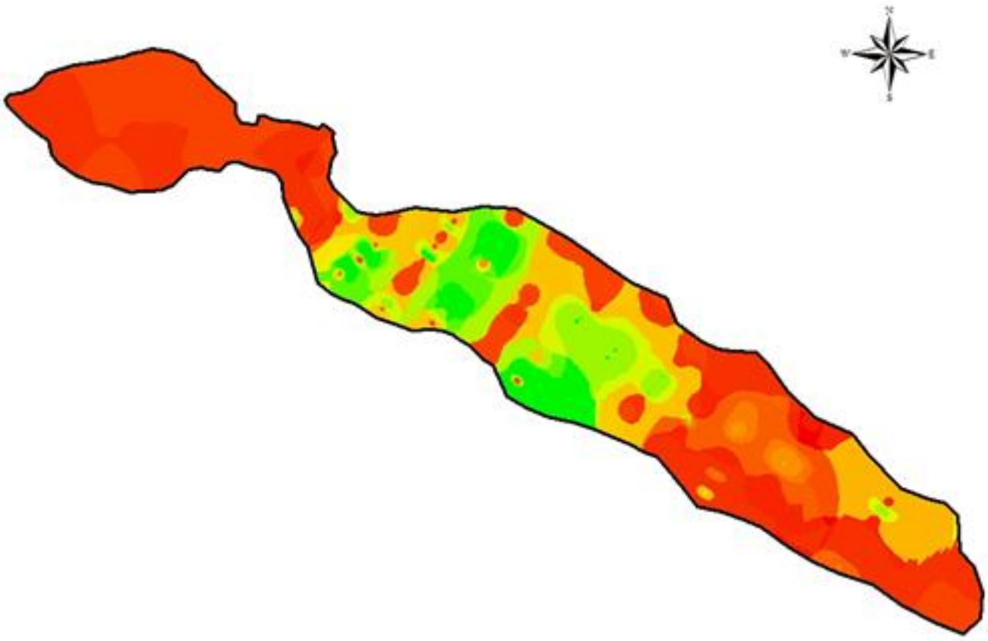

Vulnerability and Risk Assessment of Artificial Recharge of the Oanob Aquifer, Namibia

Master of Science Thesis in the Master's Programme Geo and Water Engineering

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Cover:
Map of the vulnerability of the Oanob Aquifer.

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ABSTRACT

Water plays a vital role in human life. It is therefore necessary to take care of the resources available. However, the water is not equally distributed over the world causing water scarcity in some countries. One of these countries is Namibia, the driest country in sub-Saharan Africa, where reasonable amounts of drinking water are sometimes located far away from major human settlements and where the cost of transporting it is high. The increasing water demand in Windhoek, the capital city of Namibia, has brought forward the plans of using the Oanob Aquifer as a possible water source. The aquifer, located approximately 90 kilometres south of Windhoek, lies within the alluvials of the Oanob River just south of the town of Rehoboth. Both towns consider using the water from the aquifer as an additional water supply. The aquifer is currently 24 % full and for the aquifer to be viable as a water supply, artificial infiltration is necessary. The potential of artificially recharging the aquifer could then provide Rehoboth and possibly Windhoek with spare water.

The aim of the project was to do a vulnerability and risk assessment of the Oanob Aquifer to investigate the possibility of artificial infiltration and to recommend a sustainable solution for additional water supply to Windhoek to continue supplying Rehoboth. A Geographical Information System software called ArcGIS 9 was used to perform the vulnerability assessment. The assessment shows that most of the aquifer is highly vulnerable to contamination due to its alluvium content and protective measures have to be implemented to protect the aquifer and the artificial recharge scheme. This is more particularly in the upstream compartment, where there are higher water levels and where the clay content is assumed to be relatively low. After the vulnerability assessment was performed, the identified pollution sources on the aquifer and in its vicinity were rated according to the risk they pose to the groundwater. Together with the vulnerability map this was used to perform a risk assessment that showed that the highest risks are in the upstream compartment, due to the high concentration of hazardous sources and its high vulnerability.

The assessments conclude that artificial recharge of the Oanob Aquifer is a good option for Windhoek as well as for Rehoboth to extend their security of water supply, though protective measures are necessary to prevent the aquifer from being polluted.

Key words: groundwater, aquifer, hydrogeology, vulnerability assessment, risk assessment, drinking water system, pollution sources, hazardous activity, conceptual model, Namibia

Sårbarhets- och riskbedömning av konstgjord infiltration i Oanob-akviferen, Namibia

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SAMMANFATTNING

Vatten har en livsviktig roll i människors liv. Det är därför viktigt att ta hand om de vattenresurser som finns tillgängliga. Dessvärre är vattnet på jorden inte jämnt fördelat över hela världen, vilket leder till att det råder vattenbrist i vissa länder. Ett av dessa länder är Namibia, det torraste landet söder om Sahara, där det finns en ganska bra tillgång på dricksvatten men problemet är att det inte finns där människorna lever. Dessutom är kostnaden för att förflytta vattnet hög, då avstånden inom landet är stora. Den ökande efterfrågan på vatten i Windhoek, huvudstaden i Namibia, har medfört planer på att använda Oanob-akviferen som en potentiell vattenresurs. Akviferen, som är belägen 90 kilometer söder om Windhoek, finns i floden Oanobs alluviala sediment strax söder om staden Rehoboth. Båda städerna överväger att använda vatten från akviferen som en kompletterande vattenresurs. För tillfället är akviferen fylld till 24 % och därför är det nödvändigt med artificiell infiltration om akviferen skall kunna användas för vattenförsörjning. Artificiell infiltration skulle då förse Rehoboth och möjligtvis även Windhoek med en vattenreserv.

Målet med projektet var att göra en sårbarhets- och riskbedömning av Oanob-akviferen för att undersöka möjligheterna för konstgjord infiltration och rekommendera en hållbar lösning för Windhoeks och Rehoboths kompletterande vattenförsörjning. Ett GIS-program (Geographical Information System) kallat ArcGIS 9 användes för att genomföra sårbarhetsanalysen och framställa kartor. Av utvärderingen framgick att akviferen är mycket sårbar för föroreningar till följd av dess alluviala uppbyggnad och därför måste förebyggande åtgärder genomföras för att skydda akviferen och planerna för konstgjord infiltration. I synnerhet i den övre delen av akviferen där grundvattennivån är hög och jordens lerinnehåll antas vara lågt. Efter sårbarhetsanalysen var genomförd klassificerades föroreningskällorna på och omkring akviferen utifrån vilken risk de utgör för grundvattnet i akviferen. Hoten tillsammans med sårbarhetskartan användes för att göra en riskanalys som visade att högsta risken för förorening finns i den övre delen av akviferen då där är en stor ansamling av farliga källor och hög sårbarhet.

Bedömningarna resulterade i att konstgjord infiltration av Oanob akviferen är ett bra alternativ för både Windhoek och Rehoboth att trygga sin vattenförsörjning. Dock är skyddsåtgärder nödvändiga för att förhindra förorening av akviferen.

Nyckelord: grundvatten, akvifer, hydrogeologi, sårbarhetsanalys, riskanalys, dricksvattensystem, föroreningskällor, farlig aktvitet, konceptuell modell, Namibia

Contents

Preface and Acknowledgements

In this Master's Thesis a vulnerability and risk assessment of the Oanob Aquifer in Namibia have been performed. The project has been carried out during the spring of 2010 at Chalmers University of Technology (CTH) in corporation with the Ministry of Agriculture, Water and Forestry (MAWF) in Windhoek, Namibia. It has included a 9 week long field study in Windhoek, were the necessary data and information for the assessments were gathered. The project was partially financed through a Minor Field Study (MFS) Scholarship received from the Swedish International Development Cooperation Agency (SIDA). Supervisors of this project have been Professor Lars Rosén and LicEng Andreas Lindhe at CTH and Deputy Director of Geohydrology at the Department of Water Affairs and Forestry (DWAF) at the MAWF, Greg Christelis.

We wish to thank all those who have contributed and been involved in this project, especially our supervisors Lars Rosén, Andreas Lindhe and Greg Christelis for their interest and support. We also wish to thank Nils Kellgren at SWECO for his help with the GIS analyses, and of course Sofie Flod and Hanna Landquist for our time together in Namibia. Without you it would not have been as enjoyable.

We would like to express our sincere gratitude to a number of people in Namibia; JJ Strauss and Jonathan Ockhuizen at the Rehoboth Town Council, Diganta Sarma at Namib Hydrosearch, Henry Beukes, Lothar Menge, Penny Shidute and Othero Mulele at the DWAF, Immo Peters at the City of Windhoek, N P du Plessis, Hanjörg Drews, Martin Harris and Koos Theron at NamWater, Israel Hasheela at the Geological Survey of Namibia, and John Esterhuizen at the New Goreangab Water Reclamation Plant. We also thank Professor Jürgen Kirchner for his assistance with the editing and review of the thesis.

Finally, we would like to thank our friends and family for their support and encouragement.

Göteborg, June 2010

Emma Kullgren and Jennie Perdell

Abbreviations

DEA – Directorate of Environmental Affairs

DWAF – Department of Water Affairs and Forestry

GDP – Gross Domestic Product

GIS – Geographical Information System

GWTP – Gammams Wastewater Treatment Plant

mamsl – metres above mean sea level

MAWF – Ministry of Agriculture, Water and Forestry

mbgl – metres below ground level

MDG – Millennium Development Goals

NDVI – Normalized Difference Vegetation Index

NGWRP – New Goreangab Water Reclamation Plant

NWPS – New Western Pump Station

SADC – Southern African Development Community

UN – United Nations

WASP – Water Supply and Sanitation Sector Policy

WDC – Water Demand Centre

WDM – Water Demand Management

WHO – World Health Organization

WSASP – Water Supply and Sanitation Policy

1 Introduction

1.1 Background

Water is essential for life, not only for meeting human basic needs but for contributing to a sustainable development. It is crucial for all socio-economic development and is necessary for agriculture and many industrial processes. Water is important for maintaining healthy ecosystems and water related ecosystems provide valuable services to humans (UN-Water, 2005). However, the increase in population and the socio-economic development mean that the amount of potable water today will not meet the need in the future, leading to a greater need for allocation of groundwater and surface water. The increased pressure on the water resources leads to conflicts between water users and excessive strain on the environment (UN-Water, 2006).

A rising demand together with a wasteful use of water and growing pollution is becoming a great concern. In countries where water scarcity is a reality the seriousness is even greater. The imbalance between availability of water and the demand leaves many people with water shortages (UN-Water, 2006). There are today 2.8 billion people living with water scarcity, representing 40 % of the world's population. Many of them live in Sub-Saharan countries and the lack of water is often visible through underdeveloped water infrastructure, high vulnerability to droughts and difficult access to water supplies (UN, 2008).

The United Nations have set one of the Millennium Development Goals (MDG) to halve the proportion of the world population living without sustainable access to safe drinking water and basic sanitation. Meeting the MDG for water and sanitation, set by the State Members of the United Nations for 2015, is fundamental for achieving the ultimate goal of providing all people with safe drinking water and adequate sanitation. Reaching the targets is also central for attaining the other Millennium Development Goals such as reducing world poverty, hunger and child mortality (UN-Water, 2005).

Namibia is situated on the west coast of southern Africa. It is considered as one of the most sparsely populated countries in the world with a land area of more than 824 000 km^2 and a population of 2.1 million (CIA, 2010). It is one of the most arid countries in Africa and water scarcity is a serious problem. Rainfall is irregular and sparse and the potential evaporation is almost ten times the precipitation in the country (DWAF, 2009). To alleviate the lack of water, measures such as Water Demand Management and a sustainable resource utilisation is of highest importance. Though, with a growing population and increasing development the need to allocate new water resources is pressing (ENVES, 2009).

Windhoek, the capital of Namibia, is an example of a city that has implemented such measures. Situated in the middle of the country at an altitude of 1600 mamsl (metres above mean sea level) Windhoek is far from any perennial rivers or the ocean, leaving ephemeral rivers and groundwater as its primary sources of drinking water (ENVES, 2009). The bulk water is mainly supplied from three dams outside of the city, but also from reclaimed water as well as groundwater from the Windhoek Aquifer (Menge et al., 2009). However, the inhabitants and development are increasing in the city and so is the water consumption. Most of the water sources in the central area of Namibia have been fully developed and are nearing the maximum limit of their potential. The necessity to develop reliable additional water resources that will meet the rising demand is therefore soon a fact (ENVES, 2009).

The town of Rehoboth, 87 kilometres south of Windhoek, is situated just north of the Oanob Aquifer that is contained within the Oanob River, see Appendix I (DWA, 1989a). The town is growing and so is the water demand. The Oanob Dam upstream on the river provides the town with water, but it has been proposed to use the aquifer instead. The aquifer is comprised of alluvial sediments contained in and along the river bed, and is divided into two compartments, upstream and downstream. There is natural recharge of the aquifer from leakage of the dam, rainfall and in certain times releases of dam water, yet the stored water is only about 24 % of the total storage capacity (Namib Hydrosearch, 2009).

With the use of artificial infiltration the aquifer can be replenished and at the same time prevent the infiltrated surface water from evaporating, as it would in the dam. The groundwater can then be abstracted from well fields and distributed in Rehoboth, as well as being transported to Windhoek via a pipeline.

In a country were water is scarce and there is an increasing water demand, the protection of water resources is imperative. A vulnerability assessment of groundwater aquifers is the first step to design protective measures for the resource. The continuation is a risk assessment of possible hazardous activities in the area that may contaminate the groundwater through pollution.

A vulnerability assessment of the Oanob Aquifer is essential in the analysis of the possibility to artificially recharge the aquifer. The assessment will map the areas most vulnerable to pollution and areas more suitable for artificial infiltration. The inclusion of a risk assessment will give a deeper understanding of which areas are in need of protective measures and the hazardous activities that need regulating and monitoring. This project aims to categorise the vulnerability of the aquifer into three levels and produce a vulnerability map of the area using GIS (Geographical Information Systems). The same approach is taken for the identification and rating of hazards and a risk map is generated through GIS.

The vulnerability and risk assessment of the connection of the two towns, Windhoek and Rehoboth, is as important as the assessment of the aquifer. The proposed pipeline connecting the distribution systems is assessed and analysed in the project *"Risk and Vulnerability Assessment of Expanding the Windhoek Drinking Water Supply"* by Sofie Flod and Hanna Landquist (2010). The field studies for the two projects were carried out in Namibia in cooperation with the Department of Water Affairs and Forestry at the Ministry of Agriculture, Water, and Forestry in Windhoek.

1.2 Purpose

The overall aims of this project are to assess the vulnerability of the Oanob Aquifer and to identify and to analyse possible hazards and the resulting risk. Furthermore, areas for possible artificial infiltration will be analysed. The specific objectives of the project are:

1. To identify the relevant hydrogeological parameters to be included in the assessments of the aquifer in the Rehoboth region, with respect to their relevance on groundwater vulnerability and data availability.
2. To adapt the method for vulnerability mapping from the report "Groundwater Vulnerability of the Windhoek Aquifer" (Interconsult, 2000), to the hydrogeological conditions of the Oanob Aquifer.
3. To assess the vulnerability of the aquifer.
4. To combine the assessment of vulnerability and potential hazards into a risk map.
5. To provide recommendations for sustainable groundwater supply for Rehoboth and Windhoek.

1.3 Scope of Work

This project intends to identify the hydrogeological parameters necessary for the vulnerability assessment of the Oanob Aquifer. The studied geological and hydrogeological area is the aquifer and its vicinity. No regard has been taken to the thermal aquifer adjoining the alluvial one, as it was assumed there is little connection between the two.

The Vulnerability and Risk Assessments are based on a method used in the report "Groundwater Vulnerability of the Windhoek Aquifer" (Interconsult, 2000). The implemented vulnerability assessment method is modified to better suit the specific conditions of the area. The assessment is based on a conceptual model of the aquifer and its surroundings. Assumptions have been made where the data of the area is sparse or unavailable. The geological information of the upstream compartment is estimated based on the available data, borehole completion reports and the geological survey of the downstream compartment, see further in section 5.2.1.

The area considered for the identification of hazardous activities in the risk assessment is the town of Rehoboth and the aquifer. Natural water dividers such as topography and geology determine the flow of possible pollutants and also the activities included in the assessment. The assumption is made that the thermal aquifer is disconnected from the Oanob Aquifer and is disregarded with the exception that it is considered as a possible threat to the aquifer. The identification and characterisation is followed by the rating of the hazards, where each activity is rated using a risk rating table.

The subsequent results are used in the GIS programme ArcGIS 9 where vulnerability and risk maps of the area are produced. The maps visualise the specific areas more vulnerable to pollution and in greater need of protective measures. A first suggestion for possible location of artificial infiltration basins can also be deduced from the maps.

1.4 Disposition of the Report

This report begins with background on the importance of water and the problem with water scarcity, first globally and then nationally (Chapter 2). The international work towards safe drinking water for all, lead by the UN, is described as well as the economy and legislation of water in Namibia. Then a description of the Oanob Aquifer and Rehoboth area is provided (Chapter 3). Topography, hydrology, geology and hydrogeology are presented giving a conceptual model of the aquifer. A system description of the water supply and distribution systems of Windhoek and Rehoboth is then presented (Chapter 4). It is a brief explanation of the different water sources that supply the towns. Background concerning artificial infiltration is presented with a technical description of the process and a mentioning of possible pollution risk.

The methodology chapter presents the different methods used in the project, as well as the assumptions made (Chapter 5). Starting with a description of the vulnerability assessment the chapter continues into the risk assessment including the identification of pollution sources. The results from the assessments are presented in both text and GIS maps (Chapter 6).

The authors discuss the results and possible sources of error (Chapter 7) and give a conclusion and a recommendation (Chapter 8) at the end of the report. The report concludes with further investigations recommended or already planned (Chapter 9).

2 Water as a Resource

2.1 A Global Perspective

Water has for a long time been treated as a renewable resource. This has resulted in under-pricing, wasting and excessive use of water. As a result of this water reserves are depleted in many areas, with little to no ways of replacing them. The possibility to satisfy future demand is badly affected, meaning that potential consequences will be serious when considering economical, political and health aspects (WEF, 2009).

With the expansion of the world economy, the population of the world grows and so does the demand for water (WEF, 2009). Due to this, societies soon will have to change their way of thinking regarding water use and water's vital role for survival. Unfortunately there are no alternatives or substitutes for water, the only option is to take better care of the resources available. Since no one government or institution owns all water, the issue is something that will have to be solved collectively (WEF, 2008). Some of the efforts that are being made to sustain the water resources and keep them clean are described in chapter 2.2.

Even though the amount of water available in humid regions is vast, the distribution of available water does not always correspond with the distribution of human demand (Kanae, 2009). As the demand grows so does the need to improve the efficiency of the water utilisation, to still have water left for when it is needed. There is no possibility of managing water the way it is done today and still be able to have enough of it in the future. For that reason it is essential that good regulations for the use of the water resources are available. As all people over the world, rich or poor, are affected by this problem, all will benefit from improvements in the managing of water (WEF, 2009).

The amount of fresh water on Earth today is the same as when it was formed, the problem is that the water demand is larger now. This has to do with a larger world population and a more developed world, where people use more water then sometimes necessary (The Green Lane, 2003). In Figure 1, an overview of how the water on Earth is distributed over different resources is shown.

About 95 % of the freshwater on Earth, if disregarding the water stored in polar ice, is found as groundwater. According to Morris et al. (2003) two billion people are dependent on water from aquifers for drinking water, and the part of agriculture that depends on groundwater for irrigation produces about 40 % of the world's food. Thus, groundwater is essential for human life and economic development. It is therefore important to manage the water well and keep it safe from contamination and inappropriate use, in order for it to sustain for future generations.

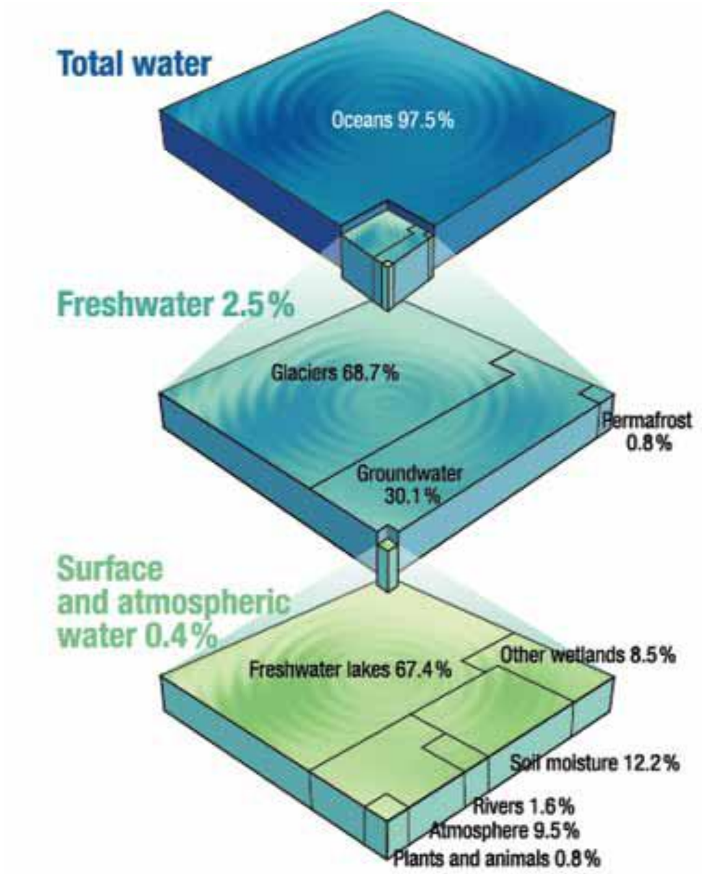

Figure 1: Global distribution of the world's water (WWAP, 2006).

Groundwater is the only source of freshwater available in many parts of the world, this due to limited rainfall and in some cases in combination with high evaporation. As an estimation, approximately 75 % of the African population use groundwater as their main source for drinking water, especially so in Southern African countries such as Botswana, Namibia and Zimbabwe. However, of the continent's renewable resources, groundwater only stands for about 15 % (ECA et al., 2005). The cities in Africa, dependent on groundwater, are shown in Figure 2. Groundwater dependency with little rainfall and high evaporation can lead to groundwater being greatly exploited. According to Morris et al. (2003) the consequences are especially notable, with degradation of groundwater, where there is:

- excessive exploitation
- inappropriate or uncontrolled activities at the land surface
- major change of land use

The use of water and the availability to other water sources are important matters that must be investigated to be able to find out how severe the consequences of an aquifer being contaminated would be. Often the ones affected the most by groundwater degradation are the poor, since changed ways of living and alternative water sources could be expensive. It is therefore important to try and protect the groundwater reserves, and all other water as well, in advance to assure that drinking water will be available for all people over the world.

Figure 2: Showing groundwater dependent cities in Africa (Morris et al., 2003).

2.2 Challenges in Developing Countries

Water is important to all socio-economic development and the prosperity of the world’s ecosystems. With the increase in population and development the supply of groundwater and surface water for domestic, agricultural, and industrial use is put under pressure. The increased stress on the water resources leads to tensions, conflicts among users, and extreme pressure on the environment. The rising water demand and excessive use, together with increased pollution worldwide, put severe strain on the freshwater resources and lead to water scarcity (UN-Water, 2006).

Water scarcity describes the relationship between demand for water and its availability. It is determined both by the availability of water and by consumption patterns (Water Policy International Ltd., 2000). The UN-Water report (2006) defines water scarcity as “the point at which the effect of all users imposes on the water supply or quality to the extent that the demand by all, including the environment, cannot be completely satisfied”.

There are more than 2.8 billion people in the world living with water scarcity, this represents 40 % of the world’s population. Of those, 1.2 billion live under physical water scarcity. The other 1.6 billion people live in economic water scarcity where it is the human, institutional, or financial capital that limits the access to water, not the water available in nature. In Sub-Saharan countries this is often the case and it is visible through underdeveloped water infrastructure, high vulnerability to droughts, and difficult access to water supplies, especially for people living in rural areas (UN, 2008).

Since 1990 about 1.6 billion people have gained access to safe drinking water, but there is still over 1 billion people living without. The United Nation's (UN) Millennium Development Goals (MDG) include the target to halve the proportion of the population living without access to sustainable safe drinking water and basic sanitation by 2015. The MDGs were agreed on by all 191 United Nations Member States at the Millennium summit in 2000 and set to be achieved by 2015. Sub-Saharan Africa stands for more than a third of the world's population living without safe drinking water supplies (UN, 2008).

The improvement of safe water and sanitation is important for reducing poverty, but also for achieving the MDGs for health. More than 2 million people, mostly children, die every year from diseases associated with unsafe drinking water and poor sanitation and hygiene. When considering the increasing demand for water and the finite resources of freshwater it is evident that the need to manage and protect water resources properly is crucial. Member States have by agreeing to the MDGs committed to ensure the environmental sustainability and to reverse the loss of environmental resources (UN-Water, 2005).

In Africa there are a number of socio-economic problems that need urgent attention, e.g. endemic poverty and pervasive underdevelopment. Furthermore, it is established that water has an important role when meeting the needed socio-economic targets. Generally Africa has plentiful water resources, however both natural and human factors constitute threats to the sustainability of the water resources (ECA et al., 2000). As a result, the UN has developed an Africa Water Vision for 2025 where it is stated that the business as usual approach to water resource management is unsustainable. The available water resources will in the future become insufficient for the demand for sustaining life, economic development, and the environment. The vision is designed to prevent the severe consequences of the threats and lead to a future where the full potential of the African water resources can be used to encourage and sustain growth in the region's economic development and social well-being (ECA et al., 2000).

As stated earlier, water plays a vital role in sustaining human lives, maintaining the ecosystems and in socio-economic development (UN-Water, 2006). The Millennium Development Goals set by the member states of the United Nations are an important first step towards eradicating world poverty and providing all people with access to clean drinking water and adequate sanitation (UN-Water, 2005). With five more years to go, the commitment to the joint venture of meeting the targets set and collectively take action is more important than ever (UN, 2009).

2.3 Water in Namibia

Of all the countries south of the Sahara Desert, Namibia is the most arid one with an average rainfall that is less than half of the average in the world. The evaporation levels in the country are high, the spatial distribution of water is uneven and the droughts are periodic and long-lasting. Due to all of this and the fact that the variation in runoff is large, to supply water in Namibia at an affordable cost is difficult (LCE, 2008).

It is not only the environmental conditions that affect the water resources, but also the social conditions. In Namibia the number of people is increasing rapidly. There is underdevelopment, illiteracy, poverty and unemployment, all of which affect the water resources. People need to be made aware that water is a common good and that every single person is responsible for the water they use. If one person uses far too much water, then others may be left without. The water is also important for the development of the country, though development will in turn affect the water resources. Therefore, water must be used in a sustainable way to assure sustainable development (Heyns et al., 1998). As stated in a report on the principles and methodology for calculating costs and tariffs for water supply by NamWater (LCE, 2008):

"It is an accepted fact that water in Namibia is scarce, and becoming all the more so with the passage of time."

Due to Namibia's arid environment, its hydrological cycle is in many ways distorted. This refers mostly to the fact that inputs e.g. rainfall and runoff are scarce and irregular, while outputs e.g. aquifer leakage and abstraction are continuous. In the arid areas, such as the south and the costal belt, the variation in rainfall is very large. Due to these unstable circumstances there is a need for sustainable solutions and strategies (DEA, 2001).

2.3.1 Groundwater

For a large part of Namibia, groundwater represents the only viable source of potable water. For domestic and livestock purposes, both rural communities and farmers all over the country rely on it. Aquifers supply a number of large urban areas with bulk water. The bulk water consists of different sources of water, one is water from alluvial aquifers that is being replenished by ephemeral rivers, another is fractured and karst aquifers, another is from other porous sedimentary formations, and a fourth one is surface water sources, i.e. dams (DEA, 2001). The greatest hazard to the quality of groundwater is contamination from human activities. These can for example be leakage from waste disposal sites or sewage pipes, application of fertiliser on irrigated lands, and human and animal faeces contaminating water in wells (Heyns et al., 1998).

Almost 73 % of the total water consumed in the country is provided from groundwater, if disregarding water from the perennial rivers. For that reason it is essential for the economic development to maintain these resources. In various parts of the country both primary and secondary aquifers can be found, and in certain places also a combination of the two. Groundwater is a difficult resource to manage due to the fact that it cannot be seen. Therefore special attention is needed to prevent overexploitation and pollution (Heyns et al., 1998). The fact that groundwater is considered to be a finite resource is another important aspect as to why Namibia must try to manage and control this resource in a sustainable way. Efforts to artificially improve recharge of aquifers are being made to augment the water supply (DEA, 2001).

Irrigation of agricultural land is a major part of the water use in Namibia (DEA, 2001). In most cases it is not economically viable to use groundwater for irrigation, and there is always a need for careful, scientific planning to see if the soil and water is compatible. If they are not, salinisation of the soil may be the result (Heyns et al., 1998).

2.3.2 Water Supply and Demand

The perennial rivers in the north and south are primary sources of water in Namibia. If these sources could be distributed in an economically sustainable way to the central and coastal parts of the country, then the water supply would not be an issue (DEA, 2001). However, that is not the case.

Of Namibia's water consumption, groundwater accounts for 51 % out of which the majority is stored in eight aquifers. The main goal, when talking about aquifers and dams, is to reduce the evaporation losses from the surface. This is why the surface water of the dam is used first, while the groundwater is kept for when there is no surface water available. Another way to escape evaporation is to artificially recharge underground aquifers with the surface water (DEA, 2001).

According to DEA (2001) the definition of water consumption or water use is "the actual quantity of water consumed by a consumer or at a Water Demand Centre (WDC)". Water demand according to the same source is defined as "the quantity of water required to meet the needs of a WDC or other consumer". In Namibia the water consumption is divided as such: about 50 % is used for irrigation, 25 % is used by urban consumers, 13 % for livestock and the final 12 % is split between mines, rural consumers, and wildlife and tourism. The water use for urban residential varies between income groups.

2.3.3 Economics of Water Supply

The contribution from water, in different sectors, to the gross domestic product (GDP) gives a guideline to the economic value of water. The activity demanding most water in Namibia is agriculture, using over 60 % of the country's water, but only contributing with about 10 % to the GDP. If comparing the value contribution per cubic metre water from agriculture with manufacturing and service sector, the manufacturing gives about 38 times as much and the service sector gives about 80 times as much as the agriculture (DEA, 2001), although as a developing country, agriculture is the main activity in Namibia (UN-Water, 2005).

The fact that water resources are so greatly exploited is not difficult to understand. The population is growing rapidly and the standard of living is rising, and to be able to manage this people need water. However, if the management is bad and the control of water abstraction is poor then the consequences may be disastrous. Depletion might not be seen until five, ten or even fifty years from now, when it is too late to do something about it (Heyns et al., 1998).

It is important to regard all aspects of cost in the price of water to be able to maintain the environment, while meeting the water demands. Matters that must be regarded when deciding the price of water are: financial costs, opportunity costs, social benefits associated with water supply, and environmental costs. It is also necessary to ensure that all people can get access to at least a minimum of water, even those who do not have the economic power. The price of bulk water changes from one region to another and also depends on how much water is being used, the more water a consumer uses the more expensive it is per m^3. The approximate annual cost for bulk water for Namibia is N$170 million (DEA, 2001).

NamWater is a state-owned company with the directive to effectively and sustainably supply bulk water to municipalities and other large consumers, such as mines, all over Namibia. The use of tariffs for water pricing, by NamWater as well as municipalities, is a way of controlling the demand and supply of water in Namibia and these need to be designed according to sensible principles to optimise the distribution of the water resources. The cost elements to be included in the tariffs are seen in Figure 3 (LCE, 2008).

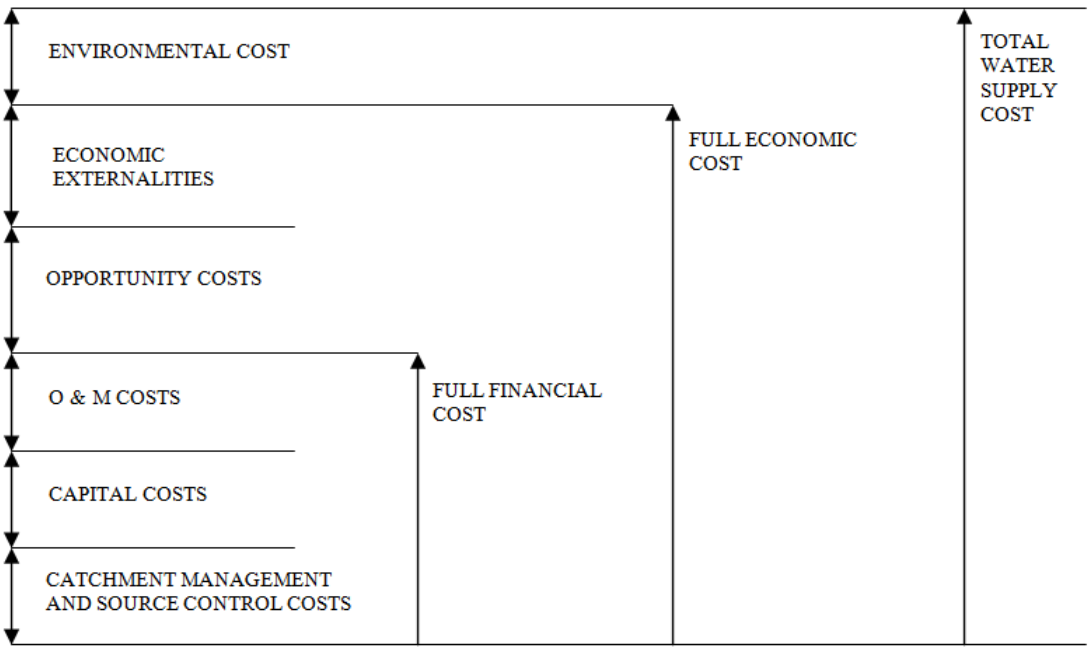

Figure 3: Different components of water costs (LCE, 2008).

General principles for developing tariff policies are applied within all sectors and declare that money generated through domestic water use or sanitation should not be used to subsidise water to any other economic activity. Industrial, commercial, and mining activities should pay the full cost recovery tariff, taking the water scarcity and the cost for future water supply augmentation into account (Van der Merwe, 1999). Rising block tariffs are widely used both in developed and developing countries, Namibia being one of them. It involves the cost of water increasing in steps for the consumed water. Water deemed necessary for basic human needs is included in the first block and the cost progresses from there (LCE, 2008).

The application of fair rising block tariffs can under unusual circumstances, e.g. severe droughts and periods of water shortages, be an important tool for limiting excessive water consumption where the volume of water included in each block tariff is lowered (Van der Merwe, 1999). Equitable tariffs are also important to improve access for poor and marginalised communities (MAWF, 2008).

In Windhoek the cost recovery tariffs cover full capital costs, bulk water supply cost and full operation and maintenance cost, adding to that an administrative levy of about 9 % to cover overhead cost of the Municipality. During periods of drought and water shortages, the volume included in each block tariff is lowered (Van der Merwe, 1999).

2.3.4 Legislation

In a country as arid as Namibia, water management is of highest importance. The control and regulation of the use and exploitation of water is one of the means available for the government. Namibia was the first country in the world to incorporate the environment into its constitution, providing for the maintenance of ecosystems and essential ecological processes (CIA, 2010; Republic of Namibia, 2010). There are two existing guidelines for water development and use: The Water Act, and the Water Supply and Sanitation Sector Policy, (Heyns et al., 1998).

The Water Act 54 (MAWF, 1956) was legislated in South Africa and is still the water act in effect in Namibia. In the introduction of Act 54 it says:

"The Provisions of the Water Act are intended, amongst other things, to promote the maximum beneficial use of the country's water supplies and to safeguard water supplies from avoidable pollution."

The Water Act has a colonial origin and thus is not only outdated but also incompatible with Namibia's hydrological reality (UNESCO, 2010). It regulates the use of underground water in subterranean water control areas. Under the act it is not allowed to pollute water and the discharge of effluents is regulated (Heyns et al., 1998). However, the current Water Act does not recognise nature as a user of water nor as a provider of goods, services and processes essential to man. This is not in accordance with Namibia's Constitution. The sustainable use of water resources is not specified in terms of environmental, social and economic sustainability in Act 54 (DEA, 2001). There is now a new Water Act being developed, but it has not yet been enacted by the government (UNESCO, 2010).

In 1993, a Water Supply and Sanitation Sector Policy (WASP) for Namibia was approved. WASP was formed in order to make affordable water supply and sanitation systems available to all Namibians. In 2008 a new Water Supply and Sanitation Policy (WSASP) replaced the policy from 1993. The environmentally sustainable development and utilisation of the water resources of the country is the focus of the new policy (MAWF, 2008). The principles are in accordance with Integrated Water Resource Management with an emphasis on Water Demand Management (WDM) and water use efficiency (LCE, 2008; MAWF, 2008).

The overall management and regulation of the water cycle and water resources in the country is the task of the MAWF. Their main objective is to ensure that the resources will be properly investigated and used in a sustainable manner to provide the water needed by people and to sustain Namibia's environment (MAWF, 2008). Within the Ministry, the Department of Water Affairs and Forestry is responsible for the national and regional monitoring and sustainable management of water resources (NEEN, 2004). The Geohydrology Division in the department assesses, manages, monitors, and regulates the amount and quality of groundwater available and utilised to maintain a sustainable water source. The division assist Rural Water Supply and other agencies with the development of new and the rehabilitation of existing groundwater sources (MAWF, 2010).

In Windhoek an integrated Water Demand Management (WDM) policy was developed in 1994. It was the only viable way to use the existing water resources more efficiently for a growing population and was identified as the cheapest option to lower water demand (NamWater, 2004). Water Demand Management is included in an integrated approach for sustainable development and use of water resources. A part of the WDM is implementing policies for the efficient use of water, for economic efficiency and for environmental sustainability (Heyns et al., 1998).Using rising block tariffs and a more efficient use of water in all sectors to remove overconsumption, was the main driving force for the policy (Van der Merwe, 1999).

2.4 Risks to Groundwater Resources

Groundwater supplies almost 73 % of the total water consumption in Namibia, when disregarding the perennial rivers at the borders to neighbouring countries. It is therefore essential to maintain the resource, both from a health and an economical perspective. One problem with groundwater however, is that the resource cannot be seen which makes management difficult. In order to manage it properly measurements has to be made on parameters that can be measured to be able to do calculations, as a substitute to the fact that the water cannot be observed (Heyns et al., 1998).

The scarcity of water in Namibia makes it an expensive good. Groundwater is not an exception, but the main problem with groundwater is that it is hard to locate and abstract. It is also often so that the water has to be transported over long distances, due to it not being situated where it is needed. There are also a few things that have to be considered when managing groundwater, such as that the sources are easily overexploited, and when the water table is shallow they are very susceptible to pollution. Therefore special attention is required in order to keep the water sources safe. One measure that has been done to preserve the water that exists, and keep it from being overexploited, is that several parts of the country have been proclaimed Subterranean Water Control Areas. This means that the abstraction of groundwater by consumers is monitored and regulated. The control of abstraction is not only done to prevent the water sources from being overused, but also to make sure that each consumer can receive their share of the sustainable yield. A Groundwater Level Monitoring Programme has also been initiated and is run by the Department of Water Affairs and Forestry to keep track of the groundwater levels all over Namibia. Another measure to preserve water is to use a combination of the groundwater and the surface water sources. The surface water should be used first, since it evaporates quickly, and the groundwater should be used when there is no available surface water, since the groundwater does not evaporate. It is important to integrate the management of water with other sectors affected by the water use. These are for example agriculture, industrial development, and population growth (Heyns et al., 1998).

One major issue concerning groundwater is that once the water has been polluted it is difficult and expensive to remediate the aquifers. In developing countries it can be almost impossible (Morris et al., 2003). Because water flows so slowly underground, it takes many years or decades for the pollution to appear, and by then it may be too late to prevent serious contamination. Sometimes the water source just cannot be cleaned, and in other times it is not economically viable to clean the water since it still may not be suitable for drinking afterwards. Then an additional water supply is needed, which is costly and unnecessary if the source would have been managed and protected properly in the first place (UNEP, 1996).

2.4.1 Threats to Groundwater

The greatest threats to groundwater quality are posed by human activities. Pollution may come from leakage of water from waste disposal sites or sewer pipes, fertilisers and pesticides spread on irrigated land, and from faeces, both human and animal, contaminating wells (Heyns et al., 1998). Naturally, pollution is the first that comes to mind when considering threats to water but overexploitation is another major problem that must be handled. As development is progressing, more water is required and as a result to this water is abstracted in an unsustainable way (UNEP, 1996).

2.4.1.1 Pollution

Waste water and sewage is becoming more and more common as a pollution source to groundwater. This is a result of developing countries and cities having inadequate sanitation systems. The waste water contains substances such as nitrate and micro-organisms, usually harmful to humans and animals, which will pollute wells and boreholes supplying drinking water (UNEP, 1996).

Groundwater is also polluted by spill or releases of effluents from industries. The liquids exist in the effluent released into surface water or leaking into the ground. It may also come from leaking storage tanks containing chemicals such as hydrocarbon fuels and chlorinated solvents (UNEP, 1996).

Another source for contamination of groundwater is agriculture. This can pollute groundwater in two different ways. The first is through fertilisers and pesticides being used on crops and not being taken up by the plants, but instead leaches through the soil and into the groundwater reserves below. As agriculture gets more and more intense, the potential for this increases (UNEP, 1996). The second potential pollution is by agriculture through irrigation. Irrigation requires much water and if groundwater is used for this then careful planning is needed, otherwise the groundwater source could salinate the soil cover due to a build-up of salts from the groundwater within the soil by too intense pumping and sometimes causing saline water to leak into the aquifer (Heyns et al., 1998).

Chemicals can come from rubbish dumps and landfills and when it is raining the chemicals are dissolved in the water and then transported with the water into the ground. They might come from petroleum development as well. Mining, both active and abandoned mines, is another pollution source for groundwater (UNEP, 1996).

Other ones are effluents from tanneries, toxic dust, gases and soluble salts emitted from mines and smelters (NWAC, 2002).

2.4.1.2 Overexploitation

Serious problems can occur from using too much water from a source. When regarding wells and boreholes the yield may be reduced, which increases the cost of pumping of water and in the end the price of water from suppliers. High water abstraction may also cause the ground to settle. In many urban cities in developing countries this is big problem with expensive consequences, as buildings and streets may be affected and has to be repaired or even rebuilt (UNEP, 1996).

In coastal areas overexploitation may lead to salt water leaking in to the groundwater sources. This can reach as far as several kilometres inland. Saline water may also reach inland areas from the underground from pumping at high rate. Groundwater aquifers can be harmed by drought as well. If the groundwater level is less than three metres below ground surface, evaporation will take place. If the groundwater source is limited, and especially if situated in a semi-arid or arid area, then dry periods will affect the aquifer negatively (UNEP, 1996).

2.4.2 The Protection of Groundwater

Even though groundwater is a resource that more than 2 billion people depend on, the protection of it is inadequate and the control is poor. In many parts of the world the groundwater is also already polluted (UNEP, 1996).

To sustain groundwater resources, better protection is imperative. There are two basic ways of protecting the groundwater resources; controlling the abstraction of water and controlling groundwater pollution. The groundwater abstraction is especially important to control in areas where there is a possibility of irreversible side-effects from over-utilisation such as saltwater intrusion and land subsidence. Monitoring and assessing risk of pollution is done through evaluating the aquifer vulnerability, assessing potential pollution loads and implementing plans for the protection of groundwater (UNEP, 1996).

The first priority is the control of groundwater abstraction. In many urban areas a significant number of boreholes are drilled in shallow aquifers with no regard for overall yield, other users or the possibility of saltwater intrusion and land subsidence. The controlling of abstraction includes legal and administrative work, such as the issuing of permits for drilling of boreholes and well digging and later the issuing of licences for groundwater abstraction (UNEP, 1996).

Controlling groundwater pollution involves assessing the vulnerability of the aquifer to contamination. The result is a map over the aquifer indicating where protection zones are most needed (UNEP, 1996). Zoning is one of the most important measures of protecting vulnerable groundwater sources. Using hydrogeological principles, the area around the borehole is defined and is then divided into different zones, where the protection with its restrictions increase as the abstraction point is reached (Xu & Braune, 1995).

To consistently supply safe drinking water the most cost effective and protective way is to apply some form of risk management with monitoring on the system as a whole, i.e. from catchment to consumer. The setting of water quality standards are firstly done by the World Health Organization (WHO). The standards are essentially a health risk assessment, based on the available evidence, expert's opinions and scientific consensus (WHO, 2005). The WHO has developed guidelines for drinking water quality as a preventative management framework for safe drinking water. It consists of five components, of which a water safety plan comprises three. A water safety plan includes; system assessment and design, operational monitoring and management plans (WHO, 2005). The framework for safe drinking water can be seen in Figure 4.

The aim of a water safety plan is to secure safe drinking water through good water supply practices. The practices are: the prevention of contamination of water sources, the treatment of water to reduce and remove contaminants to the extent needed to meet the quality targets set, and the prevention of re-contamination of the drinking water during storage, distribution and handling. The water safety plan is the last step in the protection of the water system, from catchment to consumer (WHO, 2005).

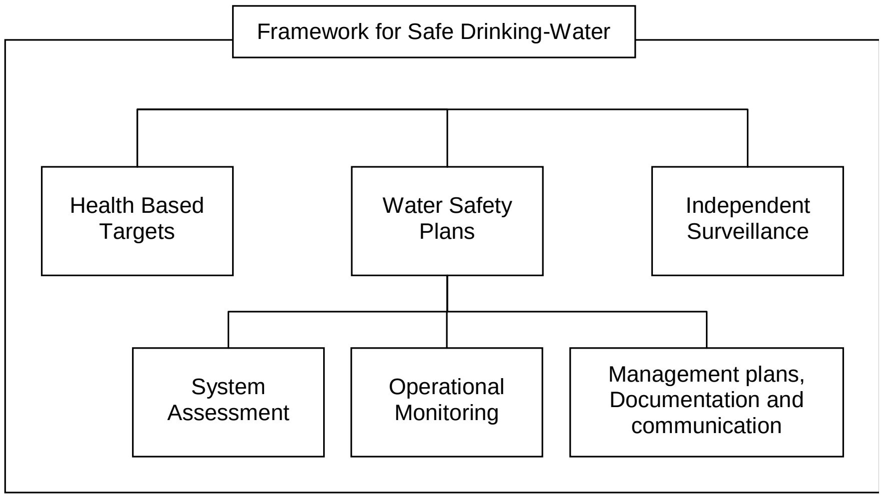

Figure 4: Framework for safe drinking water (WHO, 2008).

If pollution occurs, measures to try to remediate the polluted area and to prevent further contaminant movements are necessary to perform. The cost of pollution does not only address remediation costs, but also damages to natural resources, ecosystems, and the population health. In many investigations the cost of remediation is equalised with the cost of pollution. An example that shows that this is not all true is potable groundwater. There is a reduction in value when groundwater, that used to have the quality for potable water, is polluted and then remediated. The water that is returned after the process is water for irrigation, which does not have the same value as clean groundwater. However, eventually the water will return to the remediated aquifer and by infiltration go back to its previous quality. The fact still remains though, that the value of the original groundwater will be reduced for a period of time. The costs for remediation stand for at least the value of the recovered water, which in the case of polluted groundwater is the irrigation water (Paleologos, 2008).

There are four ways of valuation that affects ecological resources, remediation, natural resource damage assessment, and stewardship:

- The value of the resource itself (to the ecosystem)
- The value of the resource to the people
- The value of ecological resources to services for communities
- The value of intact ecosystems

While each category can be evaluated separately, it is also useful to evaluate them all, at least briefly, at the same time. This because different experts evaluates the different parts, so though the parts may seem similar, they are not the same (Burger et al., 2008). Previous experience from remediation projects shows that remedial actions are very difficult and not likely to be successful (Interconsult, 2000). Remediation is not very common in southern Africa due to high costs and lack of experience. This together with that the majority of aquifers in Namibia are in fractured rock means that successful treatment is improbable (Harris, 2010).

3 General Area Description

3.1 Topography

Rehoboth lies in an area of transition. The highest elevation is to the south of the town with the Langberg Formation and the Marienhof Formation, with an altitude of 1720 metres above mean sea level (mamsl). The lowest elevation is at the southeast end of the downstream compartment with an altitude of 1315 mamsl, see Figure 5 (Namib Hydrosearch, 2009). The elevation of the Rehoboth area declines from west-northwest to southeast.

The terrain west of the town consists of rocky hills (DWA, 1986). River channels cut deep into the mountainous area and on the south-eastern slope of the Auas Mountains north of Rehoboth, the Oanob River rises. At first the river flows southward before the general direction of eastward is continued through the Rehoboth area. Southeast of town the river runs over an alluvial plain, which constitutes the Oanob Aquifer (SWECO, 2002). When out of the hills, the river bed becomes much wider and less well defined. East of town the landscape changes to flat inland plateau and plains, though there are some rocky outcrops, e.g. the Langberg formation (DWA, 1986). In the Rehoboth area there is 54 000 ha of farmland (Strauss, 2010).

3.2 Natural Vegetation

The vegetation around the area consists mostly of grass and Acacia trees, specifically Camel Thorn. Rehoboth occupies the largest concentration of Camel Thorns, in the entire Southern African Development Community (SADC) Region (Strauss, 2010). The type and distribution of vegetation is of importance to the groundwater in the aquifer since a considerable factor of the hydrologic budget is the loss of groundwater from plant uptake. When considering groundwater, grass and trees differentiate in how far the root system extends downward. Grass, being short rooted, relies on the soil moisture directly related to precipitation, while trees have roots which tap the saturated soil from where groundwater is also abstracted (DWA, 1989a). In 2008 an Aster Normalized Difference Vegetation Index (NDVI) image was acquired of the aquifer, highlighting mainly tree vegetation. The image was taken two months into the rainy season and indicated less tree vegetation cover than the 40 % that was reported in DWA (1989a) (Namib Hydrosearch, 2009). This is most likely a sign of a lower water table in the aquifer.

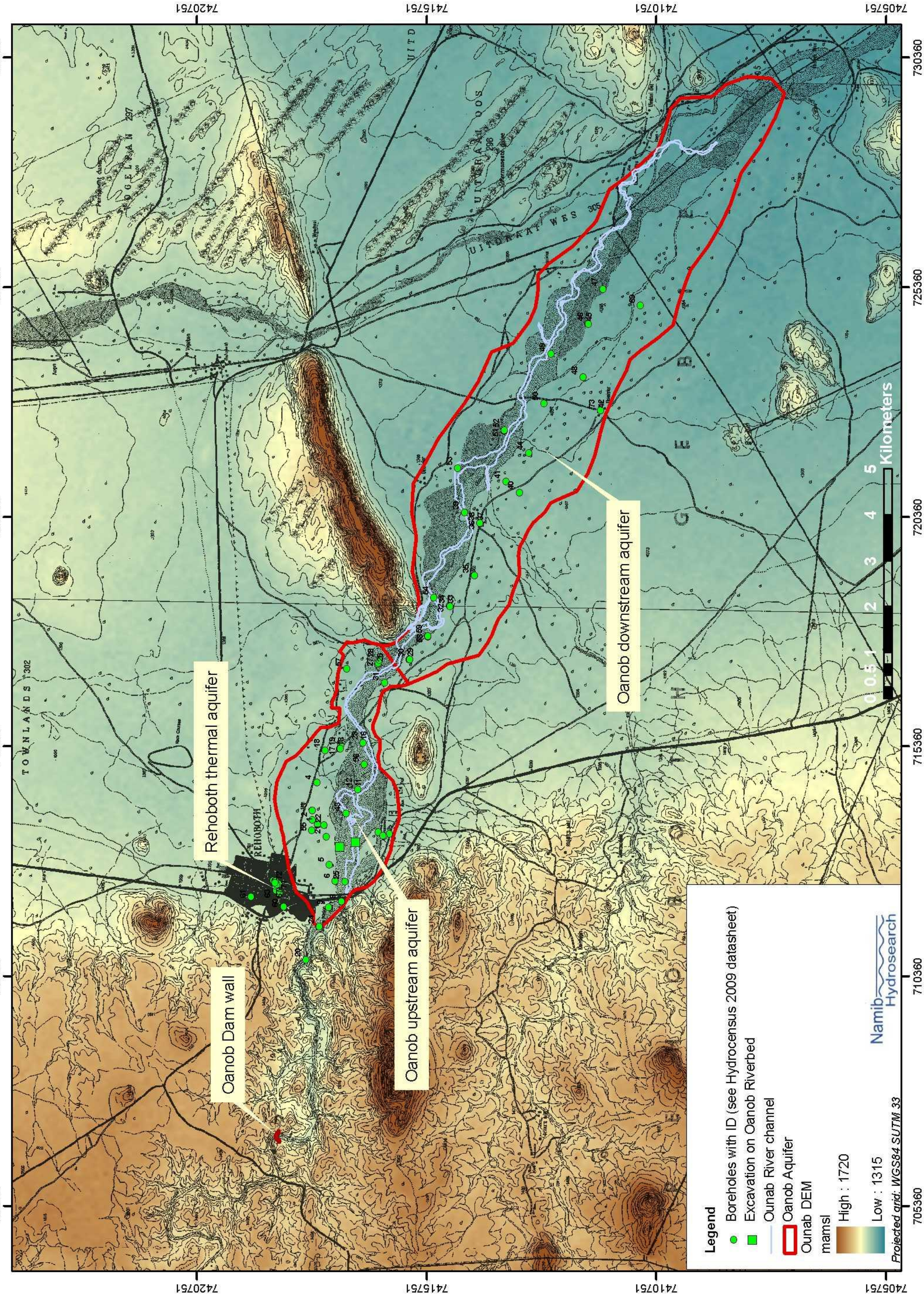

Figure 5: Oanob Aquifer (Namib Hydrosearch, 2009).

3.3 Hydrology

In Namibia the water usually falls in intense showers, which is common in dry climates. This leads to large variability both over space and time, within and between years. The dry climate also affects the country through droughts with harsh impacts on the biological production (DWAF, 2009). During years of drought, aquifers are sometimes the only water supply available and are utilised as water sources since the groundwater was replenished during earlier rainfalls and floods.

The Oanob Aquifer is situated in the Rehoboth area and data of rainfall, recharge and losses from the area is presented below.

3.3.1 Rainfall

Namibia is the most arid country in southern Africa. The climate essentially consists of two seasons; sub-tropical dry winters from May to September and hot summers from October to April. The rainfall is irregular and sparse with an annual average precipitation ranging from 50 mm in the Namib Desert to 600 mm in the north-eastern Caprivi Strip. The mean annual rainfall in Windhoek and Rehoboth, is 250-350 mm, see Figure 6 (DWAF, 2009), and the Oanob Aquifer has a mean annual rainfall of 280 mm (MAWRD, 1993).

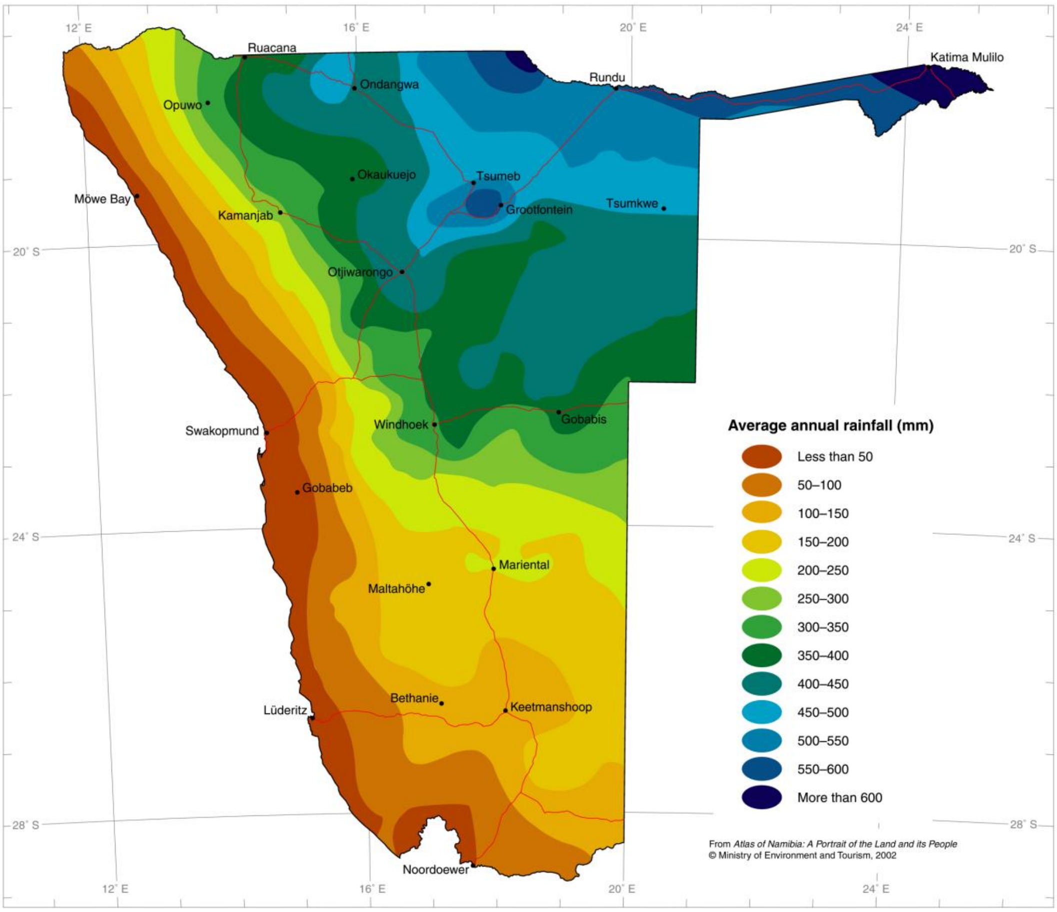

Figure 6: Average Annual Rainfall in Namibia (DWAF, 2009).

The rainfall in Namibia is highly seasonal, with distinct wet and dry seasons, see Table 1. The dry period usually extends from April/May to September/October, with the wet period over the rest of the year. The general pattern of the rainfall is consistent over the country, though the amount of precipitation varies between the years. The rain starts in the northern part of Namibia and usually one month later in the southern part. By November the rain period should have begun over the whole country. The months with most rainfall are February and March, with March being relatively wet in the southern parts of Namibia. At the end of April the rainy season has normally ended (DWAF, 2009).

The monthly total rainfall in Rehoboth can be seen in Table 1 and a block chart of the data is shown in Figure 7. The precipitation data that have been used in the report from Namib Hydrosearch is from the years of 1992 until 2008, though the monitoring of the rain gauge station has been sporadic and the years 1999, 2000 and 2002 - 2005 have not been recorded at all.

Table 1: Average monthly rainfall data for Rehoboth in mm (Namib Hydrosearch, 2009).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
1992	17.0	25.0	11.5	0.0	0.0	0,0	0,0	0.0	2.0	0.0	0.0	8.7	64.2
1993	43.2	66.3	83.2	21.9	0.0	0.0	0.0	0.0	0.0	4.7	21.6	9.0	249.9
1994	128.1	78.5	0.0	3.0	0.0	0.9	0.0	0.0	0.0	0.4	8.0	14.7	233.6
1995	0.0	33.7	33.0	0.0	13.0	0.0	0.0	0.0	0.0	0.0	14.2	3.9	97.8
1996	42.2	10.0	10.8	0.0	0.0	0.0	5.0	0.0	0.0	0.0	17.5	23.0	108.5
1997	109.0	39.5	26.3	13.5	0.0	0.0	0.0	0.0	7.2	8.8	2.5	95.6	302.4
1998	24.5	16.6	8.5	0.0	0.0	0.0	0.0	7.6	9.9	13.0	11.5	12.5	104.1
2001	78.5	9.9	32.0	125.3	32.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	278.4
2006	159.0	220.1	39.2	71.9	0.0	0.0	0.0	0.0	0.0	19.7	1.5	0.0	511.4
2007	34.0	0.0	3.0	15.9	0.0	0.0	0.0	0.0	0.0	0.0	4.5	1.5	58.9
2008	3.5	194.0	112.2	23.0	0.0	0.0	0.0	0.0	0.0	9.0	46.1	17.5	405.3

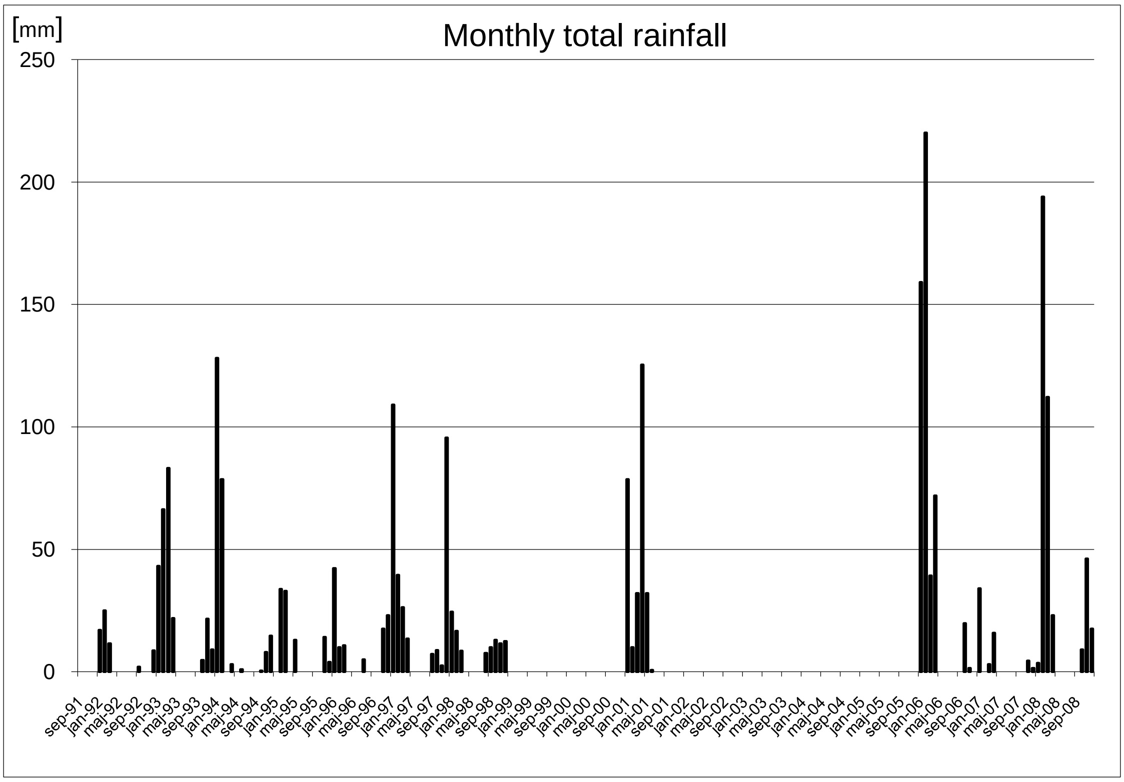

Figure 7: Monthly Total Rainfall (Namib Hydrosearch, 2009).

During years of good rainfall, flows in the Oanob River have been recorded as a result of spillage from the Oanob Dam. Years of high rainfall are also visible in the water levels in the aquifer due to the flood events caused by the releases of water from the dam. The yearly total rainfall is shown in Figure 8 (Namib Hydrosearch, 2009).

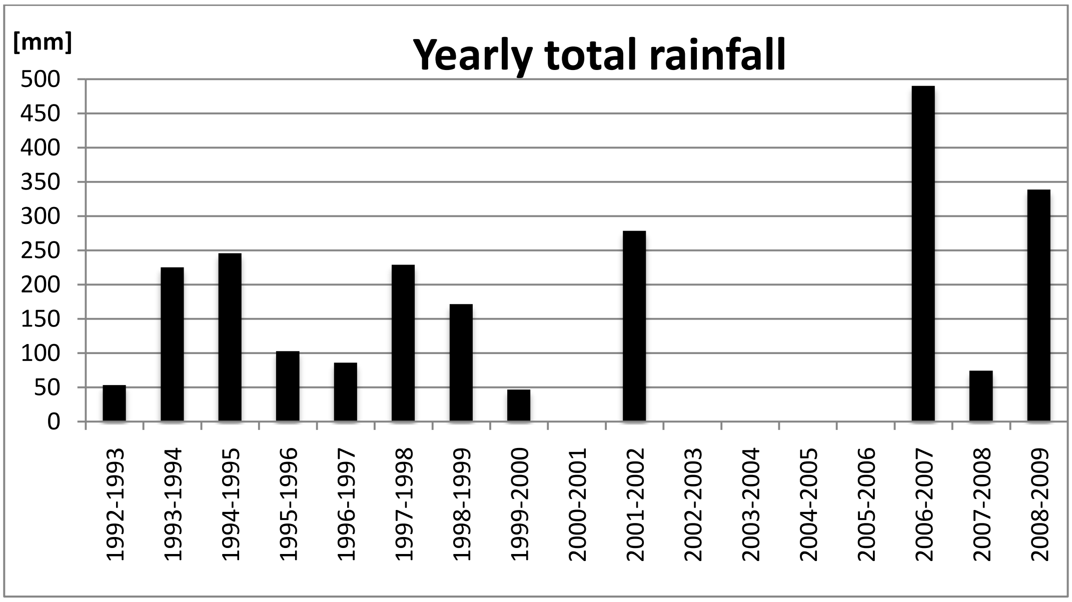

Figure 8: Yearly Total Rainfall in Rehoboth (Namib Hydrosearch, 2009).

3.3.2 Evapotranspiration

In areas where water is scarce, potential evapotranspiration is an important measure. It is a measure of the amount of water that would evaporate from the soil and transpire from vegetation, would there be unlimited water in the soil. In Namibia the potential evapotranspiration exceeds the rainfall (DWAF, 2009). The average annual evaporation for Namibia is shown in Figure 9, and the mean annual evaporation for the Oanob Aquifer is 3400 mm (MAWRD, 1993).

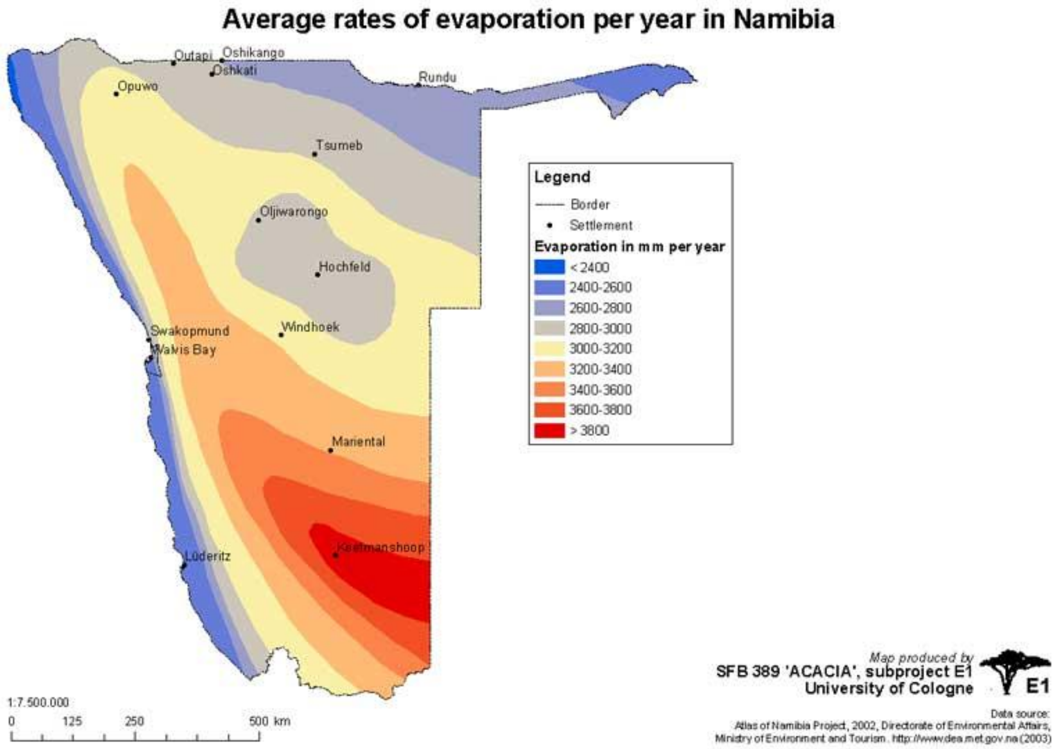

Figure 9: Average annual evaporation in Namibia (Atlas of Namibia Project, 2002).

3.4 Geology

The area in and around Rehoboth is underlain by a variety of metamorphosed sediments and igneous rocks of the Sinclair Sequence. Intruded into these rocks are dolerite dykes. The most common outcrops are schist and quartzite. On the eastern side of the road B1 to Windhoek the rocks are covered with unconsolidated red sandstone and calcrete (DWA, 1986). Thrusts striking approximately east-west, containing groundwater, occur in the area. According to a borehole in such a thrust, it has a strong yield but is disregarded for water supply due to the high content of fluoride and sulphate, see further in section 6.2 (DWA, 1983; DWA, 1989a). Weathering of metamorphosed sediments has resulted in material of varying grain size from cobbles and boulders to silt and clay. This material has been transported from the area of high relief, to the northwest of Rehoboth, and has then been deposited in the course of the Oanob River. As a result of this, to the south and southeast of Rehoboth, a substantial amount of unconsolidated alluvium has been deposited, forming the Oanob Aquifer (DWA, 1989a).

The underlying and surrounding bedrock of the Oanob Aquifer mostly consists of quartzite and phyllite-rich meta-sedimentary rocks. In the south and north, the aquifer is bounded by meta-sedimentary basement rocks of the Marienhof Formation, also known as the Rehoboth Sequence. In the east the formation is mostly covered by sand, and in the north it outlines prominent ridges to the west of Rehoboth. The bedrock is considered impervious due to its low permeability, and therefore the boundaries below and at the sides of the aquifer are regarded impermeable (Namib Hydrosearch, 2009; SWECO 2002). In the southeast of the aquifer bedrock outcrop of granite can be seen, and to the east there is a ridge called the Langberg Formation, striking northeast-southwest, consisting of quartz-phorphyry and subordinate schist belonging to the Nückopf Formation (DWA, 1983).

The main aquifer consists of the alluvium in the Oanob River. The alluvium consists mainly of unsorted sand and gravel which is rounded to sub-rounded with occurring lenses of silt and clay (DWA, 1983). In the longitudinal, lateral and vertical distribution there is a great variation in grain size. Also the clay percentage of the material in the aquifer is varying significantly, from 1 to 49 % (SWECO, 2002). There are two major peaks in clay content in the area. A possible reason for the first peak could be that flood water has changed from relatively high to low velocity somewhere near the Langberg Formation, and that sedimentation due to this has taken place just upstream of where the Swart Modder River joins the Oanob River (south of the Langberg Formation’s western side). For the next peak it could be possible that the Swart Modder River represented a new source of energy which led to less sedimentation where the river joins the Oanob and more sedimentation about three kilometres further down, where the water slowed down again (DWA, 1989a). The aquifer is made up of transmissive surface layers (Namib Hydrosearch, 2009), and the surficial deposits vary over the area, though mostly consisting of sand there are areas of gravel and clay (DWA, 1989a).

In the north end of the upstream compartment the thickness of the alluvium is less than 10 metres, and therefore it cannot store much groundwater. In the downstream compartment the alluvium is much finer and contains a greater percentage of clay. This, due to the fact that downstream the Langberg Formation the floodplain widens and the velocity of the water becomes slower (DWA, 1983).

3.5 Hydrogeology

The Oanob Aquifer is 21.5 km long and the width varies between 0.5 and 3 km. It is an alluvial aquifer partly divided in two compartments; the upstream compartment and the downstream compartment. The division is made by elevated bedrock at 5.8 km from the north-western end of the aquifer where a ridge of the Langberg - Nückopf Formation rises to about 11 mbgl (metres below ground level), making a barrier in the aquifer. The divide is visible at the surface as bedrock outcrop on both sides of the aquifer. The bedrock surrounding the aquifer is considered to be impermeable. The thickness of the aquifer varies between 10 and 38 metres, the average thickness being 20 metres and the depth to the bedrock below the alluvium can be seen in Figure 10 (Namib Hydrosearch, 2009; SWECO, 2002). The total area of the two aquifer compartments is 35.7 km^2 and the total volume of the alluvial material is estimated to 900 Mm^3. The downstream compartment is 15.5 km long and has no distinct end boundary. However, the alluvial deposits get narrower and thinner at the lower end (SWECO, 2002).

3.5.1 Storage Capacity

The most important function of the bedrock surrounding the aquifer is that it prevents water from leaking to greater depths. Even though the bedrock is impermeable, it is brittle by nature and due to that groundwater can be found in faults, master joints, and thrusts. This groundwater contains high amounts of fluoride and sulphate and is therefore not considered for groundwater abstraction, see further section 6.2 (DWA, 1989a; DWA, 1983). Different water levels and the artesian characteristics of the groundwater contained in the fractures means it is not in contact with the alluvial aquifer and will not affect the alluvial groundwater (Sarma, 2010).

Because of fluvial sedimentation during flood events, the sedimentation layers in the aquifer are laterally and longitudinally heterogeneous. The aquifer is considered unconfined even though there are clay lenses that give some areas semi-confined conditions. The semi-confined conditions are due to the lower permeability of the clay that slows down the flow of groundwater through the aquifer (Namib Hydrosearch, 2009).

The average specific yield used by Namib Hydrosearch (2009) in their calculations was 4.3 %, a modification of the specific yield of 5 % from the Department of Water Affairs (1989a). The specific yield is a measure of the storage capacity. It is defined as the amount of water which will drain naturally from a unit cube of aquifer material under gravity and is normally quoted as a percentage (DWA, 1989a). The calculations by Namib Hydrosearch with the specific yield resulted in a maximum potential storage volume for the aquifer of 26.7 Mm^3.

The total amount of water in the aquifer is a product of the 4.7 Mm^3 that is the storage volume in the upstream compartment and 32 Mm^3 in the downstream, though due to a maximum groundwater level in the downstream compartment of 5 mbgl the volume decreases to 22 Mm^3. A reasonable assumption is also that 60 % of the stored water can be abstracted lowering the amount of water available as water supply even further. The reported volume of water stored in the aquifer in 2009 is 8.9 Mm^3, about 24 % of the full capacity, and the abstractable amount is 5.4 Mm^3, see Table 2 (Namib Hydrosearch, 2009).

Table 2: Available resources in the Oanob Aquifer (Namib Hydrosearch, 2009).

Oanob Aquifer	Volume in Mm^3
Current available resource	8.9
Abstractable resource	5.4
Maximum stored resource	36.7
Maximum abstractable resource	26.7

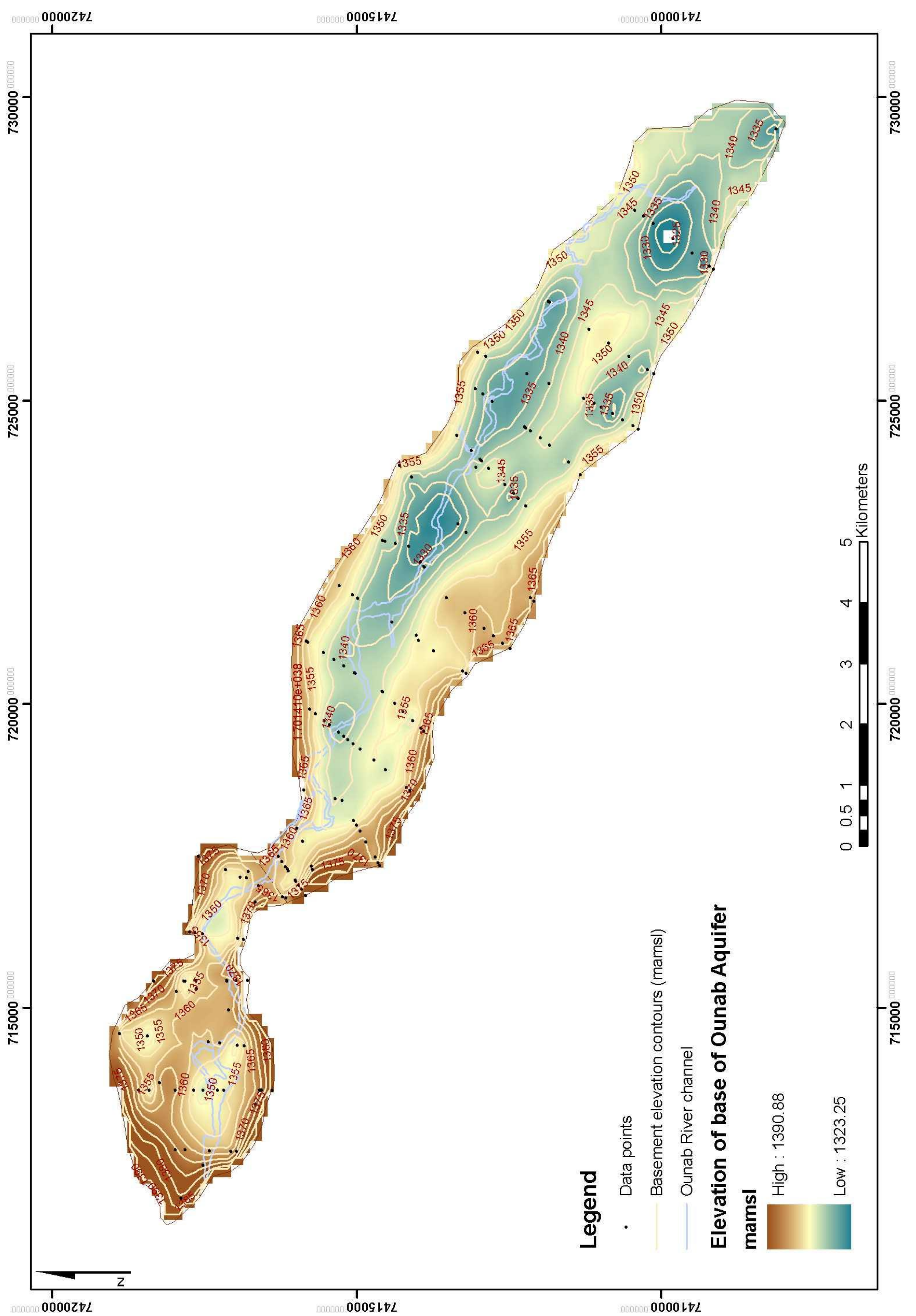

Figure 10: Depth to basement (Namib Hydrosearch, 2009).

3.5.2 Recharge

There are four possible sources for recharge of the Oanob Aquifer. Those are: leakage from the Oanob Dam, direct recharge from precipitation, recharge from the river, and discharge and leakage from the oxidation ponds constructed for treatment of the Rehoboth sewage water. Since the rainfall rate is very modest, the recharge by rainfall infiltration is negligible. Due to the large evaporation only very large rainfalls will result in water saturation of the alluvial sediments and if vegetation grows on the surface, up to 50 mm of rain needs to fall for recharge to occur (IWRM, 2009).

The most important source of recharge to the aquifer is river recharge. Earlier the aquifer was naturally recharged by river flow at regular times, but since the Oanob Dam was built it is only replenished by occasional water releases from the reservoir when there are sufficient rainfalls. This has affected the vegetation on the aquifer, when lower water levels have reduced the water available for plants (DWA, 1983; SWECO, 2002). From a flood event, 33 % of the water is estimated to infiltrate, though a maximum is set of 10 Mm^3 for each event due to saturation of the top soil layer (DWA, 1989a). With natural decline from through flow and vegetal transpiration accounted for, the effective recharge of the aquifer ranges from 10 to 20 % of the spillage volume. During years of sufficient rainfall the water level rises rapidly during the rain event and then the water level naturally dissipates due to discharge from the aquifer (Namib Hydrosearch, 2009).

Water is discharged from the aquifer by through flow, evapotranspiration, and by well abstraction. The main loss of water in the aquifer results from evapotranspiration when the aquifer is nearly full. The losses are to a large degree controlled by the vegetation. The factor of loss decreases with the falling water level, and for a water table more than 10 m below the surface, it is estimated that evapotranspiration from vegetation becomes negligible (DWA, 1989b). It is also noted that for the vegetation, the Acacia forest in particular, plant stress sets in when water levels goes below 14 m from the ground surface. The DWA estimated in a report in 1989 that the losses from evapotranspiration, when the aquifer is full and groundwater levels are at 4 mbgl, would be 8.4 Mm^3/a (DWA, 1989b).

With water levels below 10 metres from the surface, through flow is extensive, 0.6 Mm^3/a. In the report by the DWA (1989b), the calculated through flow in the aquifer when full, groundwater levels at 4 mbgl, would amount to 0.89 Mm^3/a. However, when empty, groundwater levels at 6 metres above basement, the through flow would be a mere 0.04 Mm^3/a.

There is a natural outflow at the southeast end of the downstream compartment, which lowers the water table in the compartment through drainage even if left untouched (DWA, 1989a). The rate of natural water level decline, following flood events, is about 1 m/a for the entire aquifer (Namib Hydrosearch, 2009).

3.5.3 Boreholes

There are 79 boreholes in the area of the Oanob Aquifer, and according to Namib Hydrosearch (2009), water levels could be measured in 25 of them. From the measures a water table elevation contour map was produced, see Figure 11.

The most productive and efficient boreholes are located in coarse alluvial environments. However, it is required that substantial care must be taken considering borehole location, design and development due to the anisotropic nature of the alluvium in the Oanob Aquifer (DWA, 1989a). Of all the boreholes in the aquifer only nine are currently being used for water withdrawal; seven for stock watering and the remaining two for irrigation and other farming purposes in the newly created farm plots south of town. The lower groundwater levels in the downstream compartment confirm pumping from boreholes on the aquifer, though the record of recent abstraction is nearly nonexistent (Namib Hydrosearch, 2009).

3.5.4 Groundwater Levels

The flow in the Oanob River is restricted to the active river channel, and therefore direct infiltration is constrained. The upstream compartment show shallower water levels in the northern part closer to the Oanob Dam, most likely due to seepage below the dam. In the upstream compartment, along the channel, elevated water levels between 3 and 9 mbgl are shown, while the levels are deeper, more than 12 mbgl, away from the channel. Water levels at the divide of the two compartments indicate that through flow to the downstream compartment is constricted, due to the bedrock rising to about 11 mbgl and the water level measured being 9.7 mbgl (Namib Hydrosearch, 2009).

The contour values of the water levels show; the influence from leakage below the dam wall, and the higher water levels below the river channel that dissipate laterally, see Figure 11. The difference in water levels for the upstream compartment, between inflow and outflow, is as much as 18 metres over a distance of approximately 5.5 km, giving it a gradient of 0.0033 (Namib Hydrosearch, 2009).

In the downstream compartment water levels are deeper, from 10.5 to 17 mbgl. In the central area of the compartment, a depression in the water table is evident due to abstraction of water. There are limited data from the southeastern part of the downstream compartment and none at the extremity, making the water levels in the area uncertain. The data available show a difference in head of about 20 m, which for the downstream aquifer give a gentler gradient of 0.0020. In general the boreholes away from the channel show water levels below 10 mbgl with a maximum of 13.75 mbgl (Namib Hydrosearch, 2009).

From hydrographs done by Namib Hydrosearch (2009) the influence flood events have on the aquifer is easily observed. The Oanob Dam has, since its completion, released water three times due to high rainfall (1996-1997, 1999-2000 and 2005-2006). The boreholes on the river channel show the earliest and highest influence from the water spillage, with no relevance to upstream or downstream compartment. Boreholes located off the channel have delayed and less pronounced increases of water levels. It is assumed that during a flood event the water is restricted to the river channel, thus infiltration occurs through the river bed.

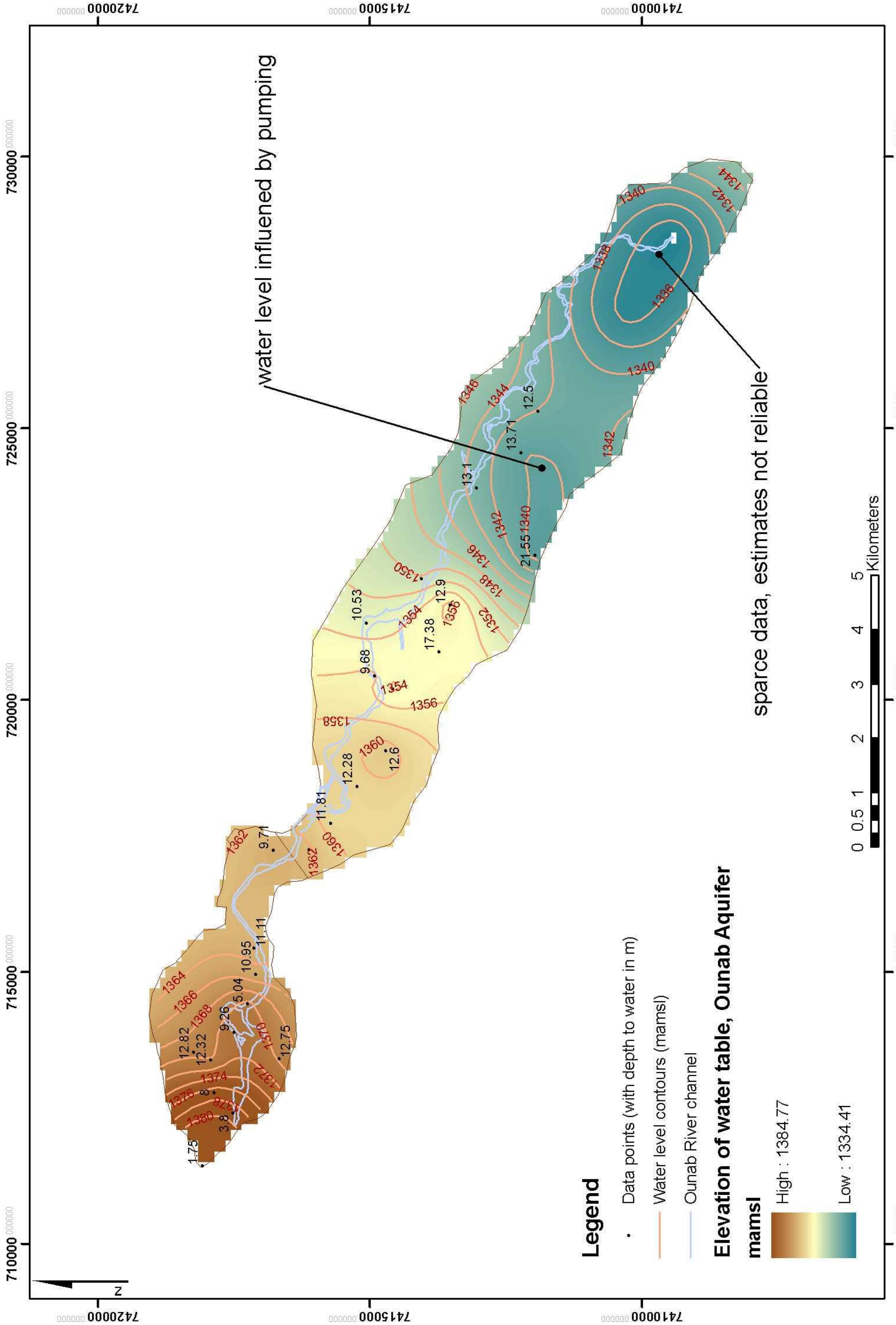

Figure 11: Elevation of water table (Namib Hydrosearch, 2009).

3.6 Conceptual Model

A conceptual model was produced with the information on the geology and hydrogeology of the Rehoboth area. The model was then used in the vulnerability assessment of the Oanob Aquifer. A conceptual cross-section can be seen in Figure 12.

- The area in and around Rehoboth is underlain by a variety of metamorphosed sediments and igneous rock. The most common outcrops are schist and quartzite. To the east of the B1 road to Windhoek, the rock is covered with unconsolidated red sandstone and calcrete. The aquifer itself is of alluvial sediments from the Oanob River. The outlying and surrounding bedrock of the aquifer is dominated by meta-sedimentary rocks of quartzite and phyllite. The bedrock is considered impervious due to its low permeability. The boundaries below and around the aquifer are thus regarded as impermeable.
- The Oanob River runs over an alluvial plain and the fluvial sediment from the river forms the Oanob Aquifer. The aquifer is divided into two compartments by a ridge of bedrock that transects the Oanob River, striking northeast-southwest, approximately 6 kilometres from the northern end. Southeast of the town of Rehoboth the upstream compartment begins and runs to the southeast for 5.8 km. With the length of 15.5 km, the downstream compartment is longer than the upstream, and continues in a southeast direction. The downstream compartment has a more indistinct boundary at the lower south end, where the alluvial deposits become thinner and narrower.
- The material in the aquifer is metamorphosed sediments which have weathered in varying grain size from cobbles and boulders to sand, silt and clay. The aquifer consists mainly of unsorted sand and gravel, with lenses of clay occurring. The thickness of the aquifer varies between 10 to 38 m.
- The interlaying clay in the aquifer varies, with the percentage of clay ranging from 1 % up to 49 %. The high clay content is located in the central part of the downstream compartment, and there are two major peaks of clay in the area. The first peak is situated approximately where the Swart Modder River joins the Oanob River, south of the Langberg Formation's western side. The second peak is three kilometres further down the river bed. The large clay lenses gives the aquifer semi-confining conditions, though the Oanob Aquifer as a whole is considered unconfined.
- The aquifer is made up of alluvial sediments, so it is the varying amount of clay content in the aquifer that governs the hydraulic characteristics. The hydraulic conductivity changes over short distances, due to the lenses of clay in the alluvial sediment. The hydraulic conductivity and transmissivity is dependent on the rock and soil type. The abstraction potential is also governed by the recharge of the aquifer, affecting the groundwater levels, the evapotranspiration, and through flow.
- The groundwater flows in the direction of the surface gradient. It flows from downstream of the Oanob Dam, southeast along the river bed and out of the aquifer as a natural outflow at the southeast end of the downstream compartment. The surface flow in the river is constricted to the active river channel.
- The elevation of the surface of the aquifer will influence the groundwater table. The hydraulic gradient of the upstream compartment is 0.0033, while it is 0.0020 for the downstream one.

- The hydrogeological system is heterogeneous, due to the variation in grain size in longitudinal, lateral and vertical directions.
- There are three sources of groundwater recharge:
    - Leakage from the Oanob Dam, which is visible as shallow groundwater levels in the southeast of the aquifer, downstream of the dam.
    - Recharge from the river, which since the dam was built only happens during years of high rainfall, when the dam needs to release water.
    - Leakage and discharge from the oxidation ponds northwest of the aquifer.
- The change in saturated volume in the aquifer, at a maximum rise in water level during a flood event, gives the total infiltration of surface water into the aquifer. It was estimated that about 10 to 20 % of the flow volume is infiltrated into the aquifer. Larger flow volumes do not give proportionally larger infiltrated volumes. This is probably because of saturation of the aquifer, resulting in increased runoff and higher losses by through flow.
- The groundwater levels vary between 2 and 22 mbgl. In the upstream compartment the water table is shallower, likely due to seepage from the dam. The river channel also shows higher water levels than the area further away, and this is because of direct infiltration from the active river channel. Along the channel the water levels are between 3 and 9 mbgl, and these decline away from river to around 12 mbgl. In general the downstream compartment has lower water levels with a water table of 10 to 13 mgbl under the river channel and around 17 mgbl away from it. The lowest point in the water table, 22 mbgl, is caused by water withdrawal at the central part of the compartment. The data is limited for the south-eastern part of the downstream compartment and entirely lacking at the extremity.
- Since the alluvial sediment of the aquifer is heterogeneous in grain size and there is no particular distribution of the material, the areas most vulnerable to pollution are where the groundwater table is the shallowest, where there is little unsaturated material to adsorb or absorb the contamination.
- In the evaluation of groundwater resources the key parameter is the aquifer storage coefficient, or the specific yield in the case of the Oanob Aquifer. The geometric mean of the specific yield is 4.3 %.
- Through re-interpretation of past test pumping in a few boreholes new figures on the hydraulic conductivity (K) were calculated by Namib Hydrosearch (2009). In the borehole situated in the upstream compartment the hydraulic conductivity value was 7.16 m/day. In the northern part of the downstream compartment the K-value was 22.43 m/day while about two kilometres further down it was 0.40 m/day. The next two boreholes were situated one and two kilometres further down in the downstream compartment with values of 2.97 m/day and 1.78 m/day. One borehole at the southeast end of the downstream compartment was test pumped and had a hydraulic conductivity of 2.84 m/day.
- From the same re-interpretation of the boreholes, the transmissivity was derived. In the upstream compartment the value was 52.26 m^2/day. In the upper part of the downstream compartment the values were 621.50 m^2/day and two kilometres away 9.86 m^2/day. The two boreholes one and two kilometres further down respectively had values of 35.60 m^2/day and 41.91 m^2/day. The borehole at the end of the downstream compartment had a value of 16.48 m^2/day.

- The most productive parts of the aquifer are the larger areas away from clay lenses that will restrict the flow of water. The downstream compartment can hold almost eight times more water than the upstream one, though it is further away from town.

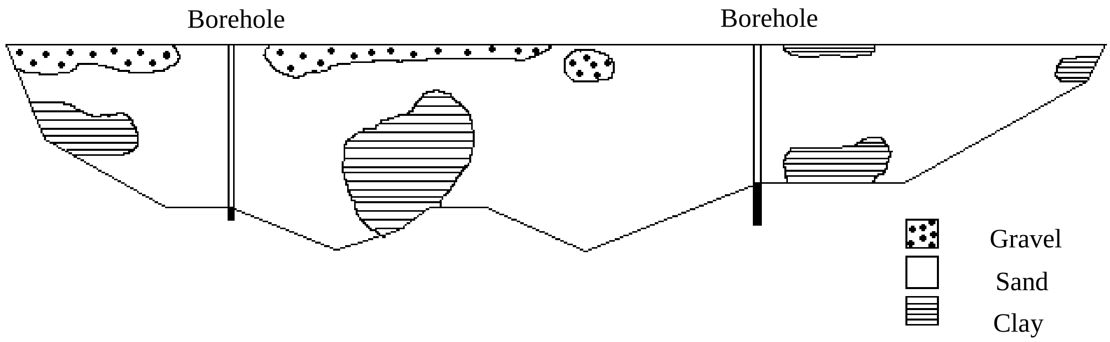

Figure 12: Conceptual model of a typical cross-section of the Oanob Aquifer (DWA, 1989a).

4 System Description

4.1 Drinking Water Supply System in Windhoek

The city of Windhoek receives its water from three different sources. Surface water from the Three Dam System, reclaimed water from the New Goreangab Water Reclamation Plant (NGWRP), and groundwater abstracted from boreholes in the Windhoek Aquifer, see Figure 14. Water from the dams make up 74 % of the average daily consumption of water in Windhoek. About 14 % of the water is provided from reclaimed water and the rest from groundwater (Menge et.al, 2009). The amount of water supplied from the different sources can be seen in Figure 13.

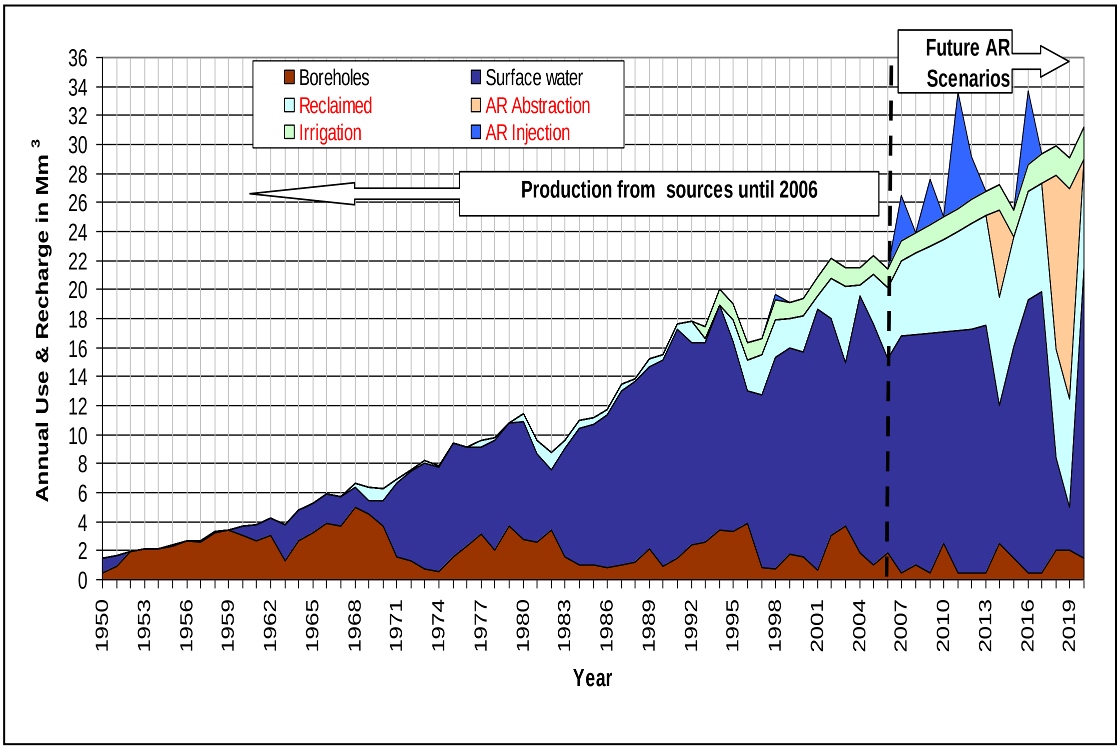

Figure 13: Past and future water supply for the Windhoek area from 1950 to 2020 (Van der Merwe, 2009).

The water consumption in Windhoek decreased after Water Demand Management (WDM) was implemented in 1994 (Van der Merwe, 1999), however due to an increasing population and development, the demand now continues to increase. Annual demand will, according to forecasts, increase to approximately 40.2 Mm^3 in 2021 (ENVES, 2009). With a population of 240 000 (City of Windhoek, 2010) the daily consumption of water in Windhoek today is around 60 000 m^3 (Esterhuizen, 2010), with an annual demand of 21 Mm^3. The cost for the Municipality for the different water sources supplying Windhoek can be seen in Table 3.

Table 3: Cost and supply volume for the water sources in Windhoek (Van der Merwe, 2009).

	Cost of Water [N$/m^3]	Present volume supplied [Mm^3]	Maximum supply capacity [Mm^3]
Groundwater	1.95	0.5-5.5	35
Surface Water	6.44	15	20
Reclaimed	7.84	5.8	7.6

The rising block tariffs are a part of the Water Demand Management implemented in Windhoek and involve full cost recovery, meaning that the tariffs cover full capital charges, as well as bulk water supply cost and operation and maintenance costs. The tariffs do not change in time of water shortage but the volume interval in each block may become smaller to impede high levels of consumption (Interconsult, 2000). The water prices for the tariffs can be seen in Table 4. The Municipality of Windhoek pay NamWater for the bulk water supplied from the Three Dam System at a price of 6.25 N$/m^3 (Peters, 2010).

Table 4: Rising Block Tariff for Windhoek (Peters, 2010).

	Volume [m^3/month]	Cost [N$/m^3]
Domestic	0-6	6.77
	6-45	11.26
	>45	20.75
Domestic (Flats)	0-6	6.77
	6-54	11.26
	>54	20.75

4.1.1 The Three Dam System

The bulk water in Namibia is supplied by NamWater, a parastatal enterprise established in 1997 (du Plessis, 2010). NamWater owns and operates all water infrastructure outside of the city of Windhoek's service area, including the Three Dam System (SWECO, 2002).

The Three Dam System consists of the Von Bach Dam, the Swakoppoort Dam and the Omatako Dam. The Von Bach and the Swakoppoort Dams are both situated on the ephemeral Swakop River, 60 km respectively 80 km outside of Windhoek. The Omatako Dam is located on the ephemeral Omatako River, 200 km outside of the city. The three dams are all interconnected, with Swakoppoort and Omatako Dams feeding the Von Bach Dam with water (Menge et.al, 2009). See Table 5 for hydrology and statistical data on the dams.

In central Namibia the evaporation losses are so big that the annual volume of water evaporating from the dams is greater than the water consumed in Windhoek (Menge et. al, 2009). The Von Bach Dam, due to its basin characteristics, has the lowest evaporation rate. When it is possible, water from the other two dams is transferred and stored in Von Bach Dam. This improves the 95 % safe yield for the Three Dam System, to about 20 Mm^3 (ENVES, 2009). The current supply from the dams is 15

Mm^3/a (Van der Merwe, 2009). In the Von Bach Dam the aim is to have a two year safety supply of water (du Plessis, 2010).

At the Von Bach Dam, a purification plant is situated to treat the surface water before it is distributed to the city of Windhoek. The capacity of the Von Bach Treatment Plant is approximately 6500 m^3/h (NamWater, 2004) The Von Bach Water Treatment Plant links the Von Bach Dam to Windhoek where there are reservoirs for water storage (Peters, 2010).

Table 5: Statistics of the Central Area Dams (NamWater, 2004).

		Omatako	Von Bach	Swakoppoort	All dams
Year in which completed		1983	1970	1979	-
Capacity	[Mm^3]	43.5	48.6	63.5	155.6
Supply Levels					
Lowest Abstraction Level	[mamsl]	1353.2	1329.5	1115.7	-
Full Supply Level	[mamsl]	1359.0	1350.0	1135.0	-
Annual Rainfall and Evaporation					
Average Catchment Rainfall	[mm/a]	368	320	360	349
Average Evaporation	[mm/a]	2247	2400	2456	2367
Annual Runoff					
Mean	[Mm^3/a]	32.5	17.1	20.9	70.5
Median	[Mm^3/a]	16.1	7.7	6.7	32.6
Yield at 95 % Assurance	[Mm^3/a]	2.0	6.5	4.5	20.0*

* When used conjunctively and operated to obtain the optimum yield.

4.1.2 Reclaimed Water

In Windhoek the domestic and industrial wastewater is treated separately. There are two biological wastewater treatment plants treating the domestic effluent, of which the Gammams Wastewater Treatment Plant (GWTP) receives most of the water, about 33 ML/day. After treatment the effluent is transferred to the NGWRP through a 1 km long pipeline. In the reclamation plant the water produced has a high enough quality for drinking water and irrigation. In Windhoek the direct potable reuse system to supplement the drinking water supply has been applied since 1969 (Menge et.al, 2009). The old reclamation plant started in 1969 and in 1993 the construction of the new plant began (Peters, 2010). The new plant has a maximum capacity of 21 000 m^3 and is currently producing around 16 000 m^3 of drinking water daily (Esterhuizen, 2010).

From the reclamation plant the water is transferred to the New Western Pump Station (NWPS). There the reclaimed water is blended, at a ratio of 1:2, with the surface water from the Von Bach Scheme, and then pumped into the distribution system (Menge et.al, 2009). The limit of one third reclaimed water in the drinking water is stated by the municipality of Windhoek (Esterhuizen, 2010).

The second wastewater treatment plant, Otjomuise, is under construction for expansion and treats water for irrigation (Peters, 2010). The industrial wastewater is transported to oxidation ponds north of Windhoek, where anaerobic and aerobic processes treat the water before it is discharged into an ephemeral river. There are currently plans for constructing an industrial wastewater treatment plant at the location of the oxidation ponds (Peters, 2010).

The Goreangab Dam is situated near the NGWRP and is part of the Windhoek reclamation scheme (Menge et.al, 2009). The city of Windhoek is located in the catchment area of the dam, which has affected the quality of the water to the point that the water in the dam is now only treated for irrigation purposes (Peters, 2010).

4.1.3 Windhoek Aquifer

There are 60 production boreholes situated around Windhoek, yielding groundwater that under normal circumstances is only used for peak demand. The present volume supplied varies between 0.5 and 5.5 Mm^3 depending on the water demand and if there is a water shortage. The Windhoek Aquifer has an available storage of 35 Mm^3. However, if deep boreholes are drilled, the available storage can increase to around 66 Mm^3 (Van der Merwe, 2009). It takes approximately 6 to 8 years to fill the Windhoek Aquifer with sufficient rainfall (Peters, 2010). To enhance the underground water the boreholes are also used to recharge the aquifer, through artificial injection (Menge et.al, 2009). With artificial recharge the time to replenish the aquifer can be shortened to 3 years instead. The aquifer is also serving as a storage facility to reduce the evaporation losses from the dams. The groundwater from the boreholes is not treated, but only chlorinated and put through carbon filters as it enters the storage facilities (Peters, 2010).

4.1.4 Distribution System

The distribution system in Windhoek is composed of 13 pressure zones (Peters, 2010) with pump stations, reservoirs, and transmission and distribution pipelines. The main purpose of the infrastructure of the distribution system is to move the water from the Windhoek terminal reservoirs, with a storage capacity of 30 000 m^3, to the people in Windhoek (SWECO, 2002; NamWater, 2004). The water losses in the whole distribution system are approximately 12 % per year (Peters, 2010). However, with leakage reduction in low-income households and government properties in Windhoek, it is estimated that more than 800 000 m^3/a of water could be saved (NamWater, 2004).

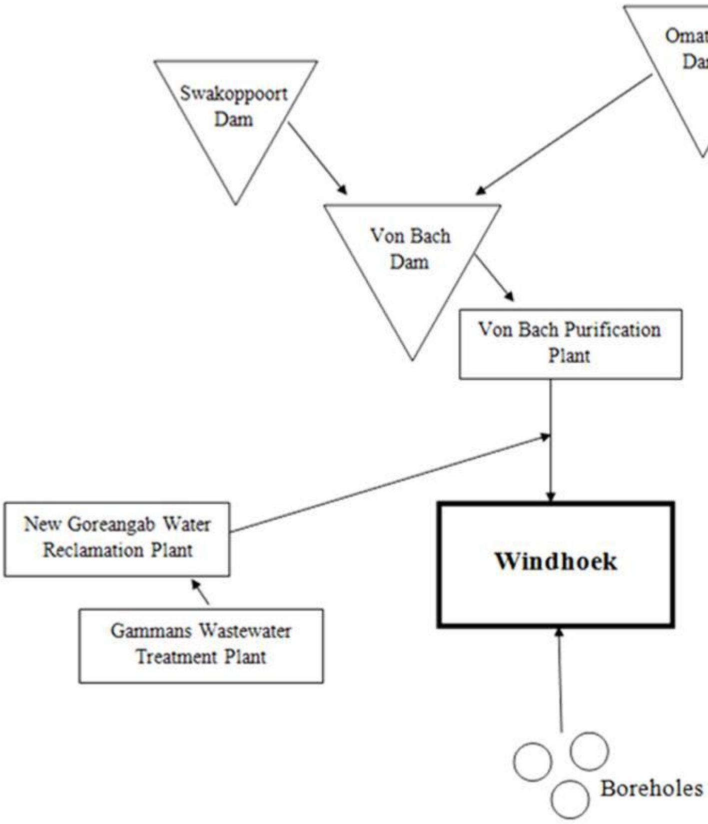

Figure 14: Schematic view of the drinking water supply system in Windhoek.

4.1.5 Alternative water supply

The regional and local water sources of Windhoek will soon be fully developed and therefore not able to meet the future demand. Today in Windhoek there are limited opportunities to further lower the water demand through Water Demand Management, instead additional sources need to be brought forward to increase the water supply to the capital city (ENVES, 2009). Of the existing sources, augmentation of the Windhoek aquifer is the only option for increasing the water supply in the medium term, as seen in Table 6. The current available storage in the Windhoek Aquifer is 35 Mm^3, though with deep boreholes the storage can be increased to 66 Mm^3 (Van der Merwe, 2009). The limit of the amount of reclaimed water being mixed with the surface water excludes the reclaimed water from being a suitable option for augmenting the water supply and the dams are already close to providing their safe yields. Instead alternative sources need exploring such as; water from the Okavango River at the border to Angola, The Tsumeb Aquifer approximately 400 kilometres from Windhoek, and desalinated water from the west coast (NamWater, 2004). The volumetric cost of the alternative water supplies (excluding desalination) can be seen in Table 3.

Table 6: Alternative water supplies with comparative unit reference values (Van der Merwe, 2009).

Cost of Water (2009) Alternative Supplies [N$/m^3]	
Okavango Pipeline	210
Tsumeb Aquifer	25.20
Artificial Recharge (Windhoek Aquifer)	11.87

4.2 Drinking Water Supply System in Rehoboth

Rehoboth receives its water from the Oanob Dam and NamWater provides the water at a cost of 6.50 N$/m^3 (Strauss, 2010). The town's current consumption of water is 1.2-1.5 Mm^3/a, though the estimation is that it will increase to 4.7 Mm^3 to year 2023/24 (Namib Hydrosearch, 2009). As Windhoek, Rehoboth uses Rising Block Tariffs for pricing their water when supplying it to the residents. The first 20 m^3 cost 8.10 N$ and it increases from there, see Table 7.

Table 7: Rising Block Tariff for Rehoboth (Strauss, 2010).

	Volume [m^3/month]	**Cost [N$/m^3]**
Domestic	0-20	8.10
	21-36	10.25
	37-46	10.70
	>47	11.88

4.2.1 Oanob Dam

The Oanob Dam, located on the Oanob River approximately 7 kilometres northwest of the town of Rehoboth, was constructed in 1990. The purpose of the water from the dam is at present irrigation and domestic supply to Rehoboth. The surface area of the dam is 3,603 km^2 and it has a capacity of 34.505 Mm^3 (NamWater, 2006). About 18 % of the water from the dam is evaporated every year (Strauss, 2010).

The Purification Plant, treating the dam water, is situated about 4 kilometres from the Oanob Dam (Du Plessis, 2010). The water is treated using a standard purification process. The capacity of the plant is 720 m^3/h and due to high costs of re-circulating water in the plant, the water not being treated properly is discharged into the Oanob River (Strauss, 2010). Before the water is released into the distribution system, it is stored in three reservoirs at the treatment plant, with a combined storage of 7500 m^3. By using gravity the water is then distributed through the town (Strauss, 2010).

The wastewater from the town is pumped to oxidation ponds, situated northeast of Rehoboth, where it is treated through anaerobic and aerobic processes. The water is then discharged into open land and measurements in boreholes downstream of the ponds show higher levels of contamination due to it. The hope of the Town Council is to have agricultural development near the oxidation ponds to utilise the treated water (Strauss, 2010).

4.2.2 Oanob Aquifer

There are 79 boreholes in the area of the Oanob Aquifer. 9 boreholes are in use at present, 7 for stock watering and 2 for irrigation and other farming purposes. However, there are no records of how much water the farmers withdraw from the aquifer (Namib Hydrosearch, 2009)

The Town Council is in the process of obtaining permission from the DWAF to abstract 1.3 Mm^3/a from the Oanob Aquifer. Half is intended to be supplied to a commercial poultry farm. The remaining water is to be supplied to the town to lower the quantity purchased from NamWater. The Town Council is considering using the Oanob Aquifer for its entire water consumption and to establish its own water supply scheme with a well field (Namib Hydrosearch, 2009).

4.2.3 Alternative water supply

The existing water supply in Rehoboth today is the Oanob Dam, and would be the most likely alternative water supply if the aquifer in the future would be utilised as the main supply source. Another possibility would be to construct a reclamation plant to help supply the town, though there are currently no construction plans (SWECO, 2002). The cost for Rehoboth would then be the bulk water cost that NamWater charges.

4.3 Possible Artificial Infiltration

To ensure a reliable supply of water to Windhoek and Rehoboth, artificial infiltration is a good option. It does not only give security of supply for years of drought, but also keeps the evaporation losses down when the water is stored in the ground. The Oanob Aquifer is considered as a potential extension of the water supply for Windhoek and as the potential main supplier of water for Rehoboth. A schematic overview of the prospective Oanob water supply scheme can be seen in Figure 15. With artificial infiltration as well as natural recharge from rain and spillage from the Oanob Dam, the recharge rate of the aquifer will be higher and the time to replenish the aquifer will shorten.

The Town Council of Rehoboth sees the chance to develop and operate the town’s own water supply in order to end the town’s dependency on NamWater. With a municipality-owned supply system the council can easier set their own tariffs and subsidise low-income households (Strauss, 2010). For Windhoek the aquifer represents an additional source of water not too far away from the city that soon will be necessary. The combined utilisation of the aquifer will also lower the construction, operation, and maintenance costs for both towns.

Moreover, the replenishment of the aquifer will have environmental benefits as well. Higher groundwater levels will for instance help sustain the Acacia forest on the aquifer and increase the vegetation growth. Storing the water underground will leave space in the Oanob Dam for new rainfall events to fill it up. It will also prevent loss of water from the dam through evaporation (Namib Hydrosearch, 2009).

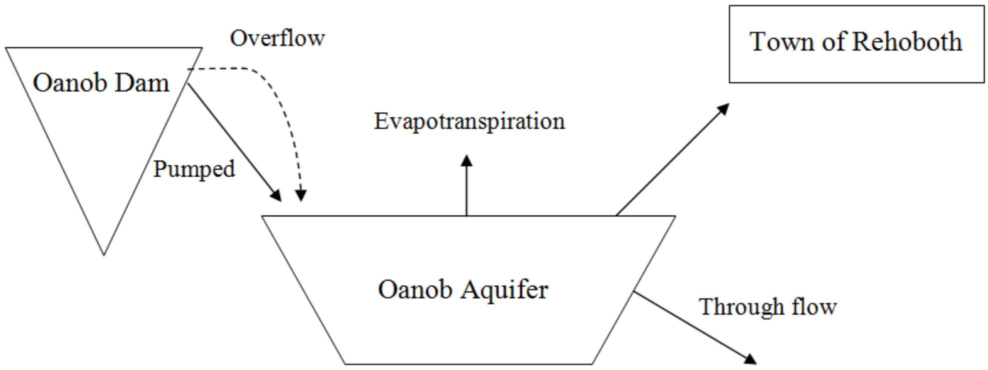

Figure 15: Schematic diagram of possible future scenario of the Oanob Aquifer (SWECO, 2002).

4.3.1 Key Parameters of Artificial Recharge

The infiltration of water is dependent on many parameters. To find the most suitable location for the recharge basins, information about the geology and hydrogeology of the area considered is needed. Factors influencing the infiltration are; the material's ability to transmit water, measured in hydraulic conductivity and transmissivity, the depth to groundwater and the thickness of the saturated zone. Important parameters to consider for the abstraction of the infiltrated water are the specific yield of the aquifer and the continuity of permeable layers between the infiltration and abstraction points (Parsons, 2003; SWECO, 2002).

The storage volume of the aquifer is important when investigating if artificial infiltration is viable. If there is not enough storage in the aquifer to provide the water needed, artificially recharging it is economically impractical. If there is no end boundary in the aquifer stopping the natural outflow of groundwater or abstraction of the out flowing water, it is equally as impractical to recharge the aquifer (Drews, 2010).

The Oanob Aquifer has a storage capacity of 37 Mm^3, almost the same volume as the Oanob Dam can hold. To infiltrate that volume of water into the ground would leave the Dam to be filled again during years of high rainfall, increasing the water available for Rehoboth and Windhoek (Theron, 2010; Drews, 2010). The aquifer has a semi-boundary at the southeast end of the downstream compartment that can be artificially improved to stop the water from flowing out (SWECO, 2002). The boundary can be seen as granite outcrop on either side of the aquifer and an underground "barrier" to stop the natural flow is planned to be built on the granite below the alluvial sediments (Namib Hydrosearch, 2009).

4.3.2 Basin Recharge

Basin recharge is the option, for artificial recharge, investigated in this study. The evaporation losses from the infiltration basins will be small, 1 to 2 %, for an infiltration rate of 0.5 and 1 $m^3/m^2/d$. The quality of the water from the Oanob Dam is good and can be used in the recharge scheme. Only during periods with heavy floods does the turbidity of the dam water increase to levels not suitable for infiltration and should during such periods be stopped. The water treatment capacity of the unsaturated zone will be used and minimal treatment of the abstracted water will be necessary (SWECO, 2002).

4.3.2.1 Technical Description

A basin recharge facility is composed of a water inflow structure, a construction for infiltration and an outflow structure. The water is gravitated from the dam, through a pipeline, to the recharge basins. The basins should be located on an as thick unsaturated zone as possible to have a longer distance to the groundwater (Hanson, 2000).

The water in the recharge basins is aerated so the concentration of oxygen in the water increases to enable the degradation of organic material. At the bottom of the recharge basins slow moving filtration sand is placed to create even conditions for the infiltration. Another reason for the sand is to have a grain size distribution that is beneficial to the natural treatment processes (Hanson, 2000).

After a time of running, a bio-layer will evolve at the bottom of the basins. When it becomes too thick and impenetrable, the basins need cleaning to remove the layer. The basins are then dried out and the layer of organic material is removed (Drews, 2010). In the sand filter the treatment processes start and then continue down in the unsaturated and saturated zone. Organic material is decomposed and adsorbed and iron and manganese precipitate. The sand also functions as a mechanical filter, removing particulates (Hanson, 2000).

When the infiltration water has gone through the saturated zone, it is abstracted as ordinary groundwater through wells. The retention time of the water underground is important to insure a satisfactory microbiological quality through the decay of bacteria and viruses, as well as the removal of organic material. However, a too long retention time can mean a decrease in oxygen and lead to substances like iron and manganese to dissolve (Hanson, 2000).

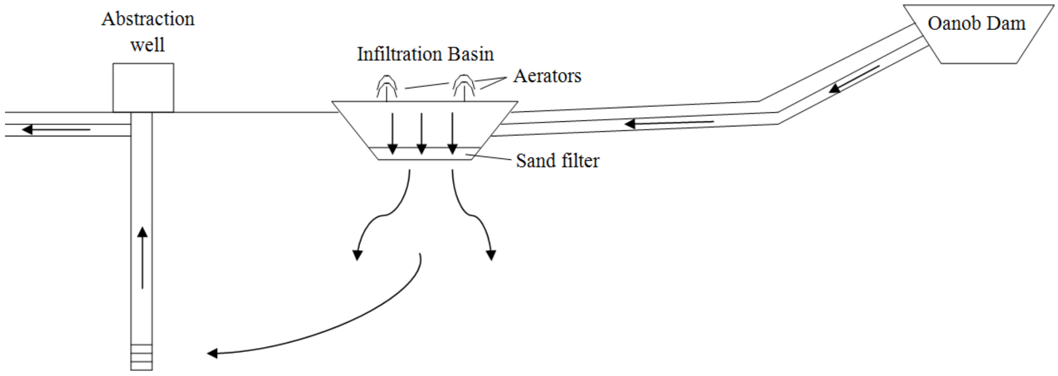

Figure 16: Schematic view of artificial recharge with basins (Hanson, 2000).

4.3.2.2 Problems with Basin Recharge

One of the biggest problems with infiltration ponds in alluvial aquifers is the suspended solids in the water that clog the sand filter at the base of the ponds, leading to the necessary cleaning of the basins (SWECO, 2002). When the main basins are out of commission either for cleaning or servicing, there then need to be provisional basins to use instead (Drews, 2010).

A pipeline should be used to transfer water from the dam to the infiltration ponds. The infrastructure of the pipelines, infiltration basins and abstraction wells should be protected so it won't be damaged from occasional overflow of the dam (SWECO, 2002). At another artificial infiltration project in Namibia, the Omdel Dam on the Omaruru River, the recharge basins are situated directly on the river channel. Every time there is a flooding the basins are destroyed and need rebuilding, this because the basins are ponds with sandbanks (Drews, 2010).

4.3.3 Risk of Pollution

The disadvantages of utilising the aquifer are the increased risk of polluting the water supply, the environmental repercussions of lowering the water table in the dam and the cost of constructing, operating and maintaining artificial infiltration basins and water infrastructure on the aquifer. There are hazardous activities on and near the aquifer which can contaminate the groundwater and if that is the case, the water resource can no longer be used. If the water levels in the dam are lowered there may also be considerable implications for recreational activities in and around the dam (SWECO, 2002).

To implement artificial recharge in the Oanob Aquifer, preventive measures against contamination need to be applied. It is necessary for the Rehoboth Town Council to control and regulate the activities happening on the aquifer (Strauss, 2010). Industrial development on or upstream of the aquifer need to be prohibited and the use of fertilisers, herbicides and pesticides need to be controlled, especially when irrigation is used. The oxidation ponds for wastewater treatment need to be moved further from the aquifer so as not to pose a threat of polluting the groundwater (Drews, 2010). When implementing an artificial recharge scheme there needs to be a groundwater protection strategy (SWECO, 2002). Protection zones with increasing restrictions closer to the infiltration and abstraction areas are recommended (UNEP, 1996). To protect the infiltration basins from animals and humans there need to be a fenced protection zone around them (Drews, 2010).

Artificial recharge may raise the groundwater levels in the aquifer significantly, which will make it more vulnerable to contamination. Particularly in areas where the upper layers already are polluted will the aquifer be more susceptible to contaminants (ENVES, 2009).

It is important to evaluate the possible locations of the infiltration basins to have optimum conditions for recharge. Not only do the hydrogeological parameters have to be right, but the pollution risk needs to be investigated to decide on suitable location and preventive measures.

5 Methodology

5.1 Overview of the Methodology

A pre-study is performed to incorporate all necessary information and data for the vulnerability assessment in the project. The study includes material from the archive at the Department of Water Affairs and Forestry at the MAWF in Windhoek, Namibia, as well as information obtained verbally from meetings, and in digital form as documents. The information is summarised in a conceptual model of the Oanob Aquifer. The method for the vulnerability assessment is based on the methodology explained in the report "Groundwater Vulnerability of the Windhoek Aquifer" (Interconsult, 2000). The method is implemented and adapted to suit the specific conditions of the aquifer and its surroundings and a vulnerability index is produced for the area and visualised through the use of Geographical Information Systems (GIS) techniques. The files for the GIS analysis are acquired from the consulting firm Namib Hydrosearch, which have previously investigated the Oanob Aquifer.

The hazardous activities are identified through previous documentation, meetings with people involved, and field studies to the area on two separate occasions. Assigned ratings of different parameters are integrated into one final rating for each activity and give the potential pollution loads from the sources. Together with the vulnerability index the pollution load gives the risk value. The provisional risk assessment is performed with the use of GIS and a map is constructed showing the risk index for the aquifer.

A flowchart of the proceedings of the methods for this project can be seen in Figure 17.

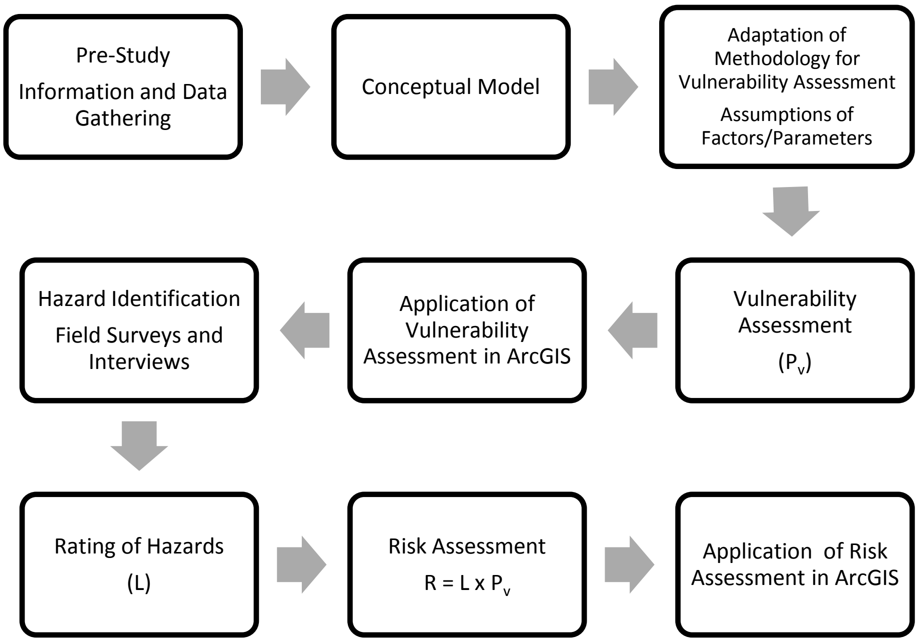

Figure 17: A flow chart of the methodology for the project.

5.2 Vulnerability Assessment

The concept of vulnerability assessment is based on the assumption that the system, involving soil, rock, and groundwater, can offer a degree of protection against contamination of the groundwater by “natural attenuation”. Vulnerability is an intrinsic property depending on the sensitivity the system shows to impacts, both natural and human (UNESCO, 2002).

Intrinsic groundwater vulnerability can be explained as the systems incapability of protecting its water against contamination (UNESCO, 2002). The difference between intrinsic and specific vulnerability is, the latter being contaminant specified meanwhile the first is contamination in general (Focazio et al., 2002). It is not only the groundwater-flow system that influences the vulnerability of the groundwater, but also the proximity to and the characteristics of contaminants. Furthermore, the vulnerability is a function of other factors that may increase loads of specified contaminant to the aquifer and their release to a groundwater source (Focazio et al., 2002).

There are numerous approaches for assessing groundwater vulnerability. Most widely used and well known is DRASTIC, a qualitative rating method. Qualitative methods assess intrinsic vulnerability and have many factors weighted to a final index. These methods are often easy to use and much of the information needed is already available (Aller et al., 1987). Quantitative methods on the other hand are more complex and not always appropriate to use, due to the unavailability of necessary data. They are based on analytical or numerical solutions to flow or transport equations and often give more distinct and clear answers than qualitative methods (Interconsult, 2000).

5.2.1 Vulnerability Assessment Methodology

The method used in the vulnerability assessment in this study is based on a probabilistic method developed in the report “Groundwater Vulnerability of the Windhoek Aquifer” (Interconsult, 2000). It is performed within a risk-based framework where the end target is a risk assessment, consisting of the assessment of groundwater vulnerability and the identification and evaluation of potential hazards.

With this method the assessment of the Oanob Aquifer can be used for more risk-based groundwater management. The approach will, as in the report by Interconsult (2000), be more focused on transport of contaminants in a probabilistic sense. This method also helps to avoid relative weights and instead reflects a model based on transport processes, where mainly existing information can be used. The results are expected to aid in further risk-based evaluations.

The risk for groundwater to be polluted can be visualised through an event tree, where the hydrogeological parts of the risk of a groundwater supply being polluted by human activities are displayed, see Figure 18. The model describes the possibilities for pollutant transport through the three major components of the hydrogeological system; the land surface, the unsaturated zone and the saturated zone.

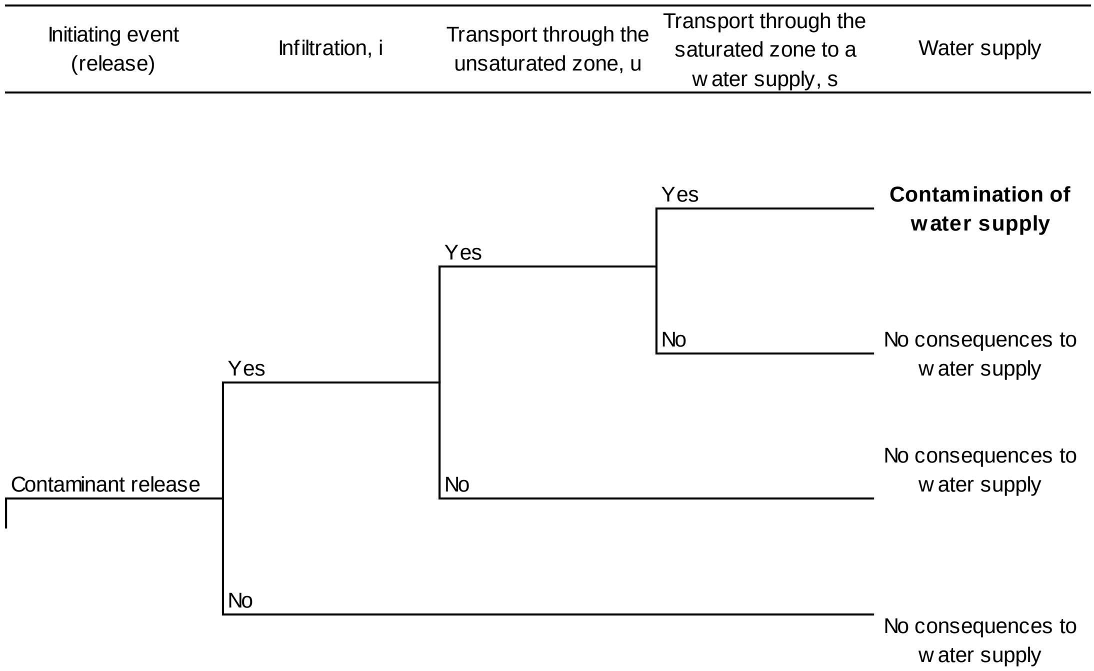

Figure 18: Event tree showing the interrelations of events leading to pollution of a water supply (Interconsult, 2000).

There are three main factors of concern in the assessment:

P_i: The probability for infiltration of pollutants at the land surface, given that a pollutant release has taken place.

P_u: The probability for transport of pollutants through the unsaturated zone, given that a pollutant release and infiltration have taken place.

P_s: The probability for transport of pollutants in the saturated zone to existing or potential future groundwater abstraction points, given that a pollutant release, infiltration, and transport through the unsaturated zone have taken place.

Three simple fault trees describing the parameters influencing transport through the three layers can be seen in Figure 19.

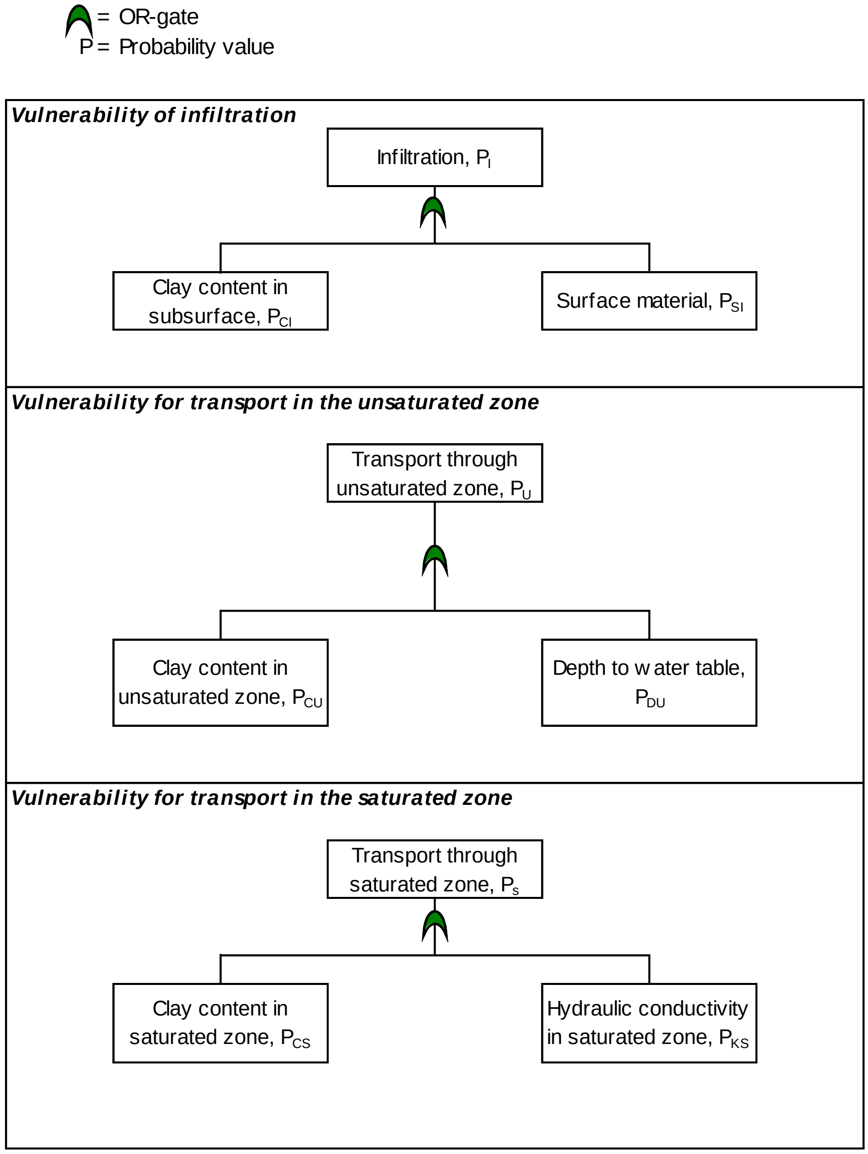

Figure 19: Fault trese showing the parameters influencing the transport in each zone (Rosén, 2010).

Each factor is given a rating between 0 and 1. This is firstly based on existing information and the conceptual understanding of the aquifer, and secondly the experience and knowledge of people both within the project team and others familiar with the study area and the hydrogeological conditions. It was assumed, due to the alluvial formation and the heterogeneity of the aquifer, that no dependency between the three factors exist, giving each layer its own probability for contamination governed by specific parameters. Probability estimations were used for the ratings for pollutant transport through each section of the hydrogeological system. The resulting product of the three factors is an estimation of the probability of a groundwater well, present or future, becoming polluted, given that a release will take, or has taken, place.

5.2.2 Assumptions of the Assessment Method

From the conceptual model of the Rehoboth area and available information, assumptions on the three factors concerned in the assessment were made.

P_i: The probability for infiltration of pollutants at the land surface. Given that a pollutant release has taken place it is assumed that the infiltration at the surface is dependent on the characteristics of the surface layer. In this case the clay content in the soil (P_{CI}) and the surficial deposits (P_{SI}) are the governing factors.

Low clay content means higher possibility of pollution infiltrating the surface layer and is given a higher index, see Table 8. Gravel as soil material enhances the infiltration possibilities for contaminants and is given a high vulnerability index, see Table 9. On the other end of the scale, given a low index, is clay as surficial deposits since it reduces the possibilities of contaminants infiltrating the subsurface.

Table 8: Clay content in subsurface, and in the unsaturated and saturated zones. The assumption is that clay is more impermeable than sand, and therefore determines the potential infiltration of pollution.

Vulnerability:	Assumption:	Rating
High	Mostly sand (alluvial sediments) Clay percentage: 0-15 %	0.97
Medium	Mostly sand (alluvial sediments) Clay percentage: 15-35 %	0.75
Low	Mostly sand (alluvial sediments) Clay percentage: 35-50 %	0.60
Areas with high clay content	Mostly sand (alluvial sediments) Clay percentage: >50 %	0.50

Table 9: Surface material, P_{SI}. The assumption is that gravel is more permeable than clay.

Vulnerability:	Assumption:	Rating
High	Gravel at surface	0.95
Medium	Sand at surface	0.80
Low	Clay at surface	0.50

P_u: The probability for transport of pollutants through the unsaturated zone. Given that infiltration has taken place it is assumed that further transport through the unsaturated zone is governed by the clay content in the soil (P_{CU}), as well as the depth to groundwater (P_{DU}).

For the conditions to be unfavourable in a vulnerability perspective, either shallow water levels or low clay content is required. Short distance to the groundwater table means less distance for the pollutants to travel and be attenuated before reaching the saturated zone and is given a higher index, see Table 10. Clay particles have a very large specific area, giving them a great capacity to adsorb chemical and biological substances. The low hydraulic conductivity of the clay leads to a low flow velocity for the water (UBC, n.a.). Although the amount of pore space in clay soils is larger, the average pore size is smaller making the ability to transmit water poorer. A fine-textured medium, such as clay, will slow down the material, e.g. air, water and micro-organisms, moving through the soil (Maier et al., 2000). See Table 8 for the rating of areas with different clay content.

Table 10: Depth to water table, P_{DU}. Longer distance to groundwater means better possibility for attenuation of contaminants and lower vulnerability.

Vulnerability:	Assumption:	Rating
High	Depth to groundwater 0-10 metres	0.90
Medium	Depth to groundwater 10-20 metres	0.70
Low	Depth to groundwater 20-30 metres	0.50

P_s: The probability for transport of pollutants in the saturated zone to existing or future groundwater abstraction wells. Provided that pollutants have reached the groundwater table it is assumed that the key factors for transport to abstraction points are the composition of the soil, clay content (P_{CS}), and the ability to transmit water, in terms of the hydraulic conductivity (P_{KS}).

High hydraulic conductivity, or a low amount of clay in the soil, indicates unfavourable conditions when considering the vulnerability. The ability for the water to travel in the soil is better with higher conductivity and is given a higher index. See Table 8 for rating with respect to clay content and Table 11 for rating with respect to hydraulic conductivity.

Table 11: Hydraulic conductivity in the saturated zone, P_{KS}. The ability to transmit water is what decides the vulnerability.

Vulnerability:	Assumption:	Rating
High	Hydraulic conductivity $>10^1$ m/d	0.90
Medium	Hydraulic conductivity 10^{-1}-10^1 m/d	0.70
Low	Hydraulic conductivity $<10^{-1}$ m/d	0.50

Regarding the clay content and the surface material the estimation for the boundaries between the three zones is based on information from the cross-sections in combination with previous investigations on depth to groundwater and basement. The infiltration zone and the unsaturated zone are set to a specific depth below ground surface, whereas the saturated zone is set from the bottom of the unsaturated zone to the bedrock. The generalisation of depth to the unsaturated zone means that little regard has been taken to measured groundwater levels in the aquifer.

5.2.3 Assumptions of the Area

To produce a vulnerability map of the area, general assumptions of the aquifer have to be made. The data available for the upstream compartment do not include geological information. The hydrogeological conditions of the compartment are therefore based on the data available, drilling borehole completion forms and data from the geological survey of the downstream compartment. The same procedure is used for areas on the boundaries of the aquifer and at the lower end of the downstream compartment, where data is sparse.

The Oanob Aquifer is surrounded by bedrock below and at the sides. The boundaries of the aquifer are, as a result, treated as impermeable. Based on information from previous investigations of the thermal aquifer, adjacent to the assessed one, the assumption is that the two sources are not connected.

Cross-sections of the downstream compartment were created from the geological survey of the area during an investigation in 1989 by the DWA. They are spaced one kilometre apart and describe the soil composition. The cross-sections present the percentage of the area each soil type amounts to. It is then assumed that the proportion of the cross-section area consisting of clay is 100 % clay and the area consisting of sand is 100 % sand. The ability to transmit water is evaluated from that assumption. Though the aquifer contains clay it is considered as an open aquifer.

5.2.4 Final Vulnerability Assessment

Each of the three main factors is given a rating between 0 and 1, where values close to 1 indicates a high pollutant transport probability through the hydrogeological system. Ratings close to 0 meanwhile indicate low probability of pollutant transport and values close to 0.5 point to equal possibility for pollutant transport and no transport. Hence, the highest uncertainty concerning pollutant transport in the hydrogeological system is for ratings of 0.5.

The final vulnerability index is formed by multiplication of the probabilities for each specific section of the hydrogeological system:

$$\text{Vulnerability}, P_V = P_i \times P_u \times P_s \qquad (1)$$

where:

P_i = *Probability of infiltration*

P_u = *Probability of percolation through the unsaturated zone*

P_s = *Probability of transport in the saturated zone*

Taking into account the governing parameters in each specific section of the hydrogeological system, as described by the fault tress in Figure 19, the vulnerability index can be calculated as follows using basic probability theory.

$$P_V = (1-(1-P_{CI})(1-P_{SI}))\cdot(1-(1-P_{CU})(1-P_{DU}))\cdot(1-(1-P_{CS})(1-P_{KS})) \qquad (2)$$

The vulnerability assessment shows where the aquifer is most vulnerable, and where actions need to be taken, and where it is less vulnerable, and suitable for artificial infiltration from a contamination point of view. A map of the special distribution of the vulnerability was performed using the software ArcGIS 9.

5.2.5 GIS Application

To visualise the results of the vulnerability assessment, maps are produced using GIS techniques. Files from Namib Hydrosearch offer a basis for the layers created in the GIS software. A map of each main component in the hydrogeological system is generated by the parameters governing them, see Appendix III (Maps 1-6).

For infiltration through the subsurface two layers are created, one of the soil materials and one of the percentages of clay in the ground. From geological maps as well as cross-sections of the aquifer, information of the soil materials are derived and used as input data in the GIS programme. Information of soil material is used as input in points of the cross-sections and then interpolated to cover the aquifer area. For the amount of clay in the soil, the same cross-sections are used as input data and the clay percentage is noted in each point and later interpolated. Transport through the unsaturated zone is determined by the groundwater levels and the percentage of clay in the ground. A map of the groundwater table is derived by interpolation of monitoring data of boreholes in the aquifer. In the saturated zone the transport to a groundwater abstraction point is controlled by the hydraulic conductivity of the aquifer material and the percentage of clay in the ground. The data of hydraulic conductivity is collected from calculations, from pumping tests performed in some of the wells on the aquifer, as well as from the soil material in the saturated zone. From a figure in Parsons (2003) the hydraulic conductivity for each soil type is then derived, with a range of 10^4 for coarse gravel to 10^{-4} for clay, for the areas where no boreholes are situated. Interpolating the data over the area gives the hydraulic conductivity for the aquifer. Each interpolation is performed by the Inverse Distance Weighted approach, where a specific number of points and a specific radius around the point interpolated give the value for that particular point.

The compilation of the layers will produce a map where the vulnerability will be indexed from low to high, relative to the area. Using the final vulnerability equation in the programme will add the map layers together in accordance with equation 2 and a vulnerability map with the probability of contamination will be constructed.

5.3 Hazard Identification and Rating

A hazard is a situation that in certain circumstances can lead to harm. Identifying hazards is the process of finding and listing hazards and defining their characteristics. It entails documenting all events with unwanted outcomes that may result from natural circumstances, a proposal or human activities. Hazard assessment estimates the consequences of the hazards, if they are to occur (Burgman, 2005).The description of the identified hazards is a detailed process and there are various methodologies used to identify sources depending on the purpose, objective and scope of the inventory (UNESCO, 2002).

5.3.1 Hazard Identification Methodology

The potential hazards to the aquifer are evaluated with respect to sources on the aquifer itself and sources outside of the hydrogeological boundaries. The characterisation of the potential sources is based on a method used in the report "Groundwater Vulnerability of the Windhoek Aquifer" (Interconsult, 2000). The three parts of the method are:

- Identification of pollution sources
- Screening of identified sources
- Characterisation of sources

The identification of potential sources is made through interviews with informed people, using existing information and doing short field surveys of the area. Through the screening, the pollution sources are organised into categories, on and off the aquifer, see further chapter 6.2. Due to the assumption that the bedrock surrounding the aquifer is impermeable, the hazards outside of the aquifer boundary are regarded as less severe than the ones on the aquifer. Therefore, only the sources located on the aquifer are regarded in the risk assessment.

5.3.2 Hazard Rating and Pollution Load Methodology

The small number of possible sources made the categorisation a minor part of the evaluation. Five factors are then used to characterise the identified sources:

L_1: Toxicity of materials used at the potential source.

L_2: Possible release quantity.

L_3: Probability of release of pollutant.

L_4: Type of deposition, i.e. wet or dry.

L_5: Possibility of remediation in case of pollutant release.

Each factor is given a rating between 0 and 1 using a rating table shown in Table 12. The rating is based on existing information and the opinions of people informed of the study. A high rating close to 1 signifies a high potential pollution load with respect to the specific factor, whereas a low rating indicates a low potential pollution load.

The ratings are compiled into a final rating of the potential pollution load (L) for each possible source as:

$$L = \frac{1}{5}\sum_{i=1}^{5} L_i \qquad (3)$$

for the factors i = 1-5.

Table 12: Rating table for characterisation of potential pollution loads (Interconsult, 2000).

L_1 Toxicity		L_2 Release quantity		L_3 Probability of release		L_4 Type of release		L_5 Possibility for remediation	
Very low	0-0.1	**Very small**	0-0.1	**Very low**	0-0.1			**Very limited**	0.9-1.0
Low	0.1-0.2	**Small**	0.1-0.2	**Low**	0.1-0.2	**Dry**	0-0.3	**Limited**	0.7-0.9
Low – Moderate	0.3-0.4	**Small – Moderate**	0.3-0.4	**Low – Moderate**	0.3-0.4			**Limited – Fair**	0.6-0.7
Moderate	0.4-0.6	**Moderate**	0.4-0.6	**Moderate**	0.4-0.6	**Wet/dry**	0.3-0.7	**Fair**	0.4-0.6
Moderate – High	0.6-0.7	**Moderate – Large**	0.6-0.7	**Moderate – High**	0.6-0.7			**Fair – Good**	0.3-0.4
High	0.7-0.9	**Large**	0.7-0.9	**High**	0.7-0.9	**Wet**	0.7-1.0	**Good**	0.2-0.3
Very high	0.9-1.0	**Very large**	0.9-1.0	**Very high**	0.9-1.0			**Very good**	0-0.1

From the characterisation each potential pollution source has been given a rating between 0 and 1. The rating for each source is then incorporated into the creation of GIS maps.

5.4 Risk Assessment

A risk assessment is an overall process divided into two parts, a risk analysis and a risk evaluation. The risk analysis involves identifying both the likelihood and the severity of adverse consequences occurring due to a given activity, facility or system. A risk estimation then follows to produce a measure of the level of risk being analysed (IEC, 1995). The information and knowledge obtained in the risk analysis is then the basis for the risk evaluation, where decisions are made on the tolerability of the risks and options for possible risk-reduction are analysed (IEC, 1995).

5.4.1 Risk Assessment Methodology

This risk assessment is a continuation of the method in the report by Interconsult (2000), where the vulnerability together with pollution load is incorporated. A provisional risk value is calculated for each identified contamination source. The product of the potential pollution load (L) and the consequences (C) of the load gives the risk (R).

$$R = L \times C \qquad (4)$$

The consequence (C) of a specific pollution load is a function of the vulnerability to pollution (P_V). The effective and strategic prioritisation of protection efforts is a favourable outcome of this type of risk-based approach. The risk product is then:

$$R = L \times P_V \qquad (5)$$

The provisional risk value is calculated according to the equation above. The co-ordinates for a few of the identified pollution sources were not available and the positions for them are instead determined from satellite photos, see Appendix II for specific sources. Areas outside of any potential hazardous activities are given a low pollution load of 0.05 and thus also a risk value. This is based on the assumption that polluting activities may take place away from potential sources (Interconsult, 2000). At the locations where more than one activity is operating, the pollution load for each specific source is added together using probability theory. This generates a probability for the position where all activities could occur independently of each other or all at once (Burgman, 2005).

The provisional risk value is also visualised using a risk matrix, see Figure 20. The matrix's rating interval ranges from low to high and is visualised through the colours green, yellow, and red. Where red is unacceptable risk, green is acceptable and yellow is an area of judgment. The boundaries between the zones are not fixed but can be adjusted depending on the conditions of the area, regarding both the potential pollution sources and the vulnerability of the aquifer. The placement of the boundaries is often decided by the decision-makers. The positions in the matrix for each potential source are determined by cross-plotting, where the potential pollution load of each source is matched with the vulnerability of the area where it is located. A risk evaluation is then performed in the results chapter and later discussed in Chapter 7.

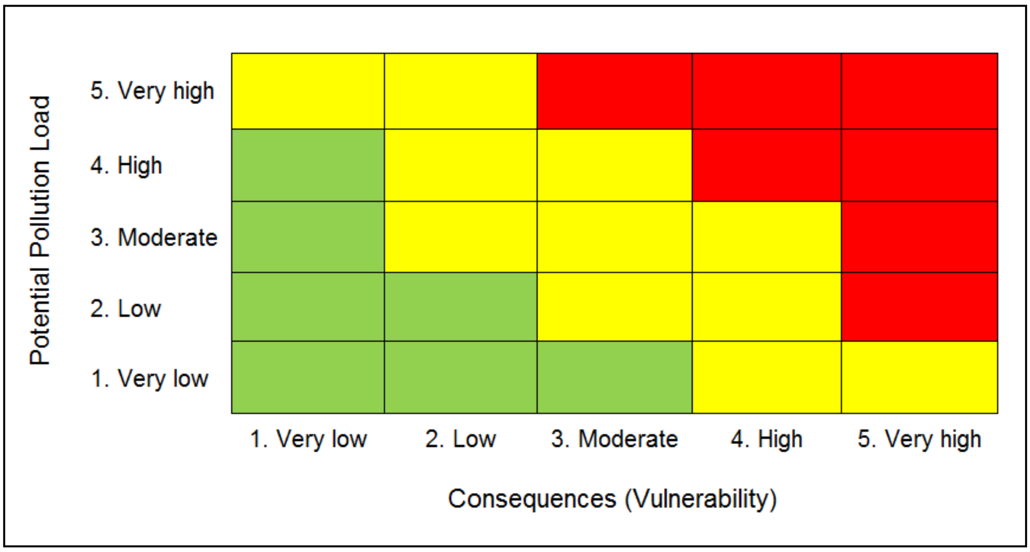

Figure 20: Risk matrix.

5.4.2 GIS Application

For the risk assessment map to be created, the final rating of each hazardous activity needs to be used. Each identified hazard is then assigned a radius of 250 metres, due to the uncertainty of the exact position of each hazard as well as a precaution for pollution spreading. The maximum risk value within the 250 metre radius is assigned to the pollution source. Areas with no potential pollution sources are assigned a low potential pollution load. The risk value is calculated in the GIS software, assigning the maximum risk value found within the 250 metre radius to the specific hazardous activity. Areas away from any identified pollution sources are assigned a risk value, based on the assumption that hazardous activities may take place away from potential pollution sources identified.

A compilation of the vulnerability map and the layer with the potential pollution loads gives a risk map over the area. The risk value is a product of the vulnerability index of the aquifer and the rating of the identified hazards, giving a map of the aquifer showing an estimate of the high and low risk of the area.

6 Results

6.1 Vulnerability Mapping

The compilation of the different layers in the GIS software ArcGIS 9 resulted in a final vulnerability map of the Oanob Aquifer, see Figure 21. The map shows the groundwater vulnerability in graduated colour, with values ranging from 0 to 1 where high values represent the most vulnerable areas. For a larger map, see Map 11 in Appendix III.

The map clearly reflects the distinct hydrogeological conditions of the Oanob Aquifer due to the importance of the lithology to the aquifer characteristics. The clay lenses in the ground govern the movement of the potential contaminants and thus have a major influence on the vulnerability of the aquifer. The most vulnerable areas are located in the northwest part of the upstream compartment and the lower south bank of the downstream compartment. These areas are associated with low clay content in the alluvium and either thin unsaturated zone or transmissive surface layers.

Also the areas with high water levels are associated with high vulnerability, particularly along the river channel and the top end of the upstream compartment due to infiltration and seepage below the dam wall. Areas of coarser alluvial deposits at the south-eastern part of the downstream compartment are associated with a high vulnerability due to high infiltration capacity. Areas of the eastern part of the upstream compartment and southern areas from the middle of the downstream compartment exhibit relatively high vulnerability, due to high water levels and for the latter high hydraulic conductivity.

Areas with high clay content are given a relatively low vulnerability. The northern and central part of the downstream aquifer is considered to be less vulnerable. However, the distribution of the clay in these areas is not clearly defined. The probability for pollution in the case of a pollution release is relatively low in these areas, but no area can be regarded as "safe".

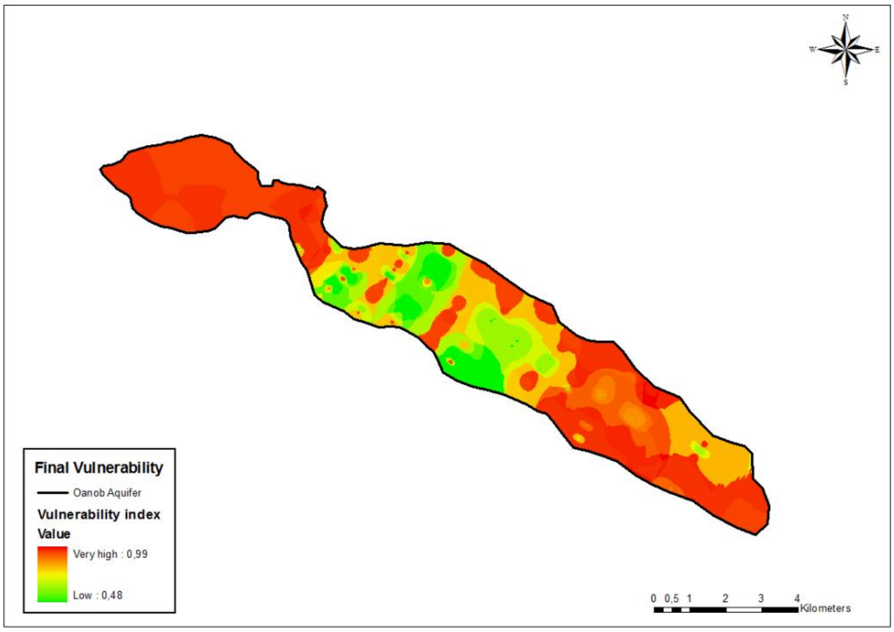

Figure 21: Vulnerability of the Oanob Aquifer.

6.2 Pollution Load

The field surveys together with meetings and information from reports resulted in the identification and rating of potential pollution sources. The hazardous activities identified are presented in a map where the ratings for each source show the potential pollution load. The results of the identification and rating follow below.

6.2.1 Hazard Identification

There are 15 categories of potential pollution sources found in the area around the Oanob Aquifer. All together there are 51 potential pollution sources on the aquifer and 24 potential sources off the aquifer identified. During two separate field surveys most of the sources on the aquifer were visited and information was gathered. In the sections below the sources are briefly described.

6.2.1.1 Potential Sources on the Oanob Aquifer

Green Houses

On the southern bank of the upstream compartment of the Oanob Aquifer, green houses are situated. Water from the Oanob Dam is supplied through a pipeline to these, as the groundwater is too hard and not suitable for irrigation (Sarma, 2010). According to Namib Hydrosearch (2009) the management of the green houses claim they recycle almost all of the water and very little is discharged onto the aquifer. The water from the green houses is collected in a tank and then pumped to a garden in the backyard where it is used as irrigation water. Tomatoes, sweet pepper, and cucumbers are cultivated, as well as flowers. There are approximately 800 tomato plants and each plant gets 3 litres of water per day. The plants are sprayed for insects.

The major threat from the green houses is the irrigation water. The possible pesticides and fertilisers will with the water infiltrate into the ground and then possibly pollute the aquifer.

Slaughter House

On the plot next to the green houses is an abattoir, using a pipeline to transport the effluent to town. The water is pumped to a pump station on the premise and then to the sewage ponds east of Rehoboth. There is another pipeline for the transport of animal entrails from the abattoir to a field where it dries out. The dry substance is then sold as compost.

The sewage pipeline is stretched across the aquifer and possible leakages may be a threat. The drying substance may leach water with high amount of nutrients through the surface into the ground.

Illegal waste disposal

A town waste disposal site, located in the north of town, is not functioning properly. Instead, the open ground of the Oanob River bed is being used as a site for dumping of domestic waste and building rubble (Namib Hydrosearch, 2009). This is occurring on the area of the aquifer closest to town, in the upstream compartment (Sarma, 2010).

The pollution threat from the waste disposal is large as the aquifer is unconfined and the surface layers are made up of permeable sand.

Sand mining

There are several sites where sand and gravel is illegally excavated for building material along the Oanob River. The excavation is taking place in the upstream compartment near the town. Two large sites at opposite sides of the Oanob River channel are also being used for illegal waste disposal. In the report from Namib Hydrosearch (2009), ponding was noticed in one of the sites, indicating that excavation could be to saturated levels.

The largest threat from the excavation is the disposal of waste being done at the sites. The aquifer is unconfined and the saturated zone is nearer to the ground surface due to excavation, which heightens the possibility for contaminants to reach the groundwater.

Thermal aquifer

There is a thermal aquifer in the fractures in the bedrock under the town of Rehoboth. The thermal groundwater is in the fractures north of the upstream compartment and these probably run through the bedrock of the river within the intersecting area of the alluvial aquifer. Different water levels and the fact that the thermal aquifer is artesian suggest that the two aquifers are not connected.

When drilling on the edge of the Oanob Aquifer there is a risk of intersecting a fracture with thermal groundwater that is below the alluvium. The content of fluoride and sulphate are much higher in the thermal water and if mixed will lower the quality of the groundwater being abstracted.

Thermal Spa

Thermal groundwater from below the town is used at the town's Thermal Spa located on the aquifer. Water is pumped from the spring in town to the spa and used in the hot water swimming pools. The effluent then goes into an evaporation pond within town (Sarma, 2010).

There is no information on any discharge of water into the aquifer or of any possible pollution.

Livestock farming and boreholes

The Oanob Aquifer has a surface area of 35.7 m^2. Most of the aquifer is covered by grass vegetation and Acacia trees, and is used as grazing land for livestock. The farmers utilising the aquifer area for their animals do not have any fences, though the animals tend to graze around the boreholes used for watering the livestock (Sarma, 2010). There are 7 boreholes in use on the downstream compartment of the aquifer. During a hydrocensus carried out by Namib Hydrosearch (2009), pumps were found leaking oil into three of the boreholes. Water samples were taken and analysed for 4 boreholes and 3 of those were found to have good quality water, and one was classified as having low risk water (Namib Hydrosearch, 2009). This is of no risk for the livestock, however for domestic use it may be of concern. At present there is no information on the number of animals or other practices at the farms. Neither is it recorded how much water is abstracted from the boreholes, though influence from pumping in the downstream compartment is visible from the lowered water table (Namib Hydroserach, 2009). The Town Council are trying to educate the farmers on the abstraction of water from the wells and how to manage it properly.

The aquifer is at risk from the oil and diesel leakages into the boreholes and directly to the groundwater. The areas around the boreholes are sensitive to the nutrients in the animal droppings and there is a possibility of nutrients infiltrating the soil close to the borehole and affecting the water, if animals are kept close. Overgrazing is another threat to the aquifer since contaminants infiltrate easier through surfaces without any vegetation. There is no information on possible use of feeding or antibiotics.

Agriculture plots

New agriculture plots have been established on the northern bank of the Oanob River at the south end of Rehoboth. There are 35 plots of 5 ha each, created for crops and horticultural farming. There are an additional 4 community plots planned for 2010, for people who cannot afford the commercial plots already developed. At present there are no municipal services, i.e. water and electricity, at the agricultural plots. There is little activity so far, none of the plots are operating at full capacity, since the Town Council needs to approve their agricultural activities and permits need to be issued. The Town Council is now in the process of gathering information from the farmers of what activities will take place, what pesticides and fertilisers will be used and the amount of water the farmers will need to abstract from the aquifer. With the information gathered and the permits issued, the Town Council hopes to enforce more control and better regulations on the activities on the aquifer (Strauss, 2010).

There are mostly communal farmers on the aquifer thus far. However, a few companies have started development:

- The company Reho-Olives, owns one of the agricultural plots and is planning to grow olive trees. The possible use of fertilisers, herbicides, and pesticides are a threat to the aquifer.
- A Chinese company, owning one of the plots, is planning to build a poultry factory.
- A pig farm, temporarily set up on a plot, has applied for new land and is planning to move to a more permanent place further east. The farm uses borehole water collected in a tank and the waste from the pigs is used as compost and fertilisers by other farmers.

The major threat from the agricultural plots is the irrigation. The possible pesticides and fertilisers will with the irrigation water infiltrate the ground and then possibly pollute the aquifer. Many Acacia trees are being cut down in the area of the plots for the agricultural activities. Not only are the trees a protected species in Namibia, but the possibility of pollution of the aquifer increase with less vegetation.

Domestic Households on the aquifer

Block E of the town of Rehoboth is situated on the aquifer, according to Mr. Strauss of the Rehoboth Town Council (2010) it is approximately 10 % of the town area. The block mainly consists of low cost residential houses with one school and small businesses. When visiting the place a lot of waste was visible, especially south of the road that divided Block E from the agricultural plots.

The absence of a proper waste disposal site in the area is a major threat to the aquifer. The local households seem to use the other side of the street, where the agricultural plots are located, as a dumping ground. The pollution from that waste can then infiltrate into the ground.

6.2.1.2 Potential Sources off the Oanob Aquifer

Oxidation Ponds

The eight oxidation ponds are located approximately 2 kilometres east of Rehoboth. The ponds are not lined and seepage is expected to be high. The treated wastewater evaporates, seeps into the ground or spills onto open land. A field survey was done by SWECO (2002) for the study of artificial recharge to aquifers in the central area of Namibia. During the inspection it was observed that the outflow from the last pond was small. The inflow of wastewater is not known, however an estimation made by SWECO showed that 40-50 % of the water consumption reaches the ponds. The ponds were cleaned two years ago (Ockhuizen, 2010).

Leakage and discharge from the oxidation ponds are a source of recharge for the aquifer as well as a potential pollution source (SWECO, 2002). Higher levels of pollution are noted in boreholes downstream of the ponds, though no changes in quality in the aquifer have been noticed. The Town Council wants development of agricultural properties around the ponds so that the water can be used for irrigation instead of going directly into the ground (Strauss, 2010).

Poultry Farms

There are plans for the establishment of 16 poultry farms around Rehoboth and the Oanob Aquifer. The plots will be spaced with a distance of 5 kilometres. They will be situated along the south side of the Langberg Formation, located north of the aquifer, south of the mountain ridge southwest of the town and the aquifer, and also north of the town and the aquifer (Strauss, 2010). The plan is for the farms to use water from the aquifer, and for the Town Council to have regulations on the operation of the farms, so the council can control what is released.

Rivers and dams

The Oanob Dam is located 7 kilometres to the west of Rehoboth and supplies the town with water. During years with high rainfall, the dam releases water into the Oanob River and naturally recharges the aquifer. The Swart Modder River joins with the Oanob River in the middle of the aquifer, about 6 kilometres into the downstream compartment.

The surface water in the dam is deemed suitable for artificial infiltration, hence no pollution of the aquifer if water is released into it (SWECO, 2002). The Swart Modder River running from the mountains to the west of Rehoboth can bring contaminants to the aquifer from roads, though as an ephemeral river the water only flows during sporadic rainfall events.

Roads

The main road, B1 that goes through Rehoboth, crosses the Oanob River at the top end of the upstream compartment of the aquifer. It then travels along the boundary of the aquifer for about one kilometre before it changes direction to the south, down to the South African border. On the aquifer there are gravel roads, as is the case in the urban area located on the aquifer.

Vehicles represent a threat to the aquifer through emissions and leakages. Since most of the roads are made of gravel, the pollution may infiltrate into the ground during rain events. Transports of hazardous goods pose a risk for pollution of the groundwater, though most transports will be on the main road through town and either continue south of the aquifer or north up to Windhoek. The main road later crosses the Swart Modder River and pollution can reach the aquifer through transport in the river.

6.2.2 Rating of Potential Pollution Sources

Each potential pollution source was rated according to Table 12 in Chapter 5.3. Several of the sources identified were rated multiple times with the regard to different possible ways of contamination. The final ratings of the different pollution sources can be seen in Table 13.

The highest pollution load ratings were assigned to the agricultural activities with regard to cultivation, this due to the high possibility of contaminants infiltrating with the irrigation water. Disposing of waste at the sites where sand has been excavated is rated as having an equal pollution load, due to the short distance to the saturated zone and the groundwater. An almost equally high rating was given to the green houses on the south bank of the Oanob River due to the high amount of water used for irrigation and the fact that fertilisers and pesticides are used.

Illegal sand mining was rated as having the lowest potential pollution load given that the excavation is non-commercial and most likely performed by people with shovels or smaller trucks. The Thermal Aquifer is considered to have a low threat to the groundwater since the thermal water in the fractures is not connected to the alluvial aquifer. The only way of contaminating the Oanob Aquifer with thermal water is to drill close to the edges of the aquifer and into the bedrock. This event is assumed to be associated with a low probability and even if this event would happen, the content of fluoride and sulphate in the water is not considered as highly toxic. Livestock farming was given a low rating due to the nature of the contaminants. Nutrients from animal droppings may, especially in close vicinity to boreholes, infiltrate and lead to high levels nitrate in the groundwater. Though, due to the assessment that rain is scarce and that remediation is quite easy, a low rating was achieved. Complete rating tables can be seen in Appendix II.

Table 13: Final rating of the identified hazardous activities.

	Hazardous Activity	Final Rating, L
	On the Oanob Aquifer:	
1	Green Houses	0.67
2	Slaughter House – Sewage pipe	0.42
3	Slaughter House – Animal waste	0.39
4	Sand Mining	0.02
5	Illegal Waste Disposal	0.64
6	Illegal Waste Disposal - Sand excavation pit	0.68
7	Thermal Spa	0.33
8	Thermal Aquifer	0.28
9	Livestock Farming – Animals	0.32
10	Livestock Farming – Fuel	0.60
11	Boreholes	0.65
12	Agriculture Plots – Animals	0.38
13	Agriculture Plots - Vegetables	0.68
14	Domestic Households	0.40
15	Roads – Traffic/Road	0.42

A GIS map was produced identifying the different pollution sources and their ratings were incorporated into the attribute data, see Map 10 in Appendix III. The activities off the aquifer are not included as the impermeable boundary of the aquifer is assumed to stop any contaminants from being transported to the groundwater. The highest pollution load is concentrated to the upstream compartment and particularly the northern part, where most of the activities are present closer to the town.

6.3 Risk Assessment

The results of the provisional risk assessment are shown in a risk map in Figure 22 as well as a risk matrix in Figure 23. For a larger map, see Map 12 in Appendix III. The map presents the risk estimate of the identified and rated potential pollution sources of the aquifer. However, the risk assessment should be considered as qualitative and relative because the rating of the hazards is an interpretation of available information and the vulnerability assessment is in itself relative to the aquifer.

The interval between 0.05 and 0.60 (yellow in legend) is chosen to display the absence of risk values within this range. The aquifer is either considered as having a higher risk (from 0.60 and higher) or a very low risk (0.05 and lower). The yellow areas illustrate that without any pollution sources in the area, the vulnerability of the aquifer is of little importance when regarding the potential risk.

Pollution sources associated with a high potential pollution load and located in areas of high vulnerability have received high risk values. From Map 12 it can be seen that most of these sources are located in the northern part of the upstream compartment, where the residential areas as well as the agriculture plots are situated. The boreholes spread over the downstream compartment are subject to high risk due to the combined potential pollution loads of fuel from farming equipment, animal waste, and leakage of fuel from pumps into the boreholes.

The provisional risk assessment indicates the relative significance of measures to be taken to protect the aquifer from quality degradation. From the results presented in Map 12, it can be seen that protective measures are most urgent in the northern part of the upstream compartment, especially within the agriculture plots. Also the areas around the boreholes on the downstream compartment exhibit high risk values. These areas have a high risk due to the activities taking place, as well as being in an area vulnerable to pollution. The importance of groundwater abstraction from the boreholes also indicates the necessity for preventive and protective efforts to be made.

Areas in the upper part of the downstream compartment, especially on the southern bank of the river, exhibit low risk values, since there are few activities taking place and there is a large amount of clay in the area.

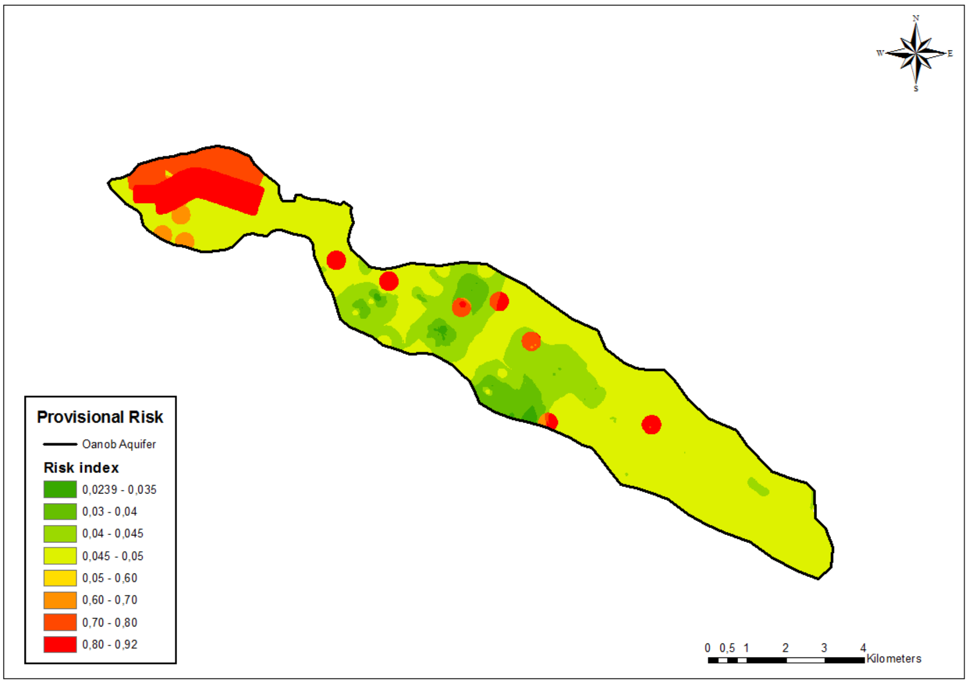

Figure 22: Map of the provisional risk.

The provisional risk is incorporated into a risk matrix where the potential pollution load and the vulnerability are considered. The larger part of the potential pollution sources are located within the unacceptable red area. Only 3 of the sources are in the yellow area where every case needs to be evaluated individually. The reason for the high number of sources in the unacceptable risk zone is due to the high vulnerability of large areas of the aquifer. Particularly the upstream compartment has a vulnerability close to 1 and when the potential pollution load of each source is plotted against the vulnerability of the area, almost all of the sources are placed in the unacceptable zone.

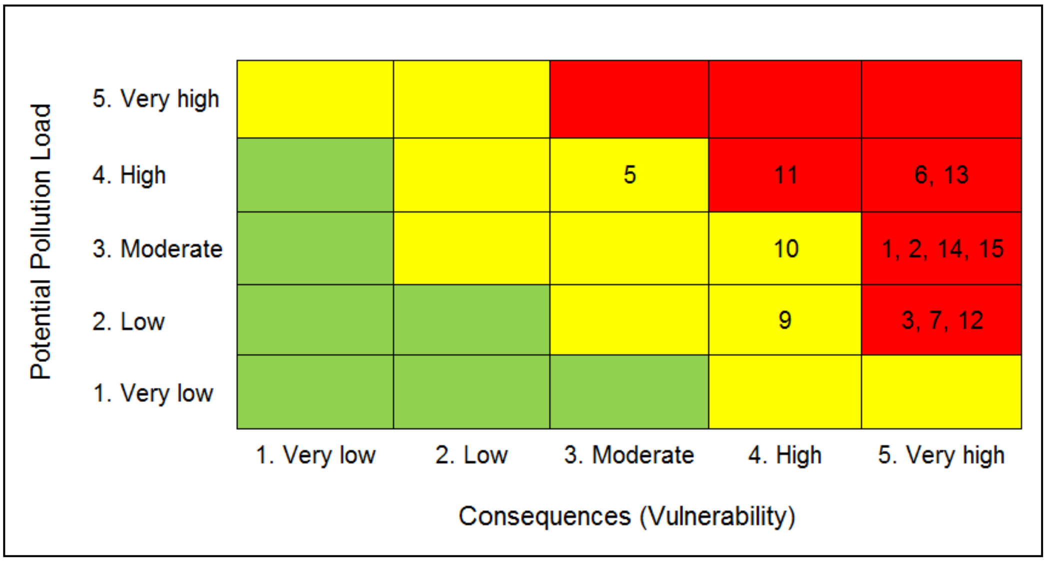

Figure 23: Risk matrix including the potential pollution sources. The numbers correspond to the hazardous activities rated in Table 13 (No. 4 and 8 are excluded).

7 Discussion

7.1 Methodology

It is important to note that assessments of vulnerability and risk are only based on the available data and are not exact truths. The methodology used in this project is not able to give certain answers regarding neither vulnerability nor risk which makes the results from the adapted method only a possible outcome. Nevertheless, the data gathered is comprehensive, giving the assessments performed a good foundation and the results are therefore assumed to correlate well with reality.

The method applied to this project was originally developed to assess vulnerability in a fractured rock aquifer. Adapting the method on the Oanob Aquifer meant that the hydrogeological parameters influencing the transport of contaminants had to be modified to suit the local conditions of the Oanob Aquifer. This gives an uncertainty of the modified method and consequently also the results.

The vulnerability index of high, medium, and low and the values for each interval and parameter are decided by the project team and are only set in relativity to each other. A high vulnerability must not necessarily mean a high vulnerability in a broader sense when comparing to assessments of other areas. It is a representation of the relative vulnerability of the specific aquifer. The probability values of infiltration and transport through the soil are, though set by informed people, still only interpretations and not absolute reality. These interpretations will influence the vulnerability assessment and the layer maps are only an indication of the situation of the aquifer and should be regarded as such.

The rating of the hazardous activities is, as the probability values, set by people either involved in the study or with knowledge of the activities and their possibility to pollute. The ratings are however only estimates and a low rating does not necessarily mean a harmless activity. The following risk assessment and map is therefore only a relative estimate of the risk for the specific aquifer.

7.2 Vulnerability Assessment

The vulnerability assessment is based on data collected from a number of investigations and assessments made on the Oanob Aquifer. The assumptions of limiting factors for the aquifer were based on information from previous investigations, and meetings with people involved. The lack of available data for the upstream compartment has resulted in somewhat conservative estimates of the parameters vulnerability model. This may lead to an overestimate of the vulnerability of the area, though it can also be argued that the assumptions can be regarded as precautious.

In the downstream compartment where geological information is available, the percentage of clay in each cross-section is based on previous geological surveys. The amount of clay is one of the main parameters governing the probability of transport through each hydrogeological component, thus also the vulnerability of the aquifer. Any uncertainties around the percentage of clay may change the outcome of the vulnerability map and it should be pointed out that the clay content is estimated based on the cross-sections and not based on specific data. However, a careful approach has been taken and a lower amount of clay has been set when in doubt of the percentage, meaning that the vulnerability map presented in this report show the aquifer in the higher end of the vulnerability index. The same went for all of the parameters. When no information was available the values were set to the higher end of the vulnerability index.

The cross-sections were also used, in combination with previous investigations on depth to groundwater and to basement, to determine the boundaries for the three transport zones. The boundaries were used when determining the amount of clay in each zone and the surface material. Both the infiltration zone and the unsaturated zone were set to a specific depth below ground surface, whereas the saturated zone got the range from the unsaturated zone and down to the basement. In the vulnerability assessment the fact that more arbitrary surfaces are used will give an uncertainty in both that a too high and too low vulnerability could have been calculated. Further studies should therefore be conducted to give more precise ranges of the zones.

However, for the hydraulic conductivity the values were set a bit differently. Data was only available from a few boreholes, through test pumping, and not enough to make an estimation of the whole aquifer. Values were therefore set with regard to the soil material in the cross-sections by using general hydraulic conductivity estimates for the specific soil types, giving values ranging between 0.0001 and 10 000 m/d. The interpretations of previous test pumping show hydraulic conductivity values within the same range though they are not consistent with the values set according to soil type. One of the boreholes located at a cross-section with high amount of clay have according to test pumping data a hydraulic conductivity closer to sand. This shows that the movement of groundwater, and then also pollution, is not hindered by clay lenses. An assumption is then that due to the heterogeneity, the aquifer material will quite easily transmit water around the areas with high clay content.

Due to the assumption of impermeable rock around the aquifer, there is no connection between the thermal aquifer in the fractures in the bedrock and the alluvial Oanob Aquifer. If a connection does exist, the vulnerability would almost certainly be higher since contaminants could be transported through fractures to the groundwater. Hazardous activities outside of the aquifer would also need to be accounted for. Nonetheless, the data suggesting that there is no link between the aquifers is comprehensive, though further studies should be undertaken for more detailed information.

With the ArcGIS software, layers and maps necessary for the compilation of the vulnerability map were produced. The parameters important for each hydrogeological component were given a layer where the probability values were set. Interpolation was then used to assign values for the entire area. This was done using Inverse Distance Weighted interpolation, where 20 points and a maximum radius of 1500 m were used to estimate values in the aquifer. The tool is a reliable way of interpolating values over an area, though it is not a substitute for detailed investigations.

Moreover, the results from the vulnerability assessment and the following vulnerability map must be regarded as qualitative and relative. The vulnerability index is produced relative to the area. The values only show which parts of the aquifer are more vulnerable than others and do not give information on vulnerability in relation to other aquifers.

The final vulnerability map shows the areas of the aquifer most vulnerable to a pollutant release. Viewing the map from the perspective of possibly recharging the aquifer artificially, the results need to be interpreted differently. The areas of low vulnerability have stronger attenuation capabilities, though given that this is due to high clay content the area is not optimal for artificial infiltration. High clay content means low hydraulic conductivity and slow moving groundwater. Infiltration into the saturated zone will be slow and the time for the water to travel from infiltration point to abstraction point will be long. The issue with artificial infiltration is that the areas often most vulnerable to contamination releases are also the areas most receptive to infiltration of surface water. Using protective measures on the aquifer in general and the areas for artificial infiltration in particular is a recommended way of lowering the possibility of contamination. It is then the costs and benefits of the activity that decides the measures taken and the protection of the aquifer.

As a conclusion it is important to emphasize that this assessment is an overview of the vulnerability and should not be taken as a replacement for detailed studies. It should be regarded as a helping tool when planning for further investigations and protective measures.

7.3 Hazard

The investigation that identified the potential pollution sources included field surveys, where the aquifer and surrounding areas were surveyed considering potential pollution releases. The field surveys conducted in this project were brief and did not include all of the identified sources. The short field investigations restricted the team from acquiring any detailed information, which may be necessary for a better basis for judgement. In the field all conversations with the locals were through a translator, leading to the risk of misunderstandings, either in the phrasing of the questions or the translation of the answers. This could affect the perception of the hazards and then also the rating of them.

Meetings with the Town Council in Rehoboth were another part of the identification process where potential hazards were discussed, though it should be noted that the council were a bit resistant at identifying and discussing possible hazardous activities in town and on the Oanob Aquifer. They insisted that the activities were few, and that the Town Council controlled and regulated the activities present. The assumption of no connection to the thermal aquifer meant that potential pollution sources off the alluvial aquifer were not regarded as having the same possibility of harming the aquifer, giving them lower weight in the rating of the identified hazards. The main issue with the thermal aquifer is the possible risk of penetrating the aquifer when drilling in the outskirts of the alluvial aquifer. Too deep drilling may cause the thermal water to intrude into the alluvial aquifer. To be fully certain of the separation of the two aquifers, further investigations are necessary.

There were a smaller number of hazardous activities identified when only regarding the alluvial aquifer. The land is mostly used for livestock and no fences are used between the sources. A difficulty is the increase in development in Rehoboth. Many of the agriculture plots just south of town are not yet developed, or in operation, and the potential pollution load from each plot is difficult to estimate. The same issue concerns the planned commercial poultry farms around the aquifer. Rehoboth Town

Council however sees this time as a good start to shape regulations to be able to control the activities on the aquifer and the pollution they may produce.

As previously stated, the rating of the potential pollution sources could be affected by the perception of the Town Council and locals. It is also important to note that the ratings are only interpretations from the project team and other people involved in the project. The rating of the sources is only a means of indicating the possible hazards most threatening to the aquifer and the potential contamination from them. The probabilities are of no certainty and should only be regarded as an estimate. Different ratings might change the outcome of the risk assessment significantly. The final pollution load is a parameter in the calculation of the risk and a too high or low rating may indicate areas of concern where none is necessary or the other way around. More detailed investigations of the hazards in the Rehoboth area are therefore important for further risk assessments. A difficult decision is the determination of what is the ultimate rating of hazards. A high rating ensures the safety of the aquifer, though the hazard then also requires better protective measures and involves higher costs. Where is the limit, and how does one obtain the optimum rating?

7.4 Risk

The risk assessment is affected by two things, the vulnerability assessment and the identification and rating or hazardous activities. Any uncertainties in these two will give an uncertainty also in the risk part.

The vulnerability of the aquifer is important to the risk assessment, though without any specific pollution source in the area the risk for contamination of the aquifer will be low or even non-existent. The risk for the aquifer to be polluted is determined by the present activities and without any contaminants to release the high vulnerability of the area does not matter.

For the vulnerability assessment the issue was the lack of information in the upstream compartment and the subsequent assumptions made, as well as the sparse information in the lower part of the downstream compartment. Therefore assumptions regarding these areas concerning geology, hydraulic conductivity, depth to water table and surface material had to be made. Since a worst case scenario was assumed, some of the areas may not be as vulnerable as implied on the final vulnerability map, see Figure 21 and Map 11 in Appendix III.

Considering the hazardous activities, it is possible that some sources have not been identified. Furthermore, if the rating of the threats had been different the resulting risk would also be changed. The fact that three of the sources, namely the green houses, the thermal spa and the slaughter house, do not have exact coordinates could possibly have affected the results. The fixed radius of 250 m around all of the pollution sources, put there as a precaution for pollution spreading, could be tailored for each source instead of a general distance being used for all of them. A tailored radius would give a better and more accurate result for the activities taking place in different parts of the aquifer, since the pollution spreading is different for each source. Areas without any specific pollution load have still been given a low pollution load and also a risk rating, since there is always a chance that pollution may arise. Of course this also affects the risk, meaning that the entire aquifer has an assumed risk, although low in most areas it is still present.

The fact that the assessment has been limited to only regard the aquifer and not the surrounding areas, has probably affected the results. This does not mean that the risk would have been greater if including these areas, just that the assumptions may have affected the outcome. Some sources of pollution have been identified off the aquifer though have not been included in the risk assessment. If they had been, then the resulting risk may have been different.

When studying the risk map (Figure 22 and Map 12 in Appendix III) most areas are green. This indicates a low risk, risk of pollution being lower than 5 %, for most parts of the aquifer. The smaller areas with high risk value in the downstream compartment is due to a combination of pollution loads from animal waste, leakage of fuel from the water pumps, and fuel from farming equipment. If information was available, then it would be possible to determine if the assumptions of all activities are correct for all boreholes on the downstream compartment, or perhaps for none of them. The reality might be that for some of them the combined risk is as close to reality as possible, while for others it may just be one of the activities that should be taken into account.

The high risk index in the upstream compartment, due to assumptions and risk rating, might be lowered if further investigations are made on the parameters deciding the different layers in each zone. The result may also differ if more detailed investigations are performed on the different hazards, for example the agricultural plots and the residential areas which have within the area been given equal rating.

The results shown in the matrix can be argued as being unreasonable. The positions of the sources in the matrix were determined by cross plotting the potential pollution load with the corresponding vulnerability for each source. Due to the high vulnerability of the upstream compartment, where most activities take place, the positions in the matrix are in the unacceptable area. Though when calculating the risk for each source, using equation 5, the provisional risk is lower. It can be reasoned that this will place the sources in a more acceptable area of the matrix. Moreover, the position of the boundaries in the matrix can be changed with regards to the opinions of the decision-makers. Altering the acceptable and unacceptable limits may place the pollution sources in a different category of the risk matrix. With the lower pollution loads in mind, specifically sources number 3, 7, and 12, the unacceptability could be discussed and the sources investigated further.

In conclusion protective measures are needed to lower the risk for contamination of the aquifer. The most critical part where measures are needed is the agriculture plots and the residential areas in the northern part of the upstream compartment. Here further investigations should be performed to conclude if all of the areas are as vulnerable as indicated in the report. If they are, then actions have to be made to make sure that the possible pollution does not reach the aquifer. In the downstream compartment there are also some areas of concern, namely the areas surrounding the boreholes. The high risk here is due to the activities taking place, the mostly high vulnerability of the areas, and that the areas are of high importance for groundwater abstraction. This risk has to be lower and one important measure for this is to have better control of the groundwater abstraction pumps, which are known to occasionally leak oil into the boreholes.

7.5 Overall Discussion

This project involved doing a vulnerability and risk assessment regarding artificial recharge of the Oanob Aquifer. The results produced in this project suggest that the aquifer is suitable for artificial infiltration and is a good option as a water resource for both Windhoek and Rehoboth. Using artificial as well as natural infiltration will increase the volume of water that can be infiltrated and shorten the time for the aquifer to replenish. This is essential if the aquifer is to be used as a water supply during a longer period of time. Though the assessments made in this report are a good basis for future planning of using artificial recharge, further investigations are necessary. Extensive and quantitative economic and financial evaluations are needed to investigate the viability of a scheme like this, as well as more detailed examinations of suitable locations for the infiltration basins.

The vulnerability and risk assessment indicate that the aquifer is a good alternative for water supply, nevertheless it is of importance that the town of Rehoboth does not expand too much onto the aquifer. The control of the activities taking place on the aquifer at present or in the future is essential. It is also imperative that the Town Council properly investigate each activity and that each of them needs to be approved before any development can be established. The monitoring of possible pollution releases is important and a record must be kept of the abstraction of groundwater from boreholes already on the aquifer. This to monitor the volume of water still stored in the aquifer and to determine the amount of water the farmers use.

The Oanob Aquifer is an option suitable for both Windhoek and Rehoboth. Though, since no extensive investigations into the viability of artificially recharging the aquifer have been performed, it is difficult to give definite answers. The most important part of the possible scheme is to determine the amount of water the aquifer can safely supply each year. It can be argued that the specific yield of the aquifer is quite small and will not be able to provide the amount of water that will be needed in the future, though it should be able to supply Rehoboth with water and still have enough left for Windhoek to use it as an additional source. Nevertheless, further studies are needed to determine the safe yield for the aquifer. Even with the clear advantages of using the aquifer, costs for construction, operation, and maintenance need to be considered. The benefits of using the aquifer should outweigh the costs.

If the Oanob Aquifer would be polluted in some way, preventing it from being used as a water supply, external sources will be necessary for both Windhoek and Rehoboth. For Windhoek there are a few options available, but most are located long distances from the city, leaving high costs for infrastructure. Rehoboth would in all likelihood receive its drinking water from the Oanob Dam. Pollution of the Oanob Aquifer would result in an increased use of alternative sources and therefore also in increased cost.

Remedial actions are in all probability not an option for the aquifer. It is a difficult task anywhere in the world and it has never been performed in Namibia. The type of pollution will determine if remediation is a possibility and the decided form of treatment will be the factor governing the remediation costs. It can be concluded that pollution of the aquifer is associated with severe economic consequences. It can also be concluded that remediation and substitution of water can, in a case of contamination of the aquifer, result in large costs to the society.

Preventive and protective measures should be implemented as soon as possible to reduce the possibility of contaminating the aquifer. Protection zones around boreholes and future infiltration basins are a good way of guarding the vulnerable areas around infiltration and abstraction points. The Town Council also need to implement rules and regulations on what activities can take place on the aquifer and set limits for the amount of pollution that can be released.

8 Conclusions

The vulnerability assessment and the related map show the most vulnerable areas of the aquifer (Map 11, Appendix III).

- The upstream compartment is all determined to be of high susceptibility to pollution, especially the western part where the Oanob River flows into the compartment.
- The southern end of the downstream compartment is also of concern, though due to higher levels of clay and lower water table the resistance to pollution is better.
- The upper end of the downstream compartment is in the lower range of the vulnerability index, since there are several clay lenses in the area.

The vulnerability map in combination with the map for potential pollution load has generated a risk map, where the areas of most concern for contamination are shown (Map 12, Appendix III).

- The high hazardous activity in the upstream compartment leads to a higher risk for pollution of the groundwater. The close proximity to the town also adds to the high risk for contamination.
- To prevent the aquifer from being polluted protective measures have to be implemented, such as restrictions on the use of fertilisers and pesticides, and protection zones around the infiltration basins and boreholes.

The Oanob Aquifer is suitable for artificial infiltration and the vulnerability and risk maps produced in this project can be used to help determine appropriate locations for infiltration basins.

- The least vulnerable areas of the aquifer are unfortunately not ideal for artificial infiltration, due to the large amount of clay.

This study serves as a first assessment of the Oanob Aquifer. To go further with the project of artificially recharging the aquifer and supplying Rehoboth and Windhoek with drinking water, more extensive investigations are necessary. The Department of Water Affairs and Forestry in Namibia have further plans already in progress, for example to construct a flow model of the aquifer that will provide information of the groundwater flow in the alluvium as well as the through flow. Further investigations recommended by the project team are:

- A more in-depth vulnerability assessment can provide additional information of the area and suitable locations for artificial recharge basins.
- Test pumping will give further data on hydrogeological parameters, such as hydraulic conductivity.

- Geophysical investigations will provide soil composition information and the location of clay lenses in the ground as well as a more comprehensive understanding of the profile of the bedrock and the alluvial thickness.
- A more detailed survey of the potential pollution sources is necessary. To identify more sources and to obtain better and more comprehensive information of the pollution load from each source, additional field investigations are necessary.
- The ideas from the Rehoboth Town Council of monitoring and regulating activities on the aquifer also need to be properly determined and implemented.
- A quantitative economic evaluation, to more explicitly investigate the negative economic effects of a contaminated aquifer with failure to supply both Rehoboth and Windhoek with drinking water, is also advised.
- More detailed financial and economic evaluations on the feasibility of artificially recharging the Oanob Aquifer are also recommended.

Particularly the upstream compartment needs additional investigation, given that the most extensive survey done in 1989 by the DWA did not regard the upstream compartment since it was already in use as a water resource.

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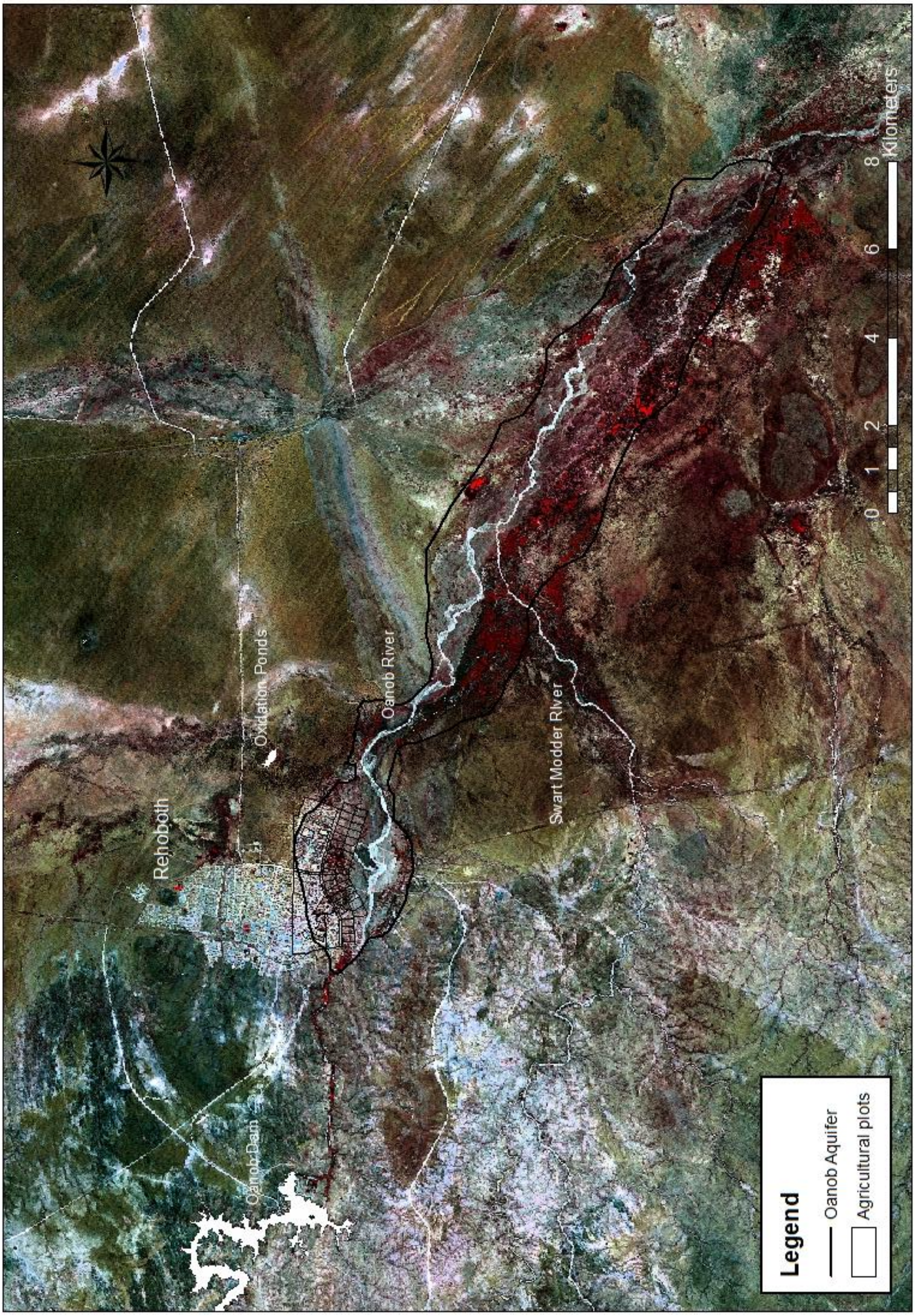
Appendices

Appendix I – Map of the Rehoboth Area



Appendix II – Rating of Hazards

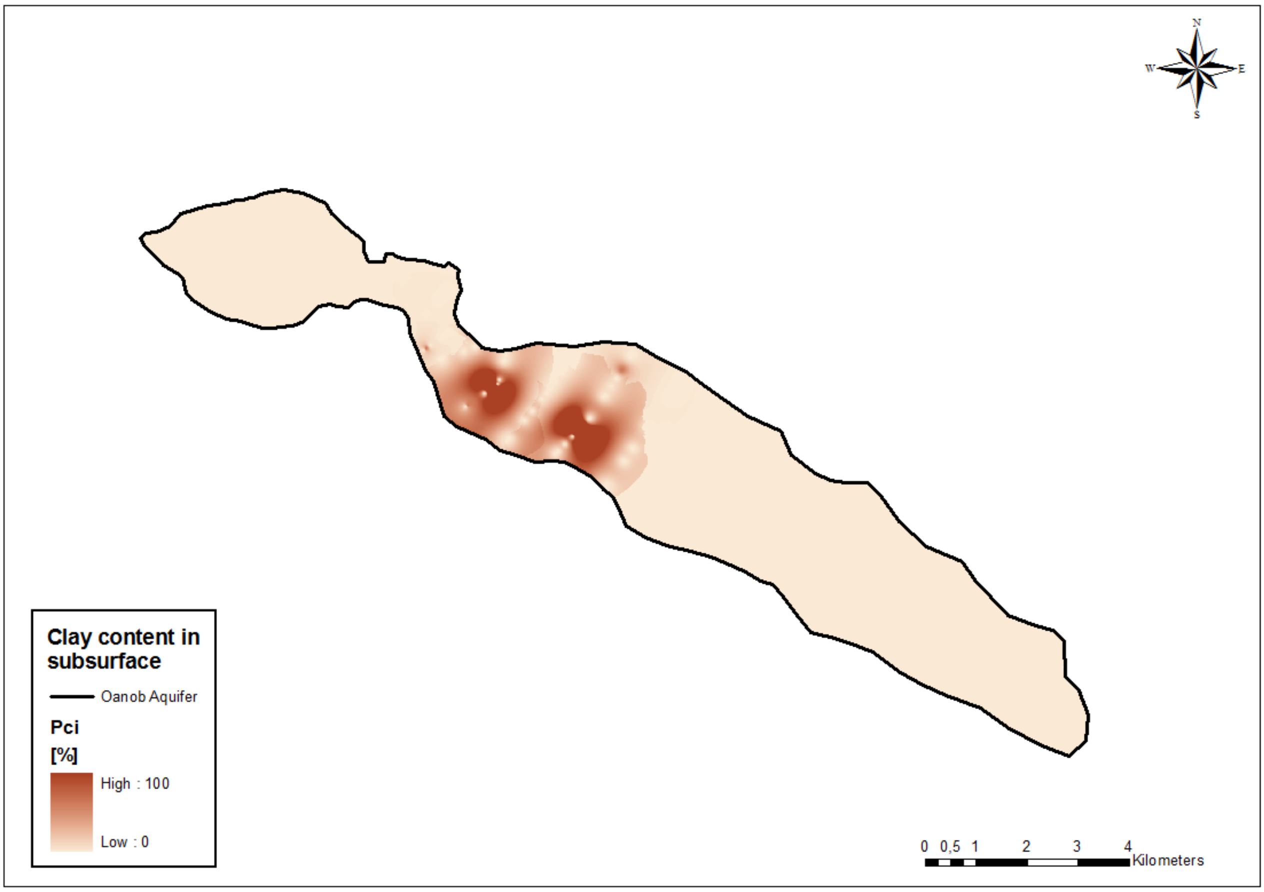
Hazardous Activity **On the Oanob Aquifer:**	Toxicity, L_1	Release Quantity, L_2	Probability of Release, L_3	Type of Release, L_4	Possibility for Remediation, L_5	Final Rating, L
Green Houses*	0,35	0,3	1	1	0,7	0,67
Slaughter House - Sewage pipe*	0,15	0,05	0,5	1	0,4	0,42
Slaughter House - Animal waste*	0,3	0,4	0,35	0,5	0,4	0,39
Sand Mining	0,05	0	0	0	0,05	0,02
Illegal Waste Disposal	0,8	0,7	0,5	0,4	0,8	0,64
Illegal Waste Disposal in sand excavation pit	0,8	0,7	0,6	0,4	0,9	0,68
Thermal Spa*	0,3	0,1	0,05	1	0,2	0,33
Thermal Aquifer	0,1	0,15	0,05	1	0,1	0,28
Livestock Farming-Animals	0,4	0,4	0,2	0,3	0,3	0,32
Livestock Farming-Fuel	0,9	0,15	0,15	0,85	0,95	0,6
Boreholes	0,9	0,15	0,4	0,85	0,95	0,65
Agriculture Plots-Animals	0,4	0,5	0,3	0,3	0,4	0,38
Agriculture Plots-Vegetables	0,4	0,6	0,7	1	0,7	0,68
Domestic Households	0,65	0,2	0,15	0,6	0,4	0,4
Roads-Traffic/Road	0,4	0,15	0,2	0,6	0,75	0,42

*Sources without exact coordinates, positions found with satellite photos

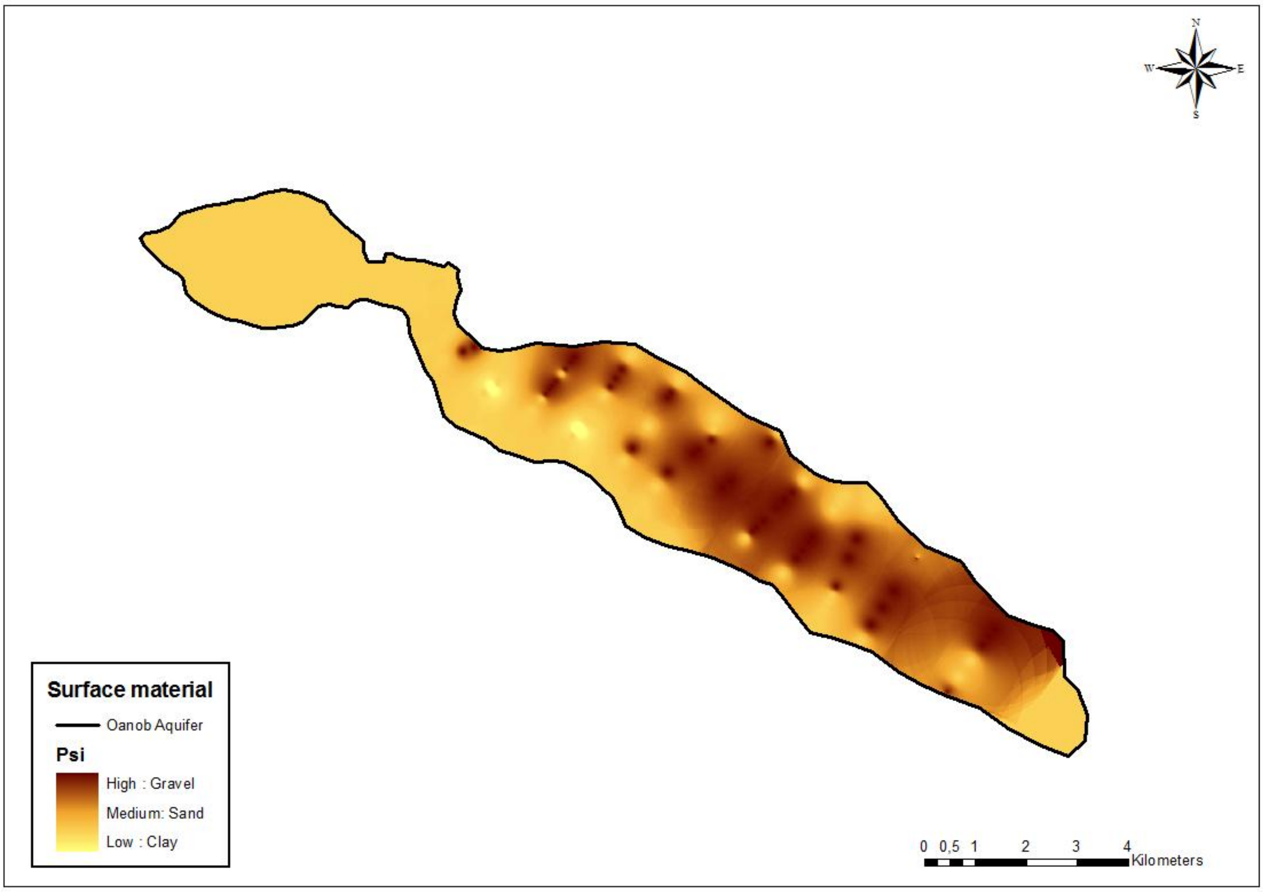
Hazardous Activity **Off the Oanob Aquifer:**	Toxicity, L_1	Release Quantity, L_2	Probability of Release, L_3	Type of Release, L_4	Possibility for Remediation, L_5	Final Rating, L
Oxidation Ponds	0,6	0,4	0,2	1	0,6	0,56
Oanob Dam-Leakage	0,05	0,1	0,9	1	0,1	0,43
Oanob Dam-Release	0,1	0,85	0,2	1	0,1	0,45
Ephemeral Rivers	0,15	0,2	0,6	1	0,2	0,43
Roads-Hazardous transports	0,8	0,6	0,1	0,5	0,9	0,58
Poultry Farms	0,45	0,3	0,15	0,5	0,45	0,37

Appendix III – Maps

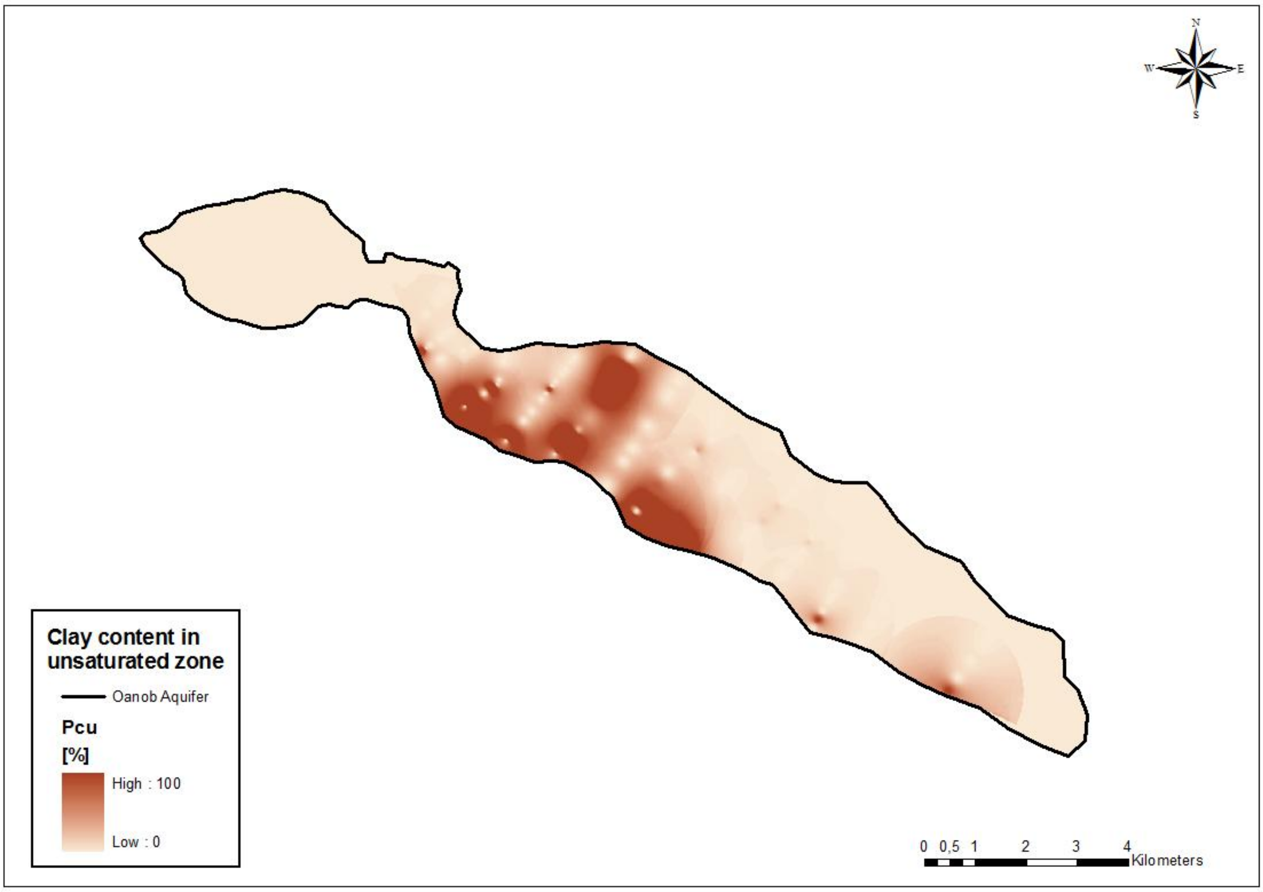
Map 1: Clay content in subsurface



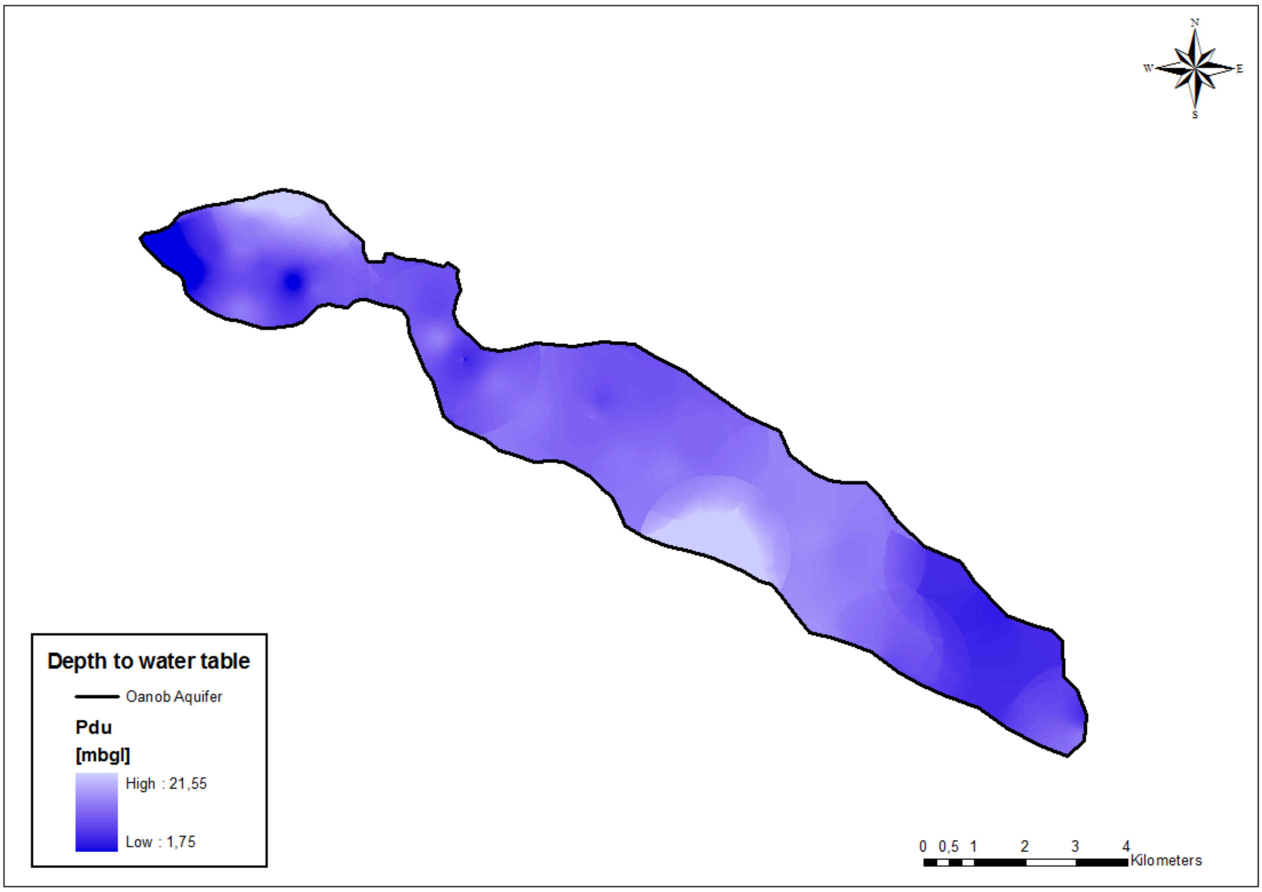
Map 2: Surface material



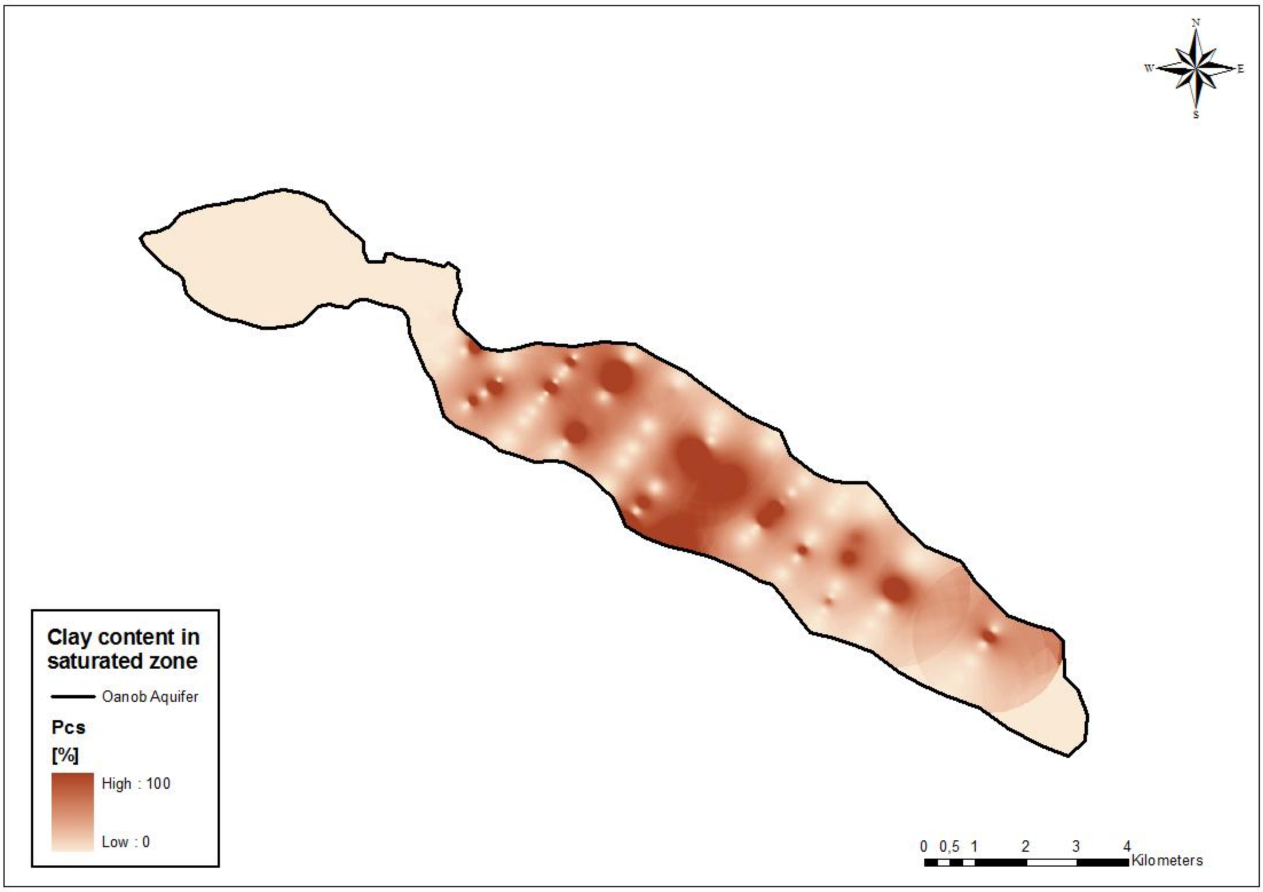
Map 3: Clay content in unsaturated zone



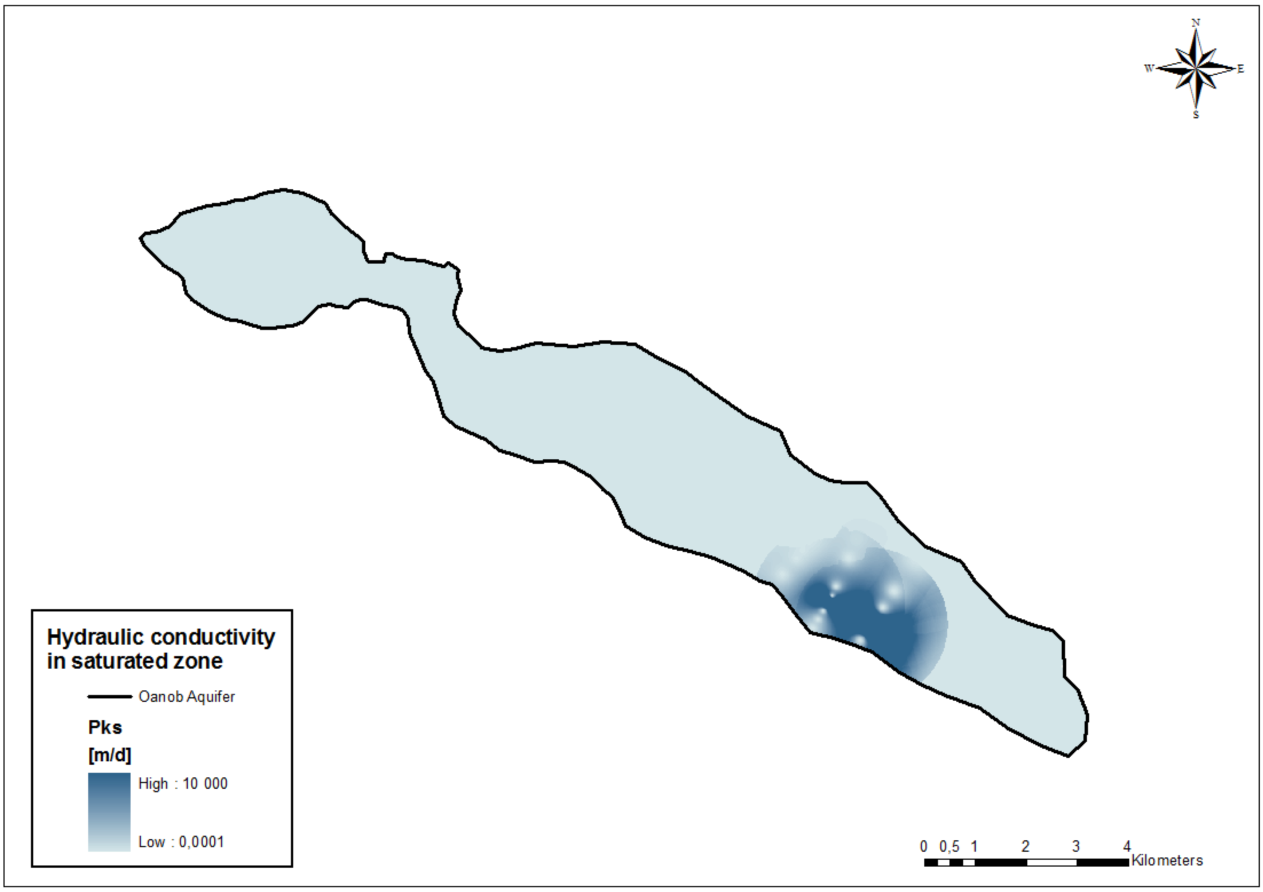
Map 4: Depth to water table



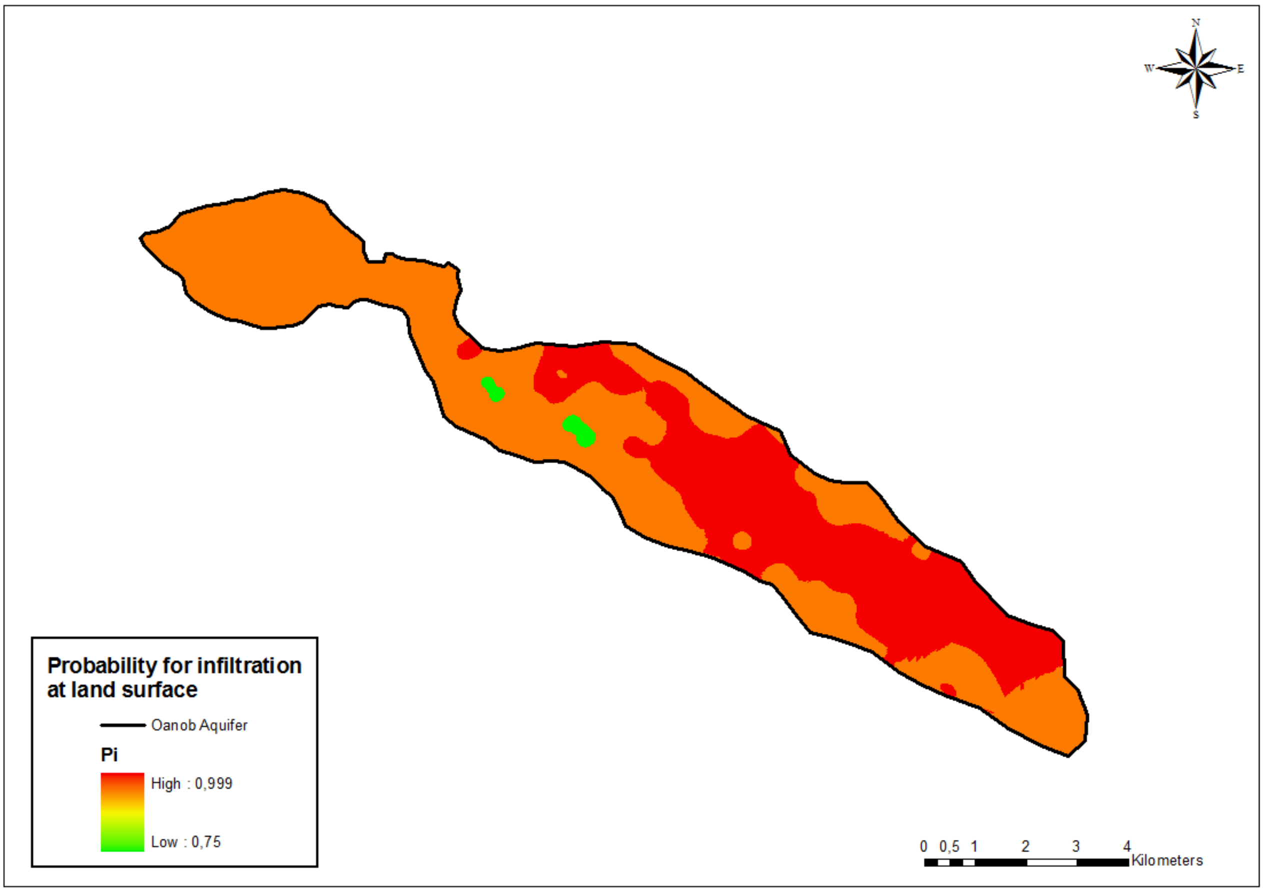
Map 5: Clay content in saturated zone



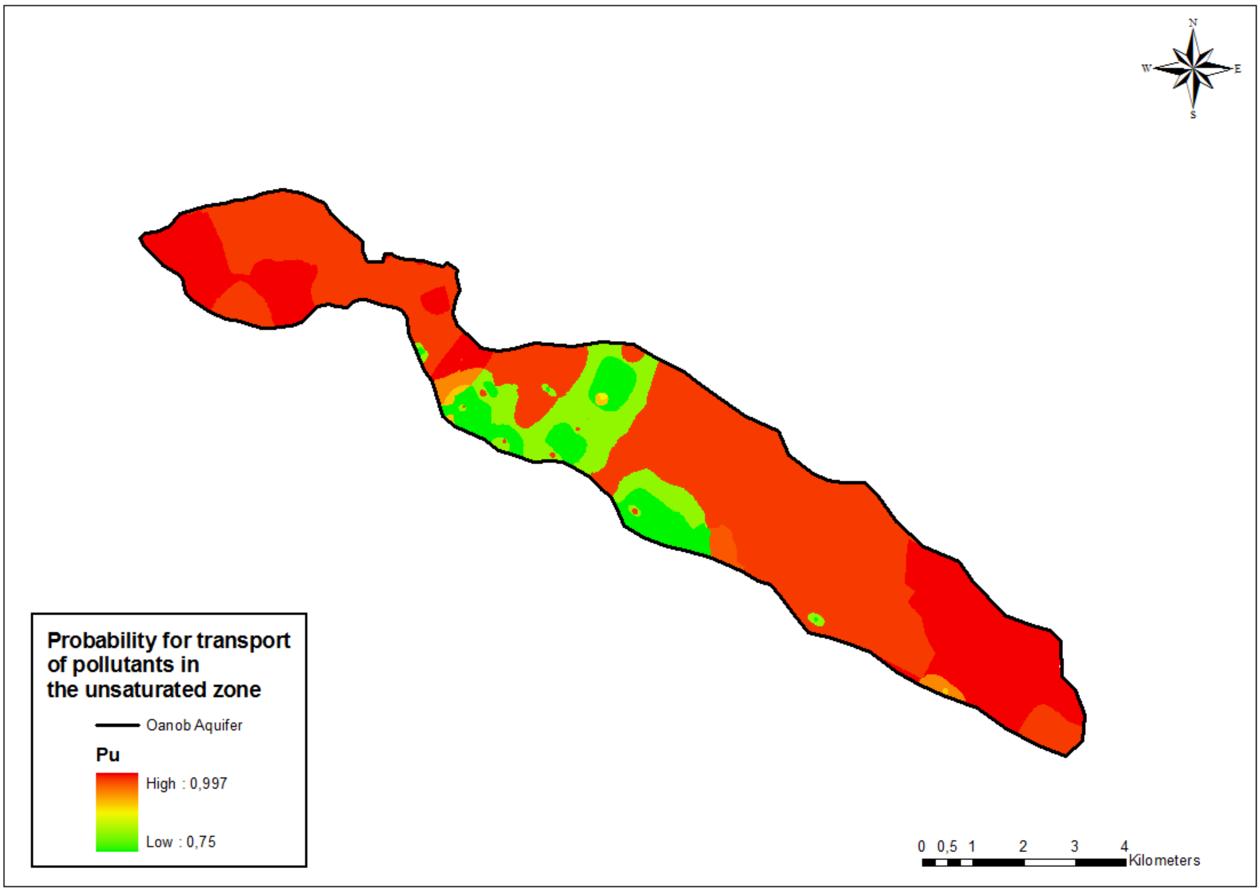
Map 6: Hydraulic conductivity in saturated zone



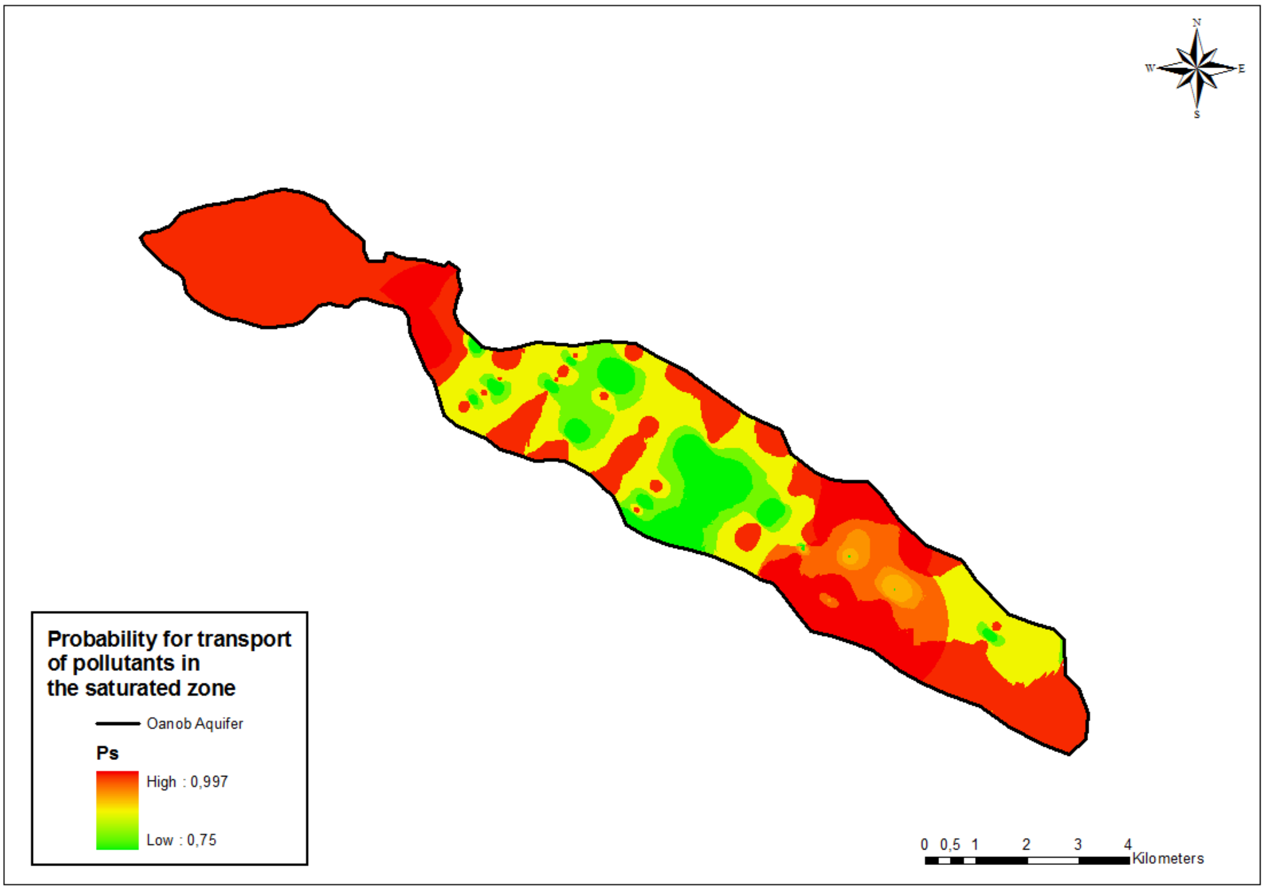
Map 7: Probability for infiltration at land surface



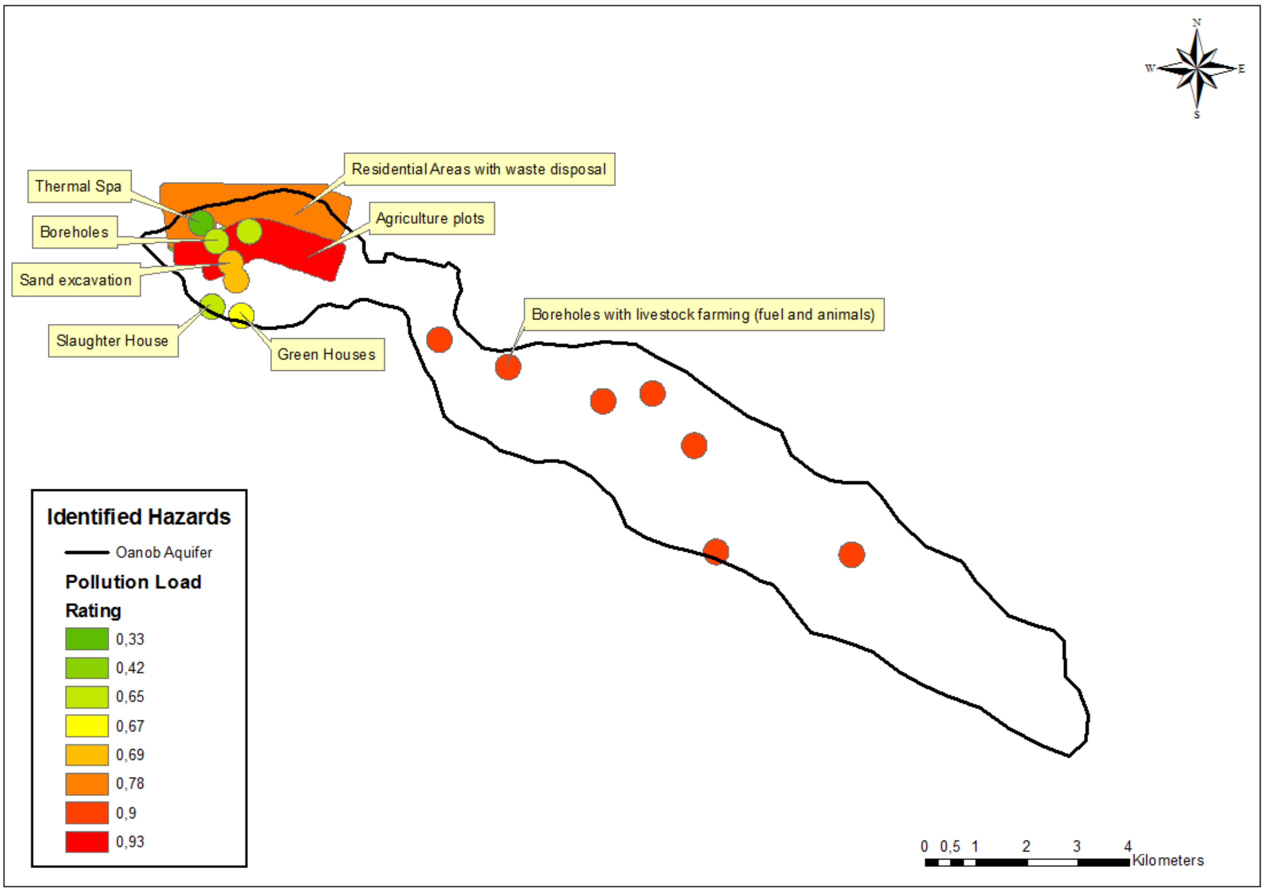
Map 8: Probability for transport of pollutants in unsaturated zone



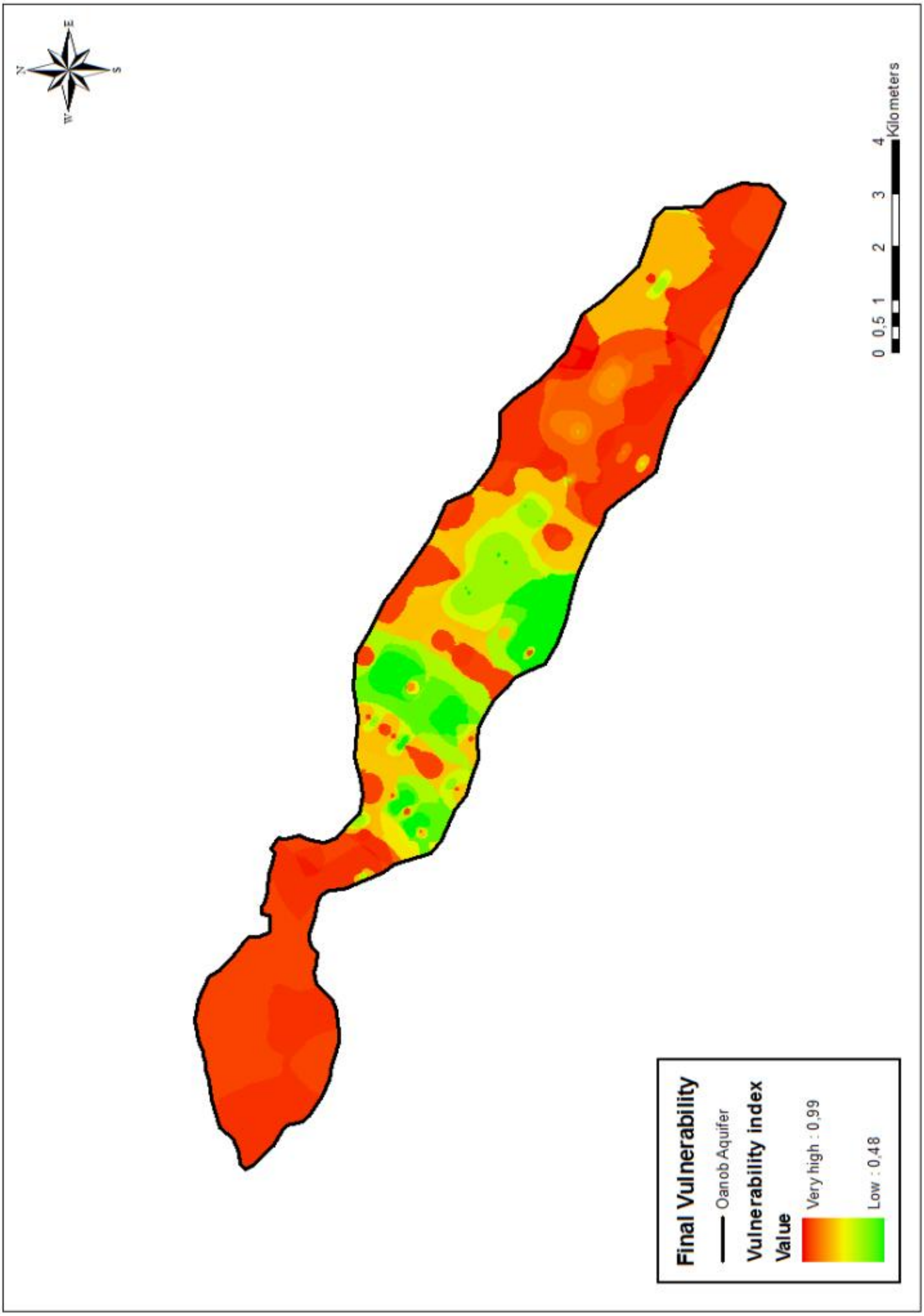
Map 9: Probability for transport of pollutants in saturated zone



Map 10: Potential pollution load



Map 11: Vulnerability of the Oanob Aquifer



Map 12: Provisional risk assessment