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Risk and Vulnerability Assessment of Expanding the Windhoek Drinking Water Supply

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

SOFIE FLOD, HANNA LANDQUIST

Department of Civil and Environmental Engineering
Division of GeoEngineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Examensarbete / Institutionen för bygg- och miljöteknik,
Chalmers tekniska högskola

Department of Civil and Environmental Engineering
Division of GeoEngineering
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Chalmers Reproservice / Department of Civil and Environmental Engineering

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ABSTRACT

The overall aim with this project was to provide a structured and operational method for conducting risk assessments concerning projects for expansion of water supplies, which might become an issue for Namibia's capital Windhoek in the close future. This report also aimed to serve as a pre-study for a possible expansion of the Windhoek water supply and as a basis for further more detailed studies.

This project was performed by identifying advantages and limitations of an expansion of the current water scheme through the construction of a pipeline between the cities Windhoek and Rehoboth, located approximately 90 km apart. The possible limitations were identified by conducting a Failure Modes, Effects and Criticality Analysis (FMECA), which identifies related risks to the system. One possible action for increasing the feasibility of a water expansion project of this kind can be to find further water abstraction points along the pipeline to increase the total available quantity of water to the system. Such extraction points can be vulnerable to pollution and should therefore be subject to a specific risk assessment. This master thesis provides an example method for conducting such a risk assessment and the extraction point chosen is the aquifer of the Omeya golf and residential oasis at the Gross Haigamas farm about 30 km south of Windhoek.

The FMECA identified in total 22 failure causes to the possible pipeline, of which 3 falls in the unacceptable risk (red) category, 13 within the potentially unacceptable risk (yellow) category, and 6 within the acceptable risk (green) category. The failure causes that were found within the unacceptable risk category are: accidental damage, flash floods and polluted water into the system. The risk assessment for the aquifer of the Omeya golf and residential Oasis at the Gross Haigamas farm identified areas where the most vulnerable ground material coincided with the largest possible sources of pollution, thus the areas of highest risk to groundwater pollution.

Recommended mitigation measures for an expanded water supply via a pipeline are careful planning of the pipeline stretch and well engineered material and construction.

Key words: Risk assessment, FMECA, vulnerability, water supply, aquifer, Namibia, Windhoek.

Risk och sårbarhetsbedömning av en expansion av Windhoeks försörjningssystem för dricksvatten
Examensarbete inom Geo and Water Engineering
SOFIE FLOD & HANNA LANDQUIST
Institutionen för bygg- och miljöteknik
Avdelningen för Geologi och Geoteknik
Chalmers tekniska högskola

SAMMANFATTNING

Det huvudsakliga syftet med masteruppsatsen var att föreslå en strukturerad och systematisk metod för att kunna utföra riskbedömningar gällande projekt som handlar om att expandera system för dricksvattenförsörjning, vilket kan komma att bli en fråga för Namibias huvudstad Windhoek inom en snar framtid. Uppsatsen syftade även till fungera som en förstudie för en möjlig expansion av Windhoeks system för dricksvattenförsörjning och som en bas för mer detaljerade studier.

Projektet innebar att fördelar och begränsningar identifierades av en möjlig expansion av dricksvattensystemet i Windhoek genom sammankoppling via en pipeline med dricksvattensystemet i Rehoboth, beläget ca 90 km från Windhoek. De möjliga begränsningarna identifierades bland annat med hjälp av en metod kallad Failure Modes, Effects and Criticality Analysis (FMECA), vilken identifierar risker relaterade till det studerade systemet. En möjlighet att öka genomförbarheten av ett expansionsprojekt gällande vattenförsörjningssystem som detta kan vara att hitta ytterligare uttagspunkter för vatten längs pipelinen som kan bidra till att öka den totala mängden tillgängligt vatten i systemet. Sådana uttagspunkter kan dock vara känsliga för föroreningar och bör utvärderas i en mer specifik riskbedömning. Detta projekt tillhandahåller ett exempel på en metod för en sådan riskbedömning och uttagspunkten av vatten som valdes för undersökningen var en grundvattenakvifer som tillhör Omeya golf and residential Oasis som ligger på farmen Gross Haigamas ca 30 km från Windhoek.

Med FMECA identifierades totalt 22 risker mot pipelinen. Tre av dessa befanns vara oacceptabla, 13 potentiellt oacceptabla och 6 acceptabla. Riskerna som återfanns inom den oacceptabla riskkategorin och därmed är viktigast att förhindra är: oavsiktlig skadegörelse, översvämningar och förorenat vatten in i systemet. Riskbedömningen som utfördes för akvifären tillhörande Omeya golf and residential Oasis identifierade de områden där akviferen var mest sårbar för förorening och där samtidigt de mest troliga förereningskällorna var placerade. Detta är de områden som löper störst risk för förorening av grundvattnet.

Rekommenderade åtgärder för de reducera riskerna med ett utökat system för dricksvattenförsörjning via en pipeline är noggrann och genomtänkt planering av pipelinens sträckning samt noga utvalda material och konstruktion.

Nyckelord: Riskbedömning, FMECA, sårbarhet, vattenförsörjning, akvifär, Namibia, Windhoek.

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Preface and acknowledgements

This master´s thesis was performed during the spring of 2010 at Chalmers University of Technology in cooperation with the Ministry of Agriculture, Water and Forestry (MAWF) in Windhoek Namibia. The collection of the data needed for performing the thesis took place in Namibia during a 9 week visit and field study. The project was partially financed by a Minor Field Study (MFS) scholarship from the Swedish International Development Cooperation Agency (SIDA) and a scholarship from Chalmers Master Card foundation.

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Sofie Flod and Hanna Landquist

Notations

The following notations are used in this thesis:

FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
GIS	Geographical Information Systems
GSN	The Geological Survey of Namibia
HHM	Hierarchical Holographic Model
MAWF	Ministry of Agriculture, Water and Forestry
WSASP	Water Supply And Sanitation Policy of 2008
WASP	Water supply And Sanitation Policy
WWTP	Waste Water Treatment Plant
WTP	Water Treatment Plant

Equations

$$Vulnerability = P_V = P_I \times P_U \times P_S \quad (6.1)$$

$$Vulnerability = P_V = (1-(1-P_{FZ})(1-P_{LU}) \times P_U \times (1-(1-P_{FD})(1-P_{JU})) \quad (6.2)$$

$$L_{fin} = \frac{1}{5}\sum_{i=1}^{5} L_i \quad (6.3)$$

$$V = R \times L \quad (6.4)$$

1 Introduction

This chapter provides background and aims and objectives of this master's thesis. Delimitations and the disposition of the report to guide the reader through the report are also presented.

1.1 Background

"Imbalances between availability and demand, the degradation of groundwater and surface water quality, intersectorial competition, interregional and international conflicts, all contributes to water scarcity" (FAO, 2010).

Today one in three people in the world are affected by water scarcity (WHO, 2010) and it is estimated that by the end of 2025 1.8 billion people will be living in countries or regions with absolute water scarcity (UNDP, 2006). Namibia is the driest country south of the Sahara and has a potential evaporation exceeding the potential precipitation (Heyns et al., 1998). The country also suffers from sporadic droughts (LCE, 2008).

There are a number of threats to drinking water quality and one of them, pollution, typically occurs in connection to development of human societies. Agriculture, urbanization and industry are causing pollution and the diversity and scale have increased rapidly in recent times (UNEP, 2003). Rapid population growth is one of the major challenges in preventing groundwater pollution and even if pollution levels in Namibia are generally low, a growing population and an expanding development will increase the amount of toxic substances in nature and water. Increased pollution will not only affect human health and environment but also the economic growth of Namibia (Tarr, 2002).

WHO (2008) states that access to safe drinking water is a basic human right and also important as a health and development issue. Moreover it is the aim of the millennium development goal number seven to halve the proportion of people without basic sanitation and sustainable access to safe drinking water (UN, 2009). In some regions it has been shown that investments in sanitation and water supply reduce adverse health effects and cost, thus creating a net benefit for the investor. Actions in improving access to safe water have also proven to have the ability to be an effective measure of reducing poverty.

Without water, life cannot be sustained and a safe, accessible and adequate supply must be provided to all. Windhoek, the capital of Namibia, daily supplies about 240,000 consumers with drinking water (City of Windhoek, 2010). Rehoboth, located 87 km south of Windhoek, supplies a smaller amount, about 40,000 people (Strauss, cited in Kullgren & Perdell, 2010) with their daily needs. In between the two cities few people live today but much development is taking place (Bochmühl, 2010), for example the Omeya golf and residential oasis situated approximately 30 km south of Windhoek.

To ensure a long term sustainable water supply and to expand the water scheme, the City of Windhoek is investigating the possibility of building a pipeline between Windhoek and Rehoboth to be able to pump water from the Oanob dam to Windhoek (Christelis, 2010). Actions to increase the economic viability of such a project can be to identify additional water supply sources to increase the available amount of water to the system and to possible developments along the pipeline in need of water. It could also be of interest to include the possibility to pump water from Windhoek to Rehoboth in case of a temporarily increased need of water in Rehoboth.

The master thesis “Vulnerability and risk assessment of artificial recharge of the Oanob aquifer” by Kullgren & Perdell (2010) has been performed parallel with this master thesis. The thesis examines the possibility for artificial recharge of the Oanob aquifer in Rehoboth from a risk and vulnerability perspective. If artificial recharge would be implemented in Rehoboth, this could result in more available drinking water for both Windhoek and Rehoboth.

WHO (2008) argues that a comprehensive holistic risk assessment and risk management are the most effective means of ensuring the safety of a water supply. A possible pipeline to expand the water supply scheme for Windhoek will be exposed to a number of threats, which result in risks of both water supply interruptions and pollution. It is thus important to identify the hazards and the consequences and probabilities related to evaluate the risk and safety of the suggested expansion scheme.

There are a number of methods for assessing and evaluating risks, and a risk analysis is according to the International standard 300-3-9 (IEC, 1995) “a structured process that identifies both the likelihood and extent of adverse consequences arising from a given activity, facility or system”. A method applied in risk assessments is the Failure Modes, Effects and Criticality Analysis (FMECA) which is a qualitative analysis where elements of the systems and correlated possible failure causes are identified. Further, possible effects of each failure cause are identified and a risk ranking of the failure causes is performed (Tweedale, 2003).

In this study the FMECA methodology and also the HHM (Hierarchical Holographic Model) was applied for investigating the feasibility of a pipeline between Windhoek and Rehoboth for an extended water supply scheme for the central area of Namibia. In addition, the risks of groundwater pollution of the groundwater aquifer at the Omeya golf and residential Oasis were performed as a basis for evaluating the possibilities for connecting the aquifer to the pipeline.

1.2 Aim and objectives

The overall aim was to provide a structured and operational method for conducting risk assessments concerning projects for expansion of water supplies, which might become an issue for Windhoek in the close future. This report also aimed to serve as pre-study for a possible expansion of the Windhoek water supply and as basis for further detailed studies.

This project was performed by identifying advantages and limitations of an expansion of the water scheme and thus the pipeline between Windhoek and Rehoboth. The possible limitations were identified by conducting an FMECA and by this method also related risks to the system was identified. One possible action for increasing the feasibility of a water expansion project of this kind can be to find additional water extraction points to increase the total available water quantity to the system. Such extraction points can be vulnerable to pollution and should therefore be subject to a specific risk assessment. The report provides an example method for conducting such risk assessment.

The specific objectives of the project were:

- To identify advantages of connecting the water distribution systems of Windhoek and Rehoboth via a pipeline.
- To identify and assess vulnerabilities and hazards related to the possible pipeline between Windhoek and Rehoboth.
- To assess the vulnerability of one possible extraction point along the pipeline and to identify relevant hazards.
- To combine the vulnerability and information on hazards into risk assessments; one for the pipeline and another for the extraction point.

1.3 Delimitations

The risk assessment connecting the water supply of Windhoek and Rehoboth provides a general overview of risks. At this stage, when the stretch, selection of material, dimensions, or if the system will be open or closed have not been decided upon, a detailed investigation is not possible. Therefore, this was an early stage risk assessment not including any events of force majeure but rather looking at operational, functional and social risks to a failure of the pipeline. This risk assessment is meant to function as a pre-study, thus more thorough investigation might be needed if the expansion project would go further.

Investigations concerning advantages of expanding the Windhoek water supply were based on interviews and questionnaires with relevant people. Logic reasoning is the core for the investigation of advantages and to derive limitations the FMECA method is partly used.

For the risk assessment of the pipeline, FMECA was chosen as method. The assessment included definition of scope, definition of the level of detail, identification failure causes and effects, and assessments of the severity of the failure modes. This report focused on identification and classification of risks as a basis for prioritisation of risk reduction measures.

The case study for the area of the Omeya golf and residential resort at the Haigamas farm was based on a methodology used to assess the risks to groundwater in the Windhoek area (IN & SCC, 2000) providing a risk map suggesting where to be careful of contaminating activities. Little focus was here put on mitigation.

1.4 Disposition of the Report

Initially the reader will be presented to the aims and objectives of this master’s thesis and hopefully brought to an interest of the subject. After this the overall risk assessment process applied is described, and further on background information concerning water as a resource both worldwide and in Namibia is given.

On this follows a general area description to orientate the reader of what characteristics affect water supply in terms of natural preconditions. Also a closer description of the area between the two cities, to give background information on the opportunity of extracting more water along a possible pipeline, is given. Subsequently a description of the water supplies of Windhoek and Rehoboth is presented to give an overview of what components are included in supplying parts of central Namibia with water.

The next chapter describes the different methods applied to conduct the risk assessment. The methods for identifying hazards and limitations to the project, the FMECA and the HHM as well as the method for analysis of groundwater risk and vulnerability assessment is presented along with how the advantages of a possible pipeline for water transport are derived. The reader is then presented to the actual studies performed on risks to a possible pipeline and risk of groundwater pollution in a specific area along the pipeline along with the results, a discussion and conclusions related to each part of the study.

After this there is a discussion on the applicability of the risk analysis methods performed along with a discussion on advantages and limitations on expanding the Windhoek water supply by a pipeline. Lastly the conclusions of the study are presented.

2 The risk assessment process

This chapter describes a general risk assessment process. Some risk analysis concepts are presented and the parts of the risk assessment, risk analysis and risk evaluation are described separately.

2.1 Foundations of the risk assessment process

The International standard *Risk analysis of technological systems* (IEC, 1995) upon which this study is based, generally aim to answer three central questions;

- What can go wrong?
- How likely is this to happen?
- What are the consequences?

The first question is investigated by hazard identification, secondly the likelihood is estimated by frequency analysis and the third question is investigated by consequence analysis. The specific study presented in this report identified hazards, analysed frequency and consequence by the FMECA and HHM methods, further described in Chapter 6.2. A case study to more thoroughly investigate risks to the system, thus risks to a part of the water supply, was performed through a risk and vulnerability assessment method developed in the Windhoek report (IN & SSC, 2000), described in Chapter 6.3.

The risk assessment was performed by compiling the estimated risks into a risk matrix where risks are evaluated by a specific number derived from estimates of frequency and consequence. This matrix described what risks are tolerable by a ranking procedure and a discussion was carried out to analyse the options.

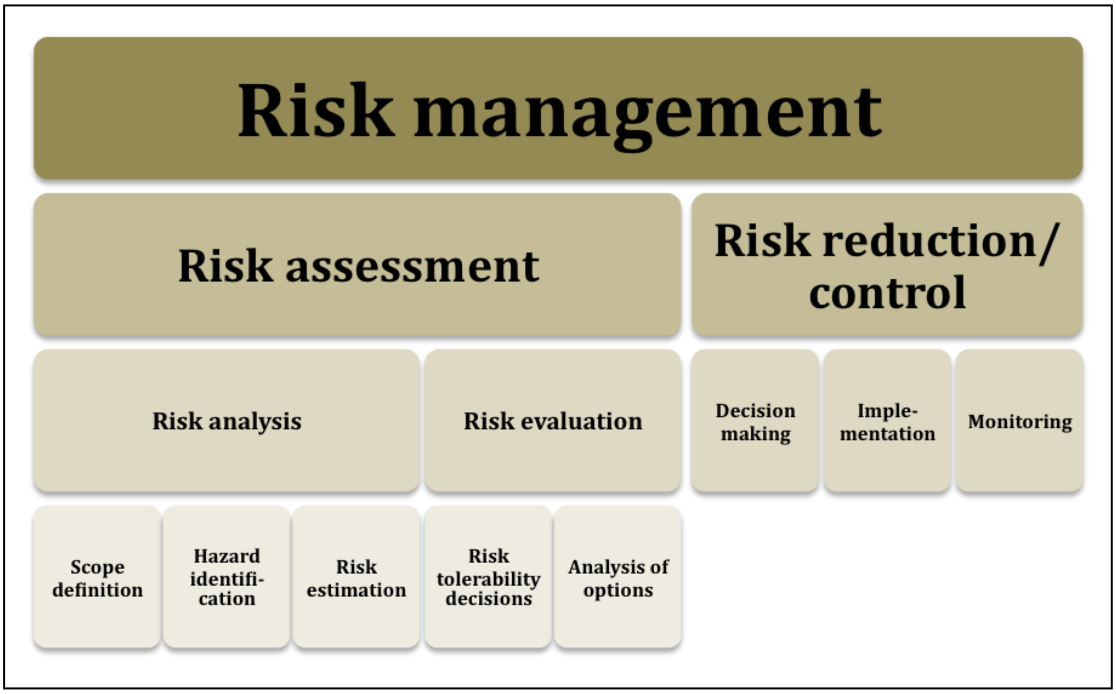

Figure 2.1 The risk management process (IEC, 1995).

Risk analysis is a structured procedure describing both the likelihood and extent of adverse consequences from a specific system or facility. In this standard, the adverse consequences of concern are physical harm to property, people or the environment.

The IEC standard focuses on describing the process of risk analysis, whereas this report comprises a more extended risk assessment. This infers that it also includes risk evaluation (see Figure 2.1), where risk tolerability decisions and an analysis of options are parts of the process.

2.2 Risk assessment concepts

There are a number of concepts and terms in risk analysis and risk assessment and to clarify the actual meaning a selection of frequent words are described below. There is of course an extensive nomenclature in the case of risk assessment and the selection below is chosen to fit this very project to avoid unnecessary confusion and communicative problems. The definitions are quoted from the standard developed by IEC (1995).

Hazard

“Source of potential harm or a situation with a potential for harm.”

Hazard identification

“Process of recognizing that a hazard exists and defining its characteristics.”

Risk

“Combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event.”

Risk analysis

“Systematic use of available information to identify hazards and to estimate the risk to individuals or populations, property or the environment”

Risk assessment

“Overall process of risk anlysis and risk evaluation.”

Risk control

“Process of decision-making for managing and/or reducing risk; its implementation, enforcment and re-evaluation from time to time, using the results of risk assessment as one input.”

Risk estimation

“Process used to produce a measure of the level of risks being anaylsed. Risk estimation consist of the following steps: frequency analysis, consequence analysis and their integration.”

System

“Composite entity, at any level of complexity, of personnel, procedures, materials, tools equipment, facilities and software. The elements of this composite entiy are used together in the intended operational or support environment to perform a given task or achieve a specific objective.”

2.3 The risk analysis process

In order to increase effectiveness and objectivity of a risk analysis, a number of steps should be followed. This can also facilitate the comparison with other analyses. The steps are as follows.

- Scope definition;
- Hazard identification and initial consequence evaluation;
- Risk estimation;
- Verification;
- Documentation;
- Analysis update.

The *scope* should make up a basis for a risk analysis plan and should include a background to the problem, well formulated objectives and criteria for failure or success of the system. Further the system, limits and assumptions concerning the project should be stated. Lastly also an identification of the decisions that have to be made, the decision-makers and the required output from the study should be presented (IEC, 1995).

The step of *hazard identification and initial consequence evaluation* implicate an identification of hazard together with how those can be realized. To identify hazards not previously known, formal methods should be used i.e. the FMECA which is applied on this project. A study of the significance of the identified hazards should be based on a consequence analysis. The analysis can be terminated here if no hazards are found (IEC, 1995).

Following this is the *risk estimation* step with the purpose to investigate the events of concern, mitigating features and nature and frequency of possible hazardous events affecting the system. An uncertainty analysis should be performed and risk estimation is conducted to measure the level of risk to the system (IEC, 1995).

There are qualitative and quantitative risk estimates where a qualitative estimate expresses risk in words while a quantitative estimate expresses risk in numbers. The quantitative analysis is the most common but there are not always enough information to perform such an analysis. A combined analysis can then be done where involved experts subjectively estimate the level of risks based on experience. When a quantitative analysis has been carried out the accuracy of numbers should not be overestimated since they are estimates and care should be taken they are not considered more precise than the level of the analysis, data accuracy and/or the methods employed (IEC, 1995).

As part of the risk estimation a *frequency analysis* should be carried out, which estimates the likelihood of a certain hazardous event. A number of techniques can be used such as use of relevant historical data and simulation, analytical techniques and expert opinions. The first two are used together while the last one is utilised when the other two are not sufficient. The use of many methods increases the confidence in the study (IEC, 1995).

A *consequence analysis* is the next step estimating the probable impact of the hazardous events and is based on the hazardous event selected and describes the consequences of these events. It should consider both immediate and future consequences as well as secondary consequences to related equipment and systems. It is also emphasized that risk should be expressed in understandable and in suitable terms (IEC, 1995).

Uncertainties are numerous when analysing risks and should therefore be well examined. The sources of uncertainty should when possible be identified and translated into the outputs of the risk model. Both data and model uncertainties are of importance and also parameters sensitive for the analysis should be identified (IEC, 1995).

Some kind of *verification* to the assessment should be carried out to confirm the integrity of the analysis. If field experience on the same issue is available, the verification can be conducted by a comparison of the results. Formal reviewing processes can also function as a verification of the study (IEC, 1995).

Documentation is made in the form of a report of the risk analysis process. This should include or refer to the plan of the risk analysis and initial hazard evaluation results and thoroughly present the technical information of the system. Strengths and limitations of methods of measurement used should be explained and uncertainties and risk estimates should be expressed in understandable terms. The scope and objectives of the analysis will decide the extent of the report (IEC, 1995).

The analysis should be prepared for an *analysis update* if the risk analysis is performed as a continuous process. The document can then be maintained during the lifecycle of the system (IEC, 1995).

It is mentioned that a thorough knowledge of the analysis method and the system is required. Further, the importance of investigator competence for the task is emphasized. In many cases a group ("risk team") rather than one person is needed to fully understand a complex system and it is emphasized that the subject under consideration should be well understood by the group. In certain cases expertise knowledge is required which should then be specified and recorded. Not all elements of the process are necessary in order to fulfil the scope of a certain risk analysis. Rather the steps needed for the specific object are chosen (IEC, 1995).

2.4 The risk evaluation process

This report comprises a risk assessment and therefore includes risk evaluation including risk tolerability decisions and an analysis of options. The Australian/New Zealand standard Risk management (AS/NZS 4360:2004) states that the purpose of the risk evaluation process is to make decisions about what risks to prioritise and treat based on the outcome of the analysis.

Risk tolerability decisions are taken involving comparison of the level of risk with set-up criteria. For example, in the analysis of options the balance between potential benefits and adverse effects should be regarded. Risk should also be taken under consideration not only affecting the organisation conducting the study. This will facilitate decisions about extent and priorities and also about the type of treatments required.

These processes are displayed in Chapter 7 and 8 through example studies. To further expand the project a risk management perspective can be adopted where decision-making, implementation and monitoring is applied.

3 Water as a resource

This chapter presents water as a resource and commences with a section about water scarcity to be followed by a segment about the water in Namibia. The Water in Namibia segment deals with how the water sector looks like in Namibia when it comes to legislation, economy and sustainability.

3.1 Water scarcity

Water scarcity occurs when the demand for water is greater than the supply in a country. Water scarcity can as well occur in regions with relatively plentiful supplies of water. It all depends on the quality, distribution and the conservation of the water (WHO, 2010). Also interregional and international conflicts and intersectional competition contributes to water scarcity (FAO, 2010). Declining freshwater causes water scarcity in terms of both quantity and quality (WHO, 2010). It is in the arid and semiarid regions of the world that are affected by droughts and wide climate variability combined with population growth and economic development, that the problems of water scarcity are most urgent (FAO, 2010).

Water demand can either be consumptive or non-consumptive. The consumptive water demand removes water from a source without directly returning it to the same place in the environment. Non-consumptive water demand is when then used water returns to the environment again, often with a reduced quality though. An example of this is untreated municipal wastewater. Around 70 percent of the total water demand on a global average is from the agricultural sector, 23 percent from the industry and 7 percent from the domestic sector. In dry areas these numbers are more distorted towards agricultural use. The water supply of a community refers to the renewable and non- renewable water that are available within a specific area (UOC, 2010).

Water scarcity can be either absolute or induced. Absolute water scarcity takes place when a region has low precipitation and a large evaporation rate, while induced water scarcity takes place when a country or a region does not have an adequate development of their water resources. Critical conditions often arise in politically weak and economically poor communities with already dry environments. Water scarcity can be defined by the Falkenmark Water Stress Indicator, which is an index that measures water availability on a per capita base (UOC, 2010).

Water scarcity affects one in three people around the world and today 1.2 billion people live in areas where the water is scarce (WHO, 2010). One in five people in the developing world lack access to sufficient clean water whereas people in e.g. some parts of Europe have access to almost unlimited amounts of clean water (UNDP, 2006). Due to urbanization, population growth and a growing industry, the situation is getting worse every year (WHO, 2010). By the year of 2025 it is estimated that there will be 1.8 billion people living in countries or regions with absolute water scarcity. It is people living in rural areas that suffer most when water scarcity occurs in a country or region (UNDP, 2006).

People living in developing countries also face water shortages due to lack of methods for collecting water from aquifers and rivers. When water scarcity occurs, people are forced to rely on unsafe sources of drinking water and it also minimizes the possibilities for them to clean themselves and their clothes. Poor water quality increases the risk for different diseases, for example cholera and typhoid fever.

Storage of water is common in water scarce areas which can increase the risk for contaminated water and the stored water also becomes a breeding ground for mosquitoes that carry diseases like e.g. malaria and dengue fever. Due to a lack of water the use of wastewater (containing chemicals and disease causing organisms) for agricultural production has increased tremendously in poor communities (WHO, 2010).

In the year of 2000, world leaders set far-sighted goals that should free the poorest people in the world from extreme hunger, poverty and diseases. Targets were established for achieving gender equality and environmental sustainability and the target date for most of the goals are set to 2015. One of the targets of the Millennium Development Goal number seven aims to halve the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015. The Sub-Saharan Africa has made notable progress in reaching the target and the population that uses an improved sanitation facility has increased by over 80 percent since 1990. The world is ahead of schedule in meeting the drinking water target, though some countries still face huge challenges and water scarcity threatens the progress (UN, 2009).

To be able to manage growing water scarcity around the world, different approaches need to be considered at both local and national river basin levels. A combination of increased water use efficiency and sound policies could lead to sustainable solutions within this complicated area (UOC, 2010). In situations where two or more countries are sharing the same river basins and there is an absence of agreements or institutions that controls this, a change within a basin can lead to instability between the involved countries (WWC, 2009). Therefore collaboration between nations is necessary and a multidisciplinary approach is needed in order to maximize economic and social welfare in an equitable manner without compromising the sustainability in vital ecosystems. Restoring and protection of ecosystems that naturally capture, filter, store and release water is crucial for being able to increase the availability of water of good quality (UNDP 2006).

3.2 Water in Namibia

Namibia is the driest country south of the Sahara and water is scarce. The country has an arid to semiarid climate which means that the potential evaporation is bigger than potential precipitation (Heyns et al., 1998). The average rainfall is much lower than half of the world average and the water that exists in the country is spatially poorly distributed. The country also suffers of heavy droughts periodic (LCE, 2008).

Namibia has a population of 2.1 million inhabitants and a population growth rate of approximately 1 percent. As the population is growing every year, the demand for water is increasing. The water in Namibia has to be shared between the growing population, agriculture, the industry and other services that provide employment (Heyns et al., 1998).

The Department of Water Affairs at the Ministry of Agriculture, Water and Forestry, on behalf of the government, administers all water resources in Namibia. The Department of Water Affairs consists of two directorates: the Directorate of Resource Management and the Directorate of Rural Water Supply. The objectives for the Directorates are:

1. Essential water supply and sanitation services should become available to all Namibians, and should be accessible at a cost which is affordable to the country as a whole.
2. This equitable improvement of services should be achieved by the combined efforts of the government and the beneficiaries, based on community involvement, community participation and the acceptance of mutual responsibility.
3. Communities should have the right, with regard for environmental needs and the resource available, to determine which solutions and service levels are acceptable to them. Beneficiaries should contribute towards the cost of services at increasing rates for standards of living exceeding the levels required for providing basic needs.

The major supplier of bulk water in Namibia is the Namibia Water Corporation (NamWater, 2006), which is a government owned corporation. NamWater was established in 1997 and has been the bulk water supplier since 1998 and the objectives of NamWater are to be found in the NamWater Act of 1997. The central responsibilities of NamWater are provide bulk water to most of the major users in a sustainable way, provide water at a cost that is affordable for all consumers and manage the water at a full cost recovery basis with all necessary costs included (MAWF, 2010). There are currently six water supply areas in Namibia, which are: Cuvelai, Okavango, Brandberg, Khomas, Namib and Karas. Windhoek belongs to the Khomas water supply area (LCE, 2008).

3.2.1 Legislation

The legislation for administration of water in Namibia is based on different articles, acts and policies, where the following five are the most important:

- The Namibian Constitution, Article 95
- The Water Act, Act No 54 of 1956
- The Water Resource Management Act, Act No 24 of 2004
- The Water Supply and Sanitation Policy of 2008
- The National Water Policy of Namibia, 2001

Article 95 of the Constitution presents the guiding principles for sustainable water development in Namibia (Heyns et al., 1998). The Water Act, No 54 of 1956, is the legislative framework for water management in Namibia and the purpose of the Act is to manage the use and conservation of water for domestic, agricultural, urban and industrial use. It covers topics concerning protection of surface and subsurface water. Even though the Act is old, it is still legally compulsory in Namibia (ORASECOM, 2007). A major limitation with the Act is that it does not recognize the natural environment as a user of water nor as a provider of essential processes and services. Furthermore, it does not specify the sustainable use of water resources in terms of economic, social and environmental sustainability (Heyns et al., 1998).

The Water Resource Management Act, No 24 of 2004, has not yet been implemented, but will hopefully be implemented by the end of 2010. When the new Act is implemented it will immediately replace the old one. The difference between the old and the new Water Act is that the new one provides a more modern legal framework for managing water resources, it classifies water as a national asset and has stronger requirements when it comes to the standard of both the drinking water quality and the effluent quality (ORASECOM, 2007). The treatment plants that exist in Namibia today will not be able to reach the high standard of water quality that the new Act demands. This means that penalty fees have to be paid until treatment plants that could manage the new higher demands are built. The building of one new plant is under discussion, but it is an expensive project meaning that finance is needed (Peters, 2010).

The Water Supply and Sanitation Policy of 2008 (WSASP) replaced the old Water Supply and Sanitation Policy (WASP) from 1993 and has a strong focus on water demand management (Republic of Namibia, 2008). The National Water Policy of Namibia sets a good basis for improved water management and pollution control. The policy states, amongst other things, that the management and planning of water sources in Namibia will take into account social, economic and environmental issues. It also states that in order to prevent and control water pollution, permits will be issued for disposing effluents. The "polluter pays principle" will be introduced and applied and reclamation of wastewater will be promoted (Tarr, 2002).

3.2.2 Economy

Water is essential for socio- economic development and for maintaining healthy ecosystems (FAO, 2010). In Namibia and many other countries where water is scarce an effective use of water is necessary. This can be a tough challenge when those countries are most often developing countries with a lack of good infrastructure for supplying water in an effective way. How Namibia develops affects the country's water resources, but the scarcity of water in Namibia also affects how the country can develop. Because of the scarcity of water, it is expensive to supply. The cost of supplying water in Namibia derives from the abstraction of groundwater, transportation and damming of river water, treatment of the water and in some cases desalination of seawater. The scarcity of water implies that there is a need to allocate costs and prioritize between different water users and that an inefficient use of water is a waste of money (Heyns et al., 1998). Figure 3.1 shows the different costs that are relevant when it comes to water supply in general (LCE, 2008).

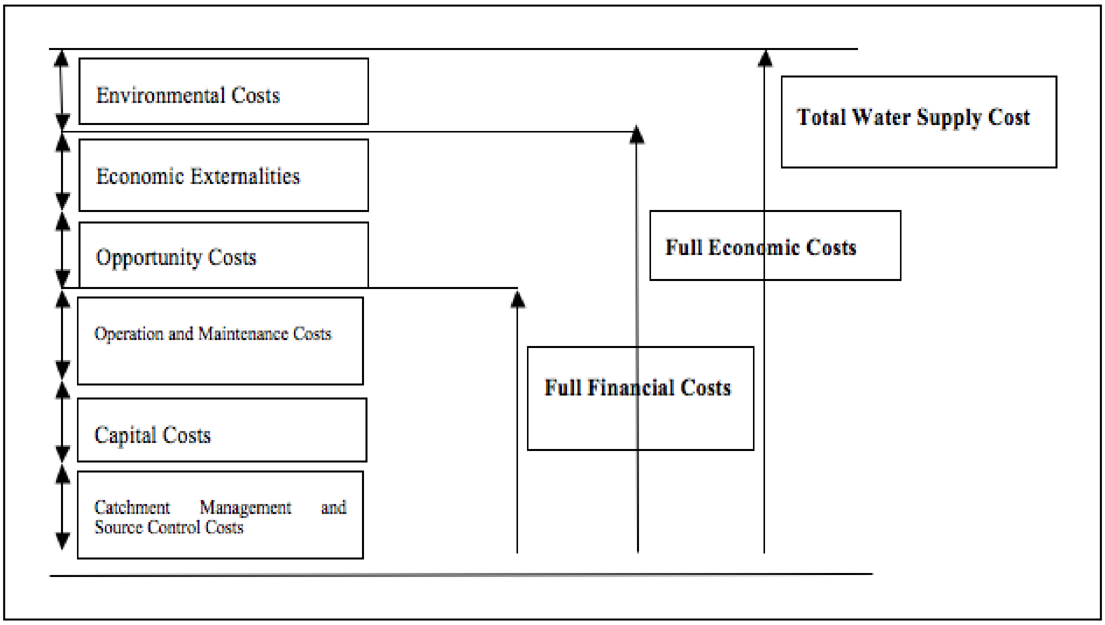

Figure 3.1 Different components of water costs (LCE, 2008).

The catchment management and source control costs are the costs for all activities that are needed to maintain and regulate the water resource for both water supply purposes and ecological purposes. Costs that can be included here in this cost category are costs for desertification, hydrological measurements, pollution control and control of algae.

Capital costs include the cost of interest and recovery of a loan needed to develop the infrastructure. Operation and maintenance costs can be divided into direct and indirect costs. The direct costs are costs for e.g. payrolls, chemicals, administration and operation and maintenance. The indirect costs are necessary for the overall management and for the control of the water resources in Namibia. Examples of indirect costs are costs for databases, information systems and education campaigns. The three mentioned costs are all included in the full financial cost. To be able to reach a financial sustainability for water supply agencies, in this case NamWater, at least these costs need to be covered (LCE, 2008).

The full economic cost for something includes the cost of what is given up to obtain it. It is not only the money spent for buying or doing something that is included in the full economic cost, also the utility that was not chosen is included. There is always a benefit, profit or value that must be given up to get something else. The utility that was not chosen becomes the opportunity cost, and is present in every decision that is made. Every resource has an alternative use and thereby an associated opportunity cost, which is the true economic price. Economics is mainly about the efficient use of scarce resources and the concept of opportunity costs then plays a central role of guaranteeing that resources are used in an efficient way (The Economist, 2010a). The opportunity costs of water are the benefits lost by using water for one reason rather than for another. If the opportunity costs would be included in the water price in Namibia, it would help to ensure that water is allocated equitable and to higher value uses (LCE, 2008).

Economic external costs are costs that affect a third part that is not directly involved in a transaction. It is those costs that are gained by one water user but paid by another user. Social costs can be regarded as an economic external cost when groundwater is exploited because it may gain costs to other users of the same aquifer (LCE, 2008). External costs can then be both positive and negative, but either way they are not reflected fully in the total price. External costs are a form of market failure since they are not a part of calculations and the activity carried out causing the external cost will be left to the free market, which is an inefficient use of resources (The Economist, 2010b). Therefore to be able to cover the full economic cost, both opportunity costs and economic external costs need to be included. To cover the total water supply cost, also the environmental cost needs to be included. Environmental costs are "costs" to the environment. When water from a river system is used it may cause negative effects such as loss of habitats for different species and reduced river flow. The environmental costs are often not reflected in the water price and are seen as a specific instance of economic externalities. Also the cost of maintaining an environmental reserve for keeping natural ecosystems is regarded as an environmental cost.

There are different ways of obtaining an efficient use of the water in Namibia, and for being able to keep an economic development in Namibia the same or a better output must be reached. Drip irrigation can for example reach the same result as sprinklers, but much less water is needed. Another option to increasing the water use in Namibia is to use the same amount of water but for a greater benefit. One has to consider where the water gives the most valuable result, filling up 330 swimming pools or irrigating one hectare of crop production. At the same time the full cost must include both opportunity and external costs for being able to obtain a sustainable value use, which is needed for being able to achieve a sustainable development within Namibia (Heyns et al., 1998).

Some industries are more water efficient than others and produce more output for less water. When choosing appropriate water use all costs and benefits need to be considered, not just the economic value. Job opportunities, ecosystem functions and foreign exchange are examples of other areas that also need to be assessed in the decisions (Heyns et al,. 1998). Due to Namibia´s scarcity of water, water supply priorities have been formed, which are:

- Priority 1: Water for domestic use
- Priority 2: Water for economic activities

Those priorities can be found in The Water Supply and Sanitation Policy of 2008 (Republic of Namibia, 2010).

What kind of good water is can be discussed. It can be regarded as a private good with public goodness attached to it, but it would probably be more correct to describe water as a quasi public good. A public good means that it is a good available to all, and nobody can be denied access to it. In an economic sense there is no reason why water should not be treated as any other good though, especially when taking into account that the real cost for the water attaches to the infrastructure of getting the water (LCE, 2008).

Pricing water is the best way of guaranteeing that it will be used in an efficient way. In cases where water is supplied by the state, people often do not pay the full cost for their water. To solve this problem the water sector should be financially self-sufficient, like the way it is attempted in Namibia today since NamWater took over 1998 as bulk water suppliers. In developing countries like Namibia, when the water consumers have to pay more for their water, people generally lower their water consumption rather than paying more. This could lead to that sanitation problems occur which can be solved by dividing the water consumers into two categories, those who can pay and those who cannot afford the full cost. Those who can pay include mining, manufacturing and service sectors as well as households. The ones excepted are the poorest urban households, which account for about one third of the water use in Namibia. The water tariffs for those sectors should include the full capital and operating costs of supply as well as external costs (Heyns et al., 1998).

The sector with those who cannot afford to pay includes poor urban households, most communal farmers and commercial irrigation farmers. The sector with the commercial irrigation farmers accounts for about 40 percent of all water use in Namibia and receives subsidized water for irrigation to grow essentially lucerne and cereal crops like wheat and maize. The farmers cannot pay the full water cost themselves and still be profitable due to the present irrigation practices. Subsidized water for irrigation falls under the policy of food self- sufficiency for the country, which also offers trade protection from cheaper imports of wheat and maize. So even if the farming practices are economically inefficient and ecologically inappropriate, they are protected and encouraged in the interest of the policy. This is not a sustainable way of using resources and the policy need to be reassessed (Heyns et al., 1998).

Subsidies are used worldwide today within the water sector and particularly in developing countries. They should be used to provide social benefits to the poor people and not be allowed to become an advantage to rich consumers, industrial users or farmers. Therefore the effect of the subsidies must be strictly monitored and openly analyzed. Subsidized water is often directed towards sectors with low economic benefits, since the water is not implicitly valued. Historically water in Namibia has been supplied at low costs, which has generated that people think that water should be supplied at low costs even now (LCE, 2008). Before Namibia became independent in 1990, water was even free of charge in most rural instances (Peters, 2010). Many water users in Namibia also consider water is a “gift from God”, and nobody should ever be expected to pay to use it. The subsidized water has in the past resulted in very high water usage within almost all sectors. Since the price of water in Namibia has increased during the past twenty years, there has been a reduction in water usage and water demand (LCE, 2008).

Using water tariffs is a way to get a sustainable water use if the costs reflect the correct price. Under the right conditions tariffs can develop water access and justice. The outcome of using tariffs depends on a diversity of factors. If the tariffs are set far below the levels needed to meet the overall costs of operation and maintenance they will not fulfil their purpose. In many countries using tariffs the cost for the initial volume is low or free, after that the cost rises (UNDP 2006).

The tariffs used need to be designed using sound economic principles in order to optimize the allocation of this scarce resource. The tariffs also need to be quite high to influence the water behaviour amongst people and reduce the use. To make the tariff structure successful, the water users must accept the tariffs as fair. The structure must be easy to understand and the tariffs need to send out the correct economic message to the water users. When large increases in the tariffs need to be done, it should be done over a longer period so that people get the chance to adjust their water consumption. Social equity within the water resource area means that all user groups have fair access to the scarce water resources in Namibia. The tariffs also need to be equitable, which means that all customers within a water supply area, linked to the same pipeline, should pay the same price (LCE, 2008).

There are a number of different tariff structures that can be used, and the four most common ones are marginal costing, rising block tariffs, two part tariffs and peak demand tariffs. Rising block tariffs are used all over the world, in both developing and developed countries, and are the structure that is used in Namibia today. The meaning of rising block tariffs is that the water is divided into blocks, and the consumers pay one price per m^3 water used within one block, and a higher price per m^3 water used within the next block. If the consumers just use the amount of water within the first block the water is quite cheap, but if they use more water the price is rising. This promotes water conservation and discourages an over usage of water. Using rising block tariffs results in higher marginal prices to the customer as the water use rises. The price for water in the initial start block can be subsidized or set very low to be able to ensure that poor people can afford it. Seen from an equity perspective, rising water block tariffs often assist low income households due to the fact that those households use less water than high income households. Using rising block tariffs often rely on the fact that each household has its own water usage meter. For people living in buildings with a number of apartments, this becomes a problem because there is often just one meter for the whole building. This means that the water costs for those people can be higher than for people living in single households, and poor people may get a disadvantage (LCE, 2008).

3.2.3 Management and Sustainability

A sustainable development is a guiding principle for use of all resources and need to include economic, social and environmental factors. Different planning strategies are needed for the water sector in Namibia and they should all be included in one bigger long term plan. The long term planning needs to take into account the environmental characteristics in Namibia such as the wide variation in rainfall, runoff, recharge and the increasing population. The worst case scenario with heavy droughts needs to be defined and accounted for in the plan (Heyns et al., 1998). Inappropriate government subsidies that encourage inefficient use of water and an excessive use of pesticides and other harmful chemicals should be stopped (Tarr, 2002).

A sustainable development within the water area requires integration with other sector activities such as family planning, range and livestock management and wetland conservation. For ephemeral rivers and perennial river basins shared with other countries a special approach is needed (Heyns et al., 1998). To be able to control pollution an integrated approach of water and natural resource management is essential. Land use management needs to be integrated with water resource management to avoid pollution of the land within the catchment area of a river by e.g. pesticides or decomposing waste matter that will reach the river in the end and pollute it (Tarr, 2002).

The government, local authorities, NGOs and individuals all need to be involved in assessing options and in making plans for water use and management. In rural areas women often are the major domestic water users and managers of water while the men decide where and when the water should be supplied. Therefore all of them need to be involved in the process, not just the men (Heyns et al., 1998).

An effective management is based upon awareness and understanding of water availability, use and development in Namibia. Understanding and awareness can be increased with inputs from research and long term monitoring. Skills can be developed and improved with training and experience. With increasing knowledge and understanding the changes in water availability can be understood and suitable management decisions made (Heyns et al., 1998).

Today the majority of the people in Namibia are aware that they need to utilize economically with the water and most people do what they can to minimize their consumption (Peters, 2010). As mentioned above, Namibia has developed a better and more sustainable legislation when it comes to water supply and water usage. To be able to reach a sustainable use, the guidelines need to be followed and the new Water Act (The Water Resource Management Act, Act No 24 of 2004) needs to be implemented (Peters, 2010).

4 General Area Description

This chapter gives a general area description of Namibia and its topography, climate, geology and hydrogeology. A more detailed area description of the area between Windhoek and Rehoboth is given.

4.1 Topography and climate

The central parts of Namibia reach an elevation of over 2,500 m, in the form of the Auas Mountains, where one of the peaks represent the second highest in Namibia (Namibian, 2010). From Windhoek the elevation decreases to around 1000 m above sea level in the northern and eastern parts as well as in the western part in the escarpment where-after it reaches at the coast. Lastly the land is generally less elevated in the south as can be seen in Figure 4.1 (DEA, 2002).

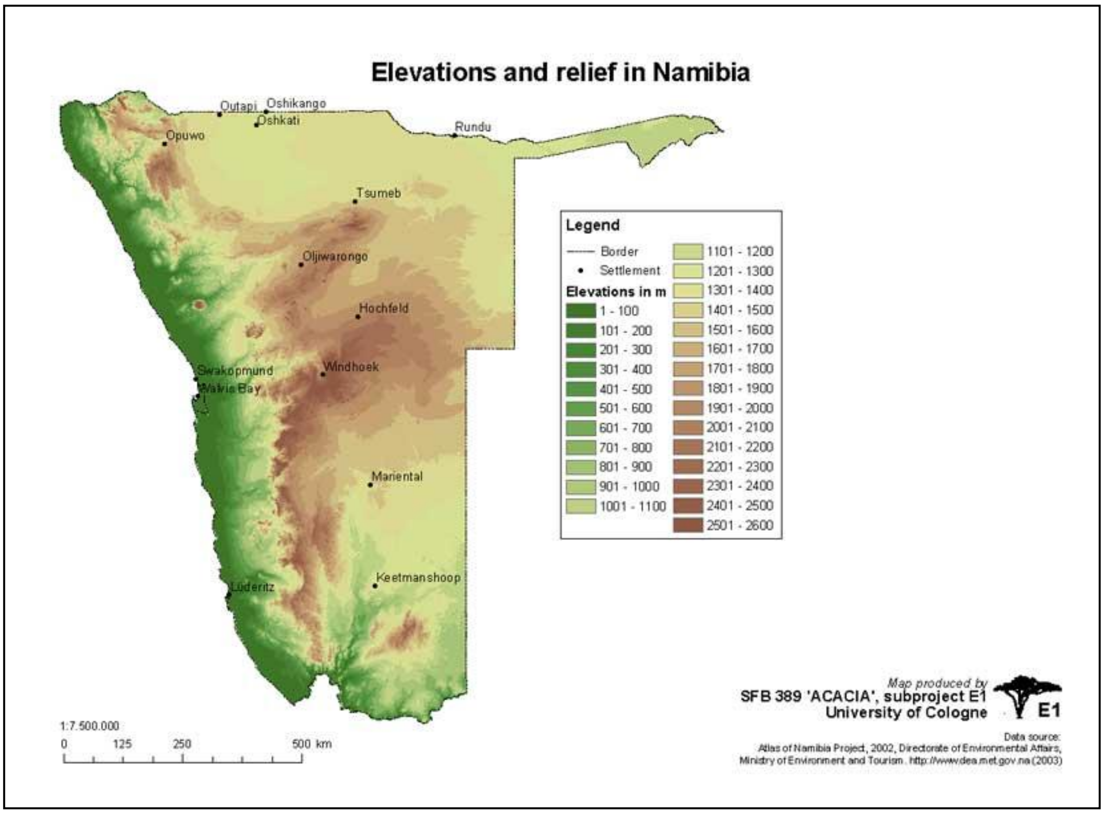

Figure 4.1 Elevations and relief in Namibia (DEA, 2002).

The two features predominantly governing the Namibian climate are scarcity of water and unpredictability of rainfall. The climate is the second in aridity after the Sahara Desert in Africa (MAWRD, 2000) and the majority of the water supply come from rainfall (CES et al., 1993). Droughts are a common phenomenon in Namibia, though floods are also a returning event (Heyns et al., 1998). It is predicted (Heyns et al., 1998) that even greater variations in precipitation will occur due to climate change. Precipitation is scarce and the annual amount is 250 mm, with a variation of less than 25 mm in the desert area to over 600 mm in the Caprivi area in the northeast (The Atlas of Namibia, 2002). In comparison, Zaire receives about 1400 mm per year.

4.2 Geology

Geology in Namibia spans over 2,600 million years from Archean to Phanerozoic times. Nearly half of the land surface is outcropping bedrock with an exception of the Kalahari and Namib deserts which are covered by young surficial deposits which in general can be found where the Kalahari group is indicated in Figure 4.2.

The oldest rocks (220-1,800 Ma) can be found in the central and northern parts where highly deformed gneisses, amphibolites, metasediments and associated intrusive rocks are present. During 1,800-1,000 Ma the Namaqua Metamorphic Complex was formed, which includes granitic/metabasic intrusions and the volcano sedimentary Sinclair Sequence of central Namibia with associated granites.

Large parts of central and north-western Namibia are composed of a variety of metasedmentary rocks. During Tertiary to Recent (less than 50 Ma), widespread sediments have been spread over the Namib and Kalahari Sequences (GSN, 2006).

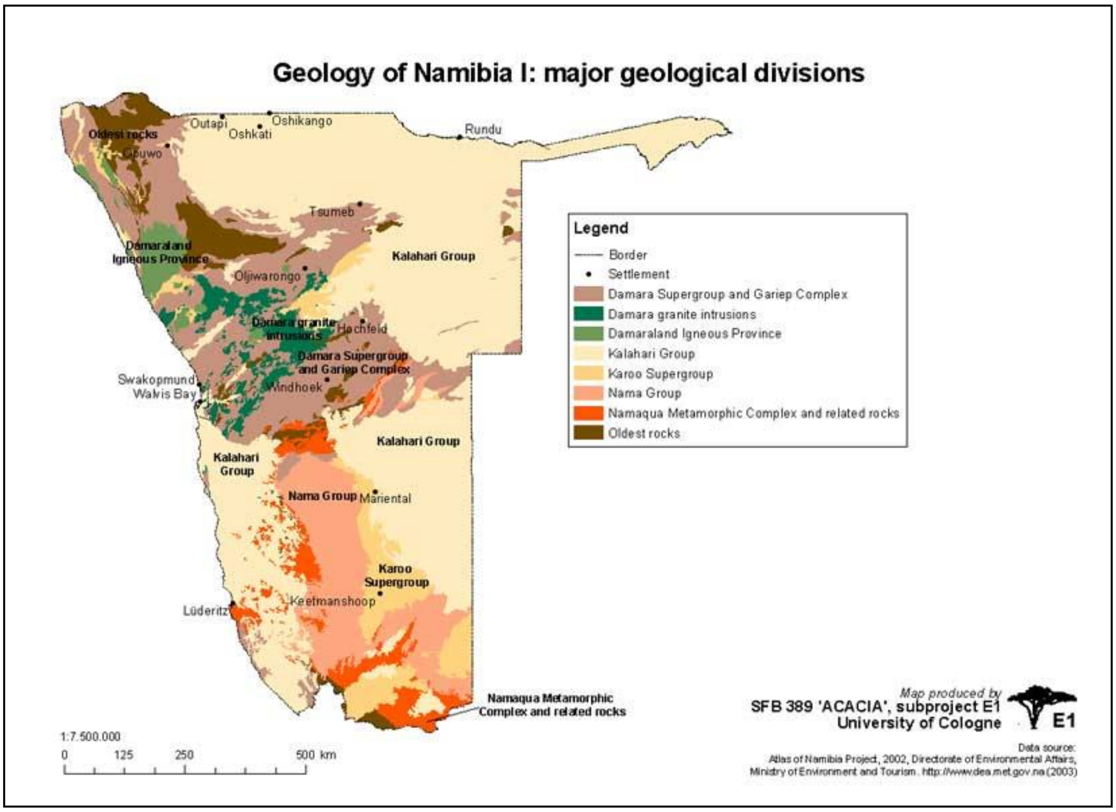

Figure 4.2 Geology of Namibia 1: major geological divisions (DEA, 2002).

4.3 Hydrogeology

As can be seen in Figure 4.3 (The hydrogeological map of Namibia), the aquifers of Namibia ranges from having a good to poor potential for water extraction. On the west coast, where the main climatic region is desert, there is very poor groundwater extraction potential, whereas the north eastern parts have a quite good potential to yield groundwater (CES et al., 1993).

About half of the country (48 percent) is covered by unconsolidated deposits that are potential porous aquifers. The rest is made up of hard rocks with various degrees of fracturing. Only groundwater-producing bodies, in which borehole yields generally exceed 3 m^3/h, are classified as aquifers and are shown in blue or green on the map. Those with borehole yields between 0.5 m^3/h and 3 m^3/h are seen as aquitards (in light brown), while formations where little groundwater is found (less than 0.5 m^3/h) are shown as dark brown aquicludes.

Only 42 percent of the country overlies aquifers, of which 26 percent of the area contains porous aquifers and 16 percent fractured rock aquifers. Within these aquifers, the borehole yields exceed 15 m^3/h only over some 14,000 km^2 or 3 percent of the total territory, making these highly productive aquifers and strategic targets for groundwater supply. Most of these areas have been declared as water control areas.

The only assured surface water supply is limited to the perennial rivers on the northern and southern borders of Namibia and this water must also be shared with the neighbouring countries. The dependence on groundwater is accentuated during prolonged periods of drought, when surface water tends to dry up (Christelis, 2010).

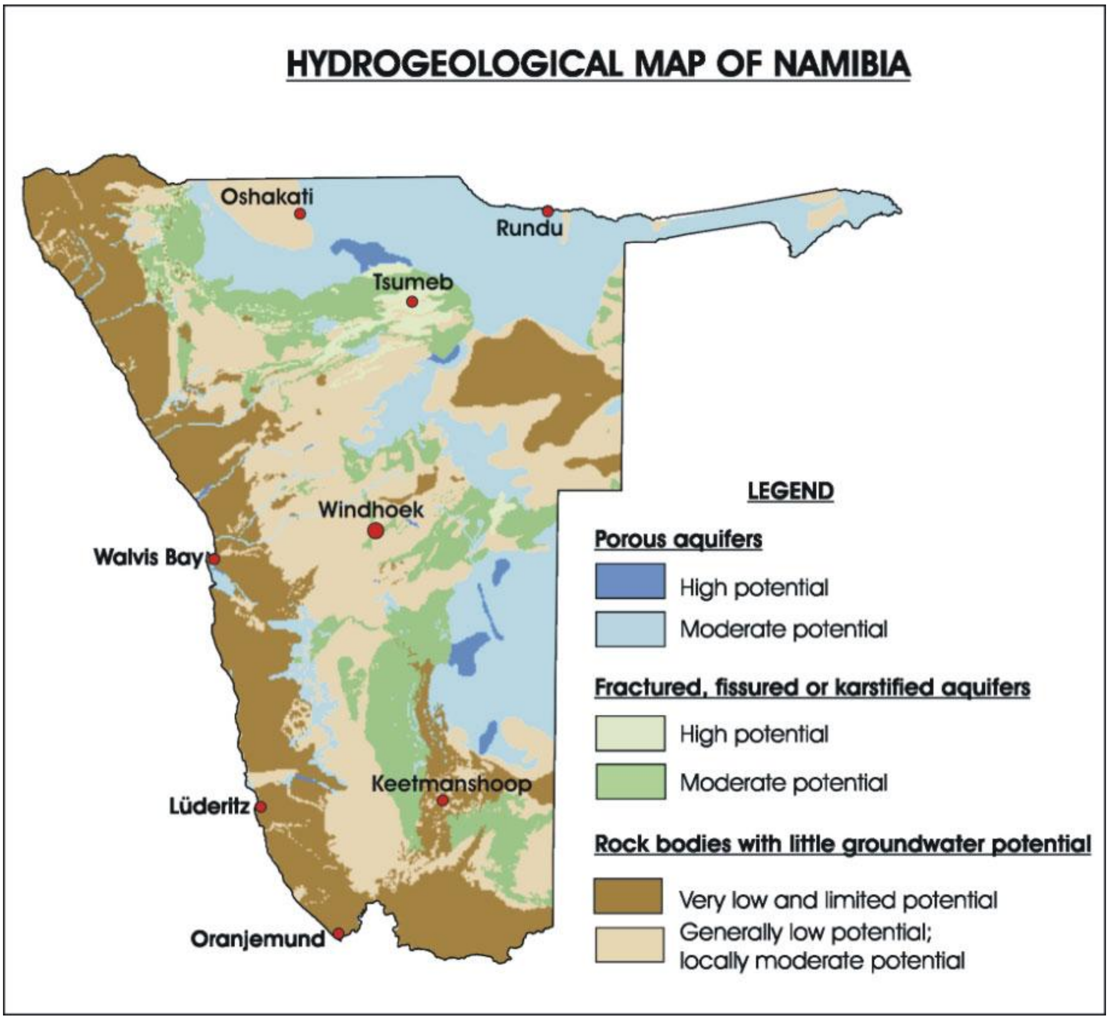

Figure 4.3 The Hydrogeological map of Namibia. (GSN, 2010)

4.4 General description of the area between Windhoek and Rehoboth

The distance between Rehoboth and Windhoek is about 90 km and is sparsely populated. A few settlements can be found, such as Groot Aub (Bochmühl, 2010) which is a low income settlement and several private farmers keep land in the area. Besides a smaller quarry and a paint manufacturing no other larger industries can be found. There is also an abandoned copper mine called Oamities. One activity taking place is a quarry in production just south of Windhoek. (Du Plessis, P. 2010).

The geology of the area is made up of a mosaic of lithological units. A larger strip of mica schists with imbedded quartzite, graphitic schists and marble is located south west of Windhoek. To the south of this area is a marble-, schist- and ortho-amphibolite quartzite belt. Other rock types are conglomerate and granites and a relatively large area is covered with alluvium such as sand gravel and calcrete (see Figure 4.4).

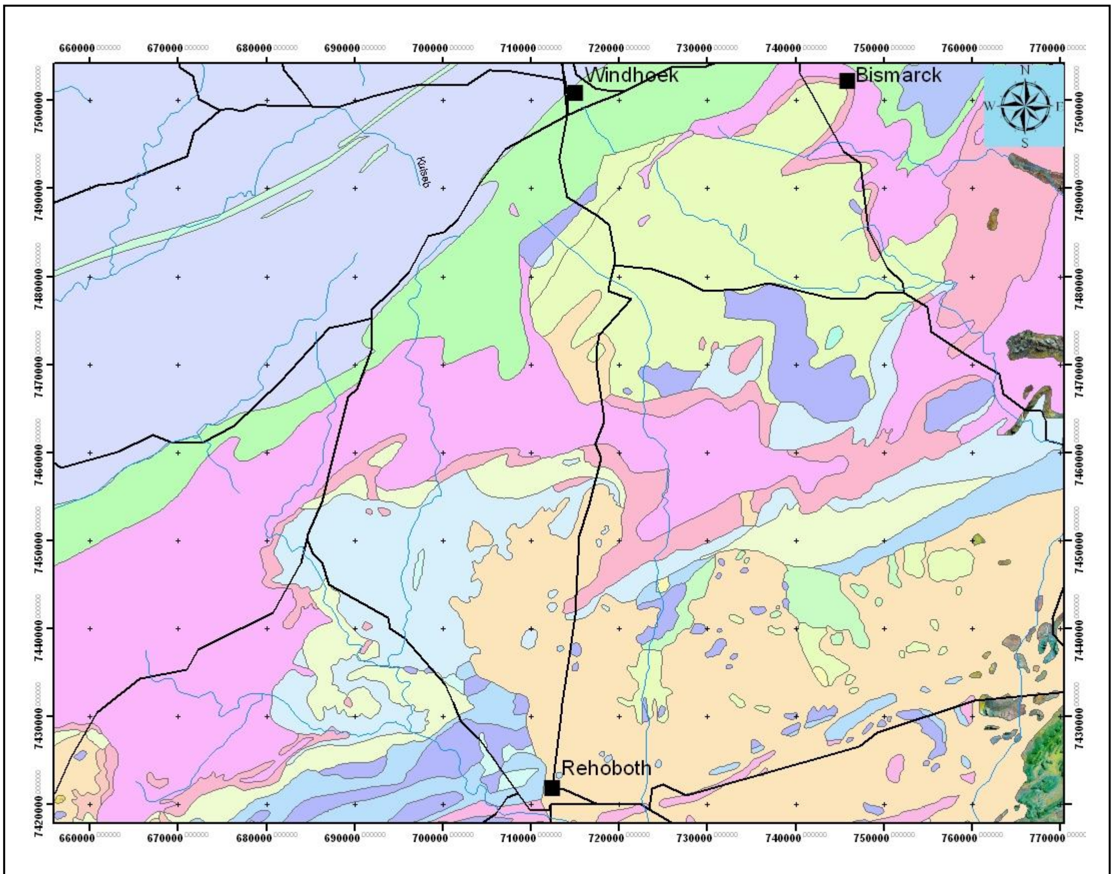

Figure 4.4 Detailed geology of the area between Windhoek and Rehoboth). Green indicate; marble, schist, orto-amphibolite and quartzite. Purple indicate; Granite. Orange indicate; alluvium, sand gravel and calcrete. Blue indicate; quartzite, conglomerate, schist and marble. Pink indicate; mixtite, minor schist, shale, quartzite, iron-formation, ortho-amphibolite and graphitic schist. Dark pink indicate; marble, schist, quartzite and graphitic schist. Yellow indicate; para-/ortogneiss, metasedimentary rocks, granite, metabasite dykes (Hasheela, 2010).

5 Water supply descriptions

This chapter describes the water supply in Windhoek and Rehoboth as well as the possible pipeline connection between the two urban centres. The descriptions of the water supply include the current water supplying sources, water costs and distribution.

5.1 The water supply in Windhoek

Windhoek is located in the centre of Namibia, about 750 km away from the closest perennial river (Menge et al., 2009). The infrastructure that supplies the city of Windhoek with water consists of a number of different facilities owned and operated by NamWater and the City of Windhoek. NamWater is the major bulk water supplier in Namibia and is a parastatal company with the Namibian government as its only stakeholder. The Windhoek population is approximately 240,000 people (City of Windhoek, 2010), and they use around 60,000 m^3 water every day (around 21 Mm^3 per year), the exact amount depends on the season (Theron, 2010).

5.1.1 Water supplying sources

Today there are three sources supplying Windhoek with water, which are groundwater, surface water and reclaimed water (Menge et al., 2009). A diagram showing the annual change in water production from the water supplying sources and the daily water consumption per capita can be seen in Appendix B (Peters, 2010).

5.1.1.1 The groundwater source

The groundwater is abstracted from the Windhoek aquifer by 60 production boreholes which are divided into three borehole groups. The water from the boreholes is not treated separately and is only chlorinated before it is placed in the storage reservoir (Menge et al., 2009). The total amount water generated from the boreholes per year ranges between 0.5 and 5.5 Mm^3 (Christelis, 2010).

5.1.1.2 The surface water source

The surface water that supplies Windhoek with drinking water comes from three dams in ephemeral rivers. The dams are the Von Bach Dam, the Swakoppoort Dam and the Omatako Dam (Menge et al., 2009). The total amount water generated from the three dams per year is approximately 15 Mm^3 (Christelis, 2010). Water from the Omatako dam and the Swakoppoort dam is transferred to the Von Bach Dam as soon as possible due to the fact that the evaporation rate is the lowest there (Du Plessis, N.P. 2010). The goal is to have an amount of water in the Von Bach Dam that can supply Windhoek with water for two years (Menge et al., 2009).

Together the dams can produce a maximum of approximately 20 Mm^3 per year, but as mentioned earlier just 15 Mm^3 per year is used today. The surface water from the dams is treated at the Von Bach Water Treatment plant, which is owned and run by NamWater, before it reaches the water distribution system and the consumers (Du Plessis, N.P. 2010).

5.1.1.3 The reclaimed water source

The Goreangab water reclamation plant treats domestic wastewater (Menge et al., 2009). Before the water reaches this plant two treatment plants treat the domestic effluents, the Gammams wastewater treatment plant and the Otjomuise wastewater treatment plant. Gammams treat around 25,000 m^3 every day and the sludge produced in the treatment process can be used for growing crops but is not regarded as completely safe due to the contents of heavy metals and bacteria. The Otjomuise plant is smaller than the Gammams plant and has a capacity of treating around 5 Mm^3 wastewater per year, but is now under construction and will in the near future be able to treat 15 Mm^3 per year (Peters, 2010).

After the wastewater has been treated at the Gammams wastewater treatment plant the effluent goes to the Goreangab water reclamation plant for drinking water treatment. The Goreangab water reclamation plant is owned by the City of Windhoek, but operated by Windhoek Goreangab Operating Company (WINGOC) with the shareholders Berlinwasser International, WABAG/ VATECH and Veolia Water (NGWRP, 2010).

The new Goreangab plant purifies about 16,000 m^3 per day, but are designed to for 21,000 m^3. The reclaimed water is mixed with surface water from the dams, and only one third may come from the reclamation plant in order to reduce the risk for polluted drinking water. When the water from the two sources is mixed, the water is chlorinated to prevent bacterial growth (Eterhuisen, 2010).

Industrial wastewater ends up in oxidation ponds north of Windhoek. The municipality is planning to build a new wastewater treatment plant for industrial wastewater where the treated water could be used for irrigation (Peters, 2010). A simplified schematic view of the water supply in Windhoek can be seen in Figure 5.1 below.

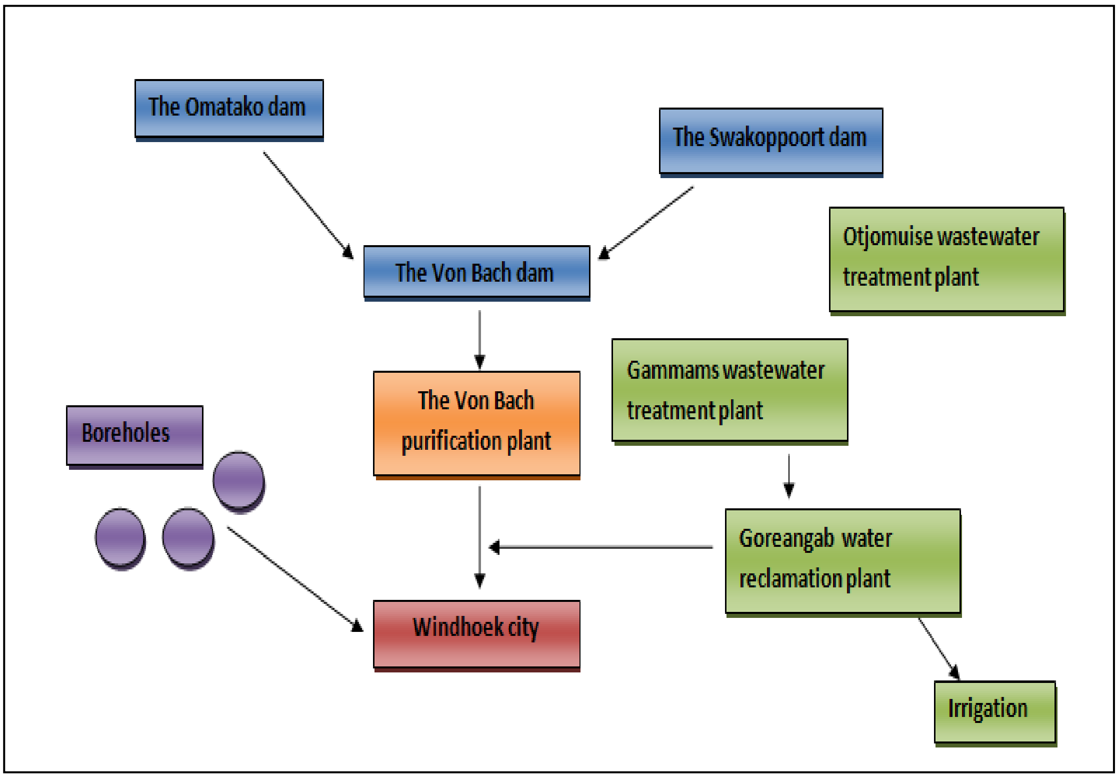

Figure 5.1 Simplified schematic view over the water supply in Windhoek.

5.1.2 Distribution system

The distribution system in Windhoek consists of 17 water reservoirs and 12 pressure zones (Menge et al., 2009). One of the reservoirs is owned by NamWater and can store around 27,000 m^3, while the other 16 are owned by the City of Windhoek (Theron, 2010). The water system of the City of Windhoek also consists of pumping stations, transmission and distribution pipelines and groundwater wells (SWECO, 2002).

5.1.3 Emergency plan

To be able to support the city of Windhoek with water during heavy droughts as in 1992 and 1997, the City of Windhoek works with emergency planning. The plan for the future is to extend the amount of boreholes in Windhoek and increase the artificial recharge with water from the Von Bach dam in the boreholes. The existence of the planned project depends on the obtaining of financial support from e.g. the World Bank. If the system is expanded, it will on completion be able to produce 17.3 Mm^3 water per year and will be able to supply Windhoek with water for two years (Peters, 2010).

5.1.4 Current water costs

The City of Windhoek buys the surface water from the three dam system from NamWater, and the price per m^3 is currently 6.25 Namibian dollars. The City of Windhoek charges the water customers in accordance with rising block tariffs. The charges are calculated on a daily consumption basis, and the customers pay at the end of each month for their water consumption. The current block tariffs for different consumer groups can be seen in Table 5.1 and the water costs for the City of Windhoek the year of 2009 can be seen in Table 5.2 below (Peters, 2010).

Table 5.1 Water consumption tariffs in Windhoek (Peters, 2010).

Customer Description and volume	Price (N$) per m^3	VAT	Total
Domestic 0-0.197 m^3 per day	6.77	0%	6.77
Domestic 0.198-1.50 m^3 per day	11.26	0%	11.26
Domestic >1.50 m^3 per day	20.75	0%	20.75
Domestic- times of limited water availability 0-0.197 m^3 per day	6.77	0%	6.77
Domestic- times of limited water availability 0.198-1.2 m^3 per day	11.26	0%	11.26
Domestic- times of limited water availability >1.2 m^3 per day	20.75	0%	20.75
Non Domestic	11.96	1.79%	13.75
Communal Water Points	11.26	0%	11.26

Table 5.2 Cost of water for Windhoek 2009 (Christelis, 2010).

Supplying source	N$/$m^3$
Groundwater	1.95
Surface water	6.44
Reclaimed water	7.84
Reused water (for irrigation)	4.03

5.2 The water supply in Rehoboth

Rehoboth is located 87 km south of Windhoek and like the capital city buys their bulk water from NamWater. Rehoboth pay 6.50 N$ per m^3 (Strauss, cited in Kullgren & Perdell, 2010) and all infrastructures delivering this water are owned and operated by NamWater (SWECO, 2002). The town of Rehoboth then supplies the citizens of Rehoboth and the total water delivery every year is about 960,000 m^3 for the estimated 40,000 inhabitants. A future (year 2023/24) water demand is estimated to 4.7 Mm^3/yr (Namib Hydrosearch, 2009c).

Infrastructure for the water supply is composed of the Rehoboth water treatment plant, the Oanob Dam, the dam outlet structure, pump stations and the distribution pipeline system. The maximum capacity is estimated to approximately 9 Mm^3/yr (SWECO, 2002).

The water treatment plant is based on chemical dosing, flocculation, sedimentation and filtration and has a capacity of 1,080 m^3/hr. The clean water is stored in three reservoirs of 2,500 m^3 each (Namib Hydrosearch, 2009c) and distributed to the city by gravity. Treatment of the wastewater takes place in oxidation ponds located approximately 2 km east of Rehoboth and according to SWECO (2002) a good estimation is that 40-50 percent of the consumed water reaches the ponds.

Payment for water is made according to a certain tariff system based on the amount of water used, a similar system to that in Windhoek (see Chapter 5.1.4). For a small amount of water used the cost is 8.10 N$ per m^3 but above 20 m^3 the sum is higher and increases with an augmented consumption as can be seen in Table 5.3 (Strauss, cited in Kullgren & Perdell, 2010).

Table 5.3 Water consumption tariffs in Rehoboth (Strauss, cited in Kullgren & Perdell, 2010).

Volume [m^3]	Cost [N$]
0-20 m^3	8.10
21-36 m^3	10.25
37-46 m^3	10.7
> 47m^3	11.88

5.2.1 The surface water source

The surface water used in Rehoboth comes from the Oanob Dam that is located approximately 7 km west of Rehoboth and is replenished by the Oanob River. The capacity of the dam is 34.5 Mm^3 and the surface area is 3.6 km^2 when full. The mean annual precipitation in the area is 250 mm (NamWater, 2006) and the total catchment area is estimated to be 2,726 km^2 (DWA, 1991).

The Oanob Dam was built in 1990 (Namib Hydrosearch, 2009c) due to an increase of water demand in Rehoboth. When the dam was completed, the town of Rehoboth started to charge for the water supplied in contrary to the free supply that had been a fact before the dam was completed. The demand has then gone down to such great extent that the dam would not have to be built at that time (Harris, 2010).

5.2.2 The groundwater source

The aquifer is a two compartment alluvial aquifer, and the bedrock surrounding it predominantly consists of quartzite and phyllite considered to be relatively impermeable. Storage potential is about 27 Mm^3 but losses from evapotranspiration are high when the groundwater level is close to surface (SWECO, 2002). Recharge to the aquifer mainly steams from leakage of the Oanob Dam, direct recharge from precipitation, river recharge, leakage and discharge from the oxidation ponds. The aquifer is, after the dam is built, mainly recharged by release water from the dam (SWECO, 2002).

The total planned utilisation of the aquifer is 1.6 Mm^2/yr (Namib Hydrosearch, 2009c). Investigations for artificial recharge are conducted for the Rehoboth aquifer (Namib Hydrosearch, 2009c; SWECO, 2002) and if this is realized the municipality plan to discontinue water use from the dam but to supply the city solely from the aquifer (Strauss, cited in Kullgren & Perdell, 2010).

SWECO (2002) further mentions that before the Oanob Dam was built in 1989, Rehoboth abstracted approximately 1.4 Mm^3 from the upper compartment and 0.3 Mm^3 from the lower annually totally relying on the alluvial aquifer. The borehole yields were between 10 and 30 m^3/h but it is assumed by SWECO (2002) that proper well design could increase the abstraction considerably.

5.3 The possible pipeline connection

The possible pipeline connection will stretch between Windhoek and Rehoboth, a distance of 87 km. The pipeline would connect the water supply in the two cities and could increase the total amount of water for the people living in the cities. The area between the two urban areas is described in more detail in Chapter 4.4, but a possible pipeline would need to cross land belonging to farmers. Otherwise there are few activities of hazardous nature going on in the area at the moment, but some new developments are to be built in the near future though. This project does not consider the exact stretch of the pipeline, if the pipeline system is open or closed, the material of the pipeline or if the pipeline will be built above or below the ground.

6 Methods

This chapter provides an overview and description of the methods applied in this master thesis. These were; identification of advantages, the FMECA including a HHM for a possible construction of a pipeline between Windhoek and Rehoboth and lastly a risk and vulnerability assessment method with respect to the groundwater pollution potential of the Omeya gold and residential oasis.

6.1 Overview of the methodological application

The three main methods described in this chapter are tools to conduct a part of a risk assessment on expanding the Windhoek water supply. As seen in Figure 6.1 below, a risk assessment contains risk analysis and risk evaluation. The first component is roughly divided into three parts; scope definition, hazard identification and risk estimation. To identify hazards the Failure Modes, Effects and Criticality Analysis (FMECA) and the Hierarchical Holographic Model (HHM) methods are applied. The risk and vulnerability assessment for the Omeya golf and residential resort is a more intense investigation of one specific hazard therefore placed below the FMECA.

The identification of advantages is not originally a part of a risk assessment but is included in this report to investigate possibilities to further increase the economic viability of the possible project. No specific method, rather logic reasoning constitutes the basis for the identification of advantages.

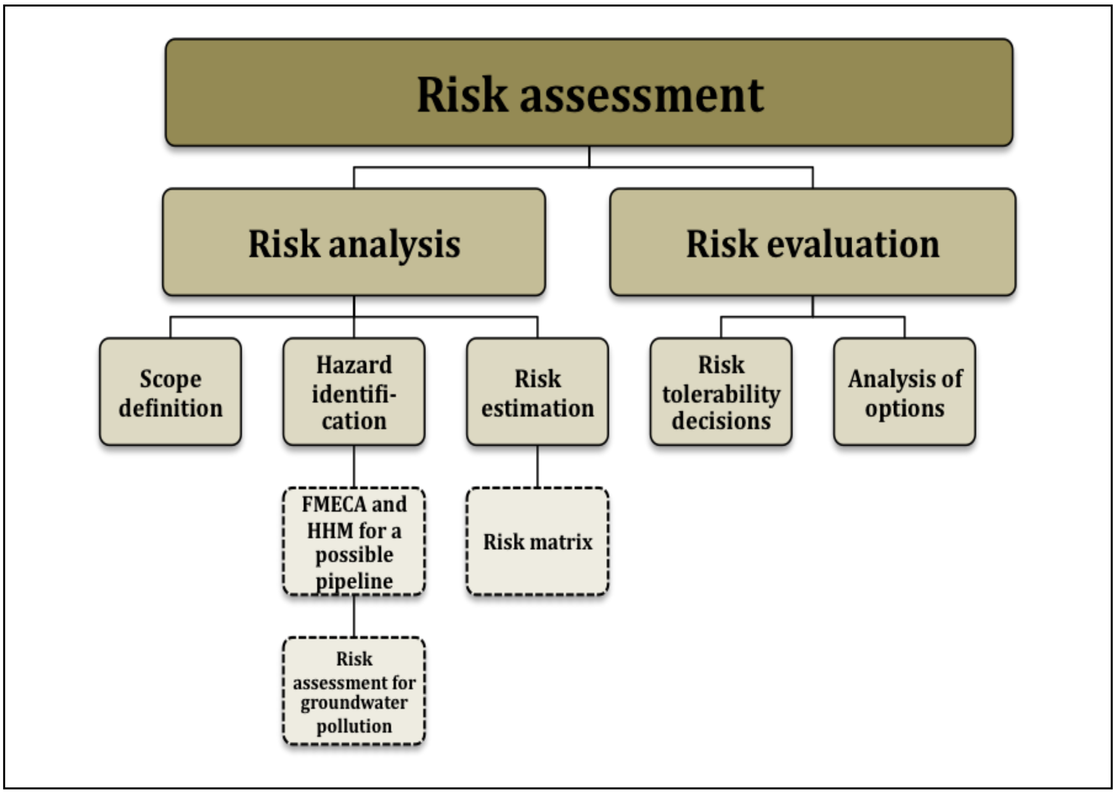

Figure 6.1 *Flow chart of the correlation between the methods applied to evaluate the risk of expanding the Windhoek water supply. The specific methods applied for hazard identification, groundwater pollution and ranking are dashed.*

6.2 The FMECA methodology

To identify and quantify the failure causes that can occur if connecting the two water distribution systems in Windhoek and Rehoboth to each other via a pipeline, the FMECA (Failure Modes, Effects and Criticality Analysis) method was used. FMECA is an extension of the FMEA (Failure Modes and Effects Analysis) method, which is a non-quantitative analysis method that aims to identify risks and reduce them. An FMEA is a systematic process that identifies potential failures before they take place and states what effects on the system the failure modes might cause. The purpose of an FMEA is to either remove the failures or to reduce the risk associated with them (Burgman, 2005). An FMECA is a semi-quantitative examination method and contains a Criticality Analysis. In an FMECA the severity of the possible effects and their probability are assessed, which will make it possible to calculate the risk for the failure modes and to rank the failure modes in terms of importance. The main steps included in an FMECA are:

1. Definition of the scope of the study by defining the limits of the system that is studied.
2. Decision of the level of analysis by identifying the different elements that are included in the studied system.
3. Identification of possible failure causes and the associated failure modes to the elements included in the studied system.
4. For each element in the studied system, consideration of the associated failure modes and identification of the possible failure effects.
5. Performance of a risk ranking of the failure causes and their modes and effects by assigning them by numbers for probability and consequence.
6. Compilation of the failure causes from the risk ranking in order of severity.
7. Documentation of measures and risk reduction options.

The identification of the different elements included in the studied system was done by making a hierarchical holographic model (HHM), where the studied system was decomposed into smaller more detailed parts, see Figure 6.2.

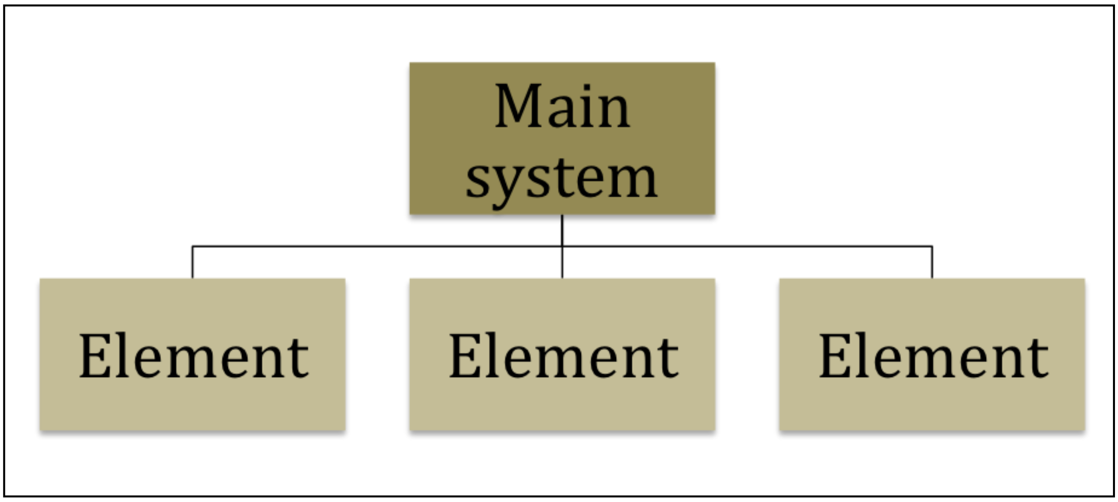

Figure 6.2 The HHM concept.

Identification of possible failure causes and failure modes was based on discussions with people within the water sector in Namibia, the HHM, discussions by the project team and relevant literature. A questionnaire (Appendix A) was used, asking for possible failure causes and failure modes to the pipeline itself and to the water supply as a whole with the connected pipeline. The failure causes and the failure modes were given numbers and put into an FMECA worksheet (Table 6.1).

The identification of the possible failure effects was also done based on expert opinions of people within the water sector in Namibia and from the project team as well as relevant literature. The failure effects were listed in the FMECA worksheet (Table 6.1) as well.

The risk ranking was done by a risk matrix (Figure 6.3). Each identified failure cause was assigned a probability and a consequence value, based on discretised scales. The probability describes how often the failure cause is expected to occur and the consequence describes the severity of the attached modes and effects. The values for probability was divided into 5 classes, where class 5 means that the probability is very high and class 1 means that the probability is very low. Each value for probability was assigned with respect to how often the failure cause happens during a year. The values for the consequence ranges between 1 and 5, where 5 means that the consequence was catastrophic and 1 means that the consequence was minor. Each value for consequence was assigned with respect to the human, economic and ecological consequences. The values for probability and consequence were estimated by people within the water sector in Namibia and by the project team.

When the values for probability and consequence were assigned, they resulted in one of the risk categories; green, yellow or red, which explained the risk of the failure cause. The risk categories are derived from the ALARP-principle, which is based on the idea that risks should be reduced to a level "as low as reasonably practicable" (Burgman, 2005). This means that a green risk for the failure cause was low and acceptable, a yellow risk that the risk of the failure cause was moderate and a red risk indicated that the risk of the failure cause was high and thereby unacceptable. All of the failure causes were then put into the risk matrix by their numbers so that it was possible to overlook the severity of each failure cause and see how many failure causes that belonged to each risk category.

The last step in the FMECA was to document measures and risk reduction options for the failure causes. Recommendations of which of the failure causes should be addressed first were proposed as well as measures for how the failure causes could be mitigated. Risk reduction options were listed in the FMECA worksheet (Table 6.1).

Table 6.1 FMECA worksheet for the potential failure causes, failure modes and failure effects (modified from Rosén et al., 2007).

System:								
Description of failure			**Effect of failure**		**Probability (failure rate)**	**Conse-quence**	**Risk (criticality)**	**Risk reduction options**
Tag. no.	Failure mode	Failure cause	On the module	On (sub)-system				

The FMECA worksheet (Table 6.1) initially expresses what kind of system that was studied. Further, there were columns that described the function of the analyzed module, the failure, the effect of the failure, the failure rate (probability), the consequence and the criticality (risk). The colours that were stated in the criticality column were a result of the values given in the columns for probability and consequence. The matrix (see Figure 6.3) was applied to see the colour, i.e. risk level and risk acceptability, for each specific failure cause. A column for risk reduction options was also included in the worksheet.

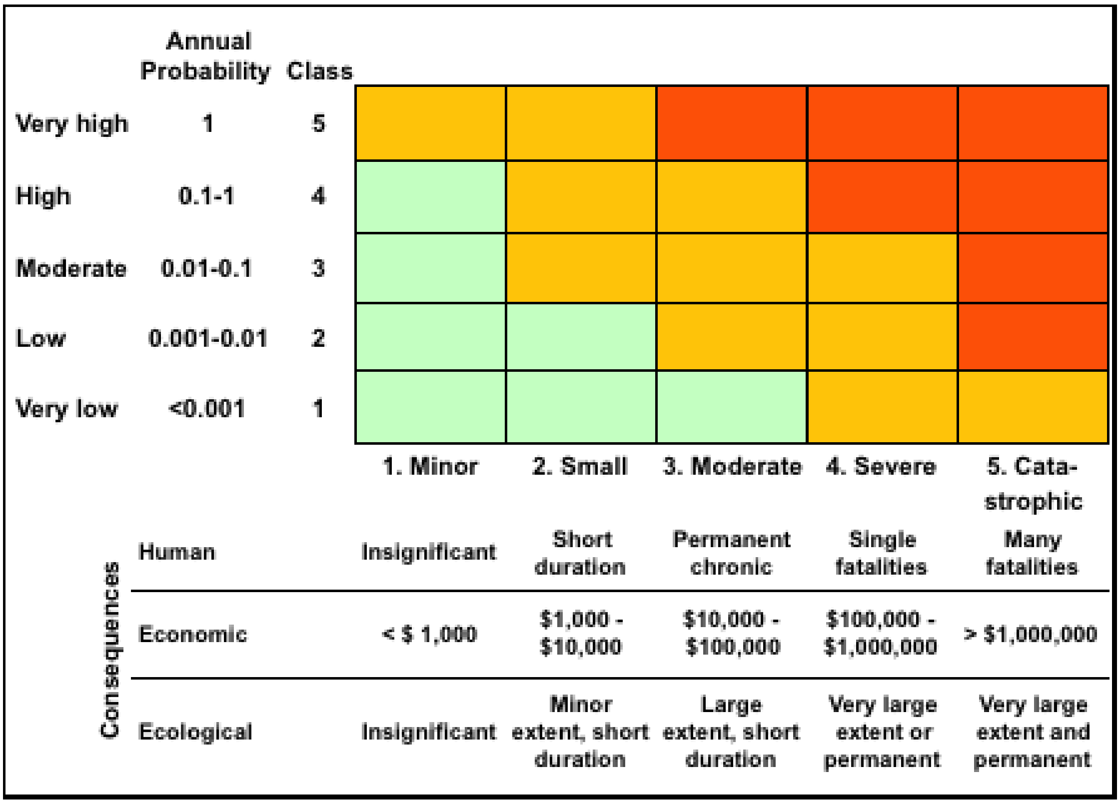

Figure 6.3 Risk matrix for the failure causes in the FMECA.

6.3 Method for risk and vulnerability assessment of pollution of groundwater

The groundwater risk and vulnerability assessment method was based on the report *Groundwater vulnerability of the Windhoek aquifer*, conducted in 2000, by Interconsult and Scandiaconsult International (IN & SCC, 2000). The chosen method was preferable due to the earlier conduct of such risk and vulnerability assessment in Windhoek because many geological preconditions are similar. This method is based on the assumption that it is not necessarily true that the area most vulnerable to groundwater pollution is the most urgent site to protect, nor that the area where the hazard is the greatest is the most vulnerable. This is an integrated approach combining the consequences and the pollution site characteristics.

Main objectives during the development of that method were to consider contaminant transport potential in the specific hydrogeological setting and to use the results in risk-based groundwater management. Because of this, the method emphasises possible transport of pollutants in a probabilistic sense as illustrated by an event tree in Figure 6.4.

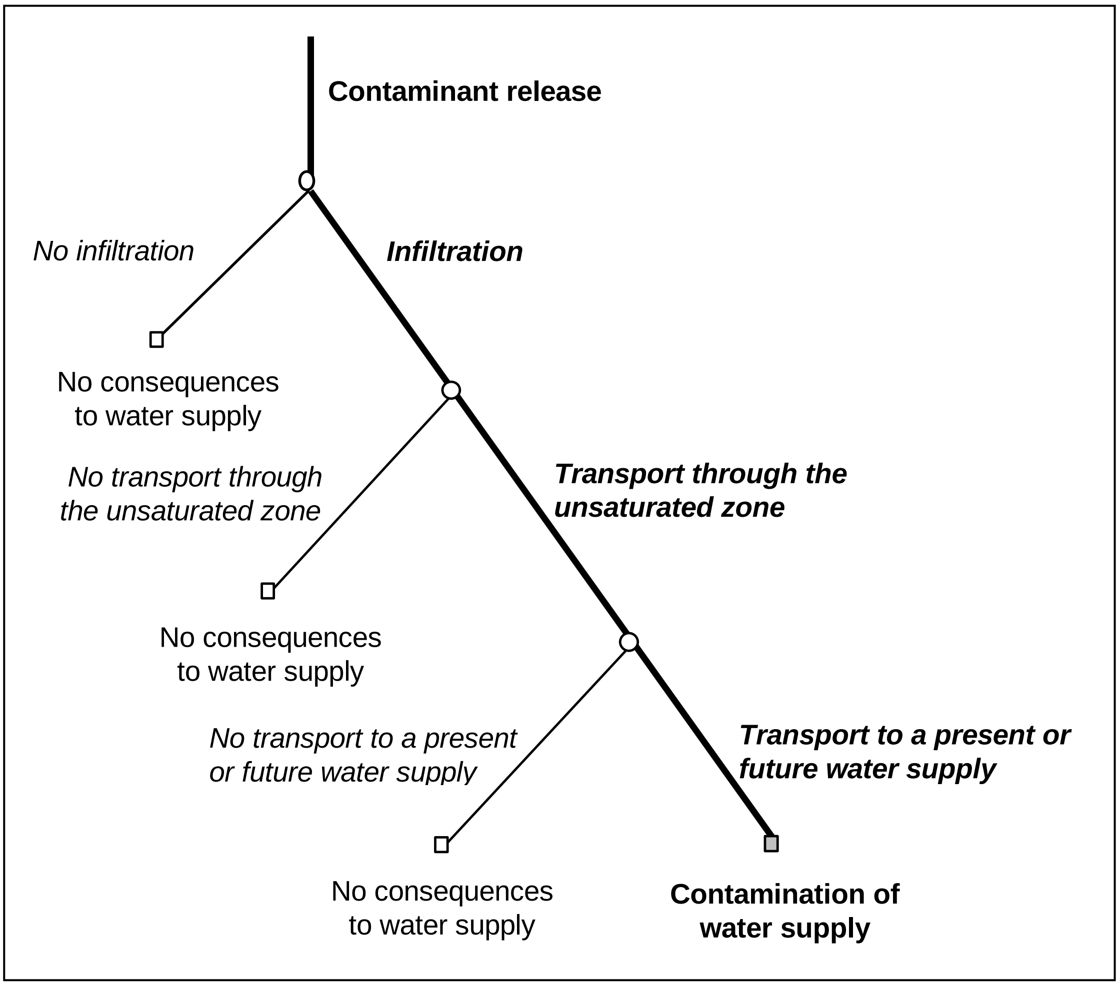

Figure 6.4 Event tree for possibility for contamination of water supply (IN & SCC, 2000).

6.3.1 Methodology

According to the model presented in Groundwater vulnerability for the Windhoek aquifer (IN & SCC, 2000), the hydrogeological part of the risk depend on the possibilities for pollutant transport through the "three major components of the hydrogeological system, i.e. the land surface, the unsaturated zone, and the saturated zone" (Figure 6.5).

The vulnerability assessment was based on the above mentioned three hydrogeological zones and determined by the identification of the following factors;

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 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 pollutant release, infiltration and transport through the unsaturated zone have taken place."

These factors were then given a rating based on information derived in the report of Groundwater Vulnerability of the Windhoek aquifer (IN & SCC, 2000) and specific estimations regarding the ground conditions of the Gross Haigamas area. The three values were multiplied to provide a value for the vulnerability, the process is shown in Figure 6.5 below and the equation used is presented in equation 6.1.

$$Vulnerability = P_v = P_i \times P_u \times P_s \qquad (6.1)$$

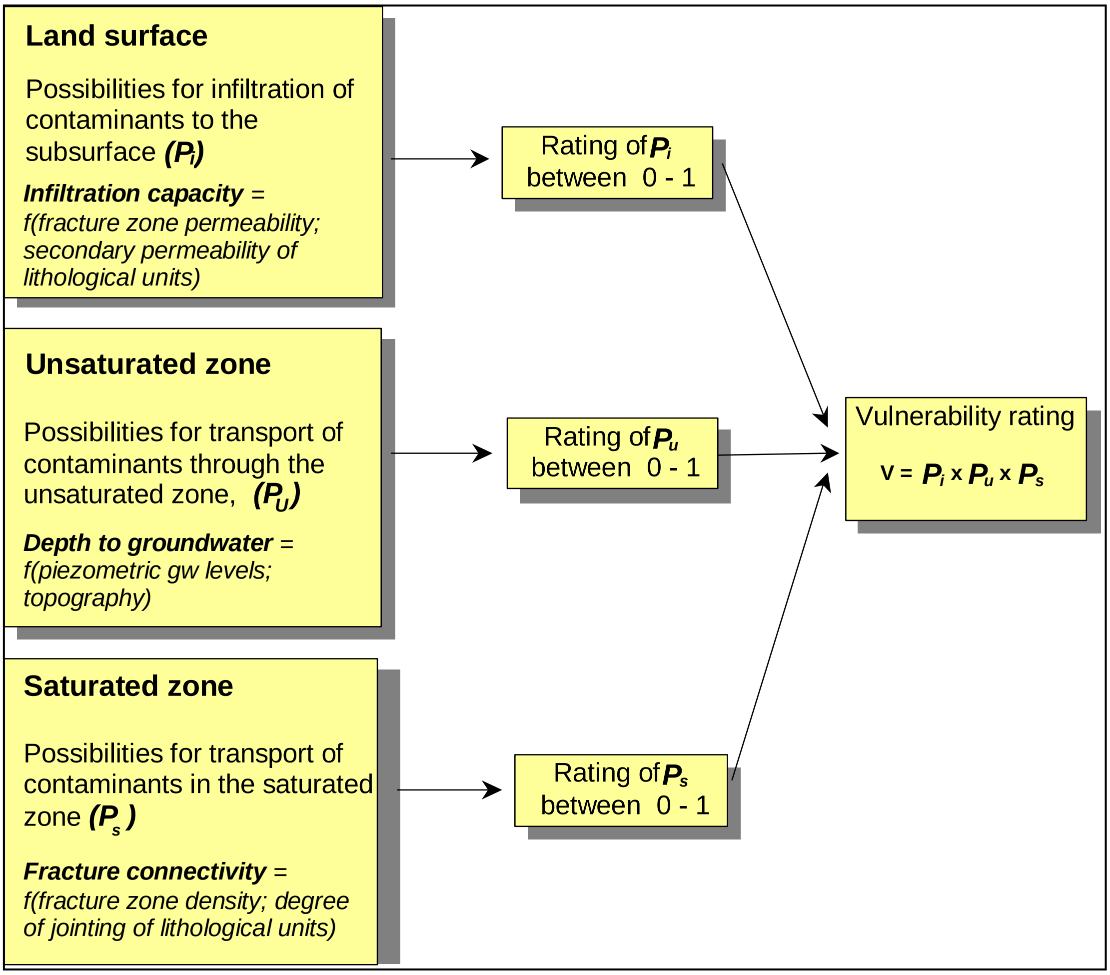

Figure 6.5 The process of assessing vulnerability to groundwater contamination (IN & SCC, 2000).

An event tree, as referred to in Figure 6.4, for this specific situation is presented in Figure 6.6 and shows how the three main hydrogeological components were further divided into subcomponents assumed to govern the probability of pollutant transport in the specific layer. The probability for infiltration at the surface, P_i, was assumed to be governed by fracture zone permeability and secondary permeability of the lithological unit. The probability of contaminant transport in the unsaturated zone, P_u, was assumed to be governed by the depth to the groundwater table and the probability for contaminant transport to the water supply, P_s, was assumed to be governed by fracture zone density and jointing of the lithological units.

The fault tree (Figure 6.6) summarizes this and the factors considered to govern the probability for pollutant transport were combined to one factor representing the specific hydrogeological component and the three factors were finally added into an estimated probability of pollutant transport through the studied geological column. This is described in equation 6.2 where the probability estimates were combined into a general vulnerability assessment for the three hydrogeological components.

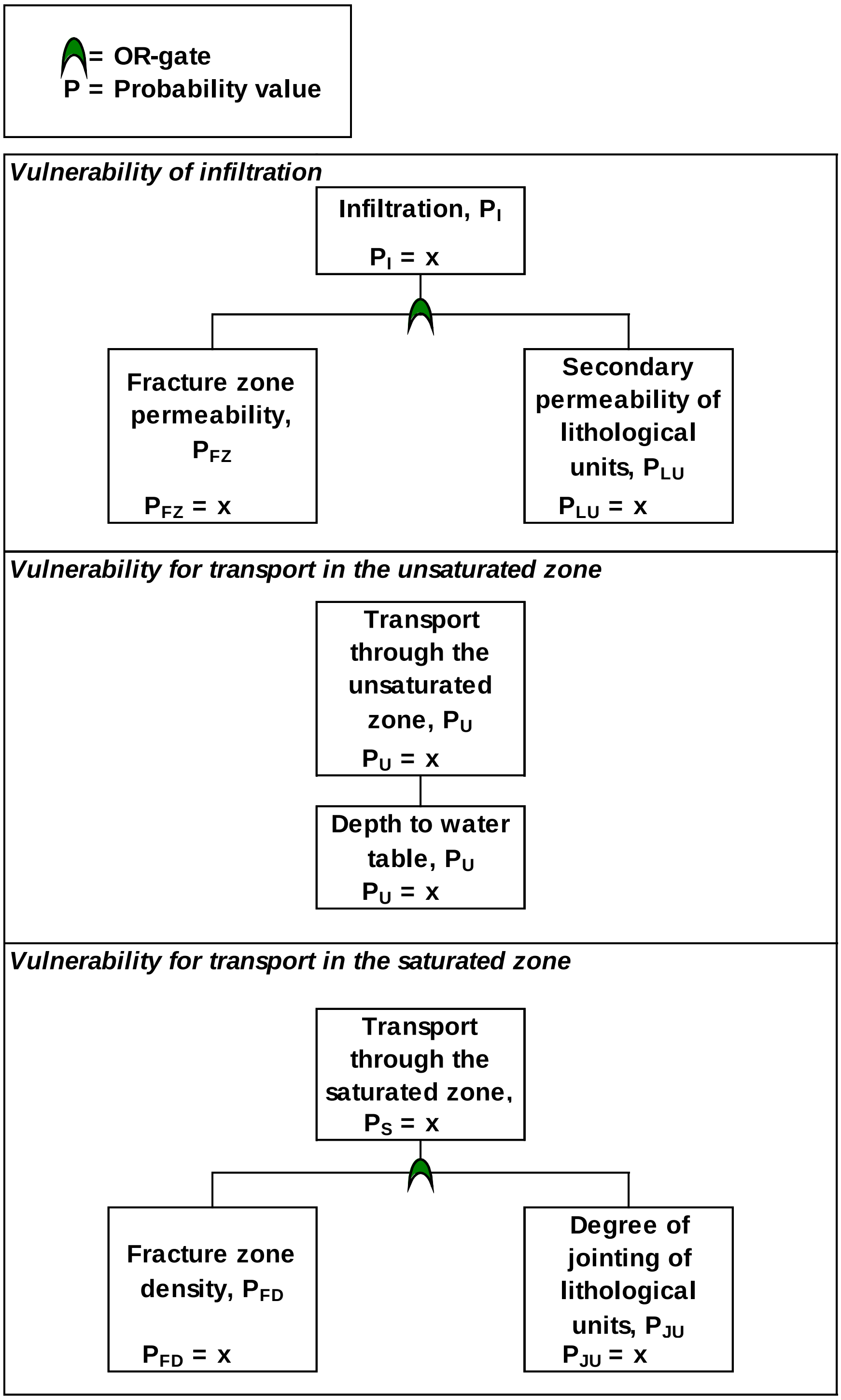

Figure 6.6 Fault tree of vulnerability to groundwater pollution through the geological column of the Omeya aquifer (Developed for this specific project).

$$Vulnerability = P_V = (1-(1-P_{FZ})(1-P_{LU}) \times P_U \times (1-(1-P_{FD})(1-P_{JU})) \quad (6.2)$$

P_V Probability of contaminant transport

P_{FZ} Probability of transport due to fracture zone permeability

P_{LU} Probability of transport due to secondary permeability due to jointing in the surficial lithological unit

P_U Probability of transport through the unsaturated zone

P_{FD} Probability of transport due to fracture zone permeability

P_{JU} Probability of transport due to secondary permeability due to jointing in the lithological unit

The estimated probabilities, P_i, P_u *and* P_s, are presented as three maps covering the Omeya golf and residential oasis by using a GIS software, ArcGIS 9 Spatial Analyst. Each map shows the probabilities of the specific event, infiltration through land surface, infiltration through the unsaturated zone and the probability for transport of pollutants through the saturated zone. The maps further constitute layers added on top of each other and multiplied to show the final vulnerability estimation for pollutants reaching the groundwater in the area. Figure 6.6 describes the process of adding layers of probability to produce a final vulnerability rating.

6.3.1.1 Assumptions

General assumptions made in the report on Groundwater vulnerability of the Windhoek aquifer (IN & SCC, 2000) were that the lithological conditions observed at the surface were continuous through the unsaturated zone. That was considered an underestimation of the vulnerability since the permeability likely was higher at the surface than at depth. For the Gross Haigamas area, the soil cover was considered to make up a small part of the total thickness of the unsaturated zone and therefore the same assumptions as for Windhoek were made. The soil type was included when estimating the vulnerability for contaminant percolation through the surface layer. Further down the dominating rock type in the column was considered the main governing material in the unsaturated zone. Other assumptions were that pathways for pollutants to reach the unsaturated zone depended mainly on fracture zone permeability and jointing in the lithological unit. This was considered relevant since fracture zones were the main conductors of water in the aquifer and small distances to a fracture zone increases the probability for contaminants to reach the aquifer. Where fracture density is high, the probability for infiltration is high. Quartzitic rocks were considered more permeable than schist due to a higher secondary permeability (jointing).

The distance to the groundwater table governs the probability for transport of pollutants through the unsaturated zone. It was assumed that a longer distance to groundwater increases the possibility for contaminant retardation and sorption. The surface was assumed to be flat and the groundwater level given a constant level at 60 m below land surface. The chosen level was based on test pumping information (see Table 8.1).

The last step in the transport cycle to be considered, transport in the aquifer and possible to wells, was in the Windhoek study (see IN & SCC, 2000) assumed to be governed by the connectivity of the fracture network. This seemed to be the case also for the Omeya aquifer and this assumption was considered relevant also on the Haigamas vulnerability assessment.

6.3.2 Assigning values for probability of contamination

The probabilities of contaminants infiltrating the subsurface, transport through the unsaturated zone and transport through the saturated zone were assigned a rating through several steps. The rating ranges between 0 and 1 where 1 indicates a high probability for pollutant transport through the specific hydrogeological component, and ratings close to 0 indicate low probability for transport. 0.5 indicates equal probabilities for no transport and pollutant transport. The estimates were done by hydrogeological experts and field observations.

6.3.2.1 Probability of contaminants to infiltrate the subsurface, P_i.

Concerning the probability of contaminants infiltrating the subsurface, P_i, the probabilities were assigned through a combination of two or three ratings by equation 6.2. One part was the character of the fracture zone and the second the secondary permeability of the lithological and surficial unit. Where clay-rich material was present an additional layer was added but the value for highest risk of infiltration was chosen in each cell, the specific ratings are presented in Table 6.2 and 6.3.

Table 6.2 Assigned probabilities for infiltration of pollutants due to fracture zones permeability (IN & SCC, 2000).

Fracture Zone	Probability
High permeability fracture zone (0-50 m)	0.98
Medium permeability fracture zone (50-100 m)	0.75
Areas away from fracture zones (100-150 m)	0.50
Areas away from fracture zones (>150 m)	0.10

Probability estimates on secondary permeability in surficial units differed from values on the same issue in the report on Groundwater vulnerability of the Windhoek aquifer. This was because rock types and surficial deposits differed between the two areas. The values presented were based on judgement from experienced hydrogeologists. Rock and soil types were derived from maps produced by Namib Hydrosearch (2009a, b) and the GSN (Hasheela, 2010).

A marble zone which is visible in the field but not indicated on the GIS-maps from the GSN used to derive the vulnerability. The marble is a minor outcrop and thus not identified on these maps. However, the marble was visible and special caution should be taken close to the outcrops.

Table 6.3 *Assigned probabilities of infiltration of pollutants with respect to secondary permeability (jointing) of surficial units (IN & SCC, 2000).*

Lithology	Probability
Unconsolidated deposits	0.90
Paragneiss	0.85
Schist	0.60
Clay	0.50

6.3.2.2 Probability of percolation through the unsaturated zone, P_u.

The probability of percolation through the unsaturated zone, P_u, was assessed through the assumption that the lithological conditions observed at the ground surface were continuous through the unsaturated zone, which was in accordance with IN & SCC (2000). Thus, the factor was exclusively dependent on the depth to the groundwater table. For the Windhoek aquifer, a probability of 1 was set for the shallowest groundwater table, (0-20 m) and for the deepest a rating of 0.5 was set since a thicker unsaturated zone is generally considered to generate adsorption to a greater extent than a thin unsaturated zone.

In some areas some clay or other unconsolidated deposits cover the ground but it was assumed that this thickness was small in comparison to the total unsaturated zone. The dominating type of rock in that column was assumed to be the governing material and the factor considered here as well as in the report of Windhoek. The groundwater level was set to 60 m below surface in the entire area and the probability for transportation to the saturated zone was thus set to 0.5 for the whole area.

6.3.2.3 Probability of transport to the groundwater supply, P_s.

Lastly, the assessment of the probability of transport to a water supply, P_s, was made with respect to fracture connectivity as a function of fracture zone density and jointing in the lithological units (see Table 6.4 and 6.5). A high density fracture zone is generally considered to transport pollutants to a greater extent than areas containing little fractures. Lineaments i.e. fracture zones of the Gross Haigamas area are indicated in Figure 8.5.

Table 6.4 Assigned probabilities of infiltration of pollutants due to fracture zones permeability (IN & SCC, 2000).

Fracture Zone	**Probability**
High permeability fracture zone (0-50 m)	0.98
Medium permeability fracture zone (50-100 m)	0.75
Areas away from fracture zones (100-150 m)	0.50
Areas away from fracture zones (>150 m)	0.10

In the maps from the GSN on which this assessment is based, the lithological unit is partly covered by surficial deposits and the rock type beneath this is unknown. An assumption based on field visits was made that there is schist underneath the whole area of surficial deposits.

Table 6.5 Assigned probabilities of transport to a water supply with respect to secondary permeability due to jointing of lithological units.

Lithological unit	**Probability**
Paragneiss	0.70
Schist	0.60

6.3.2.4 Compilation of maps

The compilation of maps has been performed in the GIS-programme ArcGis 9 Spatial Analyst. For estimating the probability of infiltration through land surface two maps where created. A map of the geology of the Haigamas area was attributed certain values depending on the secondary permeability of the specific rock or soil according to Tables 6.3 and 6.5. Where clay was present an additional layer was added due to the fact that soil called surficial deposits were presented not including clay, which was a separate layer. The maps were finally converted into raster format with cell size of 10 x 10 m.

A map describing fractures were divided into two maps; one where the larger fractures or high permeability fractures were assigned a probability of 0.98 and one where fractures of lower infiltration probability were assigned a probability of 0.75. Fractures where separated based on information on fracture characteristics in Chapter 8.1.2. Fractures of east-northeast, northwest, west-northwest and northsouth directions were considered high permeability zones and the remaining fractures were considered medium permeability fracture zones. The two fracture maps were then assigned buffer zones in three steps, 50, 100 and 150 m and within these distances estimates of the probability for infiltration in the fracture depending on the distance to the actual fracture was set (see Table 6.6). The two fracture maps were compiled to one which was converted into raster format with output cells of 10 x 10 m.

Table 6.6 Description of the assigned probabilities of infiltration of fractures depending of character of and distance to the fracture.

	***P* = 0.98**	***P* = 0.75**
0-50 m	0.98	0.75
50-100 m	0.75	0.50
100-150 m	0.50	0.50
>150 m	0.10	0.10

Concerning the probability of infiltration of the unsaturated zone the distance to the groundwater table was assumed to be the governing factor. A raster layer of the level 60 m was created because this is where the ground water level was estimated to be situated. The depth to the groundwater table was assumend to be constant in contrast to the similar analysis in Windhoek on which this method was based. The entire layer was assigned the probability of 0.5. The output cells are 10 x 10 m.

When compiling the layers of the probability of transport of pollutants to a possible source, the method was similar as for the surface layer. The differences was that no soil was assumed to be present at this depth and what was indicated as surficial deposits at surface was assumed to be schist. This assumption was based on field visits. The rock types were assigned probability ratings according to Tables 6.4 and 6.5, and the permeability due to fractures were assigned ratings as described above.

6.3.3 Possible sources of pollution and estimated degree of contamination

To assess the potential pollution load a method developed by Foster and Hirata (1987, cited in IN & SCC, 2000) and later further developed by Johansson et al (1999, cited in IN & SCC, 2000) was used. This method consists of three parts;

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

Sources of pollution and related release of contaminants were mainly identified through a field visit guided by one of the developers of the Omeya golf and residential oasis, Mr. P. Du Plessis (2010), and studies of the proposed layout and plan of activities. *Screening* of identified sources aims to categorise the identified sources of pollution and in this case where the number of sources is small, the sources were divided into a construction- and an operational phase. The sources were then *characterised* according to the following parameters;

L_1	Toxicity
L_2	Release quantity
L_3	Probability of release
L_4	Type of release
L_5	Possibility for remediation

Each factor was given a rating between 1 and 0, where 1 indicates a high probability and 0 a low probability. Factors were assessed based on Table 6.7, which also shows the applied intervals of each one of the characteristic groups.

Table 6.7 Rating characterisation of potential pollution sources (IN & SCC, 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

The five ratings were then compiled into a final rating of potential pollution load, L_{fin}, by addition of the values for the different characteristic groups, L_1- L_5. The numbers where then divided by the number of groups to derive a mean value and from this a value between 0 and 1 was provided for each source of pollution (see Equation 6.3).

$$L_{fin} = \frac{1}{5}\sum_{i=1}^{5} L_i \qquad (6.3)$$

6.3.4 Risk estimation of groundwater pollution

For each source of pollution a preliminary risk value was calculated. The risk (*R*) was defined as a product of the vulnerability (*V*), and the potential pollution load, (*L*), see equation 6.4.

$$R = V \text{ x } L \qquad (6.4)$$

In the report on Groundwater vulnerability of the Windhoek aquifer (IN & SCC, 2000), the risk is extended to be a product of partly vulnerability and potential pollution load but also the potential resource value representing the negative consequences (*C*), of a release. This modification of excluding the consequence was made to simplify the process and not include economic values into the assessment.

A risk value was calculated for each source of pollution according to equation 6.4. No risk was assigned in areas where no pollution was expected to be able to take place, however vehicles releasing pollution during the construction phase may travel all over the area and pose a threat to the groundwater and were not specifically accounted for in the risk maps.

The estimated risk values were compiled into a map showing geographically where most caution has to be taken. This was done by combining the vulnerability map and the map locating pollution sources and adjacent pollution.

6.4 Identification of advantages

The identification of advantages was based on parts of the questionnaire referred to in Chapter 6.2 and presented in Appendix A. The method used was interviews with people familiar to hydrogeology, geology and/or the water supply of the area and the mentioned questionnaire made up the basis for a brainstorming process leading to a discussion concerning possible advantages of expanding the Windhoek water supply.

7 FMECA for a possible pipeline

This chapter presents the result of the FMECA methodology described in Chapter 6.2. All the steps included in the FMECA process are presented with related information, either as results, discussion or conclusions.

7.1 Scope

The scope of this specific FMECA was to:

- Identify limitations in the shape of failure causes with related failure modes, failure effects, probabilities and consequences to the possible pipeline between Windhoek and Rehoboth.
- Identify the risk for each failure cause by combining the probability and consequence.
- Propose risk reduction options and measures for the identified failure causes.

7.1.1 Boundaries of the study

The boundaries of the studied water system were the two ends of the pipeline, e.g. where the water from the distribution systems in Windhoek and Rehoboth enters the pipeline. So when the water enters the pipeline it is either clean or polluted. The pipeline itself with attached infrastructure was included in this specific FMECA, while the dams, boreholes and wastewater treatment plants in both Windhoek and Rehoboth were excluded. A holographic view of the specific elements included in the studied system is presented in the HHM in Figure 7.1.

This project did not consider the exact stretch of the pipeline, if the pipeline system is open or closed, the material of the pipeline or if the pipeline will be built above or below the ground. All those things do of course affect what kind of failure causes that will be relevant, but the purpose of this study was to discuss the overall risks with a project like this, without regarding e.g. the specific stretch or material of the pipeline. If the decision to build a pipeline is made, some of the presented failure causes and risks will be more relevant than others, depending on the above mentioned parameters. When the exact parameters are chosen, further investigations should be performed.

7.2 Hierarchical holographic model (HHM) for the pipeline

Figure 7.1 below shows the studied system with the included elements in a connection of the water systems in Windhoek and Rehoboth. The pipeline was the studied system in this particular FMECA, and it consisted of several elements that are needed for the pipeline to function. The identified elements were as seen below; pumps, valves, access roads, material, electricity and the water intakes in both Windhoek and Rehoboth. The HHM enabled an identification of a larger amount and more specific failure causes that could be a threat to the pipeline.

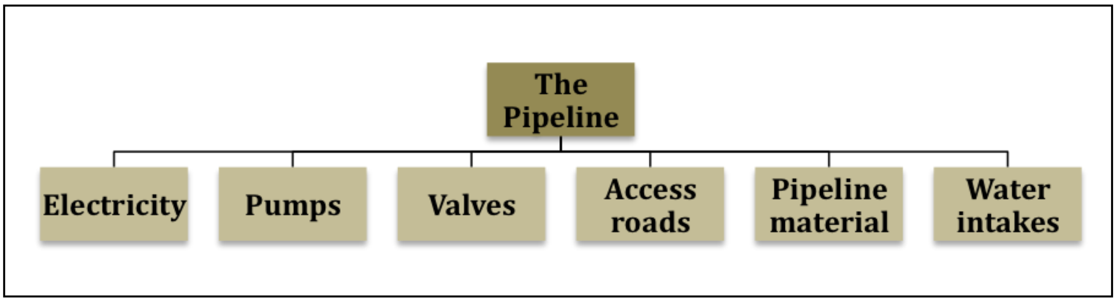

Figure 7.1 Hierarchical Holographic Model (HHM) for the possible pipeline.

7.3 Table of identified risks

Table 7.1 shows the FMECA worksheet with identified failure causes, failure modes and failure effects for the possible pipeline connection. Further, every failure cause with related failure mode and failure effects was given values for probability and consequence, which resulted in a risk estimate, represented by colours.

The probability of the failure cause “Accidental damage” (number 1a in Table 7.1) was set in an interval. This was done due to the fact that the circumstances can differ and thereby the probability is different. If the pipeline is built close to a road or a railway, the probability of accidental damage is higher than if the pipeline is built far away from any roads or railways. For being able to handle this interval, the two values for probability in both ends of the interval were accounted for. The risks that they pose were both expressed in the column for risk as well as in the risk matrix (Figure 7.2) that shows what failure causes that belongs to which risk category.

Some of the failure causes were divided into two categories, a and b. The reason for this was that the effect of the failure on the subsystem differs, which means that either no water reaches the consumer or some water reaches the consumer. Depending on whether some or no water reaches the consumer the probability and consequence will be different, so thereby those failure causes were divided into two categories.

Table 7.1 Identified failure causes, failure modes, failure effects, probabilities, consequences and risks to the pipeline.

System: Pipeline								
Description of failure			**Effect of failure**		**Probability (failure rate)**	**Conse-quence**	**Risk (criticality)**	**Risk reduction options**
Tag. no.	Failure mode	Failure cause	On the module	On (sub)-system				
01.a	*Failure to transport any water*	**Accidental damage**	*Pressure/water loss*	*No water reaching consumers*	*1-5*	*3*	*Green* *Red*	*Careful planning of stretch and material.*

02.a	*Failure to transport any water*	**Electrical failure**	*Pressure loss*	*No water reaching consumers*	*3*	*4*	*Yellow*	*Efficient maintenance.* *Access to alternative sources of electricity, e.g. diesel-electric generators.*
02.b	*Failure to transport some water*			*Some water reaching consumers*	*4*	*2*	*Yellow*	*Efficient maintenance.* *Access to alternative sources of electricity, e.g. diesel-electric generators.*
03.a	*Failure to transport any water*	**Valve failure**	*Pressure loss*	*No water reaching consumers*	*4*	*2*	*Yellow*	*Efficient maintenance.* *Easy access to spare parts.*
03.b	*Failure to transport some water*			*Some water reaching consumers*	*4*	*1*	*Green*	*Efficient maintenance.* *Easy access to spare parts.*
04.a	*Failure to transport any water*	**Pump failure**	*Pressure loss*	*No water reaching consumers*	*4*	*2*	*Yellow*	*Efficient maintenance.* *Parallel pumps.*
04.b	*Failure to transport some water*			*Some water reaching consumer*	*4*	*1*	*Green*	*Efficient maintenance.* *Parallel pumps.*
05.a	*Failure to transport any water*	**Sabotage**	*Pressure/water loss*	*No water reaching consumer*	*2*	*4*	*Yellow*	*Solid and well protected constructions.* *Guards.* *Information to the public.*
05.b	*Failure to transport some water*			*Some water reaching consumer*	*3*	*3*	*Yellow*	*Solid and well protected constructions.* *Guards.* *Information to the public.*
06.a	*Failure to transport water*	**Flash floods**	*Pressure/Water loss*	*No water reaching consumer*	*2*	*5*	*Red*	*Well-engineered constructions.* *Proper protection in the rivers.*

07.a	*Failure to transport water*	**Illegal connections**	*Pressure/water loss*	*No water reaching consumer*	*2*	*4*	*Yellow*	*Surveillance systems.*
07.b				*Some water reaching consumer*	*5*	*2*	*Yellow*	*Surveillance systems.*
08.a	*Failure to transport any water*	**Poor pipeline material**	*Pressure/water loss*	*No water reaching consumer*	*1*	*3*	*Green*	*Thorough investigations on choice of material.*
08.b	*Failure to transport some water*			*Some water reaching consumer*	*2*	*2*	*Green*	*Thorough investigations on choice of material.*
09.a	*Failure to transport water*	**Bad maintenance**	*Pressure loss, water quality degradation*	*No or unsafe water reaching consumers*	*1*	*4*	*Yellow*	*Good routines for an efficient maintenance.*
09.b				*Some or unsafe water reaching consumer*	*2*	*3*	*Yellow*	*Good routines for an efficient maintenance.*
10.a	*Failure to deliver safe water*	**Polluted water into the system**	*Water quality degradation*	*Heavily polluted water reaching consumers*	*2*	*5*	*Red*	*Efficient control systems for the water coming from the possible extraction points.*
10.b				*Polluted water reaching consumers*	*3*	*4*	*Yellow*	*Efficient control systems for the water coming from the possible extraction points.*
11.a	*Failure to transport water*	**No water into the system**	*Lack of water*	*No water reaching consumer*	*2*	*4*	*Yellow*	
12.a	*Failure to transport some water*	**Some water into the system**	*Partly lack of water*	*Some water reaching consumers*	*3*	*3*	*Yellow*	
13.a	*Failure to transport water*	**Conflicts**		*No water reaching consumers*	*1*	*3*	*Green*	*Information to the public.*

Probability						
5			7.b	1.a		
4		3.b,4.b	2.b,3.a,4.a			
3				5.b,12.a	2.a,10.b	
2			8.b	9.b	5.a,7.a,11.a	6.a,10.a
1				1.a,8.a,13.a	9.a	
Consequence		1	2	3	4	5

Figure 7.2 Risk matrix expressing the risk of the identified failure causes.

The risk matrix (Figure 7.2) demonstrate that there are failure causes represented in each risk category. 13 of the 22 identified failure causes were found within the yellow risk category, 6 within the green risk category and 3 within the red risk category.

7.4 Discussion

The failure causes and thereby the limitations that are first to be considered, and are of high piority if the pipeline connection would be built, were numbers 1.a, 6.a and 10.a (the ones found within the red fields). Those failure causes were those which imply the largest risk to the pipeline and thereby affect the consumers to the greatest extent. To prevent failure cause number 1.a, accidental damage, the stretch of the pipeline should be carefully planned and the material choice thoroughly considered. Failure cause number 6.a, flash floods, could be prevented through a well-engineered construction of the pipeline and a suitable stretch of the pipeline, as well as through installing proper flood protection in and close to the rivers. Failure cause number 10.a, polluted water into the system (with the effect on the subsystem that heavily polluted water reaches the consumers), could be prevented through efficient control systems for the water coming from the possible extraction points. The water coming from the water distribution systems in Windhoek and Rehoboth lies beyond the system limitations of this project and has no risk reduction options proposed due to the fact that those measures need to be adressed before the water reaches the ends of the pipeline.

The failure causes within the yellow risk category are 13 in total. Failure causes number 7.b, 2.a, 10.b, 5.a, 7.a and 11.a were very close to the red risk category and were thereby the yellow failure causes that should be considered first.

The FMECA method used for this risk mapping of possible failure causes to the pipeline is a semi-quantitative method. The rating of parameters like probability and consequence was difficult and required a lot of knowledge, and the values tend to differ depending on the people involved in the rating. The rating in this specific FMECA was made by the project team based on estimates from people within the water sector in Namibia. A questionnaire was sent out, but unfortunately few answers were received. Nevertheless, both the rating of probability and consequence as well as the development of failure causes has been done by a quite heterogeneous group concerning education, gender and age, which made the risk mapping more extensive. If the constellation of the group would have been different the result could have been different.

Failure cause number 1.a was represented twice in the risk matrix due to the probability interval, both in the green and the red risk category. To use an interval to describe the probability of a failure cause was a way of avoiding just using the value in the middle of the scale. To use the values in the extremes of the probability scale instead of the value in the middle of the scale was considered more relevant in this specific case. This was due to the fact that the probability for accidental damage most likely will either be very high or very low, it depends on the stretch of the pipeline. In the area between Windhoek and Rehoboth as earlier mentioned, there are not many activities going on, and the road B1 is the only road causing continuous activity. The pipeline stretch will probably either be close to the B1 or the railway or far away from any bigger roads, railways or activities, and thereby the probability for accidental damage will either be very high or very low. So by using the values in the extremes of the probability scale, two more realistic scenarios are presented.

The failure causes "no water into the system" and "some water into the system" has no risk reduction options proposed. This was due to the fact that risk reduction options that could be relevant lies beyond the system limitations of this project. The measures revelant need to be adressed before the water reaches the ends of the pipeline, and thereby they are beyond the limitations.

The probability of the two failure causes associated with "polluted water into the system" (number 10.a and 10.b) were estimated based on that there are at least a few illegal connections or further abstraction points connected to the pipeline. Both the possible extraction points and illegal connections increase the risk for the water in the pipeline to become polluted. The possibility for illegal connections somewhere along the 87 km long pipeline are considerable due to the fact that this is a common problem in Namibia according to Peters (2010) among others. In the northern parts of the country a lot of poor people get their water through illegal connections and even if the population south of Windhoek is smaller, some could possible get their water this way.

The consequences if there is a pump failure were estimated based upon that the pump system is a three parallel pump system. This implies that if one of the pumps are non functional, the others will still function and the consequences are not as bad as if there would only be one single pump at each pump station. The consequences of the failure causes valve failure and pump failure could be extenuated through an easy access to spare parts or new equipment. If the equipment has to be ordered and can not be installed quickly, the consequences will be worse.

7.5 Conclusions

Below, the conclusions from the FMECA performed for the possible pipeline between Windhoek and Rehoboth are presented.

- There were in total 22 failure causes or limitations identified to the possible pipeline. 13 within the yellow risk category, 6 within the green risk category and 3 within the red risk category.
- The failure causes that were found within the red and unacceptable field and are the most important to prevent and mitigate are accidental damage (no 1.a), flash floods (no 6.a) and polluted water into the system (with the effect on the subsystem that heavily polluted water reaches the consumers, no 10.a).
- Suggestions of risk reduction options for preventing accidental damage are to plan the stretch of the pipeline carefully and to choose a suitable material.
- Suggestions of risk reduction options concerning flash floods are to make a well-engineered construction of the pipeline, to propose a suitable stretch of the pipeline and to install proper flood protection in and close to the rivers.
- A suggestion of a risk reduction option concerning polluted water into the system (with the effect on the subsystem that heavily polluted water reaches the consumers), is to install efficient control systems for the water coming from the possible extraction points.
- It is important to work with prevention of all failure causes, not only those within the red risk category. The failure causes within the yellow risk category were many, and some of them were as well close to the red risk category, which implies a relatively high risk.
- The stretch of the pipeline, if the pipeline system is open or closed, the material of the pipeline and whether it will be built above or beneath the ground affect what kind of failure causes and risks that will be relevant to the pipeline system. If the decision to build a pipeline between Windhoek and Rehoboth is made, some of the presented failure causes and risks will thereby be more relevant than others.
- Due to the fact that this master thesis is meant to function as a pre-study and that the FMECA was an early stage risk assessment, it is important to keep in mind that more thoroughly investigations are needed if the possible pipeline is to be built.

8 Case study of the Omeya golf and residential oasis

This chapter describes a risk and vulnerability assessment of potential pollution to the groundwater of the Omeya golf and residential oasis at the Gross Haigamas farm. The scope is presented and also the geology, hydrogeology and a summary of the environmental impact assessment is given. Finally, the results of the risk and vulnerability assessment are presented.

8.1 Introduction

In the area between Rehoboth and Windhoek, Auas View Investment Trust, intends to develop a small village and golf course in a section of the Haigamas farm, the Omeya golf and residential oasis (see figure 8.1). The development is located (see Figure 8.2) east of the railway between Windhoek and Rehoboth, but west of the road B1, and is situated about 30 km south of Windhoek (EDEMC, 2009).

The estate covers an area of 245 ha, and will include an 18 hole golf course and 384 residential erven ranging between 3,000 m^2 and 500 m^2 gathered between the greens. Further activities taking place will be a clubhouse, small boutique and hotel, spa, golf driving range, tennis courts, chapel, commercial centre, pre-primary and primary school (140 pupils), equestrian facilities on the neighbouring Out of Nature, Game drives on the neighbouring farm, hiking trails and mountain bike riding trails as indicated in Figure 8.1 (EDEMC, 2009).

An Environmental Impact Assessment has been performed (EDEMC, 2009) of which a hydrogeological specialist report (Namib Hydrosearch, 2009a) has been conducted. An application of water abstraction was granted to 350,000 m^3/year, provided that monitoring boreholes are installed and water levels and production rates are reported to the Ministry every quarter of the year (Namib Hydrosearch, 2009a).

Figure 8.1 Site map of the Omeya Golf and Residential Oasis (Republikein, 2010).

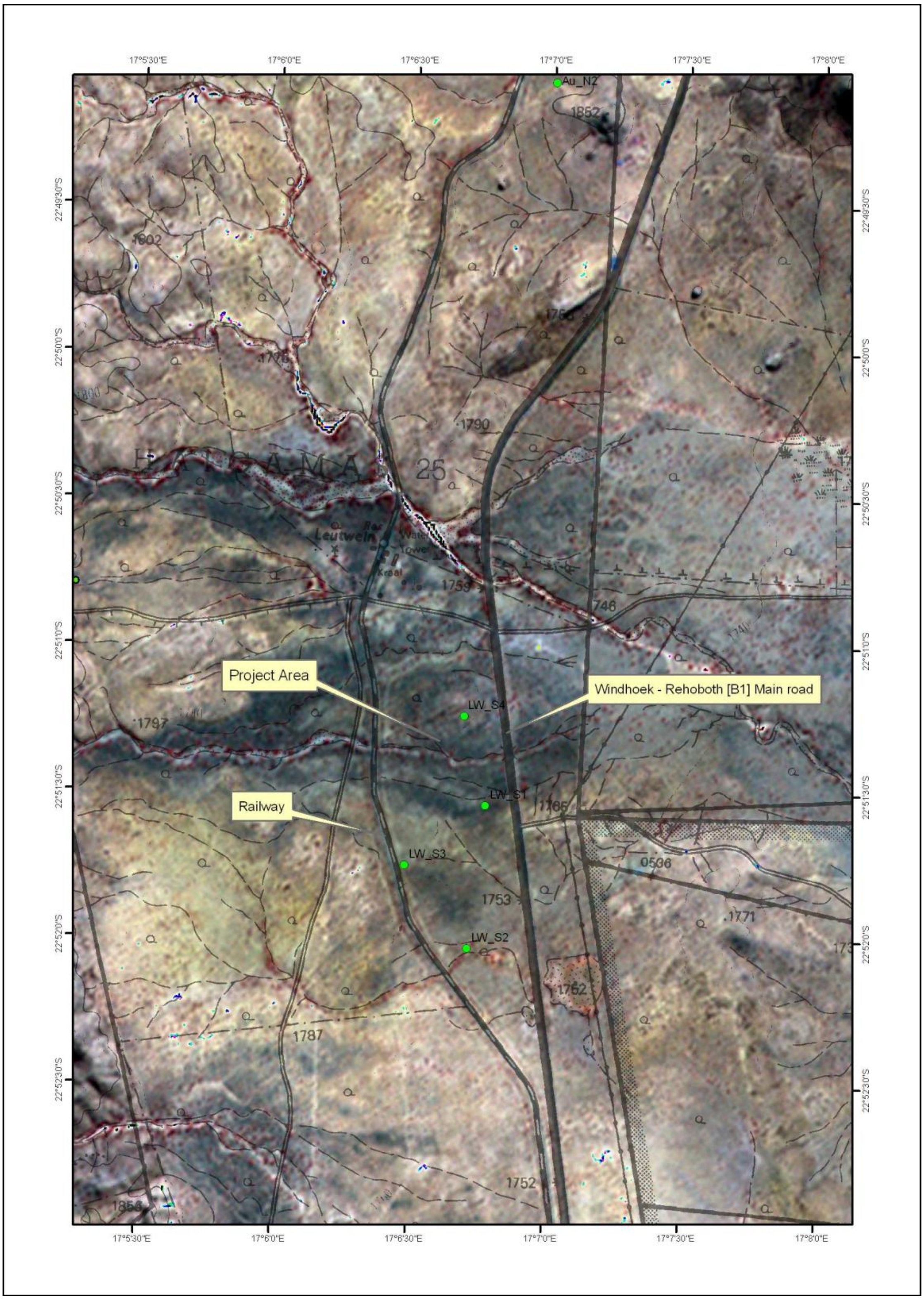

Figure 8.2 *Location of the Omeya golf and residential oasis, Gross Haigamas farm (Namib Hydrosearch, 2009b).*

8.1.1 Scope

The scope of this risk assessment was to:

- Demonstrate a method for conducting vulnerability and risk assessments of aquifers to facilitate further investigations of possible groundwater extraction in the area between Windhoek and Rehoboth.
- Provide the Omeya golf and residential oasis with a risk map for decisions concerning location of hazardous activities to avoid contamination of the groundwater.

8.1.2 Geology of the Haigamas farm

Rocks of the Hohewarte Complex (age 1,800 Ma and older) with para-gneiss and meta-sedimentary rocks dominate the area. There are also minor intrusions of Granites from the Gamsberg Suite (1,100 Ma) and plugs of phonolite and trachite (32 to 39 Ma). The rocks from the Hohewarte complex, the para-gneiss and meta sedimentary rocks, are generally decomposed close to surface and along fracture zones and are highly weathered. According to Namib Hydrosearch (2009a), the faults and fractures are often intruded by the younger trachites and phonolites, and by that to some extent destroying the secondary porosity, which have an impact on aquifer performance.

Surficial deposits are derived from the underlying lithology, and are according to the Atlas of Namibia (2002) classified as leptosol, which refers to shallow soil cover over hard rocks. Some deposits are also brought in by ephemeral drainage causing deposits of clay rich material to spread over a wider area, further sand accumulates along the channels (Namib Hydrosearch, 2009a). There has been an extensive hydrogeological investigation made (Namib Hydrosearch, 2009b) and from this a number of maps where derived. Among others a lineament density and surficial deposits map (Figure 8.3 and 8.4).

Figure 8.3 Interpreted surficial geology of the Gross Haigamas area (Sarma, 2010).

Figure 8.4 Surficial deposits, green areas indicate richness of clay (Namib Hydrosearch, 2009b).

As seen in Figure 8.4, a large part of the area is covered by clay. Other surficial material is mainly sand which seems to be underlain by further clay (Bochmühl, 2010).

The development is situated in an area of high lineament density (see Figure 8.5) and high yielding boreholes are located near related fault zones. Major lineament directions according to Namib Hydrosearch (2009b) are northwest, east-northeast and west-northwest. Further, larger structures of north south bounding lineaments could be related to the fault system in the same direction of the Windhoek area (Namib Hydrosearch, 2009b).

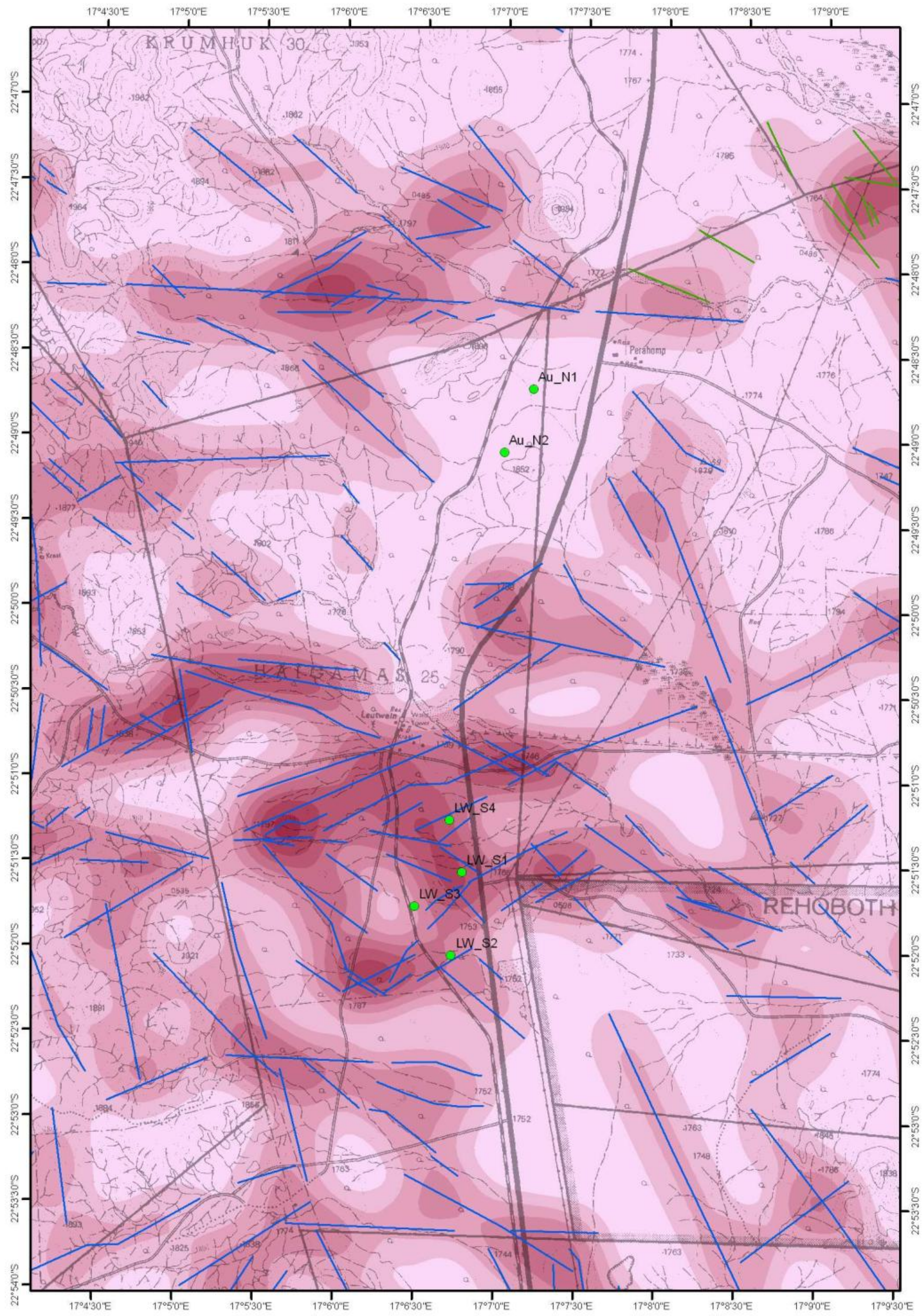

Figure 8.5 Lineament density. Indicated boreholes are not named as in Table 8.1 (Namib Hydrosearch, 2009b).

8.1.3 Hydrogeology

In the Haigamas area, groundwater can be found in secondary fracture zones, secondary porosity in joints and weathered horizons along faults. There is also mineralized groundwater at elevated temperatures in deep faults. For the basement rocks, highly weathered faults yield the most groundwater (Namib Hydrosearch, 2009a).

Existing boreholes in the area yield between 1 and 2 m^3/h and amounts up to 10 m^3/h are known (Namib Hydrosearch, 2009a). Drillings made in Haigamas yielding most water were located on a thin, dipping (40 to 50°, see Figure 8.6), and grey marble horizon within the Hohewarte Complex. The marble is exposed in an outcrop in the northern part of the area and at the northern and southern contacts of the marble unit, gneisses are exposed. This east-northeast trending fault zone is about 50 m wide (Namib Hydrosearch, 2009a).

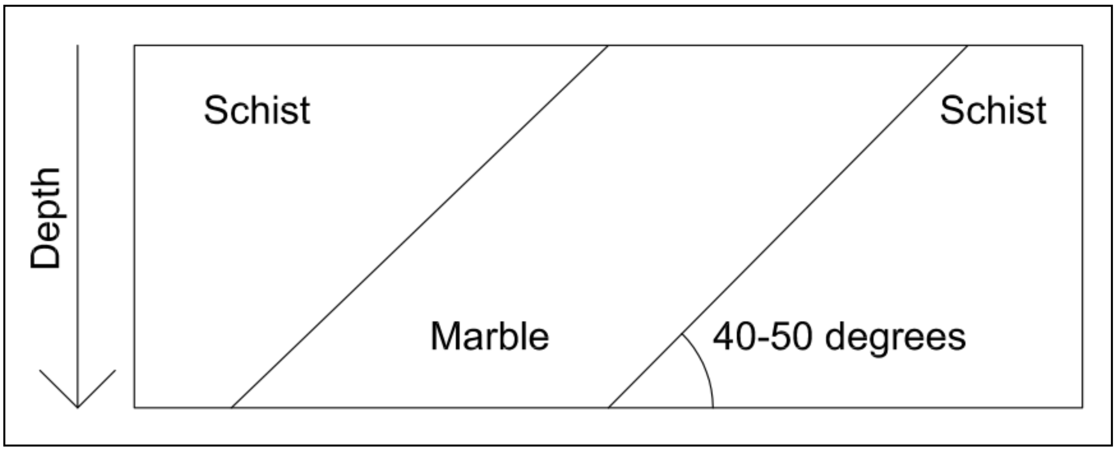

Figure 8.6 Schematic view of the marble horizon.

There are two ephemeral streams running from elevated areas in the west flowing to the north and south possible over the marble horizon. According to the Namib Hydrosearch (2009a), there are problems identifying the marble band due to alluvial deposits covering most of the surrounding area. One of the boreholes presented in the table below will be used as production borehole (see Figure 8.7). Drilling information from two boreholes is presented in Table 8.1.

Table 8.1 Drilling information from the boreholes, WW200684 and WW200683, which are drilled down dip of the fault zone. Locations are found in Figure 8.7 (Namib Hydrosearch, 2009a).

	Borehole WW200683	**Borehole WW200684**
Depth	149 m	179 m
Depth to Water Strike (fracture zone)	Main water strike at 72 m, 100 m, 126 m	Main water strike at 77 m, 120 m, 130 m
Depth to Rest Water Level	61.94 m	60.63 m
Drilling Diameter	No information	254 mm
Borehole construction	118 m cased	127 mm steel casing to 150 m; 0.5 mm slotted casing

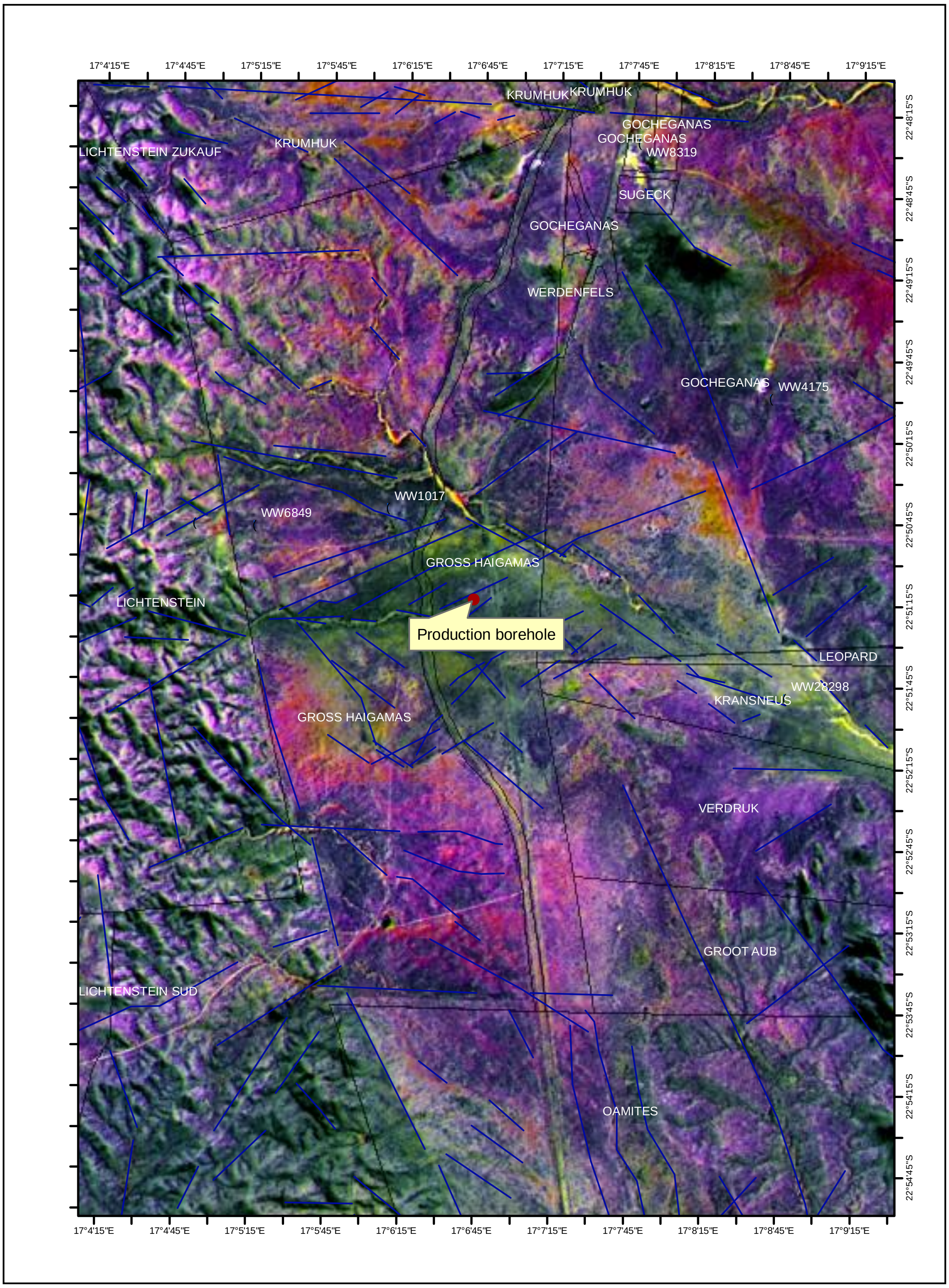

Figure 8.7 *Location of the production borehole, in relation to lineaments (Namib Hydrosearch, 2009a).*

8.1.4 Summary of the hydrogeological environmental impact assessment

A hydrogeological environmental impact assessment (Namib Hydrosearch, 2009a) was performed to investigate test-pumping and estimate aquifer parameters, assess sustainable yield and potential affect of pumping. Furthermore, a lineament map was compiled and a map of the surficial cover was produced. Finally, protection zones around the production boreholes were suggested.

There will be two production boreholes and protection zones are recommended. Zone one will be marked by a fence to prevent any immediate activity around the borehole and a second protection zone aims to protect the groundwater against viruses, microbial and nitrate pollution (Namib Hydrosearch, 2009b). Furthermore a sanitary seal is recommended to be placed on the well head (Namib Hydrosearch, 2009a). Namib Hydrosearch (2009b) also recommends that activities that might result in leakage of waste and heavy fertilisation should be avoided in the protection zone.

There will be a conventional sewerage disposal system collecting water to a treatment plant located in the south end of the project area. The sewage plant is based on growth biological treatment, in this case a trickling filter (EDEMC, 2009). Effluents from this plant are planned to be used for irrigation and gardening at Omeya. The water is not suitable for humans and sludge will be dried and used for compost (EDEMC, 2009).

A compost heap will be situated next to the sewerage works, while solid waste will be sorted and transported to Rehoboth (EDEMC, 2009). It is also stated by Barrie Watson (EDEMC, 2009) that if fertilizers are used they will be biodegradable. It is thus appointed by Bochmühl (2009) that all fertilizers contain nitrates and that such activities should be strictly controlled or forbidden in vulnerable areas.

In a situation of water scarcity, NamWater (EDEMC, 2009) approve water supply from the Nauaspoort scheme or the Oanob dam but mentions that this is not the best or only source of water if water scarcity would be reality. What is concluded is that there is lack of an integrated view including other boreholes in the area. Furthermore no hydrocensus for a larger area was made, which is seen as important for future water management. A general conclusion concerning threats to the groundwater is that the exposed fault zone would need protection to avoid surface contaminant reaching the water table since it is considered an unconfined aquifer.

Other possible pollution sources to the groundwater are considered to be sewerage line and sewer treatment facility and percolation of irrigation water. It is thus mentioned that the planned treatment plant is located 1,500 m south of the borehole, and that it is unlikely that the aquifer will be affected (Namib Hydrosearch, 2009a).

8.2 Results of the risk assessment of groundwater contamination

Five maps were produced as a basis for the assessment of the groundwater vulnerability to pollution. The maps were combined into three maps according to the methodology described in Chapter 6, describing probability of infiltration through land surface, probability of infiltration through the unsaturated zone and probability of infiltration trough the saturated zone. Two maps representing fracture zone permeability and secondary permeability of the lithological unit were combined into one describing the probability of infiltration through land surface. This map is presented as Figure 8.8. Assigned values are derived from Tables 6.2 and 6.3. Red indicates a high vulnerability to groundwater pollution and green a low vulnerability to groundwater. The black lines indicate the main road B1 to the right and the railway to the left. See also figure 8.2 where a map of the area is displayed.

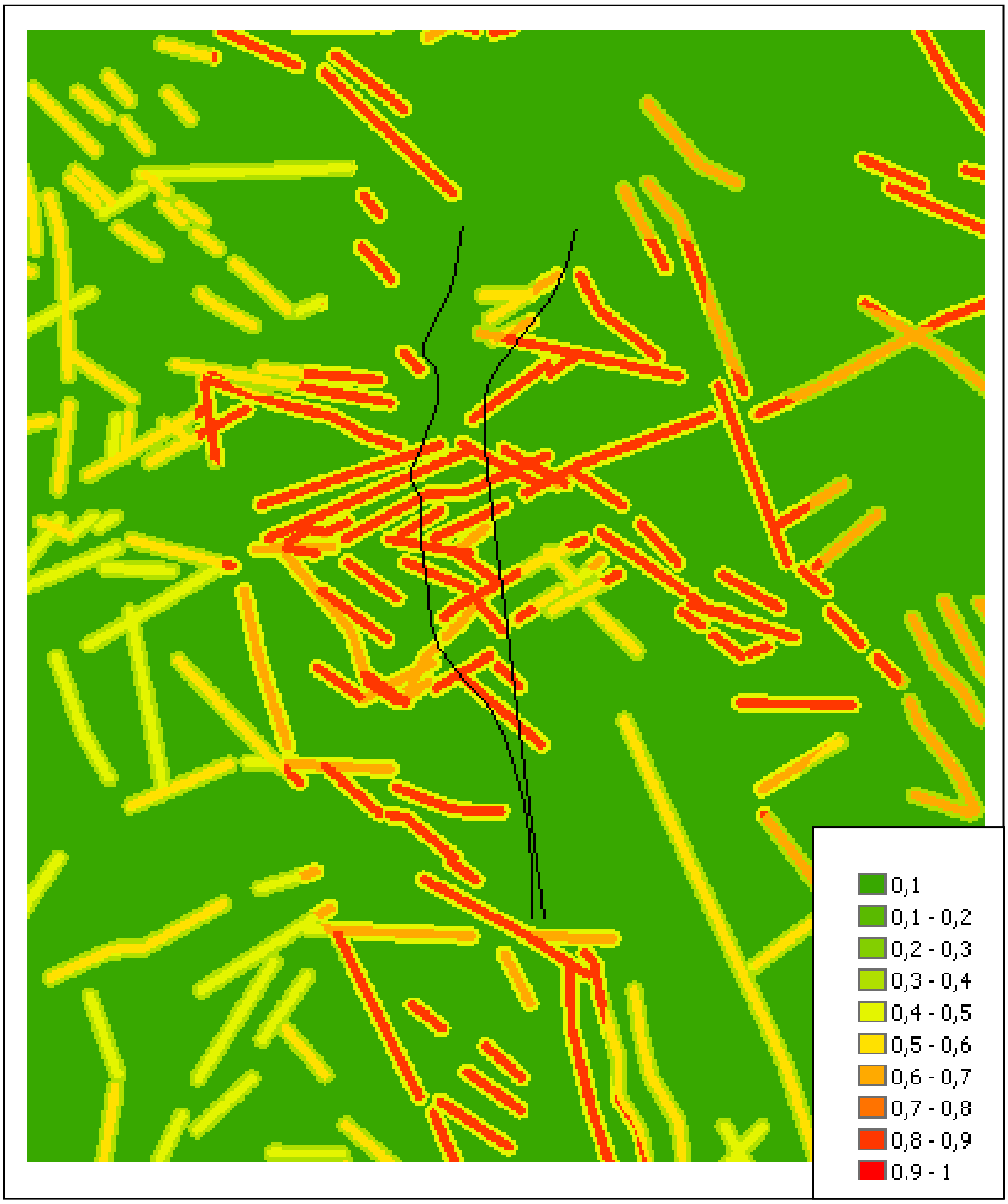

Figure 8.8 *Probability of infiltration through land surface. The black lines indicate the main road BI (the right line) and the railway between Windhoek and Rehoboth (the left line). The Omeya golf and residential oasis is situated between the two.*

The next map produced (not shown here) is a map of the depth to the groundwater table, since this is assumed to be the governing factor of pollutant transport in the unsaturated zone. Probability estimates are assigned according to Chapter 6.3.2.2 and the value is 0.5 for the entire area since the surface is assumed to be flat. The groundwater level is further assumed to be located 60 m below surface based on the test drillings presented in Chapter 8.1.3.

The last map is a combination of fracture zone density and degree of jointing of lithological units and show probability of transport of pollutants in the saturated zone. This is displayed in Figure 8.9. Estimated values of probability can be seen in Table 6.4 and 6.5. Red indicates a high probability for transport of pollutants and green a low probability. The black lines again indicate the B1 and the railway.

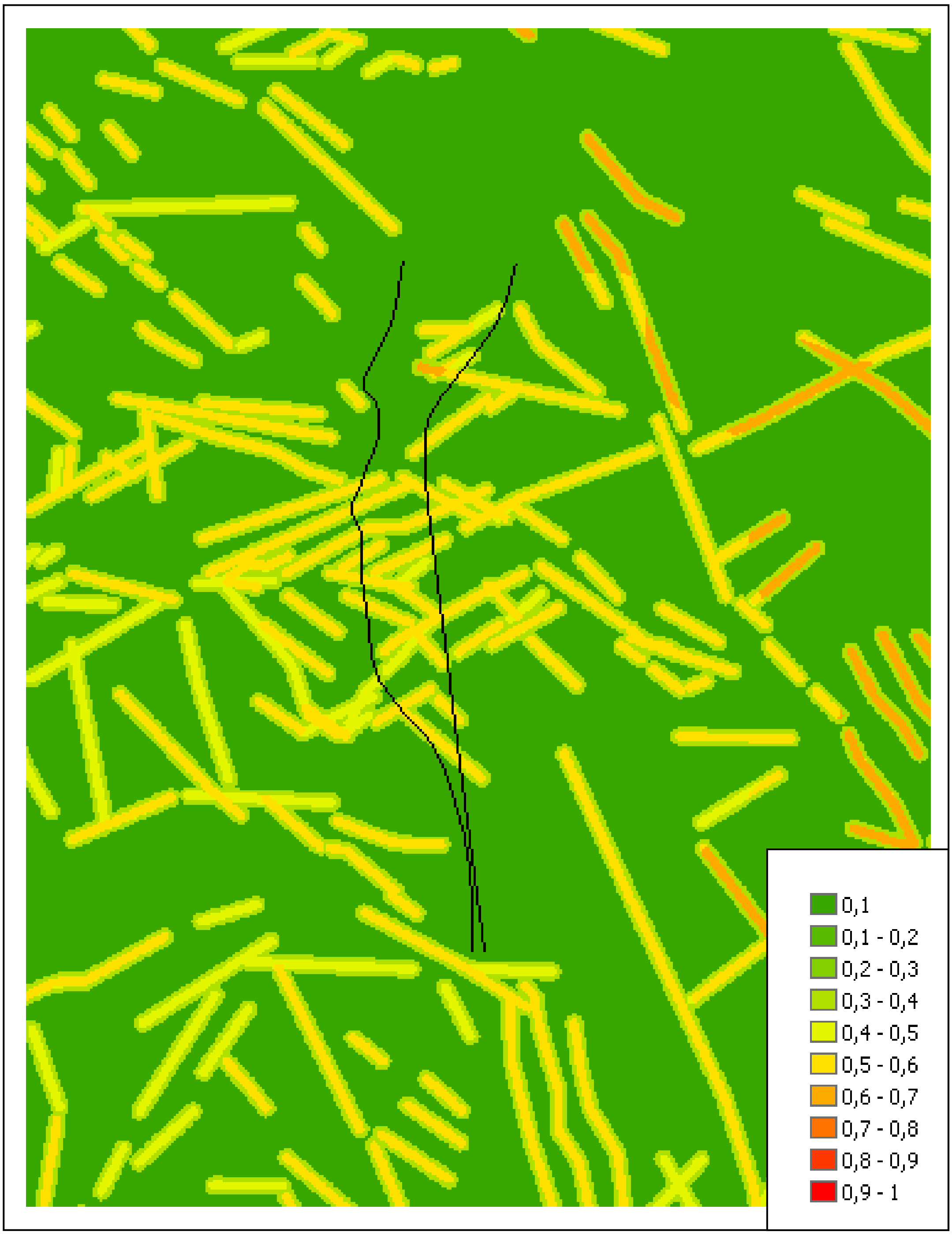

Figure 8.9 Probability of pollutant transport in the saturated zone.

The three maps were finally combined by equation 6.2 into a map displaying the vulnerability to groundwater pollution (See Figure 8.10). Red indicates a high vulnerability to pollution and green a low vulnerability to pollution. Fractures are main conductors of possible pollution and are therefore indicated as red. The black lines again indicate the B1 and the railway.

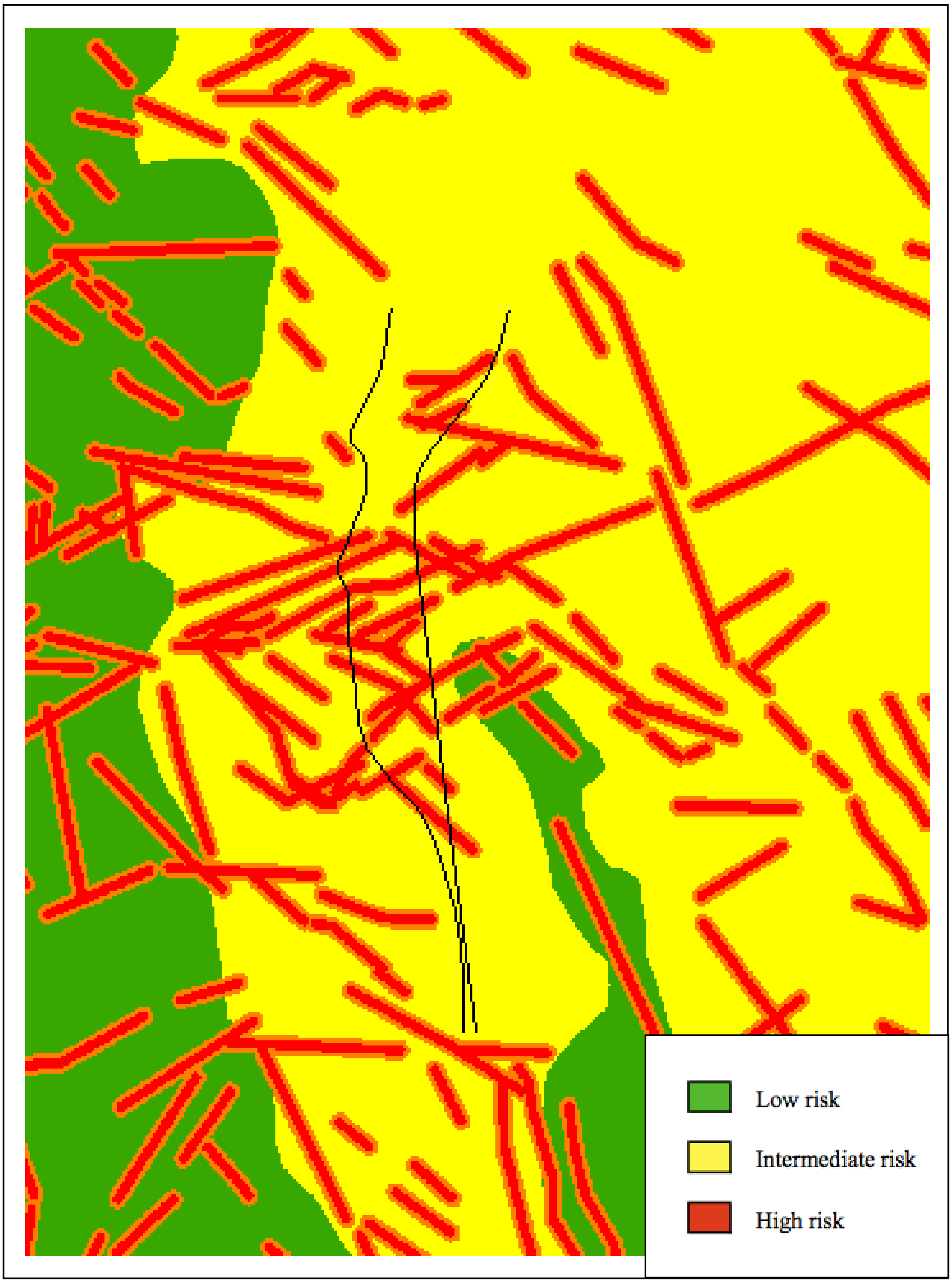

Figure 8.10 Estimated vulnerability to groundwater pollution in the Gross Haigamas area.

8.3 Identified possible sources of pollution

Several possible sources of pollution were identified in or close to the area of the resort. Table 8.2 lists the identified sources with related estimates of possible pollution caused by the specific sources. Due to that no coordinates are available to specify the exact location of these sources, no map displaying the locations is presented.

The table was divided into two main categories; sources that might appear during the constructional phase and sources that might occur during the operational phase. For the first phase four possible sources of pollution were identified, these are; vehicles, B1 (the highway running from Windhoek to Rehoboth), the railway and building material. By specifically mentioning vehicles the intention is to emphasis the possible accidents and leakages that might occur on the construction site involving vehicles used in the construction work such as excavation machines and dump trucks.

During the operational phase 10 possible sources were identified: the clinic, the golf course, sewerage, WWTP, sludge storage, internal roads, the railway, B1, ervens and waste sorting. The clinic will be a small health care centre and the solid waste produce from the waste sorting will be transported to Rehoboth to be placed on a waste disposal site.

Table 8.2 Identified sources and related possible pollution.

Source	
Construction phase	**Description of the source**
B1	Transport of chemicals and leakage from accidents.
Building material	Leakage of harmful substances e.g. chemicals like paint etc.
Railway	Transport of chemicals and leakage from accidents.
Vehicles	Accidents where harmful substances e.g. petroleum, are released.
Operational phase	**Description of the source**
B1	Transport of chemicals and leakage from accidents.
Ervens	Inhabitant activities, leakage of harmful substances such as paint, pesticides and petroleum.
Internal roads	Accidents where harmful substances e.g. petroleum, are released.
Railway	Transport of chemicals and leakage from accidents.
Sewerage	Leakage of sewage containing bacteria, heavy metals and nutrients.
Sludge storage	Leakage of heavy metals and nutrients.
The Clinic	Leakage of harmful substances e.g. chemicals and pharmaceuticals.
The golf course	Release of pesticide, fertilizers and remains from the waste water treatment plant.
Waste sorting	Leakage of heavy metals, oils, nutrients, fluorides etc.
WWTP	Leakage of chemicals and/or sewage containing bacteria, heavy metals and nutrients.

8.3.1.1 Rating of potential pollution sources

The possible sources of pollution were rated in terms of toxicity, release quantity, probability of release and possibility for remediation as described in Chapter 6.3.3. Lastly, a mean value is calculated for the final possible pollution, all values are presented in Table 8.3 and 8.4.

Table 8.3 Estimated values of toxicity, release quantity, probability of release, possibility for remediation and mean value for the construction phase.

Construction phase	***L1***	***L2***	***L3***	***L4***	***L5***	L_{fin}
Vehicles	0.8	0.6	0.7	0.9	0.9	0.8
B1	0.8	0.9	0.4	0.9	0.9	0.8
Building material	0.7	0.4	0.5	0.8	0.9	0.7
Railway	0.5	0.7	0.3	0.5	0.5	0.5

Table 8.4 Estimated values of toxicity, release quantity, probability of release, possibility for remediation and mean value for the operational phase.

Operational phase	***L1***	***L2***	***L3***	***L4***	***L5***	L_{fin}
The Clinic	0.4	0.2	0.3	0.8	0.8	0.5
The golf course	0.6	0.6	1	0.9	0.6	0.7
Sewerage	0.5	0.4	0.9	1.0	0.6	0.9
WWTP	0.5	0.8	0.2	0.9	0.6	0.6
Sludge storage	0.5	0.4	0.6	0.5	0.6	0.5
Internal roads	0.8	0.4	0.6	0.9	0.9	0.7
Railway	0.5	0.7	0.2	0.5	0.5	0.5
B1	0.8	0.9	0.3	0.9	0.9	0.8
Ervens	0.5	0.3	0.7	0.9	0.5	0.6
Waste disposal	0.6	0.3	0.5	0.9	0.6	0.6

8.3.1.2 Location and pollution level of identified sources

The sources identified are displayed in Figure 8.11 and assigned the specific final toxicity value derived in Table 8.3 and 8.4. The map was created in the GIS-program ArcGIS 9, Spatial Analyst. Due to lack of information of exact positions, three sources of pollution were selected to state as an example. These are; the clinic, the WWTP and the WTP.

8.4 Risk estimation

The risk estimation was a combination of the vulnerability of the ground, the ability to transport pollution and the actual sources and level of pollution at a specific location (see equation 6.2). The vulnerability map presented in Chapter 8.2 and the map of location and pollution level of sources in Chapter 8.3.1.2 were combined into one and displays the estimated risk of groundwater pollution from identified pollution sources in the Omeya aquifer. The preliminary risk map is displayed in Figure 8.11. High risk of groundwater pollution is indicated as red and low risk to groundwater pollution is indicated as green. Black lines indicate the main road B1 to the right and the railway to the left.

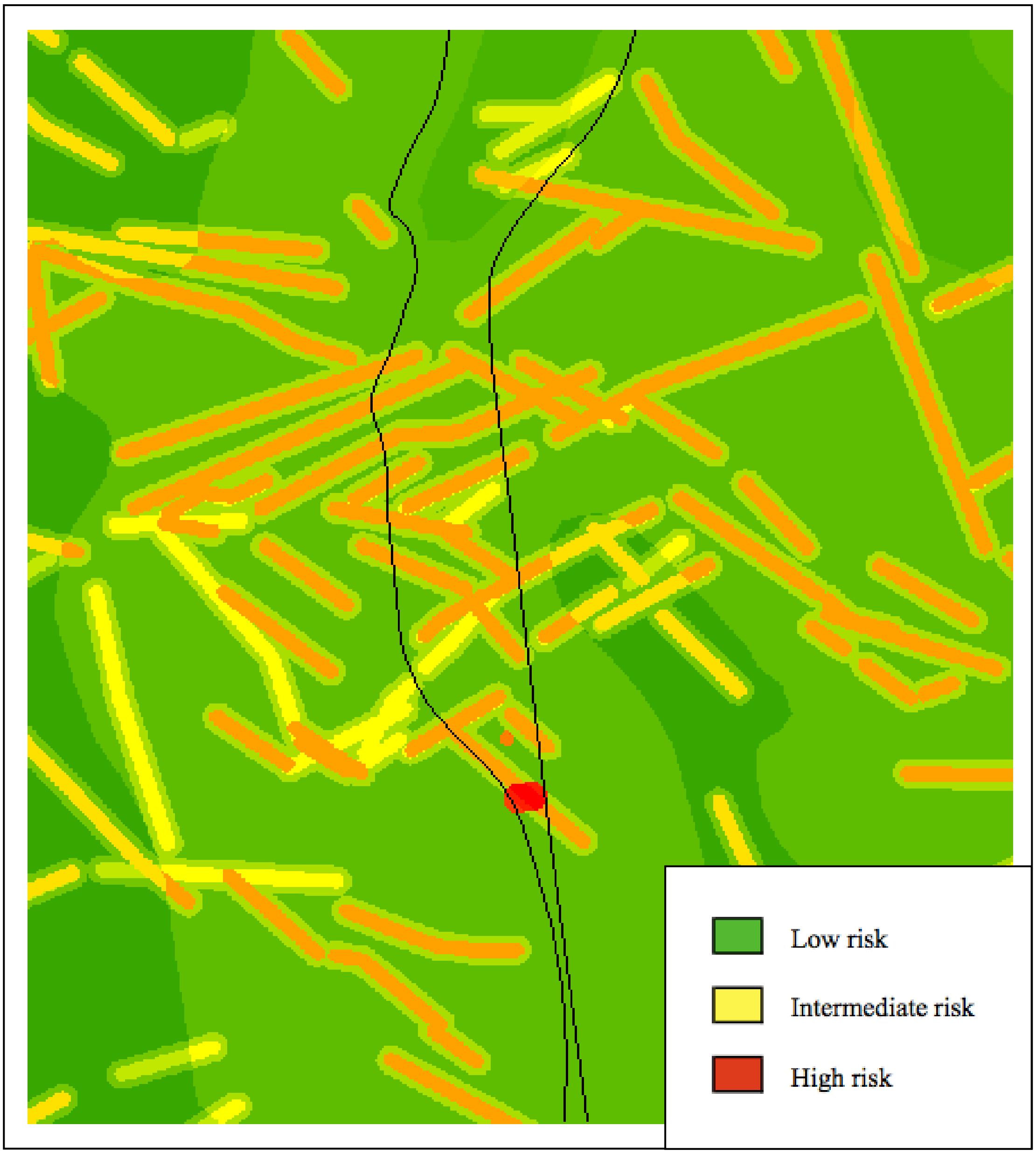

Figure 8.11 Preliminary risk map for the aquifer Omeya golf and residential oasis. The black lines indicate the main road BI (the right line) and the railway between Windhoek and Rehoboth (the left line). Omeya is situated between the two.

8.5 Discussion

The risk of pollution to the Omeya aquifer is indicated in Figure 8.11 which shows areas where extra caution should be taken. Where large fracture zones coincide with great potential pollution sources the risk for groundwater pollution is the highest. Where vulnerability to pollution is low and no sources of pollution are close, the risk of contaminating the groundwater is lower.

The maps produced indicate relative risk and vulnerability within the area. Little can be said in comparison to other areas concerning vulnerability and risk to groundwater contamination unless this specific method is applied on a number of different areas and is well documented.

Where clay-rich material is indicated, see Figure 8.4, an additional layer is inserted, thus to the geological layer and the highest probability for infiltration is chosen in each cell. This gives a slight overestimation of the risk to groundwater pollution since clay holds and prevents pollutants from further transport. It is, however, unclear how much clay there is and this was considered the most reliable and safe approach.

A marble zone strikes the area and is the reason for the high water yield. The marble is thus not indicated on the geological map used to derive the risk and vulnerability maps and extra caution should be taken where marble is visible or assumed to appear. Further field investigations and updating of the geological maps should be done and onsite inspection should assure no hazardous activities take place on or in the vicinity of marble outcrops.

The risk and vulnerability maps produced are not a final answer to the level of risk in the area. Further investigations are necessary if more detailed information is required. These maps should rather provide an overview of risks and serve as basis for discussion and decisions. It is also necessary to define the specific location of each of the identified sources of pollution to be able to produce a comprehensive risk estimation map.

8.6 Conclusions

The conclusions from the risk and vulnerability assessment of potential pollution to the groundwater of the Omeya golf and residential oasis at the Gross Haigamas farm are presented below.

- Marble outcrops need to be identified and proper protection for pollutant infiltration is required.
- Areas where large fracture zones coincide with sources of pollution pose the largest risk to groundwater contamination.
- The maps indicate relative vulnerability and risk within the area.

9 Advantages of expanding the water supply

This chapter discusses advantages of expanding the water supply for Windhoek. Several advantages are identified and qualitatively discussed.

9.1 Introduction

Connecting the water supply of Windhoek and Rehoboth is a project of great cost and to investigate additional purposes for the pipeline could be interesting in the sense of a possible increase of the economic efficiency and other advantages of the project. The absolute cost for building a pipeline between Windhoek and Rehoboth, a stretch of approximately 90 km, cannot be accounted for due to lack of information concerning pipeline material, stretch, diameter etcetera. An estimated cost has though been suggested by NamWater for a pipeline that would be 90 km long, have a diameter of 600 mm and be made out of ductile cast iron, which might be the case if the pipeline would be built in the future. The price suggestion includes transport, excavation, laying, backfilling, construction supervision, pressure testing etc, while the cost for pump stations along the pipeline and power lines to the pump stations are excluded in the cost as well as the VAT. The current cost suggestion is 688 million Namibian dollars, plus/minus 25 percent (Drews, 2010).

This section aims to evaluate actions that could further increase advantages of building the pipeline and a number of different suggestions are discussed below. As there are actions increasing the feasibility of the project there might also be also be implications by performing these actions, and therefore such measures are also evaluated below.

9.2 Further extraction points along the pipeline

The area between Windhoek and Rehoboth is generally indicated as having low potential for groundwater abstraction on the hydrogeological map. It has however been proven by the Omeya development that there are possibilities for local extraction of groundwater. However it should be emphasized that no investigations for extraction in other areas between Windhoek and Rehoboth are included in this report.

Supply figures for Omeya are planned to be 350,000 m^3/yr and demand figures for Rehoboth are 1.2-1.5 Mm^3/yr (Strauss, cited in Kullgren & Perdell, 2010). For Windhoek the corresponding figure is 60,000 m^3/day and about 21 Mm^3/yr (Theron, 2010), respectively. If other possible sources would yield in the range of the Omeya supply, an addition of an example aquifer of 350,000 m^3/yr would have an impact of the yearly total supply for Rehoboth but to a far smaller extent for Windhoek. Thus a number of such extraction points would have to be found to ensure that the supply is great enough to contribute to the demand of Windhoek. However, if such extraction points are found, this water could supply smaller developments without them being located in the vicinity of the abstraction point.

Nauaspoort Dam is located approximately 50 km south of Windhoek and has supplied the Oamities mine but now supplies a military camp at the same site (Du Plessis, P. 2010). The dam is small but further investigations of connecting the dam to a possible pipeline between Rehoboth and Windhoek should be performed in order to increase the possibilities for further extraction.

A risk of adding further extraction points is that this additional water is exposed to a risk of being polluted and thus polluting the drinking water for many people if the dilution in the pipe is not great enough. One way of decreasing this risk is to perform a risk assessment for the extraction point concerned and as a part of this report, to state as an example, such risk assessment has been conducted for the Omeya golf and residential oasis situated south of Windhoek. The results of this can be found in Chapter 8.

Other risks are that further outlets increase the number of valves, pipe parts, pumps and other infrastructure such as electricity grids and access roads, which might impact the system as a whole in case of failure. Floods, sabotage, material failure of the pipe, impact on the pipe and so forth are also threats to the supply.

9.3 Supply of new developments

In the area between Windhoek and Rehoboth a number of new developments are taking place like Omeya and Crinium Lake. Omeya has got water supply from recently drilled boreholes but in case of a water shortage a connection to a pipeline between Windhoek and Rehoboth could increase the supply. Furthermore, Gocheganas just south of Windhoek is cut for urban development. This could in the future increase the water demand of an interconnected system. There are also already existing settlements like Groot Aub that now depend on groundwater and use pit latrines for sewage disposal (Bochmühl, 2010).

One risk of the ability to supply further people with water can be the risk of water shortage due to an increased total demand. Secondly there are risks to the system as a whole when adding more parts that potentially might fail and cause water hammers and other related issues as mentioned above.

9.4 Emergency supply for Windhoek and Rehoboth

Construction of a pipeline between the two urban centres could also function as a backup system if water shortage would occur at one location. This by building either two pipelines or are two-way pipeline. However, the safe yield of the Oanob dam is about 4-6 Mm^3/yr (Du Plessis, N.P., 2010) and the present demand is 1.2-1.5 Mm^3/yr (Strauss, cited in Kullgren & Perdell, 2010) but is estimated to reach 4.7 Mm^3/yr in 2023/24 (Namib Hydrosearch, 2009c). There have been investigations for artificial recharge for the Rehoboth aquifer. This water would be taken from the Oanob dam (SWECO, 2002).

The demand in Windhoek is about 21 Mm^3/yr (Theron, 2010). The reclamation plant is built for 21,000 m^3/day (7.7 Mm^3/yr), though now producing 16,000 m^3/day. It is however estimated that full capacity will be reached at the end of 2010 (Eterhuisen, 2010). The municipality of Windhoek also derives water from boreholes and performs artificial recharge, which is around 4-5 Mm^3/yr (Theron, 2010).

The third source supplying Windhoek with water is the von Bach dam system yielding 20 Mm^3/yr (Du Plessis, N.P. 2010). According to Mr Peters (2010) the Municipality of Windhoek plan to rely on boreholes and artificial recharge along with the reclamation plant in the future, leaving the supply from the von Bach dam available for other use. There are numerous risks on using a pipeline between Windhoek and

Rehoboth and these are further investigated in Chapter 7 where an extensive risk assessment has been performed.

10 Discussion

This chapter is mainly divided into two parts, the first concerning the evaluation of the methodological implementation of the operational method of this study. The methodology and included sub-methodologies applied are reviewed step by step and the application of the method as well as the outcomes is reviewed. The second part is a discussion on the project as a pre-study for further investigations.

10.1 Evaluation of the methodological implementation

The overall method applied in this project is a risk analysis based on an international standard (IEC, 1995), which is extended to a risk assessment by including the risk evaluation steps risk tolerability decisions and analysis of options. To identify hazards and estimate risk the FMECA and the HHM methods were applied on the pipeline and for a smaller case study on vulnerability to pollution, a risk assessment method from the report of Groundwater vulnerability for the Windhoek aquifer (IN & SCC, 2000) was applied.

10.1.1 Choice of method and level of analysis

Which method to use differs from project to project. The method most suitable for the specific problem should be used in order to perform an as effective and accurate risk assessment as possible. The FMECA was not the original choice, rather a number of methods were discarded before finding the method appearing to be the most suitable for this specific project.

The case study methodology was earlier used in a similar study in an area close to the Omeya golf and residential oasis and was therefore considered a reliable method. Physical parameters were similar as well as the problem formulation.

10.1.2 Scope definition

The scope definition must be defined in order to produce a risk analysis plan and should include certain steps; the reasons and problems that originated the risk, including formulation of the objectives of the study and defining the criteria for success/failure, a definition of the system concerned, and an identification of sources of details of relevant circumstances, e.g. technical, environmental and legal. Moreover the assumptions and constraints governing the analysis should be presented and lastly an identification of the decisions that have to be made, the decision-makers and the required output from the study (IEC, 1995).

Setting goal and scope for this study was performed in cooperation with the Ministry of Agriculture, Water and Forestry of Namibia, and specifies in detail what this study should bring forth. These goals were achieved by applying methods such as the FMECA and the method for assessing risks to groundwater pollution. Performing this step of the risk assessment did not generate any problems. Being clear and presenting specific objectives provided good guidance throughout the project.

10.1.3 Hazard identification and initial consequence evaluation

Hazards should be identified together with how they can be realized. Formal methods covering the specific situation should be used when identifying hazards not previously known. A study of the significance of the identified hazards should be conducted based on a consequence analysis (IEC, 1995).

To identify hazards an FMECA and an HHM method was applied. The FMECA provides a structured process of identifying and present the identified hazards while the HMM visualises the system to facilitate hazard identification. Further, to find hazards a questionnaire was sent out and also interviews were done with people with deeper knowledge of the water supply in Namibia. The questionnaire did not receive a high frequency of answers why the results might not be very extensive, though the group was heterogeneous concerning age and education, which might increase the reliability of the study. Workshops or similar gatherings where information on the project is given could by discussions give more reinforced information to base the risk assessment upon.

One specific hazard, the risk of polluted water into the system because of additional extraction points connected to the system, was investigated by a separate method developed in the report Groundwater vulnerability of the Windhoek aquifer (IN & SCC, 2000).

10.1.4 Risk estimation

The purpose of the risk estimation is to investigate the events of concern, mitigating features and nature and frequency of possible hazardous events affecting the system. Further an uncertainty analysis concerning the estimates in the study should be conducted (IEC, 1995).

There are qualitative and quantitative risk estimates where a qualitative assessment expresses risk in words while a quantitative measure risk in numbers. Not always is there sufficient information to perform a quantitative analysis, which is the most common method in risk assessments. Instead a comparative quality or quantity analysis can be performed, where experts are involved to estimate levels of risks (IEC, 1995).

As part of the risk estimation a frequency analysis should be carried out, which is used to estimate the likelihood of a certain hazardous event. A consequence analysis is further a part of estimating the probable impact of the hazardous event and is based on the hazardous event selected and describes the consequences of these events. It should consider both immediate and future consequences as well as secondary consequences to related equipment and systems (IEC, 1995). This report describes a semi-quantitative analysis and the values making a base for estimating risk are opinions rather than facts and as stated in the guidelines they should not be considered the single answer to the question of risk. For the case study of risk of groundwater pollution for the Gross Haigamas area the probability values are estimates of expert judgment and provide a relative vulnerability over the area rather than exact values of vulnerability and risk.

In the FMECA of the pipeline values of risk for each hazard were calculated and displayed in a table presenting the chain from hazardous event via effects on the system to a final risk number. This gives a good overview of risks and allows the decision maker to quickly go deeper into the consequences of a certain hazard. The risk assessment for the Haigamas farm present possible sources of pollution in a list and show the adjacent risk of contamination. This was not specifically described in the report from where the method is derived, but rather developed to suit this specific project.

Risks to a pipeline for transportation of water between Windhoek and Rehoboth are compiled into a risk matrix where the values are placed in the calculated risk range based on information from the FMECA table. This provides a simple foundation for prioritisation of mitigation measures.

Risk of groundwater pollution in the Haigamas area is presented as maps indicating more or less vulnerable areas. This displays where caution have to be taken in case of planning new activities within the area. The maps are a tool for a first decision of where to make more thorough investigations and it should be emphasized that composition of the maps demand knowledge of GIS software.

Risk estimation implies that a number of uncertainties might appear and they should be well examined. The sources of uncertainties should, to increase clearness, be expressed in outputs of the risk model. Uncertainties can origin from both data and model and also parameters sensitive for the analysis should be identified (IEC, 1995).

One important uncertainty when estimating risk is the data collection were expert knowledge is required to derive values on probability, consequence and finally risk. Identifying the right people, posing questions to get answers correlating to scope and goal and reaching a large amount of these people has been a challenge. There has been no specific uncertainty or sensitivity analysis performed in this project rather than reasoning and discussion on specific risk estimates.

10.1.5 Verification

Verification of some kind should be carried out to confirm the integrity of the analysis. A formal reviewing process can function as a verification of the study and if field experience on the same issue is available, the verification can be conducted by a comparison of the results. No verification was made in this project due to lack of adequate data and that the results are relative to each other rather than to other studies.

10.1.6 Documentation

The risk analysis should be well documented and present the risk analysis process and initial results. It is stated in the (IEC, 1995) standard that technical information is a critical part of the documentation. This was done as far as possible since very little technical information was decided on when this report was compiled. Risk estimates and adjacent uncertainties should further be presented in understandable terms, and strengths and weaknesses of measures used should be explained. The risks are presented in tables and maps which gives an accessible view of the risks identified in this study. Weaknesses of measures are further analyzed in this discussion chapter.

10.1.7 Analysis update

The analysis update is not included in this specific risk assessment. This step is required if the risk analysis is a continuous process and since this report documents a pre-study the analysis update was considered not relevant (IEC, 1995).

10.1.8 Risk evaluation

The risk evaluation consists of risk tolerability decisions and an analysis of options and is a minor part of this study. Decisions on what is tolerable are indirectly done by the risk ranking procedure placing hazards in the risk matrix. In the matrix, the specific hazards are divided into groups of high, moderate and low risk based on the estimated risk value. By this a kind of tolerability assessment is exercised to the group of hazards posing a moderate and low risk to the system. These intervals can however be adjusted to suit the specific study. No deeper analysis of options was made. Mitigation measures were however suggested in the FMECA table and shortly commented in the discussion of the study.

10.1.9 Concluding discussion of the application of the method

The general risk analysis method presented in the IEC standard (1995) is dynamic and the inclusion of three further methods for indentifying hazards and estimating risk was a flexible process. The number of additional methods to choose from is great and the possibility of finding a suitable method is considerable.

Obstacles are thus the knowledge required to perform such risk analysis. The method of identifying hazards by interviews and a questionnaire can be further developed. Rather a meeting gathering key persons within the sector, well distributed in knowledge, where these people can discuss hazards, consequences and probabilities would give more information.

This was a pre-study and more thorough investigations are needed if a pipeline for transport of water should be built between Windhoek and Rehoboth. The results from this project can constitute a basis for determining focus areas for further investigations.

10.2 Discussion concerning the project as a pre-study for further investigations

One of the aims of this report was to constitute a pre-study for a possible expansion of the Windhoek water supply and a number of advantages and limitations have been identified. This is a general discussion of all advantages and limitations found.

10.2.1 Advantages

Several advantages concerning the construction of a pipeline for water transport between Windhoek and Rehoboth has been identified; further extraction points, supply of new developments and emergency supply for Windhoek and Rehoboth. The suggested actions could all increase the economic viability of the project.

Nevertheless, the area between Windhoek and Rehoboth is indicated as yielding small amounts of water on the hydrogeological map and chances of finding more sources are minor. The aquifer of the Omeya golf and residential resort is high yielding and is assumed to be sufficient for their needs. Several of such sources need to be found and yield a sufficient amount of water to be economically interesting. The amount of water Rehoboth can spare is also of importance for this alternative. If there is no water to pump from Rehoboth the need of further supply is even greater.

The supply of further developments is a possibility if a pipeline should be built. Several new developments will shortly be populated and are in need of water. The possibility to transport water between Windhoek and Rehoboth could also serve as emergency supply provider for the both urban centres. What needs to be further investigated is during how long period of time the amount of water in Rehoboth is enough for being transported to Windhoek. Rehoboth is a smaller community which means that Windhoek is better prepared for supplying a smaller town during a short period than the other way around.

There are additional risks to the water supply of Windhoek and the pipeline if these actions are to be implemented. These will to the extent possible be found in an early risk assessment and mitigated.

Actual costs were just briefly suggested for the very construction of the pipeline and need to be further investigated if any alternative should be interesting. Groundwater recourse value and actual costs of prospecting and extraction of the water as well as additional infrastructure and pumping costs in relation to produced water need to be taken into consideration.

10.2.2 Limitations

The FMECA performed on constructing a pipeline between Windhoek and Rehoboth indicated a number of risks and several mitigation measures should be taken. Accidental damage, flash floods and polluted water into the system are according to this study the largest threats to the water supply of Windhoek if the pipeline is to be built.

Actions to decrease the risk are to carefully select the material to be used and plan the stretch of the pipeline. This will decrease the risk of accidental damage and a well considered location of the pipeline can also reduce the risk for flash floods impacting the pipeline. To reduce the risk of polluted water into the system from possible extraction points, efficient water control systems could be installed. The water coming from the water distribution systems in Windhoek and Rehoboth lies beyond the system limitations of this project. No measures have therefore been proposed due to the fact that the revelant measures need to be adressed before the water reaches the intake of the pipeline.

Also reduction of other risks than those unacceptable is needed. A number of hazardous events can be found in the yellow category and can be realised if no measures are taken.

If additional sources of water are found along the pipeline a number of risks to the water supply might occur. The risk of pollution into the pipeline will increase and a risk assessment to groundwater pollution should be performed.

10.2.3 Concluding discussion of constructing a pipeline for expanding the Windhoek water supply

The overall aim of this project was to provide a structured operational method for risk assessments concerning projects for expansion of water supply. The aim was also to provide a pre-study for a pipeline between Windhoek and Rehoboth.

Advantages were first identified followed by a hazard identification based on the FMECA methodology and a specific area was also investigated regarding risk of groundwater pollution. The FMECA resulted in a risk matrix presenting the risks most urgent to prevent and unacceptable in red and the risk less severe in yellow and green. The risk analysis for the Omeya golf and residential oasis was presented as maps.

Several activities to improve the economic viablity of the project were presented. Also a number of hazards and threats to the system were identified. However, many factors concerning what risks are threatening the system are not yet decided on, such as material, stretch, and if the pipeline is built over or beneath the ground. Therefore, if the pipeline is built, some risks will be more relevant than others.

Deeper economic investigations are required to analyse whether this project is feasible. What is the value of drinking water? What is the value of a secured supply? Would this connection provide enough water to be considered a safe back-up system? Several questions need to be answered to decide whether this project is econmically viable.

As already mentioned there has been no specific uncertainty or sensitivity analysis performed. There has been reasoning and discussion of values estimating vulnerability, toxicity, release quantity etc for the vulnerablility analysis as well as values estimating probability and consequence in the FMECA. None of theese values can be considered as an absolute fact but rather as well informed estimates which might of course not be fully accurate. Education of people involved, number of people involved and so forth all makes a difference in results.

If further investigations are made a sensitivity analysis should be performed in order to analyse the stability of the assessment. How the output is affected should be tested in relation to a change of input parameters. If the project is realized, more thorough investigations should be done. This pre-study may constitute the basis for discussion and decisions on further action.

11 Conclusions

The conclusions concerning the project as a pre-study but also the methodological implementations of the project are presented below.

- The operational risk analysis method applied to perform this pre-study has provided dynamic guidelines and could in a flexible manner be combined with other methods to identify hazards to the system and for the case study, vulnerability to groundwater pollution.

- Advantages of connecting the water distribution system of Windhoek and Rehoboth via a pipeline are that further extraction points can be found, further developments can be supplied and the pipeline can provide an emergency water supply both for Windhoek and Rehoboth.

- The limitations i.e. vulnerabilities and hazards which are of highest priority related to the possible pipeline are accidental damage, the risk of flash floods and polluted water into the system.

- Recommended mitigation measures for an expanded water supply via a pipeline are careful planning of the pipeline stretch and a well engineered material and construction. Polluted water into the system from the pipeline ends was not further discussed since the measures relevant need to be addressed outside the defined system boundaries.

- The investigation of risk to groundwater pollution at the Omeya golf and residential oasis generated a number of possible sources of pollution. These sources are related to the vulnerability of the ground where the source are located and a final risk value for that specific location is calculated as seen in Figure 8.10.

- The area of Gross Haigamas is vulnerable in general and no highly contaminant activities should take place.

- Hopefully, this report can serve as a pre-study for a possible expansion of the Windhoek water supply and as a basis for further detailed studies. The report provides insights into the project that should be valuable as a basis for further investigations and for designing a safe and reliable future connection of the water supply of Windhoek and Rehoboth.

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Appendix A

Questionnaire

This questionnaire aims to provide information for a risk assessment where one part is to systematically evaluate the risks concerning connecting the water supplies of Rehoboth and Windhoek by a pipeline. The second part is to identify hazards for further possible groundwater extraction points in the area between the two cities.

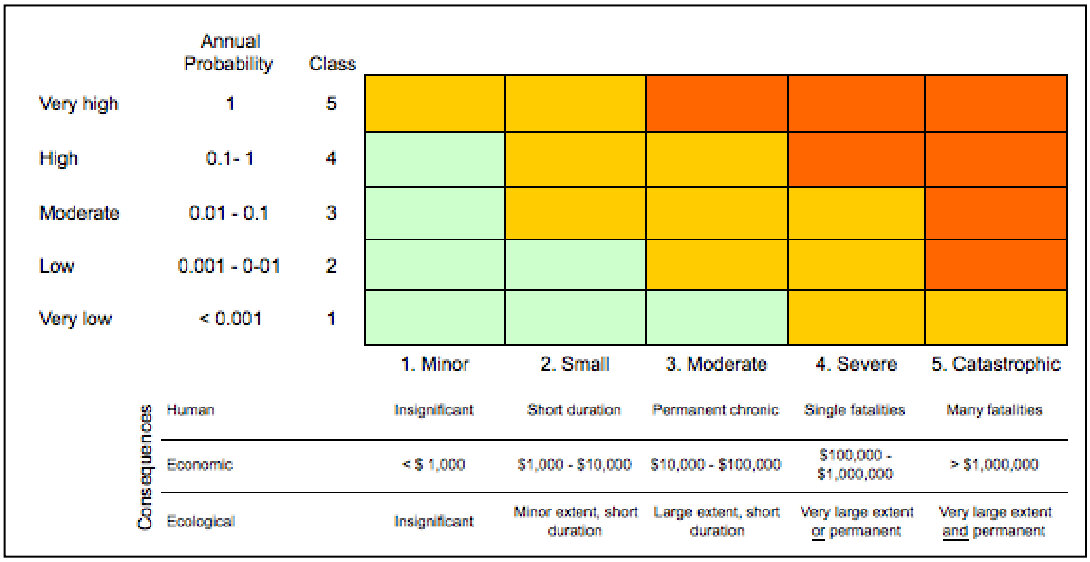
The questionnaire is divided into three parts. The first part concerning the pipeline, the second part concerning hazards to potential water extraction points and the third part concerning costs.

1. The pipeline connection

The method to be used for assessing risks is a risk matrix. You are asked to identify hazards, estimate the consequence and lastly the frequency of this hazard occurring. The matrices will be a part of an FMECA (Failure mode and effect critically analysis), which is a method for risk assessment.

Please note that hazards can be proposed both to the pipeline itself and/or the water supply as a whole when the connection has been built.

Each hazard will be defined by the two values for probability and consequence and the risk can be evaluated from the matrix seen below;



Example;

Hazard	Truck hitting pipeline, breakage
Consequence (number)	= 5
Comment	Stop in water supply transport
Probability (number) = 1	
Comment	

The risk for a truck hitting the pipeline and breakage is thus moderate (yellow). This can be evaluated from the matrix by the values assigned.

Your suggestions

Please write as many hazards as you can come up with and do not hesitate to develop your thoughts concerning the consequences.

Hazard 1	
Consequence (number)	=
Comment	
Probability (number) =	
Comment	

Hazard 2	
Consequence (number)	=
Comment	
Probability (number) =	
Comment	

Hazard 3

Consequence (number) =

Comment

Probability (number) =

Comment

Hazard 4

Consequence (number) =

Comment

Probability (number) =

Comment

Hazard 5

Consequence (number) =

Comment

Probability (number) =

Comment

2. Hazards to possible water extraction points between Rehoboth and Windhoek.

If a pipeline would be realized further possible extraction points could make the project more cost efficient. The project includes a general discussion concerning these possible threats why we ask you to repeat the procedure from above on this matter.

Hazard 1 Consequence (number) = Comment Probability (number) = Comment

Hazard 2 Consequence (number) = Comment Probability (number) = Comment

Hazard 3 Consequence (number) = Comment Probability (number) = Comment

Hazard 4
Consequence (number) =
Comment
Probability (number) =
Comment

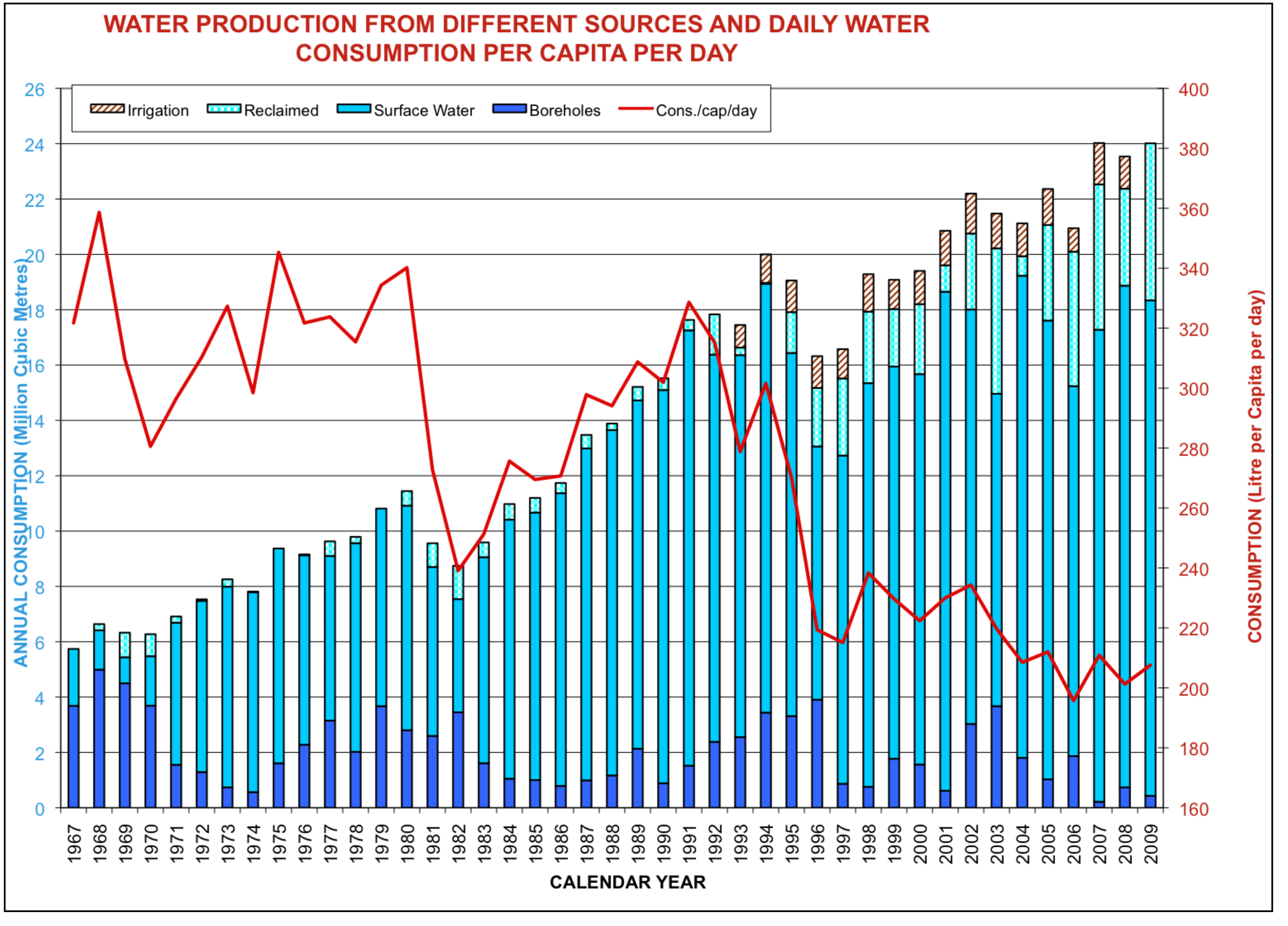
Hazard 5
Consequence (number) =
Comment
Probability (number) =
Comment

3. Cost

Do you think it would be cost efficient to build a pipeline for water emergency supply as the water supply situation is today and in the future, why/why not?

Can you estimate the cost of building such a pipeline?

Appendix B



WATER PRODUCTION FROM DIFFERENT SOURCES AND DAILY WATER CONSUMPTION PER CAPITA PER DAY
Irrigation
Reclaimed
Surface Water
Boreholes
Cons./cap/day
ANNUAL CONSUMPTION (Million Cubic Metres)
CONSUMPTION (Litre per Capita per day)
CALENDAR YEAR
0
2
4
6
8
10
12
14
16
18
20
22
24
26
160
180
200
220
240
260
280
300
320
340
360
380
400
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