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Risk Assessment for South Africa's first direct wastewater reclamation system for drinking water production

Beaufort West, South Africa

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

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

Cover:
From top-left: Activated sludge, Secondary settler, BAC filters, Reverse osmosis membranes, H_2O_2 in Beaufort West’s wastewater reclamation system, © Olle Ivarsson & Andreas Olander

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ABSTRACT

In Beaufort West, South Africa's first direct wastewater reclamation plant (WRP) for the production of drinking water was constructed in the end of 2010 as a result of acute water scarcity. Due to high pathogen load and limited knowledge of WRP's a risk assessment were conducted. Information and knowledge were gathered during a study visit to the world's first direct reclamation plant in Windhoek, Namibia. As suggested by the EU project TECHNEAU risks were not only assessed by water quality, but also by water delivery interruptions (quantity). The system boundaries were defined in such a way that the new reclamation system could be stressed and risks originating from the reclamation system could be identified. Hazards were identified by using a hazard database also developed by TECHNEAU, and an early version of a hazard database from South Africa's Water Research Commission. The databases were useful, but to general to be used without modification of the defined hazards.

The risk analysis was performed by using risk matrices, and an ALARP approach when evaluating the risks. Originally, 70 risks were identified as valid to the system and five critical risks were identified, one quality related risk and four quantity related risks. The most important treatment barrier used in Beaufort West is reverse osmosis, which has high treatment efficiency with very few pathogens able to pass through. Therefore fewer quality-related risks were identified compared to quantity related risks. By the use of Multi-Criteria Decision Analysis, suggested risk reduction measures were ranked by costs and reduced risk in both quantitative and qualitative terms.

Key words: Risk Assessment, MCDA, Wastewater Reclamation, Water Scarcity, South Africa, Beaufort West

Riskanalys för Sydafrikas första direktreklamationsanläggning av avloppsvatten för framställning av dricksvatten
Beaufort West, Sydafrika
Examensarbete inom Geo and Water Engineering
OLLE IVARSSON, ANDREAS OLANDER
Institutionen för bygg- och miljöteknik
Avdelningen för Vatten och Miljöteknik
Chalmers tekniska högskola

SAMMANFATTNING

I Beaufort West, konstruerades Sydafrikas första anläggning för direktreklamation av avloppsvatten för framställning av dricksvatten i slutet av 2010 efter en längre period av akut vattenbrist. På grund av den höga koncentrationen av patogener i råvattnet och begränsade kunskaper om denna typ av system har en riskbedömning genomförts i detta projekt. Information och kunskap har samlats in genom en studieresa till världens första anläggning för direktreklamation av avloppsvatten för framställning av dricksvatten i Windhoek, Namibia. Som framgår av EU-projektet TECHNEAU bör dricksvattenrisker inte endast bedömas utifrån vattenkvalitet, men också utifrån distributions avbrott (kvantitet). Systemgränserna har definierats på ett sådant sätt att det nya återvinningssystemet är i fokus och risker som härrör från anläggningen kunde identifieras. Initierande faror identifierades med hjälp av en databas som utvecklats inom TECHNEAU, och en tidig version av en databas från Sydafrikas Water Research Commission. Databaserna var ett bra verktyg, men farorna är specificerade för allmänt för att användas utan modifiering.

Riskanalysen som utfördes gjordes med hjälp av risk matriser och genom att använda ALARP för att definiera risknivåer. Ursprungligen identifierades 70 initierande faror som potentiella risker för systemet. Fem risker identifierades sedan som kritiska risker, varav en berörde kvalitet och fyra kvantitet. Den viktigaste barriär som används i Beaufort West är omvänd osmos, som har hög reningseffektivitet med mycket få patogener som kan passera. Omvänd osmos är främsta anledning till att färre kvalitetsrelaterade risker har identifierats jämförts med kvantitetsrelaterade risker. Genom användning av multikriterieanalys rankades föreslagna riskreducerande åtgärder efter kostnader och minskad risk, både kvantitativt och kvalitativt.

Nyckelord: Riskanalys, MCDA, Reklamationsanläggning, Vattenbrist, Sydafrika, Beaufort West

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Preface and Acknowledgements

This master's thesis was performed during spring 2011 at Chalmers University of Technology in cooperation with Beaufort West Municipality SA, Chris Swartz Water Utilization Engineers and Pierre Marais Water and Wastewater Engineering (WWE). The risk analysis and gathering of data was performed during a 9 week study visit financed by SIDA – Minor Field Study and Chalmers Vänner.

We would like to especially express our gratitude's to Mr. Chris Swartz who arranged our time in South Africa and made it to a great experience and a lifelong memory, but also gave good support and directed our analysis. At Chalmers we would like to thank Ass. Pr. Thomas Pettersson who made the project possible from the beginning and helped us compiling the thesis and Andreas Lindhe who supported our work, especially with the MCDA. Further we would also like to thank Linda van Zyl and Magda Pretorius in Mossel Bay for good coffee and for sorting out grammatical issues.

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Göteborg June 2011

Olle Ivarsson and Andreas Olander

Notations

There are several different frameworks and national guidelines in the field of risk management that has lead to confusion regarding how some of the terms and definitions should be interpreted. This report will use the same terminology that is used in the TECHNEAU project, presented in the report *Generic Framework and Methods for Integrated Risk Management in Water Safety Plan*s (Rosén, L. *et al.*, 2007), and based on IEC (1995). Below definitions and common abbreviations are presented.

Term	*Explanation*
Backyard dwellers	People that due to e.g. poverty, unemployment or backlog of houses lives abnormally many in the same household.
Basic sanitation service	Basic sanitation facilities that is easy accessible for the household. The facilities should be operated in a sustainable way and waste/wastewater should be removed in a safe way.
Basic water service	In case of: • Communal water points, i.e. shared tap between households, 25 l/day of drinking water per supplied person with a flow of 10 l/min within 200 m of the household; or • Formal connection, i.e. house or yard connection, 6000 liters of drinking water per month Further these quantities need to be supplied 350 days per year and with no more than 48h consecutive interruptions each time. Also basic sanitation service may be includes in the definition.
Hazardous agent	A biological, chemical, physical or radiological agent that potentially may cause harm.
Hazardous event	An event, source or situation, which can cause harm.
Informal settlement	Poorer housing area with lack of access to basic water and electricity service often constructed on government ground without authorization and consisting of simple constructed dwellings built of, e.g. plywood, corrugated metal etc. Also referred to as shantytowns.
Risk	A combination of the probability of occurrence and the consequence of a specified hazardous event.
Water Board	A state owned organization/entities that operate and handle dams, wastewater systems, water supply infrastructure etc. Their task is to work as water utilities and, in cooperation with WSAs, provide people with basic water service.
Water Service Provider	Nongovernmental organizations, private companies or water boards that provide drinking water and/or sanitation service with permission from the WSA responsible for the area of jurisdiction.
Water Service Authority	A metropolitan municipality, district municipality or authorized

(WSA)	local municipality that provides water to the inhabitants within its area of jurisdiction.
Water Safety Plan (WSP)	A review of the water system initiated by WHO that, among other things, should contain a risk assessment. The WSP should be updated each third year. In South African reports/acts the term *Water Service Development Plan* (WSDP) used and it is defined as a plan for water and sanitation services in terms of the Water Service act of 1997.
Reclamation system	Used in this context as a definition of the entire system, which includes the WWTP, Reclamation Plant and the grid to the blending point.

Abbreviations

ALARP - As Low As Reasonable Practicable

DWA – Department of Water Affairs

DWAF – Department of Water and Forestry

IEC – International Electrotechnical Commission

MDG – Millennium Development Goals

MCDA – Multi Criteria Decision Analysis

SANS – South African National Standards

TECHNEAU – Technology Enabled Universal Access to Safe Water

THDB – TECHNEAU Hazard DataBase

VIP – Ventilated improved pit

WHO – World Health Organization

WRP – Wastewater Reclamation Plant

WSA – Water Service Authorities/Administrations

WSP – Water Safety Plan

WTP –Water Treatment Plant

WWTP – Waste Water Treatment Plant

1 Introduction

An ongoing global warming is today a fact for most people and the discussion has lately more being diverted into consequences, responsibilities and how to reduce emissions of greenhouse gases. Already now are consequences noticeable across the planet by increasing floods in one end and drought in another. Where water is already scarce, less precipitation in combination with increasing temperatures and growing urbanization causes major issues for any country (WHO, 2010). A lack of water to meet the daily demands, i.e. water scarcity, is today a fact for one out of three people in the world (UN, 2010a).

South Africa suffers from water scarcity in several regions around the country and almost all available freshwater resources are fully utilized and under stress. According to Department of Water Affairs and Forestry (DWAF) *et al.* (1999) only 8.6% of the precipitation is available as surface water, mainly due to evaporation, which gives one of the lowest precipitation to surface water conversion ratios in the world. Further also pollution of ground- and surface water is indicated as a major threat towards South Africa's raw water sources, where mining industries has a big proportion of the responsibility. Like the general trend in the world, South Africans are leaving the countryside and moving towards the bigger cities in search for better economic conditions, consequently resulting in more people on a smaller area further stressing the available raw water sources.

In Beaufort West, located in the Western Cape, a severe drought nearly emptied the town's raw water sources, resulting in an immediate lack of drinking water. The town was in, January 2011, relying on trucks delivering additional drinking water to support its inhabitants. Frequent droughts in combination with predicted population growth and large informal housing areas that needs to be connected to the water supply system, will increase the pressure on the raw water sources even further in future. According to WHO (2010) water scarcity is also directly connected to socio-economical impacts, which to some extent is reflected in Beaufort West's welfare statistics (BWM, 2010a).

The current situation in Beaufort West has lead to the construction of a direct Wastewater Reclamation Plant (WRP) producing drinking water. The plant functions as an addition to the existing water production system and will increase the drinking water production and reduce pressure on the existing raw water sources. Thereby the community shall be better prepared for future droughts and make it possible to supply the future growing population with drinking water that fulfills quantity and quality standards. This is the first *direct* WRP that produces drinking water in South Africa, second in the world after New Goreangab, Windhoek. See thesis *Microbiological Risk Assessment of New Goreangab Water Reclamation Plant in Windhoek, Namibia* (Ander & Forss, 2011) that was conducted during the same period as this thesis for more information about reclamation in Windhoek.

Due to the widespread water scarcity in South Africa, WRP's are considered in several other South African towns why there is a high interest on the project within the water sector[1] (DWAF *et al.*, 1999). This type of drinking water plant put higher demands on the treatment process since the raw water contains more pathogens than conventional raw water sources. Due to high pathogen load and often complex multi-barrier approaches, higher risk is connected to reclamation systems which substantiate the need for a comprehensive risk assessment.

[1] Professional Engineer Chris Swartz, Water Utilization Engineers, 2011-04-20 (Personal communication)

1.1 Aim

The overall aim of this project is to perform a risk assessment case study that identifies and quantifies risks, concerning drinking water quantity and quality, related to the new reclamation system in Beaufort West. For the most severe identified risks improvements will be suggested to reduce risks to an acceptable level. The most important objectives of the project are to:

1. Identify hazards threatening water quantity and/or quality within defined system boundaries.
2. Estimate risk levels connected to the identified hazards, by assessing the probability and consequence of each hazard.
3. Define tolerability criteria.
4. Rank the identified risks and decide if they are tolerable or not.
5. Suggest and evaluate risk reduction measures for unacceptable risks.

Further the aim is to provide an example of how a risk assessment for a reclamation system can be conducted according to the TECHNEAU Risk Management framework. TECHNEAU Hazard Database (THDB) does not include wastewater as a raw water source, why this will be accounted for and further developed. The case study is also supposed to serve as a foundation for the continuing development of the Water Reclamation Plant (WRP) and to be included in Beaufort West's next water safety plan (WSP).

1.2 Problem Definition

Reclamation systems tend to be complex since they typically use several barriers that are technically advanced. Due to lack of experience regarding reclamation systems in South Africa, and high pathogen concentration in the raw water from the WWTP, higher risks are connected to reclamation systems than conventional drinking water production. Therefore a comprehensive risk assessment is required.

Furthermore this type of systems is expected to be more common in South Africa as well as other countries suffering from water scarcity. More knowledge in the field is therefore crucial for a successful continuing progress and development.

1.3 Method

The risk assessment will be performed according to the general framework of risk management developed by TECHNEAU (2007). Hazards will be identified by the use of the THDB in combination with a hazard spreadsheet developed by South Africa's Water Research Commission (WRC). The spreadsheet will be used during discussions with South African water experts, treatment plant operators, politicians, consultants etc. Risk matrices, with focus on water quality and quantity consequences, will be used to estimate the connected risk levels and a risk tolerability decisions will be evaluated according to the principle As Low As Reasonably Practical (ALARP).

Risk reduction measures will be suggested for the most severe risks and ranked by the use of Multi Criteria Decision Analysis (MCDA), developed within TECHNEAU at Chalmers University of Technology (Lindhe *et al.*, 2010).

Literature studies will be done to gather new information in the field and to investigate arisen questions.

A three-day study visit to Windhoek’s reclamation system will be done to gather information, and discuss general problems, connected to reclamation systems. A one-day study visit and seminar to a new constructed desalination plant and an indirect wastewater reclamation system in Mossel Bay, South Africa were also part of the project.

1.4 Delimitations

The case study is limited to assess risks connected exclusively to the reclamation system, providing a general overview of risks that will constitute a basis for more comprehensive studies. The system boundaries, see Chapter 10.1.1, are defined as the water inlet of the Wastewater Treatment Plant (WWTP), through the new WRP, and to the blending point with drinking water from the conventional system.

Due to the defined system boundary interactions, or dependencies, with the conventional water treatment system may occur that is not illustrated or evaluated in this case study. In future the complete system should be considered in WSP, including an updated version of this risk assessment.

In the risk assessment the rapid sand filter and the UV/H_2O_2 were not assessed due to time restraints.

2 The General Risk Management Process

The main purpose of the risk management process is to ensure that people, the environment and assets are not exposed to unacceptable risks, by balancing the risk reducing cost against the cost of the consequences originating from the risk generating activity (Grimwall *et al.*, 2010). The interpretation of the term risk differs from person to person and their exists several different definitions in literature depending on if the focus of the risk is connected to human health, the environment or technical problems (Lindhe, 2010). One of the more widespread definitions of risk is that it is a combination of the probability and the consequence of an undesired event, i.e. a hazardous event. Kaplan and Garrick (1981) state that the term “risk” can be decomposed into three questions (also discussed by IEC, 1995; Grimwall *et al.*, 2010):

1. What can happen? (i.e. what can go wrong?)
2. How likely is it?
3. What are the consequences?

Further IEC (1995) state that the objective of the overall process of risk management is to: control, prevent or reduce loss of life, illness, injury, damage to property and consequential loss, and environmental impact. Grimvall *et al*. (2010) etc. emphasize that risk management also involves an appropriate balance between realizing opportunities for gain/profit and minimizing losses. So an efficient risk management can create opportunities by analyzing risks and reaching a deeper understanding of the situation, which can result in possibilities to mitigate or control the risk and consequently facilitate new projects. The process of risk management according to IEC (1995) (Figure 2.1) is often referred to when risk management is described.

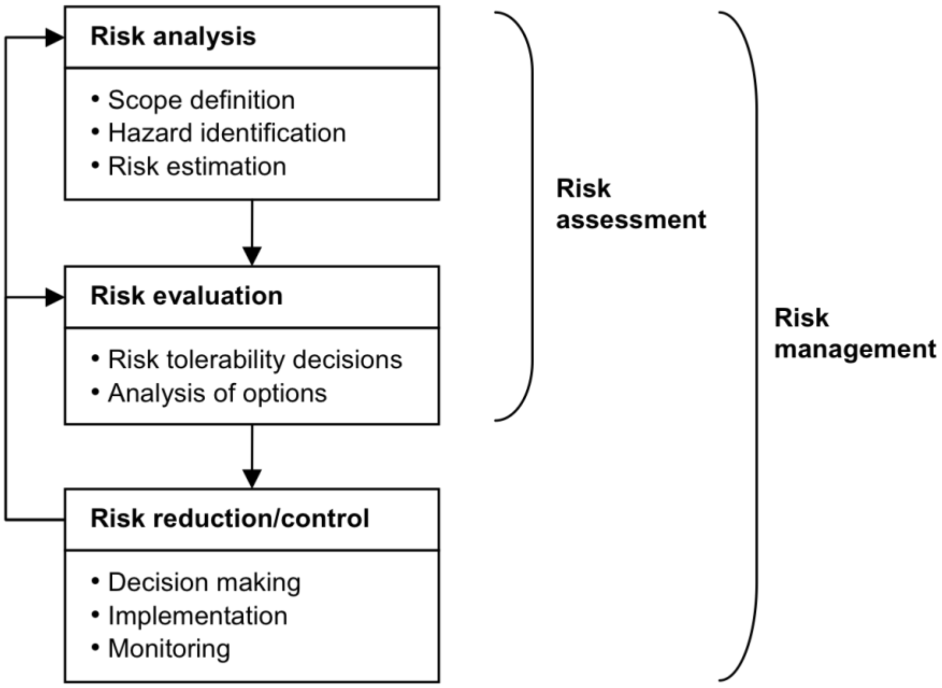

Figure 2.1 Risk management according to IEC (1995).

The last step of the risk management process, risk reduction/control, includes the implementation of possible risk reduction measures, which necessitates the involvement of decision makers, e.g. an agency or a political body. This step is however excluded in the case study performed in this report, see chapter 10, since the result from the report is planned to serve as additional information base for Beaufort West's WSP and not to take any final decision about implementations of risk reduction measures. If only the two first steps of the risk management process are performed, risk analysis and risk evaluation, the process is usually referred to as risk assessment.

In every project stakeholders are involved in different ways and extent. The ideal stakeholders are the decision-makers, cost-bearers / benefit receivers and the risk-takers (Grimwall *et al.*, 2010). In a typical project those exposed to risks are not necessarily those benefiting from the activities causing them and the decisions makers may not be directly affected by the negative consequences of the risk or the economic consequences of the decision. Consequently, it is important to involve participants from all sides since there interest areas overlap (Figure 2.2). It is crucial to firmly establish what risk levels that are acceptable or not and to have a transparent process and communicate which principles that are applied among the stakeholders.

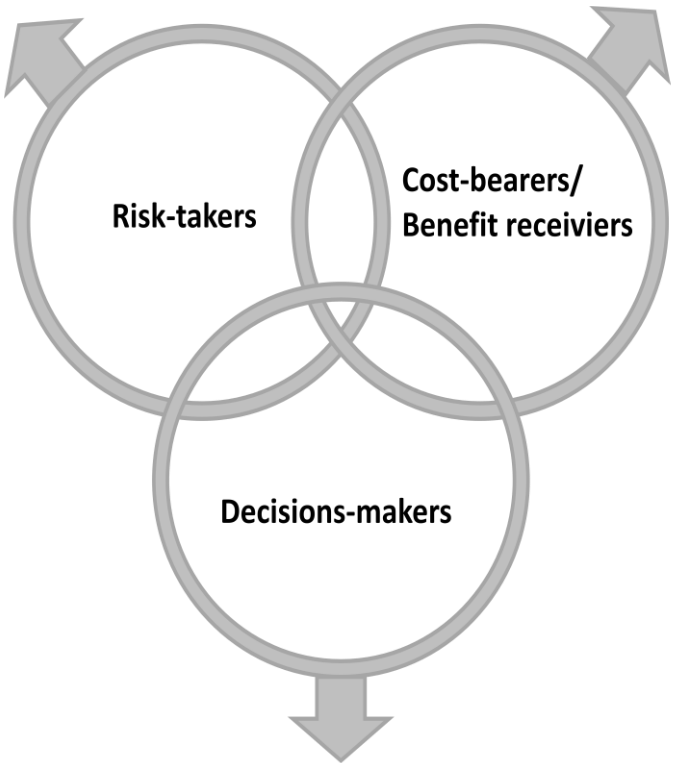

Figure 2.2 Conceptual model showing the overlapping interest areas of stakeholders involved in the risk management process (Modified from Grimwall, 1998).

2.1 Risk Analysis

The main purpose of the risk analysis is to gather information and knowledge about risk levels to support decision-making. Risk analysis, as well as risk management, is an iterative process and should be updated as new information becomes available or as surroundings change. Risk analysis should be performed in a structured order, where the main steps are as follows (e. g. Grimwall *et al*., 2010; IEC, 1995):

1. Define the scope
2. Threat and hazard identification
3. Estimation of risk

The scope includes the goal and vision with the risk analysis. The system boundaries and sub-systems that are considered are also included. How the system boundaries are defined have big impacts on the final risk since interactions between components (chain of events) are common and not always easy to overlook. It is also of importance to communicate the scope with stakeholders from all areas (Figure 2.2).

The hazard identification can be based on experience, brainstorming, checklists e.g. TECHNEAU Hazard Database (THDB), but also by more systematic processes such as What if analysis and Hazard and Operability analysis (HAZOP) (Rosén *et al.,* 2007). Stakeholders have a vital role to play in the hazard identification and it is important to have relevant people participating in the process. In general, threats and hazards can be classified in different ways e.g. cause-, consequence- or resource related (Grimwall *et al.,* 2010).

Risk estimations can be performed quantitative, semi-quantitative or qualitative. Quantitative methods generally describe risk in numbers and qualitative methods describe them by words. The quantitative method generally requires more data and is therefore not always a possible option. Semi-quantitative methods are based on qualitative data where probabilities and consequences are assigned numerical values to illustrate their importance/significance. One common risk estimation method, either quantitative or semi-qualitative, is risk ranking with the use of a risk matrix. The risk matrix method will be used in the case study in this report and is explained further in chapter 4.2.

When estimating risk levels connected to hazards, consequences and corresponding probabilities should be described. There is however uncertainties connected to the estimation of both parameters. Uncertainties connected to the estimation of the probability are generally more difficult to assess, compared to the estimation of the consequence (Grimwall *et al.,* 2010). There exist different techniques, with different level of complexity, to handle uncertainties connected to the estimation of probabilities. Which technique that is appropriate varies with the available data and which process that is considered. A general categorization of the most common techniques, used for the estimation of probability, is presented in Figure 2.3. The case study in this project will use techniques from the lowest step.

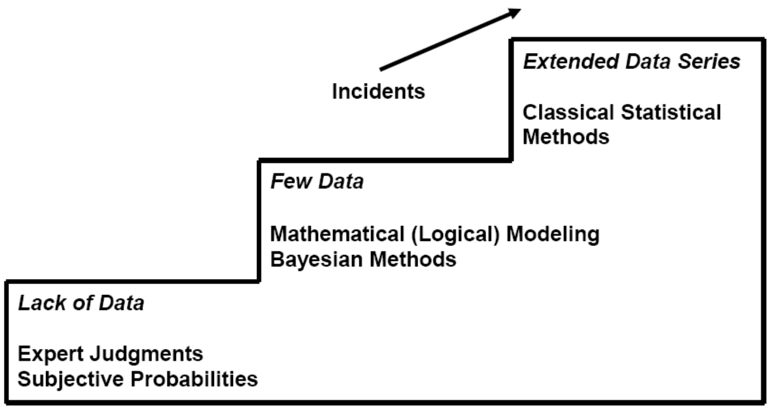

Figure 2.3 Different techniques used for the estimation of probability, depending on the quality of available data (Grimwall et al., 2010).

2.2 Risk Evaluation

When evaluating the risk, the intention is to conclude whether a risk is acceptable or not, i.e. a risk tolerability decision. If the initial risk is considered too high, risk reduction measures needs to be implemented to lower or control the risk. If a risk is decided to be acceptable it is not always necessary to reduce the risk, it may be enough to control it. As stated by IEC (1995) the risk evaluation consists of two parts:

1. Risk tolerability decisions
2. Analysis of options

One method that is used in the risk tolerability decision part is risk ranking. By the use of a semi-quantitative risk matrix are all identified hazards ranked by their risk level, and the ALARP principle can be used to conclude if the risk levels are tolerable or not. For the risks decided not tolerable risk reduction measures are proposed. By using a Multi Criteria Decision Analysis (MCDA) the options are ranked and a plan that suggests which risk reduction measures that is most efficient to implement from a set of given criteria. For further explanations see chapter 4.

2.3 Risk Reduction/control

The result from the risk assessment is presented in a report where estimated risk levels, and also often suggested risk reduction measures are presented. In the risk reduction/control step a decision should be made how to proceed with the risk reduction or if the risk is decided acceptable, how it should be controlled. This decision is often taken by a different part then those conducting the risk assessment. Therefore it is vital that the risk assessment process is transparent and understandable to the decision maker. The final result from the risk reduction/control should be presented in a report that more specifically includes:

- If there are any risks that are decided unacceptable and needs to be reduced.
- If there are any risks that are decided acceptable, but needs to be controlled.
- How and which risk reduction measures, connected to the unacceptable risks, that should be implemented.
- How risks decided acceptable should be controlled and monitored.
- How the future development of the risks should be monitored.

3 TECHNEAU

TECHNEAU started as a project, funded by the European Commission, to challenge traditional drinking water treatment and to address future demands by the development of new techniques and monitoring systems for safe drinking water (TECHNEAU, 2011a). The project constituted of eight activity work areas (WA) (Figure 3.1).

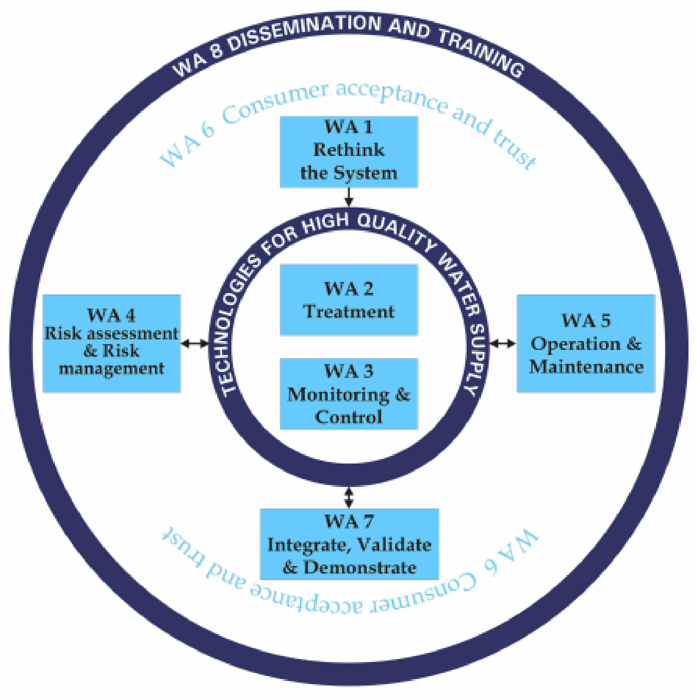

Figure 3.1 Conceptual model of the TECHNEAU project, presenting all the eight different work areas (TECHNEAU, 2010a).

3.1 Risk Assessment within TECHNEAU

WA 4 was focused on the development of a comprehensive decision support framework for risk assessment. A framework designed to facilitate cost effective risk management for safe and sustainable drinking water production – from a source to tap perspective (TECHNEAU, 2010a). TECHNEAU developed risk assessment further, based on the accepted generic framework for risk management developed by IEC (1995) and the concept of Water Safety Plans, WSP developed by WHO (2005). One important part was to put higher focus on water quantity related risks in water safety plans. Before TECHNEAU started risks were commonly analyzed from a quality perspective only, as suggested by WHO (2005).

Lindhe (2010) explained the relationship between quantity and quality failure connected to supply failure by a conceptual model (Figure 3.2). Hazards are initiated by a supply failure, which can be further categorized into quantitative supply failure or qualitative supply failure. Quantity failure can occur by either failure of components in the system or by events leading to unacceptable water quality causing a production stop. Quality failure is when unacceptable water is delivered and either is detected, but no action is taken or cannot be taken, or quality failure is *not* detected why not action can be taken.

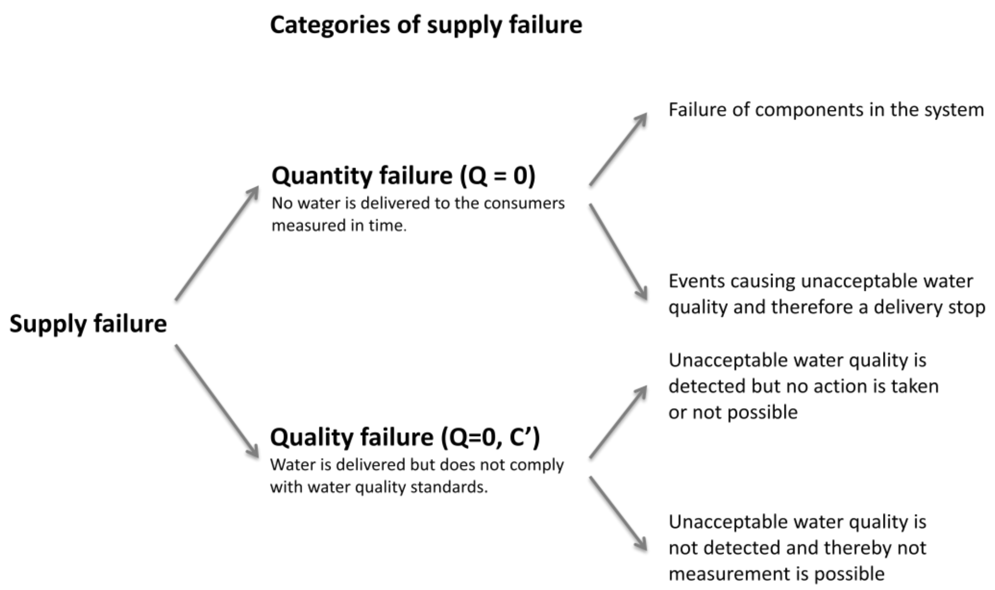

Figure 3.2 Conceptual model explaining the relationship between quality and quantity failure (Lindhe, 2010)

Other important goals within WA 4 were to:

- Improve and further integrate and provide a structure for risk management in water safety plans.
- Further stress the importance of a "source to tap" thinking.
- Enable a more transparent process.
- Divide risk assessment in two steps, where the first step is aimed at securing quantity/quality for less developed countries, while the second is adapted for developed countries i.e. more advanced often quantitative methods
- Develop a comprehensive hazard database

4 Methods

In this chapter different methods and techniques, connected to risk assessment and risk management, used in this project will be explained. The techniques are further explained and implemented in chapter 10.

4.1 Hazard Identification - Bottom-up and Top-down

According to Beuken *et al.* (2008) there are two main approaches for hazard identification, the bottom-up approach and the top-down approach. The simplest and most used approach is bottom-up, using experience and knowledge from personnel involved in the process operation to identify hazards. The hazard identification in the top-down approach categorizes hazards into subsystems to facilitate from where the hazards originate. Connected to the subsystems are then hazard checklists that are used to identify hazards that are relevant to the assessed system. Advantages with this approach are that a more extensive hazard list often is created, compared to a bottom-up approach that often only identifies well-known hazards. However, a combination of both methods is suggested to identify as many hazards as possible.

Two examples of top-down approaches are the TECHNEAU Hazard Database (THDB) and a spreadsheet developed by the South African Water Research Commission (WRC). The THDB provides a database of technical, environmental and human hazards connected to water supply systems with a source to tap perspective. The water supply system is divided into 12 sub-systems (Figure 4.1). Also hazards that may pose a threat in the future are considered in the data base, e.g. sabotage, terrorist attacks, emerging pathogens and climate change. The WRC spreadsheet hazard identification list is so far only a draft version and it is not as extensive as THDB. The spreadsheet developed by WRC also gives the possibility to estimate the probability and consequence of the hazards which THDB does not.

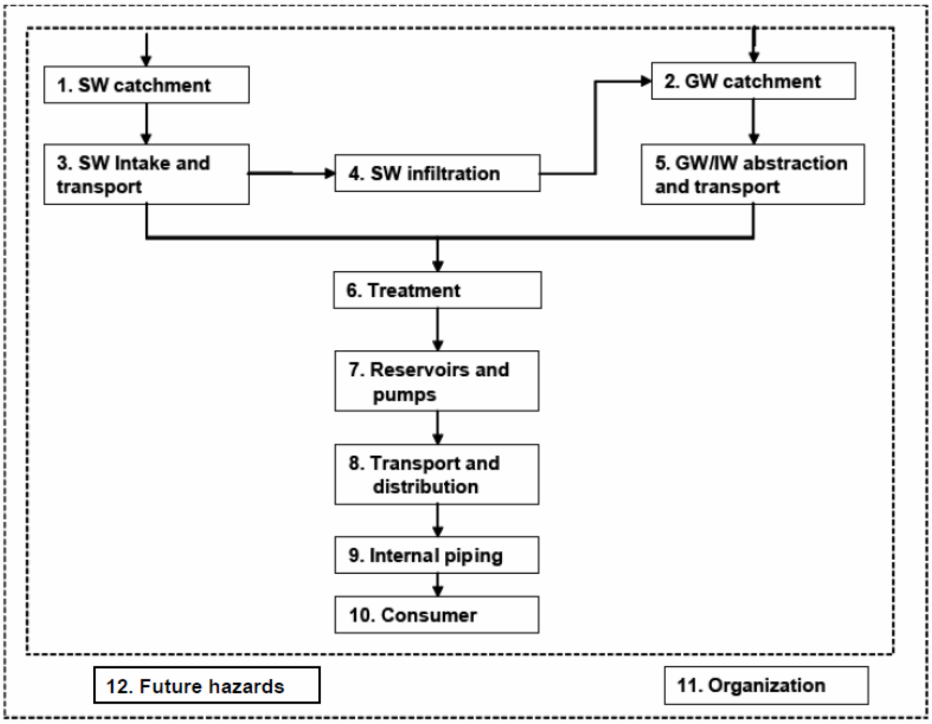

Figure 4.1 The water supply system divided into 12 sub-systems in THDB, SW = surface water, GW = ground water, IW = infiltration water (Beuken et al., 2008)

The case study in this project, chapter 10, will use a bottom-up approach to involve operators, decision makers and different stakeholders in combination with a top-down approach to cover as many hazards as possible. The spreadsheet developed by WRC formed the base for the hazard identification since it also gives the possibility to estimate risk level connected to the identified hazards. The spreadsheet was complemented with risks from the more extensive THDB, mainly from subsystem 6, 7, 8, 10, 11 and 12.

There was no subsystem connected to wastewater treatment, either in the THDB or the WRC spreadsheet. The wastewater treatment is an essential part of the Beaufort West Reclamation system, since it corresponds to the reclamation systems raw water source. Therefore the subsystem had to be developed separately and added to the spreadsheet. The WRC spreadsheet was only considering quality related risks compared to the THDB that also considers quantity related risk. The spreadsheet was updated with the possibility to estimate risks from both a quality and quantity perspective.

4.2 Risk Ranking

The aim with risk ranking is to establish the relative severity between identified risks. Risk levels are estimated by categorizing each hazard, by corresponding probability and consequence, defined in either words or numbers. Definitions by WHO (2005) of probability and consequence are commonly referred to when considering water quality related risks (Table 4.1). As suggested by TECHNEAU (2007), not only quality related risks but also quantity related risks should be analyzed in the risk assessment. For quantity related risk definitions, see chapter 10.1.3. The estimated risks are presented in a risk matrix, with probability and consequence as axis, where the more severe risks are located in the upper right corner (Figure 4.2).

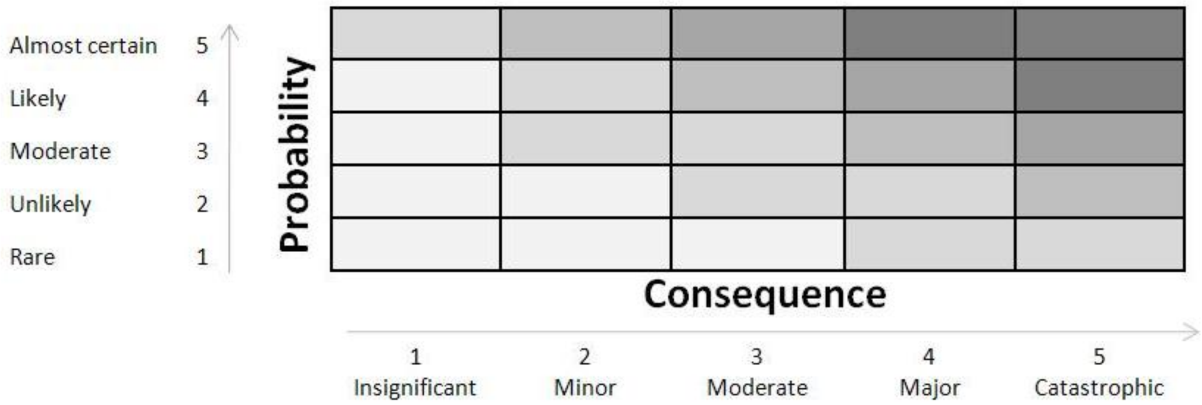

Figure 4.2 Risk matrix with probability and consequence scales expressed in both numbers and text, i.e. semi-quantitative.

Risk ranking is a common method to assess risks and the reason behind this is that it is easy to perform, with relatively transparent results that are easy to communicate. Risk ranking does however have several limitations. According to Lindhe (2010) hazards can have several different possible outcomes, but this is not easily considered in a risk matrix since only one consequence with a connected probability is illustrated for each hazard. There is no formal procedure to consider and illustrate chain of events in a structured order in risk matrices. Chain of events and interactions does however have big impacts on several of the estimated

risks. For some risks to occur it is not enough that one process is malfunctioning but typically a series, or chain of events, needs to take place before there is any real threat.
There is also no common procedure for uncertainty analysis in risk ranking.

Table 4.1 Definitions of probability and quality consequence/impact categories used in case study (WHO, 2005).

Level	Descriptor	Description
	Probability	
1	Rare	Once every 5 year
2	Unlikely	Once per year
3	Moderately likely	Once per month
4	Likely	Once per week
5	Almost certain	Once a day
	Consequence	
1	Insignificant	No detectable impact.
2	Minor	Minor aesthetic impact causing dissatisfaction but not likely to lead to use of alternative less safe sources.
3	Moderate	Major aesthetic impact possibly resulting in use of alternative but unsafe water sources.
4	Major	Morbidity expected from consuming water.
5	Catastrophic	Mortality expected from consuming water.

To be able to present risk levels in a quantitative manner a risk priority number, *R*, is commonly calculated. To calculate a risk priority number the consequence and probability scales are assigned numbers. A risk priority number, *R*, can be calculated as,

$$R = P^{a} \cdot C^{b} \qquad [1]$$

where *P* is the probability and *C* is the consequence. It is also possible to assign different weights to the probability (a) and consequence (b), if they are considered to contribute differently to the overall risk level. Consequently, by adding a weight to the scales, people's perception of risks may be taken into consideration. For example an unlikely accident with expected catastrophic consequences, e.g. airplane crash, is often experienced as more severe compared to a more frequent accident with expected less severe consequence, e.g. car crash; even if, from a strictly statistical view, this is not correct. Several factors influence the risk perception and this means that, within some categorizes, higher risks can be tolerated compared to others, even if the risk itself is equally large. Relative differences in risk priority number can be used to evaluate which risk reduction measures have the biggest effect. Further it is also possible, by using non-linear scales, to exaggerate the more severe risks, mainly to benefit risk reduction of higher risks compared to lower.

In this case study the consequence scale is interpreted as more important than the probability. The reason behind this is that some consequences normally never acceptable; so the consequence should be premiered to decrease instead of the probability.

4.3 Customer Minutes Lost (CML)

Customer minutes lost is used to express the expected time that the average consumer is affected by a failure, often expressed in minutes per year. This can either be connected to water quality or quantity problems. When considering quality, CML is expressed as the expected time that consumer is exposed to drinking water of inadequate quality. When considering quantity, CML is expressed as the expected time the consumer is not supplied with water (Lindhe, 2010). Consequently, CML can be used as a performance indicator to indicate how robust a system is and as a quantitative measure to evaluate the relative severity of risks against each other. The expected value of CML can be calculated as,

$$R\ (\mathrm{CML}) = P_F \cdot C_A \qquad [2]$$

where C_A is the proportion of consumers affected and P_F is the probability of failure, defined as the probability of a quantity failure multiplied with the corresponding consequence.

4.4 As Low As Reasonably Practicable (ALARP)

A common way to conclude whether a risk is acceptable or not is by applying a principle named As Low As Reasonably Practicable (ALARP). It is used to evaluate the severity of risks, i.e. if the risk level is acceptable or not. A risk can be judged unacceptable, see red field in Figure 4.3, which means that all necessary measures must be taken to reduce or eliminate the risk. Applied together with a risk matrix the unacceptable risks will be displayed in the red field in the upper right corner. Risks can also be acceptable, meaning that no further action needs to be taken and these are displayed in green in the lower left corner of the matrix. Risks that fall between these areas are within the ALARP region. These risks may be acceptable if it is economically and/or technically unreasonable to reduce them, i.e. risk levels should be reduced to the lowest level reasonably possible.

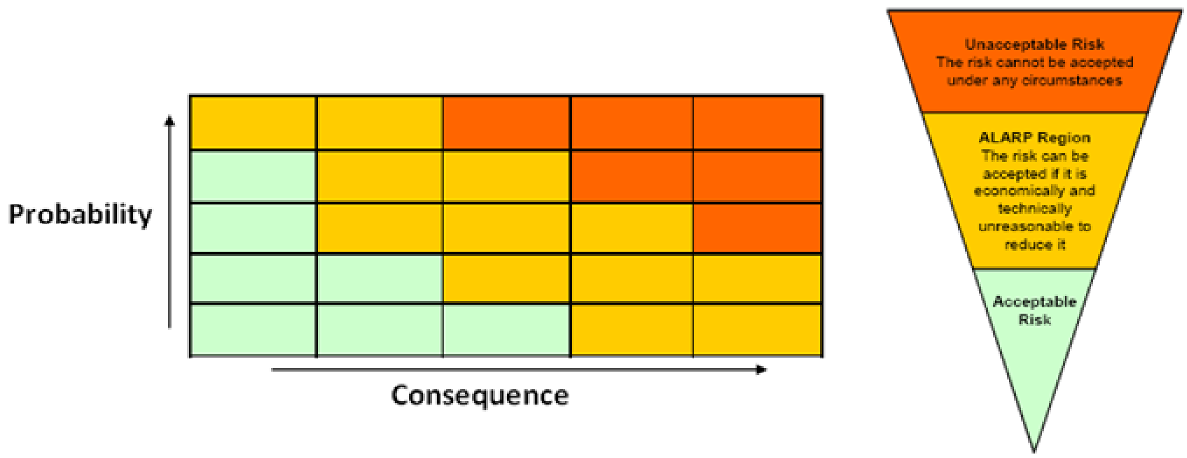

Figure 4.3 ALARP levels implemented in a risk matrix (Modified from Melchers, 2001).

The boundaries of the different ALARP levels are often decided through discussion with experts, decision makers and other stakeholders. ALARP levels need to be decided, or at least discussed independently for each new risk assessment project, since risks acceptable in one context may be unacceptable in another.

4.5 Risk Reduction

Risks that were identified as unacceptable have to be lowered. Developing and applying risk-reduction measures aims to reduce the risk to an acceptable level. Different measures may reduce the risk to an acceptable level in different ways. Commonly the measures should be cost effective, meaning that the measure reduces the risk to an acceptable level for the least amount of money. Other criteria that measures are desired to fulfill may be acceptance among the consumers or to have a persuasive affect or fulfilling environmental criteria.

Common ways to define risk-reduction criteria are for example expert judgment or structured/non-structured brainstorming. Another option is a checklist of risk reduction measures on common problems in water treatment systems developed by TECHNEAU (2010b).

4.6 Multi Criteria Decision Analysis (MCDA)

MCDA is a structured and transparent method used to evaluate how well different alternatives, e.g. risk reduction measure meet different criteria. If the problem is to decide which car to buy, different criteria can be e.g. engine power, possible passengers, price, size etc. These criteria are then used to evaluate which car that best suits the predetermined demands. It is also possible to assign weights to the different criteria if they are judged to have different impact on the final decision.

There are several MCDA methods available when evaluating risk reduction measures, but they all have the same aim: to facilitate the decision making process when several alternatives to reduce the risks are available. In the literature there exist other similar terms like: multi criteria analysis (MCA) and multi-attribute decision analysis (MADA). These are however methods used for the same purpose as the MCDA (Lindhe, 2010). In this report the term MCDA is used to describe a method that evaluate and prioritize different risk reduction alternatives according to how well they perform to a set of criteria.

From previous studies on MCDA methods related to drinking water supply (Hajkowicz and Collins, 2007) it was concluded that there was a lack in handling risk and uncertainty in MCDA models. Lindhe *et al.* (2010) remarked this and developed a new MCDA method that considers uncertainties in a formalized manner. The MCDA model uses risk ranking (risk matrix) as a basis with risk priority numbers to calculate the risk reduction of a measure. Uncertainties in the estimation of risk reduction are considered with either discrete or beta distributions. The discrete method assigns uncertainties to the input data, i.e. to the initially estimated probability and consequence, resulting in that also the uncertainty concerning the risk reduction can be calculated, while the beta method only assigns uncertainties to estimated risk reduction.

The case study in this report has used the MCDA method developed within TECHNEAU at Chalmers University of Technology (Lindhe *et al.*, 2010) to rank suggested risk reducing measures. Beta distributions are used to model uncertainties. The MCDA is evaluating risk reduction measures from their cost of implementation and risk reduction potential. Further is also the probability that a measure is *not* achieving an acceptable risk level calculated. The results from the MCDA are displayed in a performance matrix, which includes the cost, calculated benefit (risk reduction), the overall performance score and the initial and final risk level. It is by including the initial and final risk levels possible to evaluate the final risk level with the ALARP approach (Chapter 4.4), and consequently decide if the final risk level is low enough.

5 The Necessity of Water

Water is one of our main components for a societal growth and development. Historically fresh water, and an early water management, has been one of the most important reasons for civilizations to be able to prosper – but lack of water and overexploitation of fresh water resources is also believed to have been the main reason for some of the major civilization downfalls. The relation between accessible water and development is just as valid today (UN, 2010a).

5.1 Water Scarcity

Water scarcity evolves when the demand is higher than the supply. According to FAO (2007) water scarcity is defined as the point at which the aggregate impact of all users affect on the supply, or quality of water, under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully. Water scarcity does not only evolve where fresh water is limited, but also as a consequence of poor water management. Shortage of water causes not only quantity problems, but often also a degradation of the quality.

Water is essential for basic welfare and is necessary to sustain and maintain healthy ecosystems. Furthermore it is a crucial ingredient for all socio-economic development. Good sanitation and provision of water works as an engine for economic growth. A lack of water to meet the daily demands, i.e. water scarcity, is today a fact for one out of three people over the world (UN, 2010a) and one fifth of the world's population has physical scarcity (FAO, 2007).

For the majority of countries with water scarcity, agriculture is the predominant consumer of water. Historically, irrigated agriculture has played a major role for developing economies in rural areas. At the same time these poorer communities have also often suffered from inadequate water supply resulting in health issues. Due to inadequate health status they have not been able to develop further, but instead been stuck in poverty and disease. In many semi-arid regions, rural poor are seeing access to water for food production, livestock and domestic purposes as more critical than access to primary health care and education. According to FAO (2007) it is crucial that areas that suffer from water scarcity protect and focus on efficient use of all water resources, as well as enhancing the water productivity of all sectors to sustain their basic needs.

Groundwater has played a major role in arid regions for irrigation and domestic demands. Because of a lack of adequate planning, legal frameworks and governance a new debate has arisen regarding the sustainability of the use of extensive groundwater mining. Since the extraction of groundwater has grown, about half of the wetlands have disappeared during the 20^{th} century and this has lead to losses of eco services, bio-diversity and productivity of eco systems (FAO, 2007).

According to the Millennium Development Goal, MDG, #7, the proportion of the population without sustainable access to safe drinking water and basic sanitation will be halved 2015 (UN, 2010a). According to the latest report there is a progress in the supply of drinking water but also rising threats in terms of urbanization, population growth and increase in demand from households and industries. UN (2010a) further stresses the importance of a safe water supply that remains a challenge due to expanded activities within agriculture and manufacturing. This expansion has led to more pollutants being in circulation, and more aquifers being polluted. FAO (2007) points out that water quality degradation can be a major cause of water scarcity. To cope with these challenges, tools need to be developed and applied.

5.2 Water Condition in South Africa

As indicated by FAO (2007), South Africa is having acute water stress in several regions and freshwater is indicated as their most limiting resource. Almost all available freshwater resources are fully utilized and under stress. Further most of the rivers have been dammed and 50% of South Africa’s former wetlands have been converted for other purposes. There are several reasons behind this. South Africa is a semi-arid country, which means that the potential evaporation is larger than the potential precipitation. Only about 8.6% of the precipitation is available as surface water, which is one of the world’s lowest conversion ratios. This situation, as in many other arid countries, is expected to get worse with an increasing population and increasing water quantity demand (Department of Environmental Affairs, SA, 2009).

Pollution of surface and groundwater, as well as eutrophication is indicated as a major concern. Furthermore, South Africa is may suffer severe consequences due to climate change, especially the Western Cape. Regardless of any exact temperature increase, due to the greenhouse effect, Western Cape can expect to have shorter periods of rain and increasing evaporation (Department of Environmental Affairs, SA, 2009).

Water is indicated as a crucial element to battle poverty and will become a major restriction to the future socio-economic development. South Africa is aware of the situation and there are several ongoing projects to increase water quantities. In 2006 the MDG goal concerning halving the proportion of the population without sustainable access to safe drinking water was fulfilled. However the goal of providing basic sanitation is going slower (UN, 2010b).

A rapid and uncontrolled growth of informal urban settlements puts high stress on South Africa’s, water supply system. It is not only problematic for the authorities to supply the housing with infrastructure for drinking water and to handle sewage. It also constitutes an increasing risk on raw water sources since the housings often are located near surface waters. Numbers presented by UNESCO (2006) mention about approximately 5 million people living in informal settlements in South Africa, a figure that certainly has increased since. The future trends, that was expected to influence the drinking water supply in the southern part of Africa, were presented during a workshop in Namibia in 2006 (Swartz, C.D & Offringa, G., 2006). During the workshop it was predicted a fast and increasing population growth from today’s 48 million, which probably will lead to an increase in the number of informal housings and increased problems related to drinking water. A growing middle-class also increases the requirements on the quality of the water and demand (Swartz, C.D & Offringa, G., 2006).

In Beaufort West the demand for low cost housing has grown constantly over the last few years and 1500 new houses were built 2004 - 2009 but still 3000 people are listed for houses. Moving people from informal settlements into new houses means that in general there are fewer people per tap and this has consequences on the quantity of water in terms of higher demand (BWM, 2010a).

The poverty in the country is widespread. Over 34% of the population live on less than 2$ per day, and 70% of them live in rural areas where the main raw water source is groundwater. The groundwater sources represent, due to geological conditions, less than 10% of the available water in the country and over 70% of the rural housings depend on it as its raw water source.

With very modest amounts of precipitation and recharge of groundwater aquifers, it is a riskful strategy to have so many people relying on groundwater as their main raw water source. In future, major investments in infrastructure projects will be needed to be able to comply with quality and quantity standards. (UNESCO, 2006)

5.3 Management and Sustainability

Water is a renewable resource and low quality water, such as wastewater, should whenever possible, be considered as an alternative source for less restrictive use. The United Nations Economic and Social Council provided a management policy in 1958: "*No higher quality water, unless there is a surplus of it, should be used for a purpose that can tolerate a lower grade"* (UN, 1958).

In the report by UNEP (1997) *Water Pollution Control – A Guide to the use of Water Quality Management Principles* it is pointed out that the single most adequate approach for solving the global problem of water shortage is to apply appropriate techniques for developing alternative sources of water, together with improvements in the efficiency of water use and with adequate control to reduce water consumption. Appropriate techniques can also be used to reduce impacts and to relieve the pressure on already stressed natural water sources.

Membrane treatment and reverse osmosis, is used in large scale in the world today. Already millions of people are relying on desalination for their daily demand of water and the trend is that desalination systems will become increasingly common throughout the world (Tampa Bay Water, 2010; Water-technology, 2011). In 2004 it was estimated that seawater desalination capacity would increase by 101% by 2015. The latest reports are that this prognosis will be vastly exceeded (WWF, 2007). Desalination and Water Reclamation Plant (WRP) share many difficulties and treatment processes. They may provide solutions to water scarcity for similar situations and in South Africa they are more frequently presented as competing techniques. Treating wastewater into drinking water with a WRP costs about half compared to using desalination[2]. Mainly due to lower pressure required in the reverse osmosis process.

Membrane techniques are energy intensive and connected to serious greenhouse gas emissions, but able to treat almost all types of water. They may divert focus from more sustainable options and might be seen as an ultimate solution to water scarcity. WWF's (1997) view is that these techniques should only be used when there is a genuine need to increase water supply and are the best and least damaging method of augmenting water supply. Assess impacts and managing water demand of large scale engineering solutions is needed in an early stage to avoid irreversible damage to nature. The preceding process before deciding upon which solution that will be used should be transparent and exhaustive in which all alternatives are properly considered and fairly judged in their environmental, economic and social impacts. Better solutions in terms of costs and environment would be water conservation, water use efficiency improvements and water recycling. Water recycling in this context means using low quality water for suited purposes, like irrigation, flushing toilets etc. (WWF, 1997).

Extensive treatment techniques are also expensive to construct, where the membranes often corresponds to a significant part of the costs[3]. Due to the high costs these techniques are often

[2] Cobus Oliver, Veolia Water South Africa, Engineering Manager, 2011-05-23 (PP presentation)
[3] Contractor, Professional Engineer Pierre Marais (WWE), 2011-04-15 (Personal communication)

found in areas that already are developed. When these techniques are used in less developed countries in the world it may be problematic to allow poorer people access to the treated water if the construction and operating costs will be covered by tariffs. All membrane treatment techniques need to handle brine and backwash water. Backwash water often contain chemicals that may be harmful for the environment if released untreated and the rejected water or brine contains a high pathogen load and/or salt content due to changes in concentrations.

South Africa's economy is structured around large and energy intensive mining and primarily minerals beneficiation industries. Only ten other countries have higher commercial primary energy intensities, and South Africa is the 13th highest emitter of greenhouse gases (UNFCC, 2011). The primary energy source in South Africa is coal, followed by oil. The renewable energy sources, in this case only hydropower amounts to 0.1% of the total energy production, (Figure 5.1) (IEA, 2008). This means that the energy to supply treatment facilities of water would consist almost exclusively of energy produced from fossil fuels.

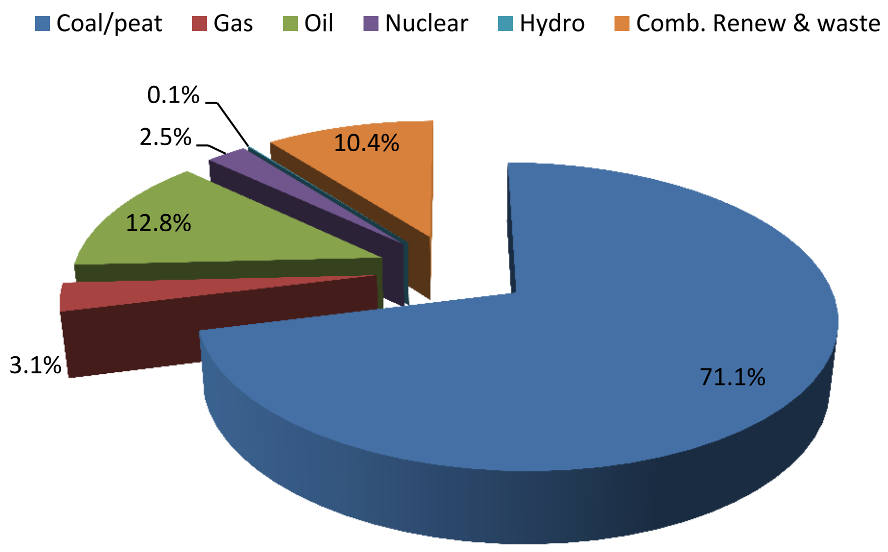

Figure 5.1 Share of total energy supply in 2008 (IEA, 2008)

6 Governing Structure and Management Control for Water Distribution in South Africa

This chapter will explain the administrate system responsible for South Africa's water resources and drinking water production. The most important bodies, organizations, departments etc. that are involved will be presented and the cooperation between these will be clarified. One of the most substantial tools for water efficiency and safety is water safety plans (WSP), and will be further described.

6.1 Department of Water Affairs

The Department of Water Affairs, DWA, earlier a part of Department of Water and Forestry, DWAF, is the central unit responsible for South Africa's water affairs. The department has since the end of the 20th century acted as the custodian for the country's water resources and been responsible for development of the water resource infrastructure (DWAF, 1994; DBSA, 2006). The main task for the DWA is to formulate and implement policy documents concerning South Africa's water resources and monitor that all South Africans have access to clean and safe water and sanitation service (DWA, 2011). A definition of the term "safe drinking water" is presented in the report *Drinking Water Quality Management Guide for Water Services Authorities* (DWA, 2005); the report states that safe drinking water is water that: "…does not pose a significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages…"

In 1994, the DWAF composed a policy document called: *Water Supply and Sanitation policy*, or the "*White Paper*". The document was intended to, in a provocative way challenge South Africans involved with water questions at all levels, to participate and contribute towards a sustainable water and sanitation policy (DWAF, 1994). Later on came the *Water and Service act of 1997* (act no 108, 1997), which declared the rights for every citizen to have access to basic water supply and sanitation service (DWAF, 1997). The act defines the responsibility distribution between water service authorities/administrations and water service providers (DBSA, 2006) and also places a duty on South Africa's Water Safety Authorities (WSA) to provide and maintain the current water safety plan (WSP) for their area of jurisdiction (BWM, 2010a). In South African acts and documents WSP's are often called Water Safety Development Plans (WSDP), which basically is the same methodology as WHO's water safety plan (WSP), see chapter 6.3. In this report the term WSP will be used.

In 2004/2005 DWA presented a regulation program, intended to increase drinking water quality and facilitate a sustainable drinking water management, called *The drinking water quality regulation program*. The reason behind the program was that in 2004, less than 50% of the WSAs could monitor their drinking water quality according to legislated requirements, i.e. there existed a widespread lack of knowledge of how to monitor drinking water quality in a proper way. In the beginning of 2008, three years after the program was implemented, the monitoring compliance had increased to 100%. However, this does not mean that 100% of the drinking water quality met the national standard; it only means that all municipalities could monitor their quality according to legislated requirements. As the actual drinking water quality still was insufficient, the Blue Drop Certification was presented in the summer of 2009. The Blue Drop certificate takes into account and grades 9 parameters, e.g. the water safety plan, compliance with SANS 241 standards presented in the report *Drinking Water Quality Management Guide for Water Services Authorities* (2005), process control and maintenance ability etc., to indicate how well municipalities manage their drinking water supply. To be assigned the Blue Drop certificate is seen as a big acknowledgement in South

Africa and shows that the drinking water system maintains a high international standard (DWA, 2010). There exists a similar certification for wastewater management, called the Green Drop Certificate.

6.2 Water Safety Authorities/administrations and Water Boards

A water safety authority, WSA, is e.g. a district municipality or authorized local municipality that provides water to the inhabitants within its area of jurisdiction (DWAF, 2003). The DWAF (2003, 2005) state that, the primary legal responsibility for providing safe drinking water to the consumers rests with the WSA. Also the Service act of 1997 state that: "*Every WSA has a duty to all consumers or potential consumers in its area of jurisdiction to progressively ensure efficient, affordable, economical and sustainable access to water services*" and further explains that a WSA also can function as the water service provider and that "*No person may operate as a water services provider without the approval of the water services authority having jurisdiction in the area in question*" (DWAF, 1997). The main tasks for the WSA's are to:

- Supply the inhabitants in its area of jurisdiction with basic water service.
- Monitor and evaluate the quality of the drinking water against national standards.
- In case of an emerging health risk, communicate it to the consumers and appropriate authorities.

Local WSA's can either supply their inhabitants themselves with basic water service, or they can involve external water service providers, e.g. non-governmental organizations, private companies, or so called water boards. Water boards are state owned organization/entities that operate and handle dams, wastewater systems, water supply infrastructure etc. Their task is to work as water utilities and, in cooperation with WSAs, provide people with basic water service. Today's water boards were originally private owned companies or organizations that saw the emerging need for water supply as a business opportunity. This form of ownership, and the lack of control, resulted in high tariffs and misuse, which forced the authorities to legislate the area of water production and supply. The first act was written in 1956 and was later followed by the Water Service Act of 1997, which brought all different water boards under its sphere and gave the Department of Water Affairs the option to establish and resolve water boards. It also defines water boards as public entities, with control and shareholding by the national government. (DBSA, 2006)

6.3 Water Safety Plan

In 2004 the World Health Organization, WHO, presented the WSP framework as an initiative to facilitate the process of risk assessment and risk management connected to water (WHO, 2004). The framework was required, since there was a need for an increase in both awareness and understanding of risk issues concerning drinking water (Rosén *et al*., 2007).

The main purpose of the WSP is to provide guidance to be able to produce sustainable and safe drinking water (WHO, 2005). A comprehensive WSP should include the whole supply chain, i.e. a source to tap approach. The use of a multi-barrier approach implies that actions are taken at all levels in the chain to assure that safe drinking water is delivered to the consumer. According to WHO (2005) the main objectives of WSP's are to ensure:

- Raw water sources do not get contaminated or that the raw water supply is interrupted in any other way.

- The treatment process is sufficient and delivers water that meets existing quality standards.
- The water should not get re-contaminated in the distribution system or during handling, before it is consumed.

The *Water and safety act of 1997* (DWAF, 1997) states that the responsibility to provide a WSP lies with the WSA, and further, that all South Africans have the right of access to basic water supply and basic sanitation provided for in the WSP. In a report by Thompson and Majam (2009) guidance, directed to WSA's, on how to develop a WSP, was presented. Furthermore the concept with WSP is also adopted in the Blue Drop certificate. Consequently, the framework is adopted and implemented in many municipalities and responsible authorities in South Africa and will likely see an increasing use in the future.

7 General Description over Beaufort West Municipality

Beaufort West Municipality (Figure 7.1) is situated in central Karoo, one of the driest areas in South Africa, and functions as the economic, political and administrative centre of the central Karoo. There are 41 000 estimated inhabitants in Beaufort West municipality and the municipality consists of three towns; Beaufort West, Merweville and Nelspoort, where Beaufort West is the administrative centre. The municipality functions as both drinking water authority and drinking water provider and the three society's drinking water supply systems are independent of each other and supported by raw water from different sources (DWA, 2010).

Figure 7.1 Map over South Africa (Welt-Atlas, 2011).

The highway N1 passes through Beaufort West and is one of the major driving sources for economic growth, while agriculture and agri-processing forms the backbone of Beaufort west economy. Agriculture accounts for the largest labour force of the population (BWM, 2010a). Next to Beaufort West lies one of South Africa's largest national parks, Karoo, which attracts thousands of tourists each year.

7.1 Water Supply System in Beaufort West (without WRP)

Beaufort West relies on surface water from the Gamka Dam and groundwater from several boreholes spread widely around the town. The water from the dam is treated at a local WTP with the treatment steps: flocculation, stabilization, filtration and chlorination. The treated water from the dam is then mixed with the borehole groundwater and via three reservoirs distributed to the consumers (Figure 7.2).

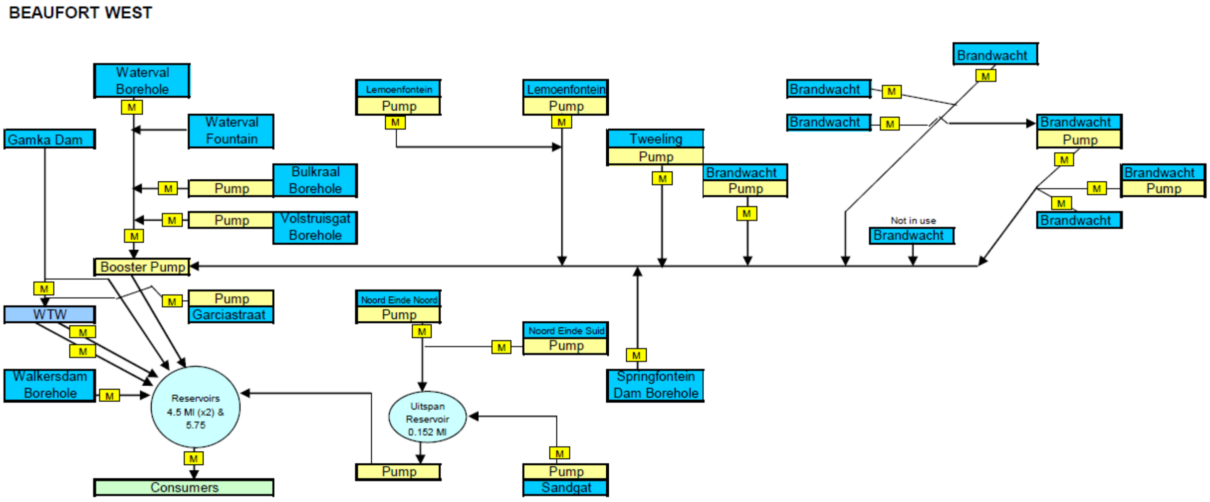

Figure 7.2 Schematic layout over Beaufort West's drinking water supply system before construction of WRP (BWM, 2010a).

Beaufort West also has a sewage system connected to the local WWTP, for all formal households, while storm water is not directed to the WWTP. No larger industries are situated in the area meaning that it mainly is wastewater from households that is being treated in the WWTP. For more information on the WWTP, see chapter 9.1. (BWM. 2010a).

7.2 Tariffs

The tariff for households in Beaufort West is defined by using a rising block tariff structure (Table 7.1). The first block, Free Basic Water, corresponds to a monthly water quantity of 6000 l per household or 25 l/person per day, also defined in the basic water service. This amount of water is provided free for consumers who qualify for indigent relief. As comparison, the mean consumption of water in households in Sweden is 160 l/person per day (Svenskt Vatten, 2011). The intention of the rising tariff structure is to discourage wasteful or inefficient use of water, and punitive tariffs have been introduced for excessive water consumption. The tariffs are also influenced by different drought phases meaning that it costs more to consume water during a severe drought compared to during normal conditions. Basic water service is however excluded from this cost-increase since basic water service should be available for people in spite of their income (BWM, 2010a).

Table 7.1 Block tariff structure in Beaufort West Municipality (BWM, 2010a).

<table>
<tr><th>Block (kl/month)</th><th>Normal condition</th><th>Drought Phase 1</th><th>Drought Phase 2</th><th>Drought Phase 3</th><th>Comment</th></tr>
<tr><td>0-6</td><td>R3-64</td><td>R3-64</td><td>R3-64</td><td>R3-64</td><td>Free Basic Water</td></tr>
<tr><td>7-10</td><td rowspan="3">R4-17</td><td rowspan="2">R4-17</td><td>R4-17</td><td>R4-17</td><td rowspan="2">Low volume use.</td></tr>
<tr><td>11-15</td><td>R5-46</td><td>R8-34</td></tr>
<tr><td>16-20</td><td rowspan="2">R5-46</td><td>R6-73</td><td>R10-43</td><td rowspan="3">Typical use volume, including garden irrigation.</td></tr>
<tr><td>21-25</td><td rowspan="3">R4-58</td><td rowspan="2">R8-92</td><td rowspan="2">R12-51</td></tr>
<tr><td>26-30</td><td rowspan="2">R6-73</td></tr>
<tr><td>31-50</td><td rowspan="4">R12-74</td><td rowspan="4">R14-60</td><td rowspan="2">Above average use, including garden irrigation.</td></tr>
<tr><td>51-60</td><td rowspan="3">R4-96</td><td rowspan="3">R8-92</td></tr>
<tr><td>61-100</td><td>Wasteful use and/or severe garden irrigation.</td></tr>
<tr><td>>100</td><td>Significant waste and/or unnecessary garden irrigation.</td></tr>
</table>

The step block tariff structure has not been implemented for industrial and commercial consumers, and there is no system to charge industries for effluent that needs to be extraordinary treated. However, since there are no major industries in Beaufort West it is not a big issue.

At present, 1 m^3 of drinking water costs approximately 0.9 South African Rand to purify with the conventional system (BWM, 2011a). Treating water with a reclamation system, explained further in chapter 9.2, costs approximately double that amount[4] and treating seawater with desalination plants costs almost four times as much[5].

7.3 Beaufort West Municipality's Water Safety Plan 2010/2011

BWM constructed their first WSP in 2010/2011 (BWM, 2010a). The result from the report shows that the water services provided for the inhabitants in the municipality generally meet national standards according to standard SANS 241 presented in the report *Drinking Water Quality Management Guide for Water Services Authorities* (2005). For more detailed information regarding the municipality's water quality, see the report - *Annual publication of drinking water quality performance against SANS 241*, published at http://www.beaufortwestmun.co.za/ (BWM, 2010b).

[4] Christopher Wright, Beuafort West Mun. Manager: Technical Services 2011-04-21 (Personal communication)
[5] Cobus Oliver, Veolia Water South Africa, Engineering Manager, 2011-05-23 (PP presentation)

7.3.1 Essential Shortcomings

The municipality is today providing help to farms that do not have basic sanitation service to install so called ventilated improved pits (VIP). There are economical resource limitations that do not make it possible to provide waterborne sanitation systems for the moment. The future goal is to investigate and determine the quantity and quality standard of available drinking water and to be able to provide all farms in the municipality with drinking water that meets national standards. (BWM, 2010a)

There are problems with informal settlements and backyard dwellers in the municipality and there exists a backlog i.e. a shortage, to support these inhabitants with in-house water connections and sanitation service. The goal is that all houses in informal areas shall be provided with basic water services that meet national standards. Today many households are using shared services, i.e. shared water taps and toilets between households/families. According to BWM (2010a) it is not a permanent solution and the maintenance cost of these shared services is not financially sustainable.

As an addition to these problems there is also a large backlog of houses, approximately 3000, despite that 1500 new houses were built between 2004 and 2009. Hence, large future investments are required to supply new and old households with sufficient drinking water and sanitary service. (BWM, 2010a)

7.4 Blue/Green Drop Certificate

Beaufort West was issued with the Blue Drop certificate in 2010 (DWA, 2010). The town's water supply system scored 95% compliance towards the nine evaluated performance areas. However, that is also the minimum limit to be awarded the certificate so there exist possibilities for improvements. The 2010 Blue Drop report (DWA, 2010) further states that "…*Beaufort West Local Municipality displayed impressive improvement since the 2009 assessment*…".

The municipality has applied for Green Drop certification and this is still under investigation. The municipality expects an answer about their score during the end of 2011. Fulfilling Green Drop requirements is an important aspect in future water production since it would certify that their treated wastewater, which is the raw water source of the Reclamation Plant, will have a good quality.

7.5 Water Shortage - Construction of a Reclamtion Plant

In 2010 a long drought was severely affecting the drinking water production of Beaufort West. The Gamka dam, which is the main raw water source for Beaufort West, was empty by the end of 2010, resulting in a lack of raw water for the drinking water production. Water from boreholes was not enough and drinking water had to be transported to the town by trucks to fulfill the immediate need. The drought was the worst drought during the last century, and made the municipality aware of the extent of the problem.

To encounter this severe situation several options were investigated and implemented, e.g. managing water losses, optimize existing aquifers and exploring new groundwater sources. However, none of these options were sufficient, resulting that the construction of a Wastewater Reclamation Plant (WRP) was decided on as the only suitable solution. The WRP will increase the drinking water production and make it possible to supply the present and growing population with drinking water that fulfills quantity and quality standards. The WRP will produce water all year around, and thereby relieving pressure on the Gamka dam and boreholes, so that there is storage of water if a similar drought occurs.

Beaufort West's reclamation system is the first direct WRP producing drinking water in South Africa. The plant was initially intended to be constructed as a public-private partnership (PPP), i.e. financed and operated by an external contractor. However, the municipality of Beaufort West was assigned a governmental grant from the drought relief fund, resulting therein that the municipality could finance the plant. A tender document specified requirements for the project and the plant was built according to the design and build approach[6]. The contractor designed the plant in Beaufort West, after a multi-barrier concept successfully used at the New Goreangab reclamation plan. The following barriers are used in Beaufort West: Ferric-chloride dosing at inlet to the secondary settling of the WWTP, Pre-chlorination, Sedimentation basin, Post-chlorination, Rapid sand filtration, Ultra filtration, Reverse Osmosis, UV-Hydrogen peroxide, Final chlorination. The contractor is also responsible for operating the plant for 20 years. For more information about Beaufort West's Reclamation Plant, see chapter 9.2.

Reclamation systems tend to be complex and connected to higher risks since the raw water contains more pathogens, which requires more technically advanced barriers, compared to conventional water treatment plant. Consequently, a comprehensive risk assessment is required to identify hazards and estimate risk levels. It is also crucial to have a dialog and acceptance from the inhabitants since doubts towards drinking water produced from enhanced wastewater is inevitable. Furthermore this type of systems is expected to become more common in South Africa as well as other countries suffering from water scarcity. Therefore more knowledge in the field is crucial for successful continuing progress and development. The risk assessment for the Reclamation Plant was performed as a case study and is presented in chapter 10.

[6] Christopher Wright, Beuafort West Mun. Manager: Technical Services 2011-04-19 (Personal communication)

8 Reclamation System in Windhoek, Namibia

The Reclamation Plant in Windhoek, New Goreangab, has reclaimed wastewater and treated it to potable water for almost 60 years. It has for many years been the only direct Wastewater Reclamation Plant (WRP) in the world and a lot of experience has been gathered during operation. New barriers have been introduced and problems had to be solved as they occurred. Since it was the first of its kind the WRP has also worked as a research project to gather information and expertise in the field of reclaiming wastewater and treating it to drinking water. Due to the research approach, additional extensive funding has also been available, which is not the case for Beaufort West.

The WRP in Beaufort West is based on a multi-barrier concept that has successfully been used in Windhoek. The two WRP's share many solutions and difficulties. This is why a case study was performed in Windhoek, 2011. Both the WRP in Goreangab and Gammams Wastewater Treatment Plant (WWTP) were studied since they are equally important to achieve a good result. The following results came up during discussions with Jurgen Menge, analysis responsible for Gammams WWTP City of Windhoek, John Esterhuizen, General Manager for WINGOC Water Reclamation Plant and Truddy Theron-Beukes, consultant and former employee at City of Windhoek.

- In the long run, indirect risks have been harder to solve and a good contract between the WWTP and the WRP is crucial.
- The reclamation system in Windhoek would not have been constructed in the same way if designed today. RO would have been used instead. Partially since the membranes and the technique overall has become cheaper, but also since the salt content in the treated water from the WRP is too high, why reverse osmosis is evaluated. Brine may become a problem in arid parts, and the dilution factor is important to consider.
- Politicians need to be involved to a large degree to make adequate decisions and investments. WRP's does not consist of a one-time investment but needs to be maintained and future investment needs to be accounted for.
- The majority of the long-term disputes and indirect risks have occurred due to the fact that the WWTP and the WRP are operated by different owners. Optimally, the system is operated and owned by the same owner to be able to make correct and most cost-efficient investments and adjustments.
- J. Esterhuizen considers that reverse osmosis is the best solution since it requires less experience to operate and is safer.
- Monitoring becomes substantially more comprehensive for WRP's compared to using surface water or groundwater. More monitoring means higher costs and it also requires highly skilled personal.
- On high-tech plants maintenance and availability of spare parts cannot be compromised. Gammans wastewater treatment plant indicated this as a problem. When they have needed to order parts it has taken them much time due to slow bureaucracy and not always easy to get approval. This is not indicated as a problem for Goreangab since they are operated as a private company and do not have the same problem with slow bureaucracy.
- The water from the Reclamation Plant should have a higher, or at least as high, quality as the water from the conventional system.

- A specific flux for the UF and RO should be incorporated in the contract to avoid the operator of the WRP operating the membranes under too high pressure and thereby reducing the life span of the membranes.
- Public acceptance is crucial for a successful project. Therefore it becomes important to have a well-adapted information campaign and dialogue with the consumers. It has sometimes proven to be a challenge to decide how much information should be released to avoid external threats as sabotage, terrorist attacks etc. There is also a widespread resistance towards drinking enhanced wastewater among Muslim people, which needs to be considered.
- Human errors are very difficult to control. To avoid this as much as possible staff needs continuous training by regular programs and external audits. If this is not done the whole project may slowly deteriorate into failure. A good, and proven, way to minimize human errors is to get an ISO-certification, where external audits certifies that staff and operative responsibilities can operate the plant and handle deviations in a appropriate way.

9 Beaufort West Reclamation System Description

The reclamation system in Beaufort West uses wastewater as its only raw water source to produce drinking water. The system consists of an existing WWTP with conventional treatment and a new constructed membrane Wastewater Reclamation Plant (WRP). The system is a direct reclamation system, which means that it, compared to indirect reclamation system, cannot benefit from any dilution of the wastewater due to mixing with other water sources. Wastewater is a very complex raw water source, compared to groundwater or surface water, since it contains high amount of pathogens and the quality and quantity has a tendency to vary. There are also compounds which effect to humans in a longer perspective is unknown. The sewage system is separated, meaning that no storm water is supposed to enter the sewage system; further no industrial effluent is diverted to the WWTP. Still the flow to the WWTP is affected during heavy rain[7].

The WRP in Beaufort West uses fewer barriers compared to the WRP in Windhoek. The treatment process is therefore easier to operate since it mainly relies on two membrane filtration barriers, ultra filtration and reverse osmosis, which are highly atomized. WINGOC stated that if their plant had been built today, they would also have been using reverse osmosis due to that it is safer and easier to operate[8]. A system like Beaufort West’s that is highly automated and using reverse osmosis with connected alarms does not require as much skilled personal for the daily handling, as the system in Windhoek.

Due to advanced and expensive treatment barriers Beaufort West municipality could not carry the installation cost alone. The WRP was granted funding from the government, due to the extreme water shortage, and is today owned by the municipality. The same contractor that has constructed the plant is also responsible for the daily operation as well as the maintenance work on a 20 years contract period. Production rate will start at a minimum of 1 Ml per day, with an increase of 10% over a period of ten years. This means that after the first ten years of operation, when reaching design capacity, the plant needs to produce water for 20 hours per day. The contractor does have mandate to change operation or demand additional barriers in the WWTP if considered necessary with regard to the reclamation process. The WWTP is both owned and operated by the municipality.

9.1 Treatement Barriers – Wastewater Treatment Plant

The Wastewater Treatment Plant, WWTP, in Beaufort West is a rather uncomplicated system and relies on conventional treatment techniques. The plant has two parallel treatment trains that use different treatment techniques, but the WRP uses only one (Figure 9.1). The reason for that only one of the two treatment trains is used is because one is enough to support the WRP with raw water and that treatment train is also more efficient.

[7] Christopher Wright, Beuafort West Mun. Manager: Technical Services 2011-04-19 (Personal communication)
[8] John Esterhuizen, General Manager: WINGOC 2011-03-29 (Personal communication)

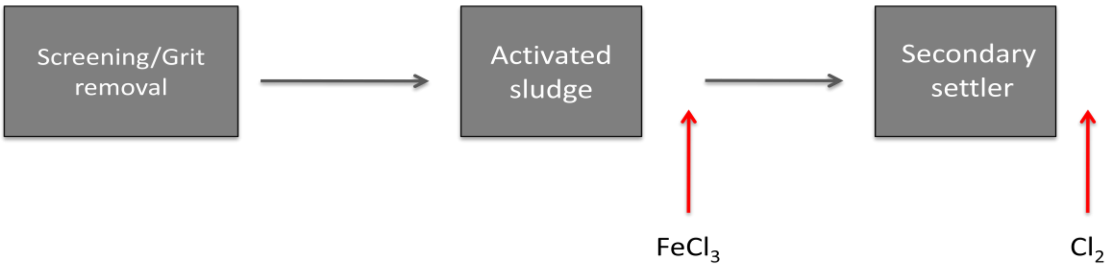

Figure 9.1 Conceptual model over Beaufort West WWTP.

Very few changes have been made to the WWTP after the introduction of the WRP. On initiative of the contractor for the WRP, ferric chloride is added after the activated sludge process to increase settling and to have a more efficient removal of phosphates. This has shown to be a big improvement for the reclamation system.

9.1.1 Screening and Grit Removal

The screening and grit removal is the first treatment step. A new screener was recently installed since the former model created a lot of problems. There is also a manual screener available. If the screener is not functioning properly it affects the sedimentation basin in form of bigger particles. The screener removes bigger pieces in the incoming water by size exclusion. The particles attach to the screener and are later burnt.

9.1.2 Activated Sludge

The activated sludge process is a biological treatment process, relying on microorganism's removing/converting pollutants. The growth and understanding of the microorganism is therefore in focus for these methods. Biological treatment can function either as an *aerobic*- or *anaerobic* processes and is proven effective in removing nitrogenous and organic matter (Gray, 2004).

The activated sludge process in Beaufort West is divided in different zones were aerobic and anaerobic conditions are predominant. Aerobic conditions are created by aerators, which in principle are rotating arms, diverting oxygen into the water. The activated sludge is constantly fed by organic matter in the feed water and converts it into biomass, CO_2, water and minerals (Gray, 2004).

The sludge age and Sludge Volume Index (SVI) is crucial parameters to monitor in the activated sludge process. Sludge age is the average time in days the suspended solids remain in the entire system and SVI is an indication of the sludge settle ability in the final clarifier. If the sludge age is too high commonly "pin flocs" are formed and particles settles faster in the second clarifier and the effluent tends to be very turbid. If the sludge age is too low a light and fluffy sludge is formed commonly called "straggler flocs" which can be observed in the secondary settler. These problems are long lasting, meaning that they often remain for a week or more depending on the system (Gray, 2004).

9.1.3 Secondary Settling

The secondary settlers are common Dortmund tanks with a retention time of approximately 4 hours. What comes over the weir of the secondary settlers will end up in the sedimentation basin, see chapter 9.2.2, and is more or less a result of the treatment efficiency of the activated sludge. Therefore the activated sludge is the core of the wastewater process. Problems with excessive sludge going to the sedimentation basin have occurred due to too high sludge age.

Sludge ending up in the sedimentation basin means more frequent backwashing of the sand filters and UF-membranes in the WRP as well as more frequent cleaning of the sedimentation basin.

9.2 Treatement Barriers – Wastewater Reclamation Plant

The reclamation system used in Beaufort West (Figure ***9.2***) can roughly be divided into three parts: pre-treatment, main treatment and post treatment or polishing. Pre-treatment, which is the pre-chlorination, sedimentation basin, intermediate-chlorination and rapid sand filtration, is mainly used to relive pressure of the membranes and prevent fouling. Thereby the life-length of the membranes is extended, which is highly prioritized since replacing membranes is connected with high costs. The main treatment is the membrane barriers where the majority of the pathogens and particles will be separated. The post treatment, UV/H_2O_2 and final chlorination, can be regarded as a safety barrier and used to kill of eventually existing pathogens. Final chlorination is used to prevent eventual microbiological re-growth in the pipes and as a protective measure towards re-introduced pathogens.

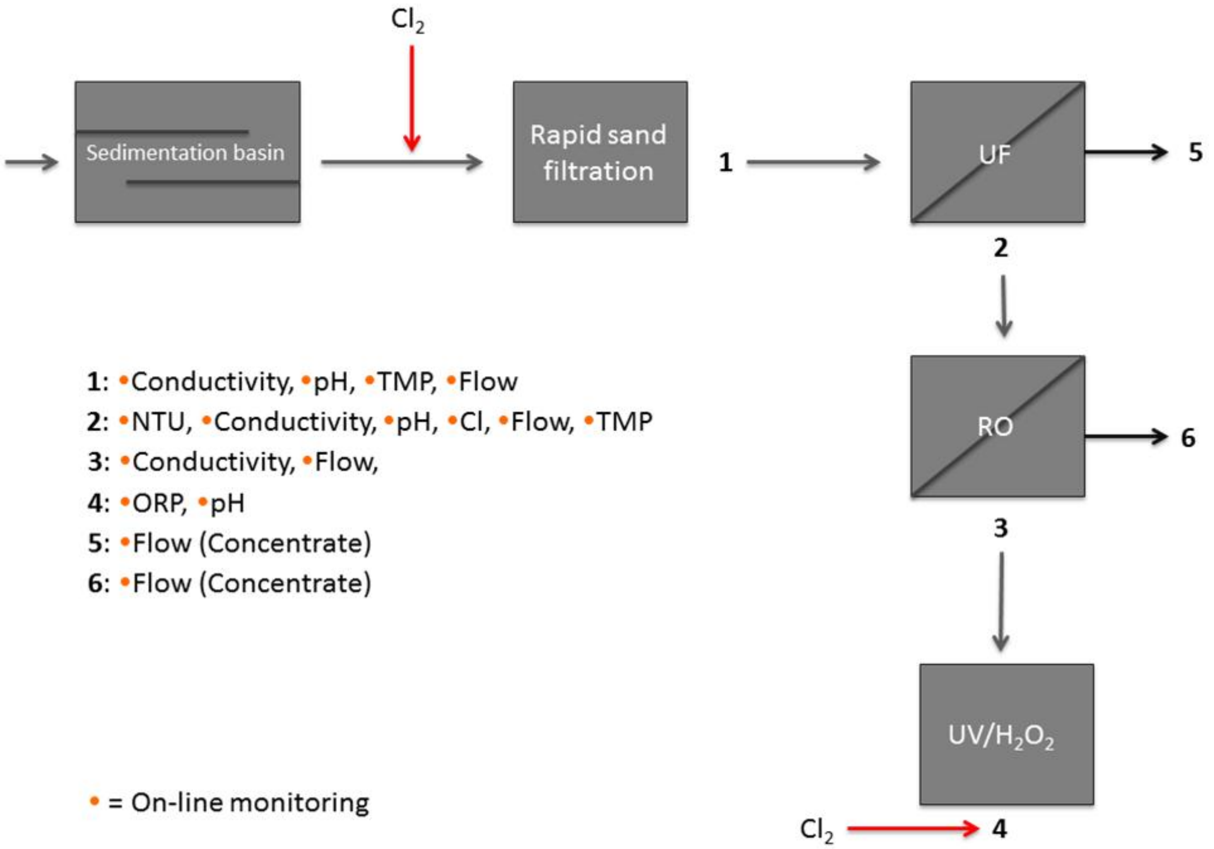

Figure 9.2 Conceptual model over Beaufort West WRP with on-line monitoring points.

9.2.1 Pre-, Intermediate- and Final-chlorination

The treated wastewater is pre-chlorinated between the secondary settler and the sedimentation basin. The pre-chlorination point has three major functions:

- Disinfection of the feed water.
- Hinder algae growth in the sedimentation basin.
- Facilitate oxidation of iron and manganese in the sedimentation basin, which will increase the settling potential.

After the sedimentation basin there is an additional chlorination point, intermediate-chlorination, which is used if additional disinfection is considered necessary. Final-chlorination is also used, after the UV/H_2O_2 treatment, to disinfect the treated water, hinder microbiological re-growth inside the pipes and as a safety measure towards pathogens entering the system after leaving the WRP.

Pre-chlorination has so far shown more benefits to the treatment process then intermediate-chlorination. During winter, when temperature goes down and algae growth is not as extensive as during summer, the pre-chlorination can quickly be changed into intermediate-chlorination.

9.2.2 Sedimentation Basin

When constructing the WRP a new sedimentation basin was also built. The total retention time for the water inside the sedimentation basin is approximately 18 hours and it has several important functions:

- Work as a buffering zone to handle variations in wastewater flow and composition.
- Dilute contaminant peaks.
- Increase the settling of particles due to the long retention time.

The long retention time may allow algae to grow inside the river. High amounts of nutrient in the feed water will increase this risk further, which will result in more frequent cleaning and backwashing becomes necessary. Cleaning is also necessary to remove settled particles and sludge (Figure 9.3). When cleaning of the sedimentation basin takes place the feed water may be by-passed to the rapid sand filters. Without the water passing the sedimentation basin the rapid sand filters will have to be backwashed more frequent.

Figure 9.3 Cleaning of sedimentation basin

9.2.3 Rapid Sand Filtration

The coagulation and flocculation process is often commonly followed by a filtration step. By forcing the water to pass through a granular media, e.g. sand or gravel, suspended solids and particular matter larger than the pore size of the media are removed. There are two major filtration techniques, rapid sand filtration and slow sand filtration.

The rapid sand filtration technique (Figure 9.4) is used in Beaufort West's WRP after the sedimentation basin. The water passing the rapid sand filter is not aimed at removing any bacteria or viruses, as in the slow sand filtration, why the processed water often requires additional treatment to use as drinking water. The flow rate is higher compared to slow sand filtration and since the rapid sand filter can be put into operation directly after backwash it has a good cleaning capacity in relation to the required installation area (WHO, 2011b).

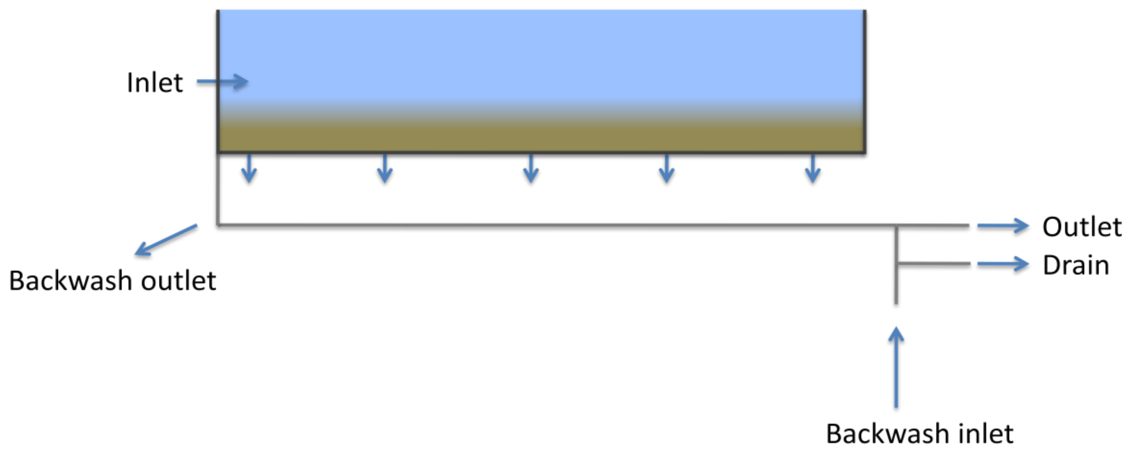

Figure 9.4 Conceptual model over typical rapid sand filtration

The rapid sand filters in Beaufort West WRP uses backwash pump blowers to backwash the filter media by the use of air and water, either separately or simultaneously. The blower technique will according to Swans water treatment both lower the capital and operational costs. Three separate pumps are installed to feed the two sand filters with water from the intake sump. Two of the pumps are working simultaneously and one is on standby during normal conditions. All backwashing are operated on-site by the operators and the backwash water from the rapid sand filters is diverted and discharged into the irrigation ponds.

9.2.4 Ultra-filtration

The third barrier in the treatment train consists of ultra-filtration (UF). It is an advanced process but relies on basic separation principles and is today a proven technique. The UF consists of membranes and treats the water by physicochemical separation techniques that use differences in permeability to separate contaminants from the water. The predominant removal mechanism is straining, or size exclusion. UF refers to the pore size used in the membranes that are about 0,01 microns in diameter which means that smaller particles then that will pass through the membranes. Typically UF removes smaller colloids, particles, sediment, algae, protozoa, bacteria and viruses. Today many membranes are also using chemical processes for removal of contaminants by adding different coatings. The removal efficiency of targeted impurities for membrane filtration is typically 99.9999% (6 $\log_{10}$ reduction) or greater. (Drinking Water Engineering, 2009)

UF is commonly operated as a dead-end flow pattern (Figure 9.5) meaning that the flow direction is perpendicular to the membrane surface. It is a more simple way of operating the membranes and requires less energy than cross flow operation. The disadvantage is that the cake, which consists of accumulated particles, grows with time and consequently the flux decreases and eventually the dead-end filtration process needs to be stopped to clean, or in extreme conditions replace, the membranes. The flux decline, due to accumulation of particles, is one of the main reasons why membrane process remains a challenge both economically and technically when introduced in a large scale (Swartz, C.D., 2009).

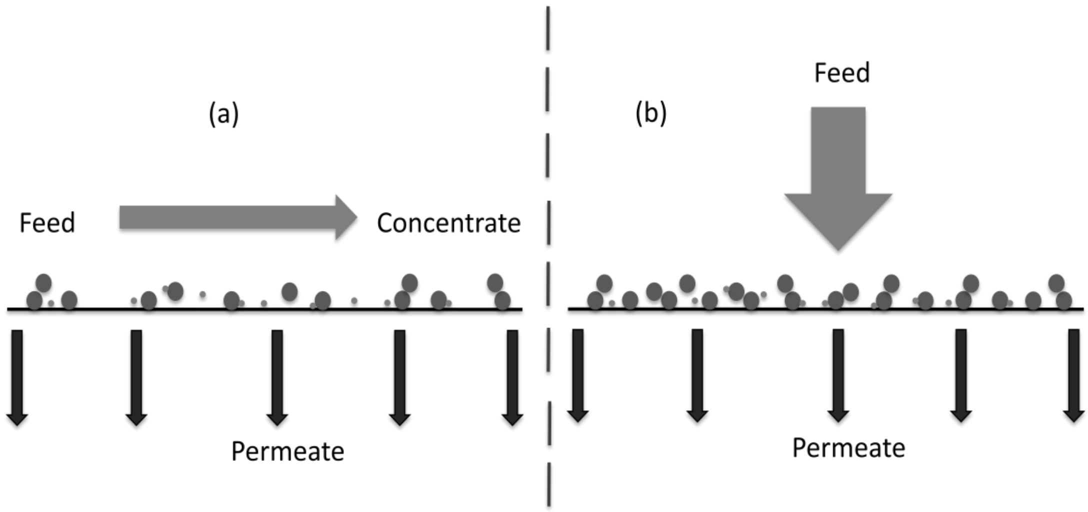

Figure 9.5 Cross flow Operation (a) and Dead-End Operation (b).

All membranes need to be washed when the flux decreases, see figure 9.6. This is typically done with a repeating pattern. Backwashing means that clean water and/or air is pushed through the membranes from the opposite side then normal operation. Even if backwashing is done properly a cake will still build up, which is not removed when backwashing, and the membranes will typically be operated under constant increasing pressure to produce the same quantities of water. Once reached a specific threshold chemical cleaning is needed. This can typically be made without disassembling anything and cleaning can be done in place, shortened CIP – Cleaning In Place (CIP).

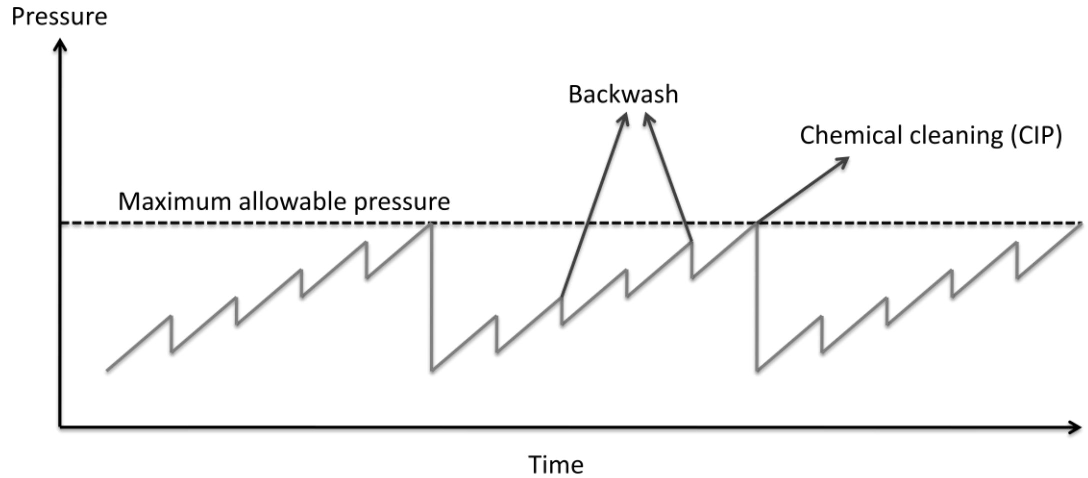

Figure 9.6 Wash cycles of membranes.

The backwash system used in Beaufort West is using blowers, which produces low-pressure aeration combined with a short reverse flow of filtrate to remove the retained solids from the membrane fiber bundle. The liquid backwash waste is then drained from the unit to a backwash waste disposal system. This is done every 20-60 minutes depending on the feed quality and can be set after a certain time period or when the pressure is increased to a certain threshold. There will also be an automatic maintenance wash after a preset time interval, or number of backwash cycles, that require chemicals and more time. This will typically be made once per week. The CIP is done every month and uses a sodium hypochlorite solution and acid for cleaning. All of the washing is automated in Beaufort West, but may also be initiated manually. The backwash water is further diverted to an irrigation pond, while all cleaning requiring chemicals are diverted to a sludge pond.

The membranes used at Beaufort West are low-pressure membranes with hollow fiber membrane filtration modules operated from the outside to the inside. Membranes can be designed to be operated in two different ways, either from the outside to the inside or from the inside to the outside (Figure 9.7). When operated from the outside to the inside it is generally easier to maintain the membranes since the area where cake is built up is spread over a larger area and easier to access, which makes cleaning easier.

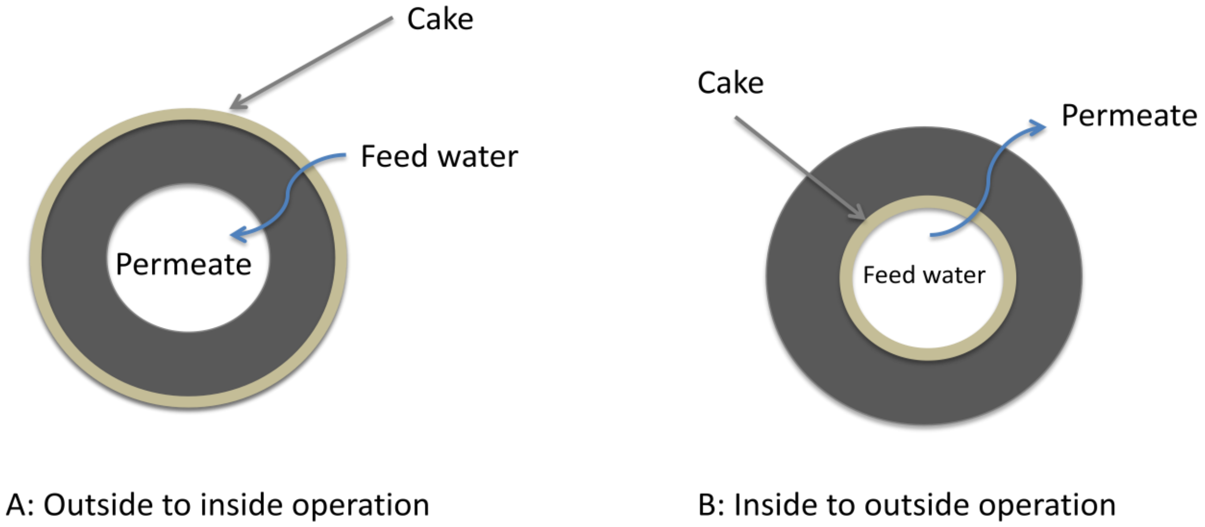

Figure 9.7 Membrane operation

When using membrane filtration there is always a loss of water that corresponds to the backwash water and the concentrate. Typically a recovery rate is specified and for the UF membranes used in Beaufort West there is a recovery rate of 96%.

UF is commonly used as a “police” for the RO membranes. This means that the UF will remove a lot of compounds and relieving pressure of the RO membranes since they are more sensitive. RO is fully capable of treating the wastewater as a single barrier, but resulting in more backwashing and reduced life length of the RO membranes.

9.2.5 Reverse Osmosis

Osmosis is a specific sort of diffusion. Diffusion occurs when molecules from a region with higher concentration moves to a region with lower concentration. Osmosis occurs when the molecules are specifically water and the concentration gradient occurs across a semi-permeable membrane. The semi-permeable membrane allows water to pass through the membrane but not ions or larger molecules. Osmosis is thermodynamically favorable and will continue until equilibrium is reached. The processes can however be stopped and reversed by increasing the pressure on the concentrated side of the membrane. The pressure must at least be higher than the osmotic pressure, which is around 27 atm for seawater, to reverse the osmosis. Due to the high pressure required, reverse osmosis is energy intensive. The water that is treated is called permeate and refused water is called concentrate or brine. Typical efficiency of targeted impurities is 50-99%, but RO is overall more efficient than UF if comparing removed compounds and particles. (Drinking water engineering, 2009)

Beaufort West uses RO membranes (Figure 9.8) that are operated in a cross-flow pattern (Figure 9.5). Cross-flow has a tendency of less frequent fouling and scaling then dead-end operation, but requires more monitoring and is overall more complex to operate then dead-end operation.

Figure 9.8 Membrane operation at Beaufort West. Ultra filtration to the left and reverse osmosis to the right and BAC filters in front.

The majority of the investment when using filtration/RO techniques is the membranes and it is therefore crucial to maximize the life length of them. To avoid putting too much pressure on the membranes, and thereby decreasing the life length, there are mainly three concerns.

- Fouling
- Scaling (mainly RO)
- Chemical attack (mainly RO)

Fouling means that the membrane becomes clogged by organic compounds and the flux decreases. Fouling occurs due to the load of particles, sediments and microbiological content. Fouling is inevitable and a fundamental part of the membrane process. When the flux has decreased to a certain level, backwashing or CIP becomes necessary, see chapter 9.2.4. The operator may choose to operate the membranes under higher pressure to compensate for fouling, instead of backwashing. This may pose a risk to the membranes since it may shorten the life length of the membranes.

Scaling means that insoluble minerals (in-organic compounds) accumulate on the membranes. Scaling mainly becomes a problem when using RO, since salts become concentrated in the concentrate. For example if an RO membrane has a recovery rate of 50%, the salt content will be doubled in the concentrate. This means that a higher recovery rate of the membrane imposes a higher risk of scaling. Adding chemicals to the feed water can prevent precipitation of salts. Different chemicals are used depending on the composition of the feed water. If the main concern is calcium carbonate in the feed water acids can be used and if there are problems with barium, strontium salts, silicates and iron, anti-scalents can be added. Adding either anti-scalents or acid to the incoming water when using RO is common praxis today and means that the salts remains in soluble form and can be separated by the membranes[9].

In the case with Beaufort West anti-scalents are being added before the RO. The anti-scalent added at Beaufort West is specifically designed for the feed water used, and the main concern is oxidation of iron or manganese. The drawback with using anti-scalents is that it can add to bio-fouling. Therefore it is necessary to have a gentle balance of the dosing anti-scalents. If necessary to add anti-scalents it may be essential to reduce the recovery of the membranes to reduce the risk of over-saturation of precipitating salts[10].

Oxidizing agents such as chlorine, bromine, hydrogen peroxide, iodine and ozone causes chemical attack. A chemical attack is indicated by increasing permeate flow, but with a lower quality since the damaged membranes passes water and also dissolved minerals. If properly monitored these situations can be avoided before causing permanent damage. While the UF membranes are cooping well with chlorine, the RO membranes will be destroyed if in contact with chlorine for more than a few hours.

For RO conductivity is one of the most critical parameters to measure. The conductivity gives an indication on how efficient the system is and can be used to trigger alarms if permeate quality goes down.

RO is connected with modest performance regarding quantities gained after treatment, typically 50% for seawater to 90% for colored groundwater. Beaufort West loses approximately 20% of the feed water, meaning that 80% is treated and distributed, which is rather high for RO membranes. If considering the losses for the UF (4%), the total gained quantities becomes 76,8%. This is theoretically possible to increase to 85% by recycling some of the backwash water. The concentrate from the WRP in Beaufort West is diverted to the irrigation channel. In many cases this may be a problem due to the high salt content and pathogen load in the concentrate and therefore unsuitable for irrigation. The backwash water from RO is diverted to the maturation pond where also the activated sludge is diverted.

[9] Contractor, Professional Engineer Pierre Marais (WWE), 2011-04-15 (Personal communication)
[10] Christopher Wright, Beuafort West Mun. Manager: Technical Services 2011-04-19 (Personal communication)

9.2.6 UV/H_2O_2

The UV/H_2O_2 treatment barrier is used for disinfection of the water after the reverse osmosis treatment. A mercury UV source with a wavelength spectrum between 200 – 400nm is used to enlighten the water. The most effective result for water treatment is possible between 200-280nm (IJ pelaar *et al*., 2007). The UV radiation is inactivating pathogenic microorganisms, which also means that they cannot replicate, decreasing the risk for infection further. UV-light also has the capability to reduce organic micro-pollutants by photolysis, but since this effect is low H_2O_2 (hydrogen peroxide) is added to combine photolysis with oxidation to degrade micro pollutants (IJ pelaar *el al*., 2007).

UV is added as an extra precaution if something happens to the RO. When the systems operates under normal conditions, the permeate from the RO is clean.

9.3 Monitoring

Monitoring means that different parameters, usually connected to water quality, is measured. The monitoring can either be performed on-line, meaning that results can be seen momentously, or by physical sampling analyzed in a laboratory, which means that there will be a delay of the result. Monitoring is a crucial part for any water treatment plant for two main reasons:

- To increase the efficiency of the system and its individual parts.
- To use the monitoring result as a quality certificate of the produced water and to communicate the results to the public and thereby gain trust among the customers.

The sampling is typically performed on in-flowing feed water, between barriers and on the final water. Ingoing water is monitored to know what pathogens, chemicals, salts etc. that needs to be removed or decreased in the process and to calibrate the treatment barriers. On-line monitoring can work as an indicator on the efficiency of the barrier and also alarms may be connected, while sampling of the final water is used to monitor if the final quality is adequate for the intended purposes. How extensive the monitoring needs to be is depending on the composition of the ingoing water and intended use of the final product. When using ground water as the raw water source, it generally needs less treatment compared to surface water and has lower tendency to vary and therefore also requires less monitoring.

Skepticism against direct water reclamation is high, why communication of treatment efficiency and final quality to the public is important, see further information in chapter 9.4. Therefore an extensive monitoring, beside efficient barriers, is necessary. Monitoring is usually connected to rather high costs, why there may be implications in a reclamation system like Beaufort West's, since the cost for monitoring will be carried by the contractor. Due to the costs connected with monitoring the contractor may not always want as extensive monitoring as the client. Further, monitoring is even more important in the beginning of a project when the treatment plant is new and uncertainties about the treatment process and corresponding performance are larger.

9.3.1 Monitoring Wastewater Treatment Plant (WWTP)

The monitoring of the wastewater is performed by the municipality and follows suggestions from Green Drop. No additional monitoring has been added after the construction of the Reclamation Plant.

The laboratory in Beaufort West is not an accredited lab, resulting in that a yearly sample is sent to an external laboratory for analysis to fulfill Green Drop standards. More general monitoring is conducted twice a week by the WWTP manager. Phosphates and E-coli analysis cannot be performed in the existing laboratory and is therefore analyzed at an external laboratory on a monthly basis. The parameters that are monitored and the frequency are presented in Table 9.***1***. The sampling is done individually for the WWTP and the WRP.

Table 9.1 Parameters measured at Beaufort West's WRP.

Parameters measured at WWTP			
Parameter	Twice a week	Once a month	Once a year
pH	•		•
COD	•		•
Suspended solids	•		•
Electrical conductivity	•		•
Total dried solids	•		•
Nitrogen	•		•
Ammonia	•		•
Ortho-phosphate		•	•
E-coli		•	•
Fluoride			•

9.3.2 Monitoring Wastewater Reclamation Plant (WRP)

The monitoring program for the WRP is still under development why no final monitoring plan can be presented in this chapter. However, the existing on-line monitoring will be described and explained as well as the physical sampling that is performed. Further a suggested monitoring plan from an external consultant will be presented and compared with the present monitoring plan.

According to the tender document, the produced water at the WRP must fulfill requirements for SANS: 241 2005, class 1, i.e. the quality of the drinking water must be acceptable for a lifetime of consumption. The national standard (SANS: 241, 2005) specifies the quality of produced drinking water in terms of: microbiological, physical, organoleptic and chemical parameters. Depending on what is measured they are recommended to be monitored either daily, weekly, monthly, quarterly or on an annually. The compliance for class 1 is evaluated on an annual basis, where 95% must fulfill the specified requirement (excluding aesthetic parameters). Due to increased costs connected to sampling and evaluation it is suggested in the SANS: 241, 2005 that a graded monitoring system should be implemented. That system takes into consideration the site specific conditions, e.g. raw water quality, population served, industrial activities and treatments barriers.

Since the municipality and the contractor together decide which parameters that needs to be monitored, the monitoring program will be a compromise between cost and safety through increased monitoring. According to the contractor[11] the monthly samples will be done both by the municipality and the contractor, where the contractor is carrying the cost for the sampling and monitoring process. The existing tender document suggests that the municipality will do sampling in the end of the month, while the contractor will do his sampling in the middle of

[11] Contractor, Professional Engineer Pierre Marais (WWE), 2011-04-15 (Personal communication)

the month. By doing so, and using different laboratories, more comprehensive data would be available, but for now only the contractor is taking samples once a month and sending them to an external laboratory.

Parameters that are measured by the contractor on a monthly basis can be seen in Appendix II. These parameters are sent away to an accredited laboratory, consequently leading to a delay of the results and increasing costs. The existing on-line monitoring is presented inFigure ***9.2***. All on-line monitored parameters are connected to automatic alarms that will trigger and alert the operator if any parameter deviates from specification, see chapter 9.2 for more information. Furthermore the operators at the WRP are monitoring Sludge Volume Index (SVI) of the activate sludge process and visually confirming that ferric chloride and chlorine is dosed properly.

Beaufort West municipality engaged Chris Swartz, from Water Utilization Engineers, as an external consultant and water treatment specialist, to be a part of the contract process guaranteeing that the contractor fulfils his commitments. Swartz developed a suggestion of a monitoring plan, valid for the first year of operation (Appendix III). The plan includes what parameters should be measured at what frequency. The plan is also designed to be dynamic, which is important for a new system. Further a suggestion of analysis equipment is presented. The monitoring plan is based on knowledge and experience, gathered over 50 years, at the New Goreangab reclamation system in Windhoek. There is however an important difference between the two systems. New Goreangab is, beside its larger capacity, also included in a research project that aims at gathering knowledge and information regarding wastewater reclamation[12] . Therefore they have a more extensive budget for monitoring compared to the reclamation system in Beaufort West. Consequently the monitoring plan suggested was not as comprehensive as the monitoring plan at the reclamation system in Windhoek. The present monitoring plan (Appendix II) is far less extensive than the suggested monitoring plan (Appendix III).

9.3.3 Alarms and PLC

The alarms at Beaufort West WRP are very important to secure a sufficient quality, but especially to protect the membranes. The process is constantly monitored and uses the same equipment that is used for on-line monitoring (Figure ***9.2***). If any of the on-line monitored value goes out of specification the plant automatically shuts down. Consequently, the alarms decrease the probability of low quality water leaving the system or permanently damage the membranes. All alarms that are triggered are also monitored by the supplier of the membranes to see if the operator is following manuals and taking correct actions. This is mainly to see that the membranes have been operated according to specifications and thereby keeping the warranty valid. It is also possible to operate parts of the system and give guidance on-line by the contractor, i.e. the SCADA system can be controlled by personal from Cape Town or wherever there is an Internet connection[13].

The operators have a list of possible alarms, with connected possible remedy action, so they can investigate the underlying cause that triggered the alarm and implement the correct measure. If the remedy action does not have adequate effect the operator will call the responsible installer for further assistance.

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[12] Professional Engineer Chris Swartz, Water Utilization Engineers, 2011-04-20 (Personal communication)
[13] Contractor, Professional Engineer Pierre Marais (WWE), 2011-04-15 (Personal communication)

9.4 Acceptance - Reclaimed Drinking Water

As indicated from Windhoek, reclaiming wastewater into drinking water may be connected with problems due to skepticism. Not all people feel comfortable with drinking water originating from sewage, why open information and communication with the inhabitants is necessary to build up a confidence and trust towards the drinking water produced.

Buying bottled water is increasingly common in Beaufort West, as throughout the world, and this poses a threat to the communal tap water as well as the environment. The general picture is that people originating from the middle class and above tends to drink communal tap water to a less degree than people from lower class. Information regarding the current available water and drought situation is good and the necessity of saving water is widespread amongst the inhabitants. A similar information campaign regarding quality of the produced water is necessary. Especially when introducing a WRP. This responsibility lies mainly at the contractor, but is also shared with the municipality. “Water days” and “open house” at the Reclamation Plant, where school classes and minors are the targeted group, has already been held with good results[14]. Targeting youngsters is an effective way to reach the major public, since they have a more open-minded attitude while elders and parents are more susceptible to information coming from family.

Producing water from wastewater and get acceptance for the product cannot be done on routine as when using more conventional treatment. Due to the existing doubts towards drinking reclaimed wastewater, any minor incidents that can be connected to the reclamation plant may have big impacts over long time on the confidence of the water delivered. And even more severe consequences may put the entire project into sank. Trust is gained over decades, while doubts may develop in seconds.

[14] Contractor, Professional Engineer Pierre Marais (WWE), 2011-04-15 (Personal communication)

10 Risk Assessment for Beaufort West Drinking Water Reclamation System

In this chapter the risk assessment case study performed for the reclamation system in Beaufort West, South Africa, is presented. The assessed system is a wastewater reclamation system that uses treated wastewater as raw water source to produce drinking water.
The risk assessment will be carried out according to the widely accepted risk management frameworks, see chapter 2, developed by the International Electrotechnical Commission (IEC, 1995) and risk management within the water sector developed by TECHNEAU (2007) as well as WSP (WHO, 2005). Stakeholders that are considered during the process are:

- Employees from authorities and the municipality.
- Engineers from the contractor, which are also responsible for operation and maintenance of the Reclamation Plant.
- Drinking water consumers in Beaufort West representing cost-bearers/benefit receivers and risk takers.
- Those that may be affected negatively by the reclamation system e.g. farmers using treated wastewater for irrigation purposes or inhabitants that may oppose to e.g. drink enhanced wastewater or increased tariffs.

The risk assessment was, apart from above mentioned stakeholders performed by the authors, a team of South African water experts, employees from the local government and plant operators. As new information during the work became available, the different steps were updated in an iterative process as described in WHO's WSP. Results from the risk assessment will be presented in a risk matrix with ALARP levels, ranking all identified risks and a MCDA that will evaluate suggested risk reduction measures. The risk assessment is only accounting for present conditions, which means that future planned installations or other changes will not be considered.

10.1 Risk Analysis

The risk analysis includes:

- Scope definition, system boundaries and delimitations (Chapter10.1.1)
- Hazard identification (Chapter 10.1.2)
- Risk estimation (Chapter 10.1.3)

10.1.1 Scope, System Boundaries and Delimitations

The scope of this risk assessment is to:

- Identify hazards threatening the reclamation system and consequently the production of drinking water, both from a water quantity and water quality perspective, within the system boundaries.
- Estimate risk levels connected to the hazards and rank them by their severity through the use of a risk matrix.
- Define risk tolerability criteria and decide which of the risks that is acceptable and which need to be reduced.
- Suggest risk reduction measures, estimate their risk reducing potential and rank the measures by the use of a MCDA.

- Present a suggestion for a risk reducing implementation plan intended to reduce the total risk connected to the reclamation system.

The system boundary for the risk assessment includes the wastewater treatment plant and WRP (Figure 10.1). The starting point of the system is defined as the intake of wastewater to the WWTP, and the end point is defined as the upstream, blending point, where the produced drinking water from the Reclamation Plant is mixed with water from the conventional drinking water treatment. For additional information about the wastewater treatment plant process and the WRP process, see chapter 9.

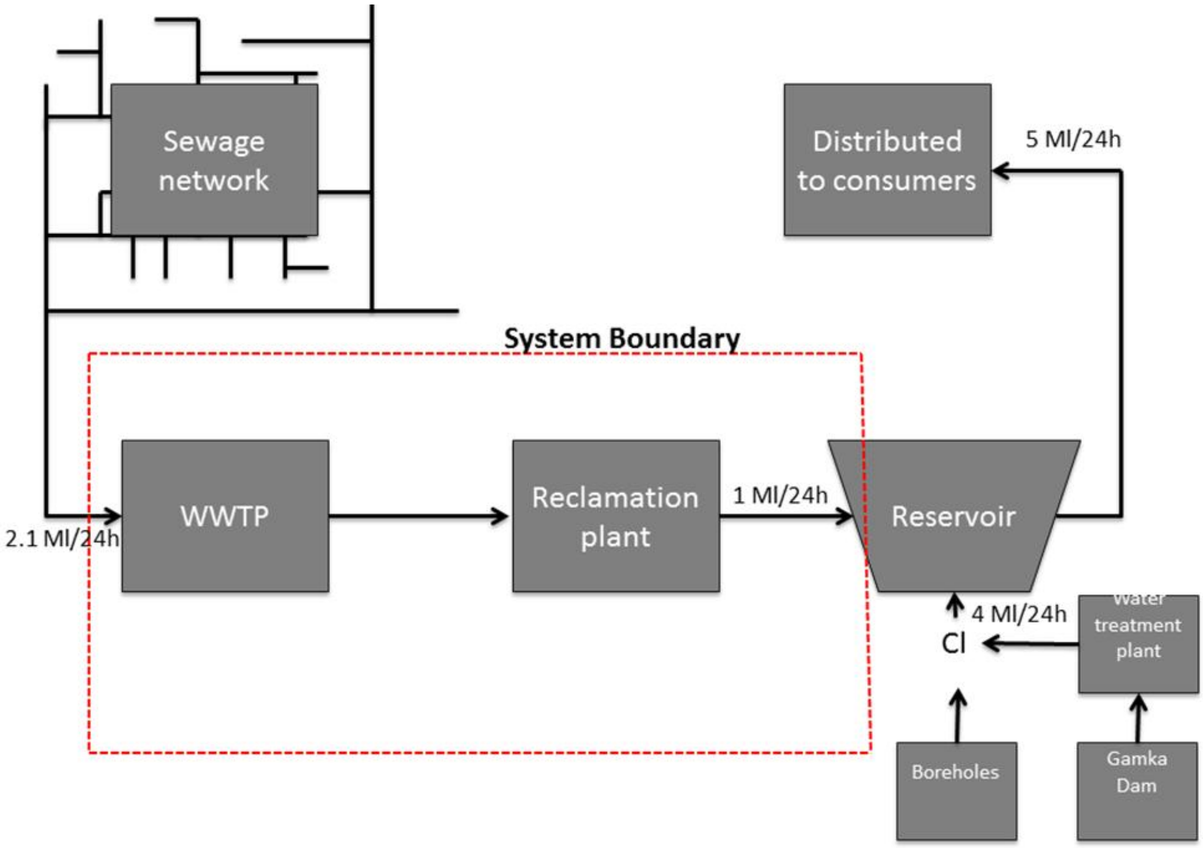

Figure 10.1 System boundary for the Reclamation system. Quantities are approximated for average operation.

As a consequence of the defined boundaries, no other sources, such as boreholes and surface water, will be considered in the risk assessment, i.e. the mitigating effects this might have on risks, mainly quantity risks, are *not* considered in the assessment. This decision was mainly done to facilitate the risk assessment process and to avoid too high complexity in order to stress problems originating from the reclamation system. In future WSPs it is however crucial to consider the entire supply system, i.e. a source to tap approach, as suggested from WHO (2004) and TECHNEAU (2007).

10.1.2 Hazard Identification

To identify hazards within the system boundaries different techniques were used such as brainstorming, experience from experts and operators, as well as checklists and databases, see chapter 4.1 for further information.

To facilitate the process and to be able to present more transparent results, the hazards were divided in four main categories:

- Organization hazards - Management of the plants, funding and contract issues.
- Source hazards – The WWTP process is considered as the raw water source.
- Treatment hazards – The WRP process is considered as the main treatment.
- Future hazards – Problems that may result in future risks.

The source and treatment hazards were further divided into subsystems and all identified hazards were evaluated, by the help of experts, to determine which of them actually posed a threat to the reclamation system, i.e. were relevant to be evaluated in the risk assessment. Approximately 70 hazards needed further investigation.

10.1.3 Risk Estimation

The risk estimation was performed in cooperation with South African water experts and operators. All hazards judged relevant to the reclamation system were assessed from a quality and quantity risk perspective and the probability of each hazard was estimated with predefined categories, suitable for this risk assessment case study, defined by the WHO (2005) (Table 10.1). Definitions used to estimate quality consequences were also taken from WHO (2005) and, to include quantity related consequences in the assessment as suggested from TECHNEAU (2007), similar definitions where developed by the authors (Table 10.2) All consequence estimations performed in this case study are made from following perspectives:

- Water quality consequences refer to threats towards human health derived from the consumption of drinking water, i.e. mortality, morbidity or aesthetic impacts.
- Water quantity consequences are defined as process downtime of the WRP, meaning that no water is delivered to the consumers within a certain time interval.

Table 10.1 Definitions of probability categories (WHO, 2005).

Probability		
Level	Descriptor	Description
1	Rare	Once every 5 year or has never occurred
2	Unlikely	Once per year
3	Moderately likely	Once per month
4	Likely	Once per week
5	Almost certain	Once a day

Furthermore, since the sedimentation basin has a retention time of more than 18 hours, it functions as a quantity buffer for the WRP. To consider this in the risk estimation a simplification was made that a quantity failure in the WWTP process must be longer than 24h before it affects the WRP process, i.e. if the WWTP process is down for 23h it will not have any effect on the reclamation process and will therefore not be considered as a quantity risk. The simplification that disruptions in the WWTP process shorter than 24h not will affect the WRP process implies that these events will not be presented in the risk matrix. The result from the risk estimation is visible in Figure 10.2 and Figure 10.3 where risks connected to the WRP has the label “R” and risks connected to the WWTP the label “W”. All risk that was evaluated as acceptable in the risk tolerability decision (Chapter 10.2.1) has been left out from the risk matrices.

Table 10.2 Definitions of the quality and quantity consequences connected to each assessed hazard.

Consequence		
Level/Descriptor	Quantity	Quality (WHO, 2005)
1 Insignificant	No detectable impact	No detectable impact.
2 Minor	0.5h-3h process downtime	Minor aesthetic impact causing dissatisfaction but not likely to lead to use of alternative less safe sources.
3 Moderately likely	3h-24h process downtime	Major aesthetic impact possibly resulting in use of alternative but unsafe water sources.
4 Major	24h-7 days process downtime	Morbidity expected from consuming water.
5 Catastrophic	More than 1 week downtime	Mortality expected from consuming water.

10.2 Risk Evaluation

The result from the risk analysis, i.e. the quality and quantity risk matrices, where used as the base for the risk evaluation. The risk evaluation includes:

- A risk tolerability decision (Chapter 10.2.1), performed with the ALARP approach.
- Quantification of risk levels (Chapter 10.2.2), performed using risk priority numbers.
- Suggestions and analysis of risk reduction measures (Chapter 10.2.3), performed with a Multi Criteria Decision Analysis (MCDA).

10.2.1 Risk Tolerability Decision

To increase the understanding of quantity related consequences a separate risk matrix was created, expressing the risk level (*R*) in Customer Minutes Lost (CML), see chapter 4.3. Since the WRP is defined as the only raw water source (Chapter 10.1.1) the proportion of the population affected, C_A, will always be equal to 1. This means that the entire population is considered affected if the WRP is not producing water. CML is then expressed as:

$$R \text{ (CML)} = P_F \cdot 1 \qquad [3]$$

P_F corresponds to the probability of failure, used to calculate estimated minutes of production standstill per year. By evaluating the result from the CML matrix (Table 10.3) it is possible to see that risks occurring more frequent (probability), with shorter downtime (consequence), may have a longer total downtime per year, then risks occurring less frequent with a more consistent downtime. Due to the defined system boundaries (Chapter 10.1.1), reservoirs are not considered in this case study. If the entire water supply system for Beaufort West had been evaluated, shorter downtimes had been compensated by the reservoir and consequently would consumers not be affected by shorter downtimes. Therefore a longer continuous downtime will be evaluated as more severe than a short downtime that occurs more frequent, even if the CML value is equal.

*Table 10.3 The quantity risk expressed as the average CML per year (Customer Minutes Lost), i.e. a quantitative measure of process downtime. The estimated probability (P) and the consequence (C) (average process downtime per incident) are used to calculate P_F. (CML = P_F*C_A)*

	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	5,475	27,375	229,950	All year	All year
Likely	780	3,900	32,760	224,640	All year
Moderately likely	180	900	7,560	51,840	120,960
Unlikely	15	75	630	4,320	10,080
Rare	3	15	126	864	2,016

By the use of the ALARP method the risk matrices were (Figure 10.2 and Figure 10.3) divided in three different risk levels (acceptable risk, ALARP region and unacceptable risk). The division between the three different risk levels was mainly decided through discussion among the authors, but opinions from experts in the water sector were also considered[15]. The technique used to decide the risk levels was to assess and evaluate the severity of all possible risk combinations from Table 10.1 and Table 10.2. Questions asked was e.g. if a quality consequence resulting in mortality occurring once every fifth year acceptable or not?

Since quality and quantity consequences were defined differently (Table 10.2), individual ALARP levels were chosen for each consequence type. By considering all possible risk combinations and the result from the CML matrix, risk levels were implemented together with the risk matrices (Figure 10.2 and Figure 10.3). As can be seen in the figures, only yellow and red risks are presented, this is due to that risk in the green area not need to be considered according to the ALARP method. Commonly risks with a more definite effect on health are looked worse upon then indirect risks with a more vague definition. Drinking water produced from wastewater is for many connected with skepticism and changes in odour and taste will be directly linked to the reclamation process, even if the reason behind lies elsewhere. The already widespread skepticism towards this type of water system means that even the slightest quality problem may have devastating effects and big impacts on the confidence for the water system among the public. This result in that the ALARP region in the quality matrix is larger compared to the quantity matrix. Consequently, the green risk region in the quantity matrix is larger, indicating that a quantity problem is evaluated less severe compared to if low quality water reaches the consumer. This means that if there is a minor quality problem in the process it is advised to shut down the plant instead of delivering low quality water.

The reason that the red risk region was chosen equally large in the two matrices is, despite the previous discussion, that a severe quantity problem will damage the thrust among the consumers for the reclaimed water in the same way as problem connected to bad quality, resulting in that the consumers may look for an alternative drinking water source. If people lose confidence of the delivered water and stop drinking the water, either for quantity or quality issues, the whole concept with water reclamation may be jeopardized.

[15] Professional Engineer Chris Swartz, Water Utilization Engineers and Ass. Prof. Thomas Pettersson, Chalmers University of Technology. (Personal communication)

	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	R10				
Likely					
Moderately likely					
Unlikely					R1
Rare				R3, R4, R5, R6, R7, R8, R9	W1, R2

Figure 10.2 ALARP regions for ***quality*** *related risks implemented in a risk matrix. Low risks in the green region have been left out. R is risks associated with the WRP and W are risks associated with the WWTP.*

	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	R26		R10		
Likely		R25			
Moderately likely			W10, W11, W12, R21, R22, R23, R24	W3, R11	
Unlikely			R1, R30	W8, W9, R16, R17, R18, R19, R20	W2
Rare				W13, W14, R4, R6, R27, R28, R29	W1, W4, W5, W6, W7, R2, R3, R7, R12, R13, R14, R15

Figure 10.3 ALARP regions for ***quantity*** *related risks implemented in a risk matrix. Low risks in the green region have been left out. R is risks associated with the WRP and W are risks associated with the WWTP.*

The risk matrices presents the severity of each identified hazards, according to the defined ALARP levels. According to the defined ALARP levels, one quality risk and four quantity risks were evaluated as high risks, i.e. unacceptable and needs to be reduced without exception. The yellow ALARP region includes risks that need to be reduced if economically and technically reasonably, and consist of 10 quality risks and 37 quantity risks. Due to limitations in time and space are only the most severe hazards, high risk, presented in more detail in this chapter. For information on less severe risks, see Appendix IV and V.

- **W2: Intake screws in the WWTP become damaged or stops functioning, leading to no flow and consequently no feed water to the WRP** (at present there is only one screw pump, the municipality has budget for one more this year)**.**

There are two intake screws (Figure 10.4) to the WWTP, but only one screw pump to run them. If the pump stops functioning the wastewater will not get transported up to the WWTP and through the screen / grit removal. It will then be by-passed into irrigation ponds untreated and the WRP will not have any feed water, i.e. no drinking water can be produced at the WRP if the intake screws are out of function.

Figure 10.4 One of the intake screws to the WWTP.

Everything is prepared for installing a second pump, e.g. electrical equipment etc., only the pump itself is missing. The municipality has budget for a new pump to be installed during 2011.

- **W3: Inadequate floc settling in the WWTP's secondary settler.**

The contractor has added $FeCl_3$ to improve the settling capacity and this has shown an improving result. Over carrying of the secondary settler (Figure 10.5) has however occurred more than once the last year (2011) due to problems with the sludge age and the recirculation pumps.

Figure 10.5 Inadequate floc settling in the WWTP's secondary settler during April 2011.

The over carried sludge will be transported to the sedimentation basin were it, if the retention time is enough, will settle. This deterioration of the effluent water quality, i.e. WRP feed water, will result in that more frequent cleaning needs to be performed of the sedimentation basin and more backwashing of sand filters and membranes in the WRP. It will due to the high sludge content not be possible to by-pass the water directly to the WRP when the maturation is being cleaning, since the backwashing will be to extensive making it impossible to run the WRP in a satisfactory way.

- **R1: Inadequate monitoring resulting in water quality or quantity risks** (at present there is adequate on-line monitoring for the reclamation process, but more physical monitoring is needed)**.**

At present, there is no laboratory connected to the WRP facilities, resulting in that all samples are sent away for analysis. None of the suggested measuring equipment's (Appendix III) is either in place and neither of the operators are educated or certified in performing sample analysis[16]. Further, far less parameters (Chapter 9.3), with suggested corresponding frequency is measured, according to what is suggested by Swartz (2011). However, there are ongoing discussions about what parameters to monitor and with what frequency. The WRP is at present producing water and still the contract, including what parameter to monitor, is discussed, which complicates the situation.

The present monitoring is not done according to a precautionary principle. Extensive monitoring should instead be in place in the beginning of a new started project to get a good understanding, and then it may be possible to decrease some of the monitoring when more knowledge is gained. There exists a very high confidence in the on-line monitoring and

[16] Contractor, Professional Engineer Pierre Marais (WWE), 2011-04-15 (Personal communication)

automatic alarm system, as well as the RO. However, even though the RO is evaluated to have very high removal efficiency, sufficient monitoring still is needed to ensure that the water quality fulfills the requirements. Further, effect to humans of commonly existing compounds in wastewater is not fully covered, why extensive monitoring is needed and knowledge of what the wastewater is containing.

At present the WRP staff only monitor the feed water from the WWTP at a monthly basis, see Appendix II. By not monitoring the wastewater on a daily basis the chance to react to deterioration in feed water quality, e.g. insufficient secondary settling or incoming toxic compounds, is less. If a quality problem could be detected before the sedimentation basin the plant could continue to produce water for a couple of hours, due to the retention time in the sedimentation basin, until the low quality water reaches the intake to the WRP. Or if on-lined monitored, the feed water, i.e. effluent water from WWTP, can be bypassed directly into the irrigation pond without passing the sedimentation basin, and when the quality is sufficient the water can be redirected to the sedimentation basin again. At present, deteriorations in feed water quality will only be noticed if visually possible in the sedimentation basin, or as a result of an increased backwash frequency. It is also possible that undetected deteriorations in feed water quality, resulting in increased clogging of the membranes, may tempt the contractor to increase the pressure on the membranes.

Quantity consequences are referring to more backwashing as a result of inadequate monitoring of ingoing water quality leading to not optimized processes.

- **R10: Inadequate local knowledge of operation and condition of the installation** (at present only one of the operators has adequate knowledge to run the plant independently, training of the other operator is in progress).

The knowledge on site is at the moment not adequate. There is only one operator that is undergoing adequate training (performed by the contractor) and can take necessary decisions. The idea is that the trained operator should be capable to train the other operator during the days, however since the workload is high the time for this is small. If upcoming problems cannot be solved by the operators, people from Cape Town need to travel to the site, which is five hours drive away.

Operators do not have education in sampling, and rely only on the on-line monitoring and automatic alarms. At present, the operators are contacting the responsible installer for the membranes almost on a daily basis[17] for questions. The lack of knowledge will not have severe water quality effects since the RO and UF is connected to automatic alarms that cannot be overridden by the operators.

- **R11: Not sufficient numbers of staff/operators** (at present there are two fulltime employed operators at the WRP)**.**

Since there only are two full-time operators employed at the plant the process is vulnerable. Already they work long shifts, and there will be limited possibilities to run the plant at full capacity if one becomes sick or during vacation periods. The knowledge between the operators also differs, see risk R10, increasing the vulnerability in case of sickness.

[17] Shawn Chaney, Responsible for installations and membranes, 2011-05-19 (Personal communication)

At present the plant is producing 1 Ml/day, which according to the contractor[18] can be produced in approximately 8h, implying that the process is not that vulnerable to staff absenteeism, i.e. that it will be enough with one operator working an 8h shift to produce the required amount. However, since the plant will increase the produced quantity with 10% a year for the next 10 years (according to the agreement between the contractor and the municipality), the plant will have to run for approximately 20h per day to produce the required capacity in year 2020. Consequently the plant needs more operators in the future to produce the required quantities. The possibility to handle less likely circumstances, as deaths or operators changing work is also small with the present working force.

10.2.2 Risk Priority Number

After the ALARP levels were set, the scales of the consequence and probability axes were defined. The reason that this was not done in the opposite order is because the ALARP levels had been defined trough reasoning and discussion. The numbering of the scales will just make it possible to present the risk in quantitative terms, i.e. with the risk priority number (Chapter 4.2.).

The Water Research Commission (WRC) recommends a nonlinear inclination of the probability and consequence scales (Figure 10.6). From the figure it can be seen that the consequence and probability curves has the steepest inclination in the middle span. This means, that a reduction of the consequence and/or probability in that span have the largest effect on the risk priority number. Consequently, the result of defining the scales according to the WRC suggestion will be that risk reduction measures are focused towards the medium probabilities and consequences. To avoid a higher focus on less severe risks, an exponential scale (Figure 10.6) is proposed and implemented in this case study. The use of an exponential scale will benefit risk reduction of high risks.

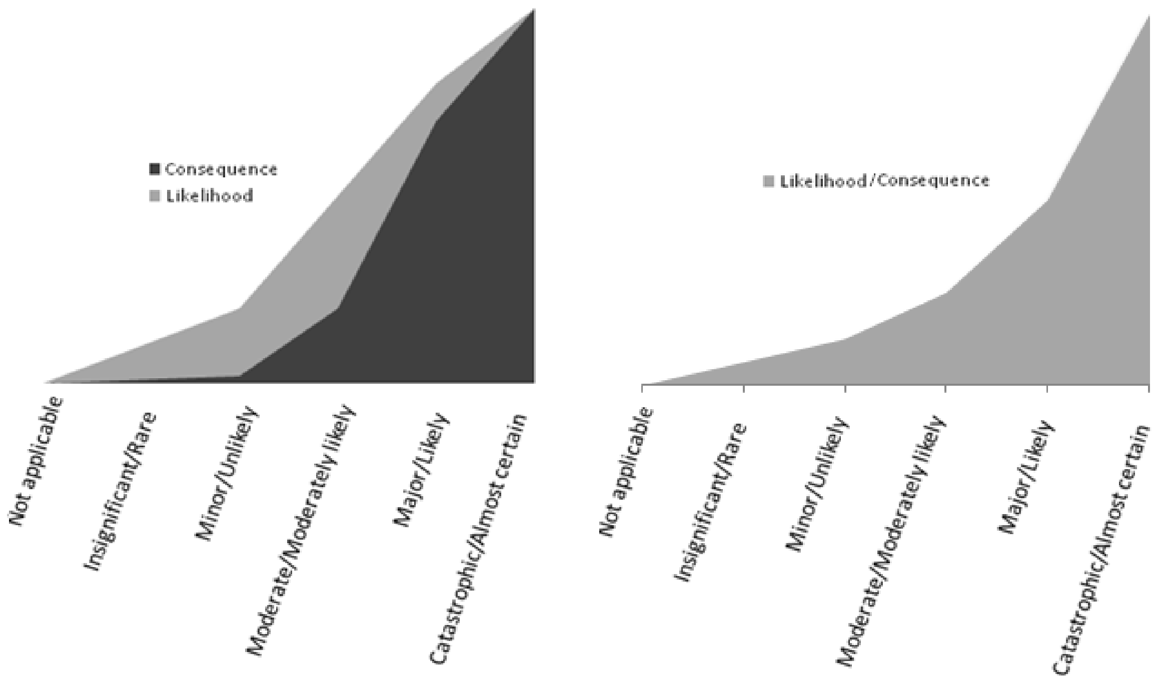

Figure 10.6 Non-linear inclinations of the probability and consequence scales as suggested by the WRC (left). Exponential inclination of the scales as used in this case study (right).

[18] Professional Engineer Pierre Marais, Contractor, (WWE), 2011-05-19 (Personal communication)

The scales and risk priority number are presented together with the ALARP levels in Figure 10.7 and Figure 10.8. As can be seen the risk priority number is *not* uniformly distributed in the risk matrices. A result of that a decrease in consequence is considered more favorable than a decrease in probability considering the total risk reduction. By applying equation [1] (Chapter 4.2) the consequence scale has been weighted higher (b=1.6) than the probability scale (a=1.0).

Risk Profile	
Low (0 < X ≤ 8)	Acceptable risk
Medium (8 < X ≤ 84)	The risk can be acceptable if it is economically and technically unreasonable to reduce it.
High (X > 84)	The risk cannot be accepted under any circumstances.

Probability \ Consequence	1	2	4	8	16
16	16	49	147	446	1351
8	8	24	74	223	676
4	4	12	37	111	338
2	2	6	18	56	169
1	1	3	9	28	84

Figure 10.7 ALARP regions and risk priority number for water quality related risks. $R=P^{1.0} * C^{1.6}$.

Risk Profile	
Low (0 < X ≤ 12)	Acceptable risk
Medium (12 < X ≤ 84)	The risk can be acceptable if it is economically and technically unreasonable to reduce it.
High (X > 84)	The risk cannot be accepted under any circumstances.

Probability \ Consequence	1	2	4	8	16
16	16	49	147	446	1351
8	8	24	74	223	676
4	4	12	37	111	338
2	2	6	18	56	169
1	1	3	9	28	84

Figure 10.8 ALARP regions and risk priority number for water quantity related risks. $R=P^{1.0} * C^{1.6}$.

10.2.3 Multi Criteria Decision Analysis (MCDA)

In the risk evaluation process (Chapter 10.2) five unacceptable risks, connected to the reclamation, system were identified (Table 10.4). Since unacceptable risks, according to the ALARP-method, cannot be accepted under any circumstances, several risk reduction measures were suggested by the authors (Table 10.5). It is of importance to consider that a risk reduction measure may affect other additional risks than the target risk, e.g. measure R1.1

that also affects risk R3, R10 and W11, which needs to be considered in the MCDA to attain a more complete result.

Table 10.4 Identified unacceptable risks

Risk	Description	Risk type
W2	Intake screws in the WWTP become damaged or stops functioning, leading to no flow and consequently no feed water to the WRP	Quantity
W3	Inadequate floc settling in the WWTPs secondary settler.	Quantity
R1	Inadequate monitoring resulting in water quality or quantity risks.	Quality/Quantity
R10	Inadequate local knowledge of operation and condition of the installation.	Quantity/Quality
R11	Not sufficient numbers of staff/operators.	Quantity

Table 10.5 Risk reduction measures suggested by the authors.

Ref	Risk reduction measure desciption	Target risk	Additional events affected
W2.1	Install a second screw pump	W2	-
W3.1	Install an additional secondary settler	W3	(W12)
W3.2	Increased monitoring of sludge age and FeCl dosing.	W3	(W10, W13)
W3.3	Replace flow control of recycle pumps to more reliable technique.	W3	(W9)
W3.4	Combination of measure W3.2 and W3.3	W3	(W9, W10)
R1.1	Installation of adequate laboratory + increased monitoring program (according to suggestions by C.D. Swartz) and education in sampling of the operators.	R1	(R3, R10, W11)
R1.2	Increased monitoring program (according to suggestions by C.D. Swartz) and education in sampling of the operators, samples sent away for analysis.	R1	(R3, R10, W11)
R10.1	Educate all operators to a minimum level to run the plant	R10	(R11)
R10.2	Increase the knowledge of the operators to a higher level.	R10	(R3, R11, R20)
R10.3	Secure the possibility to get support from external source	R10	-
R10.4	Develop operation manuals for the treatment process	R10	-
R10.5	Combination of measure R10.1 and R10.4	R10	(R11)
R11.1	Employ one more operator	R11	-
R11.2	Employ two more operators	R11	-
R11.3	Increase salaries and better working conditions.	R11	-
R11.4	Combination of measure R11.1 and R11.3	R11	-
R11.5	Combination of measure R11.2 and R11.3	R11	-

Further, all risk reduction measures have different potential to achieve an acceptable risk level for its target risk, i.e. that the final risk level after risk reduction is in the acceptable/green area of the risk matrix. The probability to achieve an acceptable risk level is larger for a measure that reduces the target risk into the green area compared to a measure only reducing the same target risk into the yellow area of the risk matrix. Since there also are uncertainties involved in the estimation of risk reduction, a MCDA method developed by Lindhe (2010) was used in the case study. The MCDA method uses beta distributions (Table 10.6) to model uncertainties connected to the estimation of a measure's probability to achieve an acceptable risk level. α and β are numerical parameters used to define the shape of the beta distributions. To combine the involved uncertainties with the probabilities of different measures to achieve an acceptable risk level, the quality and quantity risk matrices were divided in different probability categories (Figure 10.9). The categories reflect the probability that a measure is achieving an acceptable risk level for its target risk, i.e. the lower the final risk level in the risk matrix is for the target risk, the higher is the probability that the risk is reduced to an acceptable level.

Table 10.6 Probabilities to achieve an acceptable risk level modelled by beta distributions depending on final risk level position in risk matrix. α + β = 42, meaning that uncertainties for all distributions are equal. (Figure 10.9) (Modified from Lindhe, 2010).

Risk priority number (category from Figure *10.9*.)		**Probability of achieving an acceptable risk level**			**α**	**β**
Quantity	Quality	Most likely	P05	P95		
224-1351 (VII)	224-1351 (VII)	0.00	0.00	0.07	1	41
85-223 (VI)	85-223 (VI)	0.10	0.05	0.21	5	37
38-84 (V)	38-84 (V)	0.30	0.20	0.43	13	29
13-37 (IV)	9-37 (IV)	0.50	0.37	0.63	21	21
7-12 (III)	5-8 (III)	0.70	0.57	0.80	29	13
3-6 (II)	2-4 (II)	0.90	0.79	0.95	37	5
1-2 (I)	1 (I)	1.00	0.93	1.00	41	1

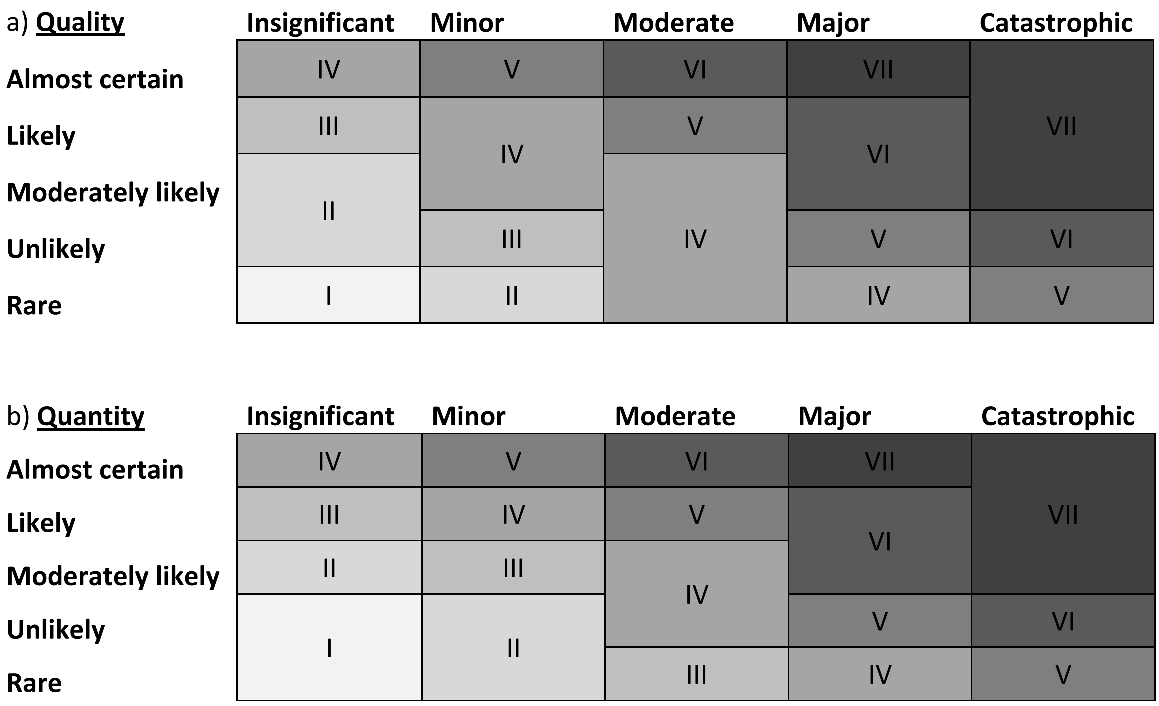

Figure 10.9 Categories defining the probability (Table 10.6) to achieve an acceptable risk level for the target risk, depending on the position in the risk matrix. I = Highest probability, VII = Lowest probability. a=Quality related risks, b=Quantity related risks.

Further the MCDA also considers uncertainties involved in the estimation of cost to implementing a measure, which was modelled by discrete distributions (Table 10.7). Normalized values between 0-1 were used in the estimation, where 0 represent the highest cost and 1 the lowest cost. Consequently favouring measure with lower cost when calculating the final performance score. Table 10.8 presents the estimated risk reduction of the target risks and Table 10.9 presents the estimated risk reduction of the additional risks, both used in the MCDA. When calculating the total benefit, risk reduction in water quality and quantity is weighted as equally important. It is of importance to remember that uncertainties (Table 10.6) only are estimated for the risk reduction of the target risk, but assigned equally if additional risks are affected by the measure.

Table 10.7 Discrete distributions used to model uncertainties in cost estimations (Lindhe, 2011).

	Probability of each cost category				
Cost	Low	Low/medium	Medium	Medium/high	High
Low	0.68	0.16	0.09	0.04	0.03
Low/medium	0.10	0.70	0.10	0.06	0.04
Medium	0.05	0.10	0.70	0.10	0.05
Medium/high	0.04	0.06	0.10	0.70	0.10
High	0.03	0.04	0.09	0.16	0.68

Table 10.8 Risk reduction/benefit for target risks expressed in the risk priority number.

Ref	**Risk priority number**				**Risk reduction/benefit of target risks**
	Quantity		Quality		
	Initial	After	Initial	After	
W2.1	169	28	-	-	141
W3.1	111	9	-	-	102
W3.2	111	56	-	-	55
W3.3	111	56	-	-	55
W3.4	111	9	-	-	102
R1.1	18	9	169	3	175
R1.2	18	9	169	3	175
R10.1	147	74	16	4	85
R10.2	147	12	16	1	150
R10.3	147	147	16	16	0
R10.4	147	74	16	16	73
R10.5	147	37	16	4	122
R11.1	111	18	-	-	93
R11.2	111	9	-	-	102
R11.3	111	111	-	-	0
R11.4	111	9	-	-	102
R11.5	111	9	-	-	102

Table 10.9 Risk reduction/benefit for additional event affected expressed in the risk priority number.

Ref	Add. event effected	Risk priority number				Risk reduction/benefit of add. risks
		Quantity		Quality		
		Initial	After	Initial	After	
W3.1	W12	37	12	-	-	25
W3.2	W10	37	2	-	-	35
W3.2	W13	28	9	-	-	19
W3.3	W9	56	28	-	-	28
W3.4	W9	56	28	-	-	28
W3.4	W10	37	2	-	-	35
R1.1	R3	28	28	28	3	25
R1.1	R10	147	74	16	8	81
R1.1	W11	37	6	-	-	31
R1.2	R3	28	28	28	3	25
R1.2	R10	147	74	16	8	81
R1.2	W11	37	6	-	-	31
R10.1	R11	111	56	-	-	55
R10.2	R3	84	28	28	3	81
R10.2	R11	111	56	-	-	55
R10.2	R20	56	28	-	-	28
R10.5	R11	111	56	-	-	55

A spreadsheet was constructed to perform the calculation for the MCDA and the result is presented in Table 10.10. When calculating the performance score, see equation [5], Monte Carlo simulations were used to handle the beta distributions. Uncertainties were assigned to the estimation of the benefit, see equation [4], and to the cost of implementation. Furthermore, the risk reduction and cost were weighted as equally important.

$$Benefit = (B_T + B_A) * B_D \qquad [4]$$
$$Score = 0.5*Benefit \text{ (normalised)} + 0.5* Cost \qquad [5]$$

B_T = Benefit of target risk (Table 10.8)
B_A = Benefit of add. risks (Table 10.9)
B_D = Beta distribution (Table 10.6)
Score = Performance score (Table 10.10)
Cost = Cost of implementation (Table 10.7)

The last column of Table 10.10 describes the probability that the final risk level is higher than the acceptable risk level and is used when choosing between measures with similar risk reduction and cost.

Table 10.10 Multi Criteria Decision Analysis (MCDA) performance matrix, using beta distributions. Benefit= risk reduction/benefits, Score = Performance score, R_I= Initial risk level, R_F = Final risk level, R_C = Critical risk level, $P(R > R_C)$ = Probability that the final risk level is higher than the critical/acceptable risk level.

				R_I -> R_F		$P(R > R_C)$	
Measure	**Benefit**	**Cost**	**Score**	qual.	quant.	qual.	quant.
W2.1	71	Low/Medium	0.48	-	◆→▲	-	0.50
W3.1	88	High	0.25	-	◆→●	-	0.31
W3.2	34	Low	0.49	-	◆→▲	-	0.69
W3.3	26	Low	0.48	-	◆→▲	-	0.69
W3.4	114	Low/Medium	0.57	-	◆→●	-	0.31
R1.1	253	Medium/High	0.66	◆→●	▲→●	0.12	0.31
R1.2	253	High	0.57	◆→●	▲→●	0.12	0.31
R10.1	51	Low	0.53	▲→●	◆→▲	0.12	0.69
R10.2	229	Low/Medium	0.80	▲→●	◆→●	0.02	0.31
R10.3	0	Low	0.43	▲→▲	◆→◆	-	-
R10.4	23	Low	0.47	▲→▲	◆→▲	-	0.69
R10.5	94	Low	0.61	▲→●	◆→▲	0.12	0.50
R11.1	47	Medium	0.34	-	◆→▲	-	0.50
R11.2	71	Medium/high	0.29	-	◆→●	-	0.31
R11.3	0	Low/Medium	0.35	-	◆→◆	-	-
R11.4	71	Medium	0.39	-	◆→●	-	0.31
R11.5	71	High	0.21	-	◆→●	-	0.31

10.3 Chain of Events

When using a multi-barrier concept, risks that require chain of events to occur, meaning that failing components or events interacts, are more frequent since there are several barriers aimed at treating the same targeted impurities. In a reclamation system, including a WWTP and the WRP itself, the interaction between the WWTP and the WRP is important. Many hazards that can be connected to the WWTP require a chain of events, proceeding into the WRP, to become a valid risk to the system. To illustrate this there are good tools, e.g. Fault tree and Event tree, but these typically requires more data and they are more of a detailed study. Wastewater also has a tendency to vary, both over short periods as well as for longer periods, which also may impact the risk.

10.4 Sensitivity Analysis and Uncertainties

Due to lack of data, the authors, in cooperation with South African water experts, performed all estimations of probability and consequence. Consequently, uncertainty connected to risk level estimations need to be considered. The probability is as mentioned before (Table 10.1) defined trough frequency categories with sometimes large differences between each step, e.g. moderately likely was defined as “once a month” and the next step, unlikely was defined as “once a year”. This creates difficulties when the most likely frequency for a hazard occurs between two categories. One solution to this problem is to always choose the most likely category, resulting in that probability sometimes is underestimated and vice versa. Another solution is to always estimate the more frequent of the two categories and thereby overestimate the risk level. An underestimation of the risk levels is, of obvious reasons, not appropriate when performing a risk analysis but an overestimation is neither always the best solution. An underestimation may result in that a risk is overlooked and an overestimation will result in increased risk reduction cost for some time unnecessary measures.

The solution in this case study was to rather see the probability and consequence as a combination that together define the risk level (Equation [1], chapter 4.2) and by defining the hazards more accurate. If a hazard is defined as: “Power failure affecting the WRP”, it is very hard to estimate the consequence and probability, since a long power failure will have a more severe effect but a less probability and vice versa. Consequently by defining the hazard as “Power failure longer then 24h affecting the WRP” the probability and consequence can be more accurately estimated. When the approach was unsuitable, the more frequent probability or more severe consequence was estimated to avoid underestimations.

The MCDA model that was used in this case study considers only uncertainties connected to the estimation of risk reduction of the target risk and the cost of implementing the measure. Since there also are uncertainties involved in the estimation of the initial risk level (Figure 10.2 and Figure 10.3), a MCDA method that considers this would be useful, e.g. the discrete MCDA model developed by Lindhe *et al.* (2010). The sensitivity in the result of the MCDA was also affected by the assigned importance between the risk reduction/benefit and cost when the performance score was calculated. If the cost e.g. was chosen as twice as important as the benefit, possible in a poor town like Beaufort West, it would be more beneficial to choose measure R10.1 over R10.2. This implies that the decision-makers must consider what is most valuable, to reduce the risk as much as possible or to as low cost as possible. A change of the estimated cost or risk reduction for a measure will also have large impact for the MCDA result.

10.5 Results from the Risk Assessment

The risk assessment process identified five risks as unacceptable (Table 10.4), additional 47 were identified inside the ALARP region and 29 as acceptable (not presented in the case study). It is of great importance that the 47 ALARP risks are evaluated further in a future risk assessment since they might be possible to reduce to an acceptable cost.

The full MCDA result is presented in Table 10.10 and the measures that were evaluated to be most beneficial, from the defined criteria, is presented in table 10.11. All measures illustrated in table 10.11 are the ones that have the highest performance score and they will also reduce the target risk to an acceptable level. However, it is still important that the MCDA result is analyzed with common sense and trough discussion among the decision makers.

Table 10.11 Risks identified as unacceptable in chapter 10.2.1 presented together with the most beneficial measures according to the MCDA performed in chapter 10.2.3.

Risks		**Risk reduction measures**	
Risk	Description	Ref	Description
W2	Intake screws in the WWTP become damaged or stops functioning, leading to no flow and consequently no feed water to the WRP	W2.1	Install a second screw pump.
W3	Inadequate floc settling in secondary settler.	W3.4	Increased monitoring of sludge age and FeCl dosing & Replace flow control of recycle pumps to more reliable technique.
R1	Inadequate monitoring resulting in water quality or quantity risks.	R1.1	Installation of adequate laboratory, increased monitoring program (according to suggestions by C.D. Swartz) and education in sampling of the operators.
R10	Inadequate local knowledge of operation and condition of the installation.	R10.2	Increase the knowledge of the operators to a higher level.
R11	Not sufficient numbers of staff/operators.	R11.4	Employ one more operators & Increase salaries and better working conditions.

11 Discussion

It is crucial when performing a comprehensive risk assessment to involve all major stakeholders, e.g. municipalities and contractors, to a large extent in the process. This will increase the understanding of the risk assessment concept and facilitate the process to reach an agreement concerning e.g. ALARP regions and risk estimations. The result from the risk assessment is not intended to be a surprise for the stakeholders; the process should instead be as transparent as possible.

Few things can be done on routine. ALARP regions, quantity/quality definitions, scaling of axes etc. need to be considered at each new risk assessment. Comprehensive risk assessments are time consuming and rather demanding to perform to all involved participants. If continuing with more sophisticated analysis as Fault Tree Analysis (FTA) or Event Tree Analysis (ETA) and uncertainty analysis a higher level of expertise and statistical modeling is required, further stressing the importance of an active role by the stakeholders. All parts need to take an active role and the ALARP levels should ideally be decided among involved stakeholders to avoid conflicts about the results.

WRP's differ from other conventional water treatment plants mainly due to the origin of its raw water. Since the raw water originates from treated wastewater, all processes in the WWTP need to be considered in the risk assessment. If the risk assessment only is focused on the WRP, risks may be overlooked or underestimated. It is also common that the WRP and WWTP are operated by different contractors or like in Windhoek divided between the municipality and a contractor, which may result in conflicts if not a well-defined contract, as in Windhoek[19], specifying responsibilities and commitment is available. The city of Windhoek[20] stresses that a central part for a successful WRP project and future cooperation has been to have a good contract to rely on. The risk assessment performed in this project has not analyzed any possible contract issues since the contract concerning Beaufort West WRP still is under construction. This is a big drawback, since we expected some risks to be related to contractual issues. In future risk assessments project where different parts/organizations operates the WWTP and WRP, it is crucial to include the contract in the assessment, it may also be suitable to handle it in a separate stage.

WRP's are big investments and rather complicated to operate and the acceptance for the produced water may initially be low. Further they will never be able to fully replace conventional water sources since the recovery rate is low considering the whole system, meaning that losses in the system is large. Therefore WRP's should not be considered as the first solution to handle severe water stress. First a thorough investigation of existing sources and consumption patterns should be performed to see if more simple and less expensive measures can be taken to either reduce consumption, or if there are other water sources to explore. Beaufort West did consider all other options and due to acute water stress the decision of a construction of a WRP came up rather fast. Overall the whole project did not take more than two years to accomplish. The risk assessment was initiated when the plant was already producing water. Ideally the risk assessment should have been done before the design phase to facilitate necessary changes and also relevant information would have been available earlier in the project.

[19] J.G. Menge, Analysis Responsible for Gammams WWTP 2011-03-29 (Personal communication)
[20] J.G. Menge, Analysis Responsible for Gammams WWTP 2011-03-29 (Personal communication)

Windhoek that has produced drinking water from wastewater for over 50 years has a lot of experience in the field. In future reclamation projects in South Africa, as well as the rest of the world, valuable information from Windhoek should be considered. Also, Beaufort West will now have a lot of valuable experience for future WRP projects.

Due to the initial rather limited knowledge among the authors concerning the treatment processes in the WRP, it was tempting to put a lot of focus and confidence on the hazard databases (THDB and WRC checklist). Hazard databases have an important role to play in risk assessments to facilitate hazard identification and increase the number of identified hazards. However, it is important to stress that the databases are developed as a complement for the hazard identification, only containing the most general hazards. If too large focus is put on the databases there is a risk that hazards more specific for the assessed system is overlooked. The hazards in the databases are often also not very well defined, resulting in that it becomes difficult to estimate accurate consequences and probabilities.

Reverse osmosis (RO) is known as a very efficient treatment barrier, with only few compounds able to pass through. Therefore quality risks when using reverse osmosis are not many as long as the RO is functioning as intended, the risk for breakthrough is small since there exists online monitoring of e.g. pressure. In Beaufort West, extensive alarm systems are used when the processes is operating under design conditions. When using such alarm systems there is a potential danger that it trigger too often, resulting in a longer downtime of the WPR. The RO is the main reason why such a few quality related risks have been found, but still the RO is a rather sensitive system and it is crucial to ensure adequate pre-treatment to maximize the life-length of the membranes since they correspond to such a big part of the investment. Since the UF precedes the RO and thereby needs to take the “first hit”, higher risks towards the UF-membranes can be expected.

WRP’s using RO needs to deal with rejected water, so called brine, and backwash water. CIP (Cleaning In Place) often contains chemicals that may be harmful for the environment if released untreated and the rejected water contains a high pathogen load and/or salt content. In Beaufort West is the backwash water, that contains chemicals, diverted and collected in activated sludge ponds and the less toxic backwash water is together with the rejected water diverted to an irrigation channel. The consequences these might have are not fully covered and should be further analyzed in a Environmental Impact Assessment.

Many risks were assessed to have a “Rare” probability, with “Catastrophic” consequences, resulting in that they were to be found inside the ALARP-region (Figure 10.2 and Figure 10.3). These risks are hard to handle since there are limited measures available to reduce the risk. The only possible parameter to decrease is the consequence, but for some risks, e.g. earthquakes and flooding, it is extremely uneconomical to do so. Still it makes sense to illustrate them in the risk matrix to be aware of them, but for some it may look worse than it is.

As suggested from the case study in Windhoek[21], the water from the reclamation system should be of at least as good or preferably of higher quality than existing sources to increase acceptance. This makes sense, but when considering the entire water system in Beaufort West, the water from the reclamation system is blended with water from conventional treatment, resulting in that water reaching the consumer will have almost the same taste and

[21] John Esterhuizen, General Manager: WINGOC 2011-03-29 (Personal communication)

odor as before. In Beaufort West there is a big difference in taste between water from the conventional system and water from the WRP. The water from the WRP tastes preferably better than the water from the conventional system. But since the water is mixed in the reservoirs measures focused on increasing “Minor” consequences (aesthetic impacts) will not be very beneficial as long as the conventional treatment is not upgraded.

When estimating quality consequences it is hard to distinguish between what incidents that may result in aesthetic impacts, and which might lead to illness, death etc. This since it then must be connected to what pathogens that may pass through the system. Ones again this is often requiring a chain of events. In the risk assessment quality related risks have been assessed from how severe impacts to the process the hazard may result in and for how long time may insufficient water be delivered to customers instead of a deeper analyzes including what different pathogens that may pass the system under certain conditions.

Multi Criteria Decision Analysis (MCDA) is a systematic approach to rank risk reduction measures, and provides a good background towards choosing the most appropriate measure(s) from a decided set of criteria. Even though, an MCDA does not give a final result, but more decision basis. The final decision on what risks to prioritize, and which risk reduction measures to choose, will still be a combination of sound sense and by remarking the results from the risk matrices and the MCDA analysis.

12 Conclusions

Conclusions in this chapter are divided in two parts. One part that concerns the risk assessment case study performed for Beaufort West's wastewater reclamation system and a second part were general conclusions concerning wastewater reclamation is presented.

Conclusions concerning the Beaufort West WRP risk assessment case study:

- Monitoring is crucial for any reclamation system. Beaufort West's WRP is not having adequate, monitoring due to lack of funding. An expansive monitoring plan needs to be integrated in the initial budget plan to avoid this situation. Monitoring should not come in second hand
- A second screw pump needs to be installed to decrease the probability that problems occur in connection to the WWTP intake.
- The sludge age in the secondary settler and the $FeCl_3$ dosing needs to be monitored more frequent. This in combination with the replacement of the recycle pumps flow controls to a more reliable technique will lower the probability for inadequate settling in the secondary settler.
- The knowledge of the operators needs to be increases to a higher level to minimize the probability that the WRP process stands still due to operator error.
- At least one more operator needs to be employed to decrease the vulnerability for sickness, unaccepted deaths etc.
- An ISO-certification for Beaufort West's WRP should be initiated to minimize risks for human errors and external parts may stress weaknesses in the operative system.
- Due to limitations of the risk matrix method handling chain of events, further studies that illustrates the interaction between the WWTP and the WRP is highly appropriate. By doing so, some risks may be found not applicable, while some new risks may appear.
- Sufficient monitoring to fulfill Green Drop is already established for the WWTP. To increase efficiency, and decrease costs, of monitoring for the contractor of the WRP, there are opportunities to incorporate and share some parts of the monitoring with the WWTP.
- Due to delimitations, risks in this report have been focused towards stressing the reclamation system. In future Water Safety Plans (WSP) the whole system, including the conventional WTP, groundwater sources, distribution system and reservoirs needs to be analyzed from a quantity perspective.

Overall conclusions regarding wastewater reclamation:

- An expertise group, gathering knowledge concerning direct- and possibly also indirect, wastewater reclamation systems should be established in southern Africa. Beaufort West Municipality and the operator of the WRP should set up frequent meetings with relevant participants from Windhoek's reclamation system to share information and experience.
- Ideally the WWTP and the WRP is operated by the same part to fully utilize the benefits of one system instead of needing to handle the WWTP and WRP as separate systems.
- A well-defined contract, specifying which part that is responsible for what, should be prepared before construction.

- Reverse osmosis is a very efficient treatment barrier able to treat almost all types of water. However there is a potential danger of having too high confidence on reverse osmosis. To ensure adequate performance connected alarms to the different barriers is an efficient way to increase the life-length of the membranes and to ensure an adequate quality of the water.
- Using databases when performing risk analysis is an efficient way to incorporate as many potential hazards as possible. Still it should only be used as a basis for discussions. The hazards are defined very general in THDB, which has a point, but when assessing consequences and probability it is crucial to know specifically what consequence that is addressed to be able to estimate correct probabilities. A good and simple way to handle this problem is to discuss the consequences, before probabilities.
- It is important to incorporate water quantity problems, as suggested by TECHNEAU. If there are frequent, or consistent, interruptions of the water supply it may result in a low confidence of the water system and consequently the consumers will look for other water sources.

References

- Beaufort West Municipality, KWEZI V3 Engineers. (2010). *Beaufort West Municipality Water Services Development Plan 2010/2011*. Ref 244920KSO.
- Beuken, R., Sturm, S., Bondelind, M., *et al.* (2008) *Identification and description of hazards for water supply systems – A catalogue of today's hazards and possible future hazards, updated version*. TECHNEAU
- BWM . (2011a). *Water.* [Electronic]. Available at: < http://www.beaufortwestmun.co.za/engineering/eng_water.html > (2011-03-10)
- BWM . (2011b). *Sewerage.* [Electronic]. Available at: < http://www.beaufortwestmun.co.za/engineering/eng_sewerage.html > (2011-03-10)
- BWM. (2010a). *Water Services Development Plan for 2010/2011.* [Electronic] Available at: < http://www.beaufortwestmun.co.za/engineering/content/WATER/Front%20Page%20Executive%20Summary%20WSDP%202010_2011.pdf > (2011-02-16).
- BWM. (2010b). Annual *publication of drinking water quality performance against SANS 241.* [Electronic] Available at: < http://www.beaufortwestmun.co.za/engineering/content/WATER/Blue_Drop_Summary_Report_Beaufort_West_Local_Authority.pdf > (2011-02-21).
- DBSA. (2006). *The DBSA Infrastructural Barometer 2006.* [Electronic] Midrand: Policy Research Unit. Available at: < http://www.dbsa.org/Research/Documents/Infrastructure%20Barometer.pdf > (2011-02-15).
- Dent, M., Lynch, S.D. & Schulze, R.E. (1987). *Mapping mean annual and other rainfall statistics over southern Africa*. Water Research Commission, Pretoria, South Africa. Report No. 109/1/89
- Drinking Water Engineering (2009). *Water treatment – membrane filtration.*[Course compendium] Chalmers University of Technology, Göteborg 2009.
- DWAF , Walmsley Dr R D, Walmsley J J, Mzuri Consultants, Silberbauer M. (1999). *National state of the environment report.* [Electronic]. Available at: <http://www.environment.gov.za/soer/nsoer/issues/water/index.htm> (2011-02-18).
- DWA. (2010). *Blue Drop Report 2010 – South African Drinking Water Quality Management Performance.* [Electronic] Available at: < http://us-cdn.creamermedia.co.za/assets/articles/attachments/27313_bluedrop.pdf > (2011-02-25).
- DWA. (2011). *About us – Vision.* [Electronic] Available at: < http://www.dwa.gov.za/about.aspx#vision > (2011-02-18).
- DWAF. (1994). *Water Supply and Sanitation policy, White Paper – Water: An indivisible national asset.* [Electronic] Available at: < http://www.dwaf.gov.za/Documents/Policies/WSSP.pdf > (2011-02-18).
- DWAF. (1997). *Water service act, 1997.* [Electronic] Available at: < http://www.dwaf.gov.za/Documents/Legislature/a108-97.pdf > (2011-02-18).
- DWAF. (2003). Strategic *framework for water services: Water is life, sanitation is dignity.* [Electronic] Available at: < http://www.dwaf.gov.za/Documents/Policies/Strategic%20Framework%20approved.pdf > (2011-02-21).
- DWAF. (2005). *Drinking Water Quality Management Guide for Water Services Authorities.* [Electronic] Available at: <

http://www.dwaf.gov.za/Documents/Other/DWQM/DWQMWSAGuideSept05.pdf > (2011-02-21).

- FAO. (2007). *Coping with water scarcity - challenge of the twenty first century.* [Electronic]. Available at: < http://www.fao.org/nr/water/docs/escarcity.pdf > (2011-02-21).
- Gray, N.F. (2004). *Biology of wastewater treatment, 2:nd edition.* [Book]. ISBN: 978-1-86094-328-7.
- Grimvall, G., Holmgren, Å. J., Jacobsson, P., Thedéen, T. (2010). *Risks in technological systems.* [Book]. London: Springer, cop. 2010.
- IEC. (1995). *Risk Management - Part 3: guide to risk analysis of technological systems, International Electrotechnical Commission*. [Paper]. IEC60300-3-9
- Hajkowicz, S.A. and Collins, K. (2007). *A Review of Multiple Criteria Analysis for Water Resource Planning and Management.* Water Resources Management.
- IJ Pelaarm, G.G., Harmsen D.J.H., Heringa, M. (2007*) UV disinfection and UV/H2O2 oxidation: by-product formation and control.* [Electronic] Available at: < http://www.techneau.org/fileadmin/files/Publications/Publications/Deliverables/D2.4.1.1.pdf > (2011-04-14).
- International Energy Agency, IEA. (2008). *South Africa: Statistics.*[Electronic]. Available at: < http://www.iea.org/stats/countryresults.asp?COUNTRY_CODE=ZA&Submit=Submit > (2011-02-28)
- Kaplan, S. and Garrick, B.J. (1981). *On The Quantitative Definitions of Risk*, Risk Analysis Vol 1. [Electronical] Available at: < http://josiah.berkeley.edu/2007Fall/NE275/CourseReader/3.pdf > (2011-03-09)
- Lindhe, A. (2010). *Risk Assessment and Decision Support for Managing Drinking Water Systems*. Gothenburg: Doctoral thesis, Chalmers University of Technology - Department of Civil and Environmental Engineering
- Lindhe, A. Rosén, L. Norberg, T. Rostum, J and Pettersson TJR. (2010) *Risk-based multi-criteria decision models for prioritizing water safety measures*. [Paper]. TECHNEAU.
- Melchers, R.E. (2001). *On the ALARP approach to risk management - Reliability Engineering and System Safety*.
- Rosén, L., Hokstad, P., Lindhe, A., Sklet, S., and Røstum, J. (2007). *Generic Framework and Methods for Integrated Risk Management in Water Safety Plans*, TECHNEAU
- SANS 241:2005. (2005). *South African National Standard – Drinking Water.* [Report] Pretoria: Standards South Africa. ISBN 0-626-17752-9. ICS 13.060.20
- Svenskt Vatten. (2011). *Dricksvatten - vårt viktigaste livsmedel.* [Electronic]. Available at: < http://www.svensktvatten.se/web/dricksvatten.aspx > (2011-03-03).
- Swartz, C.D, Water Utilization Engineers. (2011) *Process control and quality control data.* [Mail correspondence]. (2011-04-13).
- Swartz, C.D, Water Utilization Engineers; Cape Peninsula University of Technology; Rural Support Services. (2009). *Technical and Social Acceptance Evaluation of Microfiltration and Ultrafiltration Membrane Systems for Potable Water Supply to Rural Communities.* [Report]. ISBN: 978-1-77005-781-4. Republic of South Africa, 2009.
- Swartz, C.D. & Offringa, G. (2006). *TECHNEAU Report on trends in: South Africa/Sub-Sahara Africa.* [Electronic] Available at: <

http://www.techneau.org/fileadmin/files/Publications/Publications/Deliverables/D1.1.1a.pdf > (2011-02-14).

- Tampa Bay Water. (2011). *Tampa Bay Water Desalination Plan.* [Electronic]. Available at: < http://www.tampabaywater.org/facilities/desalination_plant/index.aspx > (2011-02-28).
- TECHNEAU. (2005). *Technology enabled universal access to safe water (TECHNEAU).* Annex I: Description of work. Proposal/Contract no.: 018320-02. EU Sixth Framework programme.
- TECHNEAU. (2007). *Generic Framework and Methods for Integrated Risk Management in Water Safety Plans*, TECHNEAU
- TECHNEAU. (2010a). *Project Summary.* [Electronic]. Available at: < http://www.techneau.org/index.php?id=2 > (2011-03-15).
- TECHNEAU. (2010b). *Technical efficiency of some existing risk reduction options in treatment systems.* [Electronic]. Available at: < http://www.techneau.org/index.php?id=124> (2011-07-07).
- Thompson, P. & Majam, S. (2009). *The development of a generic water safety plan for small community water supply*. [Electronic]. Available at: < www.dwa.gov.za/dir_ws/DWQR/subscr/ViewwebDoc.asp?Docid=804 > (2011-03-03)
- UN. (1958). *Water for industrial use.* [Report]. Economic and social council. New York. Report No. E13058ST/ECA/50.
- UN. (2010a). *The Millennium Development Goals Report - 2010*. [Report]. New York, 2010
- UN. (2010b). *MDG's in South Africa.* [Electronic]. Available at: < http://www.undp.org.za/millennium-development-goals/mdgs-in-south-africa > (2011-02-21).
- UNEP, WHO, Water Supply & Sanitation Collaborative Council. (1997). *Water Pollution Control – A Guide to the Use of Water Quality Management Principles*. [Report]. E & FN Spon, London.
- UNESCO. (2006). *Water a shared responsibility –The United Nations World Water Development Report 2.* [Electronic] New York: Berghan Books. Available at: < http://unesdoc.unesco.org/images/0014/001454/145405E.pdf > (2011-02-14).
- UNFCC. (2011). *GHG Data.* [Electronic]. Available at: < http://unfccc.int/ghg_data/items/3800.php > (2011-02-28)
- Water-technology. (2011). *Shoaiba Desalination Plant, Saudi Arabia.* [Electronic]. Available at: < http://www.water-technology.net/projects/shuaiba/ > (2011-03-02).
- Welt-Atlas. (2011). South Africa. [Electronic]. Available at: < http://www.welt-atlas.de/map_of_south_africa_2-92 > (2011-08-22).
- WHO. (2004). *Guidelines for Drinking-water Quality, Third edition, Incorporating the first and the second addenda, – Recommendations.* [Electronic]. Available at: < http://www.who.int/water_sanitation_health/dwq/fulltext.pdf > (2011-03-03)
- WHO. (2005). *Water Safety Plans - Managing drinking-water quality from catchment to consumer.* [Electronic] Available at: < http://www.who.int/water_sanitation_health/dwq/wsp170805.pdf > (2011-03-02)
- WHO. (2010). *Progress on sanitation and drinking water- 2010 update.*[Report] Genève, 2010
- WHO. (2011a). *Fact sheet 2.12 – Slow sand filtration.* [Electronic] Available at: < http://www.who.int/water_sanitation_health/hygiene/emergencies/fs2_12.pdf > (2011-04-07)

- WHO. (2011b). *Fact sheet 2.14 – Rapid sand filtration.* [Electronic] Available at: < http://www.who.int/water_sanitation_health/hygiene/emergencies/fs2_14.pdf > (2011-04-07)
- WWF. Dickie, P. (1997). *Making water – Desalination: Option or distraction for a thirsty world.* [PDF]. Available at: < http://wwf.panda.org/index.cfm?uNewsID=106660 > (2011-02-28)

Appendix I

Beaufort West Municipality Blue Drop performance score card for 2010 (DWAF, 2010).
**A=100% compliance and in a decreasing scale to F= No compliance with any of the requirements or no info.*

Performance area	**Beaufort West**
Water Safety Plan	C
Process Control and Maintenance Competency	A
Efficinecy of Monitoring Programme	A
Credibility of Sample Analyses	B
Data submission to DWA	A
Compliance with National Standard	A
Failure Response Management	A
Responsible Publication of Performance	C
Efficiacy of Asset Management	A
Microbial DWQ Compliance with National Standard	99.99%
Chemical DWQ with National Standard	99.99%
Blue Drop Score 2010 + Trend	95%
Blue Drop Score 2009	80%

Appendix II

Parameters monitored on a monthly basis by the contractor of the WRP.

Monitored parameters in final effluent from WWTP	Monitored parameters in final treated water from WRP
COD	Colour
Suspended Solids	Conductivity
TDS	TDS
pH	pH
Electrical conductivity	Turbidity
Ammonia as N	Ammonia as N
Total phosphorus as P	F-
Nitrate/Nitrite as N	SO_4
Orto Phosphate as P	Ca
	Nitrate/Nitrite as N
	Zn
	Cl
	K
	Mg
	Na
	Al
	Cr
	Fe
	Ni
	Sb
	Co
	Pb
	Se
	As
	Cu
	Mn
	V
	Cd
	CN-
	Hg
	DOC

Appendix III

Parameters suggested to be monitored, with a corresponding frequency, by the contractor of the WRP (Swartz, C.D, Water Utilization Engineers, 2011).

Process control and quality control data			
Sample	Quality parameter/ analysis	Frequency of sampling	Instrument used for performing the analysis
Raw sewage from Beaufort West WWTP (inlet to sedimentation basin)	pH	Daily	pH meter
	Conductivity	Daily	Conductivity meter
	Alkalinity	Twice/week	To be notified
	Cl, SO_4, F	Monthly	Spectrophotometer
	NO_3-N, NO_2-N	Twice/week	Spectrophotometer
	K, Na, Silica, Al	Monthly	Spectrophotometer
	Ca, Mg, Hardness	Weekly	Spectrophotometer
	NH_3-N	Twice/week	Spectrophotometer
	Ortho-P, Fe	Daily	Spectrophotometer
	B, Cu, Zn, Cd, Ni, Cr, Pb & other heavy metals	Monthly	Spectrophotometer
	COD	Weekly	Spectrophotometer
	Heterotrophic Plate Count, Total Coliforms, Faecal coliforms, E. Coli	Weekly	Microlab (Swift)
	Giardia, Crypto	Monthly	CSIR Stellenbosch
Sedimentation basin outlet	pH	Daily	pH meter
	Temperature	Daily	pH meter
	Conductivity/TDS	Daily	Conductivity meter
	Turbidity	8-hourly	Turbidimeter
	Ortho-P, Fe	Daily	Spectrophotometer
	COD, UV254, Nitrate	Twice/week	Spectrophotometer
	DOC	Monthly	City of Cape Town
	Ca, Mg, Hardness	Twice/week	Spectrophotometer
	Chlorophyll-A	Monthly, or as required	City of Cape Town
After Sandfilter	pH	Daily	pH meter
	Conductivity/TDS	Daily	Conductivity meter
	Turbidity	4-hourly	Turbidimeter
	UV254	Daily	Spectrophotometer
	Fe	Daily	Spectrophotometer
After UF	pH	Daily	pH meter
	Conductivity/TDS	Daily	Conductivity meter
	Turbidity	4-hourly	Turbidimeter
	UV254	Daily	Spectrophotometer
After RO	pH	Daily	pH meter
	Conductivity/TDS	On-line	Conductivity meter
	Turbidity	4-hourly	Turbidimeter
Final water	pH	Daily	pH meter
	Conductivity/TDS	Daily	Conductivity meter

	Turbidity	4-hourly	Turbidimeter
	Colour, UV254	Daily	Spectrophotometer
	Cl, SO_4, F, K, Na	Monthly	Spectrophotometer
	NO_3-N, NO_2-N	Monthly	Spectrophotometer
	Alkalinity, Ca, Mg, Hardness	Monthly	Spectrophotometer
	NH_3-N, Ortho-P	Weekly	Spectrophotometer
	Fe, Mn	Weekly	Spectrophotometer
	Free chlorine	On-line	On-line
	B, Cu, Zn, Cd, Ni, Cr, Pb & other heavy metals	Monthly	City of Cape Town
	COD	Monthly	Spectrophotometer
	DOC	Monthly	City of Cape Town
	Heterotrophic Plate Count, Total Coliforms, Faecal coliforms, E. Coli	Twice/week	Microlab (Swift)
	Giardia, Crypto, viruses	Monthly	CSIR Stellenbosch
	Trihalomethanes	Monthly	City of Cape Town
	EDC	Quarterly	CSIR Stellenbosch

Appendix IV

Quality related hazard

Hazard	Hazard description	Comments	Risk priority number
Wastewater Treatment Plant (WWTP)			
W1	Vandalism or sabotage polluting the water with chemicals or microbes or damage equipment and infrastructure, leading to severe/long process interruption.	The process tanks (secondary settler, activated sludge) are open and it is possible to add toxic compounds to the water. The activated sludge process is vulnerable to toxic compounds that may kill the bacteria and it will take long time to recover the biomass.	84
Water Reclamation Plant (WRP)			
R1	Inadequate monitoring resulting in water quality or quantity risks.	So far there does not exist any laboratory and none of the, by Swartz, C.D. suggested, measuring/analysis equipment is in place. Neither of the operators are educated or certified in performing analysis of sampling at the moment. Far less parameters with suggested corresponding frequency is measured, and the monitoring is not done according to any caution principle. There exist a very high confidence on the on-line monitoring and the connected alarms as well as the treatment capacity of the RO. There are ongoing discussions about what parameters to measure and, with what frequency between the contractor and the municipality. See chapter 10.2.1 for more information.	169
R2	Vandalism or sabotage may pollute the water with chemicals or microbes or damage equipment and infrastructure, leading to severe/long process interruption.	Highly unlikely. Can be decreased by increasing security. All processes are inside a locked building.	84
R3	Issues of concern are not addressed due to inadequate reporting (e.g. malfunctions, compliance reports).	Operators will call contractor on all problems. All alarms are noted in a book. Sandfilters are operated manually, no possibility for online monitoring. PLC (programmable logical control) interface can be handled from Cape Town as well. Contractor on site once a month to follow up problems.	28
R4	On-site reservoirs/ponds/watersumps can be compromised/contaminated.	If someone drops something in the cleanwater sump (only wooden cover, not sealed) it may have quality effects since there is no additional monitoring of this water before distributed. Quality related problems could happen unnoticed. According to the contractor the cleanwater sump will be sealed in the future to avoid accidental contamination. RO and UF feed tanks are neither sealed, this may have quantity effects due to triggered alarms.	28
R5	Low free chlorine residual in the final water reduces protection against fecal contamination and free-living organisms.	On-line/alarm monitoring of chlorine in final water.	28

Hazard	Hazard description	Comments	Risk priority number
R6	RO: Membrane break trough; fiber breakage.	Transmembrane pressure (TMP) alarm should pick this up, also possible to noticed during maintenance. Possibility to repair smaller breakage on their own at site. Since this is final membrane, quality may be affected if the alarms do not work.	28
R7	RO: Reduced filter performance/destruction/membrane imperfections leading to that the water cannot be cleaned to class 1 quality.	The membranes are tested every month.	28
R8	Re-contamination of the water in the pipeline before reaching reservoir.	The water is final-chlorinated (maximum allowed level of 0.8mg/l is the aim) to hinder biological growth and re-contamination in the pipelines. New built pipeline.	28
R9	Failure of the alarm system.	The alarm system is connected to the on-line monitoring. If the monitoring system fails the plant will shut down, due to that the PLC requires information from the monitoring to run the process. Alarms may however malfunction, and thereby cause quantity/quality problems due to that the failure is not communicated to the PLC or operator. Problems with to sensitive alarms, causing quantity failures, are at the moment adjusted by the contractor.	28
R10	Inadequate local knowledge of operation and the condition of the installation.	The knowledge on site is at the moment not adequate. There is only one operator that has training and can take necessary decisions. If the operator not can solve a problem, people from Cape Town need to come to the site, which is five hours away. Operators have no education in sampling and only trust the on-line alarms. For now the operators calls the responsible installer for the membranes almost on a daily basis. There is no backup if the trained operator gets sick, or decides to quit the job.	16

Appendix V

Quantity related hazards

Hazard	Hazard description	Comments	Risk priority number
Wastewater Treatment Plant (WWTP)			
W2	Intake screws in the WWTP become damaged or stops functioning, leading to no flow and consequently no feed water to the WRP.	There are 2 screws but only one screw pump, if the pump stops functioning the wastewater will not get transported up and through the screen / grit removal. It will then have to be by-passed into irrigation ponds untreated and the WRP will not have any feed water. Everything is prepared for installing a second pump, only the pump itself is missing. See chapter 10.2.1 for more information.	169
W3	Inadequate floc settling in the WWTPs secondary settler.	Over carrying has occurred due to problems with the sludge age and recirculation pumps resulting in inadequate quality of effluent water, affecting the process in the WRP. $FeCl_3$ has a positive affect on the settling. See chapter 10.2.1 for more information.	111
W1	Vandalism or sabotage polluting the water with chemicals or microbes or damage equipment and infrastructure, leading to severe/long process interruption.	The process tanks are open and it is possible to add toxic compounds to the water. The activated sludge process is vulnerable to toxic compounds that may kill the bacteria. Would take long time to recover the biomass.	84
W4	Geophysical accidents damages equipment (e.g. earthquakes, floods, landslide, lightning).	Lightning damaging electrical equipment, long reparation time. Highly unlikely. Stabile area.	84
W5	Issues of concern are not addressed due to inadequate reporting leading to breakdown of equipment resulting in downtime (e.g. malfunction of screw pump, problems in the activated sludge process).	Good cooperation between supervisor and responsibilities as well as between operators and supervisors. If some barrier malfunction and it is not reported the downtime can be more than 24h. Main concern is if screw pump is malfunctioning, which may lead to catastrophic consequences. No adequate reporting system or maintenance scheme to follow for daily inspection.	84
W6	Toxic compounds in feed water to WWTP disturb the process and/or the WRP process.	Problem with fat coming into the work has happened but this was detected so no damage to the process. The activated sludge process is vulnerable to oil and toxic compounds may kill the bacteria. No monitoring of the ingoing water to the WWTP. Oil or other toxic compounds entering the wastewater system may strike out the activated sludge. By not monitoring the wastewater there is less chance to react to incoming toxic compounds. So far the effect on humans of commonly existing compounds in wastewater is not fully covered, why more knowledge of what the wastewater is containing is needed.	84

Hazard	Hazard description	Comments	Risk priority number
W7	Quantity related problems (e.g. water shortage leading to closing of intake).	A long severe drought can affect the amount of wastewater reaching the WWTP and consequently the feed water later reaching the WRP. Salinity becomes high if there is a drought, problem to RO.	84
W8	Pump failure leading to downtime.	There are backup pumps for all treatment steps (excl screw pump) and there is local mechanical knowledge in town. There has been an incident were the activate sludge recycle pumps failed leading to that sludge was carried over to the sedimentation basin.	56
W9	Improper operation or inadequate desludging programme.	Pump with flow control decides how often the sludge should be removed. The flow control has failed resulting in sludge was carried over in the secondary settler.	56
W10	Dosing malfunction ($FeCl_3$) due to human errors or mechanical failure, can reduce floc formation and thus result in inefficiently remove of harmful microorganisms, organic material, color and turbidity (too low/high dosing).	Operators are monitoring so the dosing works at least once a day. Malfunction of $FeCl_3$ can lead to more backwashing, CIP etc. The dosing of $FeCl_3$ is decided from flow and phosphate concentration in incoming wastewater.	37
W11	Non-optimized treatment processes can result in poor process performance.	Non-optimized treatment in the WWTP will result in poorer quality of feed water and trigger more alarms in WRP and require more frequent backwashing or CIP. Algae from sedimentation basin create biofilm growth on RO membranes leading to CIP etc.	37
W12	Large quantities of storm water disturbing process, leading to over flow of activated sludge process.	Spikes during rain and too high sludge age can result in overflow, resulting in that the sedimentation basin need more frequent cleaning as well as more frequent backwashing.	37
W13	Unappropiate sludge age.	Daily monitoring of sludge age. Contractor wants a longer sludge age then the municipality.	28
W14	The site is not secure leading to theft of equipment resulting in downtime of more than 24h (i.e. no fencing, gates, locks, safety/warning signs, inadequate security).	Thieving and stealing of fencing is a fact. One guard is posted at site during night, and needs to cover a large area. Has limited possibilities to see what is happening with the fencing. Stealing of parts in the WWTP is expected to have less quantity consequences then stealing at the WRP.	28

Hazard	Hazard description	Comments	Risk priority number
Water Reclamation Plant (WRP)			
R10	Inadequate local knowledge of operation and the condition of the installation.	The knowledge on site is at the moment not adequate. There is only one operator that has training and can take necessary decisions. If a problem not can be solved by the operator's, people from Cape Town need to come to the sight, which is five hours away. Operators have no education in sampling, but only rely on the on-line alarms. For now the operators calls the responsible installer for the membranes almost on a daily basis. See chapter 10.2.1 for more information.	147
R11	Not sufficient numbers of staff/operators.	Only one operator that is trained enough, and two in total. Already they work long passes, and there are very limited possibilities to run the plant if one becomes sick. Especially if the trained operator becomes sick. The contractor will in the future train both operators to an adequate level and educate the "cleaner" to basic level of process control. There is no backup if the trained operator gets sick, or decides to quit the job. See chapter 10.2.1 for more information.	111
R2	Vandalism or sabotage may pollute the water with chemicals or microbes or damage equipment and infrastructure, leading to severe/long process interruption	Highly unlikely. Can be decreased by increasing security.	84
R3	Issues of concern are not addressed due to inadequate reporting (e.g. malfunctions, compliance reports).	Operators will call contractor on all problems. All alarms are noted in a book. Sand filters are operated manually, no possibility for online monitoring. PLC interface can be handled from Cape Town as well. Contractor on site once a month.	84
R7	RO: Reduced filter performance/destruction/membrane imperfections leading to that the water cannot be cleaned to class 1 quality.	Responsible for membranes says that the 5 years guaranty will be fulfilled, no problem. TMP alarm will trigger if something is wrong with the membranes. If membranes need to be replaced they will have to be delivered from outside the country.	84
R12	Geophysical accidents (e.g. earthquakes, flooding, landslides, lightning).	Lightning damaging electrical equipment, long reparation time. Highly unlikely. Stabile area.	84
R13	UF: Reduced filter performance/destruction/membrane imperfections leading to that the water cannot be cleaned to class 1 quality.	Responsible for membranes says that his 5 years guaranty will be fulfilled, no problem. Problems if membranes are operated/maintained out of spec. TMP alarm will trigger if something is wrong with the membranes. If membranes need to be replaced they will have to be delivered from outside the country.	84

Hazard	Hazard description	Comments	Risk priority number
R14	Fire (e.g. due to smoking inside the plant).	Smoking is taking place inside the plant.	84
R15	RO: Residual chlorine damaging the membranes.	Alarm monitoring for residual chlorine before RO. If membranes need to be replaced they will have to be delivered from outside the country.	84
R16	RO: Failure of the compressor; pneumatic system or of other installation hardware.	Spare parts are not available on site, knowledge in Cape Town.	56
R17	Hydraulic failure (e.g. pipe burst, pipe failure, pump failure) leading to process downtime.	There are backup pumps for all treatment steps. But local knowledge may not be enough to fix the problem, e.g. when they had a pipe burst in the inlet pump room and the room was flooded, leading to that 2 pumps were needed to be sent to George for repair. Always a risk of pipe burst of distribution pipeline. Flow meters with connected alarms will trigger if out of spec.	56
R18	The site is not secure (i.e. no fencing, gates, locks, safety/warning signs, inadequate security).	Problems with frequent thieving in the area and stealing the fencing are a fact. In the WRP there is more valuable equipment that is more desirable and also necessary for the process to work. Wooden doors that would not be hard to break. One guard is on site during the night and is responsible for both the WWTP and the WRP, but limited possibilities to take action since he is alone and a rather large area to cover. No locks on the chlorine station before the sedimentation basin.	56
R19	Failure due to inappropriate maintenance scheme (Not considering membranes).	No final maintenance plan at the moment, still under development. Supplier company maintains membranes. If sedimentation basin is not maintained it will lead to more frequent backwashing. If no maintenance scheme you don't know in which condition your installations are in, and therefore more breakdowns can be expected.	56
R20	Failure of maintenance (e.g. No availability of spare parts, no knowledge of how to perform maintenance) leading to failure.	Almost everything has some kind of backup system except RO. The supplier maintains UF and RO once a month first year. Shutdown of process in case of maintenance failure is noticed. Very limited availability of spare parts in Beaufort West why long downtimes can be expected if spare parts become necessary.	56

Hazard	Hazard description	Comments	Risk priority number
R21	Dosing malfunction due to equipment failure or power failure or improper dosing. Possible interruption of chlorination.	If pre chlorination fails, less oxidation in sedimentation basin leading to oxidization on membranes leading to more backwashing. Too much will lead to shutdown due to triggered by alarm before RO.	37
R22	Failure of on-line monitoring system.	If the PLC cannot communicate with the on-line monitoring the plant automatically shuts down resulting in process down time. This risk can therefore not be connected to quality related risks.	37
R23	UF: Oxidation of iron on membranes.	The iron will lead to fouling of the membrane, needs one day of backwashing.	37
R24	Problems related to low/high water or air temperature.	Water temp affects RO process, algae growth increases during summer while the sedimentation basin needs more frequent cleaning, water temp affect the sludge age. Increased risk of cyanobacteria.	37
R4	On-site reservoirs/ponds/watersumps can be compromised/contaminated .	If someone drops something in the cleanwater sump (only wooden cover, not sealed) it may give quality effects since there is no additional monitoring of this water before distributed. RO and UF feed tanks are neither sealed, this may have quantity effects due to triggered alarms. It the contamination is detected the plant needs to be shut down, resulting in quantity problems. According to the contractor the sumps will be sealed in the future to avoid accidental contamination.	28
R6	RO: Membrane break trough; fiber breakage.	Trance membrane pressure alarm should pick this up, also possible to noticed during maintenance. Possibility to repair smaller breakage on their own at site. Since this is final membrane, quality may be affected if the alarm does not work.	28
R27	Contamination or wear due to the use of unsuitable materials.	No final maintenance plan at the moment, still under development. Membranes are maintained by contracted company. If sedimentation basin is not maintained it will lead to more frequent backwashing. If no maintenance scheme you don't know in which condition your installations are in, and therefore more breakdowns can be expected.	28

Hazard	Hazard description	Comments	Risk priority number
R28	Chemical supply runs out.	Don't keep stock of chemicals but chemicals are provided by certificated trustable company (i.e. no chemical quality problem). No water will leave the plant if there is a lack of any chemical, therefore no quality effect, but quantity.	28
R29	UF: Membrane break trough; fiber breakage.	TMP-alarm should pick this up, otherwise it will be noticed during maintenance.	28
R25	UF: Increased membrane fouling, corrected with maintenance wash.	Increased backwashing is leading to more downtime, but no other problems. Life length should not be affected.	24
R1	Inadequate monitoring resulting in inadequate water quality or quantity risks.	Quantity consequences are referring to more backwashing as a result of inadequate monitoring of ingoing water quality (which may leading to un-optimized processes).	18
R30	Non optimized treatment processes can result in poor process performance.	Non optimized process will lead to more backwashes, CIP etc. Mainly a problem for the WWTP. This is where optimization will have biggest impact. RO is not likely to fail. Can treat almost any water to good quality, still there is a risk if the membranes are not optimized. If not optimized the UV is a final barrier for disinfection.	18
R26	Droppings of animals/birds (may e.g. introduce harmful micro-organisms into the water body)	A lot of birds nearby the maturation pond where visible, and a lot of bird dropping where confirmed on the water surface inside the pond. According to the operator the dropping will be removed in the sand filtration and the pathogens removed in other barriers in the reclamation system. Due to the origin of the water, this hazard should not be big risk.	16