CHALMERS
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## Identified contaminants of emerging concern affecting human health

Master of Science Thesis in the Master's programme Infrastructure and Environmental Engineering

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Master's Thesis 2015:131

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## ABSTRACT

Water reclamation can be one of the solutions when trying to solve the global water shortage. In the dry region Beaufort West, South Africa is a water reclamation plant supplying the inhabitants with drinking water, treated from wastewater. It is, however, important to evaluate the risks connected to this technology.

The aim of this study was to conduct a chemical risk assessment in order to identify the potential risks in the Beaufort West water reclamation system that may lead to adverse human health effects from identified contaminants of emerging concern, and to suggest countermeasures to reduce the most severe risks.

After identifying probabilities and consequences for the hazards and contaminants through interviews and sampling, a risk matrix was established and two increased risks identified. Both the risks were related to a high exposure of the hormone EE2, commonly used in contraceptives. One risk was connected to a long-term consumption of the final water and the other to unintentional ingestion during children's prohibited bathing in a brine channel. No increased risks related to EE2 in case of possible technical failures were found. Neither was any risk connected to any other of the analysed contaminants found. Possible countermeasures were suggested to decrease the risks of exposure from EE2 and by performing a Multi-Criteria Decision Analysis was a Granulated Activated Carbon process recommended to be implemented.

This study has shown that the Beaufort West direct potable water reclamation system results in very low risks of exposure from a large number of chemical contaminants. However, more research about hormones, degradation products and possible treatment technologies are needed. Further risk assessments should also be performed in this water reclamation system that include more contaminants as well as microbiological risks.

Key words: Water Reclamation, Wastewater, Drinking Water, Water Treatment, Risk Assessment, Risk Matrix, South Africa, EE2, MCDA, Granulated Activated Carbon

Kemisk riskanalys av återvinningssystemet för dricksvatten i Beaufort West, Sydafrika
- Utvalda föroreningar med påverkan på människors hälsa

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## SAMMANFATTNING

Att återvinna vatten är viktigt för att kunna lösa morgondagens stora utmaningar kring global vattenbrist. År 2010 byggdes ett vattenreningssystem där avloppsvatten återvinns till dricksvatten i staden Beaufort West i Sydafrika. Även om anläggningen har tjänat samhället väl i detta torra inland är det viktigt att undersöka vilka risker som finns kopplade till tekniken.

Syftet med denna rapport var att göra en kemisk riskanalys för utvalda föroreningar i vattenåtervinningssystemet i Beaufort West som skulle kunna leda till negativa effekter för människors hälsa. Syftet var även att föreslå effektiva åtgärder för att minska de mest allvarliga riskerna.

Genom intervjuer och provtagning av vattnet kunde sannolikheten för en fara samt dess konsekvens bli fastställda, vilka användes för att skapa en riskmatris. Två förhöjda risker identifierades, båda relaterade till höga halter av hormonet EE2, den aktiva substansen i bland annat p-piller. Den ena risken var kopplad till en långtidsexponering av EE2 från dricksvattnet och den andra risken skedde då barn från området olagligt badade i en kanal med restprodukter från reningsverket. Eventuella tillfälliga tekniska fel i processerna resulterade inte i förhöjda risker kopplade till EE2. Inte heller identifierades någon ökad risk kopplad till andra av de analyserade föroreningarna.

Åtgärder föreslogs för att minska de förhöjda riskerna och dessa utvärderades i en multikriteriebeslutsanalys (MCDA). Resultatet visade att tillägg av granulerat aktivt kol (GAC) är den mest effektiva åtgärden för att minska de båda identifierade riskerna.

Den här studien visar att dricksvattenanläggningen i Beaufort West med direkt återvunnet vatten innebär låga risker för ett stort antal kemiska föroreningarna funna i avloppsvatten. Mer forskning behövs dock kring hormoner, dess nedbrytningsprodukter samt möjliga reningstekniker men även en riskbedömning kring de mikrobiologiska riskerna för detta specifika reningsverk föreslås.

Nyckelord: Vattenåtervinning, Avloppsvatten, Dricksvatten, Vattenrening, Riskbedömning, Riskmatris, Sydafrika, EE2, MCDA, Granulerat Aktivt Kol

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# PREFACE AND ACKNOWLEDGEMENTS

This Master's Thesis was performed during spring and summer 2015 at Chalmers University of Technology, Sweden, in cooperation with Beaufort West Municipality, Chris Swartz Water Utilization Engineers and the Water Research Commission, all in South Africa. It was partly done by gathering data and information during a 10 week long field visit financed by SIDA (Minor Field Study scholarship).

Firstly, we would like to thank Ass. Pr. Thomas Pettersson, our supervisor at Chalmers, for all of his support. We also wish to send special gratitude to our South African supervisor, Mr Chris Swartz, for all of his help in our project and for the arrangements during our stay. Other people that have helped us in South Africa whom we want to acknowledge include:

*Linda van Zyl*
*Magda Pretorius*
*July Jacobs*
*Christopher Wright*
*Bettina Genthe*
*Herman Smith*
*Shawn Chaney*
*Lesley Petrik*
*Goliat Malouw*
*Franklin Jansen*
*Stanley Mjada*
*Richard Nongxaza*

This project would not have been the same without the help from all these people, thank you.

Göteborg, July 2015

Debora Falk and Anna Ohlin

## DEFINITIONS

| | |
|---|---|
| **Brine stream** | Waste stream containing elevated concentrations of total dissolved solids (Asano, et al., 2007). |
| **Equivalent safe dose** | The amount of a contaminant acceptable to consume per day per kilogram body weight during a lifetime. |
| **Hazard** | A source of potential harm (ISO/IEC, 2002). |
| **Therapeutic dose** | The quantity of any substance required to effect the cure of a disease (MediLexicon, 2015). |
| **NOAEL** | The highest exposure level with no significant increase in adverse effect and an ingestion of a contaminant of this concentration has not shown to be harmful (US EPA, 2014). |
| **Reference value** | The amount of a contaminant per litre acceptable to consume. |
| **Risk** | Calculated as the consequence multiplied by the probability. |

# ABBREVIATIONS

| | |
|---|---|
| **ADI** | Acceptable Daily Intake |
| **EE2** | 17α-ethinylestradiol |
| **ICEC** | Identified Contaminant of Emerging Concern |
| **GAC** | Granular Activated Carbon |
| **MCDA** | Multi-Criteria Decision Analysis |
| **NOAEL** | No Observed Adverse Effect Level |
| **QFS** | The company Quality Filtration Systems |
| **RO** | Reverse Osmosis |
| **S-ADI** | Surrogate Acceptable Daily Intake |
| **TDI** | Tolerable Daily Intake |
| **TTC** | Threshold of Toxicological Concern |
| **UF** | Ultrafiltration |
| **WRC** | Water Research Commission |
| **WRP** | Water Reclamation Plant |
| **WWTP** | Wastewater Treatment Plant |

# 1. INTRODUCTION

*This introductory chapter includes a background to present a broader context regarding issues connected to water reclamation and contaminants of emerging concern. The aim is presented, as well as the research questions and the delimitations.*

## 1.1. Background

There are approximately 1.1 billion people on earth having physical water scarcity and the available water resources are continuing to shrink (AWWA, 2008). In South Africa, more than 40 per cent of the freshwater systems are in a critical condition and this has created an urgent need for introducing new water sources (WWF, 2012). Wastewater that has been adequately treated can be used as reclaimed water and is therefore considered as a valuable resource in water stressed countries (US EPA, 2012). The microbiological risks of using reclaimed water are significant and are frequently discussed (Hamilton, et al., 2005).The potential health risks associated with exposure to chemicals in reclaimed water are however other challenges that need to be considered (Laws, et al., 2011).

The South African Water Research Commission (WRC) was established to promote and generate knowledge about water (WRC, 2015). A project founded by the WRC started in 2014 to address the health impact and risk priorities from emerging contaminants in wastewater for direct potable reuse in South Africa (Swartz, 2014). This master thesis was a part of this WRC project.

Beaufort West is located in the dry hinterland of the Southern part of South Africa, see Figure 1 (BWM, 2010). The town has approximately 41 000 inhabitants, all connected to the municipal drinking water system. In Beaufort West, no big industries are present within the municipality (Ivarsson & Olander, 2011). People living in informal settlements are connected to the water and wastewater system, but struggle with poverty and a high infection rate of AIDS (BWM, 2013). The drinking water in town is mainly collected from boreholes and dams, however due to frequent droughts in the past years a direct wastewater reclamation system for drinking water production was constructed in the year 2010 (Ivarsson & Olander, 2011).

*Figure 1. Dot indicates the location of Beaufort West in South Africa.*

## 1.2. Aim

The aim of this project was to identify chemical risks in the Beaufort West water reclamation system that may lead to adverse human health effects for the community from identified contaminants of emerging concern and to suggest countermeasures to reduce the most severe risks.

## 1.3. Research questions

The following research questions were used to fulfil the aim:

- What contaminants of emerging concern are present in the water passing the reclamation system?
- Are the treatment processes in the Beaufort West water reclamation system able to reduce concentration of the identified contaminants of emerging concern originating from the wastewater?
- What hazards may result in unacceptable exposure from the identified contaminants of emerging concern from the water reclamation system?
- What risks do these hazards result in?
- Which are the most feasible countermeasures to reduce the most severe risks?

## 1.4. Delimitations

The following statements have been used in order to delimit the aim of this study:

- The study area includes the water reclamation system, from the wastewater inflow to the point where the potable water leaves the system.
- A constant concentration of the studied contaminants in the inflow is assumed.
- Only failures leading to contaminants reaching the community will be considered. Thereby, risks related to disruption leading to no distribution of drinking water, such as pump failure, are not included.

# 2. THEORETICAL BACKGROUND

*The theoretical background includes information about the water reclamation system in Beaufort West and the identified contaminants' guideline values, together with background information used for the methodology.*

## 2.1. Beaufort West water reclamation system

The water reclamation system in Beaufort West consists of a Wastewater Treatment Plant (WWTP) connecting to a Water Reclamation Plant (WRP), see Figure 2 (Ivarsson & Olander, 2011). The water is fed to a reservoir after the treatment and mixed with water collected from boreholes and surface water that has been treated in a drinking water treatment plant. From the reservoir the mixed water is then distributed to the community. Approximately 30 per cent of the consumed water from the reservoir originates from the WRP. The stormwater is not connected to the wastewater infrastructure.

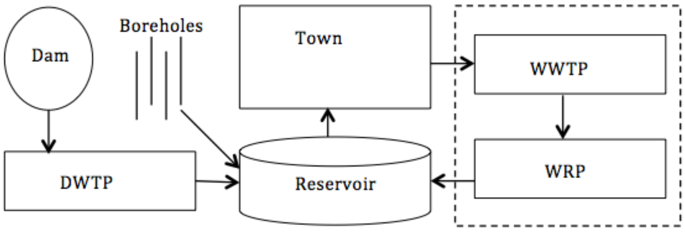

*Figure 2. The water infrastructure of Beaufort West. The dashed rectangle marks the water reclamation system. DWTP=Drinking Water Treatment Plant.*

The WWTP consists of a conventional treatment train, see Figure 3 (Ivarsson & Olander, 2011). The wastewater passes a screening and a grit removal, followed by activated sludge with ferric chlorine addition. The last process in the WWTP is secondary settling.

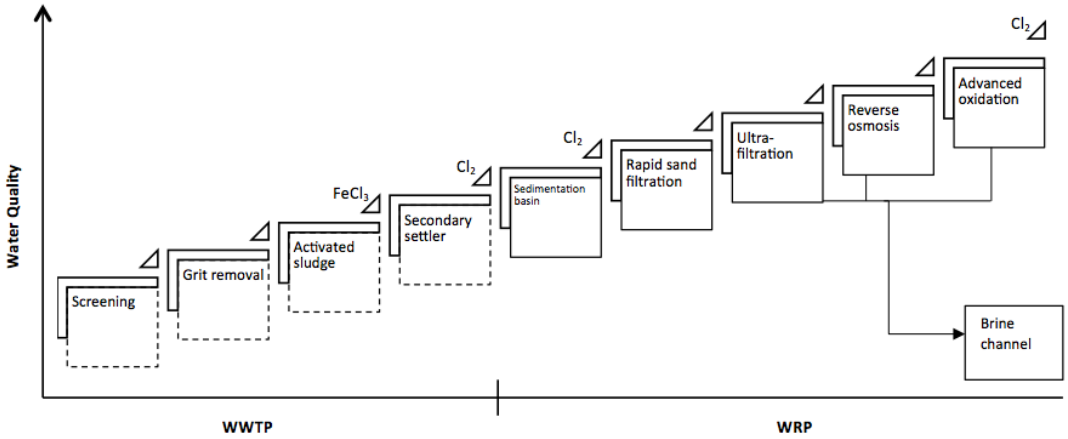

*Figure 3. Flow chart for the Beaufort West water reclamation system including WWTP and WRP.*

The first processes in the WRP consist of a sedimentation basin followed by a rapid sand filtration (Ivarsson & Olander, 2011). The purpose of this pre-treatment is to relieve the pressure of organic and inorganic particles on the membranes to prevent fouling and scaling on the Ultrafiltration (UF) and the Reverse Osmosis (RO). The final treatment consists of advanced oxidation of UV/$H_2O_2$ that, together with chlorination, remove and prevent regrowth of pathogens in the distribution system. The RO, UF and the advanced oxidation process are producing brine streams containing the removed organic matter and other contaminants.

The brine streams represent approximately 20 per cent of the inflowing water volume to the WRP according to the operator at the WRP[1]. The water from these streams is led to a channel, see Figure 3 and Figure 4, where it is then pumped away to be used for irrigation of sports fields and a golf course in the area, according to the technical manager at the municipality[2]. The superintendent of the WWTP[3] claims that children from the nearby community often are bathing in the brine channel on weekends and holidays, although these activities are not allowed. Previously, a fence was used to prevent unauthorised people from reaching the brine channel. This fence has, however repeatedly been stolen.

*Figure 4. Beaufort West water reclamation system (Google earth (July 6, 2015). Beaufort West, South Africa. 32° 22’ 53.5”S, 22° 35’ 08.4”E, AfriGIS (Pty) Ltd, 2015.)*

The WRP is remotely monitored and operated by private actors. All processes in the plant apart from the advanced oxidation, are monitored and operated by the company Quality Filtration Systems (QFS) whose office is located in the outskirts of Cape Town, about 500 kilometres southwest of Beaufort West. The status of the plant is controlled online automatically by QFS´s own monitoring system and all actions that could affect the quality of the water have to be approved by them. This include adjusting the flow and the dosage of chemicals among others. According to the director of QFS[4] are the processes equipped with alarm systems that will either give a warning or shut down the whole plant automatically in case of any indication of decreased treatment efficiency. This includes parameters like changes in pressure in membranes, changing turbidity or pump failures. The permanent staff members at the WRP on site are responsible for the everyday operation, like filling up chemicals and making sure that

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[1] Franklin Jansen (Operator, Beaufort West NEWater), interviewed by authors May 26, 2015.

[2] Christopher Wright (Manager, Technical Services, Beaufort West Municipality), private email to authors May 12, 2015.

[3] July Jacobs (Superintendent, Water and Wastewater, Beaufort West Municipality), interviewed by the authors April 22, 2015.

[4] Herman Smit (Director, Quality Filtration Systems), interviewed by the authors May 29, 2015.

the processes are operating at the right time. The processes are checked by a specialist visiting the site roughly once per week says the director at QFS.

The advanced oxidation treatment process is manufactured by the company Hanovia that also is responsible for the monitoring and the operation of this process. They are operating from an office located in Cape Town and Hanovia's alarm systems as well as their operation are similar to QFS's.

The activated sludge, UF and RO together with the advanced oxidation processes are those processes used in Beaufort West water reclamation system with highest expected removal efficiency of chemical contaminants (NRMMC, 2008). These processes are therefore described in more detail below.

### 2.1.1. Activated sludge

Microorganisms are used for degradation of biological matters and contaminants in the activated sludge process, and several parameters affect the efficiency, including retention time, changes of bacterial flora, sewage composition, aeration level and the balance between the available nutrition and mass of microorganisms (Ahansazan, et al., 2014; Esparza, et al., 2006; Gray, 2004). A common problem caused either by too low or too high sludge age is generated foam (Ahansazan, et al., 2014), which can affect later treatment steps and be long lasting (Gray, 2004). Another problem is that several industrial chemicals in wastewater have shown to be toxic to the bacteria in the process, which could lead to the transfer of untreated water before new bacteria can be introduced to the system (Yi, et al., 2006). The system used in Beaufort West is an aerobic process where oxygen is introduced to the water by aerators powered by electricity (Ivarsson & Olander, 2011). This could lead to short periods of less sufficient treatment in case of power failures, which, according to the superintendent at the WWTP[1], happens approximately twice per month.

### 2.1.2. Ultrafiltration

UF is used to separate molecules and colloids that are larger than the filter diameter, which varies between 1 and 100 nm from the water (Baker, 2012). The pore size used in Beaufort West is 40 nm, and several studies have shown that this type of membrane technology is highly effective at removing emerging contaminants (Adham, et al., 2005). The treatment technology is based on basic separation principals and size exclusion, which results in treated water passing through the membrane and untreated water leaving the process through a brine stream (Ivarsson & Olander, 2011). One big disadvantage with UF is that particles accumulate on the membrane surface leading scaling and fouling causing a higher pressure as well as a decreased flux. Therefore, both backwashing and chemical cleaning are necessary to keep the process efficient. A too high pressure is accordingly problematic and the pressure is therefore monitored and used as the most important indicator of the treatment efficiency according to the director at QFS[2]. Low pressure may also cause problems, especially rapidly decreasing pressure. This interprets a breakage in the membrane that could lead to leakage of contaminants.

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[1] July Jacobs (Superintendent, Water and Wastewater, Beaufort West Municipality), interviewed by the authors April 22, 2015.

[2] Herman Smit (Director, Quality Filtration Systems), interviewed by the authors May 29, 2015.

### 2.1.3. Reverse osmosis

In the RO system, dissolved materials are removed from the water under high pressure, separating the treated and untreated water by a membrane (Asano, et al., 2007). The separation is based on applying a pressure larger than the osmotic pressure on the untreated side where the contaminant concentration is higher (Ivarsson & Olander, 2011). This results in reversing the diffusion, called osmosis, that otherwise usually occurs when molecules move from one region of a substance concentration to another through a semi-permeable membrane, striving for equilibrium. From the concentrated side, where water is pressed through the membrane, a brine stream is produced as a waste product. The RO is highly effective for removal of chemicals (NRMMC, 2008), but pre-treatment is essential due to scaling and fouling, leading to shorter life length of the membrane (Asano, et al., 2007). The RO membrane used in the Beaufort West WRP is, according to the director at QFS[1], of the type BW30-400 elements used for brackish water (BW) with an active area of 400 square feet. A failure in this process is often revealed when a change of pressure is occurring, similar to the UF.

### 2.1.4. Advanced oxidation

By applying hydrogen peroxide ($H_2O_2$) in the inflowing water in combination with UV light, the good oxidation agents hydroxyl radicals ($\cdot OH$) are generated (US EPA, 2015c). The hydroxyl radicals can in many cases effectively destroy contaminants in the water, including pharmaceuticals and personal care products. A high quality of the inflowing water is important though to retain a sufficient system since both organic and inorganic compounds can be degraded and the hydroxyl radicals are non-selective. The degradation is therefore affected by different parameters including the organic matter content, alkalinity and nitrite concentration where these compounds can work as scavengers and consume hydroxyl radicals. This results in less efficient treatment for the intended contaminants.

The need for a high quality on the inflowing water makes this process suitable as the final step in a water treatment plant (US EPA, 2015c). The decreasing of UV intensity with time, together with fouling occurring on the lamp are examples of reduced efficiency in the absence of good maintenance. Another concern this treatment process raises is excess of peroxide, which can counteract the removal effect. The Beaufort West WRP uses a low-pressure process for the advanced oxidation, according to the director of QFS[1], with a UV dose of around 54 $mJ/cm^2$ and a $H_2O_2$ dose around 2 mg/L.

## 2.2. Contaminants of emerging concern and equivalent safe doses

Genthe et al. (2014) have presented a list of contaminants of emerging concern that are recommended to be prioritised when monitoring reclaimed water in South Africa, see Table 1. This list is a compilation of previous studies on common contaminants in wastewater adapted to the South African context.

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[1] Herman Smit (Director, Quality Filtration Systems), interviewed by the authors May 29, 2015.

*Table 1. Prioritised contaminants of emerging concern (Genthe, et al., 2014).*

| **Group** | **Contaminant** |
|---|---|
| **Industrial Chemicals** | TDCPP<br>TCEP<br>Lopromide<br>Benzo(a)pyrene |
| **Pesticides, biocides and herbicides** | Atrazine<br>Terbutylazine<br>Imidacloprid<br>Simazine |
| **Natural Chemicals** | Caffeine<br>17 β-estradiol |
| **Pharmaceuticals and metabolites** | Lamivudine<br>Stavudine<br>Carbamazepine<br>Cinchonidine<br>Cinchonine<br>Paracetamol |
| **Personal Care products** | Triclosan |
| **Household chemicals and food additives** | Bisphenol A |
| **Transformation products** | N-Nitrosodimethylamine |

NRMMC (2008) recommends the use of the following guideline values for contaminants in reclaimed drinking water during long-term exposure:

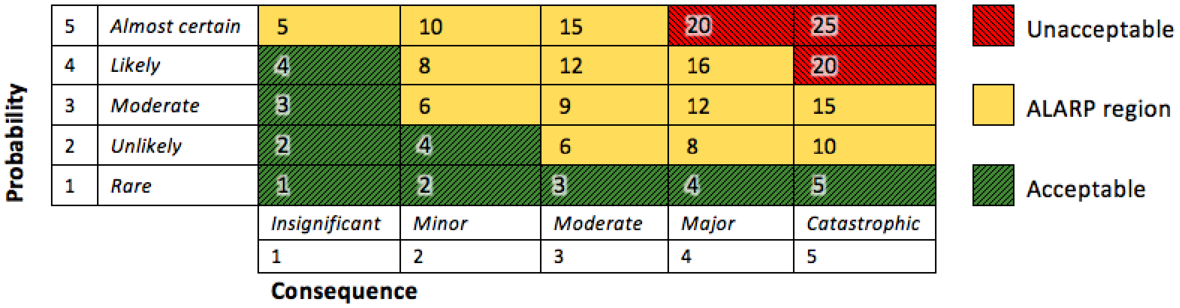
- Acceptable Daily Intake (ADI) and Tolerable Daily Intake (TDI), are usually calculated by applying a safety factor to a concentration corresponding to the No Observed Adverse Effect Level (NOAEL) (WHO, 2011b).
- Surrogate Acceptable Daily Intake (S-ADI) is used for pharmaceuticals and derived by using the therapeutic dose divided by a safety factor (NRMMC, 2008).
- Threshold of Toxicological Concern (TTC) is dividing the chemicals into toxicity groups, which gives them a representative dosage and includes a safety factor (NRMMC, 2008).

These dosages can be summarised under the concept *equivalent safe dose* with the unit µg contaminant/kg body weight/day.

## 2.3. Risk matrix

When analysing the risks a risk matrix can be used to visualise the severity of several events with the probability scale located at the y-axis and the consequence scale at the x-axis, see Figure 5 (David & Wilkinson, 2009). Each event identified and assessed will then be presented in the risk matrix grid being assigned a risk priority number that is the consequence multiplied by the probability (WHO & IWA, 2009). The highest risk is located in the upper right corner and has, in the example in Figure 5, the risk priority number 25. In addition, the lowest risk is located in the lower left corner and has the risk priority number 1.

In order to evaluate risks, the “As Low As Reasonable Practicable” (ALARP) principle can be used (Lindhe, 2010). The risks are then considered to be in one of the three different risk-tolerability levels; unacceptable, acceptable or in the ALARP region, which means that they are acceptable if it is unreasonable due to technical or economic reasons to reduce them, see Figure 5.



| | | | | | | |
|---|---|---|---|---|---|---|
| 5 | *Almost certain* | 5 | 10 | 15 | 20 | 25 |
| 4 | *Likely* | 4 | 8 | 12 | 16 | 20 |
| 3 | *Moderate* | 3 | 6 | 9 | 12 | 15 |
| 2 | *Unlikely* | 2 | 4 | 6 | 8 | 10 |
| 1 | *Rare* | 1 | 2 | 3 | 4 | 5 |
| | | *Insignificant* | *Minor* | *Moderate* | *Major* | *Catastrophic* |
| | | 1 | 2 | 3 | 4 | 5 |

🟥 Unacceptable
🟨 ALARP region
🟩 Acceptable

*Figure 5. Schematic picture of a risk matrix.*

Table 2 shows the levels of consequence and probability used by WHO (2005) and NRMMC (2008). The scales of the axis can be linear or non-linear and can be assigned different weights if the consequence and the probability are considered to contribute differently to the overall risk level (Ivarsson & Olander, 2011).

*Table 2. Levels of axis used for probability and consequences in the risk matrix.*

| **Level** | **Probability** | | **Consequence** | |
|---|---|---|---|---|
| | Descriptor | Description (WHO, 2005) | Descriptor | Description (NRMMC, 2008) |
| **5** | Almost certain | Once per day | Catastrophic | Major impact for large population |
| **4** | Likely | Once per week | Major | Major impact for small population |
| **3** | Moderate | Once per month | Moderate | Minor impact for large population |
| **2** | Unlikely | Once per year | Minor | Minor impact for small population |
| **1** | Rare | Once every five years or has never occurred | Insignificant | Insignificant or not detectable |

## 2.4. Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis (MCDA) is a set of decision-making techniques used for ranking countermeasures in a structured way by using a set of criteria (DCLG, 2009). Countermeasures can also be called risk reduction options or similar. In drinking water applications are the criteria of risk reduction and cost of each countermeasure usually used (Lindhe, et al., 2013). The objectives, which in drinking water applications are the suggested countermeasures, are given scores based on how they are expected to perform for each criteria (DCLG, 2009). The criteria are further ranked based on their importance for the result. The risk reduction may for example be considered more important than the cost of a countermeasure.

After obtaining the results from the MCDA, a sensitivity analysis should be done to see how the ranking of the criteria affect the final score (DCLG, 2009). This increases the credibility of the MCDA and the most influential criteria can be further evaluated.

# 3. METHODLOGY

*The methodology used to fulfil the aim is described in this chapter. The contaminants and hazards used in the analysis are presented as well as the method used to assign the consequence and probability in the risk matrix. Finally, the procedures used for the Multi-Criteria Decision Analysis and the sensitivity analysis are explained.*

## 3.1. Sampling

The identified contaminants of emerging concern (ICEC) found in Table 1 were prioritised by Genthe (2014). Those prioritised contaminants that also were possible to analyse with standardised methods are presented in Table 3. The contaminant 17 β-estradiol was not possible to analyse and was therefore substituted by the similar hormone 17α-ethinylestradiol (EE2) (Fredj, et al., 2015).

*Table 3. The detected and analysed contaminants as part of the prioritised list of contaminants of emerging concern for monitoring reclaimed water in South Africa (Genthe, et al., 2014).*

| **Group** | **Contaminant** | **Sampling 1 Detection** | **Sampling 2 Quantitative** |
|---|---|---|---|
| **Industrial Chemicals** | Iopromide | Not detected | Not analysed |
| **Pesticides, biocides and herbicides** | Atrazine | Detected | Analysed |
| | Terbutylazine | Detected | Analysed |
| | Imidacloprid | Detected | Analysed |
| | Simazine | Detected | Analysed |
| **Natural Chemicals** | Caffeine | Detected | Not analysed |
| | EE2 | Detected | Analysed |
| **Pharmaceuticals and metabolites** | Lamivudine | Detected | Analysed |
| | Stavudine | Not detected | Not analysed |
| | Carbamazepine | Detected | Analysed |
| | Cinchonidine | Detected | Analysed |
| | Cinchonine | Not detected | Not analysed |
| | Paracetamol | Detected | Analysed |
| | Sulfamethoxazole | Detected | Analysed |
| **Personal Care products** | Triclosan | Detected | Analysed |
| **Household chemicals and food additives** | Bisphenol A | Detected | Analysed |

The first sampling took place in April 22nd 2015 and the analyses were performed by LiquidTech based at the University of the Free State in Bloemfontein, South Africa. Qualitative analyses for each of the contaminants were made on eight sampling points, see Figure 6. Four of these samples were considered more important due to the location of where they were taken. Therefore, new samples were taken in May 25th 2015 at these locations and quantitative analyses were made to obtain concentrations of the contaminants.

Caffeine was a prioritised contaminant by Genthe (2014) because of its usage as an indicator of wastewater in unknown water sources. It has a low toxicity though and the presence of wastewater was obviously already known. Caffeine was therefore excluded in the quantitative analysis after discussions with Genthe[1]. Iopromide, Stavudine and Cinchonine were excluded due to their absence in the qualitative analysis.

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[1] Bettina Genthe (Senior resercher, CSIR Natrual Resources and the Environment), interviewed by the authors May 28, 2015.

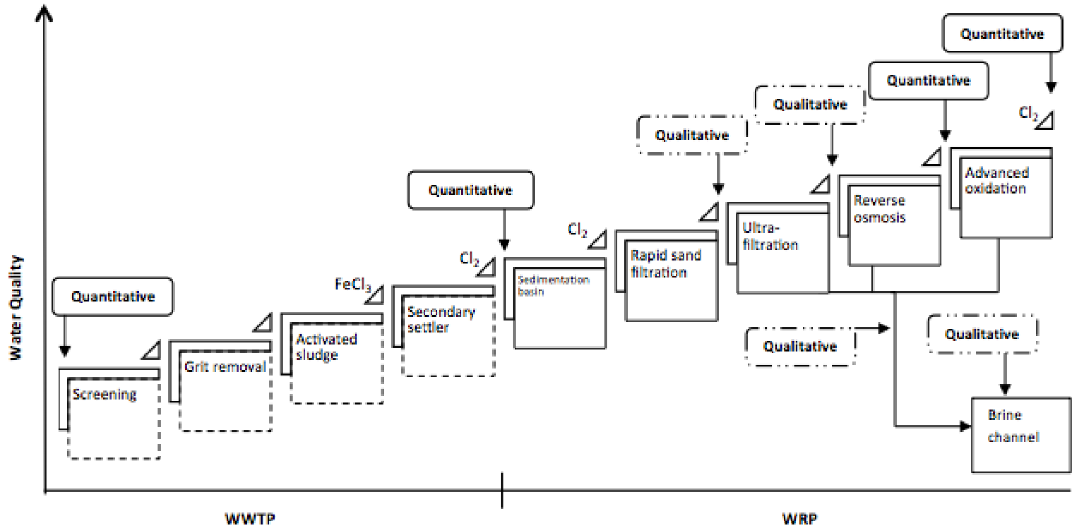


*Figure 6. The sampling location for quantitative and qualitative analysis.*

All samples were taken in dark tinted bottles of one litre which were filled to the top to prevent air in the bottles. Tin foil was placed on the bottle mouth to additionally prevent air entering before closing the bottle with a screw cap. Double pairs of gloves, which were washed or changed between each sample point, were used during the sampling. The samples from the WWTP were taken with the help of a bucket on a stick and a funnel to fill up the bottles and the bucket and funnel were washed before being reused. The samples from the WRP were taken from taps inside the plant after letting the taps flush for about a minute and rinsing each bottle with sampling water two to three times before taking the actual sample. The samples were sent to the analysing laboratory in a styrofoam box filled with ice packets and ice cubes.

### 3.2. Creating risk matrix

The following hazards that could lead to health risks caused by exposure from the ICECs were identified:

A. Insufficient treatment in the WWTP
B. Insufficient treatment in the WRP (excluding advanced oxidation)
C. Insufficient treatment in the advanced oxidation process
D. Ingestion of water from the brine channel
E. Contaminants constantly present in the drinking water

Hazards A, B and C are related to occasional technical failures in their corresponding treatment systems. The differentiation between Hazard B and C was made due to the finding in the qualitative analysis that the advanced oxidation contributed in decreasing four of the ICEC´s concentrations under the detection limit. The advanced oxidation process was therefore considered more important for the overall contaminant removal, and the removal efficiency of this single process was evaluated.

Hazard D is related to contaminants in the brine channel. It was included since unintentional ingestion also may lead to negative health impacts for the individuals bathing in the channel. These activities are prohibited but they are still considered to be a risk connected to the water reclamation system that may lead to a negative health impact for the individuals in the community.

The ICECs that are always present in the effluent and therefore constantly consumed by the population through the drinking water are included in Hazard E.

### 3.2.1. Assigning probabilities

For the hazards related to insufficient treatment (A, B and C) the probability for any event leading to a decreased water quality was used. The accumulated events sum up to the probability. For instance, if both electrical failure as well as foam building occur in the WWTP, then the probability for both events together will be used in the hazard connected to failure in the WWTP (Hazard A). To estimate the frequency of failures for the different processes information from interviews during field visits were used. The staff at the WRS and at QFS did, during these interviews estimate how often failures occur based on their experience. This, because it was not possible to access to raw data of failures.

The probability of unintentional ingestion, Hazard D, was assigned based on how often one person is estimated to be bathing in the brine channel. This data was achieved from interviewing employees at the WWTP. Hazard E was assigned the highest probability due to the constant exposure of ICECs from the drinking water.

### 3.2.2. Reference values

When calculating the reference value for long-term exposure from contaminated drinking water a body weight of 70 kg and an intake of two litres of water per day are made according to NRMMC (2008), see Equation (1). The equivalent safe doses used are presented in Table 4.

$$Reference\ Value\left[\frac{ug}{litre}\right] = Equivalent\ Safe\ Dose\left[\frac{\mu g\ per\ day}{kg\ body\ weight}\right] \times \frac{70\ kg\ body\ weight}{2\ litre\ per\ day} \tag{1}$$

To calculate the short-term reference value used during failures in the treatment plant, the long-term reference value was multiplied by the safety factors found in Table 4, see Equation (2).

$$\textit{Long-term reference value} = \textit{Short-term reference value} \times \textit{Safety factor} \tag{2}$$

This was done since it is possible to tolerate a higher concentration during a shorter time. These short-term reference values therefore represent a concentration similar to the therapeutic doses or NOAEL-values.

*Table 4. Equivalent safe doses, classes and safety factors.*

| **Contaminant** | **Equivalent safe dose** ***(µg/kg body weight/day)*** | **Class** | **Reference** ***(class)*** | **Safety factor** | **Reference** ***(safety factor)*** |
|---|---|---|---|---|---|
| **EE2** | 4.3 x$10^{-5}$ | S-ADI | (NRMMC, 2008) | 10 000 | (NRMMC, 2008) |
| **Atrazine** | 10 | ADI | (WHO, 2011a) | 100 | (WHO, 2011a) |
| **Bisphenol A** | 50 | TDI | (NRMMC, 2008), | 5 000 | (EFSA, 2006) |
| **Carbamazepine** | 2.8 | S-ADI | (NRMMC, 2008) | 1 000 | (NRMMC, 2008) |
| **Cinchonidine** | 1.6 | S-ADI * | (Petrik, et al., 2014) | 1 000 | (Petrik, et al., 2014) |
| **Imidacloprid** | 60 | ADI | (EFSA, 2013) | 100 | (EFSA, 2013) |
| **Lamivudine** | 2 | S-ADI * | (Petrik, et al., 2014) | 1 000 | (Petrik, et al., 2014) |
| **Paracetamol** | 50 | ADI | (NRMMC, 2008), | 100 | (EMA, 1999) |
| **Simazine** | 0.52 | TDI | (WHO, 2011a) | 1 000 | (WHO, 2011a) |
| **Sulfamethoxazole** | 10 | ADI | (NRMMC, 2008) | 100 | (NRA, 2000) |
| **Terbuthylazine** | 2.2 | TDI | (WHO, 2011a) | 100 | (WHO, 2011a) |
| **Triclosan** | 1.5 | TTC** | (NRMMC, 2008) | 100 | (NRMMC, 2008) |

* Calculated from therapeutic dose

** Class III

The *Australian guidelines for water recycling* use the assumption of a body weight of 13 kg for a child (NRMMC, 2008), and this value was used during calculations for the reference value regarding ingestion during bath. *The exposure factors handbook* from US EPA (2011) recommends the assumption of water ingestion while bathing for children to be 90 mL/event as an exposure factor. This is based on studies with 45 minutes long events for the children bathing and the use of the 97th percentile value. It was also assumed that each child is exposed on average once per week.

The equivalent safe dose corresponding to long-term exposure was used due to information indicating that the same children revisit the brine channel and get repeated exposure. The reference value for ingestion during bathing was therefore calculated as shown in Equation (3).

$$Reference\ Value\left[\frac{ug}{litre}\right] = Equivalent\ Safety\ Dose\left[\frac{\mu g\ per\ day}{kg\ body\ weight}\right] \times \frac{13\ kg\ body\ weight}{0.09\ litre\ /7 day} \tag{3}$$

In Table 5 follows the calculated reference values for the contaminants.

*Table 5. Reference values for long term, short term and ingestion during bath.*

| | **Reference value** | **Long-term exposure *[μg/L]*** | **Short-term exposure *[μg/L]*** | **Ingestion during bath *[μg/L]*** |
|---|---|---|---|---|
| **1** | EE2 | 0.001505 | 15 | 0.002 |
| **2** | Atrazine | 350 | 35 000 | 482 |
| **3** | Bisphenol A | 1 750 | 8 750 000 | 2 407 |
| **4** | Carbamazepine | 98 | 98 000 | 135 |
| **5** | Cinchonidine | 56 | 56 000 | 77 |
| **6** | Imidacloprid | 2 100 | 210 000 | 2 889 |
| **7** | Lamivudine | 70 | 70 000 | 96 |
| **8** | Paracetamol | 1 750 | 175 000 | 2 407 |
| **9** | Simazine | 18 | 18 200 | 25 |
| **10** | Sulfamethoxazole | 350 | 35 000 | 482 |
| **11** | Terbuthylazine | 77 | 7 700 | 106 |
| **12** | Triclosan | 53 | 5 250 | 72 |

### 3.2.3. Assigning consequences

To obtain the consequences, the concentration was divided by the reference value corresponding to the hazard, see Equation (4). This means that if the consequence is 2 the consumers ingest double of the amount set as the reference value. A consequence of 1 corresponds to consumption equal to the reference value and so on.

$$consequence\ (C) = \frac{concentration\ (c)}{reference\ value\ (RV)} \tag{4}$$

When identifying the concentrations for the hazards connected to insufficient treatment (A, B and C) a conservative approach was used by assuming that no treatment of the ICEC is possible in the corresponding processes during the hazard. For example, a failure in the UF means that Hazard B is occurring. It is then assumed that no treatment of any ICECs is possible in the whole WRP during this failure. The treatment efficiencies obtained from the sampling results were used to calculate the expected removal after the potential failure. The concentrations were then calculated according to Table 6.

*Table 6. Input for calculation of consequences for the different hazards.*

| | A | B | C | D | E |
|---|---|---|---|---|---|
| **Hazard** | *Insufficient treatment in the WWTP* | *Insufficient treatment in the WRP (excluding advanced oxidation)* | *Insufficient treatment in the advanced oxidation process* | *Ingestion of water from the brine channel* | *Contaminants constantly present in the drinking water* |
| **Reference value** | Short-term exposure | Short-term exposure | Short-term exposure | Ingestion during bath | Long-term exposure |
| **Concentration during hazard** | Concentration in influent times removal efficiency of WRP | Concentration before WRP times removal efficiency of advanced oxidation | Concentration before advanced oxidation | Removal in WRP times 5 | Effluent times 0.3 |

For Hazard D, ingestion was assumed when children from the community used the brine channel for bathing. All contaminants removed from the WRP are assumed to end up in the brine streams where the flow is approximately 1/5 of the total inflowing wastewater. The concentration was therefore calculated as the sum of the removal in the WRP times five, see Table 6.

The people connected to the drinking water system are considered to get 30 per cent of their daily intake of water from the water reclamation system, as this is the dilution in Beaufort West through the use of surface water and boreholes. The long-term exposure through drinking water is therefore calculated with the factor 0.3 as seen in Table 6. No dilution is assumed for short-term exposure, due to the possibility that only water from the WRP is consumed during a failure.

### 3.2.4. Scales and tolerability levels

Table 7 shows the probability and consequence scales corresponding to the levels. When assigning the probability to the different hazards the scale by WHO (2005) was used. For the consequence, the levels were based on the description from NRMMC (2008) see Table 2 (page 8) and the final intervals were determined after discussions with Genthe[1].

*Table 7. Probability and consequence scales*

| **Probability** | | | **Consequence** | | |
|---|---|---|---|---|---|
| **Scale** | **P** | **Description** (WHO, 2005) | **Scale** | **Interval C=c/RV** | **Description** (NRMMC, 2008) |
| **16** | 5 | Once per day | **81** | $C \geq 1000$ | Major impact for large population |
| **8** | 4 | Once per week | **27** | $100 \leq C < 1000$ | Major impact for small population |
| **4** | 3 | Once per month | **9** | $10 \leq C < 100$ | Minor impact for large population |
| **2** | 2 | Once per year | **3** | $1 \leq C < 10$ | Minor impact for small population |
| **1** | 1 | Once every five years or has never occurred | **1** | $1 > C$ | Insignificant or not detectable |

A risk with a higher consequence and lower probability (e.g. air plane crash) is often perceived as more serious than a risk with a lower consequence but higher probability (e.g. car crash). This, even though the total risk often is higher in the second case. The consequence scale does in this risk assessment, due to this reason, increase more for each level compared to the probability. The scales are defined as power functions, see Equation (5) and Equation (6).

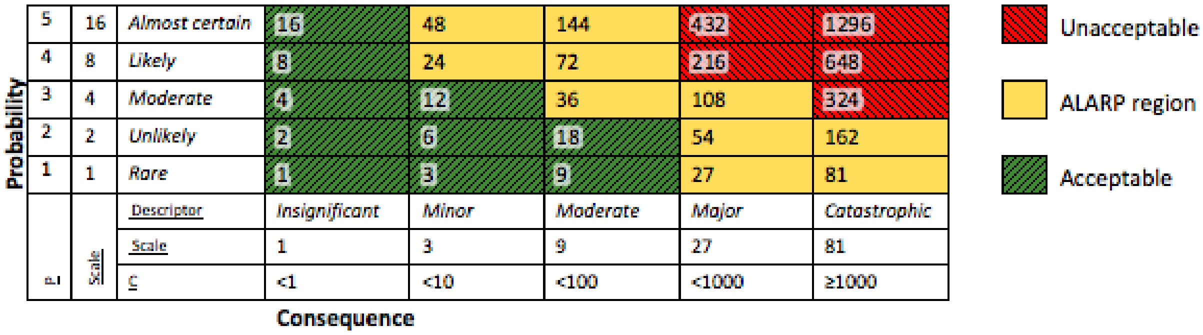
$$Scale_{probability} = 2^{level-1} \quad (5)$$

$$Scale_{concequnce} = 3^{level-1} \quad (6)$$

---

[1] Bettina Genthe (Senior resercher, CSIR Natural Resources and the Environment), interviewed by the authors May 28, 2015.

Further, using the ALARP principle (see section 2.3.) the risk-tolerability levels were identified, see Figure 7.



Probability

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5 | 16 | *Almost certain* | 🟩 16 | 🟨 48 | 🟨 144 | 🟥 432 | 🟥 1296 |
| 4 | 8 | *Likely* | 🟩 8 | 🟨 24 | 🟨 72 | 🟥 216 | 🟥 648 |
| 3 | 4 | *Moderate* | 🟩 4 | 🟩 12 | 🟨 36 | 🟨 108 | 🟥 324 |
| 2 | 2 | *Unlikely* | 🟩 2 | 🟩 6 | 🟩 18 | 🟨 54 | 🟨 162 |
| 1 | 1 | *Rare* | 🟩 1 | 🟩 3 | 🟩 9 | 🟨 27 | 🟨 81 |
| P | Scale | Descriptor | *Insignificant* | *Minor* | *Moderate* | *Major* | *Catastrophic* |
| | | Scale | 1 | 3 | 9 | 27 | 81 |
| | | C | <1 | <10 | <100 | <1000 | ≥1000 |

Consequence

🟥 Unacceptable

🟨 ALARP region

🟩 Acceptable

*Figure 7. The Risk Matrix with scales for the consequence and probability.*

The risk priority numbers for each risk-tolerability level are presented in Table 8. These levels were chosen after discussions regarding the severity of the combinations of consequences and probabilities. It was for example stated that a risk never can be acceptable if it has a major impact on the population as well as that an insignificant impact always is acceptable independent on how often it is occurring.

*Table 8. Risk priority numbers in relation to risk-tolerability levels.*

| Risk-tolerability level | Risk profile |
|---|---|
| **Low ($R \leq 20$)** | Acceptable risk |
| **Medium ($20 < R \leq 200$)** | The risk can be accepted if it is economically and/or technically unreasonable to reduce it (ALARP) |
| **High ($R > 200$)** | The risk cannot be accepted under any circumstances |

## 3.3. Multi-Criteria Decision Analysis

By studying the obtained risk matrix, the most severe risks were identified. To minimise these risks, countermeasures were suggested. The impact of each countermeasure led to new probabilities and consequences for the hazards and thereby new risk priority numbers. When an additional treatment step was chosen as a countermeasure its' expected removal and location in treatment train were found in the literature. These facts were used to introduce the treatment step in the calculations to get the expected final removal with it included. Thereby, new concentrations could be obtained in order to calculate the new consequences.

An MCDA was performed to evaluate which countermeasure that was the most suitable. The calculation of the scores of the countermeasures in the MCDA was done in the software Web-HIPRE (SAL, 2015). The criteria used in the MCDA were risk reduction and cost, see Figure 8. Risk reduction was ranked three times more important than the cost since the primary aim of the countermeasures is to decrease risks. The risk reductions were also ranked depending on how important it was considered to decrease the specific risk. The cost criteria were divided into the sub criteria of capital cost and maintenance cost, which were ranked as equally important. All the costs were converted into EUR and the maintenance cost was calculated as the cost per year during the first 15 years.

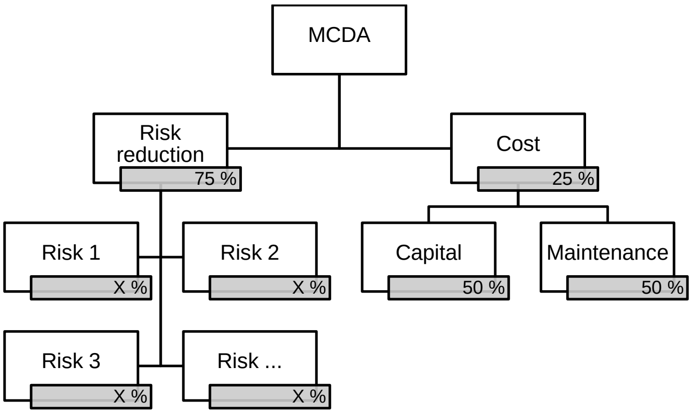


*Figure 8. Structure of MCDA.*

After obtaining the scores for the different countermeasures, a sensitivity analysis was done by using the software Web-HIPRE and it was possible to see how the ranking of the criteria affected the result. Figure 9 shows an example of a sensitivity diagram. In this example has criteria A been ranked to 75 per cent in relation to criteria B. This ranking is marked by the vertical line in the Figure.

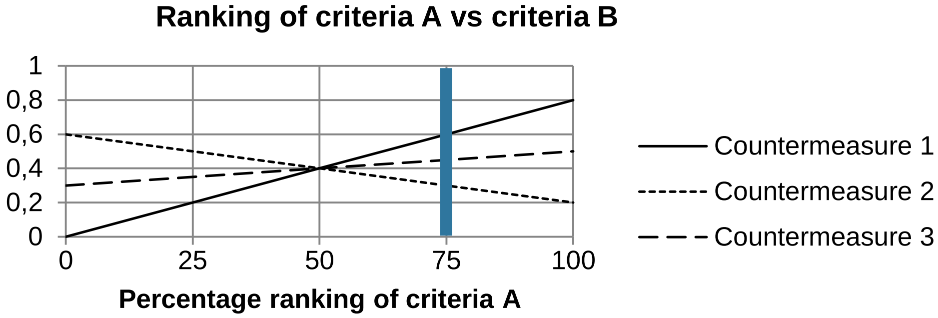


*Figure 9. Sensitivity plot for ranking of criteria A in relation criteria B. Criteria A was ranked to 75 per cent in the MCDA. Ranking of criteria B = 100 – Ranking of criteria A.*

A ranking of 75 per cent for criteria A means that criteria B has the ranking of 100 – 75 = 25 per cent. The lines in the diagram refers to the scores the countermeasures receive in the MCDA depending on the ranking of the criteria. It can be seen that if criteria A is ranked as 75 per cent does countermeasure 1 receive the highest score, which in this case is 0.6. It can also be seen that if criteria A and B would have been ranked equally (50 per cent each) all the countermeasures receive the same score in the MCDA which in this case is 0.4.

# 4. RESULTS

*In the results chapter, the concentrations of the analysed contaminants are presented and used to calculate the consequences. The motivations to the probabilities for the identified hazards are also given and used as input in the risk matrix together with the consequences. The most feasible countermeasures to reduce the most severe risks are evaluated in a MCDA.*

## 4.1. Sampling results

In Table 9 and Figure 10 the results from the quantitative sampling May 25th 2015 are presented. The concentrations are decreasing, for the majority of the contaminants, from the plant intake downstream through the treatment plant, which was expected. Imidacloprid is an exception with a higher concentration in the outflow compared to the inflow, even though this concentration also is close to the detection level. The concentration for sulfamethoxazole and simazine is also increasing along the treatment train. Cinchonidine has a concentration below the detection limit, as well as the majority of the samples for paracetamol. It can be seen that all contaminant concentrations are below their corresponding reference value for long-term exposure except EE2.

*Table 9. Concentration of chemical contaminants through the WWTP and WRP.*

| **ICEC** | **Reference value** (long-term exposure *[µg/L]*) | **Intake** *[µg/L]* | **After WWTP** *[µg/L]* | **After RO** *[µg/L]* | **Effluent** *[µg/L]* |
|---|---|---|---|---|---|
| **EE2** | 0.001505 | 2.53 | 2.38 | 0.154 | 0.13 |
| **Atrazine** | 350 | 0.0003 | 0.0006 | 0.0003 | 0.0001 |
| **Bisphenol A** | 1 750 | 0.5 | 0.179 | 0.029 | 0.015 |
| **Carbamazepine** | 98 | 0.402 | 1.08 | 0.94 | 0.72 |
| **Cinchonidine** | 56 | <0.002 | <0.002 | <0.002 | <0.002 |
| **Imidacloprid** | 2 100 | <0.001 | <0.001 | 0.003 | 0.002 |
| **Lamivudine** | 70 | 0.007 | 0.001 | 0.001 | 0.0003 |
| **Paracetamol** | 1 750 | 0.359 | <0.001 | <0.001 | <0.001 |
| **Simazine** | 18 | 0.004 | 0.028 | 0.018 | 0.014 |
| **Sulfamethoxazole** | 350 | 0.014 | 0.022 | 0.01 | 0.013 |
| **Terbuthylazine** | 77 | 0.003 | 0.004 | 0.001 | 0.001 |
| **Triclosan** | 53 | 0.35 | 0.05 | 0.008 | 0.002 |

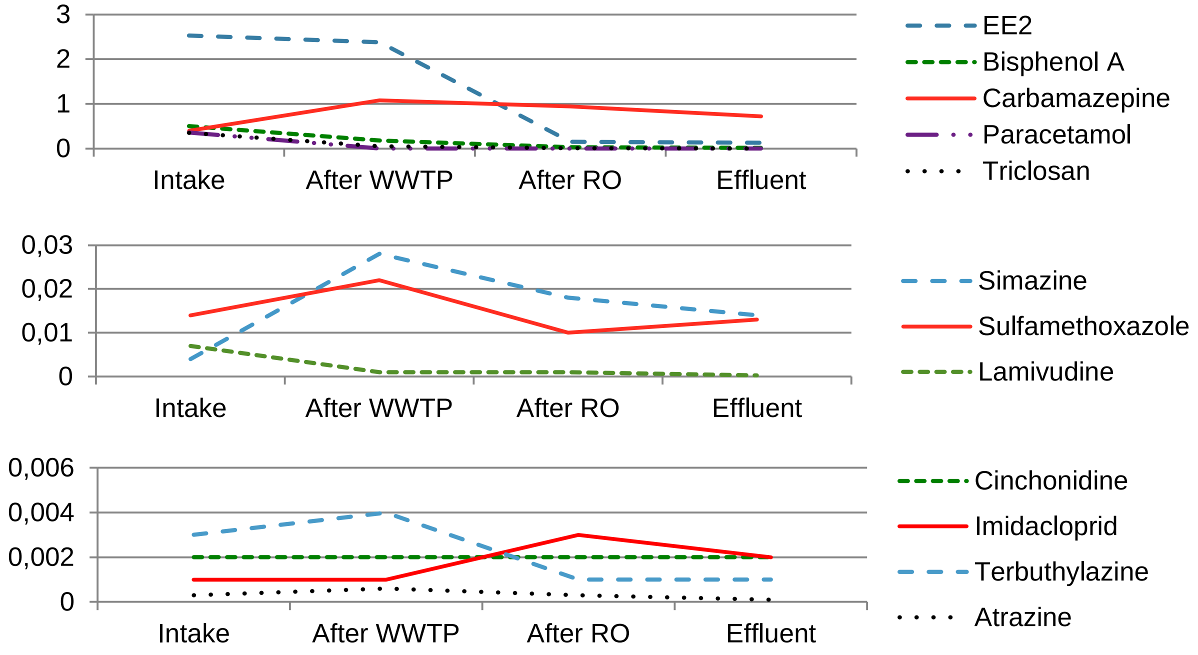


*Figure 10. Results from quantitative analysis [µg/L]*

## 4.2. Risk matrix

This chapter includes the motivation for the assigned probabilities and consequences. The resulting risk matrix is presented and the risk-priority numbers for the risks are listed.

### 4.2.1. Assigned probabilities

Hazard A includes any kind of failure or insufficient treatment in the WWTP that may lead to an increased concentration of ICECs in the WWTP effluent (and WRP influent). Since the activated sludge is the only process in the WWTP that effectively removes ICECs the probability of failure is based on this process. It was found that power cuts may lead to a decreased treatment efficiency during a short period of time in the activated sludge process, and that these occur approximately twice a month. In addition to other kinds of failures in the activated sludge processes the estimated rate of occurrence of any failure in the WWTP was assumed to be once per week. This resulted in the probability value 4.

Included in Hazard B were all incidents in the WRP leading to a decreased removal of the ICECs except incidents in the advanced oxidation process. The probability of a failure leading to an increased concentration of ICECs in the WRP effluent (drinking water) was considered very low. This is due to the alarm system in the WRP that automatically shuts down the plant in case of a sub-optional condition in the membranes. Hazard B was thereby assigned the probability value 1.

The advanced oxidation process, Hazard C, also has an alarm system similar to the rest of the WRP and a failure will shut the plant down. Since the system is remotely operated by experts and due to the low risk of failures, the probability for this Hazard was given the probability value 1.

Hazard D, unintentional ingestion during bathing, is assumed to occur in average once per week. Hazard D was therefore assigned the probability value 4.

Hazard E, long-term exposure, is related to continuous exposure of ICECs to the inhabitants of Beaufort West. Since the sampled concentrations are assumed to be constant and the exposure occurs on daily basis, the probability for Hazard E was assigned the probability number 5.

### 4.2.2. Assigned consequences

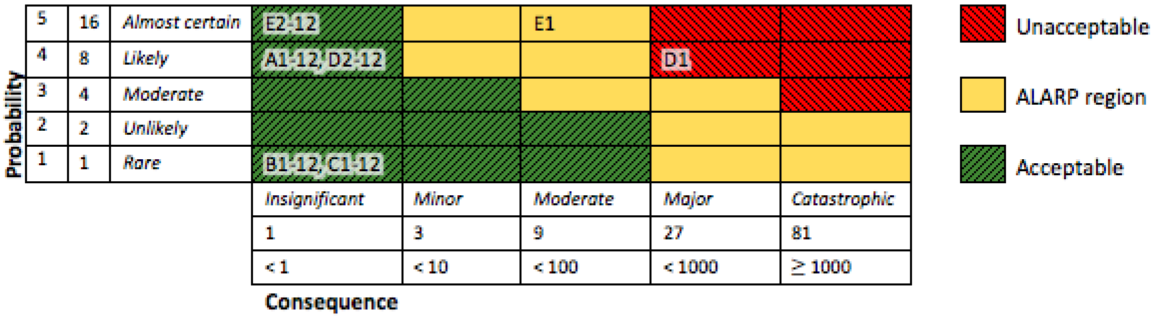
Table 10 shows the calculated consequences, using Equation 4, and the identified probabilities. A consequence <1 represents a concentration below the reference values, see Chapter 3.2.2.

*Table 10. Calculated consequences (see Equation 4) for the hazards.*

| | **Consequence** | **A** | **B** | **C** | **D** | **E** |
|---|---|---|---|---|---|---|
| **1** | EE2 | <1 | <1 | <1 | 259 | 26 |
| **2** | Atrazine | <1 | <1 | <1 | <1 | <1 |
| **3** | Bisphenol A | <1 | <1 | <1 | <1 | <1 |
| **4** | Carbamazepine | <1 | <1 | <1 | <1 | <1 |
| **5** | Cinchonidine | <1 | <1 | <1 | <1 | <1 |
| **6** | Imidacloprid | <1 | <1 | <1 | <1 | <1 |
| **7** | Lamivudine | <1 | <1 | <1 | <1 | <1 |
| **8** | Paracetamol | <1 | <1 | <1 | <1 | <1 |
| **9** | Simazine | <1 | <1 | <1 | <1 | <1 |
| **10** | Sulfamethoxazole | <1 | <1 | <1 | <1 | <1 |
| **11** | Terbuthylazine | <1 | <1 | <1 | <1 | <1 |
| **12** | Triclosan | <1 | <1 | <1 | <1 | <1 |

### 4.2.3. Forming risk matrix

The risks were placed in the risk matrix according to the probabilities and consequences as can be seen in Figure 11.



| Probability | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5 | 16 | Almost certain | 🟩 E2-12 | 🟨 | 🟨 E1 | 🟥 | 🟥 |
| 4 | 8 | Likely | 🟩 A1-12, D2-12 | 🟨 | 🟨 | 🟥 D1 | 🟥 |
| 3 | 4 | Moderate | 🟩 | 🟩 | 🟨 | 🟨 | 🟥 |
| 2 | 2 | Unlikely | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 |
| 1 | 1 | Rare | 🟩 B1-12, C1-12 | 🟩 | 🟩 | 🟨 | 🟨 |
| | | | Insignificant | Minor | Moderate | Major | Catastrophic |
| | | | 1 | 3 | 9 | 27 | 81 |
| | | | < 1 | < 10 | < 100 | < 1000 | ≥ 1000 |
| | | | Consequence | | | | |

🟥 Unacceptable

🟨 ALARP region

🟩 Acceptable

*Figure 11. Risk matrix with location of risks.*

The risk-priority numbers for all the identified risks are presented in Table 11 and the results show that two risks have increased priority numbers. Risk E1 corresponds to the constant presence of EE2 in the effluent and gets the risk priority number 144 and is located in the defined ALARP region of the risk matrix. Furthermore, risk D1, children swimming in the brine channel and ingesting the contaminant EE2, has the risk priority number of 216 and is located in the unacceptable area of the risk matrix.

*Table 11. Risk-priority numbers (probability times consequence).*

| Risk | Risk-priority number | Risk Level |
|---|---|---|
| **B1-B12, C1-C12** | 1 | Low |
| **A1-A12, D2-D12** | 8 | Low |
| **E2-E12** | 16 | Low |
| **E1** | 144 | Medium |
| **D1** | 216 | High |

In order to decrease the overall risks of the system further focus was put on decreasing these two risks and the following countermeasures are based on these.

## 4.3. Removal of EE2

17α-ethinylestradiol (EE2) is an oestrogenic hormone commonly used as the main ingredient in female contraceptives (Johnson & Sumpter, 2001) and most of the hormone is assumed to end up in the sewage water (Adolfsson-Erici, et al., 2005). The absence of effective removal of EE2 from wastewater has been shown for WWTPs all around the world (Koh , et al., 2008). Exposure of effluents from WWTPs was discovered to cause feminisation of aquatic organisms including male fishes and the fate of oestrogens and other endocrine-disrupting compounds has therefore been largely investigated (Purdom, et al., 1994).

The use of membrane technologies has shown to reduce the concentration of oestrogenic hormones in wastewater (NRMMC, 2008) but is according to Pauwels, et al. (2006) not a satisfying solution for treatment due to the production of a brine stream with elevated concentrations of hormones without degradation. The use of chlorination has shown to successfully degrade EE2 (Racz & Goel, 2009). It is a cheap technology, but has the disadvantage of increased reaction products with persistent characteristics (Hu, et al., 2003; Lee, et al., 2004; Moriyama, et al., 2004). Partial degradation of EE2 has also been shown by UV treatment but not efficiently enough to be an economically reasonable option (Racz & Goel, 2009).

When the unstable gas ozone is reacting with water, free radicals with oxidation powers are formed (Asano, et al., 2007). The process of using ozone is called ozonation and is commonly used as a disinfection process. The ozonation process has successfully shown to degrade EE2 with removal efficiencies of higher than 90 per cent (Huber, et al., 2003), but it is important to take into consideration that these technologies in the meantime could increase the formation of other oestrogens (Huber, et al., 2004). The reaction products from ozonation have been assigned lower oestrogenic activities than EE2 itself and ozonation has therefore been proposed as an effective technology for EE2 removal (Pauwels, et al., 2006). The high cost for large-scale ozonation is the largest disadvantage.

Electrodialysis is a process where a semipermeable membrane is separating ions moved by electrical potential (Asano, et al., 2007). Electrolytic removal has not yet been a widespread technology for water treatment (EPA, 2011) but a high treatment efficiency of 85-98 per cent EE2 removal has been shown in laboratory tests (Pauwels, et al., 2006). This kind of electrochemical treatment has many advantages due to low maintenance cost, low need for labour, short reaction time and relatively simple equipment (Chopra, et al., 2011).

Granulated Activated Carbon (GAC) is used in pressure or gravity filtration and consists of an organic base material with a diameter greater than 0.1 mm (Asano, et al., 2007). The removal of EE2 by using GAC varies in the literature, including an EE2 treatment around 41 ± 21 per cent according to Ho, et al. (2011) reaching over 99.8 per cent according to de Ruddera, et al. (2004) and Bodzek & Dudziak (2006). This variation could appear due to dissimilar concentrations of dissolved organic compound or humus acids that could block pores in the activated carbon structure, even though GAC is generally a very efficient treatment technology for EE2 (Racz & Goel, 2009).

## 4.4. Countermeasures

The processes in the Beaufort West water reclamation system do not treat the water to a satisfying level with respect to EE2 and development of the existing processes is therefore not selected as countermeasures to reduce the risk. Electrochemical removal could be a good option in a pilot project for the plant in the future, but more research needs to be completed for an appropriate design and implementation of this process. Ozonation and GAC are therefore the technologies chosen as countermeasures due to the reasons stated in chapter 4.3.

During interviews with the superintendent at the WWTP[1], a wall was suggested to constrain unauthorised people from reaching the brine channel. A fence has earlier been built and rebuilt several times around the area but has been stolen and is therefore not a good option to prevent the children from the community to enter. A wall was previously built around the drinking water treatment plant in the town and has been effective according to the superintendent. Building a wall around the brine channel to constrain unauthorised people to enter was therefore chosen as the third countermeasure.

### 4.4.1. Risk reduction

An ozone dosage of 1 g/m$^3$ has shown to degrade more than 90 per cent of the EE2, and an increased ozone dosage to 3 g/m$^3$ has shown a more than 99.8 per cent removal (Hashimoto, et al., 2006) which here would result in an EE2 concentration under the detection limit. The ozone dosage was in this case set to be approximately 2 g/m$^3$ and the removal is then assumed to be

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[1] July Jacobs (Superintendent, Water and Wastewater, Beaufort West Municipality), interviewed by the authors May 26, 2015.

95 per cent. The location of the ozone process is usually prior to the filtration (US EPA, 2015a). The ozone as a countermeasure was here then suggested to be placed after the WWTP but before the sand filtration in the treatment train.

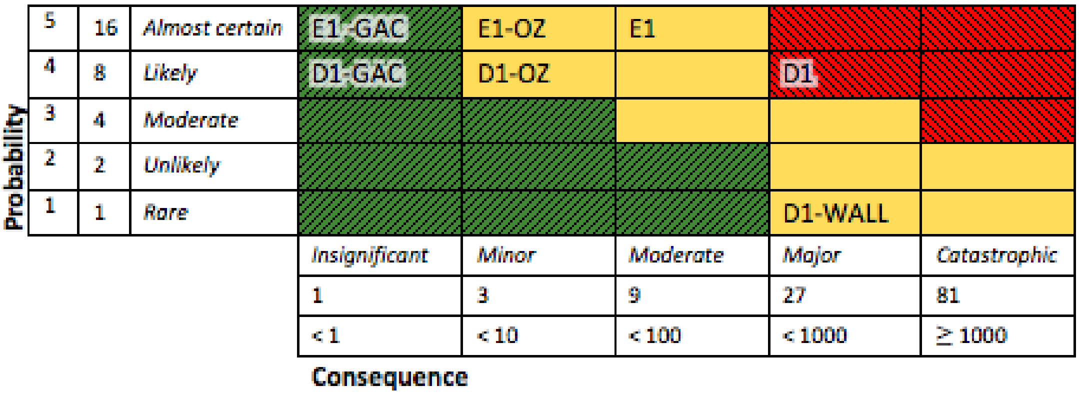
The removal rate of EE2 by GAC was set to 99.8 per cent, based on the most frequent mentioned treatment efficiency in the literature. The GAC was also placed after the WWTP in the same location as the ozone. This was because of the common use of GAC for filtration (US EPA, 2015b). It is not recommended to place the GAC before the flocculation though, since this would require frequent backwashing.

Based on the EE2 removal, corresponding to the additional processes and their location suggested above, new concentrations were obtained as can be seen in Table 12.

*Table 12. Input data for risk reduction.*

| **Countermeasure** | **EE2 Removal** | **Location** | **Calculated concentration of EE2 during bath** | **Calculated concentration of EE2 in effluent** |
|---|---|---|---|---|
| **Ozonation** | 95 % | After WWTP | 0.56 | 0.0065 |
| **GAC** | 99.8 % | After WWTP | 0.02 | 0.000026 |

The countermeasure of building a wall will only affect the probability of people bathing in the brine channel, which was assumed to decrease to level 1 on the probability scale. The wall will however not affect the consequence of exposure during an event of bathing and the probability of exposure from EE2 will not be affected by implementing ozone or GAC. Figure 12 visualises the risks location in the risk matrix after implementing the countermeasures.



| Probability | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5 | 16 | *Almost certain* | 🟩 E1-GAC | 🟨 E1-OZ | 🟨 E1 | 🟥 | 🟥 |
| 4 | 8 | *Likely* | 🟩 D1-GAC | 🟨 D1-OZ | 🟨 | 🟥 D1 | 🟥 |
| 3 | 4 | *Moderate* | 🟩 | 🟩 | 🟨 | 🟨 | 🟥 |
| 2 | 2 | *Unlikely* | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 |
| 1 | 1 | *Rare* | 🟩 | 🟩 | 🟩 | 🟨 D1-WALL | 🟨 |
| | | | *Insignificant* | *Minor* | *Moderate* | *Major* | *Catastrophic* |
| | | | 1 | 3 | 9 | 27 | 81 |
| | | | < 1 | < 10 | < 100 | < 1000 | ≥ 1000 |
| | | | Consequence | | | | |

*Figure 12. Risk reduction visualised on risk matrix. GAC = new locations of risks if implementing GAC. OZ = new location of risks if implementing ozonation. WALL = new locations of risks after building a wall (only one risk is affected in this case).*

The new risk priority numbers and the level changes in the risk matrix are presented in Table 13.

*Table 13. Risk reduction.*

| **Measure** | **D1 (EE2 in effluent)** | | | | **E1 (Ingestion of EE2 during bath in brine)** | | | |
|---|---|---|---|---|---|---|---|---|
| | **C** | **P** | **New risk priority number** | **Level Change** | **C** | **P** | **New risk priority number** | **Level Change** |
| Ozonation | 13 | 4 | *216-24*=192 | ◆→▲ | 1 | 5 | *144-44*= 96 | ▲→▲ |
| Activated carbon | <1 | 4 | *216-8*=208 | ◆→● | <1 | 5 | *144-16*=128 | ▲→● |
| Wall | 259 | 1 | *216-27*= 189 | ◆→▲ | 25 | 5 | - | ▲→▲ |

### 4.4.2. Cost

The inflowing water to a future ozonation processes was assumed to be close to pH 7.0, and the need of a pH regulator was therefore excluded in the cost. By using calculations based on Munther, et al. (2006), an annuity of 10 per cent during 15 years was done. The calculation for the maintenance cost originates from the average cost throughout 15 years. An average flow of 55 $m^3$/hour for Beaufort West WRP was assumed compared to the 40 $m^3$/hour used by Munther, et al. (2006), resulting in an approximately 50 per cent higher cost for this ozonation process. Reflecting the inflation, the approximate capital cost in year 2015 was estimated to 400 000 EUR and the maintenance cost 6 000 EUR/month.

According to an environmental consultant in water treatment[1] the capital cost for a similar GAC treatment process as the one suggested as a countermeasure was approximately 200 000 EUR in Sweden. The maintenance cost was approximately 130 000 EUR per month, mainly to buy the activated carbon needed for the process. These numbers were used without modification when estimating the cost for the GAC in the MCDA.

The cost of the wall around the other drinking water treatment plant in Beaufort West was approximately 12 500 EUR and it was 2 metres high and 250 metres long. A wall around the brine channel would be about 820 metres long. With the same price per metre this wall would have a capital cost of approximate 40 000 EUR based on the assumption of cost from the superintendent[2] regarding the already built wall. The assumed maintenance cost for the wall during the first 15 years is assumed to be close to zero. Table 14 summarises the costs for the countermeasures.

*Table 14. Cost for the countermeasures.*

| Countermeasures | Capital cost (Euro) | Maintenance cost (Euro/year) |
|---|---|---|
| **Ozonation** | 400 000 | 6000 |
| **GAC** | 200 000 | 130 000 |
| **Wall** | 40 000 | 0 |

## 4.5. Multi-Criteria Decision Analysis

A MCDA model was built up, as shown in Figure 13. The risk reduction of Hazard E1, contaminants in the effluent, was ranked as three times more important than the risk reduction of Hazard D1, bathing in the brine channel. This ranking is so since Hazard E1 affects the whole community through the drinking water while Hazard D1 only affects the children bathing in the prohibited brine channel.

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[1] Johan Magnusson (Technical Specialist, NCC) interviewed by the authors July 1, 2015.

[2] July Jacobs (Superintendent, Water and Wastewater, Beaufort West Municipality), interviewed by the authors May 26, 2015.

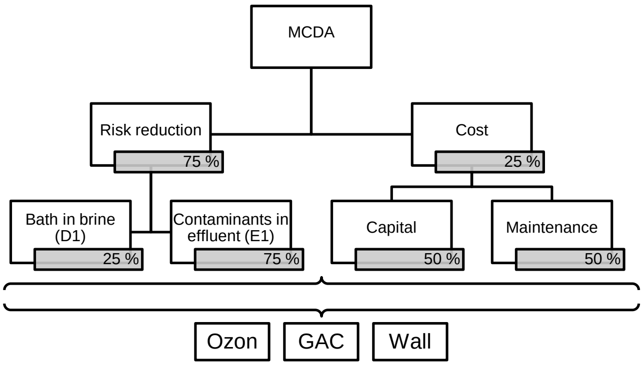

*Figure 13. Structure MCDA*

The risk reductions and the costs (Table 13 and Table 14) were put into the MCDA model and a result was obtained by using the online software Web-HIPRE.

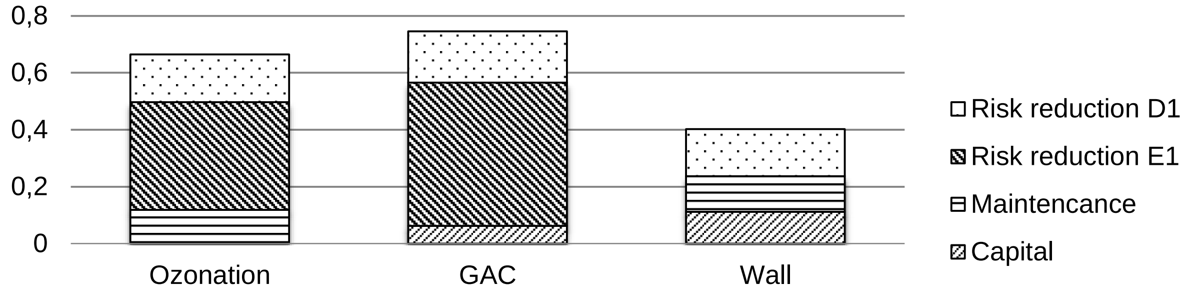

*Figure 14. Result from MCDA*

The result from the MCDA that can be seen in Figure 14, shows that the most suitable countermeasure is to implement a process with GAC. This is mainly due to the risk reduction of risk E1 (contaminant EE2 in the drinking water). The sensitivity analysis in Figure 15 to Figure 17 shows the influence that the ranking of the criteria has on the result in the MCDA.

Figure 15 shows the result of the MCDA depending on how the risk reduction is ranked in relation to the cost. The lines in the diagram represent the score of the countermeasures and the line located highest in the diagram is the most suitable for that specific ranking.

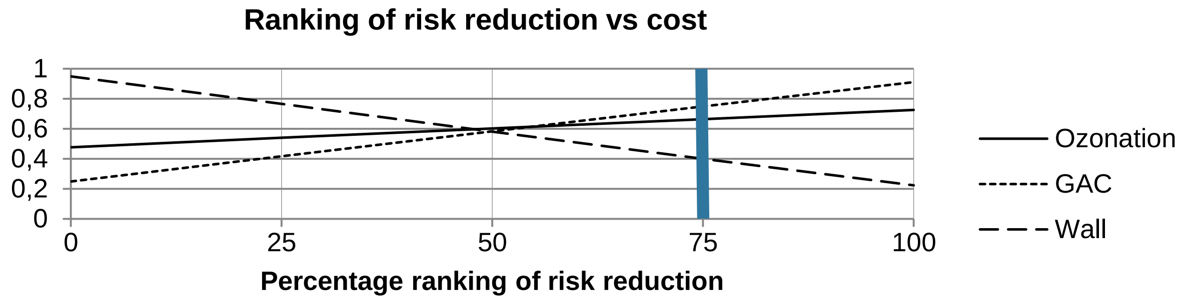

*Figure 15. Sensitivity plot for ranking of risk reduction in relation to cost. The risk reduction was ranked to 75 per cent in MCDA. Ranking of cost = 100 – ranking of risk reduction.*

The risk reduction had the influence of 75 per cent and the cost 25 per cent, giving GAC the highest score. All the countermeasures would have received approximately the same score if the risk reduction on the other hand would have been considered as equally important as the cost (50 per cent). If the risk reduction would have been ranked as less than 50 per cent in relation to the cost, the countermeasure of the wall would have been the most suitable. This since the wall has a lower cost but also a smaller risk reduction than the other countermeasures.

The sensitivity graph in Figure 16, shows how the result of the MCDA varies depending on the inter-ranking of the risk reduction of risk E1 (EE2 constantly in effluent) versus risk D1 (children exposed to EE2 through brine channel). In the MCDA the risk reduction of E1 was ranked to have a 75 per cent influence on the result while the risk reduction of D1 had 25 per cent influence.  It can be seen that GAC receives the highest score unless the risk reduction of E1 is ranked less than approximately 20 per cent of the total influence of the risk reduction.

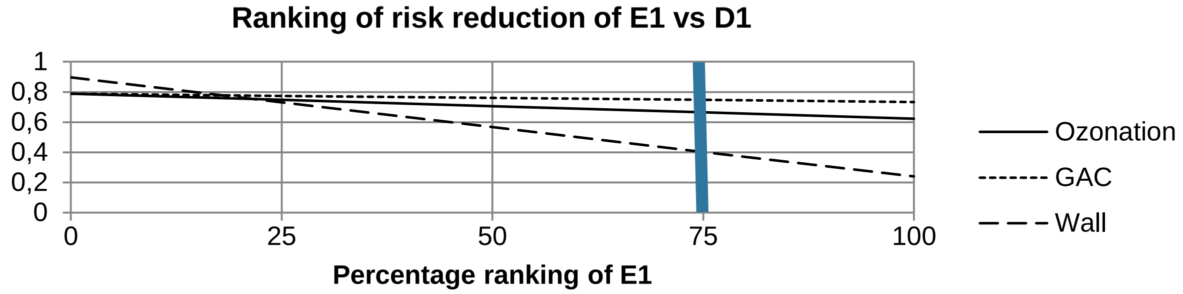

*Figure 16. Sensitivity plot for ranking of risk reduction of E1 (EE2 constantly in effluent) in relation to D1 (children getting exposed to EE2 through brine channel). E1 was ranked to 75 per cent in the MCDA. Ranking of risk D1 = 100 – Ranking of risk E1.*

The influence ranking variation of the capital cost versus the maintenance cost to the result of the MCDA can be seen in Figure 17. The capital cost is ranked to be equally influential to the result as the maintenance cost in the MCDA. If the capital cost would have the influence of 25 per cent or less, the countermeasure of ozonation would receive the highest score.

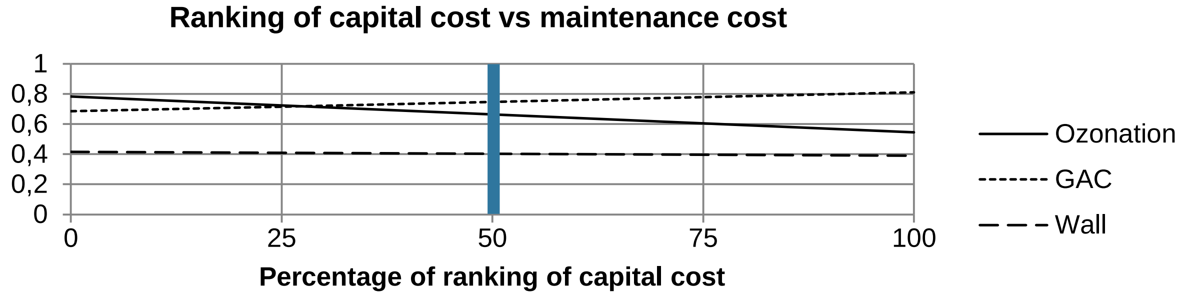

*Figure 17. Sensitivity plot for ranking of capital cost in relation to maintenance cost. The maintenance cost was ranked to 50 per cent in the MCDA. Ranking of maintenance cost = 100 – ranking of capital cost.*

# 5. DISCUSSION

*This chapter includes a discussion on the assumptions and limitations used that could have affected the result. The methodology is then discussed and the chapter ends with suggestions on further studies.*

## 5.1. Assumptions

An important aspect to keep in mind is that this study is based on the assumption that the concentration of the ICECs is constant in the inflowing wastewater. In reality, these concentrations vary due to precipitation, season and other factors. Furthermore, the concentration and the number of detected contaminants could change due to the activities in the town i.e. new industries connecting to the wastewater system or outbreaks of new diseases leading to increased usage of certain pharmaceuticals among the population connected to the WWTP.

It was assumed that the population of the community gets all of their daily intake (2 litre) from the municipal drinking water system. This leads to an overestimation of the exposure from the contaminants in the drinking water since people generally consume other kinds of liquids than drinking water, of their 2 litre intake during the day.

When calculating the long-term exposure, an intake of the same water is assumed throughout the whole life. Since most people do not get their water from the same water supply system during their whole life this assumption results in a conservative approach. However it gives an indication on whether the levels of contaminants in the water are acceptable or not over a life-time.

## 5.2. Sampling and analysed contaminants

One of the most significant findings was that the concentrations in the pure wastewater of all the contaminants except EE2 were far below their corresponding reference values (150 to 2.1 million times higher than the long-term reference value). This means that their presence, independent of the treatment efficiency of the reclamation system, will in its current concentrations never affect the health of the population even if exposed during a lifetime.

It is important to consider that the obtained result is based on only one quantitative sampling and that only a limited number of contaminants were analysed. It is therefore possible that if more samples were taken over a longer period of time and if more contaminants were analysed the result could have shown higher as well as lower risks. It is suggested that more sample occasions would be included in further studies.

Only one out of sixteen contaminants resulted in high risks. Some contaminants from the original prioritised list had to be excluded due to issues with finding a laboratory that could analyse these rare chemicals. If EE2 coincidentally had been excluded, no risk would have been found. The choice of analysed contaminates has therefore been proven to be very important, as exclusion of a single contaminant would change the result dramatically. This fact reveals the sensitivity of the sampling method and further studies that include a wider range of contaminants are therefore suggested.

The sampling results showed that some of the contaminants increased along the treatment train. This result is due to the inability to measure the exact same portion of water throughout the system and show the uncertainty of this sampling method. Taking more rounds of samples would have reduced these uncertainties.

The treatment efficiency for the ICEC in the WRP varies depending on the contaminant, see Table 15. This in contrast to the common perception that RO always is an extremely efficient treatment process. For example is the treatment efficiency as high as 96 per cent for triclosan but only 33 per cent for carbamazepine. It should, however, be kept in mind that the obtained treatment efficiency in the WRP can vary from the reality due to sampling errors. In this study is the relation between the reference value and the concentration however more important than the actual removal percentage although it is interesting to highlight them.

*Table 15. Percentage removal in WRP. The dash represents a concentration under the detection limit in the influent to the WRP.*

| Contaminant | Removal % WRP |
|---|---|
| **EE2** | 95 |
| **Atrazine** | 83 |
| **Bisphenol A** | 92 |
| **Carbamazepine** | 33 |
| **Cinchonidine** | - |
| **Imidacloprid** | - |
| **Lamivudine** | 70 |
| **Paracetamol** | - |
| **Simazine** | 50 |
| **Sulfamethoxazole** | 41 |
| **Terbuthylazine** | 75 |
| **Triclosan** | 96 |

## 5.3. Probabilities and consequences

The method of using the accumulated failure rate to estimate the probability, as well as using the consequences of nothing being treated in the specific treatment steps, results in a conservative approach (overestimation) of the risks. Since the risk assessment resulted in very low risks, despite the overestimation, the risks can be considered extremely low. If future studies with the same method would result in substantially higher risks, a more thorough investigation on the expected removal should be made.

Since all the risks connected to failures inside the plant were very low in this study was there no need for analysing the potential sub-failures in the hazards. This would have been necessary with higher risks during treatment failures. Both to better evaluate causes of the risks but also for deciding which countermeasures that most effectively can remove them.

Some processes in the treatment system experience decreased treatment efficiency during decreased water quality of the incoming water: failure in one system could therefore lead to less sufficient treatment later in the treatment train. Moreover, if a large portion of a contaminant is removed in the beginning of the treatment train it might be inaccurate to assume that the treatment in the next step would be as effective as if a larger portion would be in the feed water. This may instead lead to an underestimation of the treatment efficiency. Due to these problems, the obtained expected treatment rates should be compared to rates from similar studies in literature in case the risk assessment shows potential risks from hazards resulting from process failures.

To assume long-term exposure when calculating the risk during unintentional exposure during bathing in the brine channel is a conservative approach that led to an overestimation of the risk since this refers to a lifetime's exposure. The children bathing in the channel will most likely not be exposed through this pathway when they are grown up due to the changed lifestyle. To assume short-term exposure would, on the other hand, be an underestimation since employers at the WWTP claim that the same individuals revisit every weekend, leading to repeated exposure.

The assigned probabilities for the risks connected to system failures were decided after interviews with staff working at the reclamation system and at the company QFS. Some of these employees did not want to share information about system failures or raw data connected to the processes. The assigned probabilities could therefore not be verified by data as wanted and could for this reason perhaps be inaccurate. Their unwillingness of sharing information did not affect the result though, due to the low consequence for all contaminants connected to short-term exposure during system failures, this even if there would be a breakage every day. This could of course affect the results for future studies and raw data could therefore in these cases possibly be of higher importance.

## 5.4. The countermeasures and MCDA

The prioritisation in the MCDA was that the risk reduction is more important than the cost when choosing countermeasures. The sensitivity analysis showed that an equal rating of the risk reduction and the cost would have led to another result, which means that this ranking was essential for the results. However, this ranking was done due to the fact that a countermeasure only can be a good investment if it leads to a high risk reduction and the same cannot be said for a low cost.

The treatment efficiency found in scientific studies was given a high significance in the MCDA due to the high ranking of the risk reduction, which may be problematic due to the small selection of relevant literature about treatment technologies for the rare hormone EE2. Furthermore, the few existing reports in the area do have a big variation of their results.

The risk reduction for the hazard related to high concentrations of EE2 in the drinking water was ranked higher than decreasing the risk of exposure during illegal bathing in the brine channel. This, due to the fact that the high concentrations in the effluent can affect the whole population and the swimming activities only concern a small group during a more limited time of their life. This ranking was also made due to the general population's inability to choose alternative sources of drinking water, compared to the intentional illegal activity. The sensitivity analysis did, however, show that the same result of the MCDA would have been obtained even if the risk reduction of the two hazards had been equally rated.

It was difficult to find realistic investment and operation costs to use in the MCDA for the countermeasures. This was due to the disinclination from companies to give price information about their products, but also because of the uncertainty of the price picture in South Africa compared to other parts of the world. It was further considered very uncertain to use cost estimations that were older than a couple of years. Some prices were adjusted according to inflation but the fact remains that these kinds of technologies develop dramatically during a short period of time. It could therefore be inadequate to get price pictures from outdated reports due to the fast decrease in prices. The maintenance cost also varies due to the ozonation dosage and expected carbon consumption, which was hard to estimate due to the limited amount of literature in this field.

Ozonation and GAC, the technologies used as countermeasures in the MCDA, have scientifically shown good treatment efficiency for EE2 but could be perceived as expensive. A cheaper option than these technologies could therefore be to implement a pilot scale sized electrochemical treatment process using electrolyse. Electrolyse has proven to give a sufficient treatment of EE2 and has several benefits, including low maintenance cost. This technology was not included in the MCDA due to the limited ability to find this technology on the commercial market in South Africa, but could be very interesting to evaluate in future studies.

## 5.5. Further studies

Further studies that investigate a wider range of contaminants in reclaimed water are suggested. Other hormones used in contraceptives are especially interesting to investigate due to studies showing that decreased EE2 concentration actually could be a result of degradation to other similar hormones with negative impact on humans. To install a treatment technology that decreases EE2 is therefore only a good solution if the process does not increase the formation of other hormones. More studies have to be made in this area due to the low knowledge about different technologies' impact on the degradation of hormones and the overall treatment efficiency of these products. Chlorination should be of special concern; both because of the frequent use of this process in water treatment plants, but also due to the reported harmful degradation products.

This risk assessment did not include the microbial risks and it is therefore suggested that a similar study is conducted focusing on these risks. The same method can be used but adjusted to the fact that a small dose of microbiological organisms can have a large impact on human health. The aspect of long-term exposure can thereby not be applied. Furthermore, when applying this method to other contexts the contaminants analysed should be chosen based on the local situation. The reclaimed water in this study is, for example, mixed with ground water and surface water and consists of 30 per cent of the drinking water intake. This dilution should be modified accordingly to local situations in further studies. The microbiological risks could also be evaluated by using the method of Quantitative Microbiological Risk Assessment (Ander & Forss, 2011).

# 6. CONCLUSION

Two increased chemical health risks were found connected to the potable water reclamation system in Beaufort West, both related the hormone EE2. Long-term exposure from the final drinking water is one risk and the other is occurring during bath in the brine channel. It was recommended to implement a Granulated Activated Carbon process to reduce these risks. No other increased risks were found connected to the reclamation system. It is suggested that further risk assessments are conducted including more contaminants and microbiological risks. More research on treatment technologies for EE2 is also needed.

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