Master's thesis ACEX30

Evaluation of Risk Assessments for Source Water Protection Areas

Applying and Evaluating a New Approach for Risk Assessment Suggested by the Swedish Agency for Water and Marine Management

Master's Thesis in the Master's Program Infrastructure and Environmental Engineering

LOUJAIN ALHARFOUCH
ELIAS OLOFSSON

Department of Architecture and Civil Engineering
Division of Geology and Geotechnics
Chalmers University of Technology
Gothenburg, Sweden 2020

Evaluation of risk assessments for source water protection areas
Applying and evaluating a new approach for risk assessment suggested by the Swedish Agency for Water and Marine Management

Master's Thesis in the Master's Program Infrastructure and Environmental Engineering
LOUJAIN ALHARFOUCH
ELIAS OLOFSSON

Examensarbete ACEX30
Institutionen för arkitektur och samhällsbyggnadsteknik
Chalmers tekniska högskola, 2020.

Supervisor: Andreas Lindhe, Architecture and Civil Engineering
Supervisor: Helen Eklund, Sweco
Examiner: Andreas Lindhe, Architecture and Civil Engineering

Department of Architecture and Civil Engineering
Division of Geology and Geotechnics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 31 772 1000

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2020

Evaluation of risk assessments for source water protection areas
Applying and evaluating a new approach for risk assessment suggested by the Swedish Agency for Water and Marine Management
Master's thesis in the Master's Program Infrastructure and Environmental Engineering
LOUJAIN ALHARFOUCH
ELIAS OLOFSSON

Department of Architecture and Civil Engineering
Division of Geology and Geotechnics
CHALMERS UNIVERSITY OF TECHNOLOGY

Abstract

The aim of this master thesis is to evaluate the applicability of a new approach of risk assessment for water protection areas in Sweden. This was achieved by applying the risk assessment approach on four water sources that previously were assessed based on a common approach of risk assessment. The results from both risk assessments were compared and analysed in terms of risk sources characterisation, estimation of risk levels and presentation of the result.
It was found that the new approach in general adds significant value to the risk assessment. Mainly, by describing the physiological properties of the contaminants, consequences of contamination, and the waterworks ability to treat the contaminants. Furthermore, by including a pathway description of risk sources, the risk level could be efficiently described and motivated, which in turn makes it easier to motivate and describe restrictions in water protection areas. It was also found that the new approach is applicable on groundwater and surface water sources in both urban and rural areas. The factors that influenced the performance of the new approach the most were primarily the number of risk sources and the level of detail of the risk assessment. When the water source is particularly large, the common approach was considered more easily applicable to assess the risks.
To further improve the new approach, it is recommended to provide information about common drinking water contaminants, such as their physiological properties, health affects on humans, treatment processes in waterworks and related risk sources. It is also recommended to include guidance of how the contaminants efficiently can be grouped. Regarding future studies on the new approach, it is recommended to investigate how to incorporate and assess the risk related to future threats, water shortage and unplanned pathways.

Keywords: Risk Assessment, Source Water Protection, Water Protection Area.

Acknowledgements

This master thesis was carried out as a collaboration between the Department of Civil and Environmental Engineering at Chalmers University of Technology and Sweco. First of all, we are sincerely grateful to our supervisor Associate Professor Andreas Lindhe, for sharing his enthusiasm for risk assessment and for providing excellent guidance and support through out this work. We are also thankful for for the valuable discussions and the supervisory support from Helen Eklund from Sweco. We would like to thank Sweco for providing us with the professional data that made this work possible. Finally, We would like to thank our friends and our families for their support and encouragement. Especially, Mark Alharfouch for his constant support.

Loujain Alharfouch and Elias Olofsson, Gothenburg, June 2020

Contents

List of Figures

List of Tables

Glossary

aquifer recharge A hydrologic process that describes the water infiltration into the groundwater due to precipitation.

capillary zone The subsurface layer in which groundwater seeps up from the groundwater table by capillary action to fill pores.

carcinogenic The potential of a substance to cause cancer.

catchment area An area of land from which surface runoff, including water, sediments, nutrients and contaminants, drain into a common water body, such as a lake, river, and aquifers.

colloids Small suspended particles (size 2-200 nm). Their presence in water cause turbidity and coloring. In general, they could be electrically charge and thus, have the ability to attract other substances.

combined sewers A sewage system where wastewater and storm water drain in the same pipes.

combined sewers overflows In the event of heavy rain, the capacity of the combined sewers is exceeded leading to the discharge of untreated water to the recipient that is usually a water source.

commomly applied The risk assessment approach that is currently used in Sweden.

contaminant-based approach A method of risk assessment that assesses the risk related to contaminants rather then risk sources.

cumulative effect The combined effect of several risk sources.

delineation The process of determining the boundary of a water protection area.

genotoxic The potential of a substance to cause damage to the genetic information of the cells that leads to cancer or mutations.

groundwater table The upper surface of the zone of saturation.

group of contaminant The contaminants that shares the same physiological properties are gathered in one group and used to conduct the contaminant-based risk assessment.

hazard Source of potential harm or a situation with a potential of harm.

landfill leachate Water that has been in contact with the deposited waste, and extracts soluble or suspended solids, or any other component.

physiological proprieties Physical proprieties of a substance such as mass, density, conductivity,..etc that affect its spreading and transportation ability.

primer A type of official document used in Canada.

risk A combination of the probability and the consequence of an undesired/hazardous event.

risk source-based approach A method of risk assessment that assesses the risk related to risk sources.

sorption A transport process that slows down the movement of a contaminant due to reaction with other solutes and the geologic media.

source water protection Means protecting both the quality and the quantity of a water source from current and future threats.

Sweco European engineering consultancy company.

urban runoff A surface runoff from urban areas that causes the spread of several contaminants due to the precipitation on impermeable surfaces or saturated permeable surfaces.

water protection area An area around a groundwater or surface water source, used for drinking water supply, that is divided into different protection zones where the land use may be restricted in different ways to protect the water quality and quantity.

water source Raw water bodies such as rivers, streams, lakes, or underground aquifers that could be used in drinking water supply systems.

waterworks A utility that is responsible to treat water such as drinking water treatment plants.

Acronyms

ADWG Australian Drinking Water Guidelines.

CSOs Combined Sewer Overflows.

GAC Granular Activated Carbon.

HACCP Hazard Analysis Critical Control Points.

IDNR Iowa Department of Natural Resources.

NHMRC National Health and Medical Research Council.
NRMMC Natural Resource Management Ministerial Council.

PDP Pattle Delamore Partners.
PFAS Pre- and Polyfluoroalkyl Substances.

SGU Geological Survey of Sweden.
SwAM Swedish Agency for Water and Marine Management.
Swedish EPA Swedish Environmental Protection Agency.
SWPP Source Water Protection Plan.

TOT Time Of Travel.

WPA Water Protection Area.
WQRA Water Quality Research Australia.
WWTPs Wastewater Treatment Plants.

1
Introduction

A reliable access to safe drinking water is of key importance in society. Drinking water systems are, however, exposed to a wide range of risks due to e.g. human activities, societal development, aging infrastructure and climate change. The water sources, a fundamental part of the supply system, can be affected by e.g. industrial and agricultural activities, accidents, infrastructure projects, and urban development in general. Hence, water protection areas are an important part of securing the access to water sources of good quality and are regulated in the Swedish Environmental Code (SwAM, 2019a). The main purpose with a water protection area is to protect the water source by regulating activities that is considered hazardous. According to the Geological Survey of Sweden (SGU) around two thirds of the groundwater sources in Sweden has a water protection area, however, many of those was created based on old legislation and inadequate information, (SGU, n.d.). Even though the legislation does not require a water protection area, new environmental goals and stricter legislation suggest that unprotected water sources should be protected. According to WHO (2017), it is recommended that a risk assessment should be performed when developing a water protection area to assure safe water supply.

1.1 Background

Since 2011, the Swedish Agency for Water and Marine Management (SwAM) is the authority with responsibility for water protection areas. During 2019, they have been working on a new handbook on water protection areas and guidance on principles for risk assessment of water sources. The aim is that these documents will replace the Swedish Environmental Protection Agency (Swedish EPA) current handbook about water protection areas. According to SwAM (2019b), the reason for this change is that problems with the current use and management of water protection areas have been pointed out by the Drinking Water Inquiry (SOU 2016:32). The current handbook is outdated since new legislation have been added since 2003, when the handbook was created. Furthermore, there is limited guidance on how in detail to assess risks (current and future), analyse the effects of protective measures and compare benefits and costs in a structured decision analysis. A common problem with the current system is also that water protection regulations are handled too generally. According to SwAM (2019b), this leads to that some activities are regulated too hard while other potential risks is disregarded.

The new handbook is developed in a more risk-based approach. The idea is that the delineation of the water protection areas and regulations are directly motivated by the risk assessment results. This can be compared to the current method were the delineation is done primarily based on the time of travel, (TOT) from risk source to point of intake. The idea is that the new approach will contribute to clarify and justify regulations and create a delineation of the water protection area that is locally adapted for present and future use.

The new approach have recently been revised by different stakeholders within the drinking water supply sector. It is important to state that the new handbook from SwAM still is a proposal and needs to be evaluated and complemented before it can be applied as guidance for water protection areas in Sweden. This master thesis is made in collaboration with Chalmers and Sweco, it is built on real case studies and provides important input to evaluate the risk assessment suggested by the SwAM.

1.2 Aim and Objectives

The aim of this project is to evaluate the suggested approach for risk assessment of water protection areas. To fulfil this aim, a set of specific objectives were established:

1. To conduct a literature review on how risk assessments for water protection areas are performed in Sweden, in other countries and in the new approach.
2. To apply the suggested risk assessment approach at four different water sources where water protection areas already exist (and risk assessment previously have been performed).
3. To compare the results from the new approach with previously performed risk assessments.
4. To evaluate the applicability of the new approach to different types of water sources (advantages and disadvantages, when is it applicable/not applicable, etc.)

1.3 Limitations

This master thesis focuses on evaluating risk assessments for water protection areas, it will therefor not comment or analyze the process of creating water protection areas as a whole. Neither will it assess the delineation process or which regulations to implement within a water protection area. Furthermore, the data used as input in the new approach of risk assessment is the same as used in previously performed risk assessment with a common approach. The purpose of conducting a risk assessment with the new approach is to make it possible to compare the risk assessment. Thus, the risk assessments performed in this master thesis should not be seen as an independent risk assessment.

2

Risk Assessment for Water Protection Areas

Risk can be defined as the combination between the probability of an unwanted event to occur and the consequence that the event might lead to (SwAM, 2019a). The risk related to the production of drinking water is affected by a wide range of parameters and there are many ways a contaminant can reach the drinking water supply system. This report will primarily address the risk imposed on a water source used for water supply, hence, risk related to drinking water production and the distribution of drinking water is not addressed.

First of all, there need to be a source of a potentially hazardous contaminant, often referred to as a risk source. The spreading of the contaminant is affected by e.g. physiological properties of the contaminant, available pathway and barriers (SwAM, 2019a). For an illustration of how a contaminant can spread to a water source see *Figure 2.1*. Another important factor is how hazardous the contaminant is, in which amount it is released and the delusion factor in the receiving water source. According to the Swedish EPA (2010), it is therefore important to assess the vulnerability of the water source to be able to estimate the consequences of a potential contamination. A general risk reduction measure within a water protection areas is the implementation of barriers. Barriers may already exist as natural elements that restrict the pathway of a contaminant. This is done by e.g. sorption in the soil, biological degradation and dilution (Fetter, 2014). Implemented barriers can be physical, technical etc. and can function as risk reduction, both by lowering probability of an event to occur or by lowering the consequence. For example, the barriers could consist of embankments that prevents contaminants from reaching the water source or it could be technical barriers such as warning systems that shuts the water inlet in case of accident or if too high concentration of a contaminant is detected within the water source.

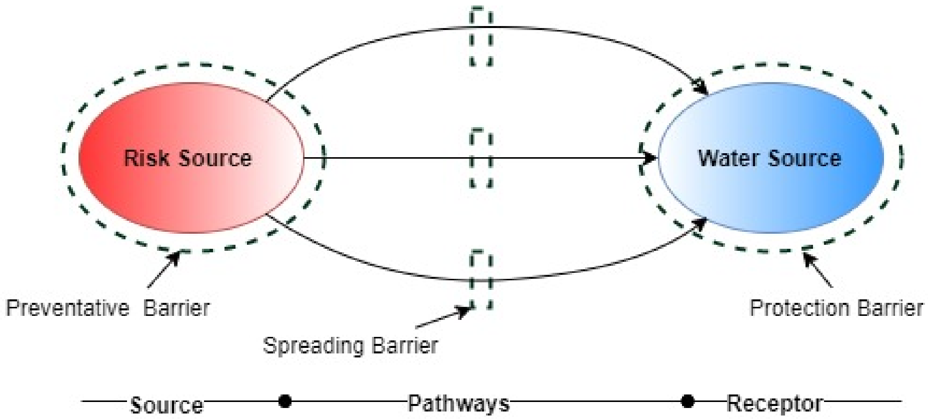

Figure 2.1: *Illustration of how a contaminant could spread from a risk source to a water source, given that there is a pathway and insufficient barriers to prevent the spread.*

2.1 Water Sources

Water sources can be of different types, in Sweden 50% of the water supply consist of surface water, 25% of natural groundwater and another 25% of artificially infiltrated groundwater (SwAM, 2019a). When assessing the risk it is important to understand the properties of each water source, mainly, because the vulnerability differs between groundwater and surface water sources.

2.1.1 Groundwater

Groundwater sources are protected by a soil layer that can be seen as a natural barrier. In the soil, nutrients are consumed, contaminants are being degraded and the water is filtered. The retention time in a groundwater source is often long, this makes the groundwater in general have a good quality, low microbial activity and low fluctuation between season and specific events. However, a contaminant that was not degraded or filtered out in the top layer of the soil could potentially accumulate within the groundwater source and deteriorate it over time (USGS, n.d.-a). An example of this is the extremely persistent group contaminants called PFAS, short for Per- and polyfluoroalkyl substances, which has been found accumulating in ground water sources due to fire-fighting activities (SwAM, 2019a). The remediation of a groundwater source is a complex, long and expensive measure (Swartjes and Grima, 2011). Therefore, the consequence of contamination could be that the water source cannot be used as water supply for a long time.
Artificially infiltrated groundwater can in legal terms be considered a groundwater if the retention time is longer than 14 days and the distance from infiltration point to extraction point is more than 40 meters (SwAM, 2019a).

2.1.2 Surface Water

Surface water sources is more exposed to the surrounding environment then a groundwater source. However, large dilution factor and fast shifts of water can prevent high concentrations of a contaminant within the water source (WHO, 2016). Due to events such as the turn of the thermocline, variations in land use and precipitation, a surface water is subject to larger fluctuation in water quality.
Since surface water contains microorganisms and is exposed to sunlight, degradation of organic contaminants may occur over time (SwAM, 2019a). Therefore, according to SwAM (2019a), the largest risk posed on a surface water source is a peak load of a contaminant rather then accumulation over time.

2.2 Drinking Water Contaminants

There are different types of contaminants that can cause harm to a water source. The effect of a contaminant spreading to a water source can be direct health effects to humans but also the ability to use the water source for present and future water supply. When performing a risk assessment, knowledge about the contaminants physiological proprieties, hazardousness and typical sources is essential. Furthermore, it is recommended by SwAM (2019a) that the contaminants are categorized based on their physiological properties, since this will affect their ability to spread the most.

2.2.1 Pathogens

Pathogens that has the potential to affect the drinking water consumer are: bacteria, viruses and protozoa (Bridle, 2014). Pathogens originate from fecal matter from humans and animals and may cause health effects. They are organisms that requires a surface to attach to and organic matter to grow (Bradford et al., 2013). Thus, water with high turbidity and high content of organic matter pose high risk of microbial contamination. Therefore, pathogens has higher presence in surface water than in groundwater. Moreover, Pathogens have different durability levels, with viruses being the most persistent. However, they can be inactivated by disinfection measures (WHO, 2004). Pathogens behaves as colloids which means that they are suspended in the water and easily spread. Due to decay, the risk of microbial contamination is a peak load in the water source rather than an accumulation over time.
If pathogens are not sufficiently treated in the waterworks, the drinking water consumers will be infected (WHO, 2008). This can cause a variety of health effects on humans, such as fever, diarrhea, vomiting, cramps, and weakened immune system. This can also lead to epidemic outbreaks and potential deaths. Another consequence of the potential health effects is the social economic costs of medical care and a populations inability to work (ibid.). Furthermore, sanitation of waterworks and intensive water quality analysis are necessary (WHO, 2006). Common sources of microbial contamination are: husbandry, combined sewer overflows CSOs and on-site sewers.

2.2.2 Petroleum Products

Petroleum products such as gasoline, diesel, crude oil, jet fuel and lubricant oil are liquid hydrocarbons that are lighter than water (Newell et al., 1999). Their chemical structure makes them persistent, however, they degrade slowly in the environment. According to Newell et al. (1999), they have low solubility in water and due to their light density, they mainly spread in surface waters or in the capillary zone above the groundwater table. This behavior enhances the lateral spreading distance while preventing vertical spreading. The fraction of more volatile petroleum products such as gasoline does not bind to geological materials which further enhance the spreading (USEPA, 1996).
Petroleum products are highly toxic to humans at low concentrations, they are also genotoxic and carcinogenic (Khanna and Gharpure, 2017). According to SwAM (2019a), low concentration (about 5 ug/L) also affects the taste and makes the water undrinkable. The consequence of petroleum products contamination is that the water source might need to be abandoned or closed to be remediated for a long time. Furthermore, if the contamination reaches the waterworks, sanitation is needed (SwAM, 2019a). Common sources of petroleum products are: transports of hazardous goods, tanks storing petroleum products, urban runoff from roads and petrol stations.

2.2.3 Common Organic Contaminants

Common organic contaminants are pesticides, chlorinated solvents, phenols and PFAS (Huling and Weaver, 1992). In general, pesticides is of most concern due to their continuous use in agriculture and forestry. The chemical structure of these organic contaminants makes them very persistent. They are not soluble in water, However, since they are denser than water, they can penetrate the groundwater table and affect a whole aquifer (Huling and Weaver, 1992). This behavior decreases the lateral spreading distance while increasing it vertically (ibid.). However, with time they also spread in a lateral direction.
They are toxic to humans at very low concentrations and they are also genotoxic and carcinogenic (USEPA, n.d.). Pesticides and PFAS can accumulate in an organism and magnify over time, which further indicates that even low concentrations are problematic (ibid.). The consequence of sever contamination by these chemicals is that the water source might need to be abandoned or closed to be remediated. Due to their vertical spreading behavior, they can accumulate in an aquifer, which pose a large risk to groundwater sources (Huling and Weaver, 1992). Common sources of these chemicals are: agriculture, forestry, old dry cleaning facilities, industry discharge, fire-fighting substances and storage of timber.

2.2.4 Heavy Metals

Heavy metals are metals with density higher than 5 g/cm3 and with similar physiological properties (Tutic et al., 2015). Examples of heavy metals are: cadmium, chromium, cobalt, copper, lead, mercury, nickel and zinc. They are mainly solids with the exception of mercury that could occur in a liquid form in nature (USEPA, 2019a). Furthermore, they are undegradable inorganic elements that naturally occur in the environment. The spreading of heavy metals highly depends on their solubility and the pH of the water. Generally, with low pH the heavy metals are more soluble (Tack, Callewaert, and Verloo, 1996). Dissolved heavy metals have high ability to spread while the solids tend to sediment. Heavy metals can also spread through attaching to negatively charged particles suspended in water (Boenigk, Wiedlroither, and Pfandl, 2005).
Heavy metals in high concentrations in drinking water are toxic to humans. They can accumulate in organisms and can therefore cause long term health effects (Tchounwou, Yedjou, Patlolla, and Sutton, 2012). Common sources of heavy metals contamination are: traffic, quarrying, industrial discharge, leakage from contaminated sites and urban run-off .

2.2.5 Nutrients

Nitrates and phosphates are inorganic compounds that occur naturally in the environment. However, man-made synthetic versions also exists. They are dissolved in water and they degrade over time. Due to the degradation, their presence in groundwater are naturally low. Therefore, they spread mainly in surface water or in the capillary zone above the groundwater table.
An abundance of nitrates and phosphates can cause eutrophication which is harmful for aquatic life (Minnesota Pollution Control Agency, 2008). High concentration in drinking water are toxic to humans (USGS, n.d.-b). Since the water source has a buffering capacity against the release of nutrients, continuous release will deteriorate the water source over time rather than have an instant effects (USEPA, 2019c). Common sources of nitrates an phosphates are: agriculture, forestry, on-site sewers, wastewater treatment plants (WWTPs) and old landfills.

2.2.6 Particles

Particles such as sand, clay, silt, humus and microscopic organisms are considered as a type of contaminant. Particles are solids that depending on their size and density could be suspended or sedimented in the water (National Research Council (US) Safe Drinking Water Committee, 1977). The suspended particles have the potential to spread for long distances. Since particles are separated through filtration in soil, only surface water sources are considered to be at risk of physical contamination. Particles can also be electrically charged, which can attract other contaminants (ibid.). In general, particles can cause high turbidity, which decreases the treatment efficiency in the waterworks. The consequence of a large release of particles could be that the water source cannot be used until the turbidity decreases. Common sources of particles are: urban runoff, forestry, quarrying and construction work in water or near by area.

2.3 Types of Contamination Sources

Contaminates can be released to a water source due to natural or anthropological causes, resulting in deterioration of the water quality. Knowledge about the characteristics of a contamination source is of great importance to assess the risk. The main characteristics of a contamination sources are described in the following sections.

2.3.1 Natural

Natural sources can transmit variety of contaminants to a water source without warning (AANDC, 2014). Wild animals (including dead animals), wildfires, natural disasters (storms, flooding, heavy rains, climate change), high concentration of contaminants in a certain area, geology (landslides susceptibility, erosion) are some examples of natural sources that impose risks on a water source. Natural sources are unpredictable which makes them hard to control or restrict. Thus, the reduction measures will be more of a mitigation nature rather than preventative. Furthermore, human activities like forestry or urbanization may cause these events to occur more frequently (ibid.).

2.3.2 Man-made

Man-made sources can be relatively controlled with regulations, restrictions and barriers. According to AANDC (2014), human activities related to land uses can be divided into four types, agricultural activities (animal husbandry, crop farming), residential activities (sewage systems, road network, landfills), commercial and industrial activities (hazardous goods transportation, fuel storage) and past industrial activities (railroads routs, mine tailings). Furthermore, man-made sources are characterized as point or non-point sources.

- **Point sources**
  A point source is a source that can be pinpointed to a certain spot (AANDC, 2014). Industrial discharge, spillage and landfill leachate can be considered as point source contamination. Since contamination can be traced back to a specific spot, it is easier to manage the contamination source through risk reduction measures such as barriers or regulations.
- **Non-point sources**
  A non-point source is a source that does not originate from one specific spot. Thus, these sources are harder to identify, which makes them harder to managed and/or restrict (USEPA, 2019b). Mainly, a non-point source is a result of a water runoff spreading all sorts of contaminants, both natural or man-made. Some example of non-point sources, which can also be referred to as

diffuse sources, could be urban runoff, activities in agriculture and forestry and leakage from contaminated sites.

2.3.3 Duration

The duration of a contamination source aims to describe when and for how long a specific source spreads contaminants. It also gives an indication of the load of a contaminant and if the contamination is caused by any specific event. Therefore, a contamination source is often described as continuous or occasional.

- **Continuous**
  A continuous source is considered to spread contaminants regularly and is not caused by any specific events. The load of contaminants from continuous sources is often relatively low and they are often considered to cause deterioration of a water source over time rather than have a direct effect on the raw water quality. However, the effect from several continuous sources must be considered as the cumulative load could be large. A continuous contamination source could be both point sources and non-point sources. Examples of continuous sources are: runoff from agriculture and continuous discharge from industries.
- **Occasional**
  A occasional source may discharge contaminates irregularly and is always triggered by a specific event (Chave, 1997). The potential load from occasional sources could be much higher that for continuous sources. Therefore, the risk is more connected to a quick decrease in the raw water quality. The occasional sources could be caused by events such as accidents and failures, which indicated that they are relatively unlikely happen but could cause large effect. Occasionally sources also includes intermittent events such as combined sewers overflows (CSOs). The CSOs is caused by heavy rain and can therefore be considered as they are expected to occur irregularly. This way they differs from sources that is related to an accident, since they are not suppose to occur at all. Occasional sources are considered to be mainly point sources.

2.4 The Waterworks Ability to Treat Contaminants

The waterworks has an important role in the drinking water supply system as it is responsible for delivering clean and safe drinking water to the consumers (WHO, 2017). To consider the waterworks ability to treat contaminants is of great importance when conducting a risk assessment. Mainly, since the treatment process could lower the consequence of a specific contaminant reaching the water source (ibid.). The waterworks treatment efficiency varies for different types of contaminants. The waterworks ability to treat the common drinking water contaminants is presented below.

Pathogens

The waterworks ability to treat pathogens is considered good since the treatment system includes microbial barriers. The microbial barriers that are commonly used are conventional treatment, ultra-filtration and disinfection by ozone, UV and chlorination (WHO, 2017). The number of barriers is related to the raw water quality, thus waterworks does not necessarily include all of them. The waterworks is in general more efficient in treating bacteria than protozoa and viruses (SwAM, 2019a). In case of a high load of pathogens, the treatment system might be insufficient. Thus, primarily virus and protozoa might still be present in the water after treatment.

Petroleum products
The waterworks is not adapted to treat petroleum products. In case of high load of petroleum products, the distribution of drinking water needs to be stopped and sanitation of the waterworks is needed (SwAM, 2019a).

Common organic chemicals
The waterworks is in general not adapted to treat persistent organic chemicals. However, treatment processes such as GAC flirtation can to some extent treating them (WHO, 2017). If the waterworks lacks the GAC filter, these chemicals can easily pass through the waterworks.

Heavy metals
The waterworks does not in general include a separate treatment process for heavy metals. However, a large fraction of heavy metals can be removed through chemical precipitation, coagulation, flocculation and sedimentation (WHO, 2017). The removal efficiency varies between different kinds of heavy metals. Thus, a high load of heavy metals in the raw water could result in the presence of heavy metals in the effluents.

Nutrients
The waterworks does not include a separate nutrients treatment process. However, phosphates can be removed through chemical precipitation, coagulation, flocculation, sedimentation and filtration. Meanwhile, nitrates are harder to treat (WHO, 2017). Waterworks with slow sand filtration could allow some degradation of nitrates to occur. However, the efficiency is uncertain. If high load of nitrates in the raw water, the waterworks might not be able to treat it.

Particles
The waterworks for surface water sources has usually efficient particle separation methods, such as sedimentation, filtration, chemical precipitation, coagulation and flocculation (WHO, 2017). In case of higher particle load, the waterworks can still manage the particles separation but with less efficiency and higher maintenance requirements. Furthermore, turbidity is always monitored (ibid.). Thus, distribution can be stopped if too high turbidity is detected in the effluent.

2.5 Water Protection Area

The purpose of a Water Protection Area (WPA) is to protect water sources so that drinking water supply can be ensured for present and future use (SwAM, 2019a). This refers to protecting the water source from contamination that could deteriorate the water quality, but also to ensure water quantity. Water protection areas is a complement to basic environmental protection legislation and is regulated in the Swedish Environmental Code (ibid.). Within the water protection area, activities that pose a risk to the water source can be regulated.
In Sweden, there is no specific quality standard on the water source used for drinking water production (SwAM, 2019a). However, better quality of the water source will reduce the stress on waterworks as well as contributing to fulfill environmental goals (WHO, 2016). Furthermore, it is advised by the WHO (2016) that risks posed to a water source primarily are reduced through source protection, which further emphasises the need for water protection areas.

2.6 Risk Assessment and Risk Management

The risk assessment constitutes a important support for the configuration of a water protection area. The aim is to provide a comprehensive knowledge about present and future threats to the water source and to justify the implementation of regulations and other risk reduction measures (Sweco, 2019a). The risk assessment constitute of two main parts, risk analysis and risk evaluation.
The risk analysis focus is to identifying potential risk sources and to estimate their risk levels. The risk evaluation focuses on determining whether a specific risk is tolerable and if not, analyse possible risk reduction measures.
The risk assessment is the basis for risk management and it is essential for decision making, implementation and control of risk reduction measures (WQRA, 2009). The whole process of the risk management is illustrated in *Figure 2.2*. Since our environment is constantly changing and that future risk sources is hard to predict, it is important to state that the risk management should be seen as a continuous process.

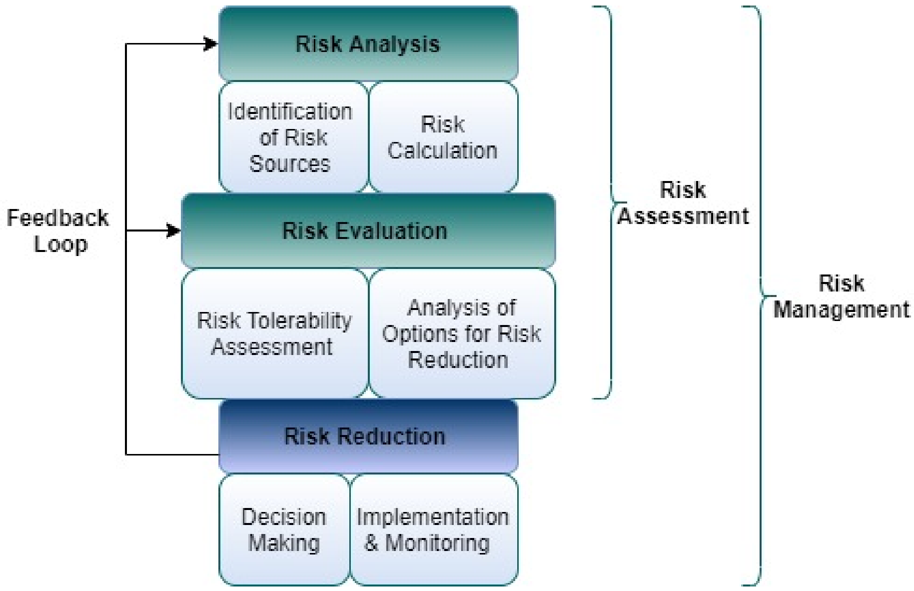

Figure 2.2: *Illustration of the risk management process regarding water protection areas. Based on ISO 31000:2018 (en)*

3

Risk Assessment Methods

In this chapter, different risk assessment approaches for water protection areas are described in therms of theory, practice and policies. First, a commonly applied approach in Sweden is presented, then approaches from other countries and finally the new approach suggested by SwAM.

3.1 Commonly Applied Approach in Sweden

A common approach for assessing risks connected to a drinking water source is built on the Swedish EPA's handbook about water protection areas (2010:5). According to Swedish EPA (2010), the aim with the risk assessment is to constitute a support for the delineation of the water protection area. The handbook does not decide a certain procedure to do the risk assessment, it is more a guideline on which parts to consider and how to think about them. It suggests that e.g. risks can be calculated in both quantitative and qualitative ways and that it is the motivation that is the important part. A risk assessment bases on this approach focuses on the risk analysis part, how to perform risk evaluation is not addressed.

A common way to assess risks today, when developing a water protection area is to perform a kind of risk ranking. A common approach is demonstrated using examples performed by Sweco, which is described in the following sections.

3.1.1 Risk Source Identification

According to the Swedish EPA (2010), it is suggested to include the whole catchment area to localize and map all potential risk sources. In practise, it is sometimes necessary to limit the area due to e.g. large catchment areas and long time of travel, hence, low risk for the water source. If so, it should be motivated why and how it is being done (ibid.). The Identification of risks is based on a source-based approach. This means that the focus is on identifying activities or places can pose a risk the water source. This can be compared with the contaminant-based approach, which instead connects the activities and places with a specific contaminant.

The risk source identification refers to identifying the activities and events that might lead to negative affect on the the drinking water source. According to Sweco (2019a), these activities and events can be categorised in number of risk sources, such as:

- **Urban environment** Storm water and sewage pipes, wastewater treatments plants, energy facilities, fire fighting substances, traffic and home chemicals.
- **Agriculture and forestry** Nutrients, pesticides, fecal matter, humus release and transportation.
- **Traffic and transport on ground and water** Storm water from roads, accidents with hazardous goods, boat traffic and airports.
- **Landfills** Landfills (opened or closed), other heaps of potentially hazardous substances e.g. salt, snow, garbage or polluted soil.
- **Earth works** Excavation for construction or quarrying activity in near by area.
- **Environmentally hazardous activities** All activities or industries that handles environmental hazardous substances. The substances can potentially spread through accidents and drainage.
- **Polluted ground** Often referred to as old industry sites, gas stations and saw mills.
- **Extreme weather and climate change** The largest risks can be summarised by: enhanced risk of combined sewer overflows, large amounts of polluted storm water, increased risks of accidents and water scarcity due to drought.

3.1.2 Risk Source Characterization

The risk source characterization aims to describe the behavior of each risk source in terms of the type of contaminants, events and pathways that might lead to deterioration of a water source. It is important to state that depending on the depth of the study, the aim could be to characterize a specific event such as an accident on a particular road or it could be to characterize roads in general. Below there is an example how Sweco (2019a) has characterized risk sources based on three main categories:

- **Type of Event**
  - Normal function
  - Failing function
  - Accident
- **Type of Substance**
  - Chemical
  - Microbial
  - Physical
- **Duration/distribution**
  - Continuously or occasionally
  - Point source or diffuse source

3.1.3 Risk Estimation

According to Swedish EPA (2010) the risk can be calculated as the product of the probability and the consequence of a specific event. It could also be done by estimating the risk level based on the consequence, given that a specific event has occurred. Since calculating the risk for certain risk objects in a quantitative way is connected with great uncertainties, it is suggested to also consider qualitative estimations (Swedish EPA, 2010).

The risk analysis performed by Sweco (2019b), aims to rank the risk objects rather then calculating absolute values of the risk. This is achieved by estimating the risk based on pre-determined criteria of what being considered as high or low. In this method, probability and consequence is evaluated independent of each other with the aim of ranking the risk sources in three risk classes. The grading is done in qualitative way based on expertise from experienced risk assessors.

3.1.3.1 Probability

The probability is in this case defined by the probability of an unwanted event to occur with the assumption that a contaminant reach the water source and constitutes a hazard. The probability is therefore a combination of a number probabilities from the point of release to the water source. To decide the probability, the risk source is evaluated based on four probability levels with corresponding criteria, see *Table 3.1*. The criteria is in accordance with the Swedish Food Agency levels for probability classification for drinking water supply (Sweco, 2019a).

Table 3.1: *Probability levels used in a common approach in Sweden, Sweco, 2019a.*

Probability	Criteria
P1 - Small	The event is assessed to happen less then 1 time per 50 years
P2 - Intermediate	The event is assessed to happen within 10-50 years
P3 - Large	The event is assessed to happen within 1-10 years
P4 - Very large	The event is assessed to happen one or several times yearly

3.1.3.2 Consequence

The consequence reflects how large the damage to the water supply is, given that a unwanted event occurred. To be precocious, if the level of uncertainty is high, the consequence is assessed as the worst case scenario (Sweco, 2019a). When assessing the consequence, it is important to consider the vulnerability of the water source, this can be done by analysing e.g. the number of barriers in the system and the dilution factor in the water source. The consequence is divided into four levels with corresponding criteria, see *Table 3.2*. The criteria is based on the Swedish Food Agency levels for consequence classification and refers to the ability to use the water source as water supply (Sweco, 2019a).

Table 3.2: *Consequence levels used in a common approach in Sweden, Sweco, 2019a.*

Consequence	Criteria
C1 - Small	Insignificant impact on raw water quality
C2 - Intermediate	Temporary impact on raw water quality that could impact the drinking water but without danger to public health
C3 - Large	Deterioration of raw water quality that affect drinking water production and may cause direct health effect
C4 - Very large	Large deterioration of raw water quality, danger for life and health

3.1.3.3 Risk Level

The probabilities and the consequences from different risk sources are evaluated in a risk matrix, see *Table 3.3*. In this case the risk level is presented by three risk classes, with risk class three being of most significance. It is important to state that these risk classes aims to classify the risks and does not constitute any absolute values of the risk. Furthermore, even if a risk source has the risk class one, it still constitutes a risk and can therefore not be neglected. A description of the risk classes is presented in *Table 3.4*.

Table 3.3: *Risk class matrix used in a common approach in Sweden, Sweco, 2019a.*

Risk Matrix	P1	P2	P3	P4
C1	Risk Class 1	Risk Class 2	Risk Class 3	Risk Class 3
C2	Risk Class 1	Risk Class 2	Risk Class 3	Risk Class 3
C3	Risk Class 1	Risk Class 1	Risk Class 2	Risk Class 3
C4	Risk Class 1	Risk Class 1	Risk Class 2	Risk Class 2

Table 3.4: *Risk class description used in a common approach in Sweden, Sweco, 2019a.*

Risk Class	Description
Risk Class 1	Simplified risk management, preventative measures such as monitoring should be done
Risk Class 2	Active risk management, preventative measures and/or risk reducing measures should be considered
Risk Class 3	Risk needs to be reduced, preventative measures and/or risk reducing measures needs to be done

3.1.4 Risk Evaluation

As described in section 2, the risk evaluation purpose is to evaluate whether the risk from a risk source could be tolerated and if not, present suggestions on risk reducing measures. The handbook (2010:5) focuses more on the risk analysis and does not contain any specific guidance of how to perform a risk evaluation. However, it includes one section about barriers and risk reduction. It primary address the natures own ability to reduce risk from the release of a contaminant. This is done by retention, degradation and dilution in soil and water. This can be seen as the natures own barriers and the Swedish EPA (2010) address the importance of several barriers in series to have a robust system.

It is unclear how the risk evaluation is done in Sweden today. Common practice is that the stakeholder in charge of the water source hires a consultant company to perform a risk analysis. The aim is often to identify, characterise and estimate the risk levels of different risk sources. According to a risk analysis report Sweco (2019a) it is the stakeholder in charge of the water source who decide which risk sources to tolerate and which to implement risk reducing measures. The same goes with evaluating different solutions and to decide which solution to implement. It is unclear how this process is done and if it follows any general method. However, according to Sweco (2019a) there is a few preventative measures always to be considered such as:

- **Regulations**: Refers to restrict potentially hazardous activities within the water protection area.
- **Detailed risk analysis**: Means that specific risk objects is assessed in detail to further understand the risk level and provide basis for different risk reducing methods.
- **Action plan**: In case of an accident that threatens the water source it is important to develop a action plan to limit the affect of a contaminant release.
- **Physical planning**: When planing the usage of ground in e.g. the municipalities "detail plan" and "comprehensive plan" it important to consider the preservation of the water source.
- **Monitoring**: Refers to both monitoring a risk source itself and technical barriers in the system to known that they are working correctly.
- **Physical barriers**: As suggested in the handbook (2010:5) a robust system need to consist on multiple barriers.
- **Information**: To make landowners and people in general aware of the water protection area is of great importance. It motivates regulations and make people aware of the consequences some events can have on the water source.

3.2 Commonly applied Approaches in Other Countries

To gain a comprehensive understanding of how risk assessment for water protection areas is conducted in the world, a number of countries were reviewed. The chosen countries are Australia, New Zealand, Canada, Belgium, and Iowa, US, due to the professional and sufficient amount of literature that is available. The literature mainly consist of public documents and technical reports. A brief background on the reviewed documents is presented below.

- **Australia**
  Australia has an official framework for drinking water quality management. It is presented in the Australian Drinking Water Guidelines (ADWG). This document contains a detailed water source risk assessment (NHMRC and NRMMC, 2011). Furthermore, to help implementing this framework, a company funded by the Australian water industry, WQRA created a risk assessment report in 2009. This report provides a step-by-step methodology on how to perform risk assessment for drinking water sources (WQRA, 2009).

- **New Zealand**
  In New Zealand, technical guidelines for the delineation of water protection areas were developed by Pattle Delamore Partners (PDP) upon the request of the Ministry for the Environment (PDP, 2018). The document includes a description of risk assessment principles for water protection areas.

- **Canada**
  In Canada, a non-profit charitable organization concerned with environmental issues named Pollution Prob has developed a source water protection primer. This document demonstrates the concept and the importance of water source protection (Pollution Probe, 2004). It also gives an overview of a Source Water Protection Plan (SWPP). The SWPP is an assessment of contamination sources and pathways due to human activity and natural events in a catchment area. Moreover, the Canadian authority that is concerned with the indigenous affairs in the country noticed a lack of water sources protection plans in the First Nations communities (AANDC, 2014). Thus, they have created a guide to inform the First Nations on how to create a community based SWPP. It is a clear step-by-step guidance of risk assessment.

- **Belgium**
  In Belgium, a major public water services company De Watergroep, and the Flemish environmental agency developed a risk assessment approach for the protection of groundwater sources (Six, Diez, Van Limbergen, and Keustermans, 2015). The approach has been officially adopted since 2013.

- **Iowa state, US**
  The Iowa Department of Natural Resources (IDNR) created a water protection guidebook for risk assessment, in 2017 (modified in 2019). The guide-

book provides a plan for water source protection and is required for all water sources(IDNR, 2017).

3.2.1 Risk Source Identification

Identifying the risk source is very similar in all of the reviewed countries. Commonly, the entire catchment area is examined in search for possible risk sources. Details and variations on risk source identification from each country are presented below:

- **Australia**
  According to the NHMRC and NRMMC (2011), risk sources and potential hazards can be identified in the catchment area via GIS, field visits, interviewing staff from water utilities and regulators. Furthermore, records and documents from local authorities can be collected and reviewed in a desk study. Some of the possible risk sources and events that are presented in the guidelines are: agriculture and farming, forestry, industry, mining, sewage treatment plants, septic tanks, urban and rural storm water, combined sewer overflows, recreational and illegal access, wildlife, public roads and bushfires, whereas some of the possible hazards are: Pathogens, nutrients, turbidity, colour, heavy metal and organic chemicals.

- **New Zealand**
  In New Zealand, the risk sources are identified based on past and present land use in the catchment area (PDP, 2018). Mainly, since different land uses indicate different types of contamination risks. The ministry of health in New Zealand have listed ten land use categories and assigned potential activities to each one of them (Ministry of Health, 2019). Moreover, they have specified contaminants related to those activities.

- **Canada**
  In Canada, an inventory of potential contaminant sources is done based on land use and human activities. Wastewater treatment plants, landfills, agriculture, fuel storage, erosion, flooding, climate change and other natural factors, are some of the considered risk sources (AANDC, 2014). According to the Pollution Probe (2004), it is also advised to include activities that have an effect on water quantity, such as urban development and climate change. However, how to incorporate these activities was not clearly described.

- **Belgium**
  In Belgium, the risk source identification is performed based on templates of common risk sources (Six et al., 2015). The templates includes 82 possible risk sources, categorized in 13 groups. The groups are: open energy system; closed energy system in subsoil; groundwater wells of third parties; transport and transport infrastructure; sewer systems and wastewater discharge; agricultural activities; household activities; industrial sites, activities of public services, military sites; parking areas; Infrastructural works; surface water;

rainwater infiltration infrastructure and other relevant activities.

- **Iowa state, US**
  In Iowa, the risk source are identified by using GIS, field surveys and advanced hardware (IDNR, 2017). To perform the risk source identification, the risk sources are sorted in four land use: agricultural, commercial, industrial or residential sources.

3.2.2 Risk Source Characterisation

Risk source characterisation is somewhat similar in all of the examined countries. The risk sources are characterized as point or non-point sources. Furthermore, the types of contaminants are divided into five main categories: physical, microbial, organic, inorganic and radioactive contaminants.
The countries Australia and New Zealand further characterize the risk sources. In Australia, they also characterize the risk sources based on their duration. It could be continuous, intermittent or have seasonal pollution patterns (WQRA, 2009). Moreover, extreme and rare events were also taken into consideration.
The risk source characterisation in New Zealand follows a more contaminant-based approach. They categorize the contaminants into three groups based on their persistence and toxicity (PDP, 2018). The groups are: pathogens and associated compounds; contaminants from a point source; and contaminants from a non-point source. The guidelines in PDP (2018) provides a set of typical contaminants incorporated in each of the three groups with description of their persistence, their health effects on humans and their spreading ability.

3.2.3 Risk Estimation

The risk estimation in the reviewed countries (except new Zealand) is conducted with aim of ranking the risk sources. This is achieved by classifying the risk sources based on predetermined scales. The procedure was similar for Canada, Australia and Belgium, while performed differently in Iowa, US. Furthermore, New Zealand performs the risk estimation by a describing and motivating the risk level rather than classifying it. The full procedure is presented in the sections below.

3.2.3.1 Iowa, US

In Iowa, the risk estimation is performed by classifying the risk related to the type of land use, the location of the contaminant source and the vulnerability of the water source (IDNR, 2017). First, the risk related to land use are assigned with a score from one to five, with five being the highest risk. For example, industrial land use is considered a five while a recreational area is considered a one. Secondly, the distance between the risk source and the extraction point area assigned with a score based on the time of travel from one to three. finally, the water sources are assessed based on their vulnerability and given a score from one to four. The scores are then summarized to a total risk score from 1 to 12, with 12 being the most sever risk.

3.2.3.2 New Zealand

The risk estimation in new Zealand is performed by describing the risk level (PDP, 2018). The aim is to motivate and explain the factors that contributes to the risk level. According to PDP (2018), this can be achieved by describing the vulnerability of the water source, contaminant pathways, the natural barriers and the triggering events that could lead to a contaminant reaching the water source.

3.2.3.3 Australia, Belgium and Canada

The estimation of risk in Australia, Belgium and Canada is performed by classifying the probability and the consequence of each risk source. The classification uses predetermined scales and a risk matrix to rank the risk sources into different risk levels.

- **Probability**
  In Australia, Belgium and Canada classification of the probability is performed in a similar way. However, there is a small difference in the explanation of the criteria used. Nevertheless, there are five levels of probability. The description of each probability class can be seen in *Table 3.5*, *Table 3.6* and *Table 3.7*

Table 3.5: *Probability classification in Australia, WQRA, 2009.*

Probability	Criteria
A - Almost certain	Is expected to occur in most circumstances
B - Likely	Will probably occur in most circumstances
C - Possibly	Might occur or should occur at some time
D - Unlikely	Could occur at some time
E - Rare	May occur only in exceptional circumstances

Table 3.6: *Probability classification in Belgium, Six et al., 2015.*

Probability	Criteria
1 - Very unlikely	Has never happened and it is very unlikely that this will happen
2 - Unlikely	Is possible and can not be completely ruled out
3 - Predictable	Can happen under certain circumstances
4 - Very likely	Already happened in the past and can happen again
5 - Almost certain	Has happened in the past and will happen again

Table 3.7: *Probability classification in Canada, AANDC, 2014.*

Probability	**Criteria**
1 - Most unlikely	Extremely small chance of happening in the next 4-5 years
2 - Unlikely	Is possible to occure in the next 4-5 years
3 - Likely	Evenly split between likely and not likely to happen in the next 4-5 years
4 - Possible	Is expected to happen in the next 4-5 years
5 - Almost certain	Confident this will happen at least once in the next 4-5 years

- **Consequence**
  In Australia, Belgium and Canada classification of the consequences is performed in a similar way. However, there is a small difference in the explanation of the criteria used. Nevertheless, there are five levels of consequences for each risk source. The description of each consequence class can be seen in *Table 3.8*, *Table 3.9* and *Table 3.10*

Table 3.8: *Consequence classification in Australia, WQRA, 2009.*

Consequence	**Criteria**
1 - Insignificant	Insignificant impact, little disruption to normal operation low increase in normal operation costs
2 - Minor	Minor impact for small population, some manageable operation disruption, some increase in operating costs
3 - Moderate	Minor impact for large population, significant modification to normal operation but manageable, operation costs increased, increased monitoring
4 - Major	Major impact for small population, systems significantly compromised and abnormal operation if at all, high level of monitoring required
5 - Catastrophic	Major impact for large population, complete failure of systems

Table 3.9: *Consequence classification in Canada, AANDC, 2014.*

Consequence	Criteria
1 - Insignificant	No health risk: Water system interruption less than 8 hours
2 - Minor	Short term or localized non-compliance, non-health related e.g., aesthetic
3 - Moderate	Widespread aesthetic issues or long term non-compliance, non-health related
4 - Sever	Actual illness or potential short to medium term health effects (human or ecosystem)
5 - Catastrophic	Actual illness or potential long term health effects (human or ecosystem)

Table 3.10: *Consequence classification in Belgium, Six et al., 2015.*

Consequence	Criteria
1 - Unimportant	Limited consequence
2 - Small	Standard
4 - Intermediate	Not wanted
8 - High	Long term consequence on human health
16 - Catastrophic	Urgent consequence on human health

- **Risk level**
  Once the probability and consequence classification is performed, a risk matrix is used to give each risk source a risk class. For the risk matrix used in Australia, *see Table 3.11*, in Belgium, *see Table 3.12* and in Canada, *see Table 3.13*. The risk classes serves the purpose of ranking the risk and does not represent an absolute value of the risk. It is advised that the risk sources in the highest risk class should be mitigated as soon as possible.

Table 3.11: *Risk Matrix in used Australia, WQRA, 2009.*

Probability	Consequence				
	1	2	3	4	5
A	Moderate	High	Very high	Very high	Very high
B	Moderate	High	High	Very high	Very high
C	Low	Moderate	High	Very high	Very high
D	Low	Low	Moderate	High	Very high
E	Low	Low	Moderate	High	High

Table 3.12: *Risk Matrix used in Belgium, Six et al., 2015.*

Probability	Consequence				
	1 Unimportant	2 Small	4 Intermediate	8 High	16 Catastrophic
1 - Very unlikely	1	2	4	8	16
2 - Unlikely	2	4	8	16	32
3 - Predictable	3	6	12	24	48
4 - Very likely	4	8	16	32	64
5 - Almost certain	5	10	20	40	80

Table 3.13: *Risk Matrix used in Canada, AANDC, 2014.*

Probability	Consequence				
	1	2	3	4	5
1	1 (Low)	2 (Low)	3 (Low)	4 (Medium)	5 (Medium)
2	2 (Low)	4 (Low)	6 (Medium)	8 (Medium)	10 (High)
3	3 (Low)	6 (Medium)	9 (Medium)	12 (High)	15 (High)
4	4 (Medium)	8 (Medium)	12 (High)	16 (High)	20 (High)
5	5 (Medium)	10 (High)	15 (High)	20 (High)	25 (High)

3.2.4 Risk Evaluation

Risk evaluation is an important part of a risk assessment and is suggested to be performed in all countries. However, the level of details of how the risk evaluation should be performed, varies from one country to another.

- **Australia**
  According to WQRA (2009), the risk evaluation should assess the tolerability of the risk and clarify what type of risk reduction measure that is suitable to implement. When estimating the tolerability of the risks, it is important to consider existing barriers, since they can lower the severity of the risk. It is also important to consider the cumulative effect of several risk sources. Taking these consideration into account, risk reduction measure are suggested based on guidelines from the NHMRC and NRMMC. Furthermore, a cost-benefit analysis is recommend to provide support for the most suitable measure (NHMRC and NRMMC, 2011). It is also recommended that an operational action plan is established to make sure that reduction measures are implemented.

- **New Zealand**
  In New Zealand, a procedure of how to perform the risk evaluation is not addressed in details. However, a set of reduction measures are suggested to be considered (PDP, 2018). The reduction measures are primarily linked to the contaminants type and their pathways. Therefore, they mainly suggest risk reduction measures that allows natural process to help mitigating the effect from a contaminant. Other suggestions are implementation of regulations, physical barrier and water quality monitoring.

- **Canada**
  In Canada, a template with a clear set of risk reduction measures are provided based on the characteristic of each type of risk source. (AANDC, 2014). These reduction measures are divided into immediate actions and longer term actions. The purpose is to immediately mitigate the risk while implementing a long term solution. An action plan is also established to make sure that the reduction measures are implemented.

- **Belgium**
  The risk evaluation in Belgium is based on a number of suggested risk reduction measure such as the implementation of regulations, physical barriers and monitoring plans. It is recommend to use cost-benefit analysis as a method to provide support for the most suitable measures.

3.3 New Approach Suggested by SwAM

The new approach is presented in a document describing principles for risk assessment of water protection areas (SwAM, 2019a). In this document, SwAM provides a step by step guideline, which in detail describe each part of the risk assessment. According to SwAM (2019a), the aim with this method is that the risk analysis should be used when evaluating different risk reducing measures and that the delineation of the water protection areas is clearly motivated by the risk assessment. This is a qualitative method that motivates the need for explanations rather than subjective grades or quantitative calculations. To illustrate how this is done the main parts of the risk assessment is presented in the following sections.

3.3.1 Risk Source Identification

The risk source identification of this method is of both a contaminant-based and source-based approach. It aims to first identify contaminants and then link them to specific sources. The process is divide into two steps presented below.

3.3.1.1 Contaminant Identification

Contaminants identification refers to identifying substances that is harmful for the the drinking water consumer and/or is problematic to treat in the waterworks. As a first step it is recommended to study the Hazard Analysis Critical Control Points (HACCP) that is performed by every drinking water producer. It will provide information about levels of contaminants in the water source and how they fluctuate over the season. It is important to also describe the contaminants physiological properties to gain understanding of potential pathway. According to SwAM (2019a), contaminants with similar characteristics can be assessed together. The SwAM dose not present precisely which contaminants to focus on but instead recommends gathering information from the following document:

- **"Dricksvattenföreskrifterna" (SLVFS 2001:30)**: Drinking water regulation document from the Swedish Food Agency. It contains limiting values of substances for drinking water and can be used as a guide to understand the significance of different substances.

- **"Branschriktlinjer avseende råvattenkontroll" (Svenskt Vatten, 2008)**: Document from the drinking water producers trade organisation, Swedish Water. It Provides guidance of how to analyse a raw water and gives guidelines of raw water quality parameters. It includes reference levels of different substances and addresses fluctuation in a surface water source.

- **"Drinking water quality guidelines"** WHO (2017): Document from the World Health Organisation that provides guidelines for drinking water quality. Can be used as additional reference besides the Swedish sources.

3.3.1.2 Source Identification

The aim with the source identification is to link the contaminants with places and/or activities. To do this, it is important to gather knowledge about which contaminants that is related to different activities or land use. It is recommended that this step is performed in parallel to the contaminant identification, to not miss important risk sources. It is unclear how to set boundaries for the source identification since SwAM does not address whether to include the whole catchment area or just parts of it (SwAM, 2019a). The SwAM does neither refer to any specific check list but gives examples of activities, land use and event that often is connected to contaminants, such as:

- **Urban environment** Private sewers, Storm water, sewage pipes, wastewater treatments plants, energy facilities, fire fighting substances, recycling facilities etc.
- **Agriculture, aquaculture and forestry** Nutrients, pesticides, fecal matter, humus release and transportation.
- **Traffic and transport on ground and water** Storm water from roads, accidents with hazardous goods, boat traffic and airports.
- **Landfills** Landfills (opened or closed), other heaps of potentially hazardous substances e.g. salt, snow, garbage or polluted soil.
- **Earth works** Excavation for construction or quarrying activity in near by area.

- **Environmentally hazardous activities** All activities or industries that handles environmental hazardous substances. The substances can potentially spread through accidents and drainage.
- **Contaminated sites** Often referred to as old industry sites, gas stations and saw mills.

3.3.1.3 Other Risk Sources

Some risks posed on a water source cannot be defined by neither a type of contaminant or a risk source. For instance, climate change pose a risk to the water source by affecting other risk sources. It is therefore recommended to consider climate change when assessing independent risk sources rather then assessing it by itself (SwAM, 2019a). Another important risk factor for drinking water supply is quantity. If a water source is contaminated, it could mean that lower amount of drinking water can be produced from the water source or that it needs to be abandoned. Furthermore, activities such as construction or quarrying could potentially lead to lowering of the groundwater level, which would influence the amount of available water for drinking water production. Also climate change could affect the quantity of available water in case of draught or a trend of lower annual precipitation.

3.3.1.4 Method for Identifying Risk Sources

The SwAM suggested to gather information about already known risk sources from regional and national environment monitoring programs or by local industries recipient control (SwAM, 2019a). It Addresses the importance of field study parallel to desk study to provide qualitative knowledge about the overall risk level of different risk sources.

3.3.2 Risk Source Characterisation

The risk sources are primarily characterised based on the type of contaminants. The contaminant is described, regarding its hazardousness and its physiological properties. This is done to understand how the contaminant behaves if a release would occur. Understanding the behavior also makes it possible to describe potential pathways from the release point to the water source. To further illustrate how a contaminant could spread from the point of release to the water intake an event tree is used. The characterisation is described in the sections below.

Type of Contaminants

The aim with characterising the contaminant is to determine properties that affect its ability to spread within the catchment area. According to the SwAM (2019a), physiological properties such as the contaminant state of aggregation, density, solubility in water and persistence all contribute to the ability to spread. Furthermore, the contaminant is analysed based on its toxicity and the consequence of the contaminant reaching the raw water intake. In the consequence analysis, health effects on the consumer, damage to the waterworks and damage to the water source should be described.

Duration/Distribution
The risk sources is characterised as a point source or diffused source and if the discharge occurs occasionally or continuously. The risk source is also characterised based on the concentration and amount of potential or ongoing discharge.

Pathways
The identification pathways aims to identify and describe possible pathways from the risk source to the raw water intake. Depending on the depth of the risk assessment, the pathways can be described in general for the entire catchment area or detailed for specific risk sources. It is important to consider that the pathways differ between surface water sources and groundwater sources. When assessing the pathways it is also important to consider natural barriers within the catchment area. Furthermore, according to SwAM (2019a), there is a few parameters always to consider, such as:

- **Point of release**: Release on the ground, in the soil (saturated or unsaturated area), or in watercourse.
- **Type of release**: Which contaminant, what state of aggregation, solubility in water.
- **Distance to water source**: Considers the distance to water source, dikes, drainage and creaks.
- **Topography**: Refers to slope of the ground and hydraulic gradient.
- **Hydraulic conductivity**: Refers to retention time in the soil and the ability for water to infiltrate the soil.

Event
To illustrate how previously mentioned characteristics can lead to different scenarios that potentially can harm the water source, an event tree is used (*see Figure 3.1*). In the event tree, it is possible to illustrate whether there is a source of a specific contaminant, if the system has barriers and if the contaminant can reach the raw water intake. According to SwAM (2019a), the aim with the event tree is to provide a basis for which events that influence the risk level the most. If the risk is connected with large uncertainty then an event tree can be used to not oversee conditions and underestimate the risk

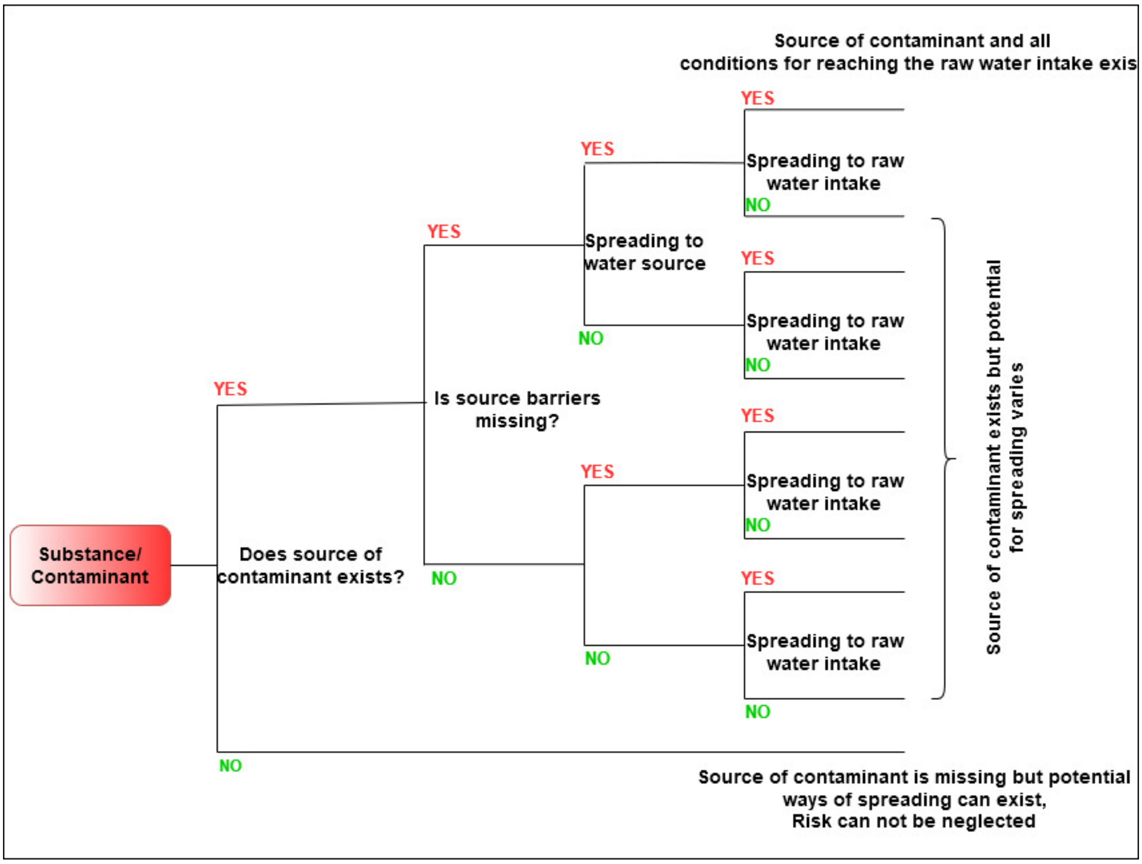

Figure 3.1: *Event tree that illustrates how different scenario might lead to a contaminant reaching the raw water intake.*

3.3.3 Risk Estimation

The risk level is estimated based on the previously performed identification and characterisation of the contaminants and the risk sources. It is recommended by the SwAM (2019a), that the information is collected in a table, illustrated in *Figure 3.2*. It is also recommended to motivate and explain, which characteristics and which events that contribute the most to the risk level. To further motivate the consequence of a specific contaminant, the waterworks ability to treat contaminants is described. The SwAM (2019a), advises not to use specific grades or criteria. Mainly, since the link between the risk level and the aspects that contribute to the risk level can be lost and that defined grades tent to poorly adapt to local conditions. The risk level can can be presented in general for the catchment area or in detail for every pollution source, depending on the necessity and the depth of the study.

Substance	Substance or group of substances		
Properties	Physical properties that affects pathway and behaviour in the environment		
Consequence	The substance health effects on humans and its ability to influence the water source		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Source 1	General pathways for Sources 1 and 2	The abilities to treat the substance in the waterworks. It gives guidance of the impact of a release	Evaluation of risk. Can be in general for a substance or derived by the different sources
Source 2			
Source 3	Pathways for Source 3		

Figure 3.2: *Example of how the properties of a substance, consequences, pollution sources, pathways and risk level can be described.*

3.3.4 Risk Evaluation

The aim with the risk evaluation is to present and evaluate different risk reduction measures. According to SwAM (2019a), the motivation of the risk reducing measures should be motivated by the risk level and the character of the risk sources. Furthermore, it is important to describe whether a risk can be reduced through implementation of regulations or if barriers is necessary. Its important to state that risk reducing measures that reduce the risk at the source is prioritized. Since risk reduction measures is hard to quantify it is suggested to motivate and explain the efficiency related to the estimated cost of the measure. Even if high risk levels from independent risk sources should be prioritized, it is important to consider the cumulative effect of several risk sources of a lower risk level, when evaluating different options. It is recommended by the SwAM (2019a), that the risk reduction measures and the description of the intended effect are presented in a table illustrated in *Figure 3.3*. The risk evaluation does not analyse whether a risk level is considered acceptable or not, instead the focus is on providing options for risk reduction measures for all risks. Neither does it evaluate which risk reduction method that best reduces the risk for a specific risk source. However, the aim is to describe the reduction measures in a way that makes it possible to use the information for further evaluation, such as a cost-benefit analysis.

Substance	Substance or group of substances		
Sources	**Risk**	**Measure**	**Intended effect**
Source 1	Evaluation of risk. Can be in general for a substance or derived by the different sources	Suggested risk reducing measures. Presented in general or pollution source specific. Priorty of risk reducing measures at the risk source	Description of how the measure reduces the risk. Effiecny relate to cost should be considered
Source 2			
Source 3			

Figure 3.3: *Example of how the risk level, risk reducing measures and intended effect the can be described.*

4

Method

This chapter presents the methodology that was applied in this Master thesis. The work was divided into four main parts:

1. First, a literature review was performed to identify and scrutinize how risk assessment of water protection areas is performed: a) in Sweden, b) in Other countries, and c) in the new approach suggested by SwAM, in terms of theory, practice and policies.
   (a) For Sweden: the literature review was performed by reviewing the water protection areas handbook (2010:5) that was created by the Swedish Environmental Protection Agency. In addition, a number of risk assessments of implemented water protection areas for both surface and groundwater sources performed by Sweco was examined.
   (b) For other countries: the literature review was performed by examining public documents and technical reports about risk assessment approaches for water protection areas from Australia, New Zealand, Canada, Belgium and Iowa, US.
   (c) The new approach suggested by SwAM: the literature review was performed by studying the document describing principles for risk assessment of water protection areas (SwAM, 2019a).

2. Secondly, a case study was performed to apply and test the new risk assessment approach suggested by SwAM. This case study consists of four water sources with different characteristics. The reason why four water sources was chosen was to test the new approach on ground and surface waters in both rural and urban environment. Furthermore, these water sources have recently been assessed by Sweco, based on a common approach of risk assessment used in Sweden. The case study was performed using the risk sources that were identified by Sweco as input in the new risk assessment.

   To perform the risk assessment, the most common drinking water contaminants was grouped into six categories. The aim was to include the contaminants in as few groups as possible and at the same time cover all contaminants related to the different risk sources. The following groups of contaminants were used:

   - Pathogens
   - Petroleum products

- Common organic contaminants
  - Pesticides
  - Chlorinated solvents
  - Phenol
  - PFAS
- Heavy metals
- Nutrients
- Particles

Thereafter, the risk sources identified by Sweco was arranged and linked to the different groups of contaminants. This was achieved using our own knowledge about typical contamination sources and by consulting Sweco. Furthermore, the risk sources that could not be linked to a specific contaminant, such as weather conditions or activities like dredging and excavating, were mentioned and described in the risk description. The aim was to describe how these events could affect other risk sources and contribute to the spread of specific contaminants.

The risk sources sharing the same pathway were assessed together to simplify the pathway description. To describe the pathway, google maps was used in addition to the information about the risk sources and the geological and hydrogeological data provided by Sweco. The pathway description was performed with the aim to answer the following questions:

- How is the contaminant linked to the risk source?
- What triggers the release of the contaminant?
- Where is the risk source situated in relation to the water source?
- How can the contaminant spread?
- How good is the ability of the contaminant to spread?
- How large is the potential load of the contaminant?

Based on the description of the contaminants and the pathways of the different risk sources, the risk level was estimated. The information was gathered in tables to present the results. To illustrate the largest risks on a specific water source, the contaminant of most concern was placed at the top of the risk analysis. Furthermore, the risk sources were prioritized within the different contaminants.

3. Thirdly, the results from the new risk assessments were compared with the results from the previously performed risk assessments. The aim with the comparison was to illustrate the main differences and similarities between the two approaches. This was done by comparing the risk sources ranked the highest and by pointing out the main differences and similarities in how they were presented and described.

4. Finally, the results from the new risk assessments were critically analyzed

to evaluate the applicability of the new approach to different water sources. Furthermore, the results were analysed based on how they can be used to evaluate possible mitigation measures in a qualitative or quantitative way using cost-benefit analysis or other decision analysis methods.

5
Case Study

In this case study four water sources with different characteristics were assessed using the new approach for risk assessment suggested by SwAM. To fulfill the objective of evaluating the applicability of the new approach on different types of water sources, this case study assesses groundwater and surface water sources situated in both rural and urban environment. The water sources are currently used for drinking water supply and have previously been subjected to risk assessment performed by Sweco.

The risk assessment performed by Sweco was performed with the aim of ranking risk sources in different risk classes and it follows the same approach as described in *Section 3.1.* The approach is characterised by classifying risk sources based on their probability and consequence. This was done using predetermined scales, for probability classification (*see Table, 3.1*) and for consequence classification (*see Table, 3.2*). When the probability and consequence class is determined the risk source is given a risk class using a risk matrix (*see Table, 3.3*). The risk classes does not represent an absolute value of the risk but rather presents the sources of most concern. Furthermore, the description of the risk classes is illustrated in *Table 3.4*.

The new approach is considered both a contaminant-based and a risk source-based approach. It differs from the common approach by evaluating the risk of different contaminants rather than independent risk sources. The risk sources are still presented but instead of evaluating the risk independently the risk is linked to the related contaminant. Furthermore, the new approach aims to describe and motivate the risk instead of classifying the risk.

It is important to state that the level of detail of the risk assessment varies depending on the size and character of the water source. For instance, when assessing the risk posed by roads on a groundwater source in a rural area, the road/roads can often be specified. However, when assessing a large water source in an urban area, the risk is often considered posed by roads in general.

The water sources that were assessed in this case study are:

- **Bolmen** - A surface water source situated in a rural area.
- **Göta älv / Vänersborgsviken** - A large surface water source situated in both urban and rural environment.
- **Grimstofta** - A groundwater source situated in an urban area.
- **Haboskogen** - A groundwater source situated in a rural area.

The following sections include a general description about important characteristics of each water source and the results from both risk assessments. Furthermore, it includes a comment section that highlight the major findings from the two risk assessments. For further discussion and comparison between the two risk assessments, see Chapter 6.

5.1 Bolmen

Bolmen is situated in the west part of the province Småland and is the 10th larges lake in Sweden (Sydvatten, 2016). Since 1987 it has been used as drinking water supply for a large population in the south west of Skåne. What is peculiar about Bolmen is the large tunnel that was constructed to transport the water from Bolmen to south west of Skåne, more than 80 km away. However, this does not affect the risk assessment. Bolmen is located in a rural area and according to Sydvatten (2016), the surrounding land use consists of 50 % forest, 22 % fen, 20 % lakes and only 9 % of farmland. There are no cities or industries in the area. The raw water intake is located in the southern part of the lake, see *Figure 5.1*. The risk assessment was done on a relatively large area, therefore, most risk sources are assessed in general. However, the most important risk sources are assessed in a more detailed manner.

Figure 5.1: *Lake Bolmen and its surrounding area.*

5.1.1 Result - Common Approach

This is a presentation of the risk sources Sweco considered the highest risk in Bolmen. The risk sources are gathered in *Table 5.1* and described below. For full summary of Sweco's result, see *Appendix A*. Furthermore, in this risk assessment it was also considered that if any of these events were to happen, the potential release of contaminants could reach the raw water intake within twelve hours.

Table 5.1: *The risk sources with the highest risk class in Bolmen according to Sweco. Including the probability, consequence and risk class for each risk source*

Risk sources	P	C	Risk
Grazing animals	3	3	3
Accidents with hazardous goods on road 25	1	4	3
Discharge from boat engines	4	2	3
Pesticides used in agriculture	3	3	3
Natural fertilizers used in agriculture	3	3	3
Combined sewer overflows (CSOs)	3	3	3

Grazing animals - It is especially shore grazing animals in close connection to the raw water intake that is considered a risk. The probability class is three and the consequence class is 3. The risk is considered being a diffuse risk source that occurs occasionally. The contaminants of concern is pathogens and chemicals. The event can occur by normal or failing function.

Accidents with hazardous goods on road 25 - The probability class is one and a consequence class is four. The source is considered to be a point source that occurs occasionally. The contaminant is categorized as chemicals.

Discharge from boat engines - It is especially discharge from old two-stroke engine that is considered a risk. The probability class is four and consequence class is two. The discharge is considered to happen by normal and failing function. The risk source is considered a diffuse source that occurs occasionally. The type of contaminant is described as chemicals.

Pesticides used in agriculture - The risk source is considered to spread pesticides as a result of normal function, failure and accidents. The probability class is three and consequence class is three. The source is described as a diffuse source that discharge the contaminants occasionally.

Natural fertilizers used in agriculture - The risk source is considered to spread pathogens and chemicals as a result of normal function, failure and accidents. The probability class is three and consequence class is three. The source is described as a diffuse source that discharge the contaminants occasionally.

Combined sewer overflows (CSOs) - The risk source is considered to spread pathogens and chemicals as a result of normal and failing function. The probability class is three and consequence class is three. The source is described as a point source that discharge the contaminants occasionally.

5.1.2 Result - New Approach

This result is a presentation of the contaminants and risk sources that are considered the highest risk in Bolmen. The contaminants and the corresponding risk sources from our risk assessment are gathered in *Table 5.2*. For the full risk assessment, see *Appendix A*.

Table 5.2: *The contaminants that pose the highest risks to Bolmen and the corresponding main risk sources according to our results*

Contaminants Group	Risk sources
Pathogens	Grazing animals Combine sewer overflows (CSOs) Angelstad-Bolmen WWTP On-site sewage systems
Petroleum Products	Accidents with hazardous goods (Road 25) Boat engine discharge/Accidents involving boats Tanks with petroleum products and contaminated sites
Pesticides	Pesticide used in agriculture/forestry

Pathogens
The risk of pathogen contamination is considered high. The risk is primarily related to shore grazing animals and CSOs.
Shore grazing animals could discharge manure containing pathogens directly into the lake or connected streams. The manure disposed on land could also be transported to the lake via runoff. subsequently, the pathogens could reach the water intake rather quickly.
There are a few places in the town Bolmen where CSOs can occur. CSOs are triggered by heavy rain and floods and it is likely to occurs a few times each year. Since the CSOs discharge directly into the lake it is considered likely that the pathogens will reach the raw water intake.
Other sources, such as on-site sewers and WWTPs also poses a risk to the water source. On-site sewers are considered a continuous source of pathogens. However, the time of travel is considered relatively long and the dilution in the lake is relatively large. Nevertheless, the cumulative effect needs to be considered. The risk from WWTPs is primarily connected to the event of accident, therefore it is considered unlikely to occur but if it does, the load of pathogens could be large. Furthermore, climate change and extreme weather conditions could increase the frequency of the discharge from CSOs and enhanced runoff from husbandry sites.
The waterworks ability to treat pathogens contamination is considered good. However, with an increased load, the treatment might be insufficient. Thus, drinking water consumers might get infected.

Petroleum products
The risk of petroleum products contamination is considered high. The risk is mainly related to accidents with hazardous goods on road 25, boat engine discharge and accident involving boats.
An accident on road 25 could cause a large spill of petroleum products. The road is situated around 300 meters south of the raw water intake area. In case of spillage,

petroleum products could reach the lake and spread to the raw water intake. For this to happen, a series of events needs to occur. Therefore, it is considered unlikely to happen but if it does drinking water production would be largely affected and remediation of the water source might be necessary.
Boat engine discharge and accident involving boats could result in a direct discharge of petroleum products close to the raw water intake. The load from boat engine discharge is considered low. However, it is likely to occur frequently. Accident with boats, primarily relates to the potential discharge of petroleum from engines. This is consider unlikely to occur but if it does, a relatively large load of petroleum could be discharged directly into the lake.
Other sources such as tanks storing petroleum products and contaminated sites might also spread petroleum products to the lake. However, the risk is considered much lower than the previously mentioned sources.
However, all sources are considered to pose a relatively large risk. Mainly, since the waterworks is not adapted to treat petroleum products. Thus, any amount of spillage could affect the drinking water production.

Pesticides
The risk of pesticide contamination is considered high. Mainly, it relates to the usage of pesticides in agriculture and forestry.
Bolmen is surrounded by agriculture sites and forests. The pesticides can spread to the lake through runoff and/or infiltrate the ground and spread through groundwater flow. The spread is likely to occur as a result of normal usage or in case of accidents with pesticide containers. Since there is a lot of agricultural sites in close connection to the lake, the cumulative load of pesticides could be large. The spreading of pesticides could be enhanced by climate change and extreme weather conditions. Primarily due to the larger risk of flooding which increase surface runoff. Furthermore, the waterworks is not adapted to treat pesticides. Thus, once they reach the raw water intake, they can pass through the waterworks and cause adverse health effects on drinking water consumers even at low concentrations.

5.1.3 Comments

The risk level in Bolmen is considered relatively high. Since the lake is situated in a rural area, the number of risk sources that could cause large consequences on the water quality is considered few. However, there are some risk sources that, mainly, in case of accidents could cause large consequence. The contaminants of most concern were found to be pathogens, petroleum products and pesticides. Note that all risk sources assessed as the highest risk in Sweco risk assessments can also be found as the highest risks in our result. However, there do exist some differences.
One difference is the natural fertilizers, which is assessed as one of the highest risk sources in Sweco's result. In our risk assessment the risk is assessed lower. Mainly since natural fertilizers that is processed the right way is considered unlikely to contain large amount of pathogens. Another difference is that we assessed the risk of accident with boats on the lake as a higher risk than Sweco. We considered that even if it is unlikely to happen the consequence would be relatively large as it could occur

close to the raw water intake. It is important to state that these differences are not affected by the method used but rather due to different opinions of the risk assessors.

5.2 Göta Älv / Vänersborgsviken

Göta älv is a large river that flows from lake Vänern to its outlet close to Gothenburg. Vänersborgsviken is the southern part of the lake Vänern. This water system is used as water source by several municipalities and it supplies drinking water for more than 700 000 people (Gävso, n.d.). The surrounding area consists of mostly farmland and the river flows through several cities, see *Figure 5.2*. There are also many industries situated close to the river. Apart for being used a water supply the river is used for other purposes such as shipping. The risk assessment has been done on a very large area and there are several waterworks that extract water from the system. Therefore, the risk sources are assessed on a general level. The area includes both the southern part of lake Vänern and the river Göta älv.

Figure 5.2: *Göta älv / Vänersborgsviken and its surrounding area*

5.2.1 Result - Common Approach

This is a presentation of the risk sources Sweco considered the highest risk in Göta älv / Vänersborgsviken. The risk sources are gathered in *Table 5.3* and described below. For full summary of Sweco result, *see Appendix B.*

Table 5.3: *The risk sources with the highest risk class in Göta älv / Vänersborgsviken according to Sweco. Including the probability, consequence and risk class for each source*

Risk sources	P	C	Risk
Wastewater treatment plants (WWTPs)	3	3	3
Combined sewer overflows (CSOs)	3	3	3
Activites in harbours	3	3	3
Accidents with shipping	3	3	3
Industry discharge	3	3	3
Landslide of contaminated site	2	4	3
Flooding	3	3	3

Wastewater treatment plants (WWTPs) - The risk is primarily related to the spread of pathogens and chemicals as a result of deficient treatment process. However, also normal function is considered to pose a risk. The probability class is three and the consequence class is three. The source is described as a point source that discharge the contaminants occasionally.

Combined Sewer Overflows (CSOs) - The risk source is considered to spread pathogens and chemicals as a result of normal and failing function. The probability class is three and consequence class is three. The source is described as a point source that discharge the contaminants occasionally.

Activities in harbours - The risk source is primarily related to the spread of chemical and physical contaminants in the event of accidents. However, also normal and failing function is considered to pose a risk. This accident is considered most likely to occur when loading or unloading hazardous goods. The probability class is three and consequence class is three. The source is described as a point source that discharge the contaminants occasionally.

Accidents with shipping - Accident with shipping could result in a discharge of petroleum products and other hazardous substances directly into the river. The probability class is three and consequence class is three. The source is described as a point source that discharge the contaminants occasionally.

Industry discharge - The risk is primarily related to an accident in an industry in close connection to the river. It is considered that an accident could cause the discharge of chemical, microbial and physical contaminants. The probability class is three and consequence class is three. The source is described as a point source that discharge the contaminants occasionally.

Landslide of contaminated site - The risk source is considered to cause the discharge of chemical and physical contaminants in the event of an accident. The probability class is two and consequence class is four. The source is described as a point source that discharge the contaminants occasionally.

Flooding - The risk is primarily related to flooding over contaminated sites, industry area and agricultural sites. The flooding could cause contaminants to spread to the water source. The event is considered an accident and the contaminates could be chemical, microbial and physical. The probability class is three and consequence class is thee. The source is described as a diffuse source that discharge the contaminants occasionally.

5.2.2 Result - New Approach

This result is a presentation of the contaminants that are considered the highest risk in Göta älv / Vänersborgsviken. The contaminants and the corresponding risk sources from our risk assessment are gathered in *Table 5.4*. For the full risk assessment, see *Appendix B*.

Table 5.4: *The contaminants that pose the highest risks to Göta älv / Vänersborgsviken and the corresponding main risk sources according to our results*

Contaminants Group	Risk sources
Pathogens	Combine sewer overflows (CSOs) Waste water treatment plants (WWTPs) Grazing animals and sewage pipes
Petroleum Products	Accidents with hazardous goods(shipping)/Harbour activities Accidents with hazardous goods (roads and railways) Leakage from contaminated sites and discharge from boats
Pesticides	Pesticides used in agriculture
Heavy Metals	Accident when remediating or leakage from contaminated Accidents in industry Runoff from urban and industrial areas

Pathogens
The risk of pathogen contamination in Göta älv/Vänersborgsviken is considered high. The risk is primarily related to sources such as CSOs and WWTPs. Due to the several large cities in close connection to the river, the load of pathogens could be large. Moreover, since the pathogens would be directly discharged into the water source, it is considered likely that they reach a raw water intake.
CSOs can occur in many places along the river. They are triggered by heavy rain and floods and it is likely to occurs a few times each year. The potential discharge from a WWTP is most likely triggered by a failure or an accident. Therefore, it is unlikely to happen but if it does the load could be particularly large.
Other sources of concern are shore grazing animals and sewage pipes. Shore grazing animals pose a considerable risk as the cumulative load of pathogens could be relatively large and the ability to spread is considered good. Moreover, large sewage pipes in close to the water source pose a considerable risk in case of breaking. It

is considered unlikely to occur but if it happens a large load of pathogens could be discharge directly into the water source.
Climate change and extreme weather conditions could increase the frequency of the discharge from primarily CSOs. The waterworks ability to treat pathogens contamination is considered good. However, with an increased load, the treatment might be insufficient. Thus, drinking water consumers might get infected.

Petroleum products
The risk of petroleum products contamination in Göta älv / Vänersborgsviken is considered high. The risk is mainly related shipping, harbour activities but also transports of petroleum products on roads and railway.
An accident during shipping or harbour activities could potentially cause the release of a large amount of petroleum products directly into the water source. It is considered unlikely to happen but if it does the discharge may reach the raw water intake rather quickly and cause large consequences. Furthermore, accidents when transporting petroleum products on roads and railway in close connection to the water source also needs to be considered. The ability for the petroleum product to spread is not as good as from the shipping. However, the load might be large and may reach the water source.
There are a few other sources, such as discharge from boats and leakage from contaminated sites that are considered to pose a risk to the water source. However, these sources have in general longer pathway and/or lower loads then the sources mentioned above.
In general, all sources of petroleum products are considered to pose a relatively large risk, with risks related to accidents being the most sever. The waterworks is not able to treat petroleum products. Thus, any amount of spillage could affect the drinking water production.

Pesticides
The risk of pesticides contamination in Göta älv / Vänersborgsviken is considered relatively high. It is primarily related to the usage of pesticides in agriculture.
There are many agricultural sites in close connection to the water source. The pesticides can spread to the lake through runoff and/or infiltrate the ground and spread through groundwater flow. The spread is likely to occur as a result of normal usage or in case of accidents with pesticide containers. Furthermore, pesticides can also be found in home chemicals and are used in gardens, sport facilities and parks. In general, the load of pesticides from each site is considered to be relatively small. However, since there are several sources, the cumulative load could be large.
The spreading of pesticides could be enhanced by climate change and extreme weather conditions. Primarily due to the larger risk of flooding which increase surface runoff. The waterworks is not adapted to treat pesticides. Thus, once they reach the raw water intake, they can pass through the waterworks and cause adverse health effects on drinking water consumers even at low concentrations.

Heavy metals
The risk of heavy metals contamination in Göta älv/Vänersborgsviken is considered

relatively high. The risk is primarily related to contaminated sites and industries.
There are many contaminated sites in close connection to the water source. The disturbance of these sites could be caused by remediation measures or landslides. This could expose contaminated soil and create fast pathways to the water source. Primarily, dissolved heavy metals could be transported to the water source via runoff or through groundwater flow. Since there are many contaminated sites, the cumulative load of heavy metals needs to be considered.
Accidents in an industry could result in a large load of heavy metals being discharged directly into the water source. It is considered unlikely to occur but if it does it could effect the drinking water production.
Runoff from urban and industrial areas is likely to contain high levels of heavy metals. If the runoff is not managed or in case of heavy rain, there is a risk of heavy metals reaching the water source.
The spreading of heavy metals could be enhanced by climate change and extreme weather conditions. Primarily due to the larger risk of flooding, landslides and erosion. Activities such as excavation, dredging or explosions is also considered to increase the spreading of heavy metals.
In general, the risk of heavy metals is more likely to deteriorate the water quality over time rather than have a direct effect on the water quality. However, events such as landslides from contaminated sites and industry discharge might cause high levels of heavy metals in the water source. Since the waterworks is not adapted to treat heavy metals, drinking water production might be affected.

5.2.3 Comments

The risk level in Göta älv / Vänersborgsviken is considered high. It was found by both risk assessments that there are many risk sources that could cause large consequence to the water source. Since the water source is exposed to both urban and rural activities, all kinds of contaminants assessed in this risk assessment are considered to pose a relatively high risk. It was found that the larges risks are related to pathogens and petroleum products. Most of the risk sources considered the highest risk are the same in the two risk assessments. The major difference is that Sweco does not include accidents with hazardous goods on road and railway and the contaminant group pesticides as one of the highest risks. In our risk assessment the risk posed by accident with hazardous goods on road and railway is considered high. Mainly, since there are many places in which a potential spillage could reach the water source. Furthermore, the usage of pesticides in agriculture are considered large. Primarily, since there are large areas of agricultural sites in close connection to the water source. It is important to state that these differences is not affected buy the method but rather due to different opinions of the risk assessors.

A result of using different approaches a difference is the event of flooding. In the common approach, flooding is considered as an independent risk source. The risk is mainly related to an increased surface runoff from agricultural and industrial sites. The new approach also addresses the risk related to flooding, however, since flooding is not a contaminant itself, it is not assessed as an independent risk source. The new approach rather aims to describe how flooding might impact other risk sources. An example of this is the contaminant pesticides. It is described in our result that pesticides could spread by runoff and that events such as flooding could enhance the spread.

5.3 Grimstofta

Grimstofta is a relatively small groundwater source situated in the town Sjöbo, in south of Sweden, see *Figure 5.3*. The source consist of three different aquifers. One aquifer is unconfined and consist of glaciofluid sand deposits, another is confined and consist of glaciofluid gravel and the third is situated in sedimentary rock (limestone). The groundwater table lies only about one meter below the ground level and the groundwater flows in northwest direction. The aquifers in Grimstofta provides water for around 9000 people in Sjöbo and for the small population in a few other small towns surrounding Sjöbo (Sweco, 2018a). The municipally lack a reserve water source, which according to Sweco (2018a), makes the water source in Grimstofta has a very high protection value. The risk assessment has been conducted on a relatively small area, therefore, several risk sources are specified and described in a detailed way.

Figure 5.3: *Grimstofta water source*

5.3.1 Result - Common Approach

This is a presentation of the risk sources Sweco considered the highest risk in Grimstofta. The risk sources are gathered in *Table 5.5* and described below. For full summary of Sweco result, see *Appendix C*.

Table 5.5: *The risk sources with the highest risk class in Grimstofta according to Sweco. Including the probability, consequence and risk class for each source*

Risk sources	P	C	Risk
Accidents with hazardous goods	1	4	2
Accidents with heavy vehicles	1	3	2
Pesticides used in agriculture	1	3	2
Home chemicals (pesticides)	3	2	2
Tanks with petroleum products (Urban)	3	2	2
Tanks with petroleum products (agriculture/forestry)	3	2	2
Energy facilities	3	2	2
Municipal sewage pipes	1	3	2
Contaminated sites 15/16/18	1	3	2

Accidents with hazardous goods - The risk is primary related to accident on the roads in close connection to the water source. The contaminant is most likely petroleum products. The probability class is one and the consequence class is four.

Accidents with heavy vehicles - The risk is primary related to accident on roads in close connection to the water source. The contaminant is petroleum products. The probability class is one and the consequence class is three.

Pesticides used in agriculture - The risk is mainly related to the usage of pesticides for plants in close connection to the water source. The probability class is one and the consequence class is three.

Pesticides used in home chemicals - The risk is mainly related to accidents with pesticide containers used is private gardens. The probability class is three and the consequence class is two.

Tanks storing petroleum products (both rural and urban) - The risk is mainly related with a potential spillage in close connection to the water source. The probability class is three and the consequence class is two.

Energy facilities - The risk is primarily related to the cumulative effect of many energy facilities installed in soil. The probability class is three and the consequence class is two.

Municipal sewage pipes - The risk primarily relates to the breaking of sewage pipes in close connection to the aquifer area. The probability class is one and the consequence class is three.

Contaminated sites - The risk is mainly related to pesticides found at the sites of former gardening markets. The probability class is one and the consequence class is three.

5.3.2 Result - New Approach

This result is a presentation of the contaminants that are considered to pose the highest risk in Grimstofta. The contaminants and the corresponding risk sources are gathered in *Table 5.6.* For the full risk assessment, see *Appendix C.*

Table 5.6: *The contaminants that pose the highest risks to Grimstofta and the corresponding main risk sources according to our results*

Contaminants Group	Risk sources
Pesticides	Home chemicals (pesticide) Contaminated sites 15/16/18
Petroleum Products	Accidents with hazardous goods/heavy vehicles on roads Tanks with petroleum products (close to the aquifer)

Pesticides
The risk of pesticide contamination is considered high. The risk is mainly related to the usage of household pesticides near the aquifer area.
There are many places in close connection to the aquifer where these pesticides are used, such as gardens and parks. In case of spillage, the load of pesticides could be relatively large. Since the groundwater table lies only about one meter below the ground surface, the pesticides could infiltrate the unconfined aquifer rather easy. Furthermore, the cumulative load from normal usage also needs to be considered as the pesticides could reach the aquifer.
Other sources, such as contaminated sites (former gardening markets) and agricultural sites are also considered to pose a risk. They are located upstream the aquifer area and might spread pesticides to the aquifer. However, since these sites are located relatively far from the extraction wells and the dilution is considered relatively large, they are considered to pose a lower risk that than household pesticides. The spreading of pesticides could be enhanced by climate change and extreme weather conditions. Primarily due to the larger risk of flooding which increase surface runoff. Since the waterworks is not adapted to treat pesticides, all sources of pesticides is considered to pose a relatively large risk. Mainly because once they reach the raw water intake, they can pass through the waterworks and cause adverse health effects on drinking water consumers even at low concentrations.

Petroleum products
The risk of petroleum products contamination is considered relatively high. The risk is mainly related to accidents on Tolångavägen and Långdansgatan and tanks storing petroleum products in close connection to the aquifer area.
An accident on roads Tolångavägen and Långdansgatan could cause the spill of large amount of petroleum products. Reduction measures to decrease the effect of Tolångavägen have been done such as impermeable trenches along the side of the road.

However, with large loads the trenches might be insufficient.
Moreover, there are tanks storing petroleum products that are used in close connection to the aquifer. In case of an accident, petroleum products could be spilled.
Since the aquifer is unconfined and the groundwater table lies only about one meter below the ground surface, any amount of spillage could infiltrate the aquifer. Since the spillage of petroleum products is connected to the event of an accident, it is considered unlikely to occur. However, the waterworks is not adapted to treat petroleum products. Thus, any amount of spillage could affect the drinking water production. Furthermore, in case of a large spillage remediation of the water source might be necessary.

5.3.3 Comments

It was found by both risk assessments that the risk level in Grimstofta is relatively low. Since the water source is situated in a urban area there are many risk sources. However, most part of the risk sources within the city Sjöbo is located downstream the extraction wells, thus, they do not affect the water source. Furthermore, the risk level to groundwater sources is in general lower than in surface water sources. It was found that the largest risks is related to the contaminants pesticides and petroleum products. Mainly, since risk sources exists in close connection the the water source and due to their ability to infiltrate the aquifer. Note that since this is a groundwater source, particle contamination was excluded from the risk assessment.
Most risk sources assessed as the highest risk in Sweco risk assessments can also be found as the highest risks in our result. However, there do exist some differences. One difference is that Sweco considered the breaking of sewage pipe poses as one of the highest risks. We considered that even if it does occur it is considered unlikely that the pathogens would reach the aquifer, mainly due to filtration in the soil. Furthermore, even if a small load of pathogens would infiltrate, they would probably be disinfected in the waterworks. Thus, the risk is assessed low. It is important to state that this difference is not affected by the method but rather due to different opinions of the risk assessors.

As result of using different approaches a difference regarding the risk source energy facilities was found. It is described in Sweco risk assessment that the risk of energy facilities mainly relates to the creation of unplanned pathways, primarily during construction (Sweco, 2019a). Since the energy facility in this case does not relate to a specific contaminant, it is not assessed as an independent risk source in the new approach. It is rather suggested to describe how the creation of unplanned pathways can affect the spreading of different contaminants. However, energy facilities was considered not to contribute much to the spread of any specific contaminant, thus energy facilities was not described in detail.

5.4 Haboskogen

Haboskogen is a large groundwater source located east of the town Töreboda, in the county Västra Götaland. The aquifer consists of a large subaquatic esker that have a groundwater flow in north to south direction. The aquifer is unconfined and the groundwater table lies about 6 meters below the ground surface. The water source provides water for about 4500 people in the town of Töreboda. It could supply water for a much larger population, thus, only a small part of the aquifer's capacity is used. The surrounding area consists of agriculture and forestry and there are no industries in close connection to the aquifer area, see *Figure 5.4*. The abstraction wells are located just south of road 202. Moreover, the reserve water source consists of a extraction well in the north part of the same aquifer. Since it is a groundwater source located in an rural area, the risk sources are relatively few. Therefore, several risk source is specified and described in detail.

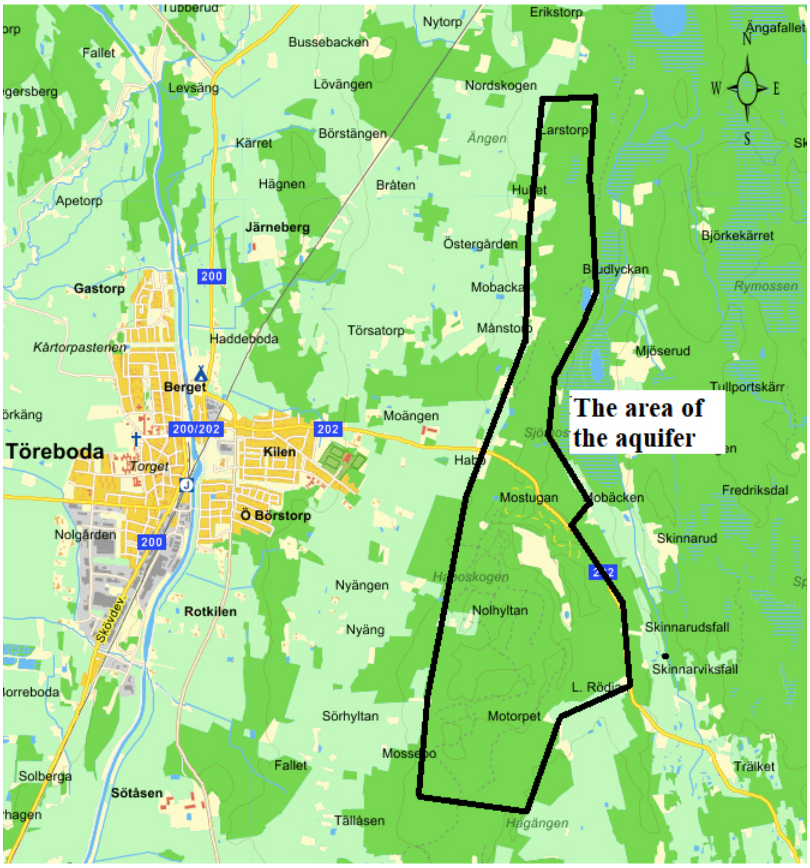

Figure 5.4: *Haboskogen water source*

5.4.1 Result - Common Approach

This is a presentation of the risk sources that Sweco considered the highest risk in Haboskogen. The risk sources are gathered in *Table 5.7* and described below. For full summary of Sweco result, see *Appendix D*.

Table 5.7: *The risk sources with the highest risk class in Haboskogen according to Sweco. Including the probability, consequence and risk class for each source.*

Risk sources	P	C	Risk
Accidents with hazardous goods on road 202	1	4	2
Accidents with heavy vehicles on road 202	2	3	2
Pesticides used in agriculture	1	3	2
Tanks with petroleum products (agriculture/forestry)	3	2	2
Heaps of timber	3	2	2
Contaminated sites, sawmill 8	2	3	2
Rifle range, 6	2	3	2

Accidents with hazardous goods on road 202 - The road is in close connection to the water source. The probability of an accident to occur is considered very low but if the contaminants reaches the water source the consequence will be very large. The probability class is one and the consequence class is four.

Accidents with heavy vehicles on road 202 - The road is in close connection to the water source. The probability of an accident to occur is considered very low but if the contaminants reaches the water source the consequence will be very large. The probability class is two and the consequence class is three.

Pesticides used in agriculture - The risk is mainly related to the usage of pesticides for plants in close connection to the water source. The probability class is one and the consequence class is three.

Tanks storing petroleum products (rural) - The risk primarily refers to the penitential spillage from tanks in close connection to the aquifer. The probability class is three and the consequence class is two.

Heaps of timber - The risk primarily refers to heaps of timber stored in close connection to the aquifer. The probability class is three and the consequence class is two.

Potentially contaminated site - The risk mainly relates to the former sawmill (site 8). The site is situated around 400 meters from the extraction wells. The probability class is two and the consequence class is three.

Rifle range - The rifle range is situated around 100 meters from the reserve water source. The probability class is two and the consequence class is three.

5.4.2 Result - New Approach

This result is a presentation of the contaminants that are considered to pose the highest risk on Haboskogen. The contaminants and the corresponding risk sources are gathered in *Table 5.8*. For the full risk assessment, see *Appendix D*

Table 5.8: *The contaminants that pose the highest risks to Haboskogen and the corresponding main risk sources according to our results*

Contaminants Group	Risk sources
Petroleum Products	Accidents on road 202 Tanks with petroleum products (agriculture/forestry)
Pesticides	Pesticides used in agriculture

Petroleum products
The risk of petroleum products contamination is considered high. The risk is mainly related to accidents on road 202 and tanks storing petroleum products in the area of the aquifer.
An accident on road 202 could cause the spillage of a large amount of petroleum products. The road 202 is located about 60 m north of the nearest extraction well. Reduction measures to decrease the effect of the road have been done such as impermeable trenches along the side of the road. However, in case of a large spillage the trenches might be insufficient. Thus, the petroleum products is likely to reach the extraction wells quickly.
Moreover, tanks storing petroleum products are used in agricultural and forestry activities in close connection the aquifer. In case of an accident, petroleum products could be spilled. Since the aquifer is unconfined any spillage could infiltrate and might reach the extraction wells.
Since the spillage of petroleum products is connected to the event of an accident,it is considered unlikely to occur. However, the waterworks is not adapted to treat petroleum products. Thus, any amount of spillage could affect the drinking water production. Furthermore, in case of a large spillage remediation of the water source might be necessary.

Pesticides The risk of pesticide contamination is considered relatively high. The risk is primarily related to the use of pesticides in agriculture and forestry.
There are many forests and agricultural sites in connection to the aquifer area. The pesticides can spread through runoff and infiltrate the aquifer as a result of normal usage or in case of accidents with pesticide containers. The load of pesticides from each site is likely to be relatively small. Therefore, the risk is more related to the cumulative load from several sites which could lead to the deterioration of the water source over time. The spreading of pesticides could be enhanced by climate change and extreme weather conditions. Primarily due to the larger risk of flooding which increase surface runoff. Furthermore, the waterworks is not adapted to treat pesticides. Thus, once they reach the raw water intake, they can pass through the waterworks and cause adverse health effects on drinking water consumers even at low concentrations.

5.4.3 Comments

It was found by both risk assessments that the risk level in Haboskogen is relatively low. Since the water source is situated in an rural environment, the risk sources are rather few. Furthermore, the risk level to groundwater sources is in general lower than in surface water sources. It was found that the largest risks is related to the contaminants petroleum products and pesticides. Mainly, since sources exists in close connection to the water source and due to their ability to infiltrate the aquifer. Note that since this is a groundwater source particle contamination was excluded from the risk assessment. Most risk sources assessed as the highest risk in Sweco risk assessments can also be found as the highest risks in our result. However, there do exist some differences.
One difference is that Sweco considered the contaminated site eight and the rifle range as one of the highest risks. In our result these risk sources is assessed lower. Mainly, since it is considered that if these sites is not disturbed they are unlikely to affect the water source. Another difference is that Sweco considers heaps of timber as a relatively high risk. In our result, the risk is considered lower. Primarily, since it is considered that there are no long term storage of timber in close connection to the aquifer. It is important to state that these differences is not affected buy the method used but rather due to different opinions of the risk assessors.

6
Discussion

To discuss different topics of this work, this chapter is divided into three main parts. First, different aspects that affected the results of the performed risk assessments are addressed. Followed by a comparison between the two approaches of risk assessment, with the aim to analyse the main similarities and differences. Finally, the new approach of risk assessment is evaluated to further discuss its performance and possible improvements.

6.1 Comments on performed risk assessments

When conducting a risk assessment based on the new approach using data from risk assessments performed by Sweco, there was a number of complications. First of all, it was required to arrange and categorize the given risk sources based on their contaminants. This created a limitation in the application of the new approach. Instead of following the recommended procedure of the new approach, we start with evaluating the risk sources given to us. This made it somewhat hard to concentrate on the main sources of a specific contaminant. Mainly since we did not want to exclude any risk source that might spread a specific contaminant. Therefore, some risk sources are assessed based on several contaminants, even if the risk was considered to primarily be related to a specific contaminant.
Another challenge of using the data from Sweco was the risk related to water quantity. The new approach suggest that water quantity is assessed, however, since the previous risk assessments did not address this aspect, it was also not addressed in our assessments.
Furthermore, when the data provided by Sweco was generic, mainly in the case study Göta älv / Vänersborgsvikenn, it was hard to apply the new approach accurately. Primarily, since the data was not considered sufficient enough to describe specific pathways of the contaminants.
Another aspect with using data from Sweco is that our result is largely influenced by their result. It was found that there do exist some differences in the interpretation of the risk level of a few risk source. However, in general the result is very similar. If performing a risk assessment with the new approach from the beginning, the data could have been adapted more efficiently. Furthermore, the risk assessment would have been done independently. Thus, the results could have been more objectively compared. However, the purpose with this master thesis was to evaluate the two approaches for risk assessment. Thus, by using the same data the result could be easily compared. Mainly, since risk sources in one risk assessment easily can be

found in the other. This resulted in that differences and similarities easily could be pointed out.

6.2 Comparison Between the two Approaches

When comparing the results of the risk assessments performed with the two approaches, it was found that the largest differences relates to how the risk sources is characterized and how the risk level is estimated. The following section will further discuss these aspect.

6.2.1 Risk source characterisation

A large difference between the approaches is how the risk sources are characterised. The common approach is a risk source-based approach and the new approach is both a contaminant-based and risk source-based approach. This primarily affected how the risk assessment is structured and how different types of risk sources are assessed. The main characteristics of the common approach, new approach and conflicts that were found are discussed in the sections below.

6.2.1.1 Common Approach

The common approach uses several of ways of characterising a risk source. When analysing the result from Sweco's risk assessments it was found that a risk sources can be described as activities, events, places, contaminants or objects. The risk sources are often presented as combinations of these categories. For example: "Pesticides used in agriculture" (contaminant and activity), "Contaminated sites" (places), "Flooding" (event), "Tanks with petroleum products" (object) or "Accident with hazardous goods on road" (event, contaminant and place). This makes the risk assessment somewhat inconsistent. It is sometimes hard to understand what the risk relates to and how it could affect the water source. Furthermore, some risk sources are assessed in more detail than others. Which could be interpreted as more important even if the risk level is considered relatively low.

6.2.1.2 New Approach

The new approach assesses one group of contaminants at the time and connect the related risk sources. Since the new approach follows the same structure when characterising the risk risk sources it can be argued that the risk assessment is more systematic. For example, when describing the pathway from each risk source the risk assessments present where the risk source is situated, what event that cause the spread of the contaminant, and the ability for the contaminant to spread. In this procedure it can be argued that most of the different ways of categorizing a risk source in the common approach are described for every risk source. By collecting this information for all the risk sources it becomes easier to understand what the risk is related to and how it could affect the water source.

6.2.1.3 Conflicts

A major difference in characterizing risk sources regards specific events and risk sources that creates unplanned pathways. Since these risk sources cannot be linked to a specific contaminant, the new approach aims to describe how these aspects affects other risk sources instead of assessing them as independent risk sources. When conducting the risk assessments a number of sources like this were found. For examples: climate change and extreme weather events such as flooding, landslides, dam failure and erosion; activities in close connection to water source, such as excavating dredging and exploding and energy facilities installed in bedrock, soil and surface water.

When these risk sources significantly affected the overall risk, it was found to be beneficial to include them in the risk description in the new approach. An example of this is to describe how flooding and climate change could increase the frequency of CSOs, thus, increase the risk of pathogen contamination. However, it was also found that when these risk sources were not considered to contribute as much to the overall risk level, these risk sources became hard to incorporate. An example of this is the risk source "Energy facilities". The risk related to energy facilities is primarily related to the creation of unplanned pathways, mainly during construction (Sweco, 2018a). When assessing the risk of the different contaminants in the new approach, it was found that the pathway created by energy facilities did not contribute significantly to the spread of any group of contaminants. Therefore, it was not suitable to mention energy facilities when describing the overall risk of the groups of contaminants. Nevertheless, since energy facilities might contribute to the spreading of all kinds of contaminants, the cumulative effect need to be considered. Thus, it could be argued that the risk of energy facilities was underestimated in our risk assessment.

6.2.2 Risk Estimation

When estimating the risk there is a large difference between the two approaches. The common approach classifies the risk sources based on predetermined scales while the new approach aims to describe and motivate the risk.

6.2.2.1 Common Approach

To estimate the risk level in the common approach every risk source is classified based on their probability to occur and the consequence they could cause to a water source if they do occur. Every risk source is given a probability class and a consequence class to motivate the risk level.
When a risk source is described in a fairly detailed way, it is considered relatively easy to understand why a risk source is given a specific class. An example of this is the risk source "accidents with hazardous good on a road" that has probability

class one and consequence class four in all the water sources examined in this master thesis. Since the risk source is related to an accident, it is easy to understand that the probability that it would occur is low. Furthermore, if the accident would occur, hazardous goods could be spilled in large quantities, thus, it is easy to understand that the consequence could be the highest possible.
However, when a risk source is described in a more generic way, it is sometimes hard to understand why a risk source is given a specific class. An example of this the risk source "natural fertilizers", that can be found in all the water sources examined in this master thesis. In the case study Bolmen, this risk source has probability class three and consequence class three. It can be argued that since the character of the risk source is not presented in detail, it is hard to understand why the risk source is given these classes. It is likely that the risk assessor have good arguments to classify the risk source this way. However, since the common approach does not include further motivation or description of why the risk sources is given a specific class, this information tend to get lost. Furthermore, it could be argued that since the description of some risks is lacking, the results is less suitable to be used as a support for evaluating risk reduction measures.

6.2.2.2 New Approach

The new approach aims to describe the risk level. It does so by clearly describing the physiological properties and the hazardousness of each group of contaminants. This provides a clear comprehensive understanding of the contaminant ability to spread and its potential to cause harm to a water source. Furthermore, potential pathways and the waterworks ability to treat the contaminants are described. When the risk estimation is formulated, this information are used to motivate and justify the overall risk level and to identify which risk sources that are considered the highest risks. The risk description also describes important factors that could increase the spread by affecting these risk sources. Since the new approach systematical collects all the information that contribute to the over all risk level, it is considered easier to understand what the risk is related to and how it can affect the water source. If someone wonders why a contaminant or risk source is regarded high or low, the motivation can be found in the risk assessment. Furthermore, it provides a better understanding of how the risk could potentially be reduced or mitigated by risk reduction measures.

6.2.2.3 Probability and Consequence Description

Another difference between the two approaches is how the probability and consequence are described and incorporated. In the common approach, the predetermined scales were considered to work good regarding the probability of a specific event to occur. Mainly, since it describes how many times a year the event is considered to happen. However, it was also found that the related event could be somewhat hard to understand for some risk sources. This can be compared to the new approach where the probability is incorporated the description of risk sources. For example, risk sources could be described as: "the spread occurs in the event of heavy rain" or "in case of an accident". When the risk source is described this way it could be ar-

gued that both the characteristics and the probability is easy to understand, which adds value to the risk assessment. However, it was also found that that probability of some events was described as it is "unlikely to happen" or it is "relatively unlikely" to happen. In this case the probability description became rather vague which suggests that adding a probability class could add value to the risk assessment.
Furthermore, it was found that how the consequence is described largely differs between the two approaches. The classification system used in the common approach poorly motivates why a source has a certain consequence class and it does not describe the characteristic of the consequence. It can be argued that important questions when assessing the consequence are: does it cause a human health effects? is the quantity of available drinking water affected?, is the waterworks affected? Does the water source need remediation? These are all relevant aspects to gain a clear understanding of the consequence. Since the new approach describes the consequences of each group of contaminant, these questions are answered in a systematic way. Thus, it adds great value to the risk assessment.

6.2.2.4 Risk Level Presentation

An interesting finding when conducting the risk assessments is how the risk is presented and how the actual risk level is perceived. The common approach uses the same criteria for probability and consequence classification when assessing risks for different water sources. Therefore, the risk level between water sources can be compared. Although, it is important to state that the result does not represent an absolute value of the risk level. Since the new approach does not use any predetermined scales the risk level cannot directly be compared between water sources. However, it can be argued that the aim of the risk assessment is not to compare it among water sources. Mainly, since the purpose of the risk assessment is to manage the risk for a specific water source regardless of the how high or low the risk level is.
Another aspect of how the risk is presented regards how easy the risk level is demonstrated. The common approach makes it possible to get a quick overview of the risk situation of a specific water source. It makes is easy to see how many risk sources that were identified and how they are classified. Thus, it is considered easy to get a comprehensive idea of the risk situation. Since the new approach describes the risk, it requires quite extensive reading to get a picture of the risk level. However, the risk level is considered more precisely described and motivated.

6.3 New Approach Evaluation

The evaluation is primarily based on how well the risk assessment describes the risk level of a specific water source and how the result can be used to motivate implementation of risk reduction measures. Furthermore, improvements regarding the grouping of contaminants, how to address the water quantity and future threats are also discussed. Lastly, suggestions for future work are given.

6.3.1 Presentation of the Risk Assessment Results

An important aspect of the risk assessment is how the result is presented. It was found that the pathway description made it rather clear which risk sources that are of most concern. Therefore, it is considered beneficial to mainly describe these sources when presenting the overall risk of the contaminant. Furthermore, by including other aspects that could affect these sources and by commenting on the the waterworks ability to treat the contaminant, the risk level can be further motivated. By presenting the risk in this manner, it also gives a strong indication of where to focus when evaluating risk reduction measures.
The risk sources regarded as lower risks are suggested to not be presented in the risk level description. However, this may result in that some risk sources is overlooked. Nonetheless, in order to not confuse the reader, it is considered better to mainly describe the risk sources of most concern than to include too many risk sources in the risk description. Furthermore, to provide a clear result, the contaminant considered of most concerns is suggested to be placed in the top of the risk assessment. This also serves the purpose of indicating the contaminants and risk sources of most concern.

Since this is a descriptive method, it was found to require quite extensive reading to get an overview of the risk situation. To make the result clearer, it is therefore suggested to include a summary of the contaminants of most concern and their connected risk sources. By presenting both a summary and the risk description it can be argued that the reader both get an overview of the risk situation while at the same time inquire in depth information of the characteristics of the contaminants and risk sources of most concern.

It is important to state that the presentation of the risk does not represent an absolute values of the risk level. Furthermore, what is considered as the highest risks for a water source are somewhat subjective. Thus, it could vary from one risk assessor to another. However, it can be argued that the parts of the new approach that describes properties and consequences of the contaminant, pathways and the waterworks ability to treat the contaminants, are to a large extent based on facts. Thus, it is considered to increase the overall objectivity of the risk assessment. Therefore, it can be used to motivate the presentation of the main risks regardless of who the risk assessor is. Thus, this is regraded as an important strength of this approach.

Another benefit with this approach regards how the result can be used to motivate risk reduction measures. By presenting the risk as mentioned, the risk sources of most concern is highlighted and at the same time the most significant characters are described. Thus, the result can be efficiently used to motivate different risk reduction measures. One of the most important risk reduction measures in water protection areas is the implementation of restrictions. It can be argued that by providing comprehensive description of the risk sources, it becomes significantly easier to understand whether the risk can be reduced through restrictions or not. Furthermore, the description of the risk sources could also be used to further motivate and support the analysis of different risk reduction measures through cost-benefit analysis or other decision analysis methods. Thus, this is regarded as another important strength of this approach.

6.3.2 Applicability to Different Water Sources

After performing the risk assessment on four types of water sources, it was found that the new approach is applicable to groundwater and surface waters in both urban and rural areas. The main aspect that affected the applicability is how extensive the risk assessment is and at what level of detail the risk assessment is performed.
It was found that when performing the risk assessment on a large water source with a large number of risk sources, the new approach was hard to apply. This can be seen in the risk assessment of Göta älv / Vänersborgsviken, see *Appendix B*. Due to the large area and the generic assessment of many risk sources, the pathways and the risk level were described in general. For example, when assessing the risk related to contaminated sites, the pathways was described as "if the cite is close to the water source, the contaminant is more likely to spread" and as "the contaminant can spread through surface runoff or groundwater flow". It can be argued that since this description is generic it becomes rather vague, thus, does not add significant value to the risk assessment. It can therefore be argued that the new approach is more demanding to be applied in this case.
It was found that the new approach was most beneficial and adds great value to the risk assessment when the risk sources can be specified and localized. This resulted in the ability to describe the pathway in more detail, thus, the risk could be more efficiently estimated. For instance, it was found that this could be achieved on the water sources Bolmen, Grimstofta and Haboskogen, primarily since the number of risk sources were rather few. Furthermore, it was found that it did not matter if it was a groundwater or a surface water source since this did not affect the performance of the pathway description.

6.3.3 Grouping of Contaminants

To perform a risk assessment based on the new approach, a number of groups of contaminants needs to be established. The following section includes an overview of how to group the contaminants according to the new approach. In addition, challenges and further improvements are discussed. Furthermore, the performance of the contaminants used in our risk assessments is evaluated.

6.3.3.1 Overview

The contaminants assessed in the new approach are recommended to be grouped based on their physiological properties. Mainly, since this affects their ability to spread the most. It is not described which contaminants to consider or how they can can be grouped. An argument for this is that the new approach aims to adapt the risk assessment to site specific conditions. In this context, it is important to state that our risk assessment of the new approach was done to compare the two approaches. Thus, the groups of contaminant that were used are the same for all the water sources. Nevertheless, it was found that creating an efficient grouping

of contaminants is quite challenging. It requires quite extensive knowledge about common drinking water contaminants, their physiological properties, health affects on humans, treatment processes in waterworks and their related risk sources.
To simplify the risk assessment, it is beneficial to establish as few groups of contaminants as possible. However, to describe and present the risk as accurately as possible, it can be argued that the use of more groups of contaminants is better. However, by assessing more groups, the risk assessment get more extensive. Thus, some results are likely to become redundant. It can be argued that only the contaminants considered being of most concern is assessed independently. However, this knowledge might not be available until the risk has been estimated, thus it is considered hard to change while performing the risk assessment.
To solve this challenge it could be argued that the new approach could be improved by collecting information about common drinking water contaminants, their physiological properties, health affects on humans, treatment processes in waterworks and related risk sources. This would decrease the workload of the risk assessors while at the same time increase the consistency of the method. Furthermore, it could be used to provide a basis for how the contaminants can be grouped. Moreover, it is considered that this change can be implemented without interfering with the aim of performing the risk assessment based on site specific conditions.

6.3.3.2 Evaluation of the applied grouping

It was found that the groups of contaminants used in our risk assessment cover the majority of the contaminants connected to the risk sources provided by Sweco. However, some generalizations had to be made and few conflicts were found.

The groups pathogens, petroleum products, heavy metals and particles worked good. Mainly, since it was found easy to define and present the risk sources considered of most concern in each group. It was also found easy to identify different aspects that enhanced the risk and to describe the overall impact on the water source.

The group Common organic contaminants was not considered as good. Mainly, since it was found that pesticides was of more significance than the other organic contaminants. Since pesticides share the same spreading behaviour as other organic contaminants such as chlorinated solvents, PFAS and phenol they were assessed as one group. This grouping did simplify the risk assessment, however, to some extent it failed to highlight that pesticides was considered of significantly more concern for all the water sources assessed in this master thesis. A solution would be to assess pesticides independently. This would provide a better presentation of the results of the risk assessment. However, it is important to not exclude the other organic contaminants as they also pose a threat to the water source. Therefore, there is still a purpose with including the group "common organic contaminants".

The group nutrients was found to not add significant value for the risk assessments. Mainly, since nutrients were found to be considered as one of the lowest risks in all the risk assessments. It was found that the risk of nutrients contamination are more related to the deterioration of the water quality over time rather than having a direct effect. However, since the nutrient could cause long term effect on a water source, it is still considered important to asses their impact. It was also found that the nutrients does not easily affect ground water sources. Therefore, it could be argued that the group nutrients could be excluded when assessing groundwater sources, at least if the aquifer is not situated in direct connection to agricultural sites.

Another aspect concerns risk sources that are considered to cause the spread of several different contaminant while the risk is considered to be posed mainly by one contaminant. An example of this are risk sources such as combined sewers overflows and breaking of sewer pipes. The risk related to these sources is primarily the spreading of pathogens. However, these risk sources could also cause the spreading of nutrients. It was found that by only assessing these sources based on pathogens, the risk assessment could be simplified without losing value. However, it is important to keep in mind site specific conditions before making this generalization.

Since the majority of the risk sources can be connected to one or several contaminants, these six groups of contaminants worked rather good. However, the risk sources described in *Section 6.2.1.3*, such as flooding and energy facilities was somewhat hard to include in this groups. Mainly, the problem occurs when these risk sources is considered to not significantly affect or enhance the spread of one particular contaminant. However, since they could affect all contaminants the cumulative effect could be significant. It was found that the risk sources energy facilities, erosion, landladies, dam failure, explosions, dredging, excavating might have been underestimated in our risk assessment. What is in common for these sources is that they primarily pose a risk to the water source by creating unplanned pathways. Therefore, to improve the risk assessment it could be argued that a group called "Unplanned pathways" is added to the risk assessment. By assessing these sources in more detailed way, the risk level could be more precisely described.

6.3.4 Water Quantity and Future Treats

It is recommended in the new approach to assess the risk related to future threats and water quantity. Since our risk assessments was limited to the data provided by Sweco, these risks were not included. However, when performing the risk assessments, these risk sources where kept in mind. It was found that when assessing present risk sources, it is hard to incorporate the risk related to water quantity and future threats. Primarily, since the risks relate to conditions that are not present at the time of the risk assessment. Furthermore, it was considered that both water quantity and future threats mainly relates to future land use and weather conditions.

Future land use could result in an increase of the amount of impermeable surfaces. This could result in decreasing the aquifer recharge and subsequently the water quantity. Especially if the impermeable surfaces were to be constructed in an area which largely contributes to the recharge. Furthermore, a change in land use could also lead to new risk sources that potentially could cause the spread of contaminants. Therefore, the water quality could also be affected.

Climate change could lead to a change in weather conditions. This could affect a water source both in terms of quantity and quality. In the case of droughts, the available quantity of water could decrease. This could affect both groundwater and surface water sources. Furthermore, climate change could lead to increased frequency of extreme whether events. This could affect a large number of risk sources and therefore increase the spread of contaminants to the water source. How climate change might affect risk sources is address while describing the risk of several risk sources. However, is is considered beneficial to further assess the impact of climate change on a water source.
How to best assess these risk in the new approach is considered hard to answer. Mainly, since they do not fit the template of how it is recommended to assess risk related to contaminants. For example, it is considered hard to describe the possible pathway for future land use. Since these risks are considered important, it is recommended to further investigate how these risk efficiently can be assessed in the new approach.

6.3.5 Parallel to New Zealand

When performing the literature review on other risk assessment approaches for water protection areas in other countries, it was found that the commonly applied approach in New Zealand is relatively similar to the commomly applied approach in Sweden. However, it is important to state that these guidelines were created and implemented quite long ago. The country that was sticking out in the literature review was New Zealand, as they recently updated there guidelines (PDP, 2018). It was found that the new guideline follows a contaminant-based approach. When compared to the new approach suggested by SwAM several similarities were found. They assessed one group of contaminant at the time and focus on describing potential pathways and the toxicity. They linked the contaminants of concern primarily to different land uses. The risk is estimated by describing and motivating the risk rather than classifying it. Therefore, this methods is very similar to the new approach suggested by SwAM.
It is interesting that the two most recent approaches of risk assessment of water protection areas are so similar. These approaches have been developed independently. Both approaches incorporate the contaminants-based approach and estimates the risk by description and motivation rather than by classification. If this is a coincidence or there is a tendency for more countries to move to a contaminant-based approach, it is considered too early to say. However, it is promising to see that Sweden is not the only country to change the way risk assessment is performed for water protection areas.

6.3.6 Further Work

Since our risk assessments was limited to the data provided by Sweco, the new approach was not fully applied. To further analyze the performance of the new approach, it is suggested to perform the risk assessment from the start. Thus, the new approach would be tested without the influence of previously performed risk assessment.

Another interesting aspect of the new approach regards how the risk sources is organized under different groups of contaminants. It was found that not all risk sources were efficiently assessed by the groups of contaminants used in our risk assessment. To further scrutinize how the groups of contaminants can be efficiently used, it is suggested to assess the risk regarding "Unplanned pathways" in more depth. Furthermore, it is recommended to analyse how to efficiently incorporate future threats and water quantity within the risk assessment.

The risk assessment performed by us primarily consist of the risk analysis part of the risk assessment. To further analyse the performance of the new approach, it is suggested to further evaluate how the results can be used for risk evaluation. A possible way this could be done is by using the results of our risk assessment to perform a risk evaluation study.

7
Conclusion and Recommendations

In this master thesis, the new approach of risk assessment for water protection areas was evaluated. This was achieved by performing the new risk assessment on water sources with a previously performed risk assessment based on a commonly applied approach in Sweden. It is important to state that the data used in applying the new approach is the same as used for the common approach. Therefor, the risk assessments performed in this master thesis should not be seen as an independent risk assessment.

By performing the risk assessment of the new approach by using data provided by Sweco, the two approaches were successfully compared. It was found that the new approach is applicable on groundwater and surface water sources in both rural and urban areas. The factors that affected the performance of the new approach were mainly the number of risk source and the level of detail of the risk assessment. It was found that the new approach added valuable information when the risk assessment is performed in a rather detailed level. Furthermore, when the number of risk sources are rather few, the pathway can be efficiently described. However, it is harder to be detailed when assessing a large area and the number of risk sources are many. In this situation, it is easier to apply a less detailed approach as the commonly applied approach to assess the risk. However, the added value by applying the new approach will be lost in that case. It is important to state that this primarily regards water sources that are particularly large, such as the the water source Göta älv / Vänersborgsviken.
In general, the new approach is considered highly applicable to most water sources. When compared to the common approach, it was found that the new approach adds significant value to the risk assessment. Mainly, by describing physiological properties of the contaminants, consequences of contamination, And the waterworks ability to treat the contaminants. Furthermore, by including pathways description of risk sources, the risk level could be efficiently described and motivated. It was also found that this information is well suited to provide support for risk reduction measures. Therefore, the new approach is considered to significantly improve risk assessment for water protection areas. However, when the water sources are particularly large and the aim of the risk assessment is to rank the risk sources, the new approach is found to be more demanding to apply.

Since the new approach is a contaminant-based approach and a risk source-based approach, the risk assessment was found to be effective when assessing the risk sources connected to a specific contaminant. However, risk sources such as specific

events or risk sources considered to create unplanned pathway was found hard to incorporate. This suggests that there is a need to assess these risks independently. Therefore, it is recommended to include a group of contaminant called "unplanned pathways" for future risk assessments.
Furthermore, since the new approach does not include information about common drinking water contaminants or how they efficiently can be grouped, it was found that the grouping is somewhat hard to perform. To further improve the new approach, it is therefore recommended to collect information about common drinking water contaminants, such as their physiological properties, health affects on humans, treatment processes in waterworks and related risk sources. It is also recommended to include guidance of how the contaminant efficiently can be grouped.
Furthermore, since the new approach describes the risk in a qualitative manner, it was found that it requires quite extensive reading to get an overview of the results. When presenting the results, it is therefore recommended to include a summary of the contaminants of most concern and their connected risk sources.

To further evaluate the performance of the new approach and its applicability, additional studies are suggested. To avoid being influenced by previous risk assessments, it is recommended to apply the risk assessment from the start. It is also recommended to further investigate how to incorporate the risks related to future threats and water quantity. Furthermore, to evaluate how the results of the the new approach can be used, it is recommended to perform a risk evaluation study focusing on how the evaluate possible restrictions in land use and other regulations. For this purpose, the results from the risk assessments performed in the master thesis could be used.

References

AANDC. (2014). *First Nations Source Water Protection Plan.* (Cited on pages 8, 18, 19, 22–25).

Boenigk, J., Wiedlroither, A., & Pfandl, K. (2005). Heavy metal toxicity and bioavailability of dissolved nutrients to a bacterivorous flagellate are linked to suspended particle physical properties. *Aquatic toxicology (Amsterdam, Netherlands)*, *71*(3), 249–259. doi:10.1016/j.aquatox.2004.11.009. (Cited on page 7)

Bradford, S. A., Morales, V. L., Zhang, W., Harvey, R. W., Packman, A. I., Mohanram, A., & Welty, C. (2013). Transport and Fate of Microbial Pathogens in Agricultural Settings. *Critical Reviews in Environmental Science and Technology*, *43*(8), 775–893. doi:10.1080/10643389.2012.710449. (Cited on page 5)

Bridle, H. (2014). Chapter Two - Overview of Waterborne Pathogens. In H. B. T. .-.-. W. P. Bridle (Editor), (Pages 9–40). doi:https://doi.org/10.1016/B978-0-444-59543-0.00002-5. (Cited on page 5)

Chave, P. (1997). Water Pollution Control. In R. Helmer & I. Hespanhol (Editors), *Water pollution control* (Chapter 5 - Legal, Pages 125–154). WHO/UNEP. Retrieved from https://www.who.int/water_sanitation_health/resourcesquality/watpolcontrol.pdf. (Cited on page 9)

Fetter, C. (2014). *Applied Hydrogeology C . W. F e t t e r , J r . Fourth Edition.* (Cited on page 3).

Gävso. (n.d.). Göta älv och Vänersborgsvikens vattenskyddsområde. Retrieved from https://gavso.se/. (Cited on page 42)

Huling, S. G., & Weaver, J. W. (1992). Ground water issue: Dense nonaqueous phase liquids. *United States Environmental Protection Agency*, 1–25. doi:10.1056/NEJMoa030660. (Cited on page 6)

IDNR. (2017). Iowa source water protection guidebook. (712), 7. (Cited on pages 19, 20).

Khanna, S., & Gharpure, A. S. (2017). Petroleum Carcinogenicity and Aerodigestive Tract: In Context of Developing Nations. *Cureus*, *9*(4), e1202–e1202. doi:10.7759/cureus.1202. (Cited on page 6)

Ministry of Health. (2019). *Handbook for Preparing a Water Safety Plan.* (Cited on page 19).

Minnesota Pollution Control Agency. (2008). Nutrients: Phosphorus, Nitrogen Sources, Impact on Water Quality. (May), 1–2. (Cited on page 7).

National Research Council (US) Safe Drinking Water Committee. (1977). IV, Solid Particles in Suspension. In *Drinking water and health, volume 1* (Volume 1780, Pages 135–205). Retrieved from https://www.ncbi.nlm.nih.gov/books/NBK234169/. (Cited on page 7)

Newell, C. J., Rifai, H. S., Wilson, J. T., Connor, J. A., Aziz, J. A., & Suarez, M. P. (1999). Ground Water Issue, 1–28. (Cited on page 6).

NHMRC, & NRMMC. (2011). *Australian Drinking Water Guidelines 6 National Water Quality Management Strategy*. National Health and Medical Research Council, National Resource Management Ministerial Council. (Cited on pages 18, 19, 24).

PDP. (2018). *Technical Guidelines for Drinking Water Technical Guidelines for Drinking Water Source Protection Zones*. (Cited on pages 18–21, 25, 66).

Pollution Probe. (2004). *The source water protection primer*. Toronto. (Cited on pages 18, 19).

SGU. (n.d.). Vattenskyddsområden. Retrieved from https://www.sgu.se/grundvatten/vattenskyddsomraden/. (Cited on page 1)

Six, S., Diez, T., Van Limbergen, B., & Keustermans, L. (2015). Development of a risk-based approach for better protection of drinking water catchments in Flanders (Belgium). *Water Science and Technology: Water Supply*, *15*(4), 746–752. doi:10.2166/ws.2015.029. (Cited on pages 18, 19, 21, 23, 24)

SwAM. (2019a). *Principer för riskbedömning i arbetet med vattenskyddsområde*. Retrieved from https://www.havochvatten.se/download/18.25d1ce5d16d9ef4f55b36fe8/1570526642995/principer-riskbedomning-arbetet-vattenskyddsomrade.pdf. (Cited on pages 1, 3–6, 10, 11, 25–31)

SwAM. (2019b). Remiss om ny vägledning för inrättande och förvaltning av vattenskyddsområden. Retrieved from https://www.havochvatten.se/hav/uppdrag--kontakt/vart-uppdrag/remisser-fran-hav/remisser/2019-10-08-remiss-om-ny-vagledning-for-inrattande-och-forvaltning-av-vattenskyddsomraden.html. (Cited on page 1)

Swartjes, F. A., & Grima, J. (2011). Groundwater-Related Risk Assessment. In F. A. Swartjes (Editor), *Dealing with contaminated sites: From theory towards practical application* (Pages 749–785). doi:10.1007/978-90-481-9757-6{_}17. (Cited on page 4)

Sweco. (2018a). *Grimstofta risk assessment*. (Cited on pages 48, 59, XLIII).

Sweco. (2018b). *Haboskogen risk assessment*. (Cited on page LVII).

Sweco. (2019a). *Bolmen risk assessment*. (Cited on pages 11, 13–17, 51, I).

Sweco. (2019b). *Göta älv/Vänersborgsvikens risk assessment*. (Cited on pages 15, XXIII).

Swedish EPA. (2010). Handbok om vattenskyddsområde. (Cited on pages 3, 13, 15, 17).

Sydvatten. (2016). Bolmen. Retrieved from https://sydvatten.se/bolmen-3/. (Cited on page 37)

Tack, F. M., Callewaert, O., & Verloo, M. G. (1996). Metal solubility as a function of pH in a contaminated, dredged sediment affected by oxidation. *Environmental Pollution*, *91*(2), 199–208. doi:https://doi.org/10.1016/0269-7491(95)00049-6. (Cited on page 7)

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *Experientia supplementum (2012)*, *101*, 133–164. doi:10.1007/978-3-7643-8340-4{_}6. (Cited on page 7)

Tutic, A., Novakovic, S., Lutovac, M., Biocanin, R., Ketin, S., & Omerovic, N. (2015). The Heavy Metals in Agrosystems and Impact on Health and Quality of Life. *Open access Macedonian journal of medical sciences*, *3*(2), 345–355. doi:10.3889/oamjms.2015.048. (Cited on page 7)

USEPA. (n.d.). Dense Nonaqueous Phase Liquids (DNAPLs) Toxicology. Retrieved from https://clu-in.org/contaminantfocus/default.focus/sec/Dense_Nonaqueous_Phase_Liquids_(DNAPLs)/cat/Toxicology/. (Cited on page 6)

USEPA. (1996). How to Effectively Recover Free Product At Leaking Underground Storage Tank Sites. *Us.Epa 510-R-96-001*, 162. Retrieved from papers2://publication/uuid/D92EB1B5-A0D3-45C8-ADBF-BB8CACDC4A05. (Cited on page 6)

USEPA. (2019a). Basic Information about Mercury. Retrieved from https://www.epa.gov/mercury/basic-information-about-mercury. (Cited on page 7)

USEPA. (2019b). Basic Information about Nonpoint Source (NPS) Pollution. Retrieved from https://www.scribbr.com/apa-citation-generator/#/sources/new/webpage. (Cited on page 8)

USEPA. (2019c). The Issue: Nutrient Pollution. Retrieved from https://www.epa.gov/nutrientpollution/issue. (Cited on page 7)

USGS. (n.d.-a). Contamination of Groundwater. Retrieved from https://www.usgs.gov/special-topic/water-science-school/science/contamination-groundwater?qt-science_center_objects=0#qt-science_center_objects. (Cited on page 4)

USGS. (n.d.-b). Nitrogen and Water. Retrieved from https://www.usgs.gov/special-topic/water-science-school/science/nitrogen-and-water?qt-science_center_objects=0#qt-science_center_objects. (Cited on page 7)

WHO. (2004). Water Treatment and Pathogen Control: Process Efficiency in Achieving Safe Drinking-water. *Water Intelligence Online*, *12*. doi:10.2166/9781780405858. (Cited on page 5)

WHO. (2006). WHO guidelines for drinking-water quality. *Water Supply*, *11*(3-4), 1–16. (Cited on page 5).

WHO. (2008). Microbial aspects. *WHO Guidelines for Drinking Water Quality. Volume 1: Recommendations*, 121–144. Retrieved from http://www.who.int/water_sanitation_health/dwq/gdwq3rev/en/. (Cited on page 5)

WHO. (2016). *Protecting Surface Water For Health*. doi:10.1002/9780470172926.ch2. (Cited on pages 5, 11)

WHO. (2017). *GDWQ*. Retrieved from https://apps.who.int/iris/bitstream/handle/10665/254637/9789241549950-eng.pdf;jsessionid=6F1F275B92DB5564C71089D7F0E1A7B4?sequence=1. (Cited on pages 1, 9, 10, 26)

WQRA. (2009). *Risk Assessment for Drinking Water Sources*. (Cited on pages 11, 18, 20–24).

A

Bolmen

In this appendix the results from the risk assessment performed by Sweco and by us are presented.

A.1 Summary of Sweco's results

This is a summary of the result from Sweco's risk assessment. The full risk assessment can be found in the report written by Sweco (Sweco, 2019a).

Table A.1: Summary of Sweco's results

Risk sources	Risk
Grazing animals	3
Accidents with hazardous goods on road 25	3
Discharge from boat engines	3
Pesticides used in agriculture	3
Natural fertilizers used in agriculture	3
Combined sewer overflow (CSO)	3
On-site sewage systems	2
Angelstad-Bolmen WWTP	2
Firefighting substances	2
Leakage from contaminated sites	2
Flooding	2
Tanks with petroleum products (agriculture/forestry)	1
Deforestation	1
Heaps of timber	1
Energy facilities in ground	1
Home chemicals	1
Accidents in marina	1
Accidents with boats	1
Breaking of sewage pipes	1
Urban runoff/Road runoff/Car wash	1
Tanks with petroleum products (Urban)	1
Synthetic fertilizers	1
Accident when remediating contaminated sites	1
Campsite, Bolmen	1

A.2 Summary of our result

This is a presentation of the summary of our result. The risk sources identified by Sweco has been categorized based on their main contaminant. The contaminants and the risk sources that is placed in the top of the list are considered to pose the highest risks to the water source.

Table A.2: Summary of our results

Contaminants Group	Risk sources
Pathogens	Shore grazing animals CSOs Angelstad-Bolmen WWTP On-site sewage systems Breaking of sewage pipes Natural fertilizer Campsite (on-site sewer), Bolmen
Petroleum Products	Accidents with hazardous goods (Road 25) Accidents in marina/Boat engine discharge or emission/ Vehicles accidents on the lake Tanks with petroleum products (agriculture/forestry) Urban runoff/Car wash/Tanks with petroleum products (Urban)/Runoff from roads Camping sites Leakage from contaminated sites/Accident when remediating contaminated sites
Common Organic Chemicals	Pesticides used in agriculture/forestry Urban runoff/Home chemicals Heaps of timber, Byholma Firefighting substances
Heavy Metals	Deforestation Runoff from roads/Urban runoff/Car wash Accidents in marina Leakage from contaminated sites Accident when remediating contaminated sites
Nutrients	Natural and Synthetic fertilizer On-site sewage systems Angelstad-Bolmen WWTP Combined sewer overflow (CSO) Breaking of sewage pipes
Particles	Deforestation Runoff from roads/Urban runoff/Car wash Combined sewer overflow (CSO)

A.3 Our Risk Assessment

This is a presentation of our risk assessment for Bolmen. The result of the six groups of contaminants that were examined are Presented below.

<table>
<tr><td>Contaminant</td><td colspan="3">Pathogens: Bacteria, viruses and protozoa</td></tr>
<tr><td>Properties</td><td colspan="3">Pathogens originate from faecal matter from humans and animals and may cause health effects. They are organisms that require a surface to attach to and organic matter to grow. Thus, water with high turbidity and high organic content impose a high risk of microbial contamination. Therefore, pathogens have a higher presence in surface water than in groundwater. Moreover, pathogens have different durability levels, with viruses being the most persistent. However, they can be inactivated by disinfection measures. Pathogens behave as colloids which means that they are suspended in the water and easily spread. Due to decay, the risk of microbial contamination is considered to be a peak load in the water source rather than an accumulation over time.</td></tr>
<tr><td>Consequence</td><td colspan="3">If microbial contamination is not sufficiently treated in the waterworks, the drinking water consumers can be infected. This can cause a variety of health effects on humans, such as fever, diarrhoea, vomiting, cramps, and a weakened immune system. This can also lead to epidemic outbreaks and potential deaths. Another consequence of the potential health effects is the social-economic costs of medical care and a population's inability to work. Furthermore, sanitation of waterworks and intensive water quality analysis are necessary. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.</td></tr>
<tr><td rowspan="2">Sources</td><td>Pathways</td><td rowspan="2">Barriers in waterworks</td><td rowspan="2">Risk</td></tr>
<tr><td>(incl. natural and technical barriers)</td></tr>
<tr><td>Natural fertilizer
Husbandry</td><td>Natural fertilizers are used in agriculture and consist of animal manure. Moreover, husbandry activities result in a large amount of animal manure. Animal manure may contain pathogens which through runoffs can be transported to the lake. There are many husbandry and agricultural sites surrounding lake Bolmen. Since pathogens tend to be filtered out via soil, the load of pathogens from natural fertilizer on Bolmen is considered low. However, pathogens from shore grazing animals could easily spread since the discharge could happen directly into the lake.</td><td>The waterworks is adapted to the present raw water quality and fulfils the requirements of microbial barriers. The barriers are: conventional treatment, UV and chlorination. The waterworks is more efficient in treating bacteria than for protozoa and viruses. In case of a high load of pathogens, the treatment system might be insufficient. Thus, primarily virus and protozoa might still be present in the water after treatment.</td><td>The risk from pathogens contamination is considered high.

The risk is primary related to shore grazing animals close to the raw water intake. The load of pathogens could be relatively large and reach the intake quickly.

The risk imposed by CSOs and WWTPs is highly related to</td></tr>
</table>

Combined sewer overflow (CSO)	CSO is the discharge of municipal wastewater and stormwater in the event of heavy rains. This will lead to the release of untreated wastewater that contains pathogens to the lake. There are a few places close to the lake where CSO can occur. In case of CSO the load of pathogens could be relatively high and the ability to spread is good.		the events of heavy rain and/or accidents. Therefore, it is unlikely to happened but if it does the load of pathogens could be large. These sources are few and located relatively far from the raw water intake. However, since the discharge occurs directly into the lake, it is likely that the pathogens reaching the raw water intake. On-site sewers with insufficient treatment are considered as a continuous source of pathogens. However, the ability to spread is considered low. Furthermore, the time of travel to the raw water intake is considered relatively long and the dilution in the lake relatively large. Nevertheless, the risk needs to be considered as the pathogens
Wastewater treatment plant, Angelstad-Bolmen	In case of failures, WWTP may discharge untreated wastewater that contains pathogens. The WWTP is situated in the town of Bolmen and could potentially discharge untreated wastewater directly to the lake. It is unlikely to occur but if it does the load of pathogens could be large and the ability to spread is good.		
On-site sewage systems	On-site sewers with insufficient treatment systems may discharge untreated wastewater that contains pathogens. This discharge could via trenches connected to watercourses end up in Bolmen. If short distance, a possible pathway is also through groundwater flow. There are many on-site sewers surrounding Bolmen and the release is considered to occur continuously. The cumulative load of pathogens from on-site sewers could be large, however the ability to spread is consider relatively low.		

Breaking of sewage pipes	Breaking of sewer pipes may discharge untreated wastewater that contains a large amount of pathogens. This can occur in the town of Bolmen, close to the shore of the lake. It is unlikely to occur but if it does the load of pathogens could be large and the ability to spread is good.		might reach raw water intake. The waterworks ability to treat pathogens contamination is considered good. However, with an increased load, the treatment might be insufficient. Thus, drinking water consumers might get infected. Climate change and extreme weather conditions could increase the frequency of the discharge from CSOs and WWTPs.
Campsite (on-site sewer), Bolmen	Campsites might have their own sewage system and they receive latrines from caravans. The campsite is located in the town of Bolmen, close to the shore of the lake. In case of an accident, pathogens could potentially reach the lake through runoff or be directly discharged. Campsites are more active in summertime. The potential load of pathogen is considered low, however the ability to spread is considered good.		

Contaminant	Petroleum products such as gasoline, diesel, fuel oil, jet fuel and lubricant oil		
Properties	Petroleum products are liquid hydrocarbons that are lighter than water. They vary in chemical structures but have similar physiological properties. Therefore, they spread similarly and have similar behavior in the environment. Their chemical structure makes them very persistent, however, they degrade very slowly in the environment. They have low solubility in water and due to their light density, they mainly spread on surface water or at the capillary zone above the groundwater table. This behavior enhances the lateral spreading distance while preventing vertical spreading. The fraction of more volatile petroleum products such as gasoline does not bind to geological materials which further enhance the spreading.		
Consequence	Petroleum products are highly toxic to humans at low concentrations and they are also genotoxic and carcinogenic. Low concentration (about 5 ug/L) also affects the taste and makes the water undrinkable. The consequence of petroleum products contamination is that the water source might need to be abandoned or closed to be remediated for a long time. If the contamination reaches the waterworks, sanitation is needed. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Accidents with hazardous goods (Road 25)	On road 25 there could be vehicles transporting petroleum products. In case of an accident on the road, a large quantity of petroleum could be spilled. The distance to the lake is around 300 meters and due to topography at the site, it is considered likely that petroleum could reach the lake. The petroleum could spread through surface runoff and/or groundwater flow. If the petroleum products reach the lake, they are likely to reach the raw water intake quickly.	The waterworks is not adapted to treat petroleum products. In case of high load of petroleum products, the distribution needs to be stopped and sanitation of the waterworks is needed.	The risk of petroleum products is considered high. Since there is heavy traffic on road 25, accidents with hazardous goods such as petroleum products could occur. The accident could cause a large spill that might reach raw water intake. It is considered unlikely that there will be an accident resulting in the discharge of a large
Accidents in marina	This refers to activities that could cause a direct discharge of petroleum products into the lake. Boat engine emissions or accidents with vehicles on the lake could potentially discharge		
Boat engine discharge/emission			
Vehicles accidents on the lake			

<table>
<tr><td></td><td>petroleum products close to raw water intake. Accidents in marina could lead to a large amount of petroleum products that are released directly into the lake and therefore it could reach the raw water intake.</td><td rowspan="5"></td><td rowspan="5">quantity of petroleum products but if it does the consequences would be large.

Boat engine discharge and accident involving boats could potentially result in a release of petroleum products close to the raw water intake. Boat engine discharge is considered as a continuous source and it is likely that the petroleum product reaches the raw water intake. The load is considered low but the consequences</td></tr>
<tr><td>Tanks with petroleum products (agriculture/forestry)</td><td>Tanks are used to store petroleum products that are used in agricultural and forestry activities. There are many agricultural and forestry activities surrounding Bolmen. In case of an accident, petroleum could be spilled. If the spill happens close to a trench or watercourse, petroleum products could reach the lake relatively fast. The petroleum products also have the potential to infiltrate the ground and spread through groundwater flow.</td></tr>
<tr><td>Urban runoff</td><td rowspan="3">Runoff contributes to the transportation of petroleum products generated by urban activities. Runoff is caused</td></tr>
<tr><td>Car wash</td></tr>
<tr><td>Tanks with petroleum products (Urban)</td></tr>
</table>

Runoff from roads	by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. Petroleum products will float on the water and they could reach the water source through dikes/stormwater systems or directly through runoff from the town Bolmen. The petroleum products also have the potential to infiltrate the ground and spread through groundwater flow. The most severe scenario is considered to be an accident involving petroleum tanks in the town Bolmen, since the load could be high and the ability to spread is good. In general, since Bolmen is situated in a rural area, the load of petroleum products from urban runoff is considered low.		could still be large. Other sources could also affect the lake, but the risk is considered relatively lower than the mentioned sources. Primarily due to the lower amount of discharge and/or a longer time of travel. However, all sources are considered to impose a relatively large risk as any discharge of petroleum products reaching the raw water intake will cause large consequences.
Camping sites, Bolmen	Campsites have vehicles with petroleum tanks. The campsite is located in the town of Bolmen close to the shore of the lake. In case of an accident, petroleum products could potentially reach the lake through runoff or direct discharge. The petroleum products float on the water surface and might reach the raw water intake. Campsites are more active in summertime. The discharge of petroleum products from campsite is considered unlikely to happen. However, if it does, the load could be relatively large and the ability to spread is good.		
Leakage from contaminated sites	Contaminated sites are likely to contain petroleum		

Accident when remediating contaminated sites	products. Accidents when remediating contaminated sites could create unplanned pathways such as boreholes. This could enhance the spreading of petroleum products through groundwater flow. Moreover, leakage from contaminated sites could release petroleum products continuously. The leakage could infiltrate the ground and spread through groundwater flow. There are many potentially contaminated sites surrounding lake Bolmen with a sawmill in the town Bolmen being the most severe one. If the site is disturbed the petroleum products could spread to lake Bolmen through surface and groundwater flow. The load is considered low, however there could be a cumulative affect from several sources.		

<table>
<tr><td>Contaminant</td><td colspan="3">Pesticides,
Chlorinated solvents
Phenols
PFAS</td></tr>
<tr><td>Properties</td><td colspan="3">These chemicals are liquid hydrocarbons that are denser than water. They vary in chemical structures but have similar physiological properties. Therefore, they spread similarly and have similar behavior in the environment. Their chemical structure makes them very persistent and they can impose a continuous source of contamination. They are not soluble in water. However, since they are denser than water, they can penetrate the groundwater table and affect a whole aquifer. This behavior decreases the lateral spreading distance while increasing it vertically. However, with time they also spread in a lateral direction.</td></tr>
<tr><td>Consequence</td><td colspan="3">They are toxic to humans at very low concentrations and they are also genotoxic and carcinogenic. Chemicals such as pesticides and PFAS can accumulate in an organism and magnify over time which further indicates that even low concentrations are problematic. The consequence of sever contamination by these chemicals is that the water source might need to be abandoned or closed to be remediated. Due to their vertical spreading behavior, they can accumulate in an aquifer imposing a large risk to groundwater sources. If large amount reaches the waterworks and the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.</td></tr>
<tr><td rowspan="2">Sources</td><td>Pathways</td><td rowspan="2">Barriers in waterworks</td><td rowspan="2">Risk</td></tr>
<tr><td>(incl. natural and technical barriers)</td></tr>
<tr><td>Pesticides (agriculture/forestry)</td><td>Pesticides are used in agriculture and forestry. They can spread through runoff as a result of normal usage or in case of accidents with pesticides containers. They can also infiltrate the ground and spread through groundwater flow. There are many forests and agricultural sites surrounding lake Bolmen. The cumulative load of pesticides could be high and the ability to spread is considered good.</td><td rowspan="2">The waterworks is not adapted to treat these chemicals. However, treatment processes such as GAC filter can to some extent treat them.
Since this waterworks lacks the GAC filter, these</td><td rowspan="2">The risk of these chemicals is considered high.

Primarily, the pesticides used in agriculture and forestry constitutes a risk to the water source. The sites that are in close connection with the lake or a watercourse are</td></tr>
<tr><td>Urban runoff</td><td></td></tr>
</table>

Home chemicals	Runoff contributes to the transportation of primary pesticides and chlorinated solvents generated by urban activities. They can be found in home chemicals and in gardens, parks etc. Runoff is caused by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. They could reach the water source through dikes/stormwater systems or directly through runoff from the town Bolmen. The Pesticides and chlorinated solvents also have the potential to infiltrate the ground and spread through groundwater flow. Bolmen lake is situated in a rural area thus the load of pesticides and chlorinated solvents from urban runoff and home chemicals is considered low.	chemicals can go through the waterworks and affect the drinking water consumers.	of most concern. The cumulative load of pesticides could be large, and they could reach raw water intake. Other sources could also affect the lake, but the risk is considered relatively low compared to the mentioned sources. However, all sources of these chemicals need to be considered as even small concentrations can be hazardous as they are not treated in the waterworks. Thus, can affect the drinking water consumer.
Heaps of timber, Byholma	Storing timber can release phenols due to the degradation of the organic matter in the wood. In Byholma, around one km from the lake there are large heaps of timber. The phenols could potentially reach lake Bolmen through runoff or groundwater flow. Since the site is large the load of phenols might be large. However, it is considered unlikely to spread since the leachate from the site is managed.		

Firefighting substances	Fire-fighting substances such as fire-fighting foams could contain the substance PFAS. In case of a fire-fighting event, PFAS could infiltrate the ground and spread through groundwater flow. If the fire-fighting event is close to the lake, then PFAS could reach the lake through direct discharge or via trenches and watercourses. It is unlikely to happen but if it does, the load could be relatively large.		

<table>
<tr><td>Contaminant</td><td colspan="3">Heavy metals such as Cadmium, Chromium, Cobalt, Copper, lead, Mercury, Nickel and Zinc.</td></tr>
<tr><td>Properties</td><td colspan="3">Heavy metals are metals with density higher than 5 g/cm3 and with similar physiological properties. They are mainly solids except for mercury that could be found in a liquid form in nature. They are undegradable inorganic elements that occur naturally in the environment. The spreading of heavy metals highly depends on their solubility and the pH of the water, with low pH the heavy metals are more soluble. Dissolved heavy metals have a very high ability to spread while the solids tend to sediment. Heavy metals can also spread through attaching to negatively charged particles suspended in water.</td></tr>
<tr><td>Consequence</td><td colspan="3">Heavy metals in high concentrations in drinking water are toxic to humans. They can also accumulate in organisms causing long term health effects. It is most likely that the release of heavy metals will not have instant effects on the drinking water supply system, but rather deteriorate the water source over time. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.</td></tr>
<tr><td rowspan="2">Sources</td><td>Pathways</td><td rowspan="2">Barriers in waterworks</td><td rowspan="2">Risk</td></tr>
<tr><td>(incl. natural and technical barriers)</td></tr>
<tr><td>Deforestation</td><td>Deforestation causes the release of a large amount of particles and enhances erosion of the soil that might contain heavy metals. In an event of rain, a runoff could transport heavy metals via trenches to the watercourses and then to Bolmen. Since Bolmen is surrounded by forests the cumulative load of heavy metals needs to be considered.</td><td rowspan="3">The waterworks does not have a separate treatment process for heavy metals. However, a large fraction of heavy metals can be removed through chemical precipitation, coagulation, flocculation and sedimentation. The removal efficiency varies between different kinds of heavy metals. A high load of heavy metals in the raw water could lead to the presence of high</td><td rowspan="3">The risk of heavy metals contamination needs to be considered.

The risk of heavy metals is more likely to deteriorate the water source over time rather than have direct effect on the water quality.</td></tr>
<tr><td>Runoff from roads</td><td rowspan="2">Runoff contributes to the transportation of the heavy</td></tr>
<tr><td>Urban runoff</td></tr>
</table>

Car wash	metals generated by urban activities and traffic. Runoff is caused by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. Heavy metals could behave as particles or be dissolved in the water. They could reach the lake through dikes/stormwater systems or directly through runoff from the town Bolmen. Since Bolmen is situated in a rural area, the load of heavy metals from urban runoff is considered low.	concentrations in the effluents.	Deforestation could cause the spread of a significant amount of heavy metals to the lake as a result of erosion and runoff. The cumulative effect needs to be considered since there is a lot of forests surrounding Bolmen. However, it is unlikely that the heavy metals from deforestation will cause direct effect on the lake. Another risk is in case of an accident in the marina leading to a discharge of heavy metals. Since it could be discharged directly in the water, a high load might reach the raw water intake. However, it is unlikely to happen. Thus, the risk is considered relatively low. Other sources could also affect the lake, but the risk is considered
Accidents in marina	Maintenance of boats, storage of chemicals and other activities in the marina could lead to accidents that cause the release of heavy metals. The heavy metals could be discharged directly into Bolmen and the load could be relatively large.		
Leakage from contaminated sites	Contaminated sites are likely to contain heavy metals. Accidents when remediating contaminated sites could create unplanned pathways such as boreholes. This could enhance the spreading of heavy metals through groundwater flow. There are many potentially contaminated sites surrounding lake Bolmen with a sawmill in the town Bolmen being the most severe one. The heavy metals are most likely to spread to lake Bolmen through diffused leakage in surface and groundwater. Disturbance of the contaminated sites could potentially cause an increase		
Accident when remediating contaminated sites			

	in the spreading of heavy metals to the lake.		relatively low compared to the mentioned sources. Climate change and extreme weather conditions could cause flooding which potentially enhance the spreading of heavy metals.

Contaminant	Nutrients: nitrates and phosphates		
Properties	Nitrates and phosphates are inorganic compounds that occur naturally in the environment. However man-made synthetic versions also exist. They are dissolved in water and they degrade over time. Due to the degradation, their presence in groundwater is naturally low. Therefore, they spread mainly in surface water or in the capillary zone above the groundwater table.		
Consequence	An abundance of nitrates and phosphates can cause eutrophication which is harmful to aquatic life. A high concentration in drinking water is also toxic to humans. Since the water source has a buffering capacity against the release of nutrients, continuous release will deteriorate the water source over time rather than have an instant effect. However, in case of an accident with a high release of nutrients, the water source might not be suitable for use for some time. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Natural fertilizer Synthetic fertilizer	Natural and synthetic fertilizers are used in agriculture and forestry. Nutrients can spread to the lake through runoff or they can infiltrate the ground and spread through groundwater	The waterworks is adapted to the present raw water quality. Since the raw water contains low amount of nutrients, the waterworks does not have a sperate nutrient	The risk of nutrients contamination is considered low. There are many sites of forestry

	flow. The spread is likely to occur during the spring when agricultural activities are high. There are many forests and agricultural sites surrounding lake Bolmen. Thus, the load of nutrients could be high.	treatment process. However, phosphates can be removed through chemical precipitation, coagulation, flocculation and sedimentation. The nitrates are harder to treat. This treatment system includes slow sand filtration where some degradation of nitrates occurs. However, the efficiency is uncertain. If higher load of nitrates in the raw water, the waterworks might not be able to treat it.	and agriculture that are using fertilizers that can result in the spreading of nutrient to the lake. However, the risk is considered to be the deterioration of the raw water quality over time rather than imposing a direct risk to the drinking water consumers. Furthermore, if the load of nutrients does not increase it is considered not to deteriorate the water source quality over time. Due to the low amount of urban activities in the area, there are few on-site sewers and small WWTPs that
On-site sewage systems	On-site sewers with insufficient treatment systems may discharge untreated wastewater that contains nutrients. This discharge could via trenches connected to watercourses end up in Bolmen. If short distance, a possible pathway is also through groundwater flow. There are many on-site sewers surrounding Bolmen and the release is considered to occur continuously. The cumulative load of several on-site sewers could be high.		

Wastewater treatment plant, Angelstad-Bolmen	WWTP have permits to release a certain level of nutrients to the recipient. The WWTP is situated in the town of Bolmen. Its discharge is directly connected to the lake. Since the WWTP is relatively small (225 households) the load of nutrients is considered low. However, in case of a failure resulting in the discharged of untreated sewage the load of nutrients could be large.		are connected to the lake. Furthermore, the risk imposed by nutrients from pipe breaking and CSO is considered low due to the low amount of urban area. Climate change and extreme weather conditions could cause flooding which potentially enhance the spreading of nutrients.
Combined sewer overflow (CSO)	CSO is the discharge of municipal wastewater and stormwater in the event of heavy rains. This will lead to the release of untreated wastewater that contains nutrients to the lake. There are a few places close to the lake where CSO can occur. In the event of CSO the load of nutrient could be large However, over the year the total load from these events is considered low.		
Breaking of sewer pipes	Breaking of sewer pipes may discharge untreated wastewater that contains nutrients. This can occur in the town Bolmen. If the pipe is situated close to the shore the discharge might reach the lake through groundwater flow or surface runoff. It I unlikely to happened but if it does the load might be large.		

Contaminant	Particles such as sand, clay, silt, humus and microscopic organisms.		
Properties	Particles are solids that depending on their size and density could be suspended or sedimented in the water. The suspended particles have the potential to spread for long distances. Since particles are separated through filtration in soil, only surface water sources are considered to be at risk of physical contamination. Particles can also be electrically charged, which can attract other contaminants.		
Consequence	Particles can cause high turbidity which decreases the treatment efficiency in the waterworks. Moreover, the particles can attract other contaminants. The consequence of a large release of particles could be that the water source cannot be used until the turbidity decreases. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Deforestation	Deforestation causes the release of a large amount of humus particles and enhances erosion of the soil. In an event of rain, runoff could transport the particles via trenches to the watercourses and then to Bolmen. Since Bolmen is surrounded by forests the cumulative load of particles could be large.	The waterworks is adapted to the present raw water quality and has efficient particle separation methods. In case of higher particle load, the waterworks can still manage the particles separation but with less efficiency and higher maintenance. Furthermore, turbidity is monitored, and distribution can be	The risk of particles contamination is considered relatively low. The risk from deforestation needs to be considered as Bolmen is surrounded by forests and deforestation could cause a release of
Urban runoff	Runoff contributes to the transportation of the		
Runoff from roads			

Car wash	particles generated by urban activities and traffic. Runoff is caused by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. Particles can naturally sediment when the velocity of the runoff decreases, or they can be filtered out if the water reaches permeable surfaces. The particle could reach the water source through dikes/stormwater systems or directly through runoff from the town Bolmen. Since Bolmen is situated in a rural area, the load of particles from urban runoff is considered low.	stopped if too high turbidity is detected in the effluent.	high loads of particles. However, the risk is considered to be the deterioration of the raw water quality over time rather than imposing a direct risk to the drinking water consumers. Other sources could also affect the lake, but the risk is considered relatively low compared to the mentioned sources. Climate change and extreme weather conditions could cause flooding which potentially enhance the spreading of particles.
Combined sewer overflow (CSO)	CSO is the discharge of municipal wastewater and stormwater in the event of heavy rains. This will lead to the release of turbid water that contains particles to the lake. There are a few places close to the lake where CSO can occur. When discharged to the lake, the particles tend to settle. However, settling will take time depending on the particle size. Thus, a load of particles could reach the raw water intake.		

B

Göta älv / vänersborgsviken

In this appendix the results from the risk assessment performed by Sweco and by us are presented.

B.1 Summary of Sweco's results

This is a summary of the result from Sweco's risk assessment. The full risk assessment can be found in the report written by Sweco (Sweco, 2019b).

Table B.1: Summary of Sweco's results

Risk sources	Risk
WWTPs	3
Combined sewer overflow (CSO)	3
Activites in harbours	3
Accidents with shipping	3
Industry discharge	3
Landslide of contaminated site	3
Flooding	3
Accidents with hazardous goods (roads/railways)	2
Urban runoff/Runoff from roads/Car wash/Industrial runoff	2
On-site sewage systems	2
Breaking of sewer pipes	2
Leakage from contaminated sites/Accidents when remediating	2
Heaps of hazardous disposals	2
Dredging/digging/excavation/explosion	2
Dam failure	2
Natural fertilizer	2
Landslides/erosion	2
Tanks with petroleum products (agriculture/forestry)	2
Pesticides (agriculture/forestry)	2
Shore grazing animals	2
Polluted filling materials	2
Maintenance of bridges/roads/railways	2
Firefighting substances	2
Quarry	1
Recycling facilities	1

Tanks with petroleum products (Urban)	1
Heaps of snow/of salt	1
Deforestation	1
Synthetic fertilizer	1
Continuous discharge from shipping	1
Old landfill	1
Home chemicals	1
Garden markets	1
Energy facilities	1
Sport facilities	1
Airport	1
Salty water intrusion	1

B.2 Summary of our result

This is a presentation of the summary of our result. The risk sources identified by Sweco has been categorized based on their main contaminant. The contaminants and the risk sources that is placed in the top of the list is considered to pose the highest risks to the water source.

Table B.2: Summary of our results

Contaminants Group	Risk sources
Pathogens	Combine sewer overflow (CSO) WWTPs Shore grazing animals On-site sewage systems Breaking of sewer pipes Natural fertilizer
Petroleum Products	Accidents with hazardous goods (roads) Accidents with hazardous goods (railways) Accidents with hazardous goods(shipping)/ Continuous discharge from shipping/Harbour activities Urban and industrial runoff/Car wash/Tanks with petroleum products (urban) Tanks with petroleum products (agriculture/forestry) Industry accident - discharge Polluted filling materials/Landslides from contaminated sites/Leakage from contaminated sites/Accident when remediating contaminated sites Airports

Common Organic Chemicals	Pesticides used in agriculture/forestry Urban runoff/Home chemicals/Sport facilities Gardening market Firefighting substances Industry accident - fire Landslides from contaminated sites Leakage from contaminated sites Accident when remediating contaminated sites
Heavy Metals	Polluted filling materials/Old landfills/Leakage from contaminated sites/Accident when remediating contaminated sites Harbour activities Urban and industrial runoff/Runoff from roads/ Car wash/Airports/Heaps of hazardous disposals/ Heaps of snow Industry accident - discharge Deforestation Quarry/Recycling facilities Continuous discharge from shipping
Particles	Urban and industrial runoff/Car wash/Maintenance of bridges, roads and railways Combine sewer overflow (CSO) Deforestation Quarry/Recycling facilities Heaps of hazardous disposals/of snow/of salt
Nutrients	Natural and synthetic fertilizer Combine sewer overflow (CSO) WWTPs On-site sewage systems Breaking of sewer pipes Old landfill

B.3 Our Risk Assessment

This is a presentation of our risk assessment of Göta älv / Vänersborgsviken. The results of the six groups of contaminants that were examined are Presented below.

<table>
<tr><td>Contaminant</td><td colspan="3">Pathogens: Bacteria, viruses and protozoa</td></tr>
<tr><td>Properties</td><td colspan="3">Pathogens originate from faecal matter from humans and animals and may cause health effects. They are organisms that require a surface to attach to and organic matter to grow. Thus, water with high turbidity and high organic content impose a high risk of microbial contamination. Therefore, pathogens have a higher presence in surface water than in groundwater. Moreover, pathogens have different durability levels, with viruses being the most persistent. However, they can be inactivated by disinfection measures. Pathogens behave as colloids which means that they are suspended in the water and easily spread. Due to decay, the risk of microbial contamination is considered to be a peak load in the water source rather than an accumulation over time.</td></tr>
<tr><td>Consequence</td><td colspan="3">If microbial contamination is not sufficiently treated in the waterworks, the drinking water consumers can be infected. This can cause a variety of health effects on humans, such as fever, diarrhoea, vomiting, cramps, and a weakened immune system. This can also lead to epidemic outbreaks and potential deaths. Another consequence of the potential health effects is the social-economic costs of medical care and a population's inability to work. Furthermore, sanitation of waterworks and intensive water quality analysis are necessary. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.</td></tr>
<tr><td rowspan="2">Sources</td><td>Pathways</td><td rowspan="2">Barriers in waterworks</td><td rowspan="2">Risk</td></tr>
<tr><td>(incl. natural and technical barriers)</td></tr>
</table>

Combine sewer overflow (CSO)	CSO is the discharge of municipal wastewater and stormwater in the event of heavy rains. This will lead to the discharge of untreated wastewater that contains pathogens to the water source. Since there are many cities in close connection to the water source, there are many places where CSO could occur. The potential load is considered high and the pathogens would be discharged directly into the water source.	The waterworks is adapted to the present raw water quality and fulfils the requirements of microbial barriers. The barriers that are commonly used are conventional treatment, ultra-filtration and disinfection by ozone, UV and chlorination. The number of barriers is adapted to the raw water quality, thus waterworks does not include all of them. The waterworks is in general more efficient in treating bacteria than for protozoa and viruses. In case of a high load of pathogens, the treatment system might be insufficient. Thus, primarily virus and protozoa might still be present in the water after treatment.	The risk of pathogen contamination is considered high. The risk is primarily related to Sources such as CSOs, WWTPs. Due to several large cities the load of sewage from these sources could be large. Moreover, it would be directly discharged into the water source. CSOs is triggered by the events of heavy rain and floods and is likely to occurs a few times each year. The potential discharge from a WWTP is most likely triggered a failure or accident. Therefore, it is unlikely to happen but if it does the load could be particularly large. Shore grazing animals also impose a considerable risk as the cumulative load of pathogens could be relatively large and the ability to spread is good. Since there are large sewage pipes close to the water
Wastewater treatment plants	There are 9 large public WWTPs in the catchment area. In case of failure, they may discharge untreated wastewater that contains pathogens. The potential load is considered high and the pathogens would be discharged directly into the water source.		
Natural fertilizer	Natural fertilizers are used in agriculture and consist of animal manure. Moreover, husbandry activities result in a large amount of animal manure. Animal manure may contain pathogens which through runoffs can be transported to the water source. There are many husbandry and agricultural sites in close connection to the water source. Since pathogens tend to be filtered out via soil, the load from natural fertilizer is considered low. However,		
Husbandry			

	pathogens from shore grazing animals need to be considered as the pathogens may be discharged directly into the water source or connected watercourses.		source, they also impose a risk. It is considered unlikely that there will be a break but if it happens a large load could be discharge directly into the water source. The waterworks ability to treat pathogens contamination is considered good. However, with an increased load, the treatment might be insufficient. Thus, drinking water consumers might get infected. Climate change and extreme weather conditions could increase the frequency of the discharge from CSOs and WWTPs.
On-site sewage systems	On-site sewers with insufficient treatment systems may discharge untreated wastewater that contains pathogens. This discharge could via trenches connected to watercourses end up in the water source. If short distance, a possible pathway is also through groundwater flow. There are many on-site sewers in the catchment area and the release is considered to occur continuously. The potential cumulative load from many on-site sewers could be high. However, the pathway and the time of travel are considered relatively long.		
Breaking of sewer pipes	Breaking of sewer pipes may discharge untreated wastewater that contains a large amount of pathogens. Since there are large cities close to the water source, the load could be relatively high. If breaking of the pipes occurs close to the water source or connected watercourses, the pathogens could be directly discharged in the water source.		

Contaminant	Petroleum products such as gasoline, diesel, fuel oil, jet fuel and lubricant oil
Properties	Petroleum products are liquid hydrocarbons that are lighter than water. They vary in chemical structures but have similar physiological properties. Therefore, they spread similarly and have similar behavior in the environment. Their chemical structure makes them very persistent, however, they degrade very slowly in the environment. They have low solubility in water and due to their light density, they mainly spread on surface water or at the capillary zone above the groundwater table. This behavior enhances the lateral spreading distance while preventing vertical spreading. The fraction of more volatile petroleum products such as gasoline does not bind to geological materials which further enhance the spreading.
Consequence	Petroleum products are highly toxic to humans at low concentrations and they are also genotoxic and carcinogenic. Low concentration (about 5 ug/L) also affects the taste and makes the water undrinkable. The consequence of petroleum products contamination is that the water source might need to be abandoned or closed to be remediated for a long time. If the contamination reaches the waterworks, sanitation is needed. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected

Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Accidents with hazardous goods (shipping) Continuous discharge from shipping Harbour activities	There are many transports of hazardous goods through shipping. In case on accident, the discharge of petroleum products could be very large. The shipping also causes the release of petroleum products by continuous discharge. Activities in the harbour may also discharge petroleum products. The potential load of petroleum products varies. However, they will be discharged directly into the water source.	The waterworks is not adapted to treat petroleum products. In case of high load of petroleum products, the distribution needs to be stopped and sanitation of the waterworks is needed.	The risk of petroleum products contamination is considered high. The risk is primary related to accidents when transporting hazardous goods by shipping and harbour activities. An accident could potentially cause the release of large amount of petroleum products being discharged directly into the water source. It is
Accidents with hazardous goods (roads) Accidents with hazardous goods (railways)	In the catchment area there are several roads and railways that might transport petroleum products. Especially road E 45 has heavy traffic. Moreover, in several places it is in close connection to the water source. The railway stretches on the east		

<table>
<tr><td></td><td>side of the water source and sometimes in close connection to the water source. In case of an accident, a large quantity of petroleum could be spilled. In several places, petroleum products might reach the water source through direct discharge. The petroleum could also spread through groundwater flow.</td><td rowspan="7"></td><td rowspan="7">considered unlikely to happen but if it does the consequences would be severe.

Accidents when transporting petroleum products on roads and railway also need to be considered. The ability for the petroleum product to spread is not as good as from the shipping. However, the load might be large and it might reach the water source.

The discharge from boats and the leaking from contaminated sites are considered to continuously discharge a small amount of petroleum products. The load is considered low but the ability to spread is good. It could affect drinking water production, thus the risk is considered relatively high.

There are a few other sources that is considered to impose a risk on the water source. However, these sources have in general longer</td></tr>
<tr><td>Urban runoff</td><td rowspan="5">For these sources, petroleum products are transported to the water source primarily through runoff. Runoff is caused by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. Petroleum products will float on the water and they could reach the water source through dikes/stormwater systems or directly through runoff. The petroleum products also have the potential to infiltrate the ground and spread through groundwater flow. The most severe scenario is considered to be an accident involving petroleum tanks in the cities in close connection to the water source.</td></tr>
<tr><td>Runoff from roads</td></tr>
<tr><td>Car wash</td></tr>
<tr><td>Tanks with petroleum products (urban)</td></tr>
<tr><td>Runoff from industrial area</td></tr>
<tr><td>Tanks with petroleum products (agriculture/forestry)</td><td>Tanks storing petroleum products are used in agricultural and forestry activities. In case of an accident, petroleum could be spilled. If the spill happens close to a trench or watercourse, the petroleum products could reach the water source relatively quickly. The petroleum products also have the ability to infiltrate the ground and spread through groundwater flow. There are many agricultural and forestry sites in close connection to the water source. The load of petroleum products could be relatively large.</td></tr>
</table>

<table>
<tr><td>Industry accident - discharge</td><td>Accidents in industries may result in the discharge of petroleum products to the recipient. Since there are many industries in the area, the discharge could occur directly into the water source or into the connected watercourses. The load of petroleum products could be relatively large and the ability to spread is good.</td><td rowspan="6"></td><td rowspan="6">pathway and lower loads then the sources mentioned above. However, they still need to be considered.

In general, the most sever events are related to accidents. However, all sources need to be considered as any discharge of petroleum products reaching the raw water intake will cause large consequences.</td></tr>
<tr><td>Polluted filling materials</td><td rowspan="4">Contaminated sites exist in many places along the water source and the connected watercourses. petroleum products could be transported to the water source via runoff or through groundwater flow. The closer the sites are to the water or a watercourse, the better the ability to spread. The cumulative load of these places could be relatively high. Accidents when remediating contaminated sites could create unplanned pathways such as boreholes. This could enhance the spreading of petroleum products through groundwater flow.
Disturbing the contaminated sites may also cause enhanced spreading of petroleum products through surface runoff.</td></tr>
<tr><td>Landslides from contaminated sites</td></tr>
<tr><td>Leakage from contaminated sites</td></tr>
<tr><td>Accident when remediating contaminated sites</td></tr>
<tr><td>Airports</td><td>There is one commercial airport in the catchment area. It is situated north of Trollhättan and in close connection to the water source. In case of spill or accidents, petroleum products could spread to the water source through surface runoff and groundwater flow.</td></tr>
</table>

Contaminant	Pesticides, Chlorinated solvents PFAS		
Properties	These chemicals are liquid hydrocarbons that are denser than water. They vary in chemical structures but have similar physiological properties. Therefore, they spread similarly and have similar behavior in the environment. Their chemical structure makes them very persistent and they can impose a continuous source of contamination. They are not soluble in water. However, since they are denser than water, they can penetrate the groundwater table and affect a whole aquifer. This behavior decreases the lateral spreading distance while increasing it vertically. However, with time they also spread in a lateral direction.		
Consequence	They are toxic to humans at very low concentrations and they are also genotoxic and carcinogenic. Chemicals such as pesticides and PFAS can accumulate in an organism and magnify over time which further indicates that even low concentrations are problematic. The consequence of sever contamination by these chemicals is that the water source might need to be abandoned or closed to be remediated. Due to their vertical spreading behavior, they can accumulate in an aquifer imposing a large risk to groundwater sources. If large amount reaches the waterworks and the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Pesticides (agriculture/forestry)	Pesticides are used in agriculture and forestry. They can spread through runoff to the water source as a result of normal usage or in case of accidents with pesticides containers. They can also infiltrate the ground and spread through groundwater flow. There are many forests and agricultural sites in close connection to the water source. Thus, the ability of the pesticides to spread is considered good.	The waterworks is not adapted to treat these chemicals. However, treatment processes such as GAC filter can to some extent treat them. Since this waterworks lacks the GAC filter, these chemicals can go through the waterworks and	The risk of pesticides contamination is considered relatively high. The risk of chlorinated solvent and PFAS need to be considered but is low compared to the risk of pesticides. Primarily, the pesticides used in agriculture and forestry constitutes a risk to the water
Urban runoff Home chemicals Sport facilities	Runoff contributes to the transportation of primary pesticides and chlorinated solvents generated		

Gardening market	by urban activities. They can be found in home chemicals and are used in gardens, sport facilities and parks etc. Runoff is caused by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. Pesticides and chlorinated solvents could reach the water source through dikes/stormwater systems or directly through runoff from the cities in close connection to the water source. They also have the ability to infiltrate the ground and spread through groundwater flow.	affect the drinking water consumers.	source. The sites that are in close connection with the water source or a connected watercourse is of most concern. The cumulative load of pesticides could be large, and the ability to spread is considered good. Contaminated sites may contain chlorinated solvents. In case of disturbance, a relatively large load might reach the water source. It is unlikely to happen but could affect drinking water production. The event of a fire in close connection to the water source is considered to impose a relatively large risk to the water source. Primarily through the potential release of PFAS. It is unlikely to happen but could affect the drinking water production. Other sources could also affect the water source, but the risk is considered relatively low compared to the mentioned sources. However, all sources of these chemicals need to be
Firefighting substances Industry accident - fire	Firefighting substances such as foams could contain the substance PFAS. In case of a firefighting event, PFAS could infiltrate the ground and spread through groundwater flow. If the firefighting event is close to the water source, PFAS could reach the water via trenches and watercourses or be directly discharged. In case of fire event in an industry, the load of PFAS could be large.		
Landslides from contaminated sites Leakage from contaminated sites Accident when remediating contaminated sites	Contaminated sites exist in many places along the water source and the connected watercourses. Pesticides and chlorinated solvents could be transported to the water source via runoff or through groundwater flow. The closer the sites are to the water source or a connected watercourse, the better ability to spread. The cumulative load from these places could be large. Accidents when remediating contaminated sites could create unplanned pathways such as boreholes. This could enhance the		

	spreading of pesticides and chlorinated solvents through groundwater flow. Disturbing the soil may also cause enhanced spreading pesticides and chlorinated solvents through surface runoff.		considered as even small concentrations can be hazardous as they are not treated in the waterworks. Thus, can affect the drinking water consumer.

<table>
<tr><td>Contaminant</td><td colspan="3">Heavy metals such as Cadmium, Chromium, Cobalt, Copper, lead, Mercury, Nickel and Zinc.</td></tr>
<tr><td>Properties</td><td colspan="3">Heavy metals are metals with density higher than 5 g/cm3 and with similar physiological properties. They are mainly solids except for mercury that could be found in a liquid form in nature. They are undegradable inorganic elements that occur naturally in the environment. The spreading of heavy metals highly depends on their solubility and the pH of the water, with low pH the heavy metals are more soluble. Dissolved heavy metals have a very high ability to spread while the solids tend to sediment. Heavy metals can also spread through attaching to negatively charged particles suspended in water.</td></tr>
<tr><td>Consequence</td><td colspan="3">Heavy metals in high concentrations in drinking water are toxic to humans. They can also accumulate in organisms causing long term health effects. It is most likely that the release of heavy metals will not have instant effects on the drinking water supply system, but rather deteriorate the water source over time. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.</td></tr>
<tr><td>Sources</td><td>Pathways
(incl. natural and technical barriers)</td><td>Barriers in waterworks</td><td>Risk</td></tr>
<tr><td>Polluted filling materials
Old landfills
Leakage from contaminated sites
Accident when remediating contaminated sites</td><td>Old landfills and other contaminated sites exist in many places along the water source and the connected watercourses. Primarily, dissolved heavy metals could be transported to the water source via runoff or through groundwater flow. The closer the sites are to the water source or the connected watercourse, the better the ability to spread. The cumulative load from these sites could be relatively large. Accidents when remediating contaminated sites could create unplanned pathways such as boreholes. This could enhance the spreading of heavy metals through groundwater flow. Disturbing the soil may also cause enhanced</td><td>The waterworks does not have a separate treatment process for heavy metals. However, a large fraction of heavy metals can be removed through chemical precipitation, coagulation, flocculation and sedimentation and by ultra-filtration. The removal efficiency varies between different kinds of heavy metals. A high load of heavy metals in the raw water could lead to the presence of high concentrations in the effluents.</td><td>The risk of heavy metals contamination is considered relatively high.

The risk is primary related to the disturbance or landslides in contaminated sites. There are many contaminated sites in close connection to the water source. It is considered relatively unlikely to happen but if it does the consequences would be large.

The disturbance of the sites could be caused by remediation. This</td></tr>
</table>

	spreading of heavy metals through surface runoff.		could expose contaminated soil and creates fast pathways to the water source. Excavation, dredging, dam failure and explosions could disturb sediments in the water source and affect the riverbank. If the soil and sediments contain heavy metals, it could cause a considerable load of heavy metals to be transported directly into the water source. Since there are many industries in close connection to the water source there is also a large risk related to an accident that result in a discharge of polluted water. It is considered relatively unlikely to happen but if it does the consequences would be large. Activities in the cities and industrial sites generate a lot runoff that is likely to contain high levels of heavy metals. If the storm water is not managed or in case of heavy rains, there is a large risk
Harbour activities	Maintenance of boats, storage of chemicals and other activities in the harbour could cause the release of heavy metals. The heavy metals could be discharged directly into the water source and the load could potentially be high.		
Urban runoff Runoff from roads Car wash Airports Runoff from industrial area Heaps of hazardous disposals Heaps of snow	Urban activities, traffic, airports and industrial areas generate heavy metals. Moreover, heaps of hazardous disposals and snow occur occasionally in the urban areas and may contain heavy metals. From these sources, heavy metals are transported to the water source primarily through runoff. Runoff is caused by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. Heavy metals could behave as particles or be dissolved in the water. They could reach the water source through dikes/stormwater systems or directly through runoff from the cities close to the water source. Since there are large cities in close connection with the water source, the load of heavy metals can be relatively high and the ability to spread is good.		
Industry accident - discharge	Accidents in industries may result in the discharge of heavy metals to the recipient. Since there are many industries in the		

<table>
<tr>
<td></td>
<td>area, the discharge could occur directly into the water source or into the connected watercourses. The load of heavy metals could be relatively high and the ability to spread is good.</td>
<td rowspan="5"></td>
<td rowspan="5">of heavy metals reaching the water source.

Another issue is deforestation that potentially could spread high amount of heavy metals to the water source as e result of erosion and runoff. However, the risk is considered to deteriorate the water quality over time rather than have a direct effect.

In general, the risk of heavy metals is more likely to deteriorate the water source over time rather than have direct effect on the water quality. However, some sources and events might cause high levels of heavy metals in the water source. This could affect the production of drinking water. Thus, the drinking water consumer might be affected.

Climate change and extreme weather conditions could cause flooding, landslides and erosion which potentially enhance the spreading of heavy metals.</td>
</tr>
<tr>
<td>Deforestation</td>
<td>Deforestation causes the release of a large amount of particles and enhances erosion of soil that might contain heavy metals. Heavy metals could behave as particles or be dissolved in the water. In an event of rain, runoff could transport heavy metals via trenches to the watercourses and then to the water source. There are a lot of forest in the catchment area. Thus, deforestation could increase the levels of heavy metals in the water source.</td>
</tr>
<tr>
<td>Quarry</td>
<td rowspan="2">Activities in quarry and recycling facilities generate heavy metals. They usually manage their stormwater. However, in case of failure or heavy rain events, they could potentially discharge considerable amount of heavy metals. Runoff could then transport the heavy metals via trenches to watercourses and then to the water source.</td>
</tr>
<tr>
<td>Recycling facilities</td>
</tr>
<tr>
<td>Continuous discharge from shipping</td>
<td>The hazardous paint that is used on ships could release heavy metals into the water source. This release is considered to occur contentiously. However, the load is considered low.</td>
</tr>
</table>

<table>
<tr><td>Contaminant</td><td colspan="3">Particles such as sand, clay, silt, humus and microscopic organisms.</td></tr>
<tr><td>Properties</td><td colspan="3">Particles are solids that depending on their size and density could be suspended or sedimented in the water. The suspended particles have the potential to spread for long distances. Since particles are separated through filtration in soil, only surface water sources are considered to be at risk of physical contamination. Particles can also be electrically charged, which can attract other contaminants.</td></tr>
<tr><td>Consequence</td><td colspan="3">Particles can cause high turbidity which decreases the treatment efficiency in the waterworks. Moreover, the particles can attract other contaminants. The consequence of a large release of particles could be that the water source cannot be used until the turbidity decreases. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.</td></tr>
<tr><td rowspan="2">Sources</td><td>Pathways</td><td rowspan="2">Barriers in waterworks</td><td rowspan="2">Risk</td></tr>
<tr><td>(incl. natural and technical barriers)</td></tr>
<tr><td>Urban runoff</td><td rowspan="6">For these sources, particles are transported to the water source primarily through runoff. Runoff is caused by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. Particles can naturally sediment when the velocity of the runoff decreases, or they can be filtered out if the water reaches permeable surfaces. The particle could reach the water source through dikes/stormwater or directly through runoff from the cities close to the water source. Since there are large cities in close connection to the water source, the load of particles could be relatively high.</td><td rowspan="7">The waterworks is adapted to the present raw water quality and has efficient particle separation methods. In case of higher particle load, the waterworks can still manage the particles separation but with less efficiency and higher maintenance. Furthermore, turbidity is monitored, and distribution can be stopped if too high turbidity is detected in the effluent.</td><td rowspan="7">The risk of particles contamination needs to be considered.

The highest risk of particle contamination is considered to be the events of heavy rains/flooding and landslides. These events could trigger a number of different sources of particles. Thus, the cumulative load could be very large.

The risk of dredging, excavating and explosions in close connection to the water source also needs to be considered. This could cause so high turbidity that it</td></tr>
<tr><td>Run off from roads</td></tr>
<tr><td>Car wash</td></tr>
<tr><td>Runoff from industrial area</td></tr>
<tr><td>Maintenance of bridges, roads and railways</td></tr>
<tr><td>Airports</td></tr>
<tr><td>Combine sewer overflow (CSO)</td><td>CSO is the discharge of municipal wastewater and stormwater in the event of heavy rains. This will lead to the release of turbid water that contains particles to the water source. There are many places</td></tr>
</table>

	close to the water source where CSO can occur. When discharged to the water source, the particles tend to settle. However, settling will take time depending on the particle size and water velocity. Since there are large cities in close connection to the water source, the load of particles from CSO could be relatively large.		would be hard for the waterworks to treat. Thus, it could affect drinking water production. Furthermore, there are several dams in the water source. In case of failure, disturbance of the sediments could occur. This would significantly increase the amount of suspended particles in the water. It is unlikely to happen but would have large consequence. In general, the release of particles is considered to cause deterioration of the raw water quality over time rather than imposing a direct risk to the drinking water consumers. Climate change could increase the frequency of heavy rain events, flooding and landslides. Therefore, climate change could increase the spreading of particles to the water source.
Deforestation	Deforestation causes the release of a large amount of humus particles and enhances erosion of the soil. In an event of rain, runoff could transport the particles via trenches to watercourses and then to the water source. There are a lot of forests within the catchment area. Thus, deforestation could increase the load of particles to the water source.		
Quarry	Quarry and recycling facilities generates large amount of particles. They usually manage their stormwater. However, in case of failure or heavy rain events, they could potentially discharge considerable amount of particles. Runoff could then transport the particles via trenches to watercourses and then to the water source.		
Recycling facilities			
Heaps of hazardous disposals	These heaps are connected to urban activities and are considered to occur occasionally. The particle in these heaps could reach the water source through dikes/stormwater or directly through runoff from the cities close to the water source. Since there are large cities in close connection to the water source, the heaps could occur frequently and the ability of particles to spread is considered good.		
Heaps of snow			
Heaps of salt			

Contaminant	Nutrients: nitrates and phosphates		
Properties	Nitrates and phosphates are inorganic compounds that occur naturally in the environment. However man-made synthetic versions also exist. They are dissolved in water and they degrade over time. Due to the degradation, their presence in groundwater is naturally low. Therefore, they spread mainly in surface water or in the capillary zone above the groundwater table.		
Consequence	An abundance of nitrates and phosphates can cause eutrophication which is harmful to aquatic life. A high concentration in drinking water is also toxic to humans. Since the water source has a buffering capacity against the release of nutrients, continuous release will deteriorate the water source over time rather than have an instant effect. However, in case of an accident with a high release of nutrients, the water source might not be suitable for use for some time. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Natural fertilizer	Natural and synthetic fertilizers are used in agriculture and forestry. Nutrients can spread to the water source through runoff or they can infiltrate the ground and spread through groundwater flow. The spread is likely to occur during the spring when agricultural activities are high. There are many agricultural sites in close connection to the water source. Thus, the cumulative load of nutrients from fertilizer could be large.	The waterworks is adapted to the present raw water quality. Since the raw water contains low amount of nutrients, the waterworks does not have a sperate nutrient treatment process. However, phosphates can be removed through chemical precipitation, coagulation, flocculation and sedimentation. The nitrates are harder to treat. If the treatment system includes slow sand filtration, some	The risk of nutrients contamination is considered low. The risk of nutrients is rather the deterioration of the water source over time than have a direct effect. The risk of nutrients primarily relates
Synthetic fertilizer			

Combine sewer overflow (CSO)	CSO is the discharge of municipal wastewater and stormwater in the event of heavy rains. This will lead to the discharge of untreated wastewater that contains nutrients to the water source. Since there are many cities in close connection to the water source, there are many places where CSO could occur. The potential load is considered high. However, this discharge only occurs occasionally.	degradation of nitrates occurs. However, the efficiency is uncertain. If higher load of nitrates in the raw water, the waterworks might not be able to treat it.	to the use of fertilizers in agriculture and discharge from WWTPs and on-site sewers. Some sources, such as CSOs or the breaking of a sewage pipe might cause significantly higher levels of nutrient. However, if it occurs, the risk is primarily due to the presence of pathogens rather than nutrients. Climate change and extreme weather conditions could cause flooding which potentially enhance the spreading of nutrients. This would also increase the frequency of CSOs.
Wastewater treatment plant	WWTP have permits to release a certain level of nutrients to the recipient. There are 9 public WWTPs in the catchment area. Their discharge is directly connected to the water source. Since the WWTPs are large, the potential load of nutrients could be high.		
On-site sewage systems	On-site sewers with insufficient treatment systems may discharge untreated wastewater that contains nutrients. This discharge could via trenches connected to watercourses end up in the water source. If short distance, a possible pathway is also through groundwater flow. There are many on-site sewers in the catchment area and the release is considered to occur continuously. The potential cumulative load from many on-site sewers could be large.		

Breaking of sewer pipes	Breaking of sewer pipes may discharge untreated wastewater that contains nutrients. Since there are large cities close to the water source, the load could be relatively high. If breaking of the pipes occurs close to the water source or watercourses, it is likely that the nutrients is directly discharged into the water source.		
Old landfill	Old landfills could contain nutrients in their leachate. There are many old landfills in the catchment area and if not managed correctly leachate could be transported to the water source via trenches and watercourses. It can also spread through groundwater flow.		

C

Grimstofta

In this appendix the results from the risk assessment performed by Sweco and by us are presented.

C.1 Summary of Sweco's results

This is a summary of the result from Swecos risk assessment. The full risk assessment is can be found in the report written by Sweco (Sweco, 2018a).

Table C.1: Summary of Sweco's results

Risk sources	Risk
Accidents with hazardous goods	2
Accidents with heavy vehicles	2
Home chemicals (pesticides)	2
Pesticides used in agriculture	2
Tanks with petroleum products (Urban)	2
Tanks with petroleum products (agriculture/forestry)	2
Municipal sewage pipes	2
Energy facilities	2
Contaminated sites 15/16/18	2
Contaminated sites 40	1
Urban runoff/Runoff from roads/Road salts	1
Husbandry	1
Chemicals (outdoor pool)	1
On-site sewage systems	1
Svevia road station	1

C.2 Summary of our result

This is a presentation of the summary of our result. The risk sources identified by Sweco has been categorized based on their main contaminant. The contaminants and the risk sources that is placed in the top of the list is considered to pose the highest risks to the water source.

Table C.2: Summary of our results

Contaminants Group	Risk sources
Common Organic Chemicals	Urban runoff Home chemicals (pesticides) Pesticides used in agriculture Contaminated sites 15 (pesticides) Contaminated sites 16 (pesticides) Contaminated sites 18 (pesticides) Outdoor pool (chemicals)
Petroleum Products	Accidents on roads Tanks with petroleum products (Urban) Urban runoff Tanks with petroleum products (agriculture/forestry) Svevia road station
Pathogens	Breaking of sewer pipes On-site sewage systems Fertilizer/Husbandry
Heavy Metals	Urban runoff/Runoff from roads Svevia road station (Heaps of hazardous goods) Contaminated sites 40 (leachate)
Nutrients	Fertilizer On-site sewage systems Breaking of sewer pipes Contaminated sites 40 (leachate)

C.3 Our risk assessment

This is a presentation of our risk assessment for Grimstofta. The results of the six groups of contaminants that were examined are Presented below.

Contaminant	Pesticides, Chlorinated solvents		
Properties	These chemicals are liquid hydrocarbons that are denser than water. They vary in chemical structures but have similar physiological properties. Therefore, they spread similarly and have similar behavior in the environment. Their chemical structure makes them very persistent and they can impose a continuous source of contamination. They are not soluble in water. However, since they are denser than water, they can penetrate the groundwater table and affect a whole aquifer. This behavior decreases the lateral spreading distance while increasing it vertically. However, with time they also spread in a lateral direction.		
Consequence	These chemicals are toxic to humans at very low concentrations and they are also genotoxic and carcinogenic. Chemicals such as pesticides can accumulate in an organism and magnify over time which further indicates that even low concentrations are problematic. The consequence of sever contamination by these chemicals is that the water source might need to be abandoned or closed to be remediated. Due to their vertical spreading behavior, they can accumulate in an aquifer imposing a large risk to groundwater sources. If large amount reaches the waterworks and the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Urban runoff	Runoff contributes to the transportation of the pesticides generated by urban activities. Pesticide can be found in home chemicals and in gardens, parks etc. Runoff is caused by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. The pesticides could reach the aquifer area through the stormwater system that is connected to Grimstoftabäcken, through groundwater flow or through direct infiltration. There are many private gardens in close connection to the aquifer. In case of frequent use or spillage, the load of pesticides could be	The waterworks is not adapted to treat these chemicals. However, treatment processes such as GAC filter can to some extent treat them. Since this waterworks lacks the GAC filter, these chemicals can go through the waterworks and affect the drinking water consumers.	The risk of pesticides contamination is considered high. The largest risks are primarily related to the usage of home chemicals such as pesticides. There are many sources in close connection to the aquifer and the cumulative effect could be large. Since the groundwater table lies only about one meter below the ground surface, the pesticides and home chemicals could infiltrate the ground
Home chemicals (pesticides)			

	relatively large and the ability to spread is good.		and reach the extraction wells quickly. There are contaminated sites that contain pesticides. If the sites are not disturbed, it is considered unlikely that pesticides would spread to the aquifer. Moreover, the distance from those sites to the extraction wells is relatively long. However, if the sites are disturbed, the load of pesticides could be large. Thus, the risk needs to be considered. The waterworks cannot treat pesticides. Thus, the drinking water consumer might be affected.
Pesticides (agriculture)	There are no agricultural sites close to the aquifer area. However, there is a few sites east of the aquifer area, upstream the Grimstoftabäcken. Pesticides can spread through runoff or infiltrate the ground as a result of normal usage or in case of accidents with pesticides containers. Since the aquifer is unconfined, they could reach the aquifer through groundwater flow. The distance from the agricultural sites to the extraction wells is relatively long. However, the pesticides might reach the aquifer.		
Contaminated sites 15 (pesticides)	The contaminated sites are former gardening markets where they used large amount of pesticides. Site 15 and 16 are known to be highly polluted with pesticides while site 18 is unclear. They are located upstream the groundwater flow. The pesticides might infiltrate the ground and could reach the extraction wells through groundwater flow. The distance from those sites to the extraction wells is relatively long. However, the pesticides might reach the aquifer.		
Contaminated sites 16 (pesticides)			
Contaminated sites 18 (pesticides)			
Outdoor pool (chemicals)	The operation of the outdoor pool includes handling chlorinated solvents. The pool is located about 500 m upstream the aquifer area. In case of accidents, chlorinated solvents could be spilled. Since the aquifer is unconfined, the chlorinated solvents could potentially infiltrate the aquifer and reach the extraction wells. However, it is considered unlikely to happen.		

Contaminant	Petroleum products such as gasoline, diesel, fuel oil, jet fuel and lubricant oil		
Properties	Petroleum products are liquid hydrocarbons that are lighter than water. They vary in chemical structures but have similar physiological properties. Therefore, they spread similarly and have similar behavior in the environment. Their chemical structure makes them very persistent, however, they degrade very slowly in the environment. They have low solubility in water and due to their light density, they mainly spread on surface water or at the capillary zone above the groundwater table. This behavior enhances the lateral spreading distance while preventing vertical spreading. The fraction of more volatile petroleum products such as gasoline does not bind to geological materials which further enhance the spreading.		
Consequence	Petroleum products are highly toxic to humans at low concentrations and they are also genotoxic and carcinogenic. Low concentration (about 5 ug/L) also affects the taste and makes the water undrinkable. The consequence of petroleum products contamination is that the water source might need to be abandoned or closed to be remediated for a long time. If the contamination reaches the waterworks, sanitation is needed. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Accident of heavy vehicle (road) Accident with hazardous goods (road)	Accidents with heavy vehicles and hazardous goods could cause the release of a large amount of petroleum products. There are two roads of concern in the aquifer area, Tolångavägen and Långdansgatan. Since the aquifer is unconfined, petroleum products could potentially infiltrate the aquifer. Due to their light density, they will spread at the groundwater table laterally. Therefore, they could reach the extraction wells relatively quickly. Reduction measures to decrease the effect of the road Tolångavägen have been done such as impermeable trenches along the side of the road. If an accident occurs, the load could be large and the ability to spread is considered good.	The waterworks is not adapted to treat petroleum products. In case of high load of petroleum products, the distribution needs to be stopped and sanitation of the waterworks is needed.	The risk of petroleum products contamination is considered relatively high. The aquifer is unconfined, and the groundwater table lies only about one meter below the ground surface. Thus, any amount of spillage could infiltrate and affect the aquifer. The largest risks are related to accidents on Tolångavägen and Långdansgatan and tanks storing petroleum products in close connection to the aquifer area.

Urban runoff	Runoff contributes to the transportation of the petroleum products generated by urban activities and traffic. Runoff is caused by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. Petroleum products could reach the aquifer area through the stormwater system that is connected to Grimstoftabäcken, through groundwater flow or through direct infiltration. There exists a number of petroleum tanks in close connection to the aquifer area. Since the aquifer is unconfined, the petroleum products could infiltrate the ground and reach the aquifer. In case of spillage from one of the tanks, the load might be large.		An accident could cause the spill of large amount of petroleum products. The impermeable trenches along the side of the road Tolångavägen might be insufficient which could result in a fast pathway to the groundwater. Furthermore, a spillage from a tank in close connection to the aquifer, petroleum products could infiltrate and reach the extraction wells relatively fast. Since the spillage of petroleum products is connected to the event of accidents, it is considered unlikely to occur. However, if it does, consequences will be large. If a large load of petroleum products reaches the aquifer the effect would be large and remediation measures are needed.
Runoff from roads			
Tanks with petroleum products (Urban)			
Tanks with petroleum products (agriculture/forestry)	Tanks storing petroleum products are used in agricultural and forestry activities. There are number of tanks in the agricultural sites east of the aquifer area. In case of an accident, petroleum could be spilled. Since the aquifer is unconfined, the petroleum products could reach the groundwater through infiltration. Due to their light density, they will spread at the groundwater table laterally and might reach the extraction wells. The load of petroleum products could be large. However, the distance is relatively long.		
Svevia road station	The road station is located about 400m upstream the extraction wells. It contains petroleum storage tanks. In case of accident, the petroleum could spread through runoff and/or infiltrate the ground. It may also reach the aquifer area through the stormwater system connected to		

	Grimstoftabäcken. If an accident occurs, the load could be large and the ability to spread is considered good.		

Contaminant	Pathogens: Bacteria, viruses and protozoa		
Properties	Pathogens originate from faecal matter from humans and animals and may cause health effects. They are organisms that require a surface to attach to and organic matter to grow. Thus, water with high turbidity and high organic content impose a high risk of microbial contamination. Therefore, pathogens have a higher presence in surface water than in groundwater. Moreover, pathogens have different durability levels, with viruses being the most persistent. However, they can be inactivated by disinfection measures. Pathogens behave as colloids which means that they are suspended in the water and easily spread. Due to decay, the risk of microbial contamination is considered to be a peak load in the water source rather than an accumulation over time.		
Consequence	If microbial contamination is not sufficiently treated in the waterworks, the drinking water consumers can be infected. This can cause a variety of health effects on humans, such as fever, diarrhoea, vomiting, cramps, and a weakened immune system. This can also lead to epidemic outbreaks and potential deaths. Another consequence of the potential health effects is the social-economic costs of medical care and a population's inability to work. Furthermore, sanitation of waterworks and intensive water quality analysis are necessary. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Breaking of sewer pipes	Breaking of sewer pipes may discharge untreated wastewater that contains a large amount of pathogens. There are many municipal sewage pipes in close connection to the aquifer area. Therefore, in case of breaking, pathogens might infiltrate the unconfined aquifer. It is unlikely to occur. However, the potential load could be large.	The waterworks is adapted to the present raw water quality. Since it is a groundwater source, the presence of pathogens is low. As a safety measure, the waterworks is equipped with a UV disinfection unit. UV disinfection is efficient if the turbidity and the load of pathogens is low. In case of increased load of pathogens and/or high turbidity, the pathogens might be present in the effluent.	The risk of pathogens contamination needs to be considered. The breaking or leaking of a sewage pipe is considered to impose a considerable risk to the water source. There are many places in close connection to the aquifer where the consequence of sewage discharge would be large. Since the groundwater
On-site sewage systems	On-site sewers with insufficient treatment systems may discharge untreated wastewater that contains pathogens. There are no on-site sewers in close connection to the aquifer area. There are few on-site sewers upstream Grimstoftabäcken. Pathogens could spread		

	through runoff. However, it is considered unlikely that the pathogens from these sources will reach the aquifer area.		table lies only about one meter below the ground surface, the pathogens could infiltrate and reach the extraction wells relatively fast. However, it is unlikely to happen. As a precautious measure the waterworks has one microbial barrier. However, a high load of pathogens could lead to their presence in the effluent. Thus, drinking water consumers could be infected.
Fertilizer (agriculture) Husbandry	Natural fertilizers are used in agriculture and consist of animal manure. Moreover, husbandry activities result in a large amount of animal manure. Animal manure may contain pathogens that could be transported to the aquifer area by Grimstoftabäcken. There are no agricultural sites close to the aquifer area. However, there is a few sites east of the aquifer area, upstream the Grimstoftabäcken. The load of pathogens from these sites is consider low. Moreover, pathogens tend to degrade and to be filtered out via soil. The distance from the agricultural sites to the extraction wells is relatively long. Therefore, it is considered unlikely that the pathogens will infiltrate the unconfined aquifer.		

Contaminant	Heavy metals such as Cadmium, Chromium, Cobalt, Copper, lead, Mercury, Nickel and Zinc.		
Properties	Heavy metals are metals with density higher than 5 g/cm3 and with similar physiological properties. They are mainly solids except for mercury that could be found in a liquid form in nature. They are undegradable inorganic elements that occur naturally in the environment. The spreading of heavy metals highly depends on their solubility and the pH of the water, with low pH the heavy metals are more soluble. Dissolved heavy metals have a very high ability to spread while the solids tend to sediment. Heavy metals can also spread through attaching to negatively charged particles suspended in water.		
Consequence	Heavy metals in high concentrations in drinking water are toxic to humans. They can also accumulate in organisms causing long term health effects. It is most likely that the release of heavy metals will not have instant effects on the drinking water supply system, but rather deteriorate the water source over time. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Urban runoff Runoff from roads	Runoff contributes to the transportation of the heavy metals generated by urban activities and traffic. Runoff is caused by precipitation on impermeable surfaces or on saturated permeable surfaces. Runoff increases during heavy rain events and occurs continuously throughout the year. Heavy metals could behave as particles or be dissolved in the water. They could reach the aquifer area through the stormwater system that is connected to Grimstoftabäcken or through groundwater flow. Since the aquifer is unconfined, the dissolved heavy metals could reach the aquifer. Reduction measures to decrease the effect of the road Tolångavägen have been done, such as impermeable trenches along the side of the	The waterworks is adapted to the present raw water quality. Since it is a groundwater source with good quality, the presence of heavy metals is low. The waterworks does not include any heavy metal treatment process. If high load of heavy metals would occur in the raw water, the waterworks will not be able to treat it. Thus, heavy metals will be present in the effluent.	The risk of heavy metals contaminations is considered low. The risk of heavy metals contamination primarily comes from urban runoff and runoff from Svevia road station that enters the stormwater system. However, only small part of the stormwater system connects to Grimstoftabäcken upstream the extraction wells. Thus, the risk is considered low.

	road. The load of heavy metals from these sources is considered low. However, the ability to spread is considered relatively good.		Moreover, Reduction measures to decrease the effect of the road Tolångavägen have been done such as impermeable trenches along the side of the road. In general, the sources of heavy metals are considered small, and the dilution is considered large. However, if heavy metals would spread into the aquifer, the waterworks will not able to treat it. Thus, it could affect the drinking water consumers.
Svevia road station (Heaps of hazardous goods)	The road station is located about 400m upstream the extraction wells. It contains heaps of hazardous goods that are likely to contain heavy metals. The heavy metals could potentially spread through runoff and infiltrate the ground. Therefore, the dissolved heavy metals could reach the aquifer through groundwater flow. It may also reach the aquifer area through the stormwater system connected to Grimstoftabäcken. However, the load of heavy metals is considered low.		
Contaminated sites 40 (leachate)	The contaminated site 40 could contain heavy metals in its leachate. It is located about 600 m upstream the extraction wells. Leachate could infiltrate the ground and spread through groundwater flow to the aquifer. The amount of heavy metals in the leachate is unclear. Moreover, the site is small and relatively far from the extraction wells.		

Contaminant	Nutrients: nitrates and phosphates		
Properties	Nitrates and phosphates are inorganic compounds that occur naturally in the environment. However man-made synthetic versions also exist. They are dissolved in water and they degrade over time. Due to the degradation, their presence in groundwater is naturally low. Therefore, they spread mainly in surface water or in the capillary zone above the groundwater table.		
Consequence	An abundance of nitrates and phosphates can cause eutrophication which is harmful to aquatic life. A high concentration in drinking water is also toxic to humans. Since the water source has a buffering capacity against the release of nutrients, continuous release will deteriorate the water source over time rather than have an instant effect. However, in case of an accident with a high release of nutrients, the water source might not be suitable for use for some time. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Fertilizer (agriculture)	There are no agricultural sites close to the aquifer area. However, there is a few sites east of the aquifer area, upstream the Grimstoftabäcken. Nutrients are highly soluble in water and can infiltrate to the groundwater and thereby spread through groundwater flow. Since the aquifer is unconfined, they could reach the aquifer. However, the load of nutrients from these sites is consider low. Moreover, nutrients tend to degrade over time. The distance from the agricultural sites to the extraction wells is relatively long. Therefore, it is considered unlikely that the nutrients will reach the aquifer.	The waterworks is adapted to the present raw water quality. Since it is a groundwater source with good quality, the presence of nutrients is low. The waterworks does not include any nutrients treatment process. If high load of nutrients would occur in the raw water, the waterworks will not be able to treat it. Thus, nutrients will be present in the effluent.	The risk of nutrients contamination is considered low. There are no large sources of nutrients in close connection with the aquifer. The risk is primarily due to the use of fertilizers in agriculture east of the aquifer area. Nutrients tend to degrade and the distance to the aquifer is relatively long. However, in case of accidental spillage close to Grimstoftabäcken, the load would be high and the ability to spread is good. Although, it
On-site sewage systems	On-site sewers with insufficient treatment systems may discharge untreated wastewater that contains nutrients. There are no on-site sewers in close connection to the aquifer area. There are few		

	on-site sewers upstream Grimstoftabäcken. Nutrients can infiltrate the ground and spread through groundwater flow. However, due to degradation and long distance, it is considered unlikely that the nutrients from these sources will reach the aquifer. Moreover, the load is considered low.		is unlikely to happen. If high load of nutrients would occur in the raw water, the waterworks will not be able to treat it.
Breaking of sewer pipes	Breaking of sewer pipes may discharge untreated wastewater that contains nutrients. There are many municipal sewage pipes in close connection to the aquifer area. Therefore, in case of breaking, nutrients might infiltrate the unconfined aquifer. It is unlikely to occur. However, the potential load could be relatively large.		
Contaminated sites 40 (leachate)	The contaminated site 40 could contain nutrients in its leachate. It is located about 600 m upstream the groundwater extraction wells. Leachate could infiltrate the ground and spread through groundwater flow to the aquifer. The amount of nutrients in the leachate is unclear. However, the site is small and relatively far from the extraction wells thus the load of nutrients is considered low.		

D

Haboskogen

In this appendix the results from the risk assessment performed by Sweco and by us are presented.

D.1 Summary of Sweco's results

This is a summary of the result from Sweco's risk assessment. The full risk assessment is can be found in the report written by Sweco, (Sweco, 2018b).

Table D.1: Summary of Sweco's results

Risk sources	Risk
Accidents with hazardous goods on road 202	2
Accidents with heavy vehicles on road 202	2
Pesticides used in agriculture	2
Tanks with petroleum products (agriculture/forestry)	2
Heaps of timber	2
Contaminated sites, sawmill 8	2
Rifle range, 6	2
Contaminated sites, scrapyard 7	1
Contaminated sites, landfill 9	1
Runoff from road 202	1
Deforestation	1
Old landfill 10, 11	1
Energy facilities	1
Tanks with petroleum products (Urban)	1
Transformer station	1
Motor cross driving in former quarry	1
Husbandry	1
On-site sewage systems	1
Fertilizer in agriculture	1

D.2 Summary of our result

This is a presentation of the summary of our result. The risk sources identified by Sweco has been categorized based on their main contaminant. The contaminants and the risk sources that is placed in the top of the list is considered to pose the highest risks to the water source.

Table D.2: Summary of our Results

Contaminants Group	Risk sources
Petroleum Products	Accident with heavy vehicle (road 202) Accident with hazardous goods (road 202) Tanks with petroleum products (agriculture/forestry) Runoff from road 202 Transformer station Motor cross driving in former quarry
Common Organic Chemicals	Pesticides used in agriculture Heaps of timber Potentially contaminated sites, sawmill (8)
Heavy Metals	Rifle range (6) Potentially contaminated sites, scrapyard (7) Potentially contaminated sites, sawmill (8) Potentially contaminated sites, landfill (9) Runoff from road 202
Pathogens	Fertilizer used in agriculture Husbandry On-site sewage systems
Nutrients	Fertilizer used in agriculture On-site sewage systems

D.3 Our Risk Assessment

This is a presentation of our risk assessment for Haboskogen. The results of the six groups of contaminants that were examined are Presented below.

Contaminant	Petroleum products such as gasoline, diesel, fuel oil, jet fuel and lubricant oil		
Properties	Petroleum products are liquid hydrocarbons that are lighter than water. They vary in chemical structures but have similar physiological properties. Therefore, they spread similarly and have similar behavior in the environment. Their chemical structure makes them very persistent, however, they degrade very slowly in the environment. They have low solubility in water and due to their light density, they mainly spread on surface water or at the capillary zone above the groundwater table. This behavior enhances the lateral spreading distance while preventing vertical spreading. The fraction of more volatile petroleum products such as gasoline does not bind to geological materials which further enhance the spreading.		
Consequence	Petroleum products are highly toxic to humans at low concentrations and they are also genotoxic and carcinogenic. Low concentration (about 5 ug/L) also affects the taste and makes the water undrinkable. The consequence of petroleum products contamination is that the water source might need to be abandoned or closed to be remediated for a long time. If the contamination reaches the waterworks, sanitation is needed. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Accident with heavy vehicle (road 202)	Accidents with heavy vehicles and hazardous goods could cause the release of a large amount of petroleum products. The road is about 60 m north to the nearest extraction well. Since the aquifer is unconfined, petroleum products could potentially infiltrate. Due to their light density, they will spread at the groundwater table laterally. Therefore, they could reach the extraction wells quickly. Reduction measures to decrease the effect of the road have been done such as impermeable trenches along the side of the road.	The waterworks is not adapted to treat petroleum products. In case of high load of petroleum products, the distribution needs to be stopped and sanitation of the waterworks is needed.	The risk of petroleum products contamination is considered high. The aquifer is unconfined, thus any amount of spillage could infiltrate and affect the aquifer. The largest risks are related to accidents on road 202 and tanks storing petroleum products in the area of the aquifer. An accident on road 202 could cause the spill of large amount of petroleum products. The impermeable trenches along the side
Accident with hazardous goods (road 202)			

Tanks with petroleum products (agriculture/forestry)	Tanks storing petroleum products are used in agricultural and forestry activities. In case of an accident, petroleum could be spilled. Since the aquifer is unconfined, the petroleum products could reach the groundwater through infiltration. Due to their light density, they will spread at the groundwater table laterally and has the potential to reach the extraction wells. Since the water source is situated in an area used for forestry, the tanks of petroleum products occur frequently. In case of an accident, the load of petroleum products could be relatively high.		of the road might be insufficient which could result in a fast pathway to the extraction wells. The spillage from a tank storing petroleum product could be relatively large and it could happen in the area of the aquifer. The ability to infiltrate is considered good. Thus, the petroleum products might reach the extraction wells. Since the spillage of petroleum products is connected to the event of accidents, it is considered unlikely to occur. However, if it does, the consequences will be large.
Runoff from road 202	Traffic on road 202 generates low amount of petroleum products. The road is about 60 m north to the nearest extraction well. The petroleum products can spread to the surrounding area through runoff. Since the aquifer is unconfined, the petroleum products could reach the groundwater through infiltration. Reduction measures to decrease the effect of the road have been done such as impermeable trenches along the side of the road.		

Transformer station	Transformer stations contain oil. In the area of the aquifer, there are four transformer stations containing 110, 110, 80, and 225 kg of oil respectively. In case of insufficient maintenance or accidents, they could potentially leak. Since the aquifer is unconfined and the stations are located close to the extraction wells, the oil might infiltrate the aquifer and reach the extraction wells. It is considered unlikely to happen but if it does the load could be relatively large.		
Motor cross driving in former quarry	Motor cross driving occurs in a former quarry south of the water source. In case of accidents, petroleum products could be spilled. Since the quarry lacks a layer of vegetation, the infiltration to the aquifer can happen quickly. Since the aquifer is unconfined, the petroleum products could potentially reach the extraction wells through groundwater flow. However, it is unlikely to happen since the quarry is located downstream the extraction wells. If it does the load is considered low.		

<table>
<tr><td>Contaminant</td><td colspan="3">Pesticides,
Phenols</td></tr>
<tr><td>Properties</td><td colspan="3">These chemicals are liquid hydrocarbons that are denser than water. They vary in chemical structures but have similar physiological properties. Therefore, they spread similarly and have similar behavior in the environment. Their chemical structure makes them very persistent and they can impose a continuous source of contamination. They are not soluble in water. However, since they are denser than water, they can penetrate the groundwater table and affect a whole aquifer. This behavior decreases the lateral spreading distance while increasing it vertically. However, with time they also spread in a lateral direction.</td></tr>
<tr><td>Consequence</td><td colspan="3">They are toxic to humans at very low concentrations and they are also genotoxic and carcinogenic. Chemicals such as pesticides can accumulate in an organism and magnify over time which further indicates that even low concentrations are problematic. The consequence of sever contamination by these chemicals is that the water source might need to be abandoned or closed to be remediated. Due to their vertical spreading behavior, they can accumulate in an aquifer imposing a large risk to groundwater sources. If large amount reaches the waterworks and the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.</td></tr>
<tr><td>Sources</td><td>Pathways
(incl. natural and technical barriers)</td><td>Barriers in waterworks</td><td>Risk</td></tr>
<tr><td>Pesticides (agriculture)</td><td>Pesticides are used in agriculture and forestry. They can spread through runoff and infiltrate the aquifer as a result of normal usage or in case of accidents with pesticides containers. They are persistent and can spread for long distances. There are forests and agricultural sites in the area of the aquifer. Therefore, the cumulative load of pesticides could be large.</td><td>The waterworks is not adapted to treat these chemicals. However, treatment processes such as GAC filter can to some extent treat them.
Since this waterworks lacks the GAC filter, these chemicals can go through the waterworks and affect the drinking water consumers.</td><td>The risk of these chemicals is considered relatively high.

The largest risks are primarily related to the use of pesticides in agriculture. Moreover, heaps of timber that are stored close to the extraction wells constitute a risk.

Pesticides is used in agriculture sites that are relatively close to the</td></tr>
</table>

Heaps of timber	Heaps of timber can release phenols due to the degradation of organic matter in the wood. The aquifer is in a forestry area and heaps of timber occur frequently. Since the aquifer is unconfined, the phenols could infiltrate the aquifer and potentially reach the extraction wells.		aquifer area. Since the aquifer is unconfined, they might spread to the aquifer. If heaps of timber are placed close to the extraction wells, phenols could be released. Since the aquifer is unconfined, phenols could reach the extraction wells. It is considered unlikely that any of these sources would cause a large release of pesticides or phenols. The risk is more related to the cumulative load from several sources and the deterioration of the water source over time. Furthermore, these chemicals are toxic in even low concentration and the water works cannot treat them. Thus, the drinking water consumer might be affected.
Potentially contaminated sites, sawmill (8)	The former sawmill site is situated 400 m north from the extraction well. The ground might be polluted with wood preserving wastes such as different kind of phenols. These substances could potentially infiltrate the aquifer. The load is considered low.		

<table>
<tr><td>Contaminant</td><td colspan="3">Heavy metals such as Cadmium, Chromium, Cobalt, Copper, lead, Mercury, Nickel and Zinc.</td></tr>
<tr><td>Properties</td><td colspan="3">Heavy metals are metals with density higher than 5 g/cm3 and with similar physiological properties. They are mainly solids except for mercury that could be found in a liquid form in nature. They are undegradable inorganic elements that occur naturally in the environment. The spreading of heavy metals highly depends on their solubility and the pH of the water, with low pH the heavy metals are more soluble. Dissolved heavy metals have a very high ability to spread while the solids tend to sediment. Heavy metals can also spread through attaching to negatively charged particles suspended in water.</td></tr>
<tr><td>Consequence</td><td colspan="3">Heavy metals in high concentrations in drinking water are toxic to humans. They can also accumulate in organisms causing long term health effects. It is most likely that the release of heavy metals will not have instant effects on the drinking water supply system, but rather deteriorate the water source over time. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.</td></tr>
<tr><td rowspan="2">Sources</td><td>Pathways</td><td rowspan="2">Barriers in waterworks</td><td rowspan="2">Risk</td></tr>
<tr><td>(incl. natural and technical barriers)</td></tr>
<tr><td>Rifle range (6)</td><td rowspan="3">Rifle range is situated 100 m from the reserved water source and 1.3 km north from the extraction well.

The scrapyard is situated 900 m north from the extraction well.

The sawmill is situated 400 m north from the extraction well.

Since these sites are located upstream the extraction wells, dissolved heavy metal from these sites could infiltrate the aquifer. The load is considered low, however they could impose a continuous source of contamination.</td><td rowspan="4">The waterworks is adapted to the present raw water quality. Since it is a groundwater source with good quality, the presence of heavy metals is low. The waterworks does not include any heavy metal treatment process. If high load of heavy metals would occur in the raw water, the waterworks will not be able to treat it. Thus, heavy metals will be present in the effluent.</td><td rowspan="4">The risk of heavy metals contaminations needs to be considered.

The risk primary related to the few contaminated sites in the aquifer area.

Primarily, the rifle range is considered the main concern as it is close to the reserve water extraction wells. The rifle range is known to contain lead that might affect the raw water. However, if the site is not disturbed, it is</td></tr>
<tr><td>Potentially contaminated sites, scrapyard (7)</td></tr>
<tr><td>Potentially contaminated sites, sawmill (8)</td></tr>
<tr><td>Potentially contaminated sites, landfill (9)</td><td>The old landfill is situated at about 400 m south-west the aquifer. It is unclear if it contains heavy metals and whether it leaks to the aquifer. Since the landfill is located</td></tr>
</table>

	downstream the extraction wells, the ability to spread to the aquifer is consider low.		considered unlikely to spread. In general, the sites are small, and the dilution is considered large. However, disturbance in the sites might cause a higher load into the aquifer. The waterworks is not able to treat heavy metals, thus it could affect the drinking water consumers.
Runoff from road 202	Traffic on road 202 is a source of heavy metals. The road is about 60 m north to the nearest extraction well. Heavy metals might spread to the surrounding area through runoff. Since the aquifer is unconfined, the dissolved heavy metals could reach the groundwater through infiltration. Reduction measures to decrease the effect of the road have been done such as impermeable trenches along the side of the road. Therefore, the load of heavy metals is considered low.		

Contaminant	Pathogens: Bacteria, viruses and protozoa		
Properties	Pathogens originate from faecal matter from humans and animals and may cause health effects. They are organisms that require a surface to attach to and organic matter to grow. Thus, water with high turbidity and high organic content impose a high risk of microbial contamination. Therefore, pathogens have a higher presence in surface water than in groundwater. Moreover, pathogens have different durability levels, with viruses being the most persistent. However, they can be inactivated by disinfection measures. Pathogens behave as colloids which means that they are suspended in the water and easily spread. Due to decay, the risk of microbial contamination is considered to be a peak load in the water source rather than an accumulation over time.		
Consequence	If microbial contamination is not sufficiently treated in the waterworks, the drinking water consumers can be infected. This can cause a variety of health effects on humans, such as fever, diarrhoea, vomiting, cramps, and a weakened immune system. This can also lead to epidemic outbreaks and potential deaths. Another consequence of the potential health effects is the social-economic costs of medical care and a population's inability to work. Furthermore, sanitation of waterworks and intensive water quality analysis are necessary. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.		
Sources	**Pathways** (incl. natural and technical barriers)	**Barriers in waterworks**	**Risk**
Fertilizer (agriculture) Husbandry	Natural fertilizers are used in agriculture and consist of animal manure. Moreover, husbandry activities result in a large amount of animal manure. Animal manure may contain pathogens that could be transported to the aquifer through infiltration and groundwater flow. There are husbandry and agricultural sites on the west side of the aquifer. However, pathogens tend to degrade and to be filtered out via soil. The distance from the agricultural sites to the extraction wells is relatively long. Therefore, the load of pathogens from agriculture and husbandry is considered low.	The waterworks is adapted to the present raw water quality. Since it is a groundwater source, the presence of pathogens is low. As a safety measure, the waterworks is equipped with a UV disinfection unit. UV disinfection is efficient if the turbidity and the load of pathogens is low. In case of increased load of pathogens and/or high turbidity, the pathogens might be present in the effluent.	The risk of pathogens contamination is considered low. The risk is primarily caused by husbandry and on-site sewers within the aquifer area. However, the pathogens tend to be filtered out in the soil and degrade over time. As a precautious measure the waterworks has one microbial

On-site sewage systems	On-site sewers with insufficient treatment systems may discharge untreated wastewater that contains pathogens. There are several on-site sewers in the aquifer area and the discharge is considered to occur continuously. Since the aquifer is unconfined, this discharge could infiltrate the aquifer. However, since pathogens tend to degrade and be filtered out in the soil, they are considered unlikely to spread.		barrier. Thus, the risk of pathogens being present in the effluent is considered low.

<table>
<tr><td>Contaminant</td><td colspan="3">Nutrients: nitrates and phosphates</td></tr>
<tr><td>Properties</td><td colspan="3">Nitrates and phosphates are inorganic compounds that occur naturally in the environment. However man-made synthetic versions also exist. They are dissolved in water and they degrade over time. Due to the degradation, their presence in groundwater is naturally low. Therefore, they spread mainly in surface water or in the capillary zone above the groundwater table.</td></tr>
<tr><td>Consequence</td><td colspan="3">An abundance of nitrates and phosphates can cause eutrophication which is harmful to aquatic life. A high concentration in drinking water is also toxic to humans. Since the water source has a buffering capacity against the release of nutrients, continuous release will deteriorate the water source over time rather than have an instant effect. However, in case of an accident with a high release of nutrients, the water source might not be suitable for use for some time. If the drinking water supply system does not have a reserved water source, drinking water distribution can be affected.</td></tr>
<tr><td rowspan="2">Sources</td><td>Pathways</td><td rowspan="2">Barriers in waterworks</td><td rowspan="2">Risk</td></tr>
<tr><td>(incl. natural and technical barriers)</td></tr>
<tr><td>Fertilizer (agriculture)</td><td>There are agricultural sites on the west side of the aquifer. Nutrients from fertilizers are highly soluble in water and can infiltrate to the groundwater. Since the aquifer is unconfined and there is farmland close to the aquifer, excess of nutrients might reach the aquifer. The spread is likely to occur during the spring when agricultural activities are high. However, the nutrients tend to degrade, thus, the load of nutrients is considered low.</td><td>The waterworks is adapted to the present raw water quality. Since it is a groundwater source with good quality, the presence of nutrients is low. The waterworks does not include any nutrients treatment process. If high load of nutrients would occur in the raw water, the waterworks will not be able to treat it. Thus, nutrients will be present in the effluent.</td><td>The risk of nutrients contamination is considered low.

The risk is primarily due to the use of fertilizers in agriculture close to the aquifer. Since nutrients degrade in the top layer of the soil over time, it is considered unlikely that the</td></tr>
</table>

On-site sewage systems	On-site sewers with insufficient treatment systems may discharge untreated wastewater that contains nutrients. There are several on-site sewers in the aquifer area and the discharge is considered to occur continuously. Since the aquifer is unconfined and the nutrients are soluble in water, they might infiltrate. However, the nutrients tend to be degraded in the soil. Therefore, the load of nutrients from on-site sewers is considered low.		nutrients will infiltrate the aquifer. However, if they infiltrate the aquifer, they will affect the raw water quality and the waterworks will not be able to treat it.