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The potential of assessing harmful algal bloom risks in Swedish raw water sources

- A study of four Swedish drinking water sources

Master's thesis in infrastructure and environmental engineering

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Risk assessment of current and future harmful algal bloom in surface water sources
-A study of four Swedish drinking water sources

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

Higher temperatures and extreme weather due to climate change are expected to increase algae growth in Swedish surface waters, potentially disrupting drinking water production through algal toxins or clogged filters. This project aimed to assess the risks associated with high algal biomass in Swedish surface waters, identify critical conditions that trigger harmful algal blooms, and explore effective strategies for how these risks can be managed.

Four case studies (Lerum, Tjörn, Sotenäs, and Sandviken) and a literature review were conducted. The analysis found no correlation between selected parameters and algal blooms in the studied waters, although weather data indicated trends consistent with climate change. The limited raw water data likely influenced the results.

It was concluded that municipal risk management for algal growth is inadequate. Improved monitoring, systematic sampling, and the use of daily measurements of pH, turbidity, and water temperature are recommended as indicators of algae growth. If changes in these indicators are detected, they should be followed by visual inspections. Additionally, more extensive measures, such as sampling total biomass or chlorophyll-a, can be used as more precise indicators of algae growth.

Keywords: Algae, Algal bloom, Drinking water, Raw water, Risk assessment.

Sammanfattning

Högre temperaturer och extremt väder på grund av klimatförändringar förväntas öka tillväxten av alger i svenska ytvatten. Algtoxiner eller algceller som sätter igen filter på vattenverken har potential att störa dricksvattenproduktionen. Syftet med detta projekt var att bedöma riskerna kopplade till algtillväxt i svenska råvattentäkter, identifiera kritiska förhållanden som kan trigga algblomningar, samt undersöka möjligheterna för en effektiv riskhantering av problemen.

Fyra fallstudier (Lerum, Tjörn, Sotenäs och Sandviken) och en litteraturstudie genomfördes. Analysen från fallstudieområdena visade ingen korrelation mellan utvalda parametrar och algblomningar i de studerade ytvattnen, även om väderdata indikerade trender som är förenliga med klimatförändringar. Den begränsade mängden råvattendata påverkade troligen resultaten.

Det konstaterades att kommunernas riskhantering för algtillväxt är otillräcklig. Förbättrad övervakning, systematisk provtagning och användning av dagliga mätningar av pH, grumlighet och vattentemperatur rekommenderas som indikatorer på algtillväxt. Om förändringar i dessa indikatorer upptäcks bör de följas upp med visuella inspektioner. Dessutom kan mer omfattande åtgärder, såsom provtagning av total biomassa eller klorofyll-a, användas som mer precisa indikatorer på algtillväxt.

Nyckelord: Algblomning, Alger, Dricksvatten, Riskbedömning,

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Björn Cederberg, Gothenburg, June 2024
Klara Eriksson Segerström, Gothenburg, June 2024

Contents

List of Abbreviations

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

HAB	*Harmful Algal Bloom*
G. Semen	*Gonyostomum semen*
TOC	*Total Organic Carbon*
MCs	*Microcystin*
NODs	*Nodularin*
HACCP	*Hazard Analysis* and *Critical Control Points*
WSP	*Water Safety Plan*
WWTP	*Wastewater treatment plant*
DWTP	*Drinking Water Treatment Plant*

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Introduction

1.1 Background

Access to safe drinking water is a human right and one of the UN's global sustainability development goals (UN, 2024). Drinking water producers in Sweden are obligated to ensure that their drinking water is safe for consumption, with no risk to human health (Livsmedelsverket, 2024). A key element to provide this is access to raw water of adequate quality. In Sweden, groundwater and surface water are used for drinking water production. Most of Sweden's 5,600 registered drinking water treatment plants (DWTPs) use groundwater as their raw water source (Livsmedelsverket, 2007). However, in terms of the produced volume, it is equally distributed between groundwater and surface water. Large DWTP generally use surface water, while smaller DWTP use groundwater.

To protect the raw water sources, Sweden has established a system with drinking water protection areas (SwAM, 2024). Activities and land usage are typically restricted within these areas to reduce the risk of contaminating the raw water sources. Water protection areas cannot eliminate all pollution risks, and there remains a possibility of contaminants being present, possibly making the raw water unsuitable for drinking water production. Accidents such as oil leakages and sewage pipe breaks are just some examples of potential threats to the water quality. Furthermore, surface water is susceptible to microbial contamination, whereas groundwater is better protected (Cabral, 2010). The dark environment in groundwater aquifers, which limits microbial proliferation, and the absorption of microbes and pathogens by the soil during transport are elements that contributes to the reduction of microbial contaminants in groundwater sources.

One microbial risk in surface water is harmful algal blooms. Some species of these microscopic organisms (often called blue-green algae or cyanobacteria) can produce algal toxins harmful to humans and animals, thereby posing a chemical risk (Hagen, 2008). Moreover, high levels of non-toxic algal species can also potentially disrupt drinking water production. They can cause filter clogging and affect the water's taste and odour. As an example, drinking water supply was interrupted for a week in 2017 due to an algal bloom in the raw water source, Andträsket, in the village of Råneå in Luleå municipality (MSB, 2017).

Algae thrive in warm, nutrient-rich water. Thus, rising temperatures as an effect of climate change could increase the risk for an increased risk of harmful algal blooms (HAB)(Hagen, 2008; Schimanke et al., 2022). Many of the factors that contribute to a harmful algal bloom are known (nutrients, temperature, light), but it is not yet fully understood how these factor together causes a bloom (Ramsdell & Glibert, 2005). Hence, there is a need for drinking water producers to assess the current and future risks connected to algal biomass growth while accounting for local conditions. Assessment of these risks can provide important insights for informed decision-making processes regarding raw water protection and drinking water production. However, at present, there is no structured decision support available for assessing these risks, neither in the present nor the future. Thus, this study intends to provide new insight into the causes behind algal blooms in Swedish surface waters and how these risks can be assessed.

1.2 Aim and objectives

The aim is to investigate the water quality risks associated with high levels of algal biomass in raw water sources, and to evaluate how the risk can be assessed by Swedish drinking water utilities.

Specific objectives are to:

- Evaluate raw water data from four case study areas (Lerum, Sotenäs, Tjörn, Sandviken) to identify critical preconditions that have the potential to cause high levels of algal biomass.
- Evaluate the possibilities to assess the current and future risks from algae growth using available data at Swedish drinking water treatment plants.

1.3 Limitation

Raw water data were evaluated to see if there was a correlation between certain parameters and massive algal biomass growth; the collection was limited to four specific raw water sources. The data were analyzed focusing on the following parameters: water temperature, pH, total phosphorus, phosphate, color, total biomass, volume of cyanobacteria, air temperature, sunshine duration, and precipitation. Other parameters were excluded from the analysis.

The study focused only on raw water quality, that is before the water enters the drinking water treatment plant. The risks that were investigated were those connected to high levels of algal biomass or algal toxins. Other risks were not considered, such as the risk of an oil leakage or natural hazard that could contaminate the raw water source. Studies of risks related to the drinking water treatment processes were not included in this project.

1.4 Case study areas

The study uses four different case study areas: Lerum, Sotenäs, Sandviken, and Tjörn. This chapter describes the different areas.

Figure 1.1: The four different case study areas each number shows where the case study areas are located 1: Lerum, 2: Tjörn, 3: Sotenäs and 4: Sandviken.

1.4.1 Lerum

The two lakes, Stora Stamsjön and Öxsjön, serve as the main raw water sources for drinking water production in Lerum municipality (a small DWTP with groundwater also exists). Stora Stamsjön has a total area of 0.6 km^2 and Öxsjön of 0.72 km^2. Both lakes have an average depth below 15 m, classifying them as middle-depth lakes (VISS, 2024c). Most of the catchment area is forest areas, about 70 % for both lakes.

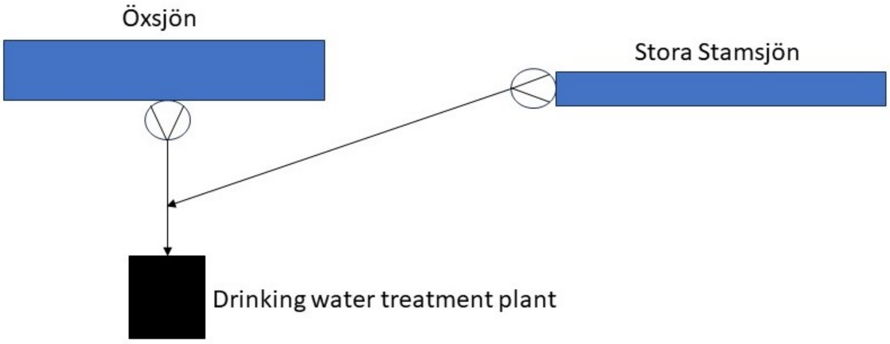


Figure 1.2: Schematic view of Lerum raw water supply.

Stora Stamsjön and Öxsjön are both nutrient-poor lakes (Medins, 2021). Stora Stamsjön is classified as a dystrophic lake, while Öxsjön, with a concentration of <30 mg Pt/l, is classified as a non-dystrophic lake according to VISS (2024c). The water transparency is higher in Öxsjön compared to Stora Stamsjön.

Öxsjön experienced massive growth of algal biomass in the summer of 2018, leading to interruptions in drinking water production (S. Lund, personal communication, 4 February 2024). As a consequence of this, the municipality of Lerum wanted to assess the risk of HABs in Stora Stamsjön and Öxsjön. The water consulting company Medins was contracted in 2021 with the purpose of evaluating the algal populations within the lakes. Medins' investigations in 2021 showed low levels of algal biomass in both lakes. Even though the total biomass almost doubled from June 2021 to August 2021, measurements of total biomass, PTI, and chlorophyll-a were all within the criteria to obtain high ecological status according to HVMFS:2019:25. The conclusion from Medins' investigation is that there is a small to moderate risk for future algal blooms and high levels of cyanotoxins.

1.4.2 Tjörn

The two small lakes, Bö tjärn and Tolleby tjärn serve as raw water sources for the municipality of Tjörn. Both lakes are dammed, and the water level has been raised. Bö tjärn has a total area of 0.72 km^2, and Tolleby tjärn 0.05 km^2. (VISS, 2024a). Both lakes have an average depth of around 3 m, Bö tjärn has a maximal depth of 12 m while Tolleby tjärn has a maximal depth of 6 m. The ecological status is high for both lakes according to criteria in HVMFS:2019:25. Water is also utilized from the artificial pond Olsby damm (R. Kareflod, personal communication,7 February 2024). The raw water intake is situated in Bö tjärn, water is pumped from Häle mosse and Tolleby tjärn to Bö tjärn. Water from the pond Olsby damm is pumped to Tolleby. See Figure 1.3 below.

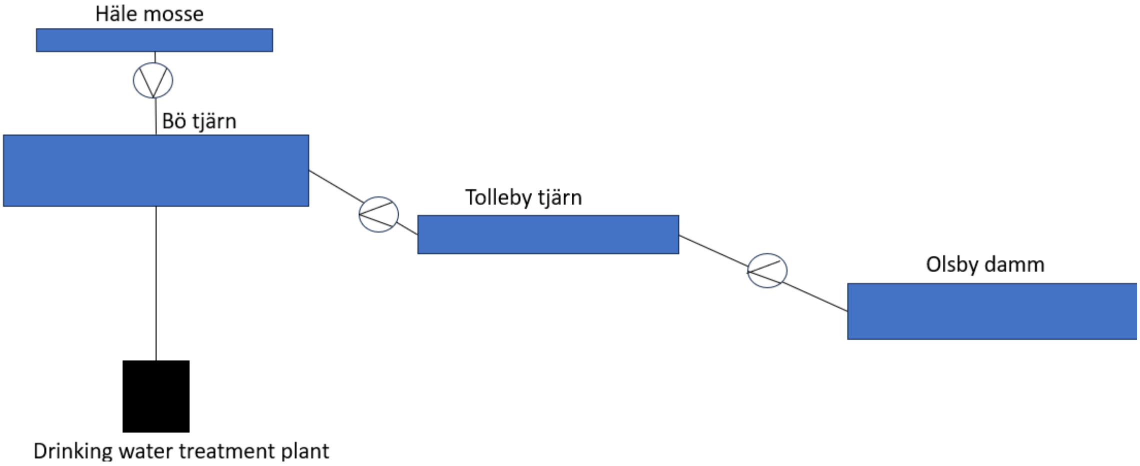


Figure 1.3: Schematic view of Tjörns raw water supply

There have been problems with algal blooms in Tolleby tjärn. In 2019, three dogs died after swimming in the lake (GP, 2019). It was concluded that the reason for this was an ongoing algal bloom in the lake, which had produced high levels of cyanotoxins. Despite this, no algal toxins were detected in the drinking water during the ongoing algal bloom, as samples were made directly after the episode (personlig kommunikation). The pond of Olsby has typically algal blooms every summer, thus pumping from Olsby to Tolleby is usually stopped during summertime (R. Kareflod, personal communication,7 February 2024).

1.4.3 Sotenäs

Sotenäs municipality takes its raw water from the small lake Lilla Dalevatten, in close vicinity of the water works and the lake Tåsteröds Stora Vatten, which is located approximately 10 km away. Lilla Dalevatten has a total surface area of 0.11 km^2 and an average depth of 3.7 m, and Tåsteröds Stora Vatten has a surface area of 0.67 km^2 and an average depth of 9.5 m. (VISS, 2024b). Raw water from the bigger lake Tåsteröds stora vatten is usually pumped into Lilla Dalevattnet via a raw water pipeline, but it is also possible to lead the water directly into the drinking water treatment plant, see figure 1.4 (M. Axelsson, personal communication, 20 March 2024). Both lakes are dammed, and the water level has been raised.

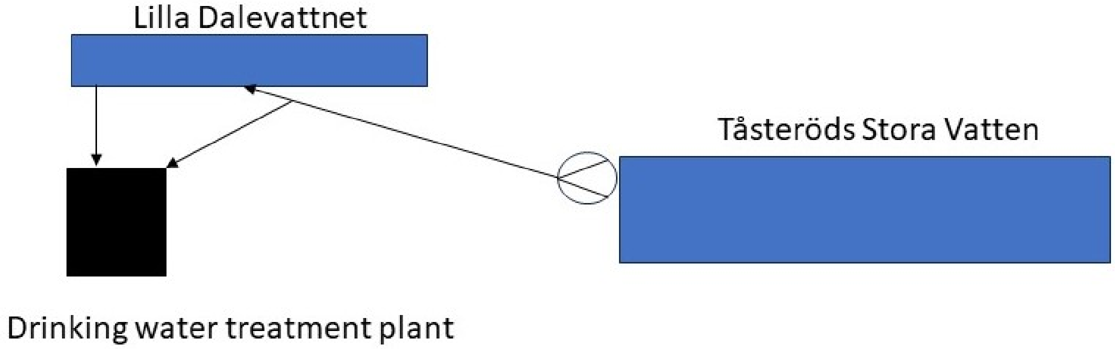


Figure 1.4: Schematic view of Sotenäs raw water supply.

Tåsteröds Stora Vatten has had extensive algal blooms several times in the last two decades. This has led to interruptions in the raw water supply from this lake during periods in the summertime (M. Axelsson, personal communication, 20 March 2024).

In 2015, plans were made to integrate bioreactors into the drinking water treatment plant processes to manage elevated algae concentrations, but the project was not implemented due to the high investment cost (M. Axelsson, personal communication, 20 March 2024). Limnological studies have been conducted annually since 2010 to monitor the algae taxa within both lakes (M. Axelsson, personal communication, 20 March 2024).

1.4.4 Sandviken

The lake Öjaren is the main raw water source for the municipality of Sandviken see figure 1.5. It has a surface area of 20 km^2 and an average depth of 3 m (VISS, 2024d). There were problems with the bad taste of the drinking water in 2016, and it was concluded that algal biomass was the reason for this (GefleDagblad, 2016).

Figure 1.5: Schematic view of Sandvikens raw water supply

2

Theory

The theory chapter covers several different areas from various disciplines. This is essential for comprehending the impact of algae cell growth in raw water sources on the drinking water supply and contemporary practices in risk management associated with this phenomenon. Algae and algae growth are described, and several species are investigated in the literature study. Due to the case study areas using fresh water as their raw water source, the theory about algae will focus on freshwater algae.

The theory chapter also delves into laws and regulations within the field, encompassing raw water control and the methods drinking water producers employ to monitor and maintain the quality of their drinking and raw water. Additionally, it addresses the implications of climate change, explaining its potential to worsen the risks associated with algae growth in raw water sources.

2.1 Drinking water supply in Sweden

Most people in Sweden are connected to municipal water supply, but approximately 15 % get their drinking water from their own private wells (SGU, 2024). Sweden generally has good access to raw water. Only a few areas suffer from water scarcity, primarily during summertime (Livsmedelsverket, 2024). Most drinking water treatment plants use groundwater sources, but in terms of produced drinking water, it is almost equally distributed between surface water and groundwater sources. There are 290 municipalities, and conditions for drinking water supply can differ a lot between them. Thus, drinking water treatment plants can be very different across the nation. Some of the bigger drinking water treatment plants produce drinking water from surface water for hundreds of thousands of people, utilizing advanced techniques. Other smaller plants produce water from groundwater for a few hundred people using simple filtration methods.

2.1.1 Regulations in Sweden

According to the law on water services, the municipalities are obliged to ensure that water supply and sewage are arranged on a broader scale, if necessary, with regard to the protection of human health or the environment (SverigesRiksdag, 2006). Thus, municipalities are responsible for constructing, planning, and operating facilities for water and wastewater treatment. There are also some private producers, but they are only a minor share of the total production (Livsmedelsverket, 2024). All drinking water producers must fulfil the quality requirements stated in the drinking water regulations (Livsmedelsverket, 2022). According to the regulations, "*Drinking water should be healthy and clean. Drinking water is considered healthy and clean if it does not contain microorganisms, parasites, and substances in such quantities or concentrations that pose a potential risk to human health.*"

There are also limits that must not be exceeded for several substances and indicator organisms included within the drinking water regulations. However, algae or algal toxins are not among these regulated substances. Nevertheless, the Swedish Food Agency has established reference values for different algal toxins in drinking water. Since drinking water should not contain substances in concentrations that pose a risk to human health, this implies that the reference values must be followed.

Drinking water producers are obliged to develop an investigation program to ensure that the quality requirements are fulfilled (Livsmedelsverket, 2022). Algae or algal toxins are not included as mandatory parameters in drinking water control programs, and none of the four case study areas has algae or algal toxins included in their control program (personal communication). Thus, there is a risk that outgoing drinking water contains toxins above the reference value without detection. The risk of this happening is considered to be low, according to staff at the drinking water treatment plant, and this is the case for all the case study areas (S. Lund, personal communication, 4 February 2024) (M. Axelsson, personal communication, 20 March 2024) (R. Kareflod, personal communication,7 February 2024) (V. Åkerlöf, personal communication, 22 March 2024) .

In the old drinking water regulations from 2001, there were no requirements for raw water control, but the Swedish Water Association, Svenskt Vatten, issued some guidelines for raw water control in 2008 (SvensktVatten, 2008). This has been corrected in the new drinking water regulations, now drinking water producers are obligated to have a control program of their raw water source (Livsmedelsverket, 2022). Even if the new regulations were implemented in 2023, obligations to do raw water control would enter into force first in 2026. The mandatory parameters for water quality sampling, as outlined in the 2008 raw water control guidelines and the 2022 drinking water regulations, do not include algae or algal toxins. Only one case study area, Sotenäs, conducts annual algae and total biomass sampling of their raw water source. This suggests that most drinking water producers have limited opportunities to monitor algae growth in their raw water sources in the short and long term. Intensive algae growth within the case study areas is typically detected through visual inspection (personal communication). Due to the limited directives and regulations regarding the control and monitoring of algae growth in raw water sources, risk management differs among various drinking water producers within Sweden. This can be observed in the four case study areas.

2.1.2 Examples from other countries

Drinking water regulations are present in most countries. For example, the Australian drinking water guidelines (ADWG) aim to protect public health and provide safe drinking water, but these guidelines are not mandatory to implement (NHMRC & NHRMMC, 2022). They are just the basis for determining the quality (Newcombe et al., 2010). The mandatory framework states that DWTP need to have a monitoring system and continuous testing of the water quality to ensure that the drinking water they provide is safe (NHMRC & NHRMMC, 2022). Testing and monitoring must be done on a regular basis so that the monitoring can provide useful information. However, algal species are not among the required parameters to be monitored.

The US Environmental Protection Agency (EPA) has developed the Public Water Systems Supervision (PWSS) program to ensure consistent quality of drinking water(EPA, 2023). The EPA, states and tribes work together under the PWSS to provide public drinking water to 90% of Americans. (EPA, 2023). The drinking water has to be monitored. However, algae or algal toxins are not included among the parameters that need to be measured (EPA, 2022). The other 10% private DWTPs are not included under the EPA and do not have to monitor or test the drinking water.

2.2 Algae

Algae can thrive in various aquatic environments, including marine and freshwater habitats and regions with varying temperatures (Hagen, 2008). They live in both aquatic and terrestrial environments. Algae are photosynthetic organisms with various reproductive processes, including asexual and sexual reproduction (Hagen, 2008). They can range in size from small cells measuring 1 µm to gigantic Kelp measuring up to 60 m (Dinabandhu & Joseph, 2015). Between 1 to 10 million different algal species are found worldwide, most of which are microalgae. Algae fossils have been discovered that date back to 2.7 billion years (Hagen, 2008). The cells in algae are microscopic and can measure between <1-10 µm (Kim et al., 2023). In Sweden, there are 1,100 existing species of macroalgae, and they are divided into six groups: cyanobacteria, brown algae, yellow-green algae, red algae, green algae and Charophyceae (Livetihavet, n.d.).

Algae play a crucial role in the ecosystem as they are the primary source of organic matter, forming the base of the food chain (Hagen, 2008). In addition, algae can contribute to the economy by being used for food, medicine, and even pollution control through bioremediation. This process involves using aerobic and anaerobic processes to degrade pollutants by algae. However, it is important to note that algae have the potential to harm other organisms by releasing toxins and causing harmful algal blooms.

2.2.1 Gonyostomum semen

Gonyostomum semen can form extensive blooms during the summers and in a humic freshwater lake with a pH <7 (Bergman et al., 2024). According to Lebret et al. (2018), *G. semen* has increased in presence and frequency and is now consisting of 95 % of the biomass of phytoplankton in lakes. The increased concentration of *G. semen* has resulted in a changed community structure and has consequences for the ecosystem functioning. *G. semen* can affect the ecosystem of lakes by creating a large and dense population, and it is considered an invasive species in Fenno-Scandinavia (Karosienė et al., 2016; Lebret et al., 2018). It has been seen that there is a correlation between an increase in *G. Semen* biomass and an increase in some environmental conditions such as temperature, lake total organic carbon, colour and iron (Hagman et al., 2020). *G. semen* often forms large biomass, which correlates with chlorophyll-a concentrations at low phosphorous levels (Hagman et al., 2015).

The *G. semen* is fragile because it does not have a robust cell wall; instead, it possesses a cell membrane (Bergman et al., 2024). Originally it was thought that *G. semen* preferred small, shallow, humic and acidic lakes, however, according to Hagman et al. (2015) it thrives in a wide range of conditions. According to Lebret et al. (2018), iron concentration in lakes has an important impact on *G. semen* where the *G. semen* is more abundant in brown water not because of carbon but rather due to the concentration of iron.

G. semen can be harmful to human health because some humans can get an allergic reaction to *G. semen's* ejection of slime threads from trichocyst (Hagman et al., 2015; Karosienė et al., 2016). *G. semen* can also interfere with the filters when treating raw water to drinking water in a drinking water treatment plant by clogging the filters (Bergman et al., 2024).

2.2.2 Chrysophyceae

Chrysophyceae or golden algae as it also is called is spread all over the world, samples have been found in every continent (Nicholls & Wujek, 2015). *Chrysophyceae* are most commonly found in freshwater, but can also be found in soil or the ocean (Bock et al., 2022). *Chrysophyceae* flourishes in so-called soft water, which has low alkalinity, conductivity, and a pH of approximately 6-7 (Nicholls & Wujek, 2015).

It reproduces by asexual reproduction. *Chrysophyceae* gather energy by photosynthesis or heterotrophy. It is a primary producer and grazer on bacteria (Bock et al., 2022). The environmental condition decides if the *chrysophyceae* can photosynthesize or not (Nemcova & Diaz-Pulido, 2023). They can absorb nutrients at low concentrations, allowing the *chrysophyceae* to dominate other algae species in a low-nutrient environment (Nicholls & Wujek, 2015). An issue with *chrysophyceae* is that it often causes the water to receive odour and taste issues (Liu et al., 2019). The odour problem that Liu et al. (2019) describes is a fishy odour from the algae.

2.2.3 Diatoms

Diatoms are among the most common phytoplankton spread in all aquatic environments (Dahiya et al., 2024). *Diatoms* live in fresh, brackish and marine water environments (Seckbach & Gordon, 2019). The cells of a Diatom are relatively thick and come in various shapes and a wide variety of sizes from about 3 μm in diameter to the size where it is visible to the eye. The *Diatoms* are microscopic eukaryotic single-celled algae, and their cell walls are built up of silica (Dahiya et al., 2024). The silica cell wall has preserved the diatoms in fossils, which today can be utilized as an indicator of previous climate and environmental conditions. *Diatoms* have their peak seasons during the early spring and late autumn, according to Aleksova et al. (2023). They have a short lifespan and are easy to sample. *Diatoms* reproduce themselves by asexual division (Seckbach & Gordon, 2019).

Diatoms' sensibility to changes in environmental conditions (organic pollution, acidification, eutrophication, temperature, pH, heavy metals, and TDS) can affect their growth biochemical composition and, therefore, they can serve as an indication for water quality (Costa & Schneck, 2022; Dahiya et al., 2024; Karosienė et al., 2016) hydrological conditions and climate variations (Costa & Schneck, 2022). *Diatoms* can cause taste odour and taste issues in drinking water; it can cause fishy odours (Liu et al., 2019). *Diatoms* can gain dominance over other algae; an example of this is when *diatoms* gain dominance over Microcystis either by artificial turbulence in the raw water source or by the *diatoms* gain an advantage in the mixed conditions (Wang et al., 2024).

2.2.4 Cyanobacteria

Cyanobacteria, commonly known as blue-green algae, is an adaptable algal species that can survive in many different climates and habitats (Dinabandhu & Joseph, 2015). *Cyanobacteria* is an oxyphotosynthesizing organism and does not have a nuclear membrane, the photosynthetic system is different from other algae (Rocha et al., 2024), they belong to the group of organisms that are called prokaryotes (Newcombe et al., 2010). The prokaryotes have a very simple structure, and the group includes bacteria. *Cyanobacteria* need sunlight to do photosynthesis and are often located at the surface (Livsmedelsverket, 2018b). According to Rocha et al. (2024), several different factors can affect the overgrowth of these organisms, such as high light, high temperature and the availability of nutrients. The peak season for blue-green algae blooming in summer, according to Aleksova et al. (2023). The *Cyanobacteria* can be both unicellular or multicellular, free-living or colonial unbranched filamentous, heterocystous or non-heterocystous, aquatic or terrestrial (Dinabandhu & Joseph, 2015).

Cyanobacteria are very adaptive to their surroundings due to their diverse capacities. Some cyanobacteria species are nitrate fixating, which means they can fix nitrogen from the air (N_2) (Annadotter, 2006). However, nitrogen fixation is an energy-requiring activity; only *Cyanobacteria* can execute it among algae. One example of nitrate fixating *Cyanobacteria* is Anabaena, which is capable of fixating nitrogen due to heterocyst cells capable of doing so (Thawabteh et al., 2023).

There are three groups of *cyanobacteria*:

1. Non-fixating of nitrogen and non-floating.
2. Non-fixating of nitrogen and floating.
3. Fixating of nitrogen and floating.

Cyanobacteria can float in the water due to the Aerotropes inside the bacteria; aerotropes are very small air bubbles (Annadotter, 2006). *Cyanobacteria* can produce hazardous toxins that can threaten the health of humans and animals. Cyanotoxins have three main groups they are classified into the groups are based on their target tissue: dermatoxins, hepatoxins and neurotoxins (Christensen & Khan, 2020). Massive growth of *Cyanobacteria* cells can increase the turbidity and affect the taste and smell of water negatively (Hagen, 2008). According to Yu et al. (2023), there is a lack of information about the trigger mechanism of blooms.

2.3 Algal toxins

Some algae species can produce toxins that can be hazardous for humans and animals. Algal toxins can be very hazardous if consumed or the body is exposed to water containing algae toxins. In the year 1996, in a village in Brazil, 60 individuals died as a result of badly treated water and algae toxins (Pouria et al., 1998). According to Livsmedelsverket (2018b), Cyanotoxins that are bound cellular in the algae can be released in the water due to some removal processes in the drinking water treatment plant if the algae cell is damaged. Some adverse effects that can result from Cyanotoxins are damage to the liver, skeleton, and the respiratory muscles becoming paralyzed. Six common toxins are presented in the sections below: Microcystin, Nodularin, Cylindrospermopsin, Saxitoxin, Anatoxin-a and Lyngbyatoxin. Table 2.1 shows the response limits for drinking water. The limit values for cyanotoxin in Sweden are decided so that an infant can consume the water for a long period without the risk of having unacceptable health risks (Livsmedelsverket, 2018b). Drinking water producers are not required to measure algal toxins levels in raw water throughout the year. However, because drinking water must be safe to ingest, they have to ensure that response limits are not exceeded. Drinking water producers sometimes test the levels of algae toxins when there is a risk of toxins in raw water (R. Kareflod, personal communication,7 February 2024). Algal cells thrive in warmer temperatures, which increases the risk throughout the summer (Vu et al., 2020).

Table 2.1: Response limits for drinking water in Sweden from Livsmedelsverket (2018b).

Toxine	Response limit [$\mu g/l$]
Anatoxin-a	1
Cylindrospermopsin	1
Microcystin	1
Nodularin	1
Saxitoxin	3

2.3.1 Anatoxin-a

Anatoxin-a is a cyanotoxin and is in the group neurotoxin (Christensen & Khan, 2020). Anatoxin-a was previously referred to as the Very Fast Death Factor because it could kill mice in 2-5 minutes (Christensen & Khan, 2020; Thawabteh et al., 2023). According to Christensen and Khan (2020), anatoxin-a has a large animal mortality and can cause death in minutes. Anatoxin-a has been studied in mostly marine environments but is a bit understudied in freshwater environments.

2.3.2 Cylindrospermopsin

Cylindrospermopsin is one of the most common algal toxins globally and can be created by various forms of cyanobacteria species including Cylindrospermopsis and Lyngbya (Kinnear, 2010). Cylindrospermopsin is named after the species Cylindrospermopsis which despite being filamentous creatures, can form deep and large blooms that can extend several meters below the surface (Thawabteh et al., 2023).

2.3.3 Lyngbyatoxin

Lyngbyatoxin has been found in both tropic, subtropic and temperated zones (Rzymski & Poniedziałek, 2012). Lyngbyatoxins pose a significant issue due to their tendency to accumulate within the tissues of aquatic organisms, which subsequently serve as a food source. Lyngbyatoxin can cause skin cancer but often results in skin irritation when the skin is exposed to water containing the toxin.

2.3.4 Microcystin

Microcystis is a common genus among Cyanobacteria living in freshwater where several of the species are capable of producing Microcystin (MCs) (Mohan et al., 2023), MCs is a hepatoxin. Microcystis is mostly found in freshwater bodies with a stable, eutrophic and warm environment (Mohan et al., 2023). Some factors that affect the abundance of MCs are a stable water column, high temperature, nutrient availability and pH. Microcystis can form large colonies when an increase in algae cell growth happens. The fine particles can last up to several millimetres (Wang et al., 2024). Microcystis life is divided into two cycles: The Benthic phase and The Planktonic phase. The toxin MCs are released when the Microcystis cell is broken, and the toxin is soluble in water. MCs are very stable and hard to remove from water due to their ability to resist hours in boiling water and a wide pH range.

According to the book Hagen (2008), MCs have caused fish deaths and deaths of domestic animals. It has been reported that MCs have resulted in a high local incidence of liver cancer in China. Except for the cause of liver cancer, MCs can also cause genotoxic and cytotoxic effects.

2.3.5 Nodularin

Nodularin is a cytotoxin with the algal toxic group cyclic peptides (Dong et al., 2023). They have a stable structure, which makes them persistent in the aquatic environment. Nodularin harm the liver by inhibiting a protein phosphate, which causes proteins to accumulate in liver cells (Thawabteh et al., 2023). Nodularin and Mycrocetin have a very similar structure (Martinez i Quer et al., 2024).

2.3.6 Saxitoxin

Saxitoxin is a Cyanotoxin in the Neurotoxins group (Christensen & Khan, 2020). Saxitoxins are commonly called paralytic shellfish toxins (Guinle et al., 2023). Saxitoxin affects humans' and animals' muscular, myalgia and respiratory systems. Consuming the toxin can lead to paralysis (WHO, 2017). The Saxitoxin is released when algae are blooming. Saxitoxin can be paralysing due to the ion channels inside the cell membrane and then changing the function of the muscle. Saxitoxin blocking the Na^+ channels. The Saxitoxin has been studied mostly in marine environments but is understudied in freshwater environments (Christensen & Khan, 2020).

2.4 Water quality parameters

Drinking water treatment plants are required to regularly sample the water they produce to ensure it meets the drinking water standards (Livsmedelsverket, 2022). The new drinking water regulations, implemented in 2023, include a requirement for raw water control. Regular sampling of raw water can help identify seasonal variations common in surface water and provide important information for designing effective treatment processes tailored to the specific raw water source. Raw water samples can also offer insights into the microbiological activity and indicate conditions conducive to algal growth. Algae growth depends on complex combinations of numerous parameters, although certain factors are particularly crucial when evaluating the conditions for algal growth in surface water. Some parameters do not contribute to an algal bloom, but changes in these parameters can indicate intensive algae growth. This section will describe both contributing parameters and those that may serve as indicators.

Algae can cause an issue in drinking water production due to obstruction of filters (Yu et al., 2023). It can be challenging to remove algae, so the primary methods include coagulation, flotation, ultrafiltration, and active carbon. Removing the algal cells can be hard due to their small size and low specific gravity(Hagen, 2008), removing the dissolved algal toxins is even harder (Yu et al., 2023).

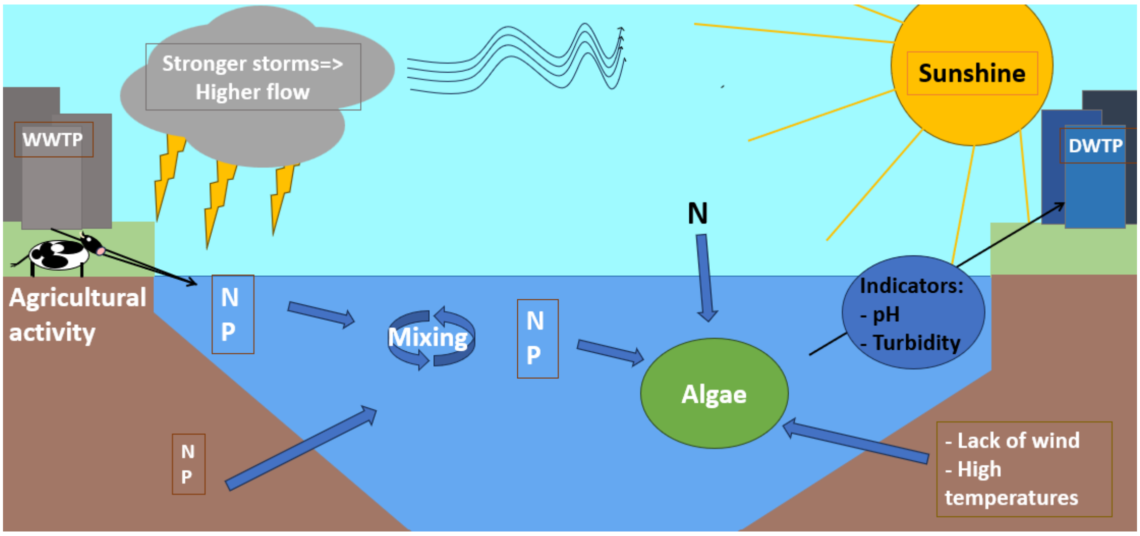
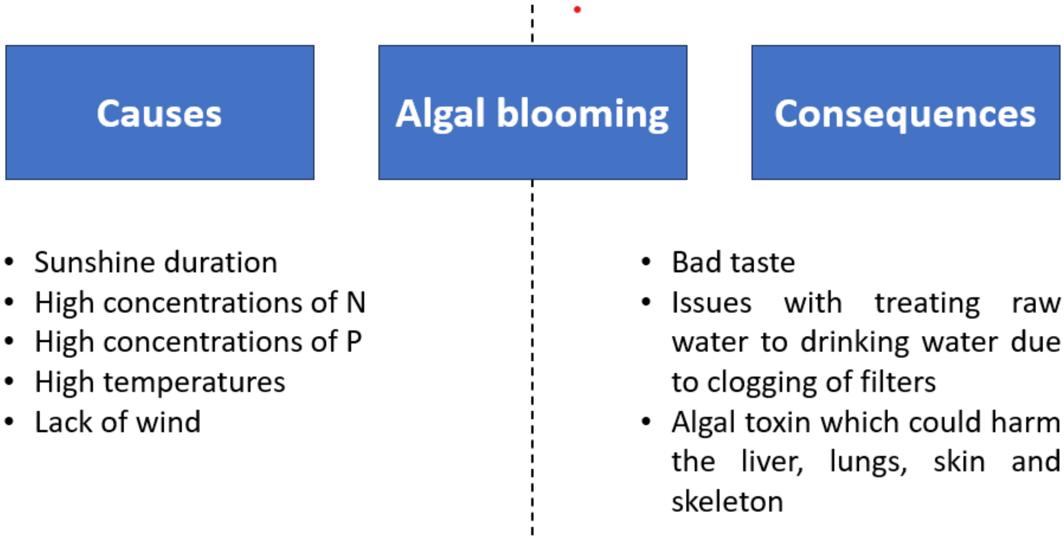


Figure 2.1: Different parameters that could affect the growth of algal cells.

Several parameters, as phosphorus and high temperatures in the water, can influence algal cell growth. The phosphorous can come from various sources, including insufficient sewage systems resulting in nutrient leakage, pipe overflow or leakage from agricultural areas such as animal faeces or fertilisers. Figure 2.1 summarises the factors that contribute to increased algal growth. Figure 2.2 summarises these factors but also includes the consequences of increased algal cell growth.



- Sunshine duration
- High concentrations of N
- High concentrations of P
- High temperatures
- Lack of wind

- Bad taste
- Issues with treating raw water to drinking water due to clogging of filters
- Algal toxin which could harm the liver, lungs, skin and skeleton

Figure 2.2: The causes of increased growth of algal cells and their consequences.

2.4.1 Water temperature

Water temperature is one of the most important factors for algal growth and also affects which species will thrive (Vu et al., 2020). A study conducted by Bhatti et al.

(2024) indicated that an increase in the duration of time with water temperatures above 20°C (from 2060 hours in 2022 to 2281 hours in 2060) would extend the duration of cyanobacteria blooms in the central area of Fairy Lake (located in Ontario, Canada) by 10.7 %. The study conducted by Piontek et al. (2023) showed that there is a strong correlation between cyanobacterial volume and water temperature in Rudno Lake (Poland).

2.4.2 Phosphorus

All algae need phosphorus and nitrogen for growth, and phosphorus is recognized as the most common limiting factor for algae growth in surface waters, this has been shown in numerous studies including Chapra (1980). Some algae species can fixate nitrogen from the atmosphere, phosphorus must be present in the water. To prevent eutrophication in surface waters, removing phosphorus sources is generally more effective than removing nitrogen sources (Schindler et al., 2008). Thus, Total-P is a crucial parameter to follow in monitoring programs that predict algae biovolume in aquatic environments (Håkanson et al., 2007). Total phosphorus concentration should not exceed 0,02 mg/l in raw water sources to prevent algal blooms (Livsmedelsverket, 2018b). Phosphorus loading from land into streams and lakes are expected to increase in northern temperate coastal regions due to increased precipitation during winter time (Jeppesen et al., 2009).

Phosphorus can be stored in the lake sediment for many years, and low oxygen levels from eutrophication can release the stored phosphorus into the water, making it available to the algal cells (Sellergren et al., 2023). This process is called internal loading and can cause issues as it is not enough to stop nutrient loading from other sources (streams, sewage overflow) to solve the issue of eutrophication in the lake. The growth of algae cells is positively correlated with total phosphorus (TP) levels according to Elhabashy et al. (2023).

2.4.3 Nitrogen

Nitrogen is also crucial for algae growth. However, some algal species can fixate nitrate from the atmosphere. Thus, phosphorus has, for a long time, been the primary target for preventing eutrophication in surface water. However, new studies have shown that nitrogen mitigation is also important to improve water quality in lakes (Paerl et al., 2016). The access to nitrogen in the water also affects which algae species will thrive and proliferate (Smyth et al., 2022).

Nitrogen can be present in several different forms in surface waters. Some common forms are nitrate (NO_3), nitrite (NO_2), ammonia (NH_3), and nitrogen bound to organic matter.

2.4.4 pH

A study conducted by Zepernick et al. (2021) showed that the pH levels in Lake Erie affected the diatoms' growth rate and influenced the lake's algae taxa. The pH levels in freshwater are correlated with the concentration of CO_2 in the water. Photosynthetic algae, such as cyanobacteria, consume free carbon dioxide during the photosynthetic process. Thus, intensive algal blooms have the potential to elevate the pH significantly to above 10 near the surface (Paerl & Paul, 2012). Elevation in pH levels can be a strong indicator of intensive algae growth in surface water, and there are warning systems that use pH levels as early warning for cyanobacteria blooms.

2.4.5 Chlorophyll-a

Phytoplankton such as cyanobacteria contain chlorophyll-a, which is used in photosynthesis, the process by which energy is absorbed from light. The chlorophyll-a concentrations in freshwater can indicate the amount of algal biomass in the water. Since measuring chlorophyll-a is easier compared to measuring algal biomass directly, chlorophyll-a is suitable to use as an indicator of algal biomass (Boyer et al., 2009). The content of chlorophyll-a in the algal cells varies between different algal species, and this variation affects the accuracy when predicting algal biomass based on chlorophyll-a concentrations. There are different methods to measure chlorophyll-a, including spectrophotometry, hyperspectral and multispectral imaging (Basak et al., 2021).

2.5 Risk management

Risk management is a systematic process that involves identifying, assessing, and prioritizing risks, followed by deciding how to minimize, monitor, and control the probability or impact of unfortunate events. In the context of drinking water production, effective risk management is critical to ensure the safety and quality of water delivered to consumers. The following chapter describes the general principles of risk management framework and the application of risk management in the context of drinking water production.

2.5.1 Risk management framework

The definition of risk includes the probability and the severity; it is a combination of probability and consequence of an event (Aven, 2010). In a risk analysis, the risk sources/hazards, pathways and possible barrier(s) should be identified in relation to the risk receptor(s), as shown in Figure 2.3. There exists a number of decision support and risk assessment methods. To take a decision, there is a few steps before the decision can be made, first, the starting point is to define the decision problem (Aven, 2003). The decision problem is typically defined as the task of choosing between different sets of defined decision alternatives, which often are defined by experts and managers. It is important to involve all the stakeholders. When the decision alternatives are defined, a risk analysis of each option is conducted. According to (Lindhe, 2010), a risk analysis should identify if any risks could be considered unacceptable. If unacceptable risks have been identified, the next step should be identifying and analysing risk-reduction measures. The risk reduction measures, as can be seen in

Figure 2.3, are referred to as barriers. The barriers are used to decrease the consequences and/or prevent the event from occurring (Aven, 2003). Analyzing barrier performance is important due to uncertainties regarding their effectiveness and the potential consequences if they fail (Aven, 2020). When the risk-reducing measures are analysed and evaluated, a review of the result by stakeholders and experts is conducted. The results are used as a base for the decision maker to decide if and what action should be taken. There are different ways to evaluate risk reducing measures. One approach is the Cost-Effectiveness Analysis (CEA), which is particularly useful when there is a clearly defined outcome, such as achieving a specific target or limit value. CEA helps identify the most cost-efficient measure to reach the specified goal, ensuring the desired result is achieved at the lowest possible cost (Dawoud & Baines, 2017). Another approach to evaluate risk-reducing measures is to perform a cost-benefit analysis to compare the benefit from measures with the cost for implementation (Aven, 2020).

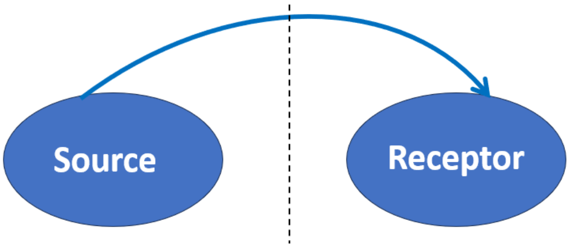


Figure 2.3: The Hazard goes via pathways through some potential barrier to reach the recipient. In this figure, the barrier is symbolised with a dashed line, and the pathway is symbolised by the arrow.

One common practice in risk evaluation is the As Low As Reasonable Possible (ALARP) approach (Melchers, 2001). The ALARP concept aims to guide regulatory decisions by balancing reason and practicality, bridging technological and social risk views, and involving society in decision-making. According to the ALARP principle, the risk can either be acceptable, unacceptable, or within the so-called ALARP region. If the risk is unacceptable, risk-reducing measures are required, and if it is within the ALARP region, measures may be needed, but they are not necessarily deemed reasonable given, for example, technical and economic conditions (Lindhe, 2010). The ALARP- area is the region between unacceptable and acceptable risks. In this zone, the balancing of costs and benefits of implementing risk-reducing measures is particularly important. Risk-reducing measures could be divided into three different types. One type lowers the consequences if the risk event happens, another type lowers the probability for the event to happen, and the third type is a combination of both. To be able to place the risk in the ALARP matrix, evaluations of both the severity of consequences and the probability that the risk events happen are needed. Natural systems (such as algal blooms) are difficult to model in a risk model, unlike a "closed" system all the components are not known and there are uncertainties in the systems (Melchers, 2001). It is not possible to fully verify and validate a numerical model of natural systems (Oreskes et al., 1994).

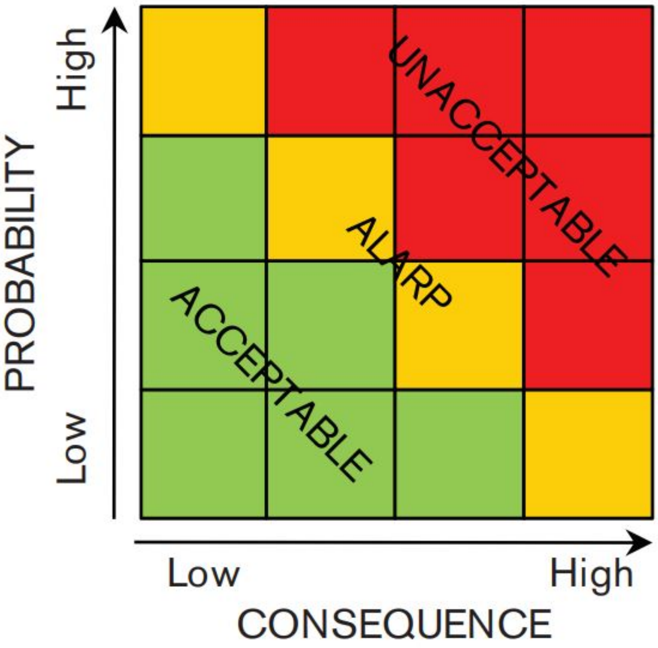


Figure 2.4: Matrix illustrating ALARP-principle (Lindhe, 2010). Green represents acceptable risks, yellow represents ALARP, and red represents unacceptable risks.

In every risk assessment, uncertainty exists in the data being used, and the uncertainties should be identified as part of an uncertainty analysis. The uncertainty analysis is used to identify the uncertainties related to the results and the uncertainties derived from the method and inputs (Aven et al., 2014). Aven et al. (2014) describes two types of uncertainties: epistemic and aleatory; the aleatory refers to natural variation in a population, and the epistemic refers to a lack of knowledge about a phenomenon. The epistemic uncertainty can be described as the uncertainty of the parameters in a mode. Aleatoric uncertainties cannot be reduced because they are random and beyond human control. In contrast, epistemic uncertainties can be reduced through better data collection.

2.5.2 Risk assessment within drinking water production

Several things can go wrong within drinking water production, e.g. water sources can become contaminated and steps in the water treatment plant can fail. Generally, hazards can be present in the water distribution system, the DWTP, or the raw water source. A risk analysis can be helpful in assessing the risk of an event caused by increased algal cell growth in a raw water source. It may also be necessary to evaluate if any actions needs to be taken.

Sweden's Hazard Analysis and Critical Control Points (HACCP) method identifies and manages risks and hazards in drinking water and food production (Livsmedelsverket, 2023). Drinking water producers are obliged to establish a internal control program based on the HACCP-principles (Livsmedelsverket, 2022). Following steps are included in the HACCP-principle:

1. Identify the hazards
2. Identify Critical Control Point
3. Determine the critical limit
4. Monitor critical control points
5. Determine corrective actions
6. Verify that the measures are working effectively
7. Documentation and records

The seven steps are developed to ensure safe drinking water is available and continuously provided without any delivery disruption. An example of this can be the increased growth of algal cells. However, this isn't the only threat to the delivery of safe drinking water. In addition to the HACCP, the concept of Water Safety Plan (WSP) is recommended by the World Health organisation (WHO) (Livsmedelsverket, 2018a) exists. WSP is built on the HACCP method, but in addition, it has some other areas included (Livsmedelsverket, 2007).

In Australia, they have also implemented the HACCP method into their guidelines to use a systematic method to identify the risks of hazards and prevent them (NHMRC & NHRMMC, 2022). According to NHMRC and NHRMMC (2022), the greatest risk towards consumers is the pathogenic microbial risk. The method they use and the guidelines they have are similar to those in Sweden.

2.6 Climate change

Climate change is causing more frequent and intense weather events, such as storms, heat waves, floods, droughts, and wildfires (WHO, 2023). In 2015, the Paris agreement stated that the global average should not exceed a rise above 2°C over the pre-industrial temperature while aiming for the more ambitious 1.5°C (Barcikowska et al., 2018). Since the pre-industrial era, which is between 1850 and 1900, the Earth's temperature has increased by around 1°C. (Fernando et al., 2018). This has affected the hydrological cycle in various ways (Schimanke et al., 2022). The affected hydrological cycle resulting in changed precipitation conditions, less snow in many places and a rising sea level (Schimanke et al., 2022). The changes in the climate are regional and local and are not the same everywhere; some land regions experience a much larger temperature change than the ocean regions (Fernando et al., 2018). Many humans have as a result started to become affected by the changed climate, and for others, the more visible changes are still in the future (Schimanke et al., 2022; WHO, 2023).

The average temperature in Sweden rose by 1.2°C from 1991 to 2020 compared to the temperatures from 1961 to 1990 (Schimanke et al., 2022). This increase in temperature is most noticeable during the winter season. Due to the increase in temperature, the vegetation season has also become longer, approximately two weeks in Götaland and one week in Norrland. The occurrence of extreme temperatures has also changed, with extremely high temperatures becoming more frequent than extremely low temperatures. Compared to the end of the 19th century, the annual mean temperature in Sweden is twice as large as the world's annual mean temperature rise. According to Schimanke et al. (2022), the higher temperatures are also linked to the observed decrease in snow in Sweden.

In Sweden, the winter will have more westerly winds with warm air from the Atlantic Ocean. According to Schimanke et al. (2022), this is a consequence of increased carbon dioxide emissions. It can be seen that, locally, some weather stations have higher aerosol particle values, which negatively affects the climate. The aerosol particles block the sun from shining through the aerosol layer, and today, when the emissions are lower, this results in more sun coming through and warming up the planet.

The precipitation has increased in Sweden from the yearly average for Sweden to be 600 mm/year in the 1930:s to almost 700 mm/year in 2020 (Schimanke et al., 2022). According to Barcikowska et al. (2018), the precipitation continues increasing with the global average temperature. Due to the change in precipitation that has happened already, the flow patterns in rivers have changed (Schimanke et al., 2022). The number of days with low flows will increase in the southern parts of Sweden and decrease in the northern part of Sweden (Klimatanpassning, 2024). The reduction in the frequency of low-flow days in the northern regions of Sweden can be linked to the mild winters with less snow. However, the rise in temperature can result in warming water bodies, leading to a decrease in oxygen levels at the bottom. (Havsmiljoinstitutet, 2024). Conversely, the southern parts of Sweden face the risk of increased precipitation, causing a transfer of nutrients such as phosphorous and nitrogen from the fields and soil to the water bodies, thereby increasing the nutrient concentration in the water.

2.7 Algal bloom prediction and detection

Several methods have been used to detect and prevent a massive accumulation of algae in surface water and marine environments as Zahir et al. (2024) mentions. The possibility to predict and give early warnings can be an important step to mitigate the effects of an algal bloom. A common method in Sweden today is a visual inspection by personnel at the drinking water treatment plants to see if there are any signs (coloured water, etc.) of massive algae growth ((R. Kareflod, personal communication,7 February 2024)). This simple and limited method is insufficient to give an early warning.

There are existing water quality models for predicting algae growth, such as the QUAL2E by the U.S. Environmental Protection Agency (EPA) (Yang et al., 2000). These models can simulate interactions among water quality variables and how these affect chlorophyll-a levels, which are strongly correlated to algae levels. However, these models are expensive to build and operate, and extensive data for various parameters are needed to predict chlorophyll-a levels accurately (Lee & Lee, 2018). Thus, introducing deep learning models has enhanced the possibility of predicting algal blooms. In a study conducted by Yussof et al. (2021), a Long short-term memory model (LSTM-model) was used to predict algal blooms on the Malaysian west coast. The conclusion was that the ability to capture long temporal dependencies makes the model suitable for the prediction of algae growth. One limitation of the LSTM model is that it is better suited for small weight initialisation and is prone to overfitting. It has been difficult to identify the species of the HAB.

According to Wu and Xu (2011), the variation of algae has a close relationship with algal cell density. The model Wu and Xu (2011) suggests is an Environmental Fluid Dynamics Code (EFDC) model. The model can predict the chlorophyll-a trend, which can then be used to predict if an increased growth of algae cells will happen. However, an issue with this prediction is that several different factors can cause increased growth of algae cells, and the model is very simplified. The depth, wind and growth rate are considered to be constant, but in reality, they are factors that fluctuate.

Another method to determine the availability of algal species is to use biological indicators. Biological indicators are when plants, microbes, animals or other living organisms are used to monitor environmental changes (Azzazy, 2020). According to López-López and Sedeño-Díaz (2015) research, early warning indicators for climate change can take the form of specific species or parameters that are exceptionally responsive to environmental shifts. These indicators must be able to identify changes before they occur and cause any harm to the ecosystem. A strategy used in South Korea to detect algae blooms is to use an algal warning system and water quality forecast system, the systems are based on the concentration of harmful blue-green algal cells and Chlorophyll-a (Kim et al., 2023). The water samples are taken once or twice weekly and then sent to a lab. The issue with this strategy is that the results can take up to weeks to receive back, and this causes an issue of reacting immediately when the algal blooming occurs. A suggestion in the research from López-López and Sedeño-Díaz (2015) is to use microalgae and their toxins in the form of fish to detect algae in the ocean. Application of this method is difficult due to determining an early warning signal of algal bloom. The study is mainly applied to determine the aquatic ecosystems' health short term and long term and the abundance of algal species. López-López and Sedeño-Díaz (2015) mentions two possible application forms, the most common is the taxonomic approach and the second is the functional approach. When the functional approach is used, the fish's behaviour is studied to see if there are any changes, and it is the most useful in the detection of algae.

3

Methodology

The projects methodology is based on several steps, including a literature study, data collection, interviews, and data analysis. Overall, the phases in this project can be seen in figure 3.13.1.

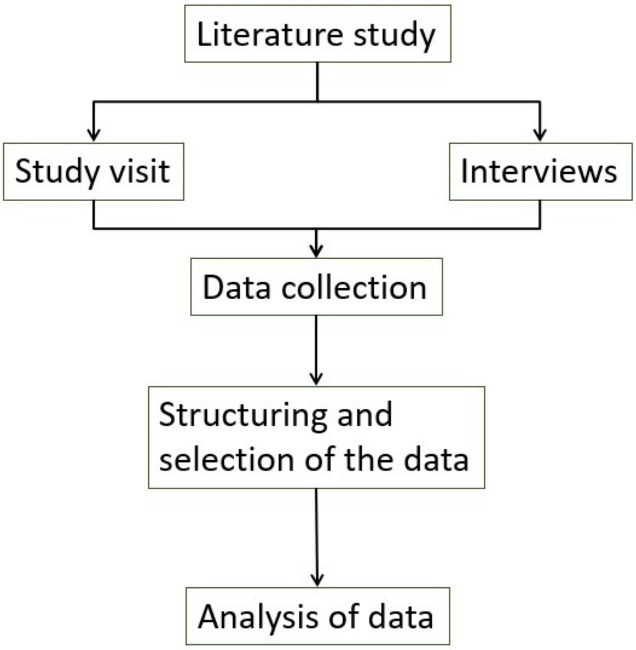


Figure 3.1: Flowchart over the methodology.

3.1 Literature study

A literature study was conducted to investigate relevant topics for the report. Four questions were formulated to simplify the literature study and obtain the necessary information more efficiently. The stated questions were:

1. Which harmful algae exist in Sweden, what toxins do they produce, and what are the issues with them and their toxin?
2. Are there other algae, non-harmful, that can cause an issue for the raw water source and the drinking water production?
3. What parameters enable the algae to flourish in the raw water source?

4. How could the risk be evaluated for a raw water source, and what parameters are needed?

During the literature study, both grey literature and bibliographic sources were utilized. Grey literature refers to literature that is not published through traditional publishing and distribution channels. To conduct the strategic literature study, the Scopus database was used. A strategic literature search was performed in the Scopus database to gain an understanding of the subject of algae and the increased growth of algal cells. The strategic search was done by combining keywords with Boolean operators (as shown in Table 3.1) to obtain a result with several papers. If the result contained below 500, the title was read and evaluated to see if it seemed relevant and worth further consideration. The selected papers' abstracts were then read, and if the paper still seemed relevant, it was read; otherwise, it was not selected.

Table 3.1: The strategic literature search.

Database	Search string	Limits	Number of records	Number of used records	number of excluded
Scopus	"algal" OR "algae" AND "risk assessment" OR "risk analysis" OR "risk" AND "algal blooming" OR "algae blooming" OR " massive growth of biomass"	-	23	9	14
Scopus	"biological indicators" AND "algae" OR "algal blooming" OR "algae blooms" OR "algal"	language: English, Document type: Book or article	216	17	199
Scopus	"climate change" AND "impact" AND "Sweden" AND "water"	-	160	5	155

In cases where the strategic literature search was not utilized, the objective of the literature searches was to gather targeted information, such as details regarding

MCs. Various databases, such as Google, Scopus, Chalmers Library, Google Scholar and Web of Science, were searched to gain information when the strategic literature search was not used. Keywords were used to simplify the search process, with the keywords often being synonyms. The search was conducted in English and Swedish to obtain more sources. Below is a list of some of the keywords that were utilized during the search.

- Algae
- Algal bloom
- Anatoxin-a
- Bacillariophyceae
- Biological indicators
- Blue-green algae
- Chrysophyceae
- Climate change
- Cyanobacteria
- Cyanotoxins
- Cylindrospermopsin
- Diatom
- Drinking water
- Freshwater
- Gonyostomum semen
- Lyngbyatoxin
- Nodularin
- Risk
- Saxitoxin

The keywords were combined into different combinations to a search string used on the selected bibliographic sources.

3.2 Data collection

Data was collected from four different municipalities, Tjörn, Lerum, Sotenäs, and Sandviken, and the data consisted of interviews and raw water data. The water parameters were collected from raw water data and limnological studies. Personal contact with the officials of the municipalities was required to collect the data, as none of the required information was available publicly. An extra study visit was made to one of the locations to receive all the information needed to look at their archive. Sandviken was never visited, and the interview was conducted online.

3.2.1 Interviews

To better understand how the environment surrounding each raw water could affect the water quality, study visits were conducted in three of the four case study locations: Sotenäs, Tjörn, and Lerum. The study visits involved conducting interviews with drinking water treatment plant employees and administrators to learn about their experiences with HABs and possible strategies for managing the algae. As for

Sandviken, which was not visited in person, a video call was arranged to perform the interview. The interviews and study visits were also a source for the data collection.

An interview template was created to simplify the interviewing process. The question was decided based on the aim, the gaps identified in the data and discussions with the supervisors for the master thesis. The template contained the following questions:

1. How does drinking water preparation work throughout the year? How is your raw water quality affected by weather conditions, rainfall, ice melting, etc.?
2. Have you had problems with raw water quality? What problems do you experience?
3. Recurring problems? At what interval and when during the year?
4. How do you deal with raw water quality problems? What measures do you take in case of quality problems? Do you have a reserve water source?
5. Have you had to close a raw water source due to quality problems? Which problems? Has this been a recurring problem, and when was the last time this happened? Have you documented when you have not used the raw water source?
6. Do you have problems with the impact on the odour/taste of raw water/drinking water? Recurring problems? What has caused it? How does it smell? Is this something you can manage, or does it affect the consumer?
7. What are your thoughts on algal toxins? Is it something you discuss within your organization? What risks do you see with toxins in the raw water supply?
8. Have you had problems with drinking water quality due to the presence of algal toxins in any of your raw water sources? Which problems?
9. What sampling and monitoring methods do you apply in your raw water sources? Do you take samples to follow the total biomass in the raw water source? Monitoring to detect algal blooms? (Limnological survey)
10. What do you think are the main risk factors for making your raw water source unusable?
11. What are you doing to prevent the risks of raw water quality problems? Are you doing anything to prevent the risk of algal blooms in your raw water sources? Specific measures? Short-term or long-term?
12. How do you deal with a situation where you get algal toxins in your raw water supply? And how do you detect that you have algal toxins in the raw water?
13. Are your treatment processes specifically adapted to deal with algal toxins or high levels of algae in the raw water, and how?

3.2.2 Data selection and analysis

Raw water data have been collected from the four different case study areas. Available and collected data differ among the case study areas. Lerum had the longest historical record of raw water data, dating back to 1974. This allowed a trend analysis of various raw water parameters over an extended period. However, the Sotenäs case study area was considered the most favourable for analysis. This was because recurring limnological studies had been conducted annually since 2010. This enabled investigation into potential correlations between certain parameters and algal growth, including the quantity of algae and the species that proliferate. Thus, the statistical analyses focused on the case study area Sotenäs. The selection of the most relevant parameters for the study was determined based on the literature study and interviews with the four municipalities. The findings revealed that the most important parameters can be categorized into two types of data: weather-based factors such as air temperature, sunshine, and precipitation, and water quality parameters such as the availability of nutrients (phosphorus and nitrogen) in the water, water temperature, pH, and turbidity. Raw water data availability varies significantly between the case study areas and also across different time periods. In some years, extensive measures have been conducted with numerous parameters, while in some years, simple sampling with few parameters has been made. The following parameters were chosen for analysis to streamline the study.

Water quality parameters:

- Water temperature
- pH
- Total phosphorus
- Color
- Total biomass (only Sotenäs)
- Nitrogen
- Volume of cyanobacteria (only Sotenäs)

Weather data:

- Air temperature (monthly average)
- Air temperature, minimum and maximum (daily)
- Sunshine duration (hourly)
- Precipitation (monthly)

The weather data was collected from SMHI (Swedish Meteorological and Hydrological Institute). Due to local weather, the original plan was to gather weather data from each case study area because for example it can rain in a small area and impact the water quality. Still, it might not rain where the weather station is situated. However, this was not feasible, so the nearest available weather station and its data had to be used instead. Unfortunately, the data collection process at each weather station vary. While some stations have recorded data daily since the 17th century, others have only been doing so for a few years. Data from various weather stations was utilized to ensure a continuous time series without gaps to mitigate this issue.

The weather stations used for Sotenäs:

- Hållö (Temperature monthly average during summer, temperature maximum and minimum during a day, precipitation monthly average)
- Sotenäs (Temperature monthly average during summer, temperature maximum and minimum during a day, precipitation monthly average)

- Måseskär (Temperature monthly average during summer, temperature maximum and minimum during a day, precipitation monthly average)

The weather stations used for Sandviken:

- Gästrike-Hammarby 4 (Temperature monthly average, precipitation monthly average)
- Gävle (Temperature monthly average, temperature maximum and minimum during a day)
- Sandviken (Temperature monthly average)
- Gästrike-Hammarby D (precipitation monthly average)

The weather stations used for Lerum:

- Göteborg-Landvetter Flygplats (Temperature monthly average, precipitation, temperature maximum and minimum during a day)
- Bollebygd (Temperature monthly average, precipitation, temperature maximum and minimum during a day)

The weather stations used for Tjörn:

- Säby (Temperature monthly average, precipitation monthly average)
- Säve (Temperature monthly average, temperature maximum and minimum during a day)
- Säve-Skålvisered (Temperature maximum and minimum during a day)
- Rörastrand (Temperature monthly average, temperature maximum and minimum during a day, precipitation monthly average)

All case study areas have experienced at least one year of a confirmed algal bloom. The selected parameters are analyzed and compared with years with registered algal blooms and those without them to investigate whether any parameters stand out. The objective is to identify the most significant parameters and the pre-conditions for algal blooms. There are other parameters that are relevant for the study, particularly water quality parameters like chlorophyll-a and turbidity. However, these were not included due to insufficient available data in the collected raw water data.

4

Results

In this chapter the results are presented for each case study, including weather data, interviews, and raw water data.

4.1 Interviews

This section summarizes the answers from the different municipalities. All municipalities were asked the same questions, these are presented chapter 3 in section 3.2.1. In addition to the pre-defeined question, additionalrelevent information was compiled and are presented below.

4.1.1 Sotenäs

According to the staff on the DWTP, their raw water quality is influenced by weather conditions like heavy rainfall and snow melt. The primary issues include high levels of manganese and increased coloration during intense rain. In response to these challenges, the drinking water treatment plant switches between the two lakes used as raw water sources. They can also adjusts intake depths. They have had to close water intakes due to algae blooms and high manganese levels, with the most recent closure happening last summer. Consumers have sometimes reported complaints about a swamp-like odour in the drinking water during summertime. Algal toxins are a concern for the personnel, and there are discussions within the organization about potential health risks. While no problems with high algal toxin levels have been reported yet, issues with taste have occurred due to golden algae. Monitoring methods include lab tests, sampling from different depths, and visual inspection with a camera. According to staff at the drinking water treatment plant, the main factors contributing to algal blooms are primarily temperature and nutrient input from agriculture. To mitigate risks, the organization is focusing on wetlands management, planning larger wetlands, and collaborating with landowners upstream of the lakes. When an algal bloom is visually detected, water intake is closed. Luckily, this has only happened in Tåsteröds Stora Vatten and not Lilla Dalevatten. Treatment processes are not specifically designed to handle algal toxins, posing a potential risk if there is a significant algal bloom in both lakes simultaneously.

4.1.2 Lerum

According to Lerum, they have a stable raw water quality throughout the year, with minor impacts from weather like heavy rainfalls. Quality issues primarily occur in

Stora Stamsjön during summer, probably due to high temperatures. They have not faced significant raw water quality problems, although there were historical issues in Stora Stamsjön during the 1970s-80s after lime was added to the lake. Only one raw water intake closure has occurred due to quality issues in Öxsjön (water scarcity combined with an algal bloom in 2018). During the closure, raw water was provided only from Stora Stamsjön. The DWTP typically uses a blend from both lakes. Occasionally, complaints about the odour and taste of produced drinking water are reported. Typically, this is due to changes in the distribution network or problems with the treatment processes. Taste is then often described as something that suggestive of moss or soil. Algal toxins are not a major concern, with only isolated cases of algal blooms in the two lakes historically, but the uncertainty regarding climate changes can increase the risks in the future. No problems due to algal toxins have been reported. Monitoring follows national guidelines, but specific monitoring for algal blooms is not conducted. Lerum thinks climate change is the primary risk factor for issues with raw water quality. The established water protection areas are preventive measures to protect the raw water sources. Algal toxins are only analysed when bloom signs appear, yet no toxins have been found so far. Treatment processes are not specifically designed for algal toxins, although existing carbon filters may capture some.

4.1.3 Sandviken

Raw water quality in Öjaren is affected by weather conditions. There are often problems with high turbidity after heavy rainfall or windy conditions. Additionally, recurrent raw water quality issues occur every spring and autumn during lake turnover. These problems can lead to high water usage in the drinking water treatment process, mainly due to increased filter flushing. They also have some groundwater, and during periods of lower quality in the lake, they can increase the share of groundwater. During the summer of 2016, there was a disturbance in the taste and odor of the produced drinking water; the reason for this was increased algae growth (probably G.semen). Surprisingly, there were no significant disturbances during the very warm summer of 2018. There is no active effort to prevent algal blooms, but the municipality conducts some upstream work to remove individual drains and connect houses to municipal water treatment, aiming to reduce nutrient supply into the lake. There are no recurrent limnological investigations, but one was conducted in 2022 to gain a better understanding of the algae taxa within the lake. Visual inspection is increased during summertime to detect algae growth. The staff at the DWTP believes that rising temperatures (due to climate change) pose the biggest threat to the future raw water quality in Lake Öjaren. In 2024, a new DWTP was opened. According to the staff, this facility is better equipped to handle raw water quality issues, including algae growth in the lake. Disturbances in taste and odor are managed through the use of bio-reactors in the treatment processes.

4.1.4 Tjörn

Raw water quality is usually good, but there are some problems with high turbidity after heavy rain or windy conditions. Flocculation in the treatment process is more challenging during winter (due to lower water temperature). There have been recurrent problems with algae growth in Tolleby tjärn and Olsby damm. Because of this and other microbial impacts on the water, water is typically not pumped from Olsby damm during summertime. There were more often complaints regarding the taste of the drinking water, but these have reduced significantly since bioreactors were implemented in the treatment train. Raw water sampling is conducted every quarter of the year, though there is no sampling of biomass, algae taxa or algal toxins. pH and temperature are sampled daily. The staff at the DWTP are aware of the risk of algal blooms, but visual inspection is the only method used to detect them. If a bloom occurs, they believe that the DWTP can remove both algal cells and algal toxins, but it is difficult to be certain. According to them, climate change is probably the biggest threat to their raw water quality.

4.1.5 HACCP

This section describes how the municipalities works according to the HACCP-method regarding risks from algae growth in their raw water sources. The HACCP-method is described in Chapter 2.3. In Table 4.1, the responses obtained from interviewing the four case study areas have been used to determine whether each municipality implements every step in the HACCP method for dealing with algae. It can be seen that Sotenäs is working on most of the seven steps in HACCP, but the other municipalities are only performing the first step of identifying the hazard.

Table 4.1: How the municipalities are working according to the HACCP method.

HACCP step		Lerum	Tjörn	Sandviken	Sotenäs
1	Identify HAB as a hazards	X	X	X	X
2	Identify Critical Control Point				
3	Determine the critical limit				
4	Monitor critical control points				
5	Determine corrective actions		X		X
6	Verify that the measures are working effectively				
7	Documentation and records				X

Based on the interview answers, all municipalities had identified HAB as a risk for drinking water production. However, it was concluded that none of the four case study areas follows all the principles in the HACCP method for the issue of HAB. Sotenäs is the only case study area that conducts recurrent limnological studies annualy where total biomass and algal species are investigated and documented. However, no critical limit of total biomass or algal toxin has been determined, and these parameters are just sampled once, hence no monitoring of critical control points. Sotenäs and Tjörn have both determined corrective actions. Sotenäs have implemented a wetland area to mitigate phosphorus loading and an online camera for better visual inspection, while Tjörn has decided not to use water from one of their raw water sources (Olsby damm) due to recurring algae growth.

4.2 Data analysis

This section presents the collected data (raw water and weather data) and provides an analysis of this data, organized by each of the four case study areas.

4.2.1 Sandviken

The average air temperature during the summer period of 1 June to 31 August was measured between 1960 and 2023 in Sandviken and is plotted in Figure 4.1. Temperature data is collected from several different measuring stations located in the area around Sandviken (SMHI, n,d). The measuring stations in the municipality of Sandviken have not recorded temperature data for the entire time period. Therefore, missing years in the time series have been supplemented with data from Gävle. Gävle is located 20 km away from Sandviken. In figure 4.1, the linear regressions trendline reveals that the average summer temperature has risen by an average of 0.012 °C annually. The maximum and minimum values do not seem to have changed much when comparing 1960 with 2023.

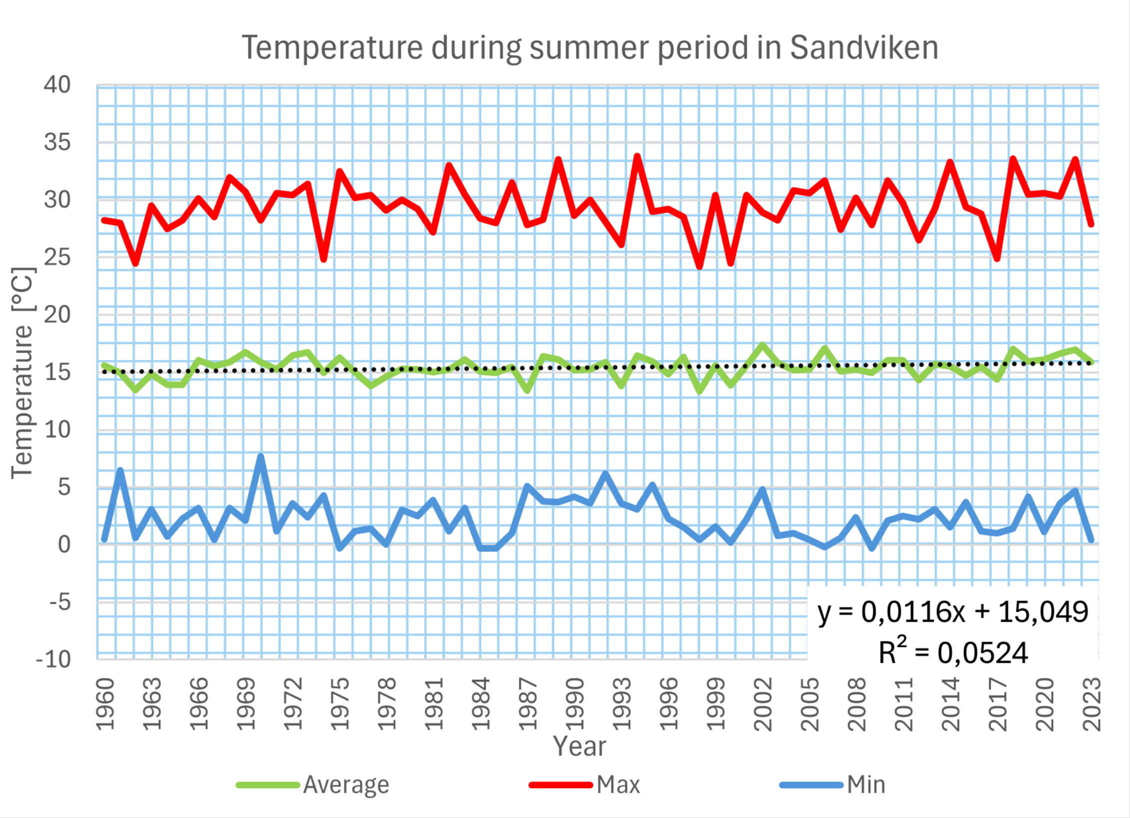


Figure 4.1: The green line in the graph indicates the average temperature, the blue line represents the minimum temperature, and the red line represents the maximum. The dotted line is the trendline of the linear regression of the average air temperature. All temperatures are during the summer period between 1 June to 31 August.

The precipitation for each summer is presented as the average monthly precipitation based on total precipitation during June to August. It is presented as mm/month from June to August. The results in figure 4.2 show that the precipitation has increased by 0.31 mm/year. The precipitation data is collected from SMHI, n,d from nearby measuring stations. In 2021 and 2023, there were very rainy summers. It can also be seen that there was a period of drought and very little rain between 2013 and 2019. The figure 4.2 shows large variation between the years which is also confirmed by the small R^2.

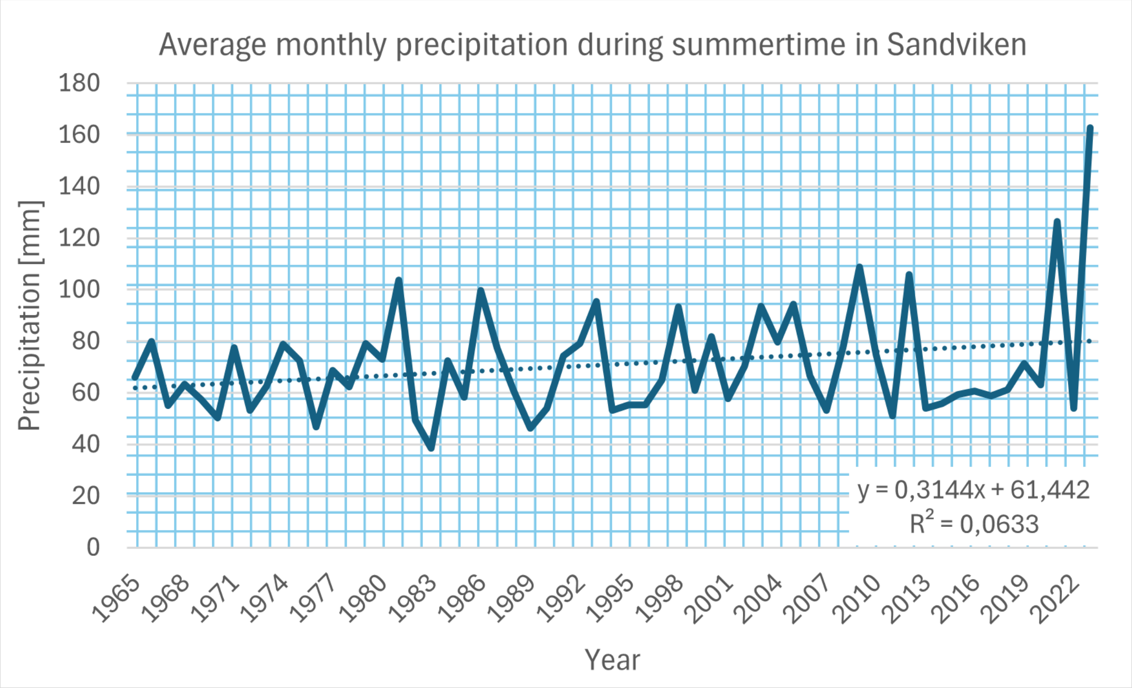


Figure 4.2: Average precipitation in a month during the summer period (June-August) in Sandviken.

In Figure 4.3 the sunshine duration in Borlänge has been analysed. It is important to note that the number of years the sunshine duration has been measured is quite short, only 36 years. The data to create the time series was collected from SMHI (n,d). The sunshine duration data are collected from Borlänge, 90 km from Sandviken. In Figure 4.3, it can be seen the sunshine duration is increasing each year by 3.5 h. The coefficient of determination is low and, therefore, shows there is a large variation in the duration of sunshine between the summers.

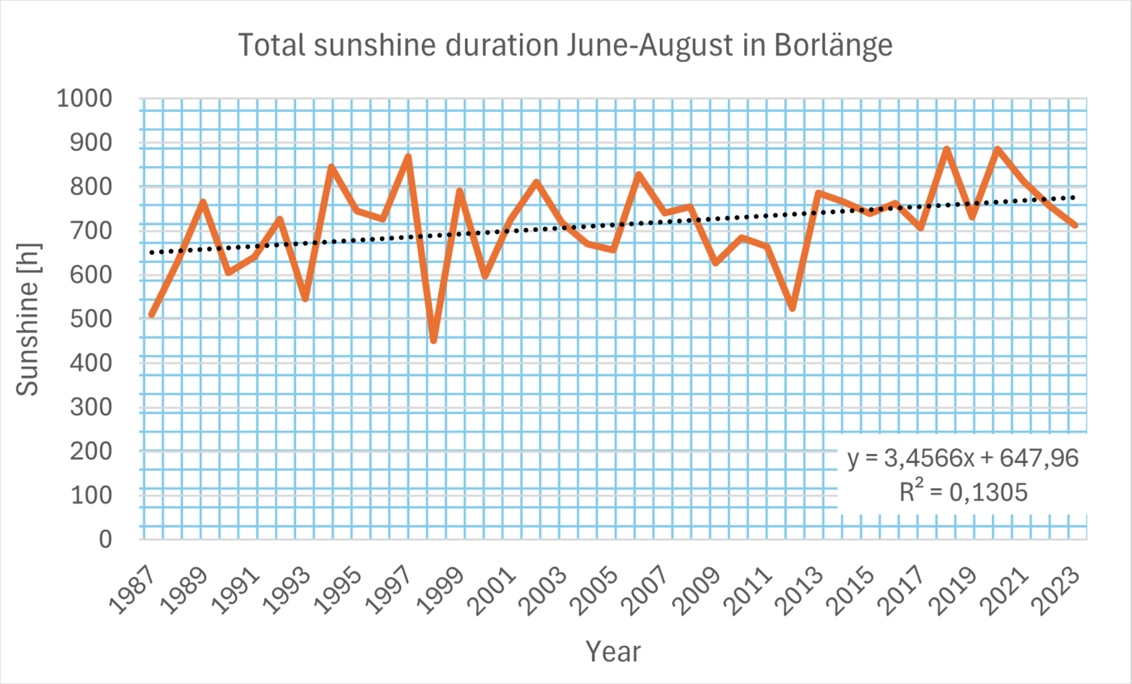


Figure 4.3: Sunshine duration in Borlänge

Sandviken have taken water samples of water quality once every four weeks. Two of the monitored parameters are pH and temperature. Figures 4.4 and 4.5 shows the highest recorded values in these samples during the summer period (june-august) for each year between 2002 and 2022. In figure 4.4, it can be seen that the temperature has varied over the years. In the coldest year, the water temperature was measured at 17.3 °C, and in the warmest year, 2018, the water reached a temperature of 22.2 °C. In 2016, there was a problem with algae growth in the lake, which affected the taste of produced drinking water. The water temperature this year was not higher compared to other years.

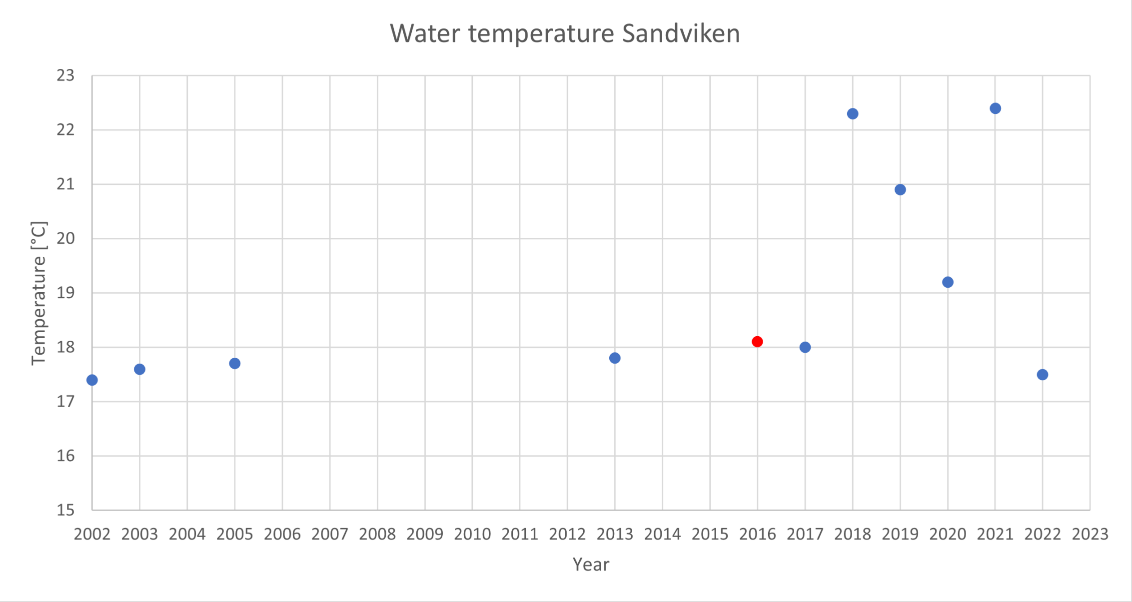


Figure 4.4: Water temperature during summer in the lake Öjaren in Sandviken between 2002 and 2023. There was problem with algae growth in 2016, this year is marked with red.

In Figure 4.5, pH during the summer has been measured the highest reported between 1 June to 31 August are plotted in the Figure. The highest recorded pH level, 7.5, occurred in 2017, while the lowest, 6.2, was observed in 2018. The red-coloured dot in the figure represents the year when an increased growth of algal cells was documented. In 2016, when there was an increased growth of algal cells, the pH was about 6.7.

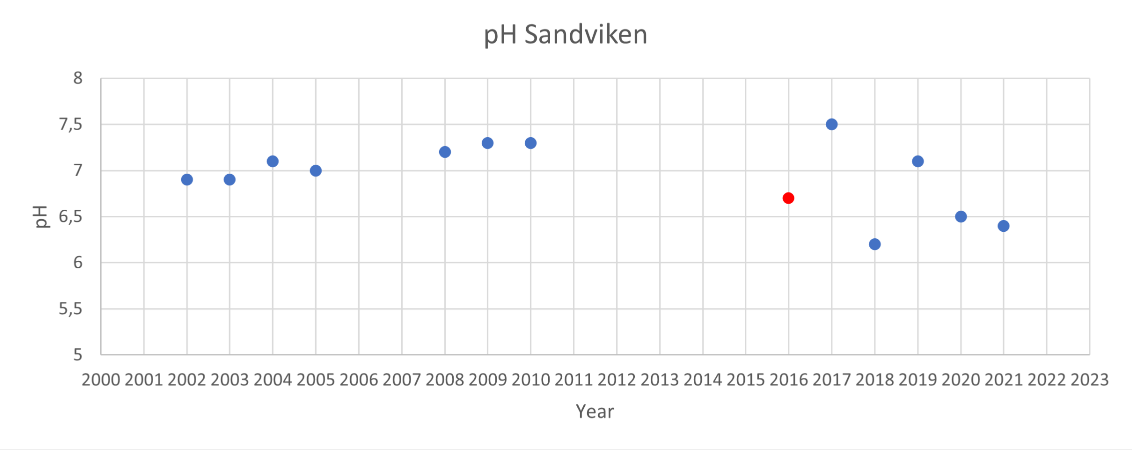


Figure 4.5: pH levels in the lake Öjaren during summer measurements (typically in early August).

4.2.2 Lerum

This section presents results from collected data from the case study area Lerum presented.

Figure 4.6 presents the recorded air temperature during the summer period 1 June to 31 August between the years 1960 to 2023. The average air temperature increases by 0.027 °C each year, which can be seen in the trendlines equation the average air temperature which was made of the linear regression of the average air temperature. The graph indicates that the maximum air temperature during the summer has remained steady, but the minimum air temperature has increased. In the early years of the recorded data, the minimum air temperature was observed to be below 0 °C on several occasions. However, since 1986, the minimum air temperature has never dropped below 0 °C during the summer period. The coefficient of determination is low, as can be seen in Figure 4.6. This indicates there is a large variation in the average temperature during the summer period in Lerum. Figure 4.6 presents the recorded air temperature during the summer period 1 June to 31 August between the years 1960 to 2023. It can be seen in figure 4.6 that both the average and minimum air temperatures have increased each year. The average air temperature increases by 0.027 °C each year, which can be seen in the trendlines equation for the tangent of the average air temperature which was made of the linear regression of the average air temperature. The graph indicates that the maximum air temperature during the summer has remained steady, but the minimum air temperature has increased. In the early years of the recorded data, the minimum air temperature was observed to be below 0 °C on several occasions. However, since 1986, the minimum air temperature has never dropped below 0 °C during the summer period. The coefficient of determination is low, as can be seen in Figure 4.6. This indicates there is a large variation in the average air temperature during the summer period in Lerum.

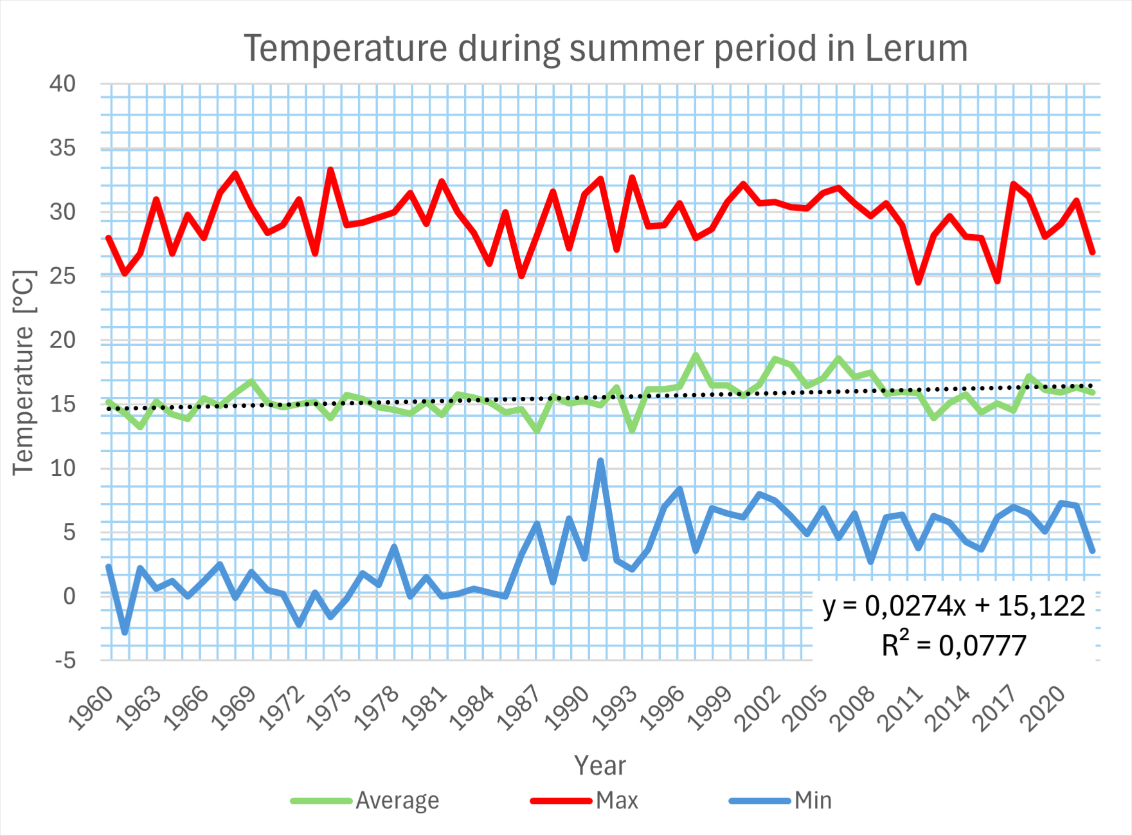


Figure 4.6: The green line in the graph indicates the average air temperature, the blue line represents the minimum air temperature, and the red line represents the maximum. The dotted line is the trendline of the linear regression of the average air temperature. All air temperatures are during the summer period between June to August.

The precipitation for each summer is presented as the average monthly precipitation based on total precipitation during June to August. Figure 4.7 shows the precipitation in Lerum, which fluctuates, but the trendline indicates an annual increase of 0.001 mm. The time series are based on data collected from SMHI SMHI, n,d. The coefficient of determination R^2 as can be seen in Figure 4.7 shows significant variation between the years which as well R^2 implies by its small number.

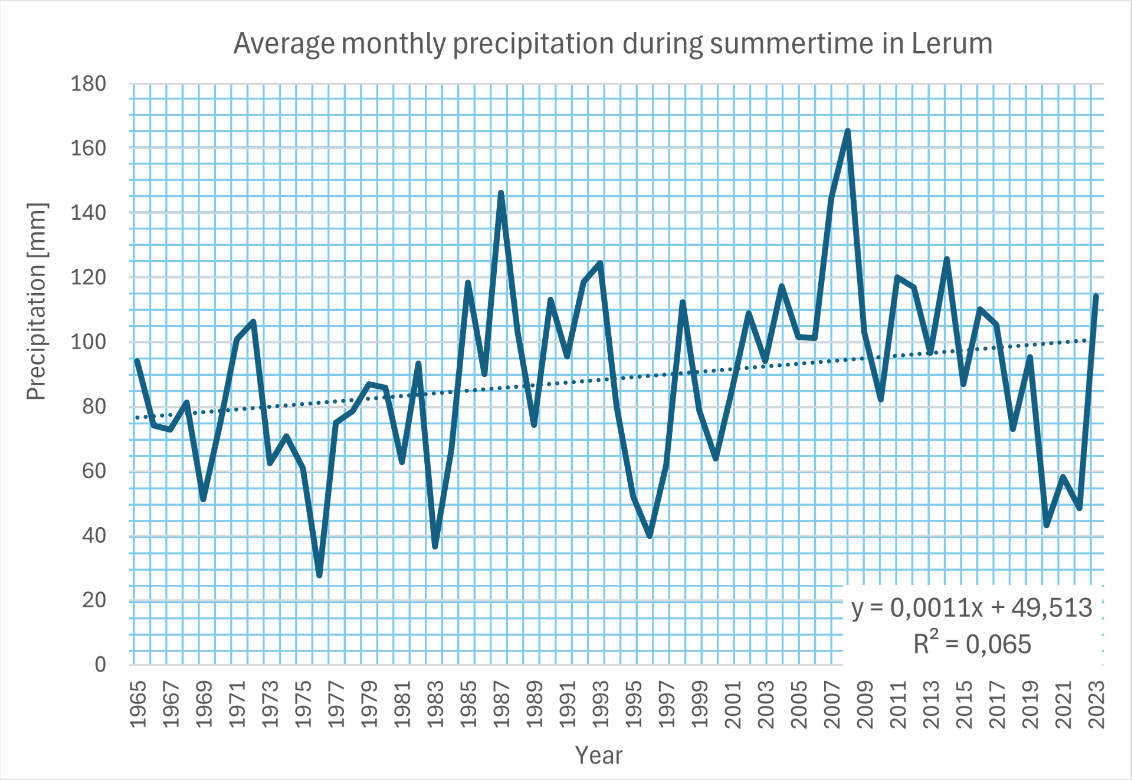


Figure 4.7: Average precipitation in a month during the summer period (June-August) in Lerum.

In Figure 4.8 the sunshine duration in Borlänge has been analysed., it can be seen that each year, the sunshine duration increases by 2.25 h every summer. The duration of sunshine varies between the summers, which is indicated by the coefficient of variation. But the time series is quite short over Gothenburg, only for 40 years.

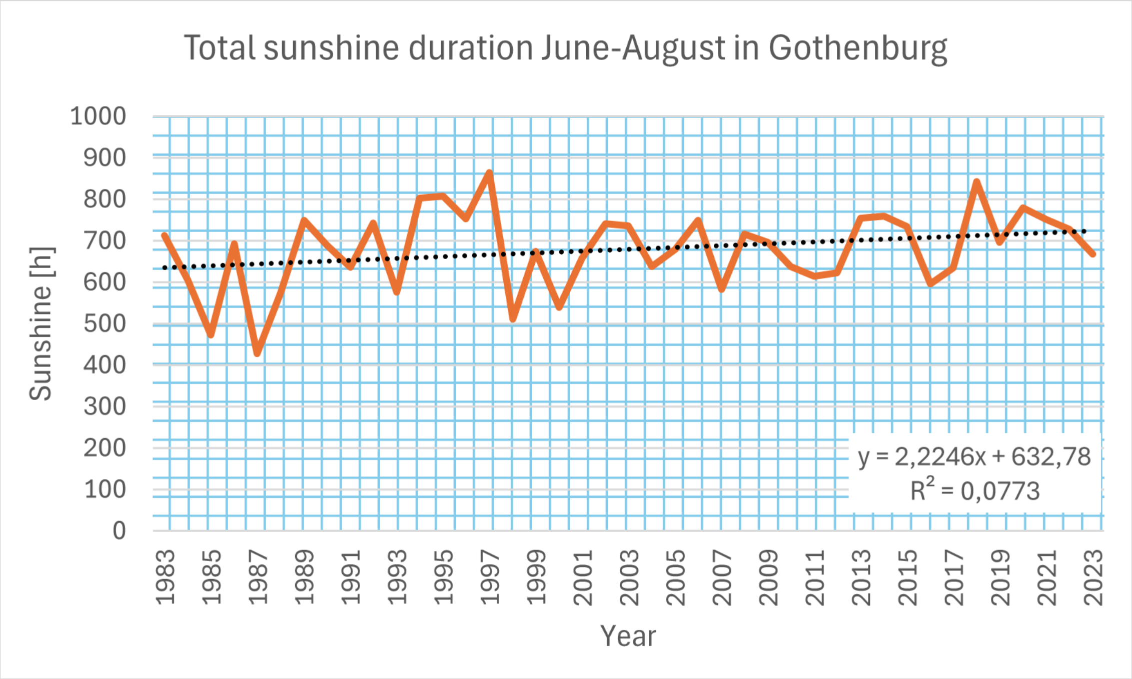


Figure 4.8: Sunshine duration in Gothenburg

In Figure 4.9, it can be seen that an algal bloom occurred during the year with the highest measured water temperature within the lake. In 2018, when there was increased growth of algal cells, the water color had quite a high value when compared to other years, as can be seen in Figure 4.10. However, the value was not the highest achieved value.

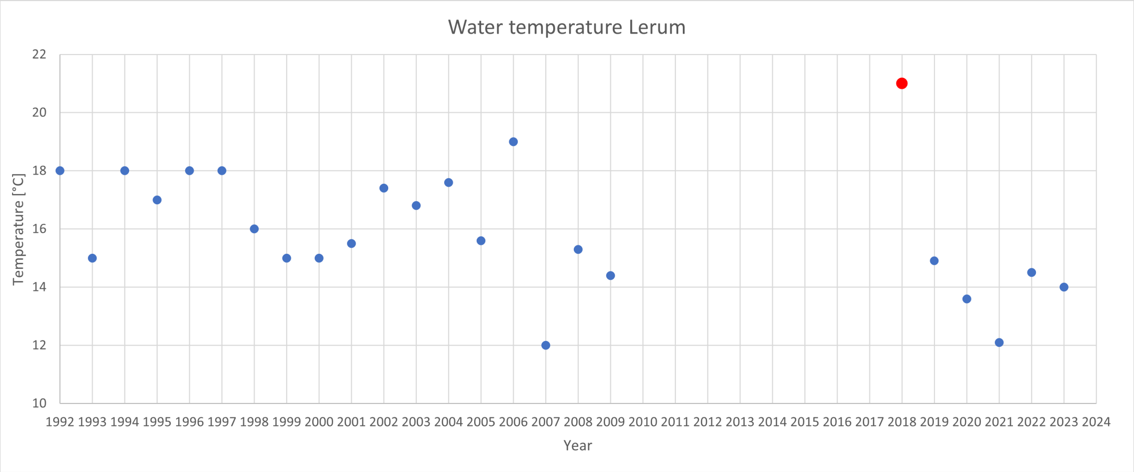


Figure 4.9: Highest measured water temperature during summer in the lake Öxsjön in Lerum between 2002 and 2023. There was a problem with algal bloom in 2018, this year is marked with red.

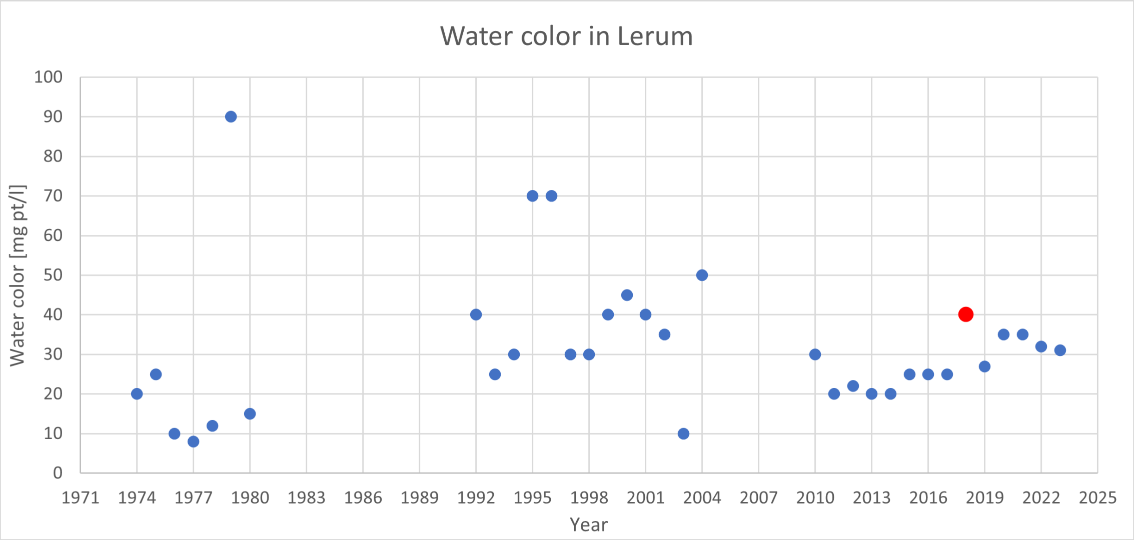


Figure 4.10: Water color in measurements during summertime in Öxsjön, Lerum. The year 2018, with an algal bloom, is marked with red.

In Figure 4.11 the pH is presented from 1974 to 2019. In 2018, the pH was around 6.7 when there was algal bloom. Between the years 1973 to 1984 the pH varied from the lowest in 1976 when the pH was 4.7 to 7,3 because of a chalk chock (S. Lund, personal communication, 18 March 2024).

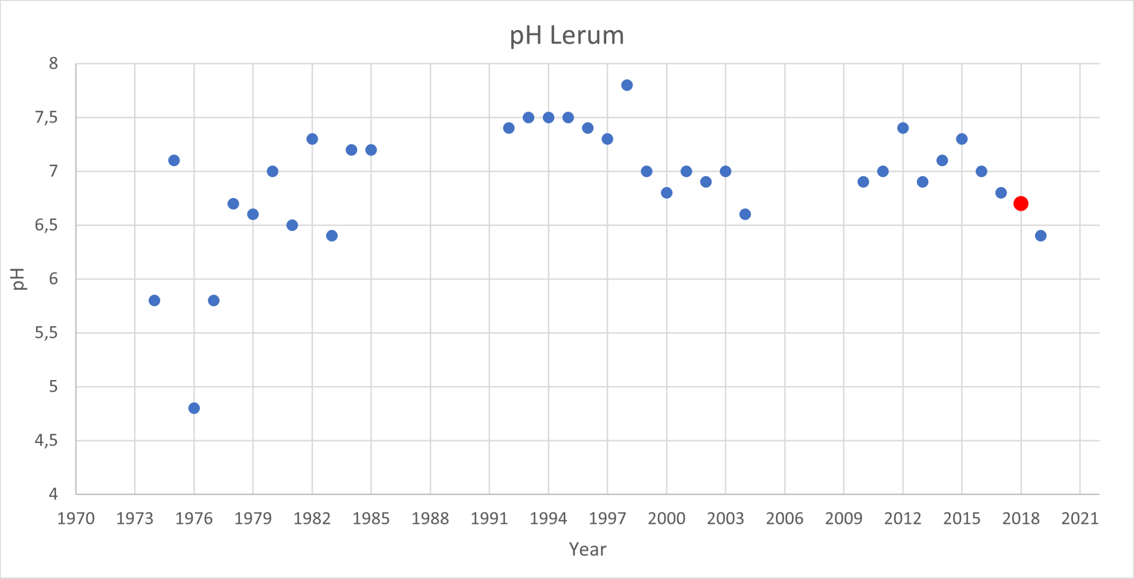


Figure 4.11: Measurements of pH during summertime in Lake Öxsjön in Lerum (typically taken early in August). The year 2018, with an algal bloom, is marked with red.

4.2.3 Sotenäs

Sotenäs has performed limonological tests since 2010, so the data is slightly different from that of the other three case study areas. The water parameters are measured in the surface water.

The average air temperature during the summer period of 1 June to 31 August was measured between 1960 and 2023 in Sotenäs and is plotted in Figure 4.12. The average air temperature has raised by 0.021 °C when 1960 is compared to 2023, which can be seen in the trendlines equation from the tangent in Figure 4.12. It has to be noted the data are from three different places: Hållö, Sotenäs and Måseskär. Hållö and Sotenäs are situated in Sotenäs, and the data collected from these two places are between 1960 and 1984. The data from 1985 to 2023 are collected from the measuring station Måseskär. The data used in the time series are collected from SMHI meteorological data that is available online SMHI, n,d. The average air temperature during the summer period varied considerably, as can be seen in the coefficient of determination R^2.

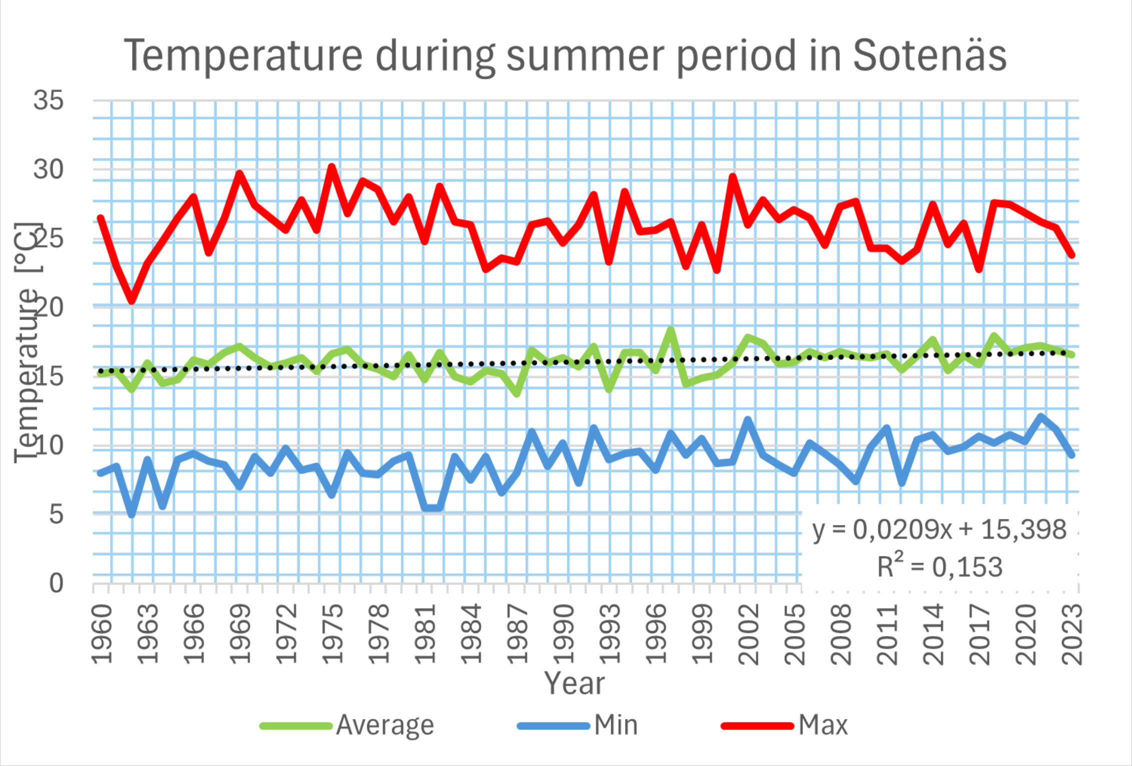


Figure 4.12: The green line in the graph indicates the average air temperature, the blue line represents the minimum air temperature, and the red line represents the maximum. The dotted line is the trendline of the linear regression of the average air temperature. All air temperatures are during the summer period between June to August.

In figure 4.13, the precipitation for each summer is presented as the average monthly precipitation based on total precipitation during June to August [mm/month]. Since 1960, precipitation has increased by 0.26 mm each year, as seen from the trendlines equation in Figure 4.13. It can also be seen that the precipitation varies and can differ a lot between two years. As can be seen in Figure 4.13, the precipitation varies considerably between the summers, and the coefficient of determination indicates this as well because of its low value.

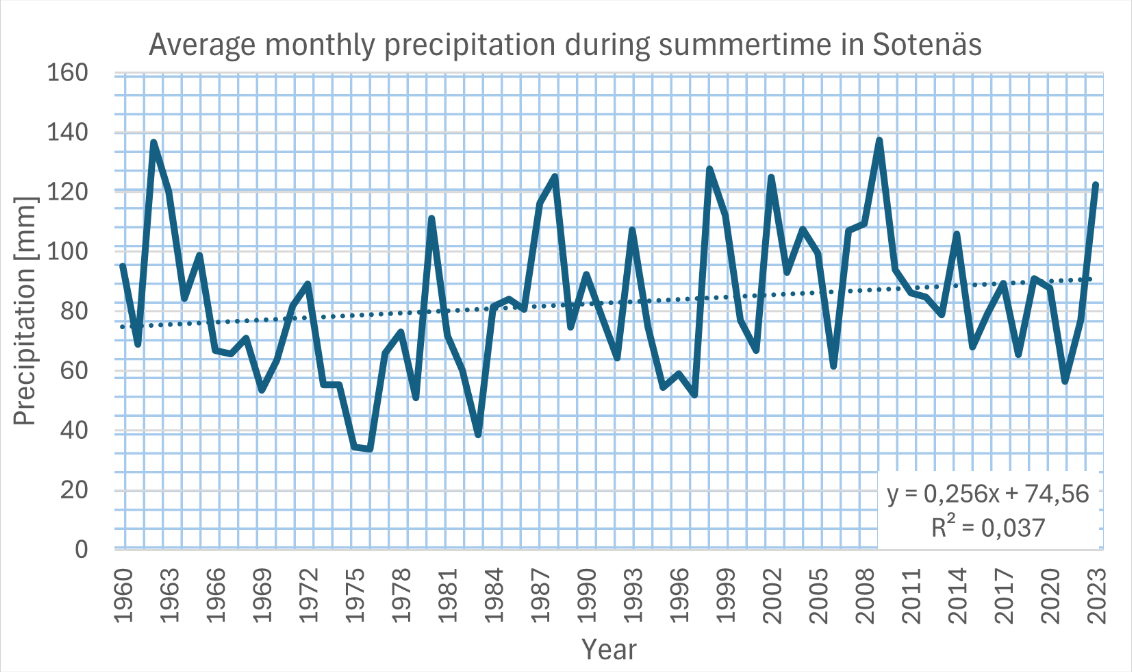


Figure 4.13: Average precipitation monthly during the summer period (June-August) in Sotenäs

In Figure 4.14, the years with documented algal blooming are visualised by red dots; it can be seen there was algal blooming in 2013 and 2023. The water temperature these years was not the highest achieved, but it was not the lowest water temperature.

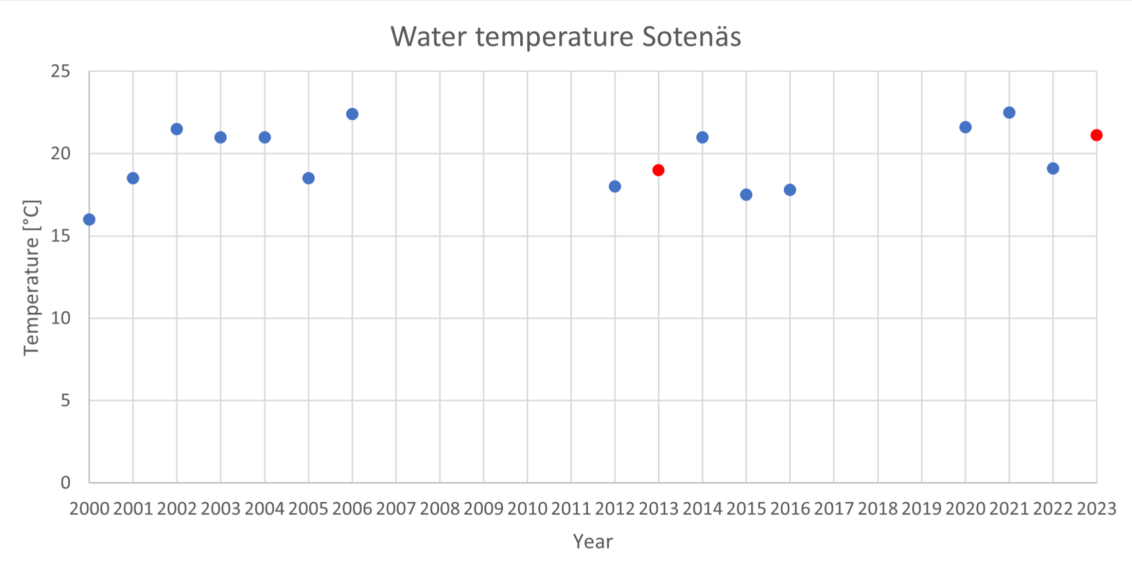


Figure 4.14: Highest measured water temperature during summer in the lake Tåsteröds Stora Vatten in Sotenäs between 2000 and 2023. Years with visual detected algal blooms are marked with red.

In figure 4.15, the pH is visualised, and for 2023, when there was an algal bloom in Sotenäs, it can be seen the pH was around 7.7. The pH presented in the Figure 4.15 is from the surface.

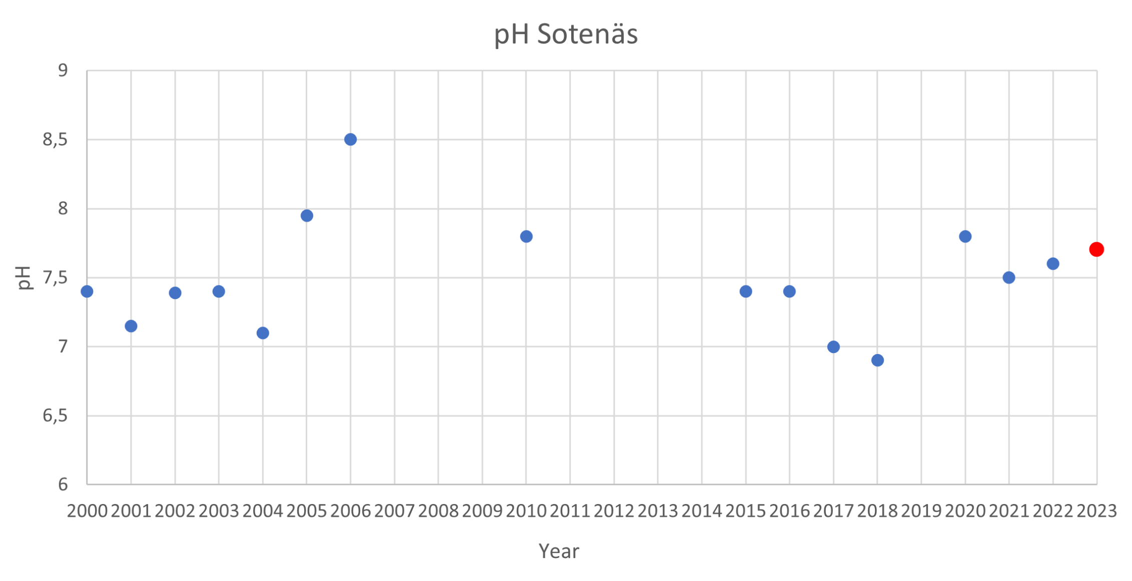


Figure 4.15: Measurements of pH during summertime in Lake Tåsteröds Stora Vatten in Sotenäs (typically taken early in August). The year 2023, with an algal bloom, is marked with red.

In Figure 4.16, it can be seen the years with algal blooming had an increased total biomass and concentration of cyanobacteria.

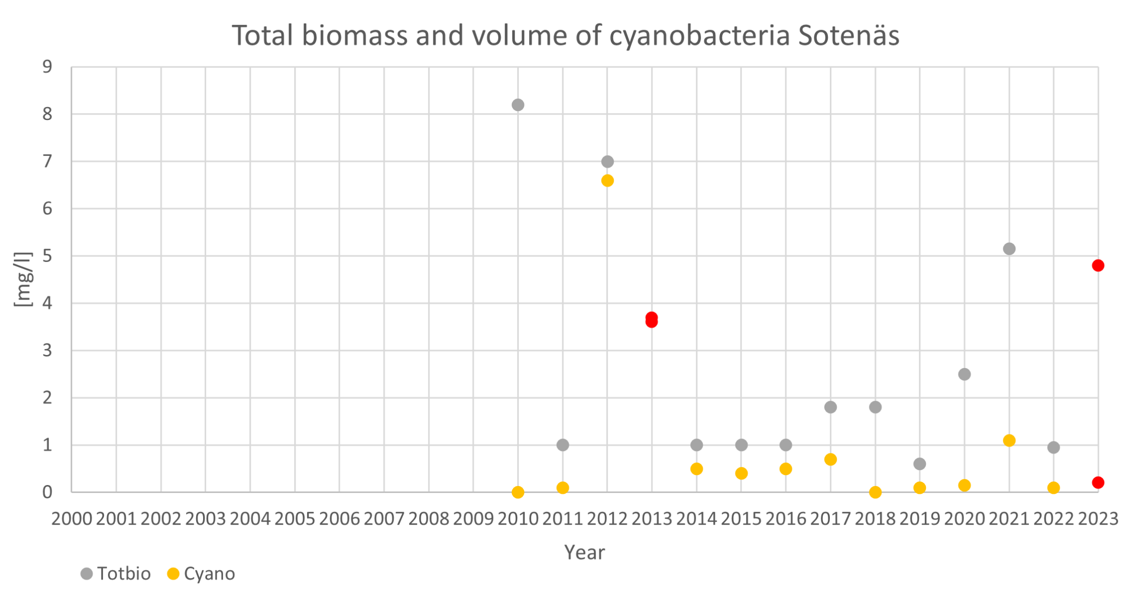


Figure 4.16: Total biomass and volume of cyanobacteria, measurements made during summertime within the annual limnological study.

4.2.4 Tjörn

Due to a lack of data, no time series of water parameters are presented for Tjörn. The average monthly precipitation and the maximum, minimum, and average precipitation are presented in Figures 4.18 and 4.17. The raw water data that were received are presented in Table 4.2.

The average air temperature from 1 June to 31 August was measured between 1960 and 2023 in Tjörn and is plotted in Figure 4.17.In Figure 4.17, it can be observed that the annual air temperature is increasing by 0.030 °C when considering the trendlines equation from the tangent on the average.

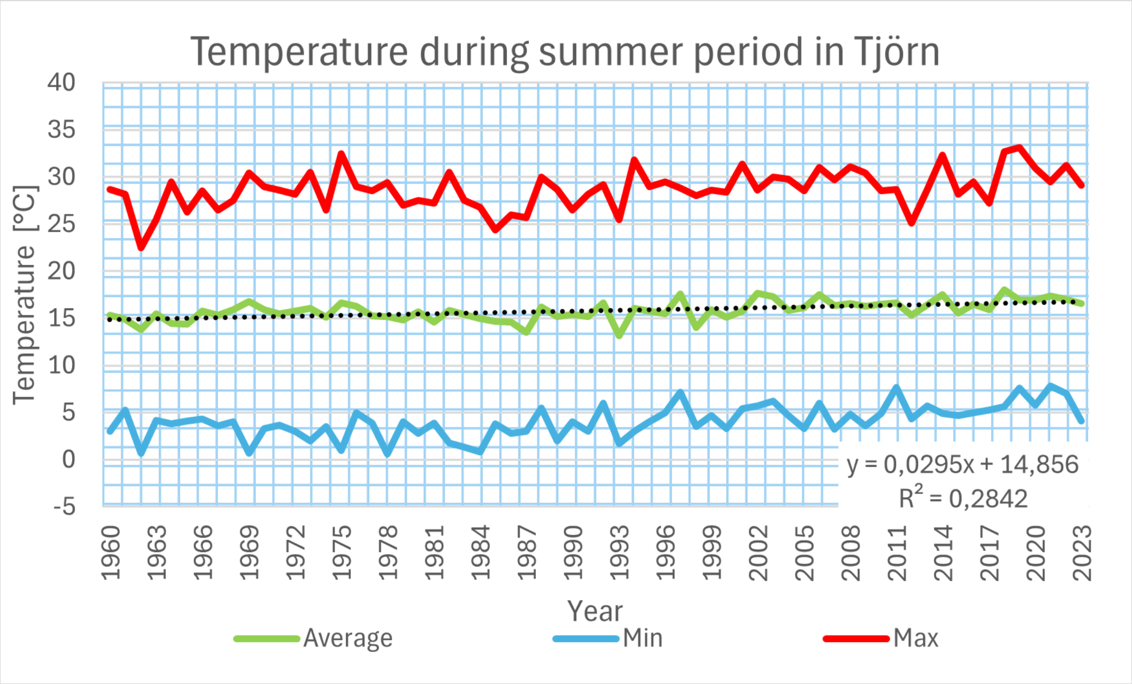


Figure 4.17: The green line in the graph indicates the average air temperature, the blue line represents the minimum air temperature, and the red line represents the maximum. The dotted line is the trendline of the linear regression of the average air air temperature. All air temperatures are during the summer period between June to August.

The precipitation for each summer is presented as the average monthly precipitation based on total precipitation from June to August. It can be seen in Figure 4.18 there was a significant variation between the years which as well R^2 implies by its small number. The precipitation shows an annual increase of 0.26 mm, as seen in the trendlines equation.

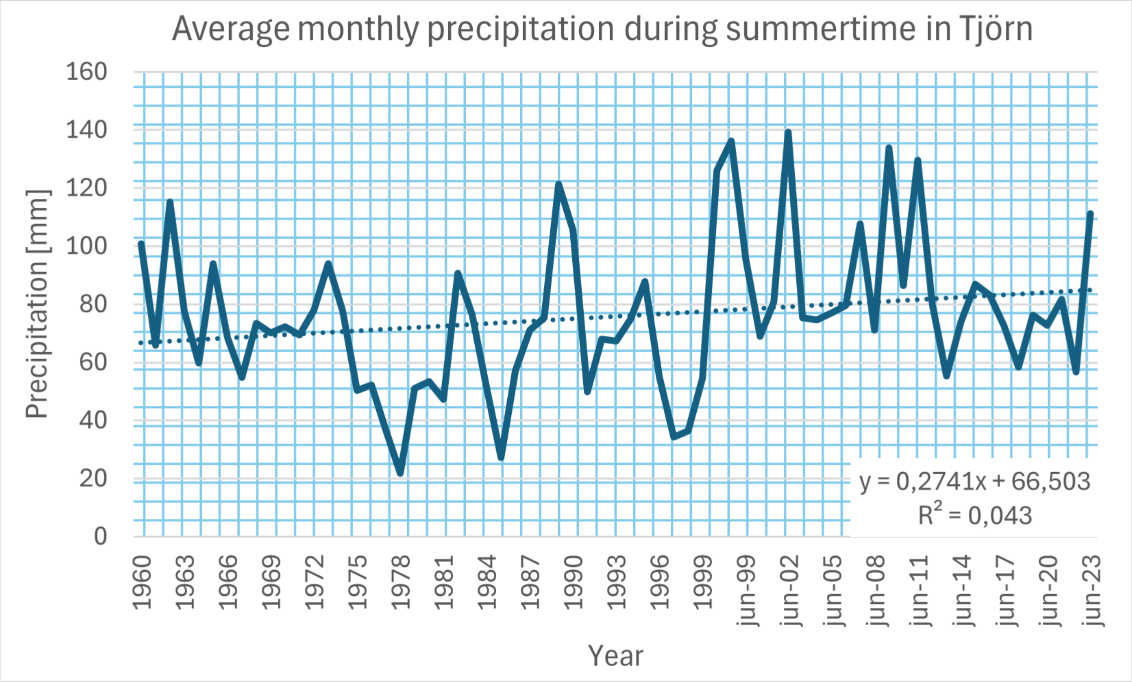


Figure 4.18: Average precipitation in summer period (June-August) in Tjörn

Table 4.2: Raw water data from Tjörn.

Date	Phosphate [mg/l]	Phosphorus [mg/l]	Air temperature [°C]
2019-03-12	<0.01	<0.04	3
2019-04-30	<0.01	<0.04	13
2019-08-13	0.013	<0.04	19
2023-03-22	0.015	0.05	5
2023-06-21	0.03	0.09	15
2023-09-05	0.78	2.4	15
2023-10-31	0.093	0.29	

Table 4.2 includes only seven tests, but it can be seen during 2023, the Phosphate and phosphorus levels were higher than in 2019. It received one limnological test that was not presented because it showed no signs of high levels of anything. All parameters that were measured in the limnological test are below the detection limit.

5

Discussion

This section will discuss the findings of algal blooms in raw water sources, the methods for detecting algae, and actions to reduce the risk of algal toxins entering the drinking water system. This section will also discuss the results and analysis that was conducted to identify pre-conditions for algal blooms (weather and raw water data).

5.1 Data interpretation and potential for risk assessment

Based on the findings from the literature study, it is concluded that algal bloom in freshwater is a complex phenomenon affected by a combination of physical, chemical, and biological mechanisms. The literature study showed that sunshine, warm temperatures, and nutrient availability are recognized as key factors when they are combined, but even if they even if they coincide, it does not necessarily cause an algal bloom (Hagen, 2008). This complexity could also be observed in the analysis of the collected raw water data. In all four case study areas, no correlation could be identified between the selected raw water parameters and the occurrence of an algal bloom. However, it's important to note that the data availability is limited. In three of the four case study areas (Tjörn, Lerum, and Sandviken), there is limited information regarding algae growth in their raw water sources, and no recurrent investigations into the algal community have been conducted. Additionally, only one year had an ascertained algal bloom in Öxsjön (Lerum) and Öjaren (Sandviken), which was determined only through visual inspection. The only extensive algal bloom in Öxsjön (Lerum) occurred in 2018 when their highest measured water temperature was recorded. But it is difficult to draw far-reaching conclusions when it has only occurred once. Consequently, the lack of comprehensive data poses challenges in drawing conclusive insights from the raw water data collected from these three case study areas. In Sotenäs, limnological studies have been performed recurrently annually since 2010 in their two raw water sources. The algal community has been investigated, and the amount of different algae species has been determined. The knowledge of algae growth in the two lakes, Lilla Dalevatten and Tåsteröds Stora Vatten in 2010-2022, provides a better opportunity to investigate correlations between specific parameters and algae growth. However, no correlation has been found between the selected raw water parameters and the amount of algae in the lakes. Years with high total biomass compared to other years have occurred both during summers with high water temperatures (above 20 °C) and during years with lower water temperatures (below 18 °C). The same can be seen for the parameters pH and total phosphorus, years with high total biomass in the lakes do not have different values of these parameter compared with years with low levels of algae growth. More detailed data is needed to determine causality and find a correlation between specific parameters and algae growth in surface waters.

Other studies have shown correlations in changes in raw water quality data. In a master's thesis 2003, long-term trends in raw water quality in Mälaren were investigated, using data from 1935 to 2002 (Johansson, 2003). The findings from Mälaren can be compared to the analysis conducted in this study of four case study areas. In two municipalities, data from 2000 onward was used; in one municipality, data from the 1970s was analyzed; and in the last municipality, only two years of raw water data were available. Another example is the study by Köhler and von Brömssen (2021). In this study, long-term trends in water chemistry and weather data were analyzed, covering the period from 1967 to 2019, to identify changes in water chemistry. Hence, a lot longer time period than this study. If this study had data from a longer time period, it might have revealed correlations with years of algal blooms. However, due to insufficient documentation on algal growth, it's possible that no correlation would have been found. A stronger correlation may have been showed with more detailed records on the events of algal blooms.

The literature study and trend analysis of collected weather data revealed that the parameters of air temperature and sunshine duration, identified as risk factors for algae growth in surface waters, are increasing. This is due to climate change (Fernando et al., 2018). Analysis of raw water data showed no increase in phosphorus levels in the investigated raw water sources, despite indications from the literature study that increased precipitation can lead to increased nutrient transport into surface waters in Sweden (Jeppesen et al., 2009). One possible explanation for this could be the upstream solutions implemented in some of the case study areas. In Sotenäs, a wetland area has been established, and in Sandviken, houses have been connected to municipal wastewater treatment systems to mitigate phosphorus sources (M. Axelsson, personal communication, 20 March 2024), (V. Åkerlöf, personal communication, 22 March 2024).

5.1.1 Risk assessment strategies and monitoring challenges

The interviews revealed that there is a variety of risk assessment strategies regarding algae growth in raw water sources in the case study areas. All the municipalities have identified HABs in their raw water sources as a hazard for drinking water production. Identification of hazards is the first step in the HACCP method (Livsmedelsverket, 2023). Despite the fact that algae growth has been identified as a potential risk to the drinking water supply, only one municipality (Sotenäs) monitors algae growth annually in their raw water sources, but this is conducted only once every summer. All four DWTPs that were investigated monitored the increased cell growth of algae by visually observing if there was any sign of algae growth in the raw water source.

This is a concern because, according to EPA (2024), once the algal bloom becomes visible, toxins may already have been released, potentially contaminating the raw water and, consequently, posing a risk to drinking water production. This is despite the fact that monitoring critical control points is one of the key components of the HACCP. (Livsmedelsverket, 2023). The lack of sampling and monitoring is interesting because it is very difficult to manage risks if one does not have the ability to monitor critical control points and relies only on visual inspection. It suggests that many municipalities have inadequate risk assessment strategies within this area. As it is now, it is not possible for the four DWTPs to detect if their raw water or produced drinking water contains algal toxins, which is surprising.

5.1.2 Risk modelling and mitigation measures

In Figure 2.3, the risk was divided into three steps: the source, the barriers and the receptors. The risk source/hazards could be seen as the presence of algal species in the lake with the potential to grow and cause toxin levels harmful to humans (both drinking water and recreational swimming). The initiating risk event would be the combination of different parameters contributing to increased algal cell growth. These key parameters include sunshine duration, precipitation, temperature, and phosphorus concentration. The barriers can be filters and processes preventing algal cells or toxins from entering the drinking water. These processes include the treatment steps in the DWTP and actions taken outside as a monitoring system. There are also measures that could be applied to decrease the probability of the risk event to occur, for example, in this case, decreasing phosphorous levels. Implementing wetlands upstream or fixing sewage leakage into the raw water source are measures that could decrease the phosphorous loading into the raw water source, hence decreasing the risk of algal bloom. The great uncertainties make this phenomenon difficult for risk assessment and risk modelling. There are uncertainties regarding both the risk event and the barriers. The risk event is specifically the situation of algae growth that can cause toxin levels that DWTPs cannot handle or algal biomass that can cause filter clogging or affect the taste and odour of the produced water in the case study areas. In this case, the barriers were the treatment process and the possibility of switching raw water sources, and some of the municipalities were unsure how well their DWTPs could handle algal toxins or algal biomass (M. Axelsson, personal communication, 20 March 2024).

The literature study showed the potential to use AI and satellite images to detect and monitor algae growth in surface waters and marine environments. In the US, it has been tested to use satellites as a system to control if there is any sign of algal cell growth (Handler et al., 2023). The satellites can be used to look at the raw water source from above and see if there are any changes in chlorophyll-a. The drawback with the satellites is that they only measure the visible algae, but the advantage is that the whole surface area of the raw water source is investigated. Handler et al. (2023) mentions that the satellite system should be complemented with in-situ study and raw water quality field samples. The satellite in the project mentioned by Handler et al. (2023)was only tested in larger raw water sources because the pixel size can be a limiting factor for application on smaller raw water, which makes applying this technique difficult in the four municipalities with smaller raw water sources. Satellites utilized to detect chlorophyll-a have been implemented in Finland and the Baltic Sea (Tarkka, n.d.). A method used in a report from Yu et al. (2023) uses AI to predict algal growth by measuring the pH, water temperature, conductivity and turbidity. The AI is utilized as an early warning system, but in 2023, it was in need of improvement to be a reliable method to predict algal growth. The presence of chlorophyll-a does not necessarily indicate the presence of algal toxins harmful to humans. Increased chlorophyll-a levels indicate biomass growth, but different algal species produce varying amounts of chlorophyll-a. Therefore, it is not an exact measure of total biomass and does not indicate toxin levels. However, if chlorophyll-a levels rise, testing for toxins may be justified.

5.2 Limitations and sources of error

The limited extent of raw water data collected is a major limitation in the statistical analysis. Raw water samples are only taken occasionally, typically once every second month. Consequently, the data only provide a snapshot from the single sampling day. Thus, this presents a weakness when identifying pre-conditions that may cause algal blooms; sampling from a single day may not sufficiently describe conditions over a longer period (such as a month or longer). The study analyzed weather data, including precipitation and temperature, in a simple format that summarized each summer. The decision to present the average temperature during the summer period was based on the fact that the exact date when an algal bloom occurred could not be determined. However, this level of simplification may be excessive.

One limitation of this study was its heavy reliance on the data and information provided by the municipalities and case study areas. Challenges in accessing the available data, due to how it was stored and the dependency on specific individuals, contributed to delays in the analysis of the raw water data. However, the primary issue complicating the analysis was the limitations in the existing data. For example, when there was a change in the laboratories used, retrieving historical data became difficult. Unfortunately, as shown in the results section, no time series or data presentation could be conducted for Tjörn due to a lack of data. Data was only received from the years 2019 and 2023, and a lot more data from different summers are needed to do a trend analysis and see any correlations between parameters and algal bloom. Thus, except for phosphorus, Tjörn was excluded from the raw water data analysis, but the available weather data was presented similarly to the other case study areas.

Throughout the development of this master's thesis, several sources of errors have become apparent. It is challenging for municipalities and DWTPs to monitor the quality of the raw water sources over time and to determine if and how they have changed due to the lack of follow-up and lab changes, which complicate data availability. Some data are missing, and the regulations have changed over time. At the beginning of the 2000s, the regulations were updated, and municipalities were instructed on how to test raw water sources. This led to some of the municipalities interpreting the new regulations and advice as they did not need to test as many parameters as before (S. Lund, personal communication, 4 February 2024). This issue probably creates a gap in the time series of measurements in many municipalities around Sweden.

It has been noted that a significant issue is the lack of digitalized data and the difficulty in locating existing data. Furthermore, there is inadequate documentation regarding instances of algae in the raw water sources. This makes it challenging to conduct thorough data analysis and determine if there is a correlation between various parameters and the substantial increase in algal cell growth. It can also be argued that relying on visual observation to detect algae, as is currently done, is not effective due to its slow nature and human fault. By the time the algal bloom is visible, there may have already been several days of increased growth.

5.3 Vulnerability

Municipalities' raw water sources are vulnerable to problems. Although the water quality is tested, there is no proper tracking of how and if the water quality has changed. Furthermore, not all municipalities do not have a second raw water source to produce drinking water. If an increased growth of algal cells happens near the intake point in the lakes, there is a risk that the DWTP will not be able to produce water. Municipalities must provide safe drinking water; if unable to do so, water must be delivered to homes by tank trucks, which can be very costly.

During a warm summer, if a major incident occurs, municipalities may become vulnerable, potentially causing DTWPs to be unable to supply water to consumers. Interviews revealed that in Lerum, they had to stop taking water from Öxsjön due to low water levels. Because of water regulations, they were not permitted to lower further the water level (S. Lund, personal communication, 18 March 2024). The municipalities encountered problems with algal blooming, which made the water unusable. If both lakes experienced these issues, the supply of safe drinking water from the two raw water sources would have been at risk. Fortunately, the four municipalities have backup raw water sources. Tjörn's three additional raw water sources are interconnected with the fourth. This arrangement could pose a problem if something were to happen to Bö tjärn, the raw water source to which the other three are connected. A significant algal blooming event could potentially contaminate all the raw water sources. There have been previous instances where extensive algal blooming in one of Tjörns raw water sources led to the deaths of dogs that consumed the water (GP, 2019).

5.4 Discussion about the methodology

The methodology involved a literature review, study visits, interviews, data collection, selection, and analysis. A strategic literature search was opted for to gather more targeted information, but the strategic literature search was not used where more specific information was needed. The search was extensive due to the lack of data, but it helped to determine reasonable limits and potential parameters that could be correlated with algal blooming.

The study visits and interviews were helpful in gaining an understanding of how the DWTPs worked with the algae and whether they were actively working to decrease the risk of algal blooming. The interviews were not recorded, and the three in Lerum, Tjörn, and Sotenäs were executed during the study visit. It was an advantage to perform the interviews in person because we better understood what the DWTPs looked like and how they worked. The question was suitable, and some supplementary questions were asked, which are not noted in the methodology section.

It would have been useful to search the archives in each case study to extend the time series by a few years. The fact that much of the material was not digitized was not considered when the data collection began. However, three of the case study areas had information spanning over 10 years, which provided insight into how the quality of the raw water source had changed over time. Some parameters had to be excluded in the selection and analysis of data due to the extensive gaps in the time series, compromising their usefulness. In the analysis, time series was chosen as the way to present the results. A regression analysis was attempted to find a correlation between parameters but yielded no successful results.

5.5 Suggestion for risk management of algae growth in raw water sources

A first step for better risk management within the area could be better monitoring and a more systematic approach. Even if algal blooms are complex and difficult to predict, are there some parameter changes that can indicate increased algae growth. Raise of pH in the surface layer and increased turbidity can both be signs of algae growth (Paerl & Paul, 2012). In addition, water temperature is a risk factor for algal blooms (Hagen, 2008). All of these three parameters are measured daily by all four DWTPs from the case study areas. It is suggested that these three parameters should be followed during the summer period (water temperature, pH, and turbidity), and if there are significant changes, samples of algal toxins in raw water and produced drinking water can be considered. Especially if there are visual signs of algae growth.

Phosphorus is crucial for algae growth, and decreasing phosphorus loading is an effective measure to prevent algal blooms (Schindler et al., 2008). The four municipalities have various knowledge of phosphorus levels in their different raw water sources. While most municipalities monitor phosphorus levels, one does not, making it difficult to assess the risk for algal blooms. According to Livsmedelsverket (2018b), total phosphorus levels above 20 µg/l should be avoided to prevent cyanobacteria blooms. Thus, better and more frequent sampling of phosphorus is recommended, with both samples at different depths in the water column and lake sediments. Lerum and Sotenäs have the most extensive sampling of total phosphorus, they sample the water at three different depths: bottom, middle, and surface. One of the reasons they have chosen to perform these tests is internal loading. The internal loading can cause phosphorous release and high phosphorous concentrations even though upstream solutions are implemented. The phosphorous stored in the sediment could be released at low oxygen levels (Sellergren et al., 2023).

5.6 Future studies

Numerous studies, including Paerl and Paul (2012), indicate that the risk of algal blooms in surface water will increase in the future due to climate change. Thus, it is important that drinking water producers in Sweden get better prepared to handle this, specifically in terms of better risk management, warning systems and better capabilities at the DWTP to handle algae cells or algal toxins in their raw water. Further studies are needed to obtain better and more precise knowledge about how weather and different water quality parameters affect the phytoplankton taxa within Swedish lakes. Studies from other countries have shown the potential to use new technology such as deep learning models, AI, and satellite sensors for better monitoring and early warning systems (Yussof et al., 2021). Hopefully, this will be used more by Swedish drinking water producers in the coming years, none of the four case study areas are using these methods today.

5.7 Recommendations for water utilities

Based on the findings from this project, several applications that can enhance risk management for municipalities in the area of algae growth in raw water sources have been identified. Since municipalities vary in size and capacity, some are larger with more resources to utilize new technology and implement extensive measures and data collection, while others are smaller with fewer capabilities. Thus, the applications have been divided into two types, basic measures, and more extensive measures.

Basic measures:

- Adopting a systematic risk management approach - Applying HACCP principles for algae growth control.
- Phosphorus monitoring - preferable at different depths and recurrent during the year. High phosphorus levels can indicate an increased risk for algal blooms.
- Monitoring of pH, turbidity and water temperature - if there are significant changes, sampling of algal toxins in raw water source could be considered.

- Follow weather data. Periods with high temperature with a lot of sunshine and lack of wind is a risk factor for algal bloom. Consider to extend visual inspection or to sample for algal toxins in the lake during these conditions.

Extensive measures:

- Satellite imaging for chlorophyll-a measures. If there are high levels, sample of algal toxins in raw water source can be considered.
- AI-Models, or other types of water quality models for algae prediction. Typically requires a lot of data and knowledge.
- Recurrent limnological studies to obtain knowledge about the total biomass and the phytoplankton taxa. Only some species produce algal toxins or cause problems for the treatment processes, so it is important to know which species that typically proliferate in the lake.

6

Conclusion

Our study found no correlation between algae growth or algal toxins in the studied surface waters and the selected raw water parameters (pH, water temperature, phosphorus) and weather data (air temperature, sunshine duration). However, findings from the literature highlight the important role of phosphorus availability in algae growth. In addition, findings from the literature indicated that warmer temperatures showed to be a risk factor for increased algae growth. Furthermore, a rise in pH (due to decreased CO_2 levels in the water) and increased turbidity in surface layers can indicate ongoing algal blooms.

Interviews from our case study areas revealed that municipalities have inadequate risk management for algae growth, with no measures in place to detect algal toxins or algal cells in raw water or produced drinking water. Only one municipality performs a recurrent limnological study annually to follow the algae taxa within their lakes. This lack of knowledge makes it challenging to do a proper risk assessment. In addition to this, the DWTP were unsure about their capability to handle algal toxins or algal cells in their treatment processes.

To mitigate the risks associated with algae growth, recommendations are to do enhanced monitoring and documentation, adopting a systematic approach to assess algae growth. It is important for the municipalities to know what, when and how to measure to be able to detect potential algal blooms. It is recommended that DWTPs follow available parameters such as pH, turbidity, and water temperature, which are measured daily at the raw water intake. Increases in pH and turbidity can act as early indicators of algae growth, while water temperature serves as a risk factor. If these parameters suggest a rise in algal biomass, visual inspections could be conducted, and, if necessary, samples for algal toxins could be taken. Additionally, more extensive monitoring could include sampling of total biomass and chlorophyll-a levels, which are strong indicators of algae growth. These measurements can be carried out more extensively during the summer months to assess the risk of algal toxin presence in the water.

7

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