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The potential effect of paper and pulp mill effluents on brownification in Hanö Bay, Baltic Sea.

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Potentiell påverkan av pappers- och massabruk på brunifiering i Hanöbukten, Östersjön.

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Abstract

The Baltic Sea is a semi-enclosed basin characterized by its brackish water and unique biodiversity. However, it is also one of the most polluted seas in the world and is exposed to multiple environmental stressors, including eutrophication, overfishing, and climate change. Freshwater and coastal browning have been observed across the Northern Hemisphere, although the cause and dynamics of brownification in coast and land is debated. Brownification is the shift in water colour and is often associated with increased organic matter which affects the optical properties of water. Hanö Bay has been under discussion due to eutrophication, dead fish, and observed browning of water. Two paper and pulp mills, Nymölla and Södra Cell Mörrum, are located along the Hanö Bay coast, and discharge wastewater into the bay through pipes.

The aim of this thesis is to investigate the potential influence of paper and pulp and effluents on possible brownification in Hanö Bay. Total organic carbon and absorbance at 420 nm of water samples were analysed at monitoring stations located in the five major river basins that drain into the bay. In addition, the chlorophyll *a* concentration, dissolved oxygen content, and Secchi depth were examined at six coastal monitoring stations close to the two mills. Both parametric and non-parametric statistical tests were used to assess if there are any significant trends. Monthly mean secchi depth created from ice-ocean model NEMO and biogeochemical model ERGOM, was analysed in ArcGIS Pro to examine spatial and temporal patterns.

The results indicate a significant increase in total organic carbon and high absorbance values in the river basins draining into the bay. However, the coastal monitoring data for Hanö Bay is insufficient to conclude the extent to which paper and pulp mill effluents contribute to brownification. The limited availability of long-term coastal water data, particularly from the 1970s makes it difficult to distinguish between the effects of paper and pulp mills from drivers such as land-use change and climate change. Modelling, past, present and future may fill in the gaps for the temporal data. Previous studies have used proxies for organic matter and pollution through total organic matter, coloured dissolved organic matter, and absorbance. Further projects should focus on water sampling near the mills and along the coast to obtain an overview of the water properties. Future research on brownification and the interactions between land and coastal ecosystems is crucial, especially under the ongoing climate change.

Keywords: Brownification, Hanö Bay, paper and pulp mills, Nymölla mill, Södra Cell Mörrums, Baltic Sea

Contents

1 Introduction

The Baltic Sea, the semi-enclosed basin characterised by its brackish and unique biodiversity, is one of the world's most polluted seas (fig. 1) (Race for the Baltic, 2026). Its brackish conditions result from the large inflow of freshwater from surrounding land, estimated to be at approximately 450 km^3/year, combined with the limited exchange of saline and oxygen rich water from the North Sea. Water exchange is a very slow process, the water has a residency of 30 years (Race for the Baltic, 2026; HELCOM, 2023a).

There are three deep basins in the Baltic Proper; the Arkona Deep, Bornholm Deep and the Gotland Deep. The saline, dense, and oxygen rich water from the North Sea enters the Baltic Sea through the shallow Danish Straits and distributes the water into the deeper basins (Thulin & Andrushaitis, 2003). The difference in density creates a distinct vertical stratification with less dense freshwater remaining on the surface, and the denser saline water settling deeper (HELCOM, 2023a). The inflow of denser, oxygen rich water from the North Sea generates flushing events in the deeper waters. These flushing are infrequent and unpredictable and play a crucial role reducing the concentration of pollutants and nutrients from terrestrial runoff (Thulin & Andrushaitis, 2003).

These characteristics make the Baltic Sea an incredibly vulnerable ecosystem to climate change and accumulation of pollutants, nutrients, and particles. In the 20th century the Baltic Sea has been subjected to anthropogenic and environmental stressors which have caused substantial ecosystem changes over the last century (Dietz, et al, 2021). Eutrophication, overfishing, pollution, changing biodiversity, and climate change are the biggest environmental problems that the Baltic Sea is facing (HELCOM, 2023a). The primary driver is an excess load of nutrients from natural runoff, agriculture and other industries. Increased nutrient loads promote algae blooms and one of the most distinct consequences is hypoxia. Once the blooms sink to the bottom, larger amounts of oxygen are utilized for decomposition at a faster rate than the mixing and flushing events. Hypoxia refers to critically low oxygen in bottom waters (<2 ml/l). Anoxia, also known as dead zones, are conditions in which oxygen is absent (HELCOM, 2013b). The changing climate and global warming are predicted to enhance the effect of eutrophication, and can intensify and spread anoxia, shift in invasive species, and elevate algal blooms (HELCOM, 2023a).

Another emerging challenge the Baltic Sea is facing is coastal brownification, an in-water colour because of increased dissolved organic matter and carbon content in water (Kritzberg, et al. 2020). There have been observations of brownification in both freshwater and coastal ecosystems across the Northern Hemisphere and this has been linked to climate change (de Wit, et al., 2016). Although brownification is widely studied in freshwater ecosystems there is limited research and understanding of the relationship between marine coastal waters and land (Opdal, et al., 2013; Aigars, et al., 2024). The discharge of wastewater from forestry related industries into rivers or/and directly into the coastal waters may potentially cause browning. However, the extent to which these industries influence the physical and chemical properties of coastal waters, as well as the ecological, remains insufficiently quantified. The aim of this thesis is to further understand and gain knowledge on the potential effect of paper and pulp mill effluents on brownification in Hanö Bay, Baltic Sea.

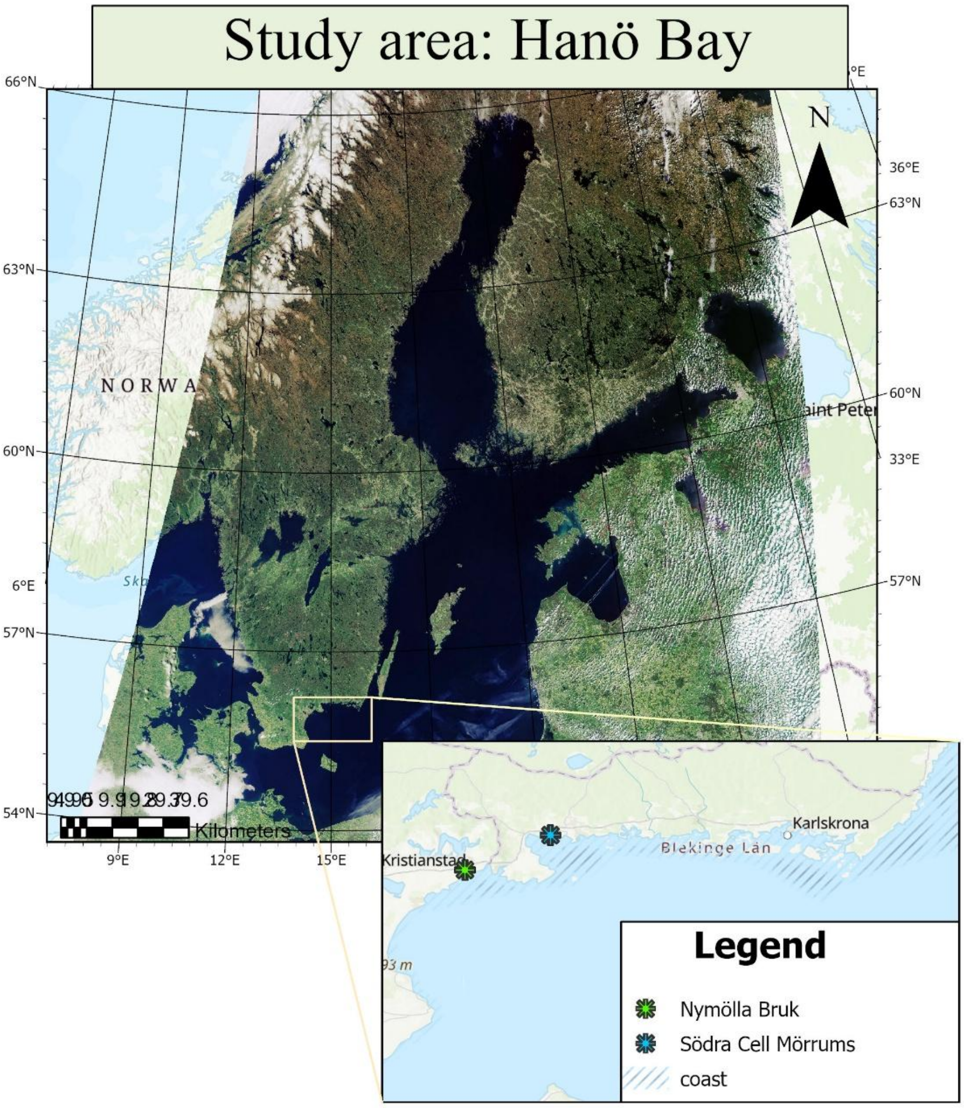


Figure 1. An overview of the Baltic Sea and the study area.

1.1 Aim and significance of the study

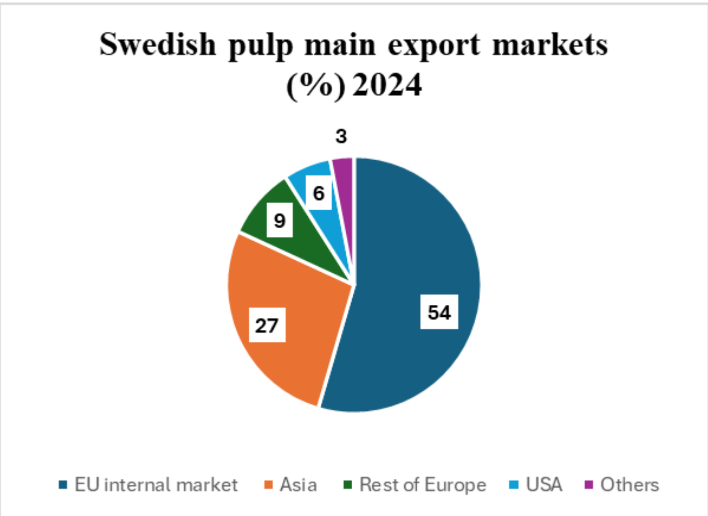
The aim of this thesis is to improve the understanding of the effect of the runoff from paper and pulp mills on brownification in Hanö Bay, Baltic Sea. To achieve this aim, the thesis focuses on the following objectives.

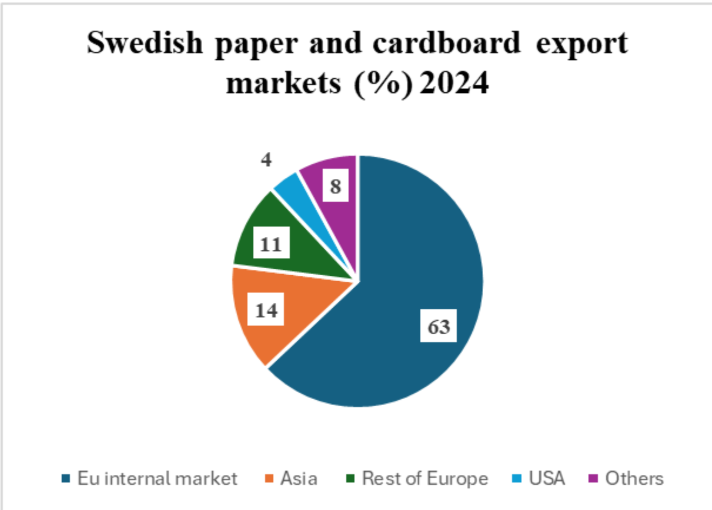
- Investigate trends and statistical significance of total organic carbon (TOC) and absorbance at wavelength 420 nm in the five largest basins that reach the Hanö bay.
- Analyse measured Secchi depth, chlorophyll a concentration, and oxygen content in 16 coastal monitoring stations in the Hanö Bay.
- Visualise spatially modelled Secchi depth.
- Studying the effect of the two mills on brownification in relation to other major causes with available data.

1.2 Background Information

1.2.1 Industries

The forestry sector is one of Sweden's most important industries for its national economy. Together with the steel and metal industry, mining industry, and other smaller non-metallic mineral industries, their exportation accounts for 54% of Sweden's gross domestic product (GDP). In 2024, the exports from the forestry industry generated around €17 billion (Swedish Forest Industries, 2025a). Paper and pulp mills are a subsector of the forestry industry, and Sweden plays a significant role in exporting globally and in Europe. There are around 50 active paper and pulp mills industries (Edlund, n.d.). These industries produce paper and pulp from wood and reused material. The primary export market for Swedish pulp in 2024 was EU internal market, Asia, rest of Europe, USA (fig. 2). The primary export market for Swedish pulp, paper and cardboard in 2024 was EU internal market, Asia, rest of Europe, USA (fig. 2 and 3) (Swedish Forest Industries, 2025b).

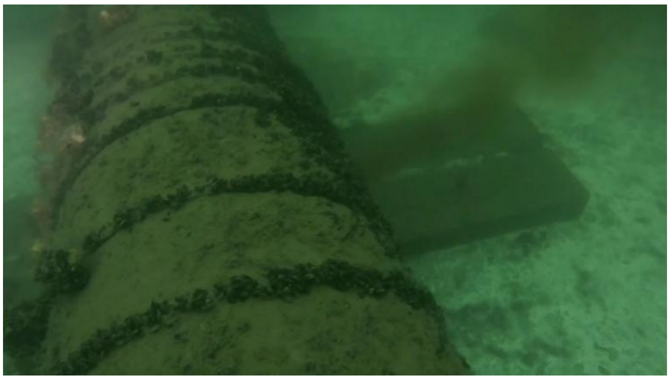




Figures 2-3. The main export markets for paper and pulp mills in 2024.

Historically, paper and pulp industries have contributed to the pollution of both freshwater and marine ecosystems through direct discharge of wastewater. In some cases, industrial wastewater is allocated into coastal waters instead of rivers and lakes in order to preserve water for drinking water and industrial water supply (Clark, 2002). Today, stricter environmental laws and regulations have been introduced to minimise the environmental effect. This includes, the amount of water that may be extracted, volume and quality of wastewater before being discharged into the bay, and wastewater treatment.

Two mills that have raised attention for their notable release of TOC in their waste water in the Hanö Bay are; Nymölla bruk, Bromölla, and Södra Cell Mörrum (Svedäng, et al., 2018). Both of these mills are located near the coast and release wastewater directly into the bay through pipes that extend kilometers under water (fig.4-5). The stricter environmental laws and conditions have significantly decreased the effect of paper and pulp mills in Hanö Bay. (HaV, 2013). Both industries follow extensive treatment processes of their wastewater including biological and physical treatments (Södra Cell, 2025a; Nymölla 2025).



Figures 4-5. Pipes releasing wastewater extending several km underwater, in Nymölla paper mill (left image), and Mörrums pulp mill (right image) (Frilagt, 2019).

1.2.2 Hanö Bay

Hanö Bay is a sandy bay in the Baltic Sea located in the Eastern coast of Scania and Blekinge Southern coast (fig 6). The bay is a part of the Baltic Proper and the sub-basin Bornholm Basin. The Bornholm Basin covers an area of 42,161 km^2 with a maximum depth of 100 m and mean depth of 44 m. The surface salinity ranges between 4.3-8.1 practical salinity unit (PSU) (Race for the Baltic, 2026).

Hanö Bay has been a problematic area since the 1980s and there have been reported issues regarding eutrophication, browner and foul smelling waters, and injured and dead marine and terrestrial wildlife (Svedäng, et al., 2018; HvS, 2013). In the mid 1980s reports from the locals highlighted that the conditions of the bay had worsened. This included injured and sick and dead fish, and increased abundance of algae (Persson & Göransson, 1989). A collaboration between Lund university, and the county of Blekinge and Kristianstad aimed to identify how chages in physical and chemical properties could potetially affect fish and other organisms. The results showed an increase in phytoplakton growth along the coast near the mills and skin injuries in fish (Persson & Göransson). An additional investigation on the fish health was conducted in 2010 by the county of Scania and Blekinge, local fishermen and Sportfiskarna (Havs- och Vattenmyndigheten, 2013). The investigation could not conclude any specific factors causing these problems. Since 1991 the Vattenvårdsförbundet for the western coast of Hanö Bay conducts annual measurements of physical, chemical, biological and ecological parameters in stations close to Nymölla mill. Today, the measurements are conducted by

NIRAS Sweden AB and Linnéuniversity in Kalmar (Blekinge kustvatten och luftvårdsförbund, n.d.). There are two paper and pulp mills located at the eastern coast of the Hanö Bay, Nymölla Bruk and Södra Cell Mörrums (fig 2.). They have released significant concentrations of pollutants from their wastewater.

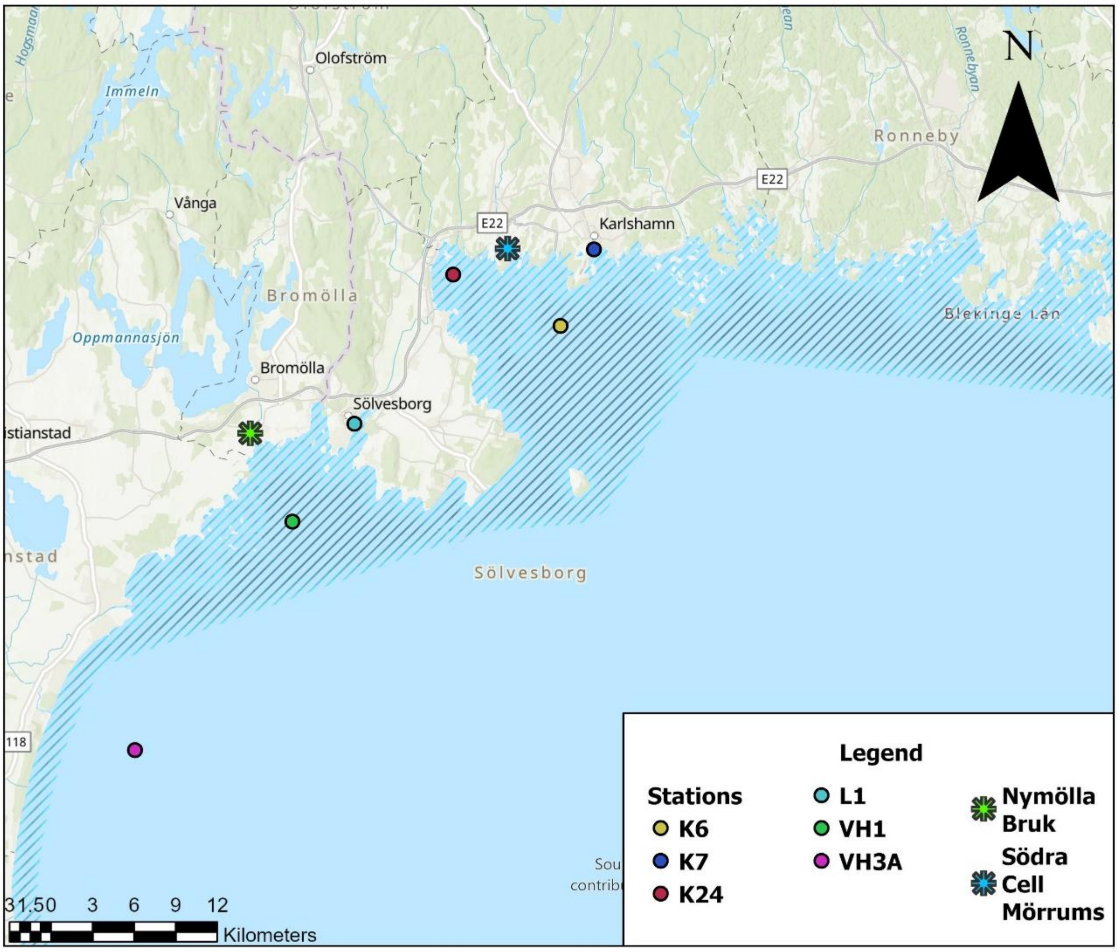


Figure 6. Overview of the Hanö Bay, the two mills, and the six stations.

Five major river basins drain into Hanö Bay: Helge Å, Mörrumsån, Ronnebyån, Skräbeån, and Lyckebyån (fig. 7). The surrounding catchment area is dominated by forest cover and cultivated land (HELCOM, 2021). There have been previous observations and monitoring that have shown increasing trends in water colour, absorbance at 420 nm, organic matter, and chemical oxygen demand (COD) (Svedäng, 2018). COD is the measure of the amount of oxygen required for chemical oxidation of all organic material into their inorganic products (Naturvårdsverket, n.d.c), These trends have been strongest in Helge Å and Lyckebyån (Havsmiljö, 2018). Mörrumsån differs from the rest of the river's basins as the streams and rivers pass through a lake before draining out into the Bay. The water flow is slowed down resulting in lower concentrations of organic and inorganic material that reaches Hanö Bay compared to the rest of the river basins (Svedäng, 2018).

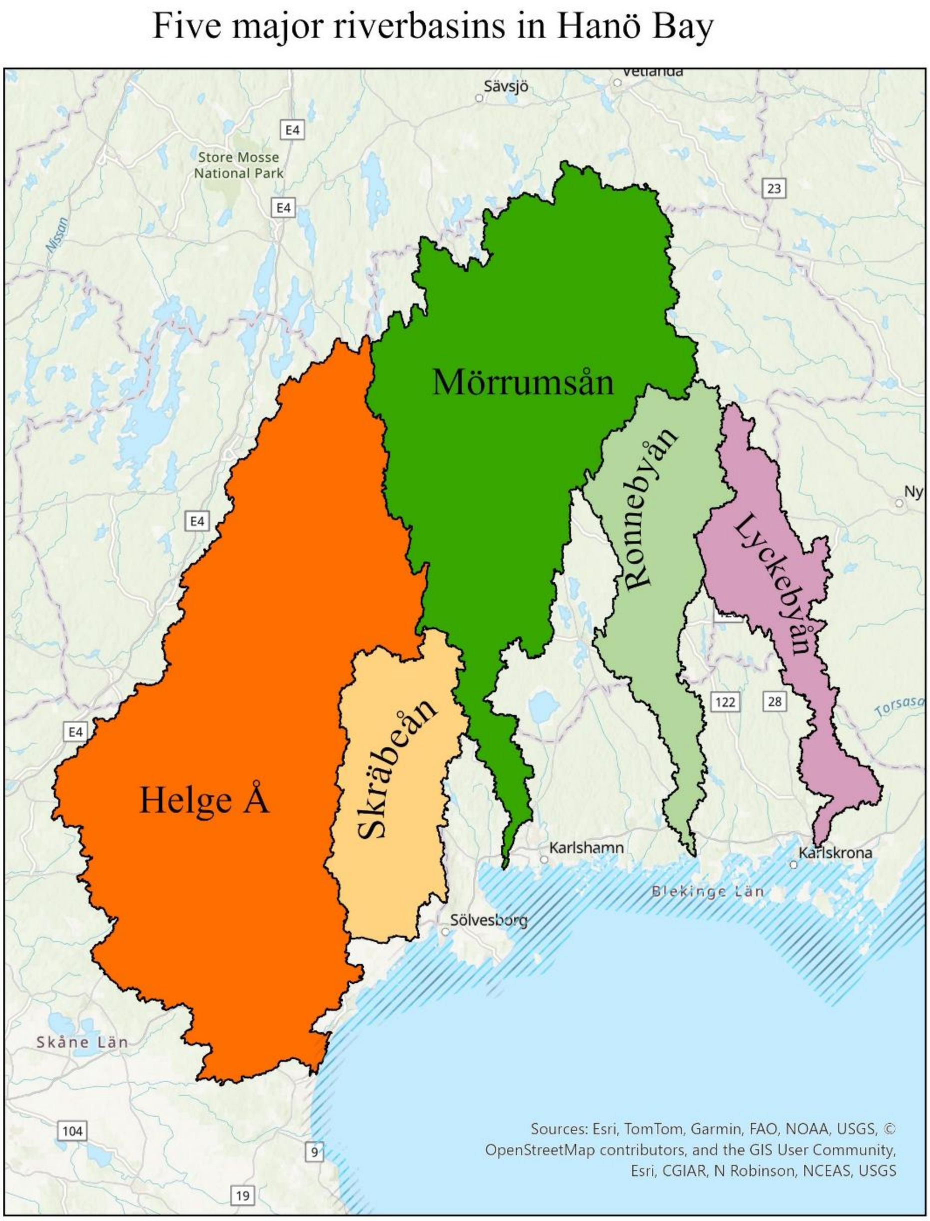


Figure 7. Overview of the five major river basins that have outflow reaching Hanö Bay

1.2.3 Brownification

The light availability plays a crucial role in both marine and freshwater ecosystems (Aigars, et al., 2024). Changes in light environment may affect macrophytes, which are large aquatic plants that are found in coastal and shallow water environments (U.S. Environmental Protection Agency, 2025). Macrophytes have an important ecological role by acting as a shelter for fish and spawning substrates, food source, and produce oxygen through photosynthesis (U.S. Environmental Protection Agency, 2025; Aigars, et al., 2024). Changes in the light environment have been documented and connected to eutrophication and the runoff of nutrients from anthropogenic activities (Dupont & Aksnes, 2013).

In coastal waters, the transition from green to browner colours have been connected to climate change, and alterations in the interactions between terrestrial and marine ecosystems (Monteith, et al., 2007; Opdal, et al., 2023). This process is referred to as brownification or coastal browning and describes the shift of water colour intensity. It is characterised by yellow to brown tones (Kritzberg, et al., 2020). There has been an increasing trend of brownification of lakes, rivers, and streams in the Northern Hemisphere (Opdal, et al., 2023). However, research on coastal browning, as well as interactions between land and coastal waters is still widely debated.

Coastal browning has been connected to increased inputs of organic matter (OM) and dissolved organic carbon (DOC) from terrestrial runoff (Wit, et al., 2016; Jane, et al., 2017). Opdal, et al. (2023), discuss that interactions between climate change, afforestation, reduced acidification promote and increase terrestrial primary production and vegetation density. This results in increased transportation of organic matter to surface waters that drain into coastal waters (Opdal, et al., 2023). Fleming-Lehtinen, and Laamanen (2012) argue that shifts in the coastal light environment are caused by an increase in coloured dissolved organic matter (CDOM).

Along the western coast of Hanö Bay there have been observations that water has gained colour and a smell (Havsmiljö, 2018). These changes occur primarily near the mouth of Helge Å, and in proximity to Nymölla paper mill. The river basins draining into the bay contain high concentrations of CDOM and OM. Kritzberg & Ekström, (2012), document that concentrations of CDOM and OM have increased significantly in the last 30 years. However, there is no clear relationship between the Secchi depth (water transparency) of the bay and the coloured outflow from the river basins.

Svedäng (2018) explains that there are two reasons why it is difficult to identify browning and its causes; red algae and photochemical reactions. Red algae may contribute to the colour and smell in the bay. Photochemical degradation is a chemical process in which CDOM absorbs ultraviolet and visible light and breaks down CDOM into colourless byproducts (Helms, et al., 2013). This may alter and weaken the relationship between terrestrial CDOM input and the observed Secchi depth. This makes it more difficult to identify brownification. (Svedäng, 2018).

1.2.4 Methods for measuring brownification

1.2.4.1 Total organic carbon

Total organic carbon (TOC) is a parameter used to quantify the concentration of organic carbon in water, including both dissolved and particulate carbon. It is commonly used as an indicator of water quality, especially in drinking water and environmental monitoring (Alcontrol AB, 2004). The TOC data source used in this thesis does not contain information about how the measurement was derived. Two common approaches are the differential method and the non-purgeable organic carbon (NPOC). The differential method takes the difference between total carbon and total inorganic carbon to derive TOC. The NPOC measures the remaining organic carbon in a sample after acidification and purging. Those two processes remove inorganic carbon and other purgeable organic compounds (Kim, et al., 2023).

Organic matter occurs naturally in aquatic ecosystems through living organisms and decomposing matter. However, elevated TOC content may result from anthropogenic inputs, including industrial wastewater, agricultural runoff, and land-based source (Naturdvårdsverket, n.d.d).

TOC and eutrophication processes are closely related. Increased nutrient inputs promote higher algal growth, which in turn contributes to higher organic matter concentrations in the water column. Microbial degradation of OM consumes dissolved oxygen, meaning that areas of high TOC concentrations there may be an increase in biological oxygen demand. This can result in oxygen deficiency, primarily in bottom waters, with negative impact on marine organisms. (Naturvårdsverket, n.d.d). The classification for the concentration in TOC can be found in table 4. in the methodology.

1.2.4.2 Absorbance

Water colour can be assessed by measuring the absorbance at 420 nm, which is an indicator of coloured dissolved organic matter (CDOM) and other light absorbing substances, Elevated concentrations of DOC, OM, suspended sediments, algal chlorophyll, and pollutants alter optical properties of water (Sveriges Lantbruksuniversitet, 2026). There is a shift in colour towards green, yellow or brown hues. Increased water colour reduces light penetration which directly affects light dependent organisms such as submerged macrophytes and phytoplankton (U.S. Environmental Protection Agency, 2025).

The absorbance data used in this thesis was measured using a spectrophotometer. A spectrophotometer measures the amount of light that is absorbed, reflected or transmitted by a substance. The spectrophotometer samples were measured in a 5 cm cuvette at wavelength 420 nm (Sveriges Lantbruksuniversitet, 2026).

Water colour can also affect the thermal conditions in surface waters; darker water absorbs more solar radiation which can contribute to elevated surface water temperatures. This may strengthen the already existing vertical temperature gradient (Sveriges lantbruksuniversitet, 2026). An increase in water colour and organic material in the five major basins water outflow have caused significant colouring in the Bay (Svedäng, 2018). Classifications and threshold of absorbance can be found in table 4.

1.2.4.3 Secchi depth

Secchi depth is a measure of water transparency and is measured by using a white disk that is lowered into the water until it is no longer visible. It is commonly used for assessing water quality in areas that are subjected to eutrophication and terrestrial runoff containing DOC and OM (HELCOM, 2023c). Secchi depth is influenced by several factors, including concentration of suspended particles such as algae and silt, water colour, and seasonal variation.

The interpretation of Secchi depth depends partly on the actual depth of the water body. For the Bornholm Basin, the summer Secchi depth threshold for the period June to September is 7.1 m. However, the water clarity for 2016-2021 only assessed a small portion of the Western Hanö Bay. The available areas were assessed as good and moderate (HELCOM, 2023c).

1.2.5 Other variables analysed

1.2.5.1 Chlorophyll a

Chlorophyll *a* (chl *a*) concentration is commonly used as a proxy for phytoplankton biomass. Phytoplankton forms the base of the pelagic food web and plays a central role in aquatic primary production (D´Costa & Nail, 2019). Algal blooms occur naturally during spring and summer when temperature, light conditions, and nutrient availability are favourable. However, excessive nutrient inputs from agricultural runoff and industrial wastewater can enhance phytoplankton growth and increase biomass (HELCOM, 2023b). Increased phytoplankton biomass contributes to a greater supply of organic matter to bottom waters as algal material sinks and decomposes (HELCOM, 2023b). This process can reduce oxygen availability and intensify the already vulnerable oxygen conditions.

The chlorophyll a data used in this thesis was measured according to HELCOM's Combine Manual method. The samples were extracted for 20 hours before being centrifuged and finally analyzed at one wavelength in a microplate reader (Isaksson, et al., 2024).

HELCOM (2023b), established a summer chl *a* threshold values for June to September based on model simulations from the TARGEV project (HELCOM, 2013). The threshold value for the Bornholm Basin is 1.6 µg/l, status in 2016-2021 for the Hanö Bay was primarily poor and moderate, with a small region classified as good. For the Bornholm Basin, the threshold value is 1.6 g L^{-1}. During the 2016-2021 assessment period, the chlorophyll *a* status in Hanö Bay was primarily classified as poor or moderate. A small area was classified as good (HELCOM, 2023b).

1.2.5.2 Dissolved oxygen

Dissolved oxygen (ml L^{-1}) is a measure of the concentration of O_2 dissolved in the sea. The oxygen content is measured using an oxygen probe placed at different depths (Isaksson, et al., 2024). The primary source for bottom-water oxygen is the inflow of oxygen-rich water from the North Sea. The enclosed nature of the Baltic Sea and minimal inflow from the North Sea characterises the Baltic Proper deep regions low oxygen content (Hansson & Viktorsson, 2024).

Eutrophication and increased concentrations of organic matter can further reduce the oxygen availability. As organic matter settles and decomposes, microbial degradation consumes large amounts of oxygen (Axe, 2010). When oxygen consumption exceeds the rate of oxygen replenishment through water exchange and mixing, some oxygen deficiency may develop. Anoxia is a condition in which there is a complete absence of oxygen in the bottom waters. Hypoxia is another condition in which the dissolved oxygen becomes critically low to sustain (Hansson & Viktorsson, 2024).

1.2.6 Mills

1.2.6.1 Pulp mill Södra Cell Mörrum

The Södra Cell Mörrum is a pulp industry that is part of the Södra Cell industry. The pulp mill is in Mörrum in the county Blekinge, close to the Pukavik bay. It has been active since 1962 and has exported pulp throughout Europe. There are two production lines, one producing pulp and the other one producing dissolved pulp that can be further utilized in textile and other applications (Södra, 2025a.). The production capacity per year is 560 000 tons of pulp (Södra cell, 2025b). Pulp production uses large quantities of water, and the primary water source is from Mörrumsån (Södra cell, 2025a). Internal daily tests are taken of TOC, P-tot, N-tot, chlorate, and weekly tests of AOX are taken from the wastewater BOD_7 is taken monthly externally. AOX, are adsorbable organically bound halogens, and in the 1980s chlorine gas was used for bleaching pulp (Naturdvårdsverket, n.d.e; Södra Cell, 2025b). From the early 1990s the use of AOX has decreased significantly but residuals can still be found when chlorine dioxide is used for bleaching (Södra Cell, 2025b). The mill is allowed to release a regulated amount of substance into the bay; those are summarized in table 1. The annual amount of TOC released into Hanö Bay from 2006 to 2025 can be seen in figure 8.

Table 1. Annual increase and limits for parameters in Södra Cell Mörrums. The following abbreviations stand for; Kgptm: kilogram per total pulp mass, RV: riktvärde/reference value, and GV: gränsvärde/limit (Södra Cell, 2025b; Södra Cell, 2002b).

Release into water						
	Unit	**2025 Annual release (tons/year)**	**Limit 2025**	**2000 Annual release (tons/year)**	**Unit**	**Limit 2000**
Parameters						
AOX	mg/l	29	10 mg/l RV/month	88	t/d	0.5 kg/ton pulp GV/year
Klorat	mg/l	-	0.3 mg/l RV/month	293	t/d	1.5 t/d RV/quarter
Nitrogen	Kgptm	40	130-ton GV/year	124	kg/d	0.4 kg/ton pulp GV/year
Phosphorus	Kgptm	7	14-ton GV/year	14	kg/d	0.04 kg/ton pulp RV/month
TOC	Kgptm	1988	3 800-ton GV/year	-	-	-
Suspended particles	mg/l	-	10 mg/l RV/month	-	-	-
COD		-	-	15 600	t/d	45 t/d RV/month

1.2.6.2 Nymölla paper and pulp mill

Nymölla is a paper and pulp mill located in Nymölla in Southern Sweden. It has been active since 1962, and in 2022 the American company Sylvamo took over from the previous owners Stora Enso. The annual allowed production capacity for pulp is around 350 000 tons, and 560 000 tons for paper. In 2024 around 300 000 tons of pulp and 380 000 tons of paper were produced (Sylvamo, 2025). The production of pulp and paper requires large quantities of processed water, and it is derived from Skräbeån. The maximum uptake of water from Skräbeån is 3 m^3/s, it has been around 1.0-1.2 2019-2024 (Stora Enso 2019, 2020, 2021, 2022; Sylvamo, 2024). The parameters and their limit and annual release in 2024 and 2021 can be seen in table 2. The wastewater is released into Hanö Bay through a 3.4 km long discharge tube (fig. 4-5) (Sylvamo, 2025). Before the wastewater is released into the bay it undergoes biological and physical cleaning treatments, and the processed water is then filtered using ultrafiltering. The annual release of TOC can be observed in figure 8. The Nymölla mill has put significant effort in reducing the release of organic substances such as COD. The biological treatment and other treatments of the wastewater have reduced the COD by 80%. Around 75 000-80 000 m^3/sec has been released into Hanö Bay (Stora Enso, 2019, 2020, 2022; Sylvamo, 2024, 2025). The annual TOC for 2006 to 2025 can be seen in figure 8.

Table 2. Nymölla paper and pulp annual release for 2024 and 2019, and the limits (Sylvamo, 2025; Stora Enso).

Release into water					
	Unit	**2024 Annual release (ton) Sylvamo**	**Limit 2024**	**2021 Annual release (ton) Stora Enso**	**Limit**
Parameters					
Total phosphorus	kg/operating time	22	50	21	50
Total nitrogen	kg/operating time	205	500	228	500
COD	ton/operating time	28	45	30	45
Waste water flow	m^3/operating time	79 589	-	78 992	-
Suspended particles (GF/A)	ton/operating time	0.7	4	1.1	4

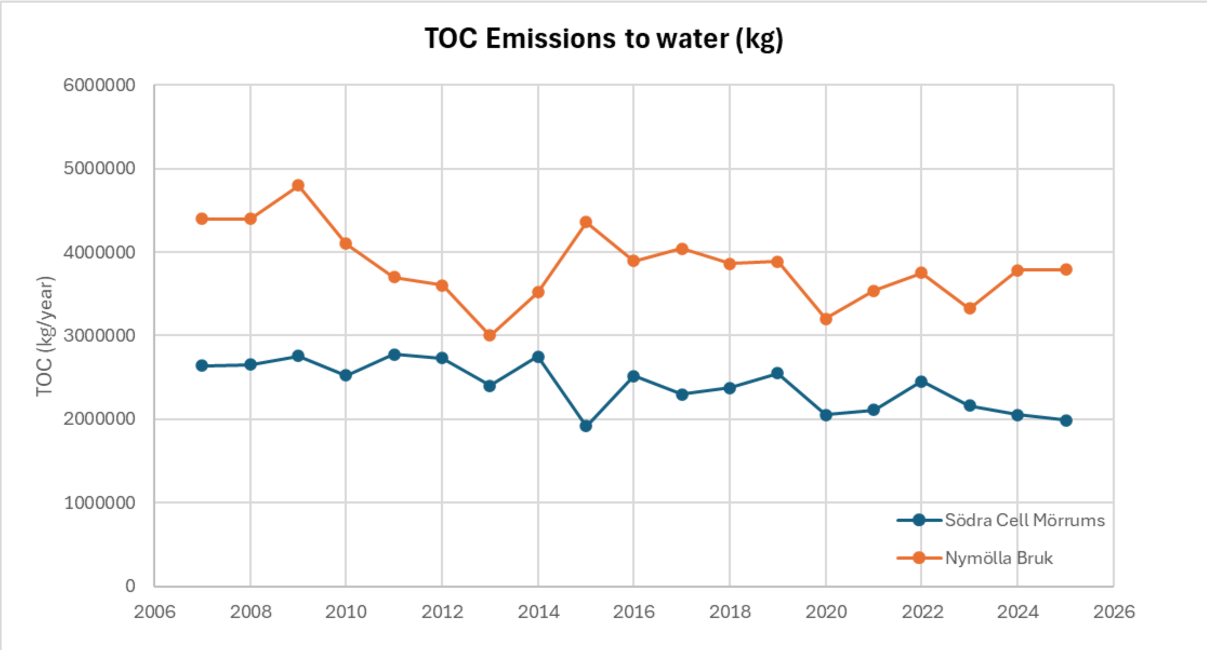


Figure 8. The emissions of total organic carbon into water (kg/year) in Södra Cell Mörrums pulp mill and Nymölla paper mill. (Naturvårdsverket, n.d.a; Naturvårdsverket, n.d.b).

2 Methodology

2.1 Data

The data used in this thesis is summarized in table 3.

Table 3. Information about the data that has been used in this thesis.

Data name	Resolution/Data type	Source
River stations in the following riverbasins: Mörrumsån, Helge Å, Skräbeån, Ronnebyån, and Lyckebyån		
Total organic carbon for monitoring stations in the river basins for the time period between 1979 to 2026.	Excel data	SLU miljö (2026)
Absorbance at 420 nm for monitoring river stations in the river basis for the time period between 1979 to 2026.		
Coastal monitoring stations in Hanö Bay		
Monthly data for Secchi depth (m), chorophyll a concentration, and oxygen content from 2011 to 2025. Six stations: VH1, VH3A, K6, K24, K7, and L1.	Excel data	Blekinges vatten- och luftvårdsförbund (n.d.)
Other data		
Monthly modelled Secchi depth data (m), 2014 to 2024 for Hanö Bay coast. The data is created by a reanalysis of two integrated model, the biogeochemical model ERGOM, and the ocean-ice model, NEMO-Nordic.	Modelled data, NetCDF	Produced by Danish Meteorological Institute (DMI) and distributed through the Baltic Marine Forecasting Centre Copernicus (2023).
Baltic Sea satellite imagery		Produced by Copernicus, and distributed by The European Space Agency (ESA, 2021).
Water drainage basins for	Polygon, vector, SWEREF 99 TM	SMHI (2026)
Sweden administrative boundaries		
Swedish Coast		

2.2 Statistical Analysis

All statistical analysis was performed in the software MS Excel. A statistical package, Real Statistics Resource Pack Software was added in Excel to be able to perform more complex statistical analysis (Zaiontz, 2026, a). The nature of the normal distribution of the datasets was determined by descriptive statistics and normality test, Shapiro-Wik. The datasets showed a mixture of normal and non-normal distribution., thus non-parametric tests including Mann-Kenn, Theil-Sen, Pettit's test, and Cox-Stuart tests were performed. These types of tests are commonly used when studying time series and change in environmental variables. The Mann-Kenn test (Mann, 1945, Kendall and Gibbons 1990) assesses whether there is a monotonic upward or downwards trend. The Theil-Sen fits the data into a linear trend. The Pettit's test, also known as the change point test, determines the change that shifts the median. The Cox-Stuart test estimates whether there is an increase or decrease in the times series (Zaionts, 2026b). A confidence level of 95% (α= 0.05) was used for all four tests. A probability value (p-value) less than p<0.05 indicates that the observed trends are unlikely to happen by chance and are considered statistically significant. Likewise, a p-value larger than 0.05 indicates an insignificant result. Based on the performed test, the results were divided into four groups; significant increase, insignificant increase, significant decrease, and insignificant decrease.

The stations chosen for the TOC and absorbance at 420 nm were based on two criteria, data of at least 10 years and measurements taken up until 2026. The annual mean was taken from each station and then a time series was created. The values from the time series from each station were compared with the classifications in table 4.

Table 4. Classes for absorbance and TOC in lakes and rivers (Alcontrol AB, 2005; Pirzadeh & Collvin, 2008).

Classification	Absorbance (Filter)	TOC (mg/l)
No or insignificant water colour	≤0.02	≤4
Weak water colour	0.02-0.05	4-8
Moderate water colour	0.05-0.12	8-12
Strong water colour	0.12-0.2	12-16
Significant water colour	>0.2	>16

Table 5. Threshold for oxygen concentration (Hansson & Viktorsson, 2024).

Condition	Threshold dissolved oxygen concentration (ml/l)
Anoxia	0
Hypoxia	< 2
Good oxygen conditions	> 2

2.3 Seasonal time series and statistical analysis of Hanö Bay

Data for chemical and physical variables for 6 out of 16 stations that were located closest to the two mills were chosen; VH3A, L1, K24, K7, VH1, and K6. The chosen period to analyse was from 2011-2025 because previous years had data gaps (Blekinge kustvatten och luftvårdsförbund, n.d.). Measurements from the stations were taken during winter (December, January, and February), and summer (July and August). Thus, this analysis looks at the variables through a seasonal perspective instead. The parameters that were used for this analysis were Secchi depth, chlorophyll a concentration, oxygen concentration (in ml/l). TOC measurements were only taken between 2011-2015, thus were decided to be excluded from this analysis. The winter and summer mean was taken for each parameter, and a time series was created to determine trends and change.

The data was tested for normality, and the results showed that the data followed a normal distribution. Thus, the common linear correlation test was performed for only Secchi depth to analyse if there is any trend in the time series.

2.4 GIS Visualization

For all map creations and visualizations, the software ArcGIS pro was used. Secchi depth monthly data for the time period 2014 to 2024 was used to analyse any changes along the coast and near the mills. The data was produced by a reanalysis of two integrated models, the biogeochemical model ERGOM, and the ice-ocean model NEMO. ERGOM stands for Ecological ReGional Ocean Model, and the updated version takes into account and reproduces variables such as oxygen, partial pressure of CO2, and nutrients (Neumann, et al., 2022). The ERGOM model stands out from other biogeochemical models as it considers a non-Redfieldian carbon fixation, better estimates for carbon fixation by primary producers. The NEMO-Nordic is a model for the Baltic Sea and the North Sea, and is based on the NEMO, Nucleus for European Modelling of the Ocean model. NEMO is generally used for short- and long-term simulations and considers anthropogenic and climate change pressure (Hordoir, et al., 2019).

The spatial resolution of the dataset is 2 km and a temporal extent from 1 January 1993 to 31 December 2024. The data format was in NetCDF and was transformed into a raster layer using the tool *Make NetCDF Raster Layer*. Due to differences in the dataset size between months, it was not possible to analyse Secchi depth trough a monthly perspective. Thus, the monthly mean was taken from 2014 to 2024 using the tool *Raster Calculator*.

3 Results

3.1 TOC

3.1.1 Overall trend

The overall TOC trend for all five river basins for the period 1979-2025 is a significant increase of 62%. Further statistical analysis was performed on the station closest to the river mouth of each basin. Four out of five stations showed a significant TOC increase. The river basins, Helge Å, Mörrumsån, and Skräbeån, which are closest to the two mills, all had a significant increase trend (fig. 9).

TOC trend

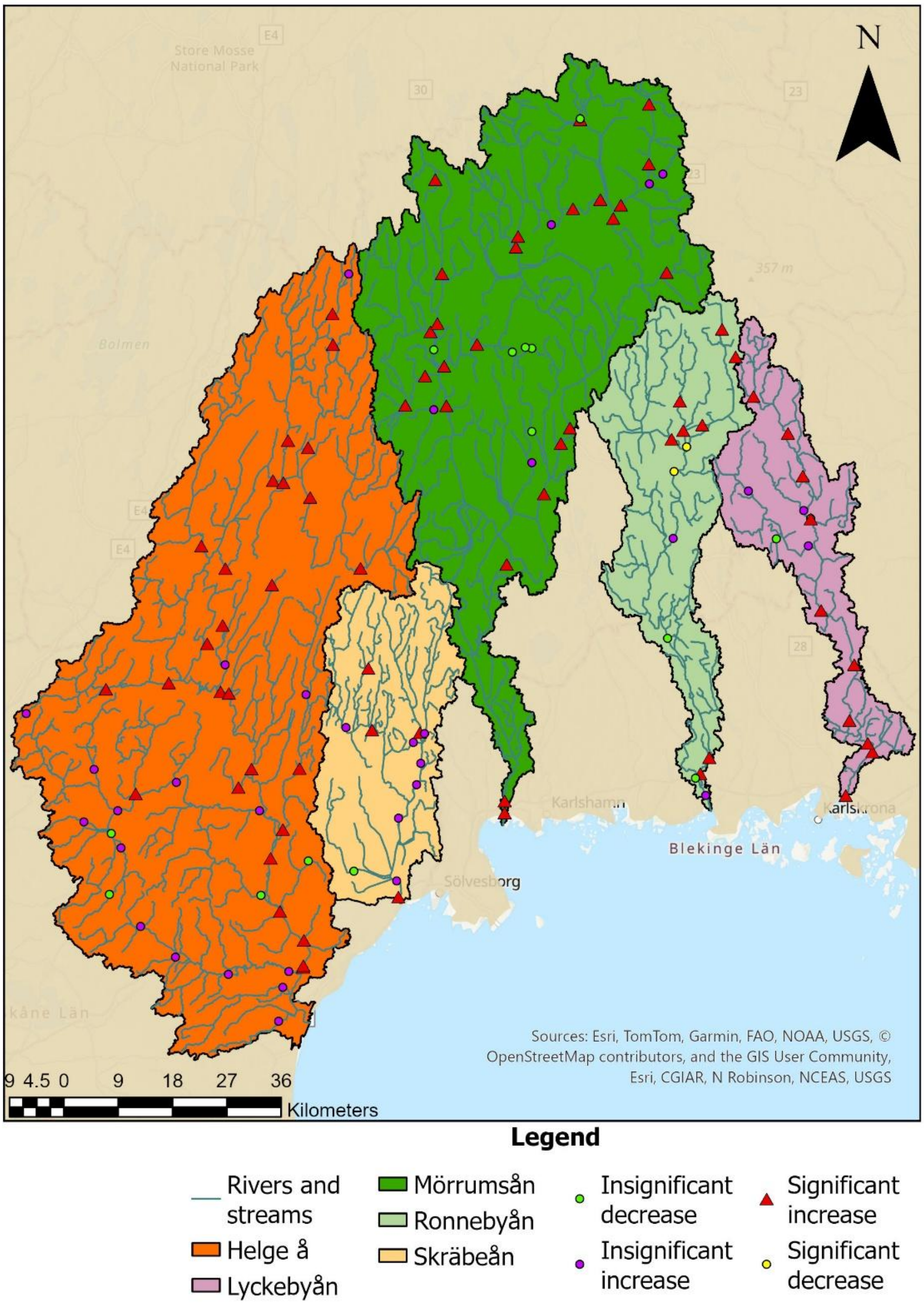


Figure 9. The overall TOC trend and significance pattern for the stations in each river basin between 1979 and 2025. The significance and trend were based on statistical tests.

3.1.2 Stations closest to the river mouths

More detailed statistical analysis of the stations closest to the river mouth of the basins was also performed. The station in Ronnebyån was not analysed as it had an insignificant increase, thus not relevant for the analysis. Pettit's non-parametrical statistical test was used to identify when the significant shift of the mean occurs in the TOC time series of the four stations. The shift for station 219, Mörrumsån occurred in 1999, a few years before the rest of the stations (fig. 10). For Helge Å Hammarsjön, Skräbeån vid Käsemölla, and 17 Lyckeby the shift of the mean occurred in 2006 (fig 11-13). According to the classification of water colour in table 4, the stations in Lyckeby, Helge å, and Mörrumsån, are classified into strong and significant high TOC concentrations. Skräbeån has had lower TOC concentrations in general and is classified into moderate TOC content The overall result shows that there is an increase in TOC concentrations in these stations. The detailed statistic for each station can be found in Appendix A.

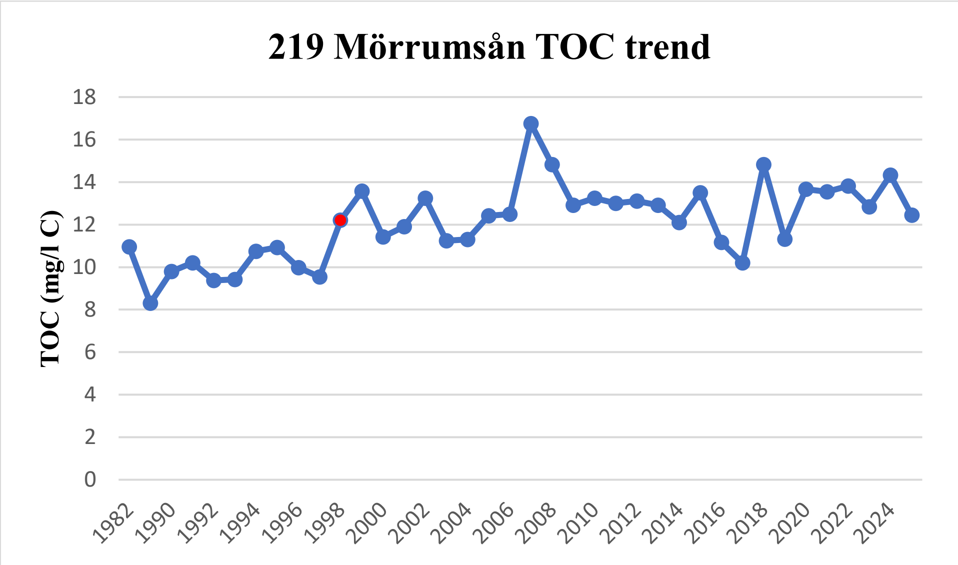


Figure 10. Time series for 219 (2 km uppströms mynningen i Östersjön). This station had a significant increase, and this shift occurred in 1999 represented by the red dot.

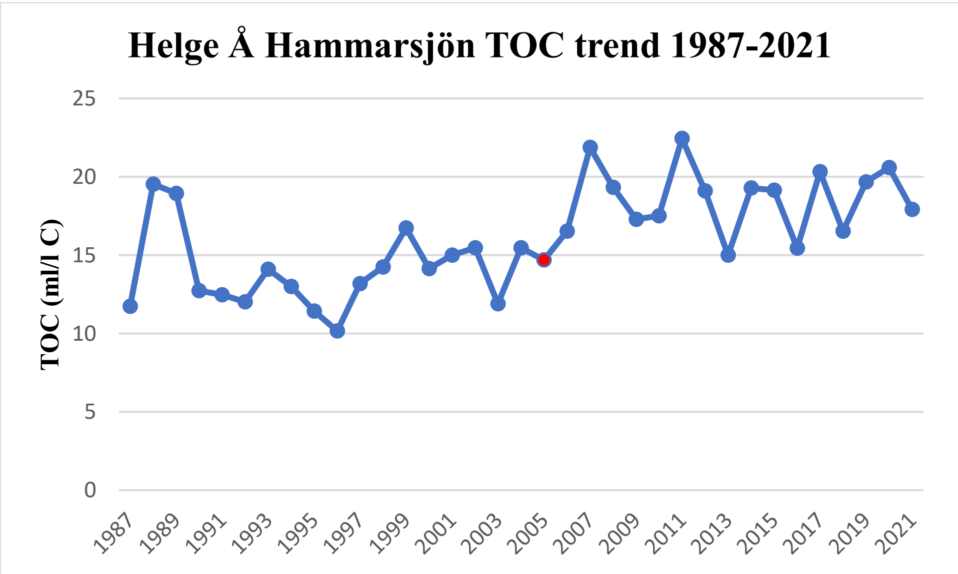


Figure 11. Time series for Helge Å, Hammarsjön. This station has a significantly increasing trend, and the shift occurred in 2006, represented by the red dot.

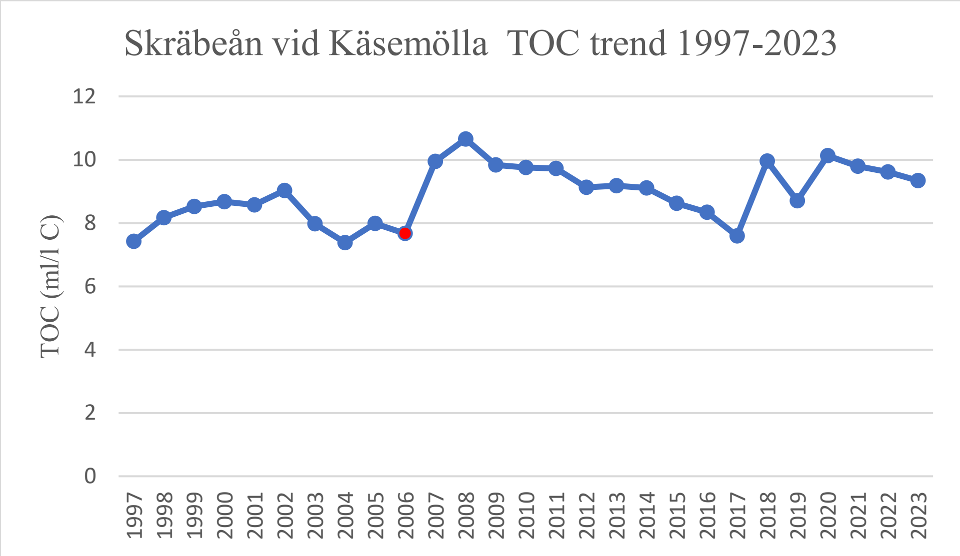


Figure 12. Time series for Skräbeån vid Käsemölla. The station has a significantly increasing trend, and the shift occurred in 2006, represented by the red dot.

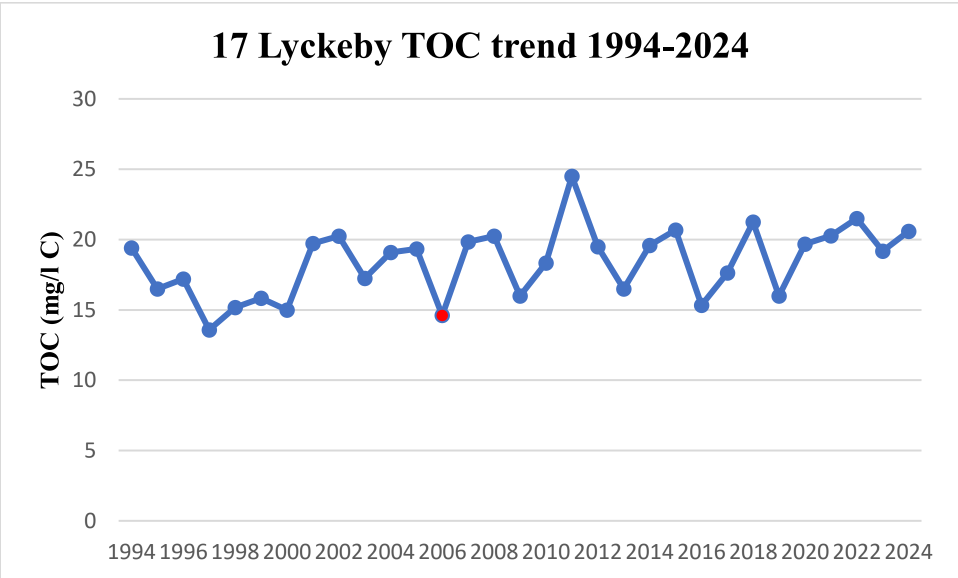


Figure 13. Time series for 17 Lyckeby. The station has a significantly increasing trend, and the shift occurred in 2006, represented by the red dot.

3.2 Absorbance at 420 nm

The trend and the significance pattern of the absorbance at 420 nm can be seen in figure 14. The primary trend was a non-significant increase and decrease. A closer analysis was performed on the stations closest to the river mouths. Helge å, Hammarsjön was the only station that had a significant increase trend. The shift of the mean occurred in 1997 (fig. 15). Between 1975 and 1997, the absorbance value is classified as strong water colour, with values in 1985 and 1988 even reaching significant water colour. After the trend shift in 1997, the absorbance values are classified as significant water colour. The rest of the stations have an insignificant increase or decrease (fig. 16-19). Helge Å, Hammarsjön, Ronnebyån, and 17 Lyckeby have values higher than 0.2, indicating that there is significant water colour in those stations. Skräbeån is classified into moderate water colour, and 219 Forsbacka into strong water colour. The overall results indicate that there is strong to moderate water colour in the five river basins.

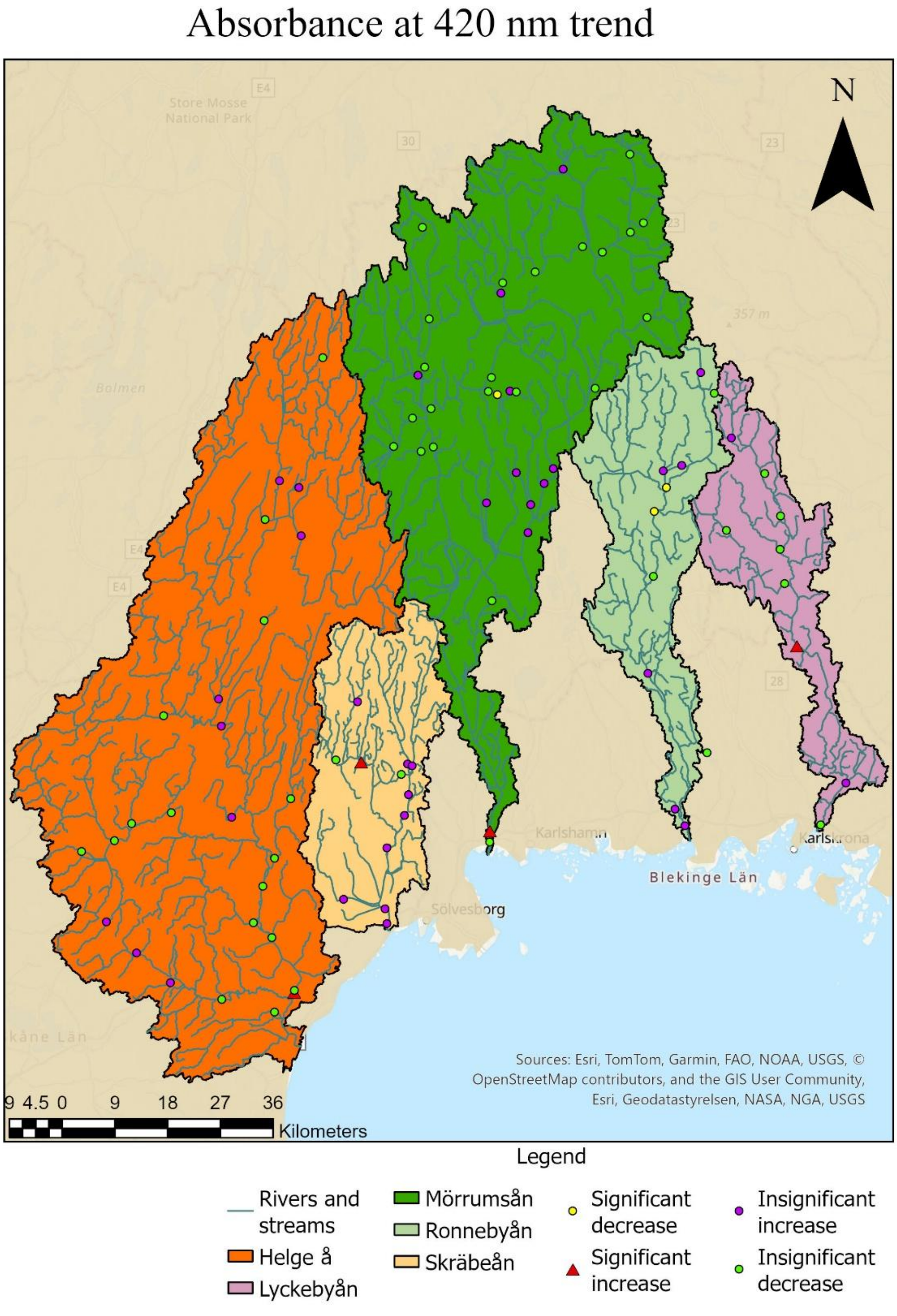


Figure 14. The overall absorbance at 420 nm trend and significance pattern for the stations in each river basin between 1979-2025. The significance and trend were based on statistical tests.

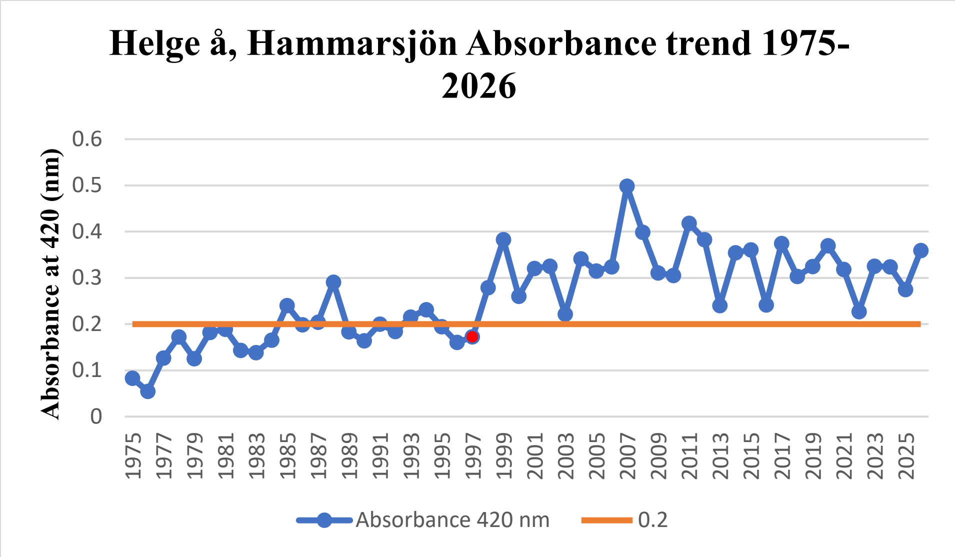


Figure 15. Time series for absorbance of 420 nm in Helge å, Hammarsjön. There are a significant increasing trend and shift occurred in 1997, represented by the red dot. The orange line, 0.2, represents the classification for significant water colour (>0.2 nm). From 1999 and onwards the absorbance is classified as a significant colour.

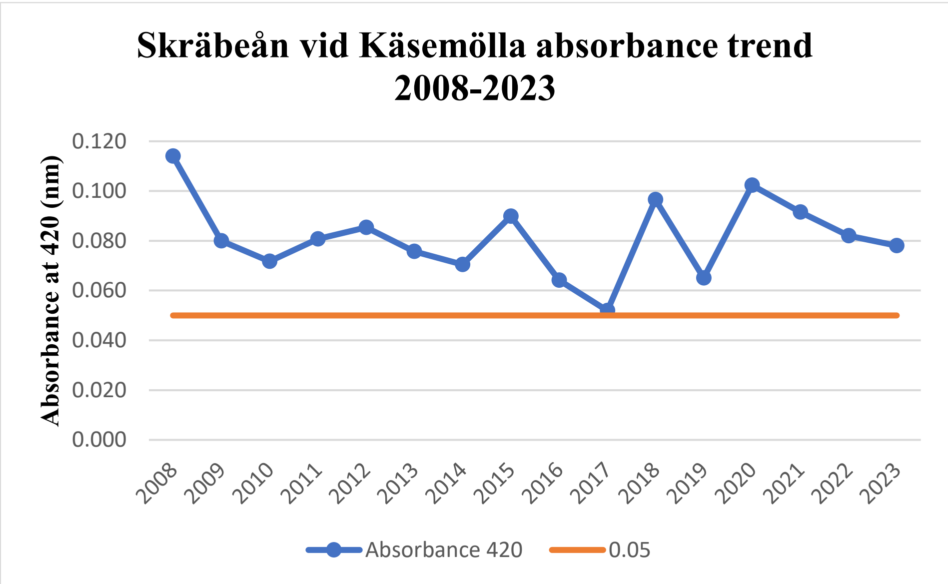


Figure 16. Time series for absorbance in Skräbeån vid Käsemölla. The station showed an insignificant increasing trend. The orange line represents the lower limit for moderate water colour classification (0.05-0.12). The values are classified into moderate water colour.

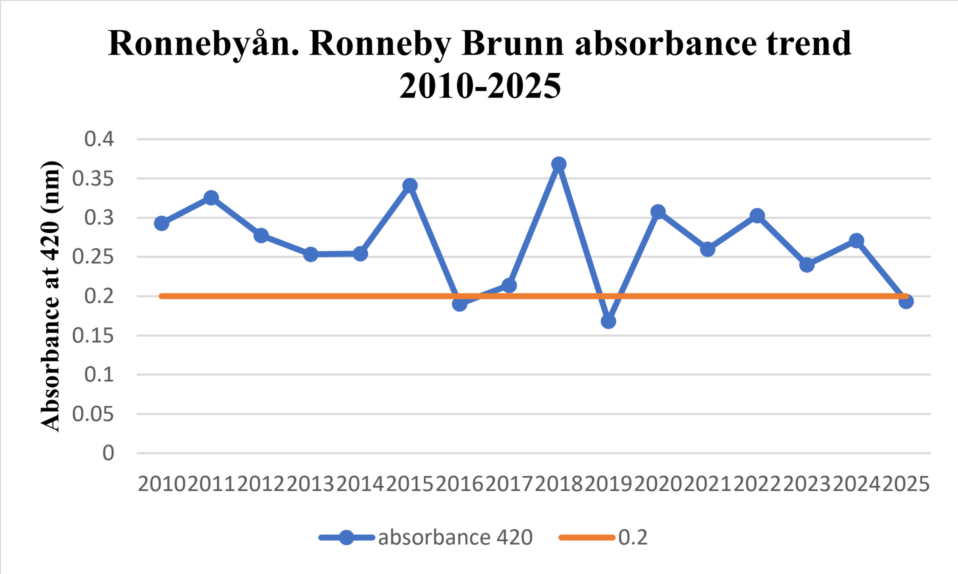


Figure 18. Time series for absorbance at 420 nm in Ronnebyån. Ronneby Brunn. The trend for absorbance is insignificant increase. The absorbance values are mainly classified into significant water colour.

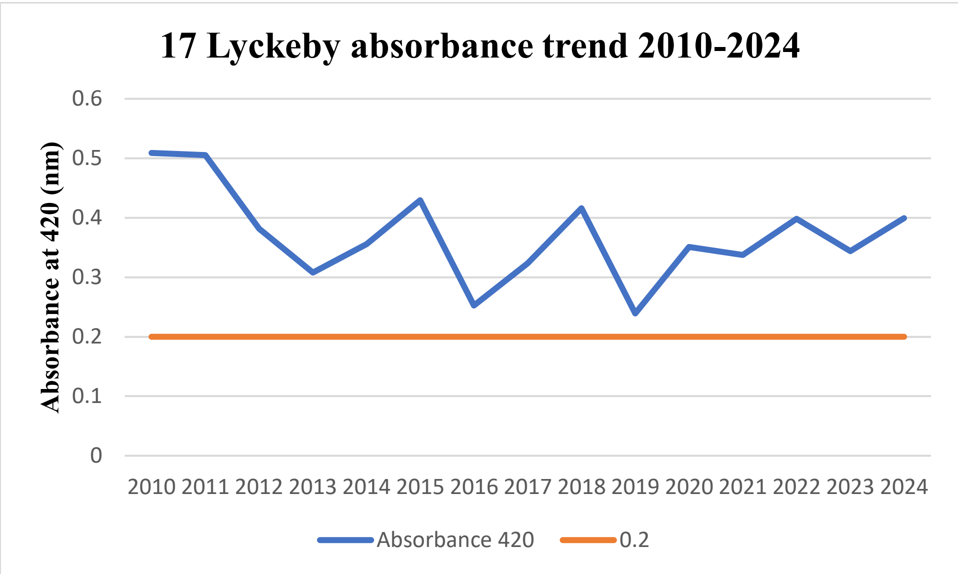
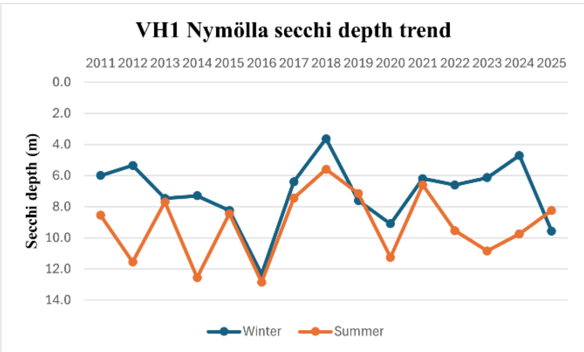


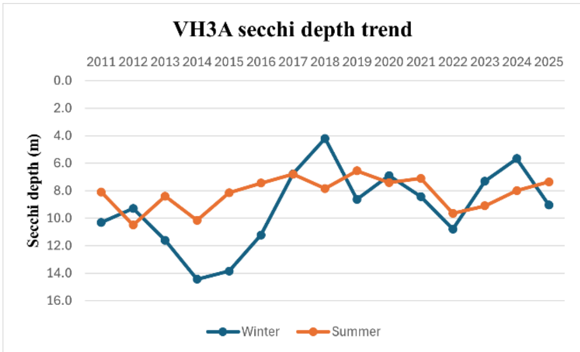
Figure 19. Time series for absorbance at 420 nm in 17 Lyckeby. There is an insignificant decrease trend, and the absorbance values are classified into significant water colour.

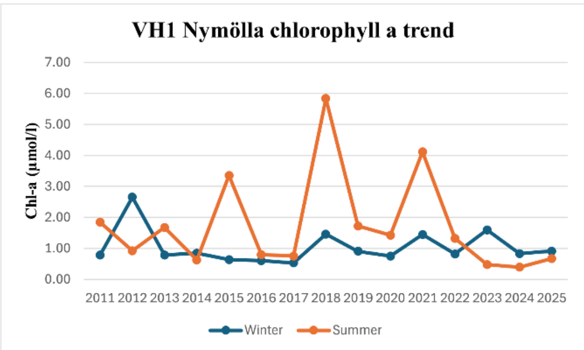
3.3 Hanö Bay stations

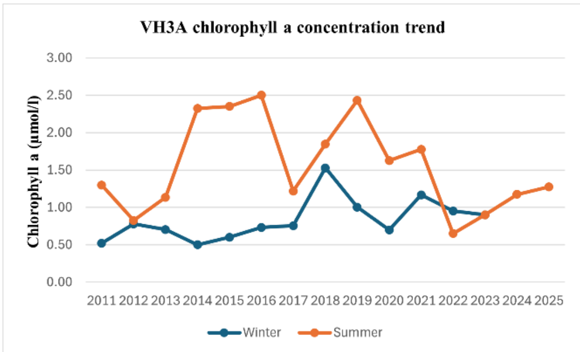
3.3.1 Time trend series of the parameters

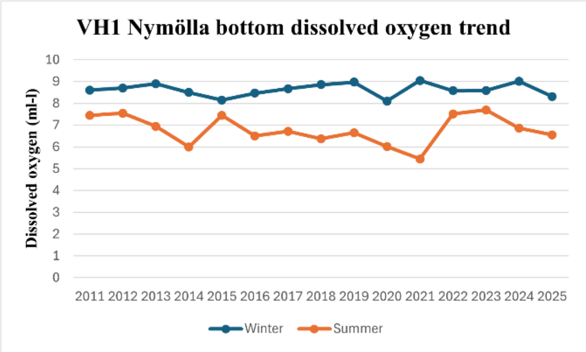
Figures 20 to 36 show time series for 2011-2025 for Secchi depth, chlorophyll *a* concentration, and oxygen concentration in the bottom, for stations VH3A, L1, K7, K6, and VH1. The oxygen concentration at bottom remained constant with little variation in each station. The only exception was in L1 in Winter, where the concentration decreases in 2017 and sharply increases from 2018 and onwards. The L1 winter oxygen concentration almost reaches the hypoxia upper limit, 2 ml/l. The rest of the stations have stable oxygen levels above 2ml/l, and the oxygen concentration is higher during winter compared to summer. The chlorophyll *a* concentrations vary greatly between seasons and stations. The general trend between stations is that the concentrations are higher during summer compared to winter. There is overlap between seasons for some of the stations (VH3A, K24, VH1). Station 24 stands out from the rest as there is no overlap between seasons. In L1 there are two high peaks in 2014 and 2015. The general Secchi depth trend is higher Secchi depth in winter compared to summer. Stations VH3A and L1 had higher Secchi depths from 2011-2017 for both seasons, and onwards the seasonal Secchi depth shows little variation and there is less difference between summer and winter. K24 is the only station that has no overlap between the seasonal Secchi depths. Stations K7, K6, and VH1 have less variation between seasons, and difference between summer and winter. There is some relationship between Secchi depth and chlorophyll a concentration. The general trend is that Secchi depth decreases during summer and chlorophyll a concentration increases, vice versa.

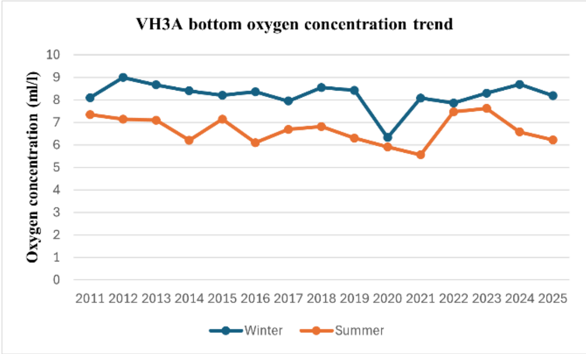


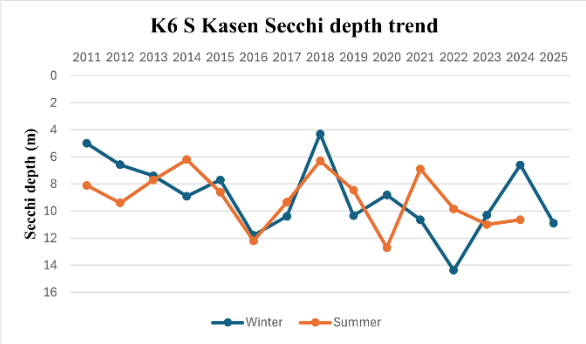


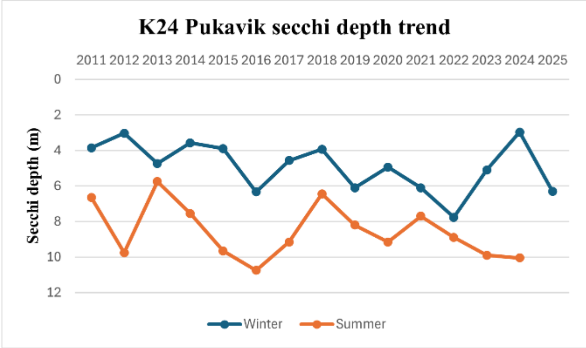


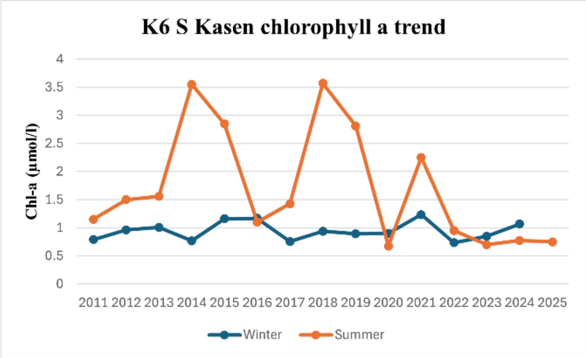


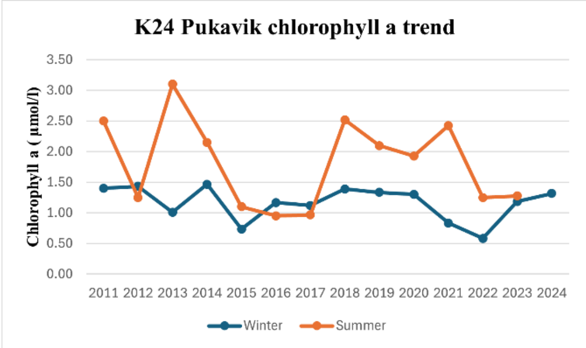

VH1 Nymölla bottom dissolved oxygen trend
Dissolved oxygen (ml-l)
Winter
Summer

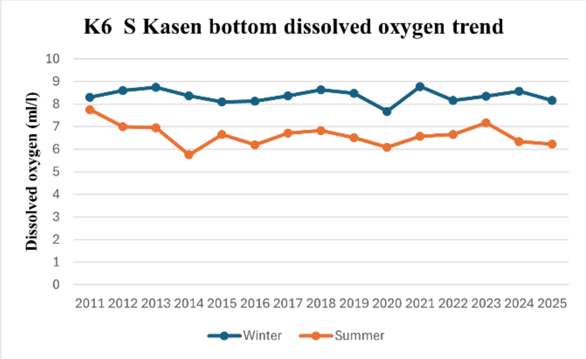

VH3A bottom oxygen concentration trend
Oxygen concentration (ml/l)
Winter
Summer

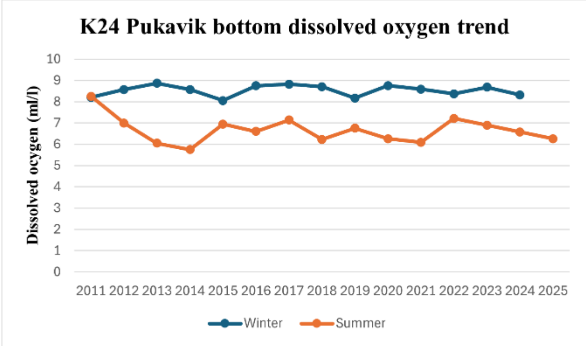

K6 S Kasen Secchi depth trend
Secchi depth (m)
Winter
Summer


K24 Pukavik secchi depth trend
Secchi depth (m)
Winter
Summer


K6 S Kasen chlorophyll a trend
Chl-a (µmol/l)
Winter
Summer


K24 Pukavik chlorophyll a trend
Chlorophyll a (µmol/l)
Winter
Summer


K6 S Kasen bottom dissolved oxygen trend
Dissolved oxygen (ml/l)
Winter
Summer


K24 Pukavik bottom dissolved oxygen trend
Dissolved ocygen (ml/l)
Winter
Summer

Figures 20-36. Time series for Secchi depth, dissolved oxygen, and chlorophyll *a* for the six coastal monitoring stations.

A linear correlation test was performed on the Secchi depth time series for winter and summer. The R^2 values for each station and the two seasons can be seen in table 10. The only stations for which positive coefficient of determination was present were VH3A and K24 in winter, and K7 in both winter and summer. K7 had a moderate positive relationship for winter, and weak positive correlation during summer. VH3A and K24 winter had weak positive correlations. The rest of the stations have a no or negligible correlation between Secchi depth and time. The overall result was dominated by no or negligible correlation.

Table 6. The significance and correlation of the Secchi depth trend in winter and summer for all stations from 2011-2025.

Station	Season	R^2	Significance
VH1	Winter	0.02	No or negligible
	Summer	5E-05	No or negligible
VH3A	Winter	0.25	Weak positive/decreasing trend
	Summer	0.01	No or negligible
K6	Winter	0.23	Weak positive increasing trend
	Summer	0.11	No or negligible
K24	Winter	0.22	Weak positive/increasing trend
	Summer	0.18	No or negligible
K7	Winter	0.38	Moderate positive/increasing trend
	Summer	0.27	Weak positive/increasing trend
L1	Winter	0.06	No or negligible
	Summer	0.14	No or negligible

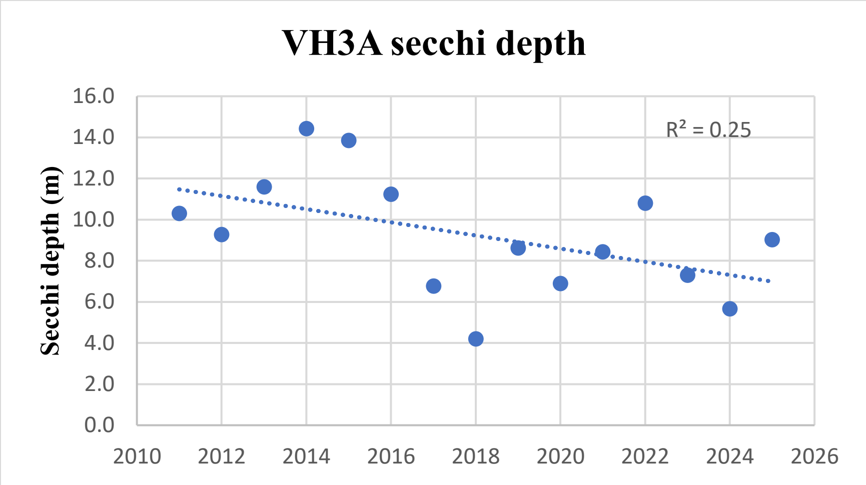


Figure 37. Regression graph for Secchi depth during winter for VH3A station over time. The R^2 is 0.25 indicating that there is a weak correlation. There is a decreasing trend.

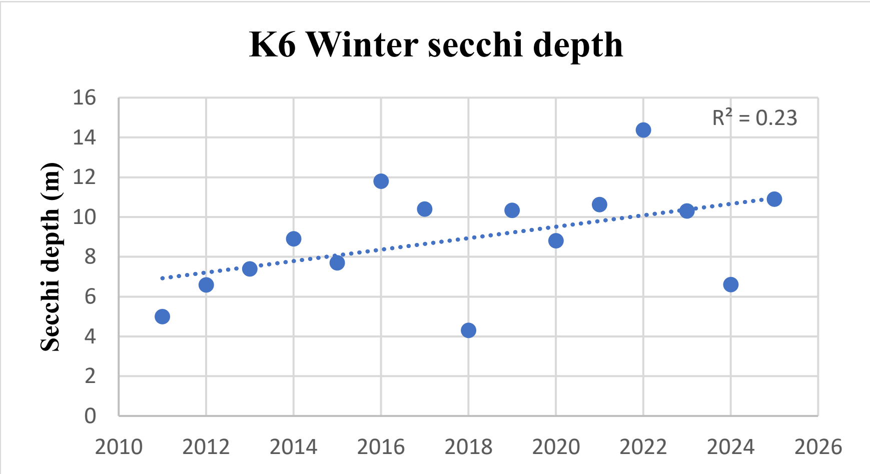


Figure 38. Regression graph for Secchi depth during winter for K6 stations over time. The R^2 is 0.23 indicating that there is a weak correlation. There is an increasing trend.

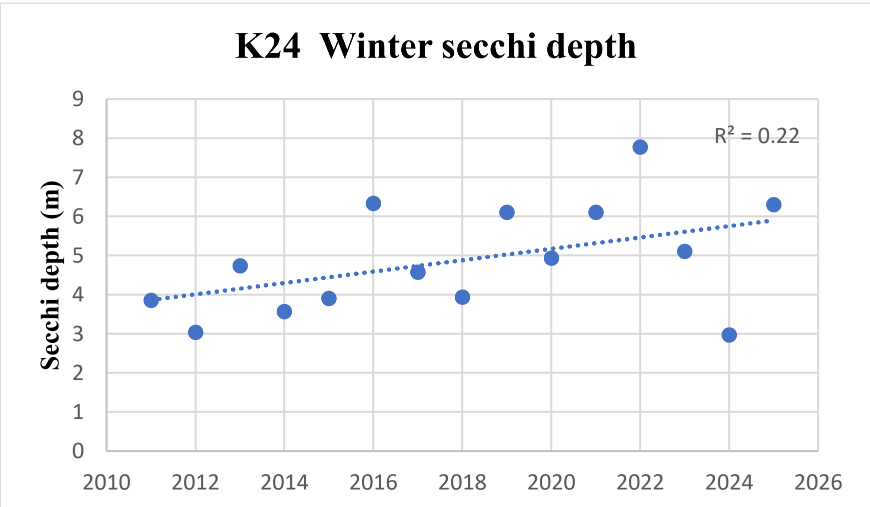


Figure 39. Regression graph for Secchi depth during winter for K24 station over time. The R^2 is 0.22, indicating that there is a weak correlation. There is an increasing trend

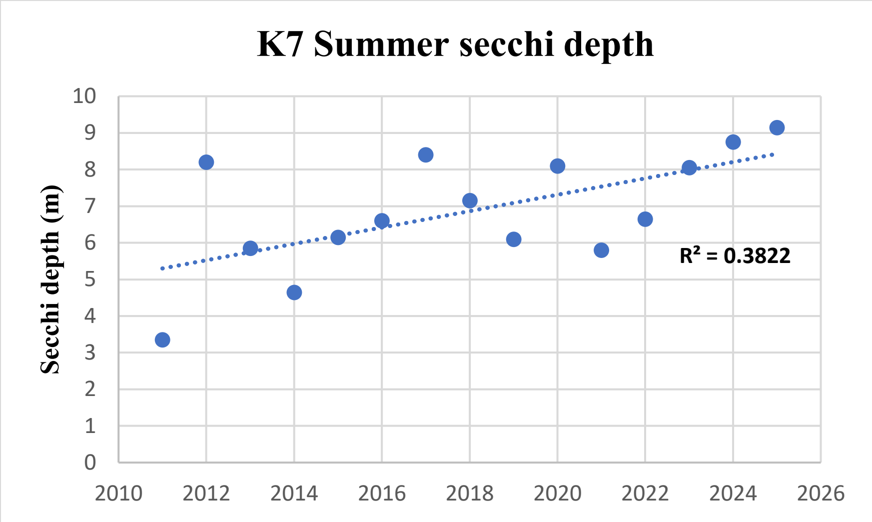


Figure 40. Regression graph for Secchi depth during summer for K7 station over time. The R^2 is 0.38 indicating that there is moderate correlation. The trend seems to be increasing.

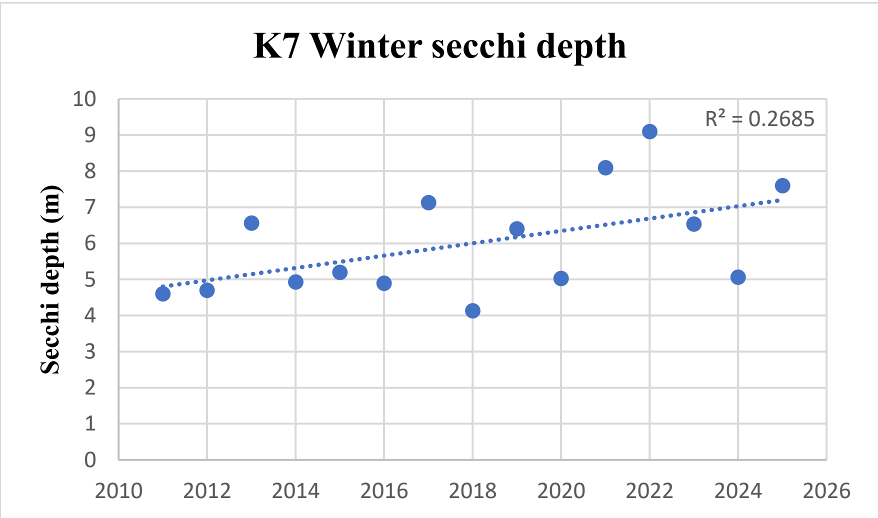


Figure 41. Regression graph for Secchi depth during winter for K7 station over time. The R^2 is 0.27 indicating a weak correlation.

The average TOC at the coastal monitoring stations from 2011 to 2015 can be seen in table 7. A normal range for TOC in marine waters is between 0.3 and 2.4 mg L^{-1} (Býden, et al., 2003), and the average values are higher than the normal range.

Table 7. Average TOC concentrations measured in the stations for 2011-2015 (Blekinges Vatten- och Luftvårdsförbund, n.d).

TOC (mg/l C) 2011-2015		
Station	Winter	Summer
VH1	2.47	3.50
VH3A	4.04	4.0
K6	3.98	4.05
K24	5.70	4.56
K7	7.09	3.83
L1	4.73	4.5

3.4 GIS

Figures 40 and 41 show the mean monthly Secchi depth from 2014 to2024, with the red colour indicating lower values, and the blue a higher Secchi depth values. In all months except for August and September, lower Secchi depth values are observed along the coasts of the two mills. The lowest Secchi depth values can be observed in February (5.01 m), and March (5.62 m) near the mills. Higher Secchi depth values near the mills can be seen in July (9.38 m), August (8.91 m), and September (8.82 m). The surroundings of the Södra Cell Mörrums pulp mill have lower Secchi depth in all months (except for July-September). The Nymölla paper mill shows more variation in the Secchi depth of the coast, with higher Secchi depth in December to January, and July-September.

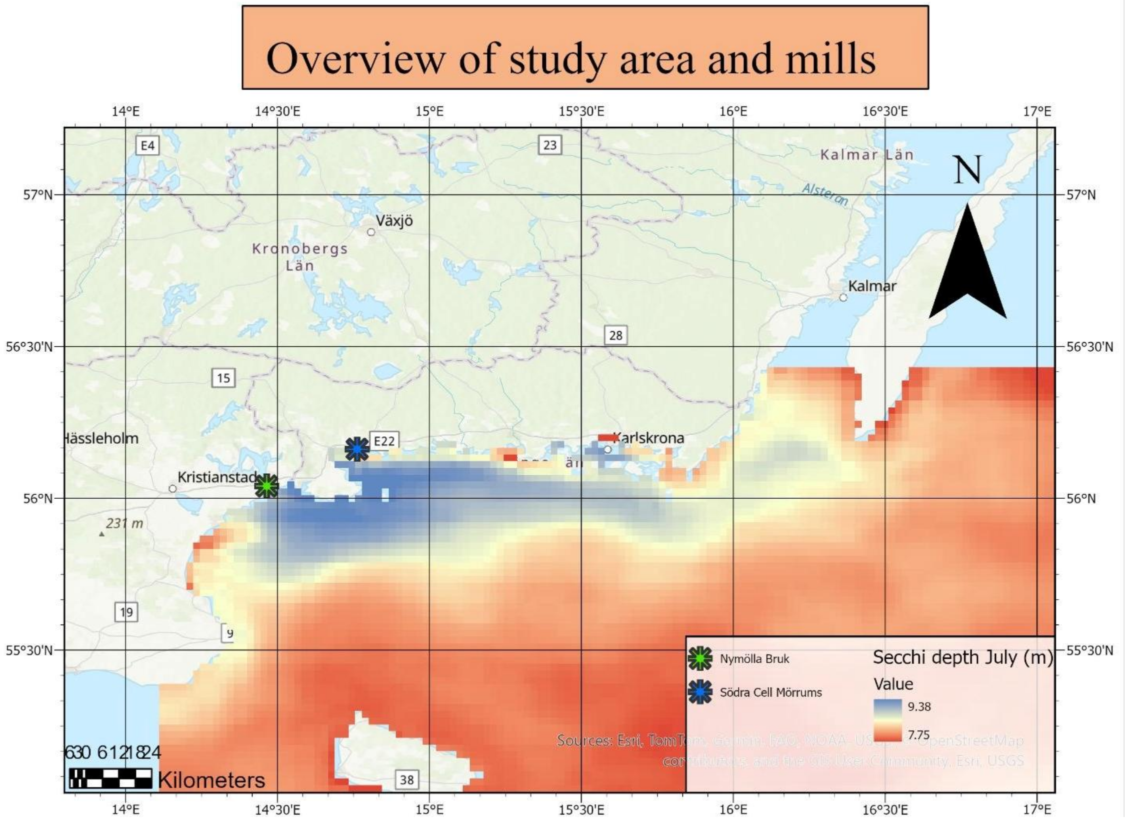


Figure 42. An overview of the extent of the area.

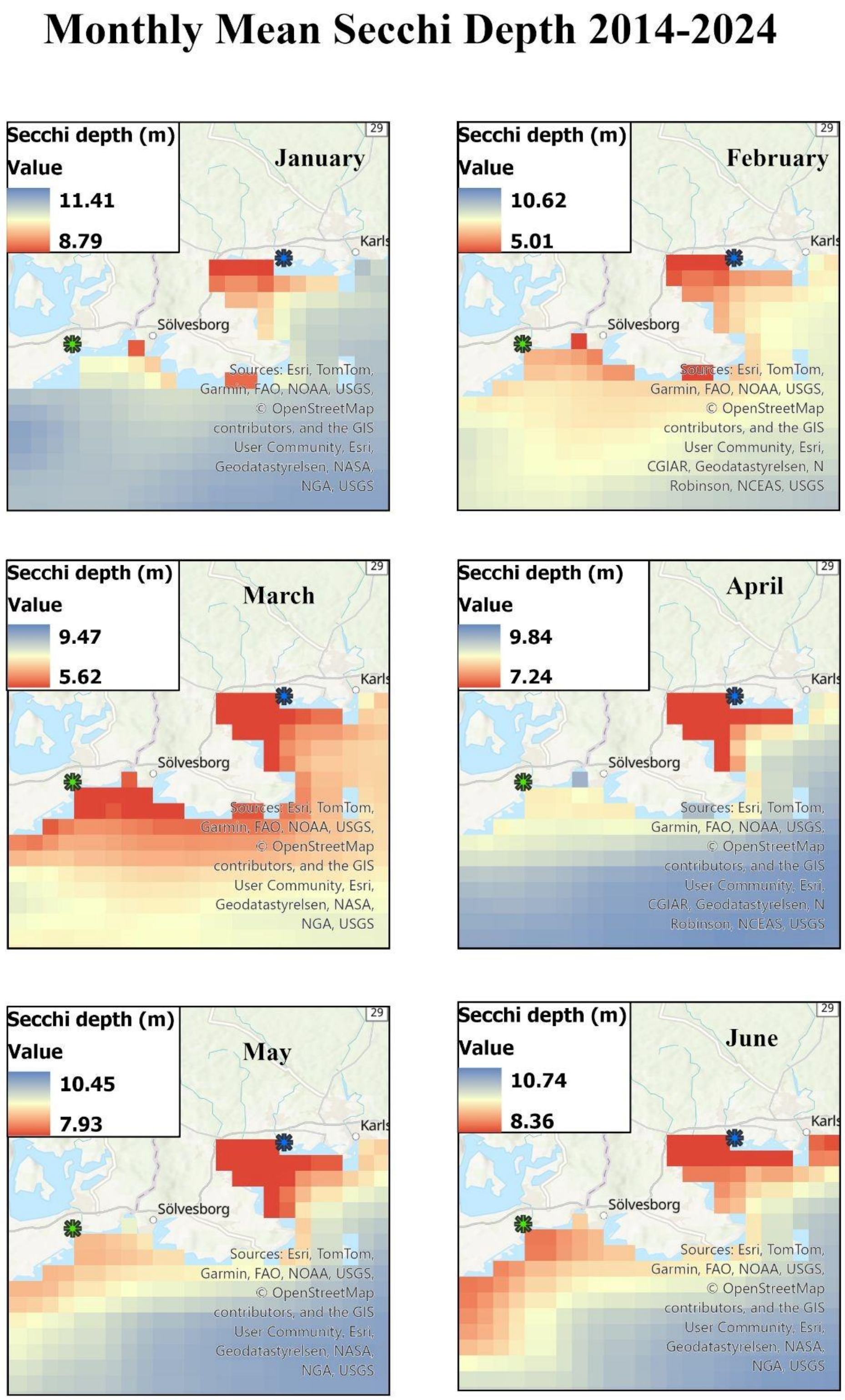


Figure 43. Monthly mean Secchi depth (2014-2024) from January to June. The blue star is Södra Cell Mörrums, and the green star is Nymölla mill

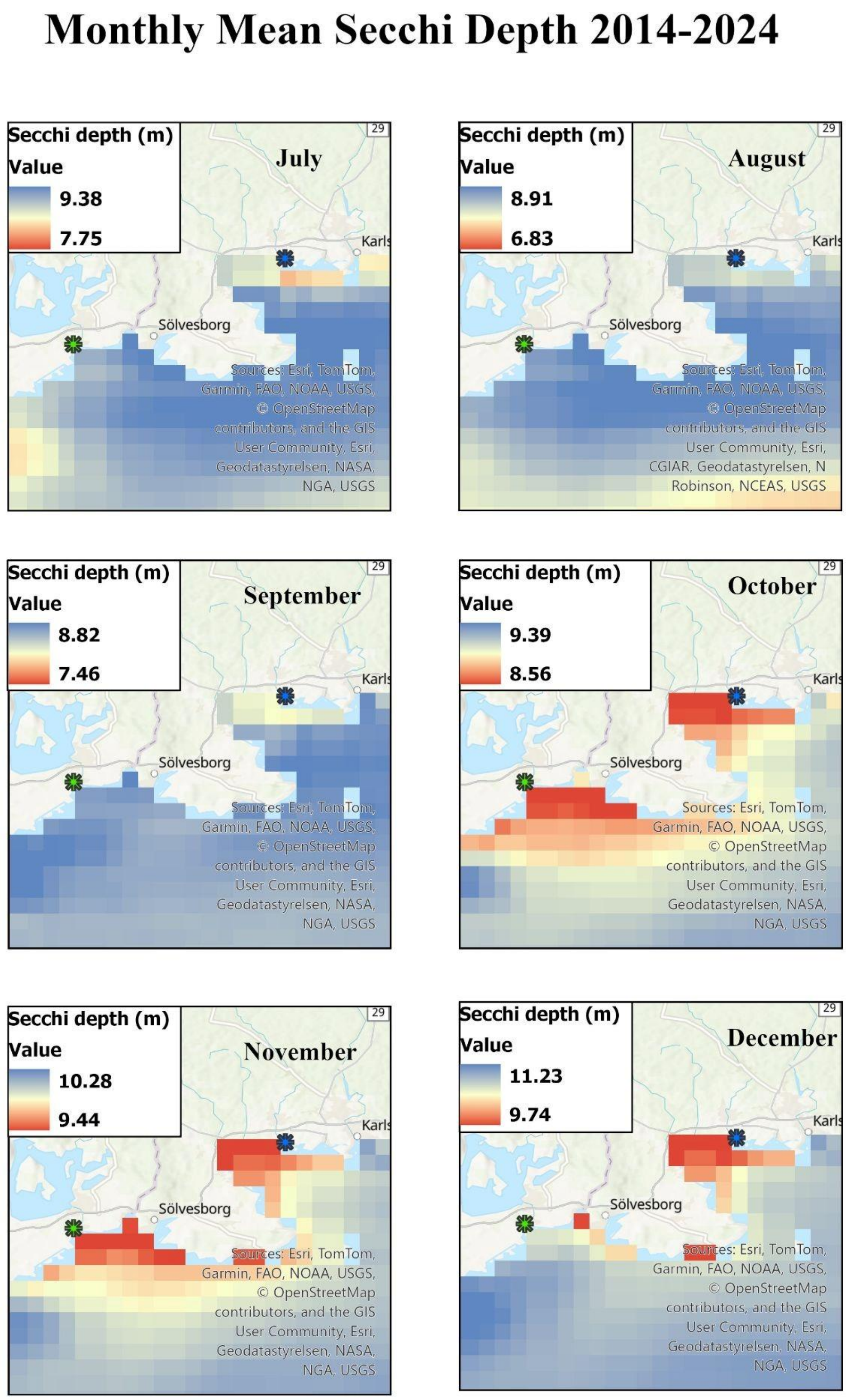


Figure 44. Monthly mean Secchi depth (2014-2024) from July to December. The blue star is Södra Cell Mörrums, and the green star is Nymölla mill.

4 Discussion

4.1 Overview of aim

Pollution from paper and pulp mill wastewater has historically had significant impact on the ecological condition of coastal ecosystems. In recent decades, stricter environmental regulations and laws, and wastewater treatment requirements have substantially reduced these impacts by limiting quantity and effluents discharged into bays. However, brownification has been observed in Hanö Bay and near the coast of the Nymölla paper mill and Södra Cell Mörrums pulp mill. This thesis aims to analyse the potential effect of paper and pulp mill effluent on brownification in Hanö Bay, Baltic Sea.

4.2 Water basins

The analysis of stations located near the river mouths show that there is a significant increase of TOC, as well as relatively high and statistically significant absorbance values at 420 nm. These results suggest that there is an increase in water colour in rivers, streams, and lakes within the river basins draining into Hanö Bay. However, the relationship between increased freshwater browning and coastal browning remains unclear. The annual TOC load from Helge Å to Hanö Bay averaged out to 20, 000 tons between 1996 and 2016 (Svedäng, 2018). As shown in figure 6, the combined TOC discharge from both mills in 2025 is 5,776 tons, corresponding to 30% of the TOC load from Helge Å. Together, these sources contribute 26, 000 tons of TOC per year to Hanö Bay. However, industrial effluents loads and forest industries were considerably higher in previous decades. This makes it difficult to determine the importance of historical industrial emissions compared to the recent drivers of coastal brownification.

Another factor that complicates interpretation in Hanö Bay is land-use change. In Sweden during the 1950s, around 1,000,000 hectares of arable land was converted into productive forestry (Svedäng, 2018). Today, spruce and other coniferous tree species dominate forestry in Scania and Blekinge (Svedäng, 2018). Brownification of lakes and rivers have been observed across the Northern Hemisphere, particularly in boreal forests (Erlandsson, et al., 2008; Opdal, 2023). The decline in sulphate deposition has increased soil pH, reduced acidity and making organ matter more soluble. This has promoted the leaching of humic substances and organic matter into surface waters (Hall, et al., 2021). Climate change, land-use change, and decrease in sulphate deposition are the primary drivers for browning of freshwater ecosystems.

Notably, TOC is not currently measured at the 16 monitoring stations in Hanö Bay. The only exception is the period between 2011 and 2015, for which averaged winter and summer values are presented in table 6. Normal TOC concentrations in marine waters range between 0.3 and 2.4 mg L^{-1} C (Bydén, et al., 2003). Based on this classification, all stations show TOC concentrations that are above the normal marine range. Other relevant variables for assessing organic matter and brownification include humic substances, absorbance at 420 nm, DOC, lignin, and water turbidity.

In July 2023, South Korea replaced the indicator for organic matter from chemical oxygen demand (COD) to TOC for water-quality assessments (Choi, et al., 2024). COD is a measure that indicates how much oxygen is required to chemically oxidise organic compounds into their inorganic end products (Naturdvårdsverket, n.d.c). Although COD has previously been used as a proxy for organic matter, studies of Korean coastal waters have found weak correlations between COD and TOC. These studies concluded, COD does not estimate the organic matter concentrations sufficiently due to its low oxidation efficiency (Park, et al, 2021; Woo, et al., 2023). This suggests that TOC may provide a more direct and reliable indicator of organic matter in coastal water-quality assessments.

Coastal browning has been briefly mentioned in HELCOM reports as an area for future research. HELCOM primarily focuses on the stressor’s eutrophication, climate change, and overfishing, Water transparency, measured as secchi depth is assessed as one of HELCOM’s eutrophication core indicators.

HELCOM identifies CDOM and phytoplankton as important drivers of reduced water transparency in the Baltic Sea. One proposed area for future research is the effect of terrestrial runoff containing organic carbon loads on brownification and declining water transparency, particularly in relation to eutrophication. However, measurements taken from stations around Hanö Bay show that the chlorophyll *a* concentration have remained stable in each station (Svedäng, 2018). This can be seen in the six stations investigated in this thesis.

4.3 Hanö Bay stations 2011 to 2025

Secchi depth, chlorophyll *a* concentration, and bottom-water oxygen concentration were analysed for six monitoring stations located closest to the paper and pulp mills. Oxygen and chlorophyll *a* concentration remained relatively stable at each station during both summer and winter. The most recent annual report for Hanö Bay was published in 2024 (Blekinge Kustvatten och Luftvårdsförbund, 2024). Based on the annual reports the bottom oxygen concentrations have been stable for the stations. The annual status of the variables is summarised in table 8.

The overall trend for the stations is a high oxygen concentration, moderate to high chlorophyll *a* concentration, and unsatisfactory to high Secchi depth. Station L1 was the only station that showed a poor status over time. Since 2011, the Secchi depth L1 remained classified as unsatisfactory, while oxygen concentrations have remained high. The chlorophyll *a* concentration was classified as moderate status (Blekinge Kustvatten och Luftvårdsförbund, 2024; Olsson, et al., 2023; Isaksson, et al., 2024). This may be partly explained by the station's semi-enclosed location near Sölvesborg (fig. 43) where restricted water exchange may influence the water-quality conditions. The classification of each variable can be found in table A5 in the Appendix.

An important contradiction is that browning has been reported by locals and fishermen, while Secchi depth in the nearest monitoring stations generally indicate good or high-water transparency status. However, the monitoring data has important temporal limitations. Measurements were only taken once a month for summer (July and august), and winter (December, January, and February) from 2011 to 2025. A single monthly measurement cannot fully capture short-term variability within a month or season, including variation in runoff events, algal blooms, and temporary changes in water colour.

The short-term data availability for the Hanö Bay makes it difficult to connect coastal browning to land use change and stricter wastewater regulations for the paper mills. In comparison to long-term TOC and absorbance data from the river basins, it is possible to identify trends and the shift in the data connecting it to land use changes, climate change, and industrial pollution (Svedäng, et al., 2018). Although, the river basins data in this thesis was from the 80s, when looking at trend from the 1960s and 1970s shifts in the data can be connected to the decreased pressure from sulphur deposition and increased forestry (Svedäng, 2018). The importance of long-term coastal data is crucial to understand the development of coastal browning and the dynamics of variables.

Aksnes, et al. (2009), highlight this challenge by showing potential drivers of light attenuation may be inferred by using other available variables. This study developed a proxy for light attenuation based on salinity and dissolved oxygen content during periods of low chlorophyll *a* concentration at depth. The results showed that variations in salinity and oxygen can affect light penetration because light attenuation accumulates with depth. This suggests that Secchi depth alone may not be enough to explain and identify coastal browning. Brownification in Hanö Bay should be assessed using multiple indicators including TOC, absorbance, CDOM, and oceanic chemical and physical variables.

4.4 Secchi depth GIS Visualization

The average monthly Secchi depth can be seen in figures 43 and 44. From December to June, Secchi depth around Nymölla and Södra Cell Mörrum is lower compared with the open-water areas of Hanö Bay. Secchi depth then increases during the summer months, indicating higher water transparency. In figure 42, lower Secchi depth may be observed in general along the coasts. However, Secchi depth is higher around the two mills, which counteracts the argument that the effluents cause coastal browning.

The modelled secchi depth was based on two integrated models, and had a spatial resolution of 2 km. Another similar study modelled secchi depth in Hanö Bay with a spatial resolution of 30 m. This report discusses that sensors with spatial resolution between 300-1000 m are not sufficient to capture details and intricate morphology like coasts (Länsstyrelsen Blekinge Län, 2015). The AquaBiota Report, 2012, has created a satellite derived Secchi depth model based on a semi-analytical optical model (Lee, et al., 1998) and related to MERIS derived reflectance ratios to field observed secchi depths. The results showed that it is possible to derive high resolution Secchi depth maps for coasts (Wijkmark, et al., 2025). However, the Secchi depth near the coast was significantly lower compared to the model used in this thesis, the lowest Secchi depth being 5 m. It is a challenge to conclude which method and model is the best as no ground truth validation has been performed. This thesis and future studies could highly benefit from validating the models by using daily data and secchi depth measurements from the coastal monitoring stations in Hanö Bay. Therefore, an accuracy assessment including user's and producer's accuracy would be sufficient way of testing the models accuracy.

Collecting water samples in marine environments can be both time-consuming and costly. More frequent monitoring of Hanö Bay could therefore be supported through governmental or municipal funding for environmental monitoring projects. Modelling of variables provides a valuable complementary approach to collecting samples. This can increase spatial and temporal coverage and reduce the need for extensive field sampling. This thesis used biogeochemical reanalysis data to examine Secchi depth patterns. The data was based on two coupled models, the biogeochemical model ERGOM and the sea-ice model NEMO (Copernicus, 2023). Secchi depth is a traditional and simple measurement of water transparency; however, it provides the most efficient results in lakes and oceans with low concentrations of suspended matter (Kirk, 2011). The coastal stations have used the Secchi depth method for deriving the water transparency. Golubkov & Golubkov (2024), discusses that when the water turbidity is high, the Secchi depth may not provide the most accurate depth of the euphotic zone (depth at which photosynthesis is supported). Turbidity, a measure of water clarity, was also analysed, and this study identified that waters with a turbidity higher than 40 NTU (nephelometric turbidity unit) provide better. Models and Secchi depth perform poorer in waters with suspended particles. This suggests it is crucial to develop models and algorithms that incorporate and interpret remote sensing based on turbidity.

5 Conclusion

The river basins draining into Hanö Bay, as well as the monitoring stations located closest to the river mouths, show high absorbance values and elevated TOC concentrations. In contrast, the six coastal stations analysed in this thesis show relatively stable chlorophyll *a* concentrations and well oxygenated. Secchi depth varies considerably between seasons, but the overall water-transparency status is generally classified as good or high. Seasonally, the Secchi depth tends to be lower along the coast, except during the summer months when transparency increases.

The processes governing brownification in coastal ecosystems remain poorly understood, and the primary drivers are still debated. Based on the available data, this thesis cannot conclude the extent to which paper and pulp mill effluents contribute to brownification in Hanö Bay. The results provide evidence of browning in freshwater systems draining into the bay, but there is no clear conclusion regarding whether Hanö Bay itself is affected by coastal brownification.

The changing climate is expected to alter weather patterns, influence the mechanisms and dynamics between land and coasts. Further research is crucial to understand how land and coast intersections have evolved brownification in the past, and how it will change in the future. Future studies should focus on taking measurements of optical properties of the water such as TOC, absorbance, and CDOM, near coastal monitoring stations and industrial discharge points.

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7 Appendix

Table A1. Results from the four statistical tests for the 219 stations.

Mann-Kendall test		**Sen's slope**		**Pettits Test**		**Cox-Stuart test**	
MK-stat	334	**slope**	0.105	**Point**	11	**p-value**	0.002
s.e.	79.52	**upper**	0.068	**W-stat**	77	**ratio**	0.84
Z-stat	4.19	**lower**	0.14	**Z-stat**	-4.41	**trend**	Increasing
p-value	2.82E-05			**p-value**	1.04E-05		
Trend	yes						

Table A2. Results from the statistical tests for Helge Å, Hammarsjön.

Mann-Kendall test		Sen's slope		Pettits Test		Cox-Stuart test	
MK-stat	287	**slope**	0.24	**Point**	19	**p-value**	0.00014
s.e.	70.41	**upper**	0.14	**W-stat**	216	**ratio**	0.94
Z-stat	4.06	**lower**	0.30	**Z-stat**	-4.16	**trend**	Increasing
p-value	4.87E-05			**p-value**	3.24E-05		
Trend	yes						

Table A3. Results from the statistical tests for Skräbeån vid Käsemölla.

Mann-Kendall test		Sen's slope		Pettits Test		Cox-Stuart test	
MK-stat	99	**slope**	0.05	**Point**	10	**p-value**	0.3
s.e.	48	**upper**	0.001	**W-stat**	70	**ratio**	0.61
Z-stat	2.04	**lower**	0.09	**Z-stat**	-3.5	**trend**	Increasing
p-value	0.04			**p-value**	0.0005		
Trend	yes						

Table A4. Results from the statistical test for 17 Lyckeby.

Mann-Kendall test		**Sen's slope**		**Pettits Test**		**Cox-Stuart test**	
MK-stat	152	**slope**	0.1	**Point**	13	**p-value**	0.06
s.e.	58.8	**upper**	0.02	**W-stat**	145	**ratio**	0.73
Z-stat	2.57	**lower**	0.22	**Z-stat**	-2.5	**trend**	Increasing
p-value	0.01			**p-value**	0.012		
Trend	yes						

Table A5. The classification for chlorophyll, oxygen content, Secchi depth for the stations,

		Total classification		
Year	**Station**	**Chlorophyll**	**Secchi depth**	**Oxygen**
2011	**VH1**		**High**	**High**
	VH3A		Good	High
	L1		Unsatisfactory	High
	K6		High	High
	K7		Unsatisfactory	High
	K24		High	High
2014-2016	**VH1**	**Good**	**High**	**High**
	VH3A	Moderate	Good	High
	L1	Unsatisfactory	moderate	High
	K6	Good	Good	High
	K7	Unsatisfactory	moderate	High
	K24	High	High	High
2020	**VH1**	**High**	**High**	**High**
	VH3A	Good	Good	High
	L1	Moderate	Moderate	Poor
	K6	High	High	High
	K7	High	Good	High
	K24	Good	High	High

Table A5. Showing the classification of the chlorophyll a, oxygen, and Secchi depth for 2011, 2014-2016, 2020, 2023, and 2024 (Kustvatten och Luftvårdsförbund, 2011, 2023, 2024).

	Station	**Chlorophyll**	**Secchi depth**	**Oxygen**
2023	**VH1**	**High**	**High**	**High**
	VH3A	High	High	High
	L1	Moderate	Unsatisfactory	High
	K6	High	High	High
	K7	Moderate	good	High
	K24	High	High	High
2024	**VH1**	**High**	**High**	**High**
	VH3A	High	good	High
	L1	Moderate	Unsatisfactory	High
	K6	High	High	High
	K7	Good	High	High
	K24	High	High	High