UMEÅ UNIVERSITY

TRACKING WASTEWATER EMISSIONS IN RIVERS ENTERING GULF OF BOTHNIA COAST

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Abstract

The Gulf of Bothnia consists of two sub-basins in the northern Baltic Sea: the Bothnian Sea (salinity 4-5‰) and Bothnian Bay (salinity 2-3‰). Changing nutrient concentrations and signs of eutrophication has recently been observed in the Gulf of Bothnia. Many rivers enter this sea area, and potentially river inflows constitute a source of nutrient pollution via waste-water emissions. The aim of this study was to elucidate effects of waste-water emissions in four rivers in northern Sweden, Luleå, Skellefteå, Umeå and Söderhamn. My approach was to compare nutrient concentrations at upstream and downstream sampling stations related to the position of waste-water treatment plants. Temporal data from 2006 to 2021 were used and statistically analyzed using non-parametric tests to establish spatial and temporal patterns for nutrient discharged to the coast. The results showed that there are statistically differences in dissolved inorganic phosphorus (DIP) in the form of phosphate (PO_4), ammonia (NH_4) and total nitrogen (TotN) between the upstream and downstream of Luleå and Umeå wastewater treatment plants. No statistically significant differences were observed in the upstream and downstream data for Söderhamn and Skellefteå. This suggest that better management and mitigation of nutrient loading from wastewater treatment plants that serve higher populations is paramount to achieve the zero-eutrophication goal in the Gulf of Bothnia

Key words: Nutrients inputs, wastewater, coastal waters, Gulf of Bothnia, wastewater emissions, nutrient transportation, marine water, nutrient loading, eutrophication.

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1 Introduction

Wastewater is a significant source of nutrients and other substance hence wastewater is treated in wastewater treatment plants before being released into the environment. The Swedish environmental protection agency (Swedish EPA/Naturvårdsverket) (2020) and the Swedish agency for marine and water management (SwAM) report (2021) investigated into net load sources of nitrogen (N) and phosphorus (P) and found that anthropogenic net load for N and P were from 1. Agriculture with net load of 19 470 tonnes N and 710 tonnes P, 2. municipal waste-water treatment plants with 14,050 tonnes N and 234 tonnes P, 3. industrial activities with 3,220 tonnes N and 210 tonnes P and 4. small-scale sewers with net load of 2,010 tonnes N and 200 tonnes P in 2017 (Swedish EPA. 2020). 460 tonnes N and 140 tonnes P in 2017 were from stormwater. Due to the sensitivity of some areas and high risk of eutrophication caused by nutrient loading, all coastal waters in Sweden have been designated as being sensitive to phosphorus discharge (Boesch et al. 2006). Thus, the Swedish government has an environmental objective of Zero Eutrophication which states that "Nutrient levels in soil and water must not be such that they adversely affect human health, the conditions for biological diversity or the possibility of varied use of land and water" (Naturvårdsverket. 2023; SvAM. 2023). Additional environmental objectives on this subject are, flourishing lakes and streams, balanced marine environment, flourishing coastal areas and archipelagos. The Swedish government also ensures that Swedish policy strives to solve eutrophication problems (Swedish EPA. 2023)

Eutrophication is one of the major problems in the Baltic Sea that has received significant attention in recent years. Eutrophication has major impacts to water quality of inland and marine waters caused by the influx of nutrients particularly N and P which leads to an increase in primary and secondary production (Bennett Carpenter and Caraco. 2001; Bonsdorff et al. 1997). It has impact on aquatic ecosystems, socio-economic impact on human livelihood and human health. Eutrophication is prevalent in many water bodies including coastal waters and rivers (Le Moal et al.2019). Marine eutrophication in Gulf of Bothnia relies on N and P enrichment at the river outlets (Desmit et al. 2018). It is largely determined by quantities of external nutrient loads. Nutrient loading due to anthropogenic activities, is one of the main causes of eutrophication in coastal areas (Cloern, 2001). However, the Bothnian Bay has very low eutrophication presence because it is mainly phosphorus-limited in comparison with the higher production capacity and temporal nitrogen limitation of the Bothnian Sea (Sandberg et al., 2004, Tamminen and Andersen, 2007). This means, any shift in the nutrient delivery from inflow rivers may lead to significant changes in the ecosystem structures and functions due to an increase in eutrophication.

The Gulf of Bothnia is the 30 percent northern part of the semi enclosed brackish Baltic Sea with a drainage basin four times larger than the sea itself (Bernes, 1988; Mörth et al. 2007; Strååt, Mörth and Undeman. 2018). It is a common recipient of water discharged from northern Sweden and Finland due to its high riverine freshwater inflow (Hänninen and Vuorinen. 2015). The Swedish rivers discharge into the Gulf of Bothnia making it a potential final recipient for nutrients and humic substances, this is because there is slow water exchange with the North Sea and there is a halocline in the Baltic Sea where the mixing of freshwater and salt water is limited (Voss et al. 2011). The drainage area of the Gulf of Bothnia and rivers transfer materials influenced by erosion, abrasion and humic substances from natural processes and anthropogenic processes from the inland (Leivuori 1998). The amount of nutrients and humic substance transported into the Gulf may vary according to seasonal variations. In addition, nutrient transfer from rivers is influenced by hydrology, total input from sources, and the in-stream processes that affect nutrient transformation, retention, and elimination of nutrients during transit (Billen et.al 2007). These in turn affect nutrient delivery rate and quantity to the Gulf of Bothnia. Nutrient input into the drainage network from diffuse and point sources may also influence total nutrient loads despite having efficient wastewater treatment plants. Thus, nutrient transfer rate can vary significantly over time, season and distance thereby affecting nutrient limitation patterns sporadically and stimulating changes in the ecosystem.

In Sweden, the Swedish EPA coordinates national and regional environmental monitoring efforts together with the SwAM and manages the national environmental monitoring programme. However, the municipalities are responsible for the wastewater treatments to ensure pollutants and nutrients do not end up in the environment and effluent discharge is regulated by national and local authorities (Andersson and Stage. 2018 and Paxéus, N. 1996). Coordinated Recipient Monitoring program ("samordnade recipientkontrollen"; SRK) organised by means of water conservation associations or water conservation associations by county councils in accordance with Swedish law (1976:997) has been implemented for environmental monitoring. The SRK programs aims at collecting data across Swedish water bodies to assess the human influence on water quality, monitor water quality changes and provide restoration advice according to data analysis outcomes. This program is regulated by environmental legislation for monitoring of environmentally hazardous activities. However, there is no mandate or obligation for municipalities to collect and submit data for their recipient control stations, municipalities deliver data to the data host (Swedish University of Agriculture Sciences [SLU]) voluntarily hence the availability of data for each municipality is dependent on their willingness to participate in the SRK program. In addition to the SRK program, the Swedish agency for marine and water management (SwAM) has the national responsibility for fresh water, sea, and coastal areas and collect data from allocated station for that purpose.

In addition to Swedish efforts to achieve zero eutrophication, the Swedish monitoring agencies have partnered with other coastal countries of the Baltic Sea under the Helsinki Commission (HELCOM) Baltic Sea Action Plan (BSAP) and have set recommendations to assess effects of pollution on coastal areas of the Baltic Sea (Backer et al. 2010 & Mörth et al. 2007). The HELCOM was established with the aim of protecting and managing marine environment based on ecosystem approach (Backer et al. 2010). Sweden has linked the BSAP to its Marine Strategy Framework Directive (2008/56/EG) which was incorporated in the Swedish legislation through the Marine Environment ordinance (2010:1341) in 2020 (Naturvårdsverket. 2023).

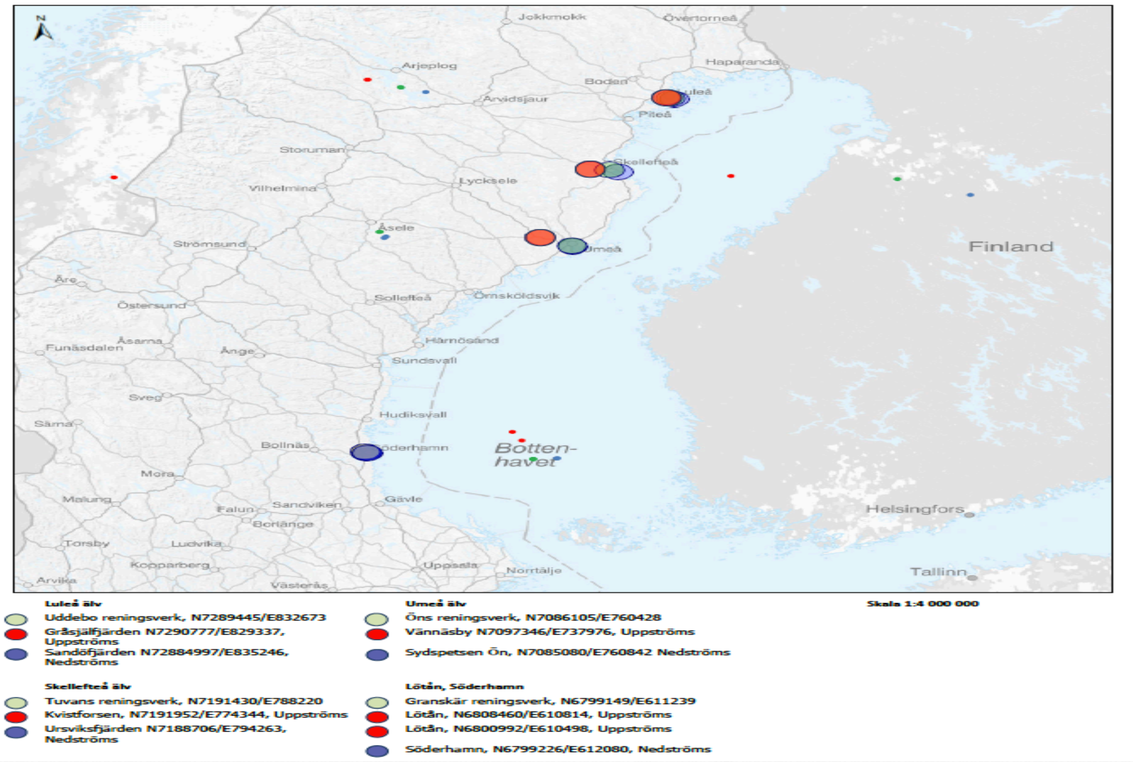
Other directives to manage European waters are the Water Framework Directive (WFD) which focuses on terrestrial ground- and surface waters including the nearshore coastal waters (Directive 2000/60/EC) and the Marine Strategy Framework Directive (MSFD) focuses on national marine waters (Directive 2008/56/EC). Additional directives for monitoring water quality are the management of waste waters (Urban Wastewater Treatment Directive, UWWTD, Directive 91/271/EEC) and the use of fertilisers (Nitrate Directive, Directive 91/676/EEC).

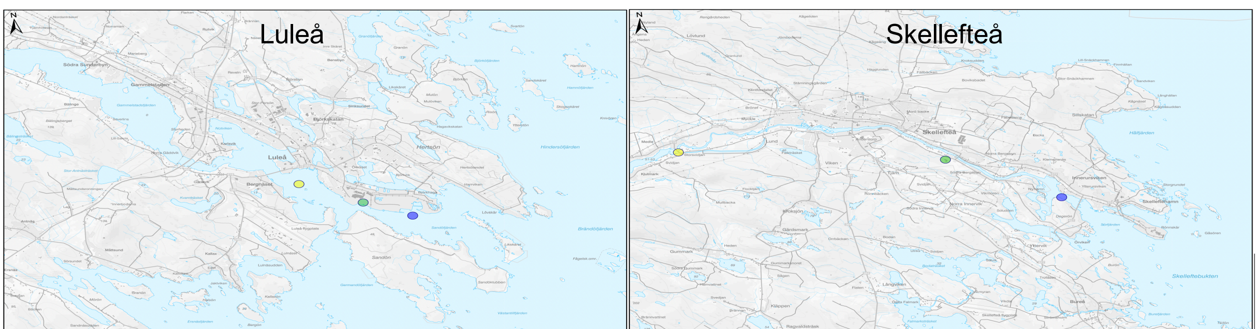
Despite having water directives supplemented by national monitoring programs providing framework for water quality management. There are no specific provisions on eutrophication and standards for the receiving environment with implementation of measures to achieve good ecological status respectively (Le Moal et al. 2019). The main objective of these directives is to evaluate compliance with water quality or ecological standards. Therefore, it is important to monitor the nutrient transfer to the coastal drainage from rivers that are recipients of wastewater treatment plants effluent to Gulf of Bothnia. This study aims at assessing the nutrient transfer from upstream the wastewater/sewage treatments plants and downstream to evaluate temporal trends and changes nutrient supply to the Gulf of Bothnia. I hypothesize that there is a significant difference between the nutrient load upstream and downstream inflow.

2 Materials and methods

2.1 Study area and description

Gulf of Bothnia is made of Bothnian Bay and Bothnian Sea basins, the Bothnian Sea (60.5 °N–63.5 °N, mean depth 68 m), and the Bothnian Bay (63.5 °N–66 °N, mean depth 43 m) (Lundberg, Jakobsson, and Bonsdorff. 2009). These two basins are separated by the North Quark (hereafter the ‘‘Quark’’), a shallow sill of only 20 m depth between Sweden and Finland (Håkansson Alenius and Brydsten. 1996). The open Gulf of Bothnia has a decreasing salinity from 7–5 ‰ in the Bothnian Sea to 4–3 ‰ in the Bothnian Bay. In the river estuaries the freshwater content can be even higher (Håkansson, Alenius and Brydsten. 1996). This study was conducted in four municipalities around the coast of the Gulf of Bothnia namely: Luleå, Skellefteå, Umeå and Söderhamn (Figure 1). Two monitoring stations were selected from each municipality except for Söderhamn which had two downstream that were close together and formed a continues timeline for the data collected.





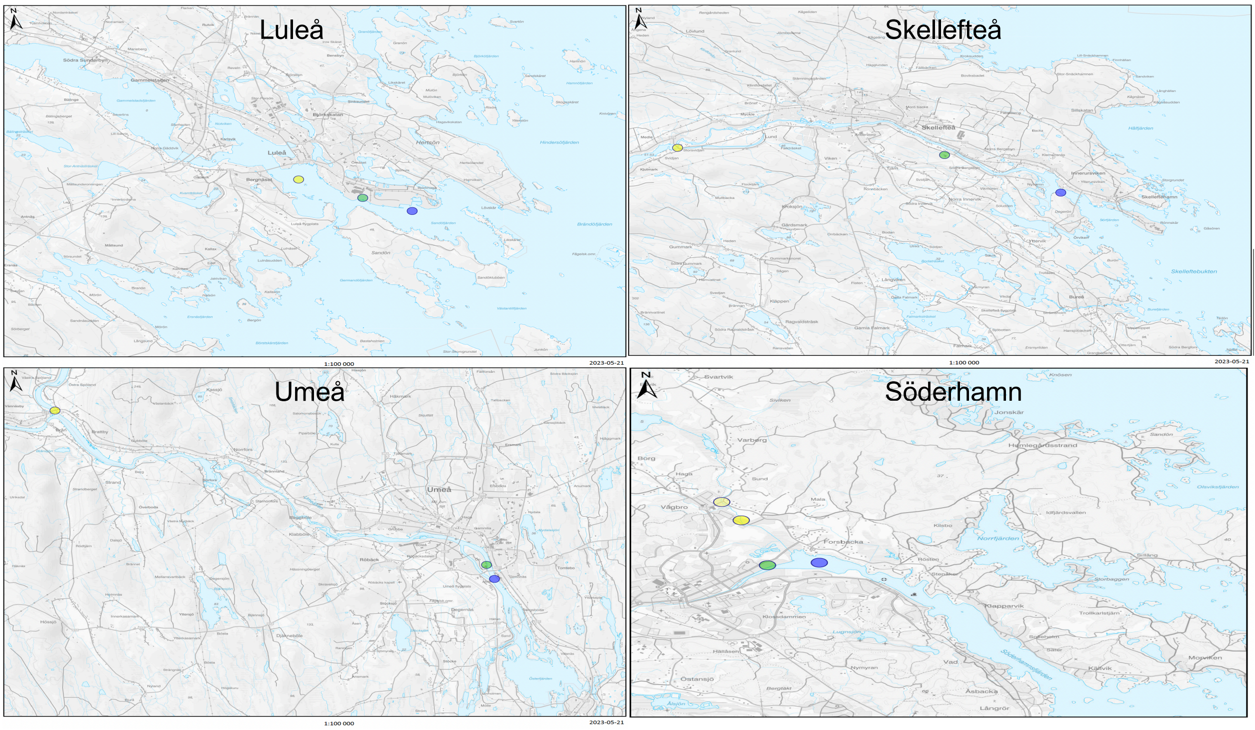


Figure 1a: Map of Sweden Showing where the municipalities in this study are located along the coast of the Gulf of Bothnia. Figure 1b: Municipality maps showing locations of the study areas. Yellow represents upstream monitoring stations; green represents wastewater treatment plant and purple represents downstream monitoring station.

2.2 Data collection

In Sweden the municipalities are responsible for the sewage water treatments. Therefore, the municipalities along the Gulf of Bothnia coast were contacted to ask for wastewater treatment monitoring control raw data refer to (Appendix D and E) for the contact letter and a list of the 17 municipalities along the Gulf of Bothnia namely, Haparanda, Kalix, Luleå, Piteå, Skellefteå, Robertsfors, Umeå, Nordmaling, Örnsköldsvik, Kramfors, Härnösand, Timrå, Sundsvall, Nordanstig, Hudiksvall, Söderhamn and Gävle stations where data was collected for this study. Depending on the response of each municipality, data was either submitted directly by the municipality or a reference to the data host platform was given with monitoring station names in some cases and just the name of their data host for others.

Of the 17 municipalities which were contacted, four municipalities were selected as the final study areas based on availability of data from upstream and downstream of the wastewater treatment plant (WWTP). Of the 44 stations (Appendix E) from which data was collected only 8 were used for this report (Table 1). For Luleå, the data covered upstream Uddebo wastewater treatment plant WWTP which processes wastewater for approximately 75,000-person equivalent users (Sanusi. 2007). Ön WWTP processes wastewater annually from households, industries and a large hospital in Umeå urban area with a capacity of 166,000-person equivalent (European Green Capital [EGCA]. 2018). Tuvans WWTP on the other hand serves approximately 34,000 persons equivalent and is mainly built to reduce phosphorus and organic from urban Skellefteå municipality wastewater. Lastly, Granskär WWTP in Söderhamn serves 22,500 local inhabitants and includes a wetland which further reduces organic matter, P and N content in the discharged effluent (Baltic Smart Water Hub. 2023). The data was collected from the municipalities and the database for Coordinated

Recipient Monitoring program under SLU (Miljödata. 2023) and SMHI for all other coastal and freshwater data.

Table 1: Municipalities included in the study, with names of their respective wastewater treatment plants, and upstream and downstream monitoring stations. The last column contains data hosts from which data for this study was obtained.

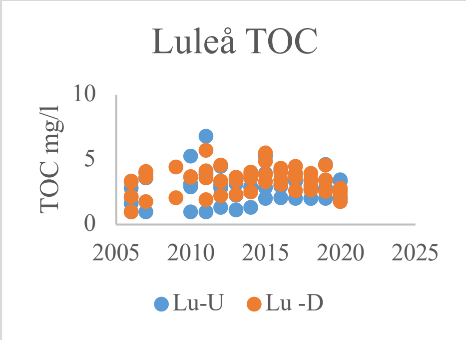
	Municipality	Upstream station	Wastewater treatment plant	Downstream station	Data source
1	Umeå	Vindelälven, Vännäsby, ovan bro (V5 (V5/U2)	Ön WWTP	Umeälven, Sydspetsen Öhn (U8 (U5)	SLU MVN
2	Luleå	L5 - Gråsjälfjärden	Uddebo WWTP	L4 - Sandöfjärden	smhi
3	Skellefteå	S2 (Skellefteälven, Kvistforsen) Upstream	Tuvans WWTP	S1(Skellefteälven, Ursviksfjärden) downstream	smhi & SLUMVN
4	Söderhamn	K338 (Soderhamnfjärden	Granskär WWTP	Lötån, nedströms våg (48028) Lötån, nedstr. Vågbro	smhi

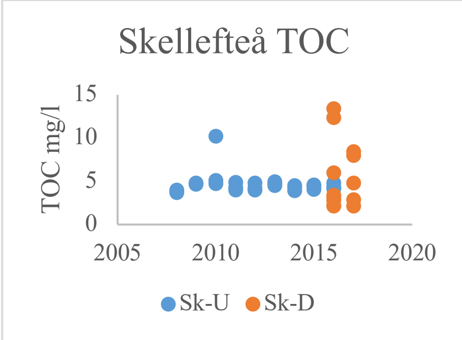
2.3 Statistical analysis

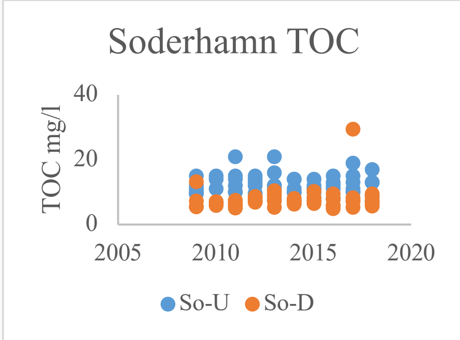
An average spectrum for each parameter for the year was obtained using excel pivot tables and then processed in R (v.4.3.0) using RStudio environment. The normal distribution of data was determined using Shapiro-Wilk test. The null hypothesis (H_0) which states that data distribution is not significantly different from a normal distribution was rejected when $p \leq 0.05$ at 95% confidence level. Differences between upstream and downstream were investigated using non- parametric Kruskal-Wallis's test. Here, all observations were tested, and differences were considered significant at 95% confidence level and p values ≤ 0.05. Thereafter the dissimilarities among the monitoring stations were further investigated using Dunn's non-parametric pairwise comparison post-hoc test to determine which specific parameters better distinguished nutrient loads from upstream to downstream. The data analysis covered a time series of 15 years, from 2006 to 2021. Total organic carbon (TOC) dissolved organic carbon (DOC), total nitrogen (TotN), total phosphorus (TotP), dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP), temperature, ammonia (NH_4) and nitrate (NO_3). These parameters were selected based on the availability of data in the database to ensure a robust comparison between upstream and downstream.

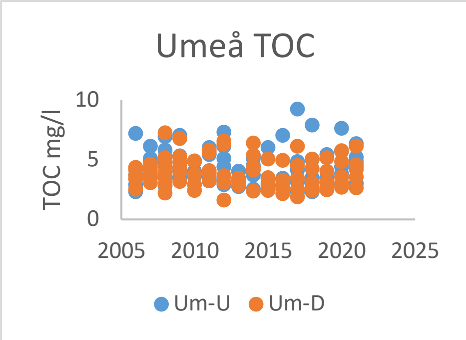
3 Results

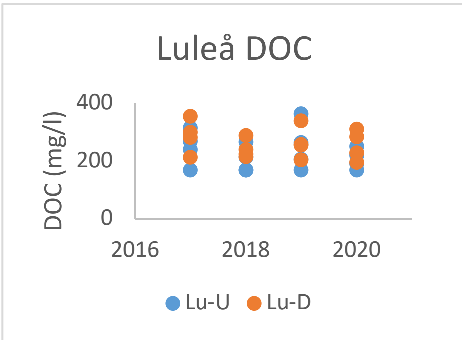
Data for ten parameters were collected from the data hosts (Table 1). Target parameters were analysed according to data availability. Among the ten parameters, seven parameters, TOC, TotP, DIN, DIP, NO_2+NO_3 and NH_4 had data in all stations while TotN, DOC, temperature values were not consistent among the stations (Table 2). Temporal trends in the nutrient concentrations of upstream and downstream of the eight data stations were plotted in (Figure 2) where trends from 2006 t0 2021 can be visually observed in TOC for Luleå, Skellefteå and Umeå, in DOC for Luleå, in DIN for Luleå, Söderhamn and Umeå, in TotN for Luleå, in TotP for Luleå, Söderhamn and Umeå, and in DIP for Luleå, Söderhamn and Umeå.

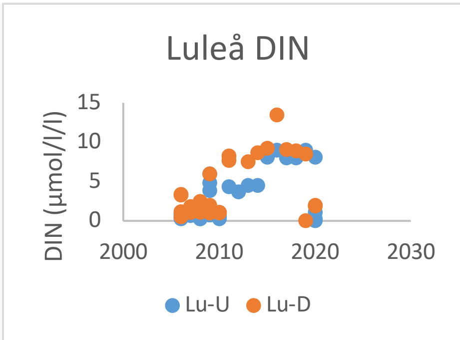

Luleå TOC
TOC mg/l
0
5
10
2005
2010
2015
2020
2025
Lu-U
Lu -D

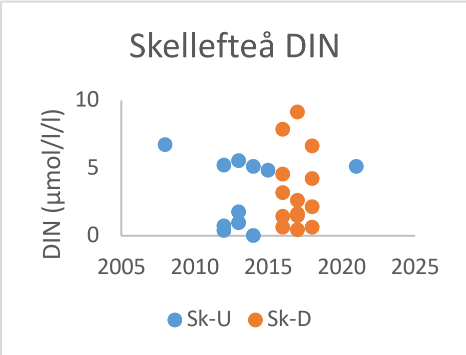

Skellefteå TOC
TOC mg/l
0
5
10
15
2005
2010
2015
2020
Sk-U
Sk-D

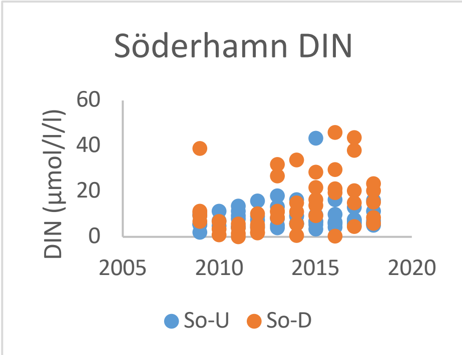

Soderhamn TOC
TOC mg/l
0
20
40
2005
2010
2015
2020
So-U
So-D

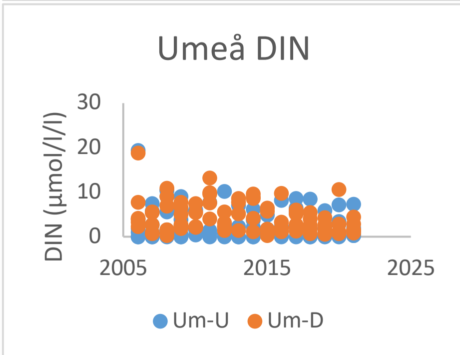

Umeå TOC
TOC mg/l
0
5
10
2005
2010
2015
2020
2025
Um-U
Um-D

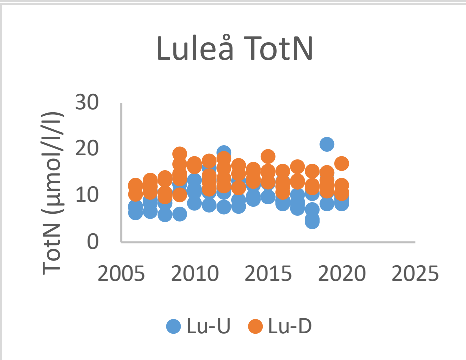

Luleå DOC
DOC (mg/l)
0
200
400
2016
2018
2020
Lu-U
Lu-D

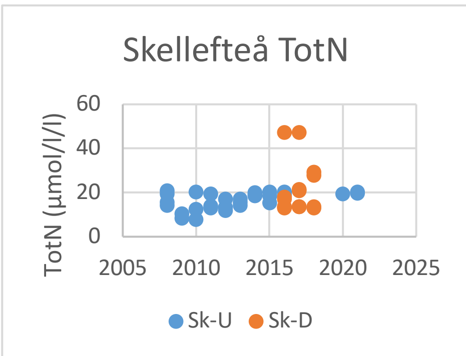

Luleå DIN
DIN (µmol/l/l)
0
5
10
15
2000
2010
2020
2030
Lu-U
Lu-D

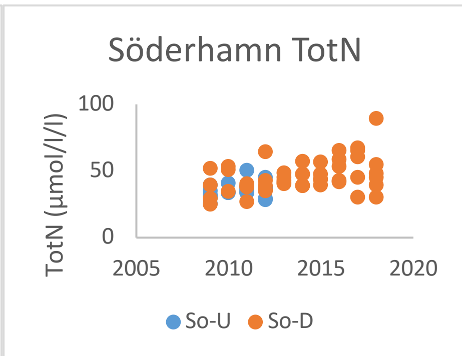

Skellefteå DIN
DIN (µmol/l/l)
0
5
10
2005
2010
2015
2020
2025
Sk-U
Sk-D

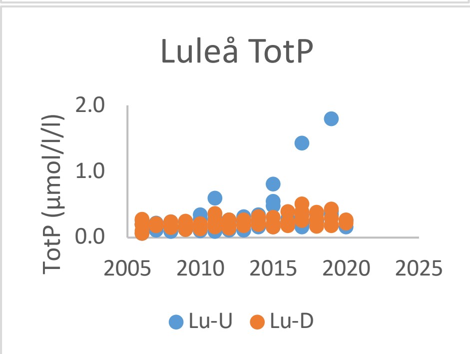

Söderhamn DIN
DIN (µmol/l/l)
0
20
40
60
2005
2010
2015
2020
So-U
So-D

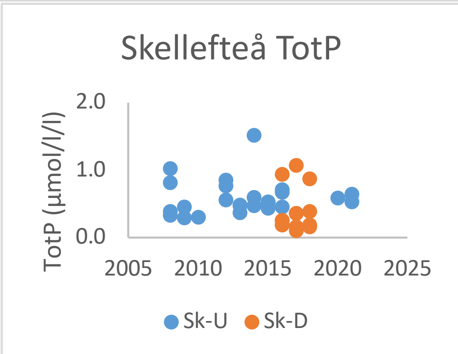

Umeå DIN
DIN (µmol/l/l)
0
10
20
30
2005
2015
2025
Um-U
Um-D

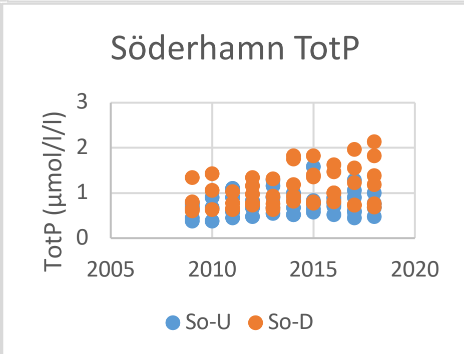

Luleå TotN
TotN (µmol/l/l)
0
10
20
30
2005
2010
2015
2020
2025
Lu-U
Lu-D


Skellefteå TotN
TotN (µmol/l/l)
0
20
40
60
2005
2010
2015
2020
2025
Sk-U
Sk-D


Söderhamn TotN
TotN (µmol/l/l)
0
50
100
2005
2010
2015
2020
So-U
So-D


Luleå TotP
TotP (µmol/l/l)
0.0
1.0
2.0
2005
2010
2015
2020
2025
Lu-U
Lu-D


Skellefteå TotP
TotP (µmol/l/l)
0.0
1.0
2.0
2005
2010
2015
2020
2025
Sk-U
Sk-D


Söderhamn TotP
TotP (µmol/l/l)
0
1
2
3
2005
2010
2015
2020
So-U
So-D

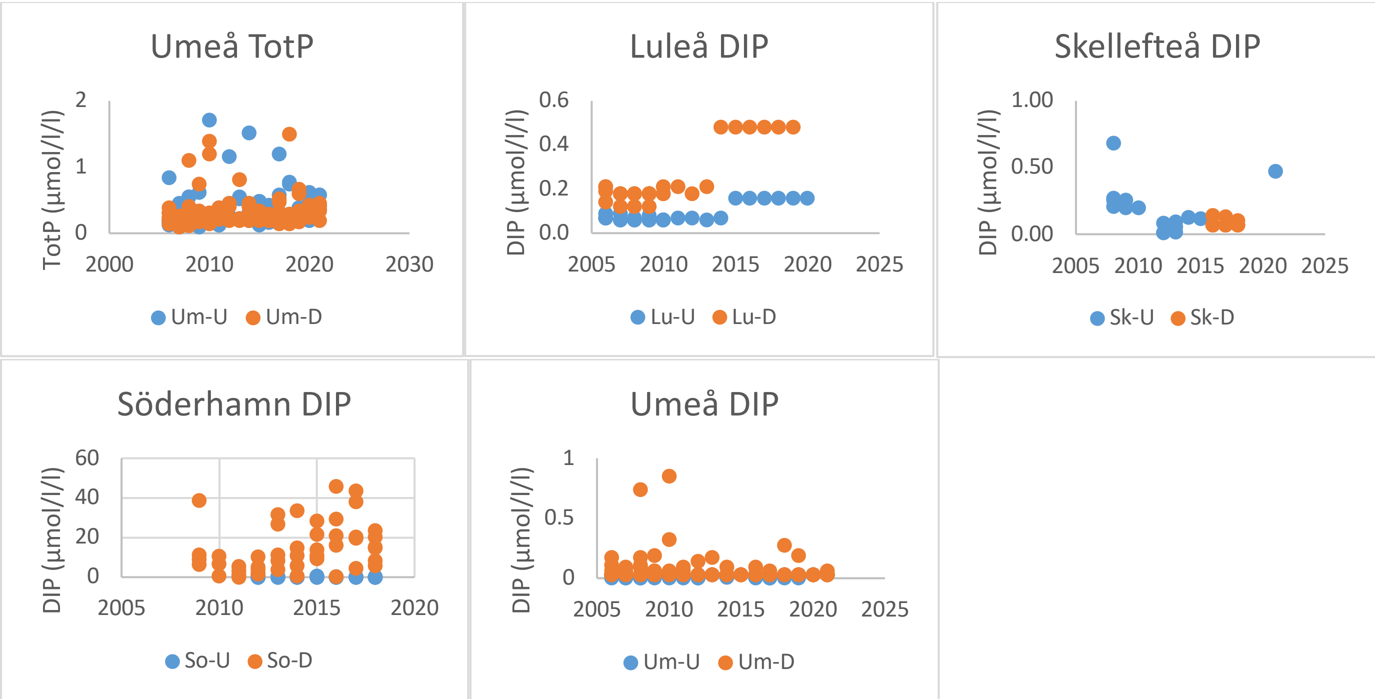
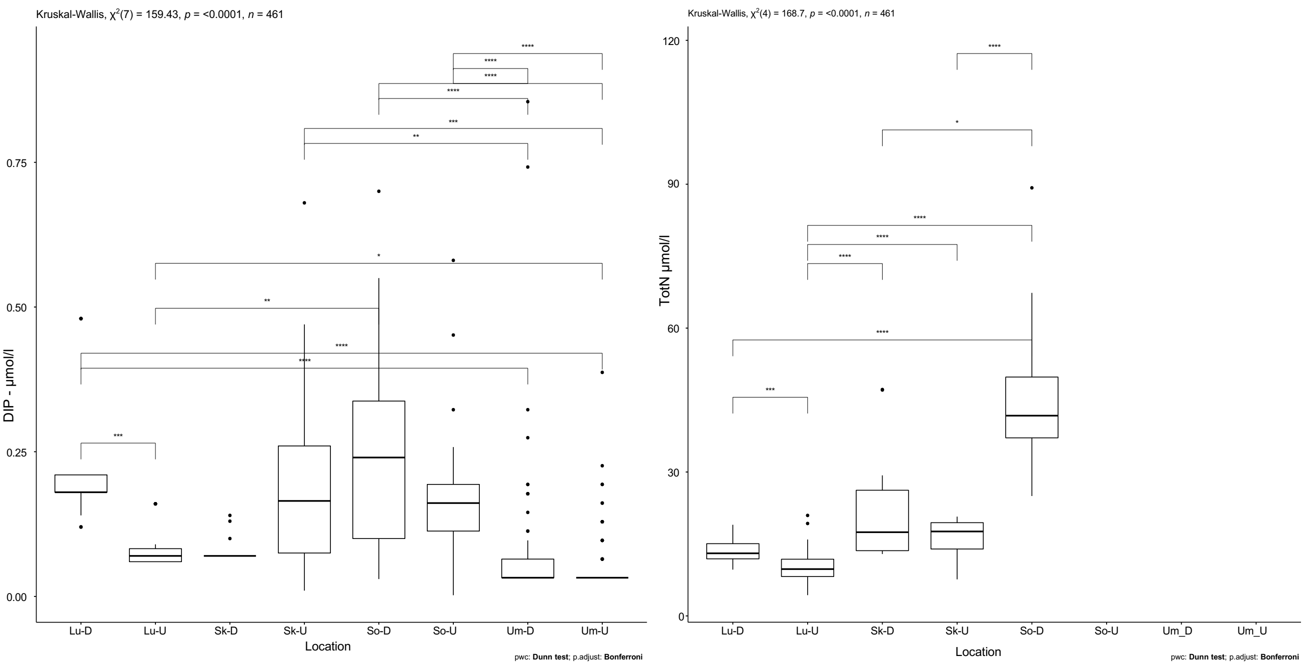


Figure 2: Temporal nutrient variations of TOC, DOC, TotP, TotN, DIN, DIP average concentrations annually over a 15-year period. Blue for upstream concentrations and orange for downstream concentration plotted against time, from 2006 to 2021.

The Shapiro-Wilk test was performed for all parameters for each station as a normality test to assess the normality of the data distribution in the data sets. It assumed the null hypothesis (H_0) that data distribution is not significantly different from a normal distribution and the alternative hypothesis that data distribution is statically different from the normal distribution. The decision criteria were based at 95% confidence level and at calculated $P<0.05$, null hypothesis was rejected, and alternative hypothesis accepted. The results showed that the alternative hypothesis is accepted in most of the data, except the following: Luleå downstream (Lu-D)& Luleå upstream (Lu-U) TOC where the p-values were 0.6694 and 0.07036 respectively, Lu-D TotN where p-value was 0.08919, Skellefteå upstream (Sk-U) temperature where p-value was 0.164, Skellefteå downstream (Sk-D) & Sk-U DIN/DIP where p-values were 0.3933 and 0.1718 respectively, Söderhamn downstream (So-D) DIP where p-value was, 0.1053, So-D NO_3 where p-value was 0.5451 and Lu-D & Lu-U DOC where p-values were 0.4627 and 0.05984 respectively (Appendix A: Shapiro-Wilk test results). Therefore, the next statistical test was a non-parametric Kruskal-Wallis test.

Kruskal-Wallis test is a non-parametric equivalent of ANOVA used to compare the distribution of three or more independent groups if one of the group medians of the data is statistically different from the rest of the group's median. The null hypothesis (H_0) of this test is that all group medians are statistically the same/similar and the alternative hypothesis is that at least one group median is statistically dissimilar/different. Decision criteria was based at 95% confidence level and calculated $P<0.05$. If $P < 0.05$, null hypothesis is rejected whereas the alternative hypothesis is accepted. Otherwise, if the computed $P > 0.05$, null hypothesis is accepted, i.e., there is no evidence that at least one of the group medians is different. From (Appendix B: Kruskal-Wallis test results), it can be observed that the null hypothesis is acceptable only for temperature, NO_3 and DOC where p-values were 0.469, 0.474 and 0.92 respectively, implying that in these three parameters, there is no statistically significant difference in group medians. Conversely, the alternative hypothesis is accepted in the rest of the parameters, implying that at least one group median is dissimilar from the other groups in each of the parameters in which P<0.05. This was followed by a post-hoc Dunn test to establish where dissimilarities occured.

Dunn test builds on results from the Kruskal-Wallis test. The objective of the Dunn's test is to provide information of which group pairs have medians that are statistically different. It provides adjusted p-values for each pair comparison. Decision is based on each pairwise comparison, if the computed P value is > 0.05 at 95% confidence level, compared groups are statistically similar. Otherwise, if the computed P<0.05, the compared groups medians are statistically different. From (Appendix C: Dunn test results), it can be observed that statistically significant differences appear for DIP where the p-value was 3.23E-05 between Lu-D & Lu-U, for NH_4 where the p-value was 1.25E-04 between Lu-D & Lu-U, for NH_4 where the p-value was 9.50E-10 between Um-D & Um-U and for TotN where the p-value was 6.29E-05 between Lu-D & Lu-U. In all set ups the values were higher downstream compared to upstream (Figure 3). The rest of the parameters and sampling station combinations were statistically similar, where all have P>0.05.



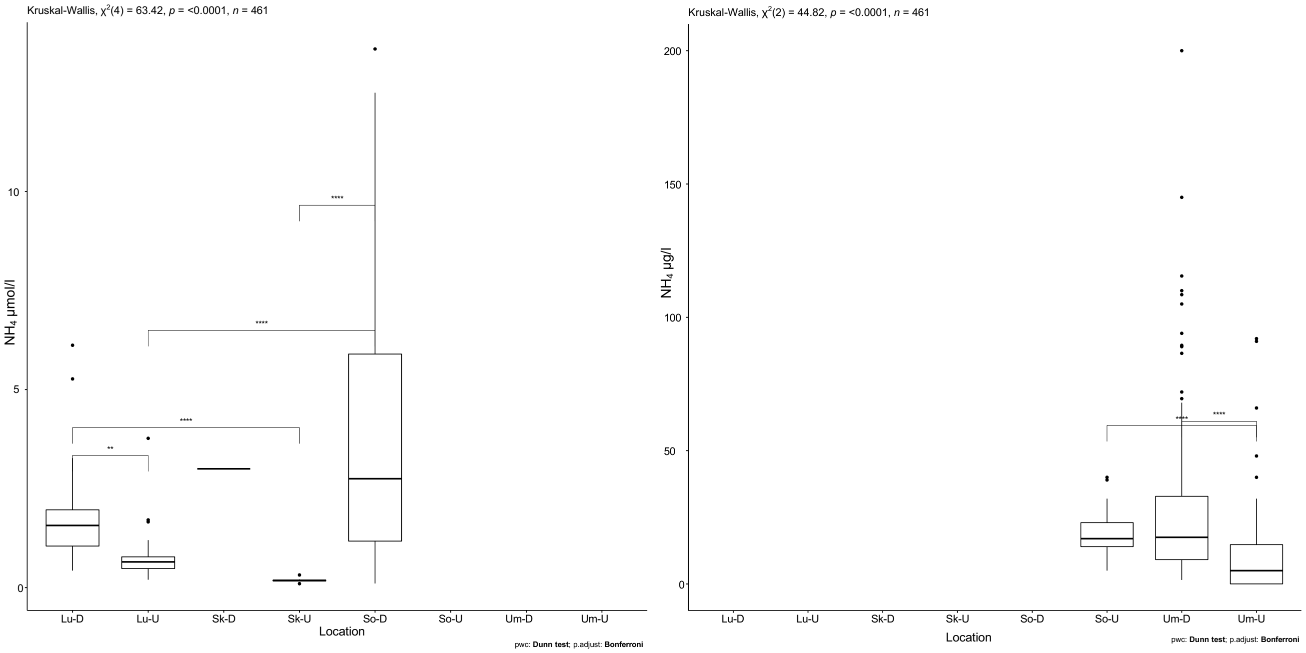


Figure 3: Shows significance difference in PO_4 (DIP), NH_4 and TotN between the upstream and downstream of Luleå and Umeå. Top figures show DIP and TotN downstream of Luleå WWTP is significantly higher than upstream, likewise in the left bottom figure, NH_4 for Luleå is higher downstream in the left bottom figure and for Umeå in the bottom right figure.

4 Discussion

4.1 Relationship between upstream and downstream nutrient loads

The results showed that there are statistically significant differences in nutrient loads in terms of DIP and NH_4 for Luleå and in NH_4 for the monitoring stations in Umeå (Figure 3). This agrees with the study by (Håkanson. 2009 and Kuosa et al. 2017), that the main deposits of phosphorus and nitrogen are in the drainage basin. It also agrees that WWTP contribute to nutrient loading in the coast of Gulf of Bothnia (Swedish EPA. 2020). However, the main sources of nutrients to the Gulf of Bothnia are forestry and agriculture (Lundberg, Jakobsson and Bonsdorff. 2009). The concentration loads of the other four monitoring stations upstream and downstream of Söderhamn and Skellefteå during the fifteen years (2006–2021) study period, showed no significant difference.

The spikes of high values of TotP, DIP and NH_4 in downstream Luleå and Umeå WWTP may be due to overflows from WWTP or point sources within the drainage basin. The varying concentrations of nutrients in different inflow rivers to the coast has been explained by hydrological conditions and physical properties of the Gulf of Bothnia drainage basin (Stålnacke et al. 1999 and Voss et al. 201). Also, the varied response in how there is higher concentrations downstream of other WWTP and not others is related to the size of the WWTP and catchment area. High downstream concentrations were found in WWTPs that serve higher populations (Umeå and Luleå). This corresponds to the findings in the Swedish EPA and Statistics Sweden (2020) report that reduction of phosphorus from wastewater treatments larger than 2,000 population equivalents has remained at 97 percent for the last decade, which means very little (approximately 3%) if any phosphorus in these rivers is from wastewater treatment plant sources. Therefore, Luleå presents a unique feature that the possible explanations for high DIP downstream Luleå WWTP may include sampling times (Appendix F) and other anthropogenic activities downstream like farming.

The statistically significant difference in NH_4 and TotN for Lu-U: Lu-D and NH_4 for Um-U: Um-D in this study demonstrates a limited efficiency of the WWTP ability to reduce nitrogen content from the wastewater. This is supported by the Swedish EPA (2020) with findings that purification/reduction of nitrogen is lower in the northern wastewater treatment plants. This means there is possible leakage of nitrogen and ammonia from the northern WWTP thereby causing these high concentrations downstream Umeå and Luleå. On the other hand, Skelleftea and Söderhamn WWTP serve the least amount of people compared to Umeå and Luleå therefore the WWTP efficiency may also be a contributing factor where higher nitrogen loads are observed downstream. In addition, Söderhamn WWTP is supported by wetlands that facilitate further reduction of organic matter and nutrient through natural processes initiated by vegetation, soils and associated microbial assemblages (Baltic Smart Water Hub. 2023). The longer the water retention in the wetland the more the nutrient transformation processes become effective (Humborg et al. 2003). Therefore, we acknowledge the relationship between wastewater and nutrient load in this study, in alignment with other studies and reports from (Hänninen and Vuorinen. 2015; HELCOM, 2013; Naturvårdsverket. 2023; SwAM. 2021 and Swedish EPA 2020;).

4.2 Other variables affecting wastewater emission

It is important to note that Sk-U and Sk-D data for NO_3 and NH_4 had only 2 samples downstream and 4 samples upstream and 1 sample downstream and 10 samples upstream respectively (Appendix C). Therefore, the p-values for these did not warrant a conclusive decision on the nutrient transfer or temporal trends. Similarly, the frequency of sampling for each monitoring station varied in the number of times samples were collected annually which ranged from eight months to three months and which months the samples were collected varied from February to December (Appendix C). This could have influenced the differences or the lack of difference in some nutrient values among the monitoring stations. This lack of consistence is sampling frequency and sampling time maybe due to the use of different data host. Data sources for this study was from two Swedish environmental monitoring data hosts (SLU MVN and SMHI) due to the inability to find all the data in one data host since monitoring programs are not mandatory, municipalities submit to data hosts voluntarily.

Decrease in nitrogen during summer in rivers is a prevalent and a natural occurrence in the Gulf of Bothnia, in winter on the other hand, DIP is imported from the sea (Humborg et al. 2003). Hence, it is not surprising that six of the eight monitoring stations presented no significant differences between upstream and downstream for DIP and TotN. Gulf of Bothnia coastal P-limited conditions are escalated in accordance with nutrient input from the rivers due to the ability of estuaries in boreal Arctic waters to import nutrients from the open sea (Voss et al. 2011). This creates a depletion of nitrogen during summer in rivers surrounding the Gulf of Bothnia (Humborg et al. 2003; Voss et al. 2011). Regardless, the effects on inflow nutrients from anthropogenic sources have high impact on sheltered coastal areas when compared with inner Bothnian Sea (Lundberg. 2009). This is counteracted with extensive water exchange in the Gulf of Bothnia which facilitates good oxygen conditions thereby mitigating the impact of internal phosphorus loading adding to its advantage due to the separation with the Bothnian sea by the Quark (Myrberg and Andrejev. 2006). Therefore, from this temporal study there is no evidence that there is significant changes in nutrient transfer from upstream to downstream over the 2006 to 2021 period (Figure 2; Appendix C).

Despite advanced eutrophication problems in the other parts of the Baltic Sea, the Gulf of Bothnia does not receive sufficient nutrient inflow from its drainage basin rivers. However, Lundberg, Jakobsson and Bonsdorff (2009) found that "Most of the stations, which show no direct signs of eutrophication, are undergoing a slow gradual degradation". In addition, major transportation occurs in small catchments that are mainly concealed by forests and peatlands drained by relatively small rivers (Pettersson, Allard and Borén. 1997). In contrast, larger rivers drain extensive areas that are diverse and contain subareas that do not discharge significant quantities of organic matter. The rivers in this study are among the regulated large rivers in the Gulf of Bothnia Coast hence other anthropogenic impacts like hydro power stations, transportation and dams may alter nutrient transfer from upstream to downstream.

5 Conclusions

The purpose of this study was to establish whether there is a significant difference in nutrient load from upstream compared to downstream that flows into the Gulf of Bothnia coast. This study does not ensure this view due to insufficient data in some of the monitoring stations. In addition, the nutrient transfer from inland waters to the coast is complex because nutrients may also be transferred from the Baltic proper to Gulf of Bothnia due to high water retention time. This makes it challenging to predict the future based on nutrient transfer alone because internal load of nutrients that is released from the sediments has impact on eutrophication. This means a distinction should be made between 'physiological' and 'systemic' nutrient limitation since in some oligotrophic environments (like the Gulf of Bothnia) algae grow at near maximum growth (Billen and Garnier 1997; Goldman et al. 1979; Paasche & Erga 1988, Thingstad & Sakshaug 1990, Thingstad & Rassoulzadegan 1995). Therefore, advanced wastewater management systems should be combined with natural buffer zones in the drainage network to reduce diffuse nutrient sources thereby reducing nutrient delivery to the coast.

There is need for better and targeted monitoring systems that focus on all sensitive environments with uniform monitoring tools and goals to meet the zero-eutrophication goal. It is equally important to consider the entire Baltic Sea as nutrients may get transferred withing the sea e.g., from Baltic proper to Gulf of Bothnia or due to other complex changing chemical and physical properties within the sea. This study presented a challenge for data collection due to language barrier, complex data host systems that have different names for the same stations, use of different units of measurement and different data structuring systems. Therefore, it important that there is coordination among the data host to provide a holistic overview of each monitoring program for non-Swedish speakers. Overall, this study illustrates that coastal eutrophication is complex and it can be mitigated through managing and monitoring nutrient sources with complete data sets.

Lower nutrient inflow reduces eutrophication, thereby maintaining consistent conditions of the coast with less primary production yielding less organic matter. Therefore, the focus should be on nutrients loads on sheltered coastal areas where effects of inflow nutrients have the most impact. As Voss et al. (2011) wrote "good riverine water quality does not necessarily result in a good water quality in the coastal waters, water quality objectives in a river, lagoon, or coastal water system cannot be determined independently for each subsystem. Rather the objectives should be defined according to the needs of the most sensitive system" which is the case for the Gulf of Bothnia if current conditions are coupled with climate change. Global climate models predict an increase in runoff due to high temperatures and excess winter rainfall in the Gulf of Bothnia catchment area (HELCOM.

2013 and Voss et al. 2011). Thus, suggesting that there will be an increase in nutrient inflow thereby potential increase in eutrophication in this region.

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7 Appendix

Appendix A: Shapiro-Wilk test results

P-values obtained from Shapiro-Wilk test with the highlighted (red) values showing that data was not normally distribution. Null hypothesis is acceptable in temperature, NO_3 and DOC parameters implying that in these three parameters, there is no statistically significant difference in group medians. Conversely, the alternative hypothesis is accepted in the rest of the parameters, implying that at least one group median is dissimilar from the other groups in each of the parameters in which $P<0.05$

Sampling Location	P-Values											
	Temp (C)	**TOC (mg/l)**	**TotP(µmol/l)**	**TotN (µmol/l)**	**DIN/DIP (µmol/l**	**DIP (µmol/l)**	**DIN (µmol/l)**	**NO_2 NO_3-N µmol/l**	**NO_3 (µmol/l)**	**NH_4 (µmol/l)**	**PO_4 (µmol/l)**	**DOC(µmol/l)**
Lu-D	0.009686	**0.6694**	0.0003982	**0.08919**	0.003048	3.089x10-7	3.661x10-5	1.573x10-13	0.001198	6.078x10-6	3.089x10-7	**0.4627**
Lu-U	0.002409	**0.07036**	2.256x10-12	0.002759	9.413x10-5	6.043x10-8	4.898x10-6	8.31x10-11	0.0009342	9.055x10-8	6.043x10-8	**0.05984**
Sk-D		0.01306	0.001857	0.001421	**0.3933**	1.281x10-5		0.03			1.281x10-5	
Sk-U	**0.164**	1.801x10-8	0.0006586	0.006678	**0.1718**	0.01378		0.03383		0.01366	0.01378	
So-D	0.02168	2.123x10-12	0.0001475	0.001486	8.635x10-12	**0.1053**	0.0001238	5.642x10-5	**0.5451**	9.514x10-5	0.01053	
So-U	0.0001321	0.02247	0.009759		7.466x10-13	3.174x10-5		1.039x10-10				
Um-D	0.01836	0.02776	6.448x10-13		1.483x10-7	2.70x10-17		1.829x10-8				
Um-U		5.976x10-5	2.545x10-11		4.55x10-15	5.0x10-16		4.983x10-10				
			TotP (µg/l)					**NO_2+NO_3 (µg/l)**		**NH_4 (µg/l)**	**PO_4 (µg/l)**	
So-U			0.009759					1.039x10-10		0.0279	6x54x10-7	
Um-D			6.448x10-13					1.829x10-8		2.604x10-11	2.71x10-17	
Um-U			2.545x10-11					4.983x10-10		7.801x10-13	4.98x10-16	

Appendix B: Kruskal-Wallis test results

Kruskal-Wallis test p-values. The highlighted (red) values show that the null hypothesis is acceptable in temperature, NO_3 and DOC parameters implying that in these three parameters, there is no statistically significant difference in group medians. Conversely, the alternative hypothesis is accepted in the rest of the parameters, implying that at least one group median is dissimilar from the other groups in each of the parameters in which $P<0.05$

Kruskal-Wallis Test	
Parameter	P-Values
Temp (C)	**0.469**
TOC (mg/l)	1.75x10-53
TotP (µmol/l)	5.77x10-49
TotN (µmol/l)	1.98x10-35
DIN/DIP (µmol/l	2.3E-09
DIP (µmol/l)	4.24x10-31
DIN (µmol/l)	1.68x10-10
NO_2 NO_3-N (µmol/l)	1.35x10-37
NO_3 (µmol/l)	**0.474**
NH_4 (µmol/l)	5.53x10-13
PO_4 (µmol/l)	3.92x10-10
DOC (µmol/l)	**0.92**
NO_2 NO_3-N (µg/l)	2.82x10-20
TotP (µg/l)	3.36x10-21
NH_4 (µg/l)	1.85x10-10
PO_4 (µg/l)	1.45x10-21

Appendix C: Dunn test results

Dunn test results showing the total number of samples tested for each parameter, p-values and the adjusted p -value and significance. The highlighted (red) numbers show where data was observed that statistically differences appeared. The statistically significant differences appear between Lu-D & Lu-U (DIP); Lu-D & Lu-U (NH_4); Um-D & Um-U (NH_4); and Lu-D & Lu-U (TotN). The rest of the parameter and sampling station combinations are statistically similar, where all have P>0.05

Parameter	Downstream Stations	Upstream Stations	Total number downstream	Total number upsteam	P-Value	P.adj	P.adj.signif
DIN- µmol/l	Lu-D	Lu-U	32	35	0.091090288	0.273270864	ns
DIP- µmol/l	Lu-D	Lu-U	30	32	**3.23E-05**	9.04E-04	***
DIP- µmol/l	Sk-D	Sk-U	14	16	0.356155379	1	ns
DIP- µmol/l	So-D	So-U	59	47	0.093304505	1	ns
DIP- µmol/l	Um-D	Um-U	86	86	0.405180209	1	ns
DIN/DIP- µmol/l	Lu-D	Lu-U	29	32	0.093094002	1	ns
DIN/DIP- µmol/l	Sk-D	Sk-U	14	10	0.705313741	1	ns
DIN/DIP- µmol/l	So-D	So-U	59	47	0.734850983	1	ns
DIN/DIP- µmol/l	Um-D	Um-U	86	86	0.124215985	1	ns
NH_4- µmol/l	Lu-D	Lu-U	31	34	**1.25E-04**	0.001254316	**
NH_4- µmol/l	Sk-D	Sk-U	1	10	0.02056596	0.205659602	ns
NH_4-µg/l	Um-D	Um-U	86	86	**9.50E-10**	2.85E-09	****
NO_2 NO_3-N µmol/l	Lu-D	Lu-U	60	50	0.32572754	1	ns
NO_2 NO_3-N µmol/l	Sk-D	Sk-U	14	10	0.823965946	1	ns
NO_2 NO_3-N µmol/l	So-D	So-U	58	62	0.724136193	1	ns
NO_2 NO_3-N µmol/l	Um-D	Um-U	86	86	0.194895533	1	ns
NO_3- µmol/l	Lu-D	Lu-U	9	9	0.669045249	1	ns
NO_3- µmol/l	Sk-U	Sk-D	2	4	0.137987031	0.827922185	ns
NO_2 NO_3-N µg/l	Um-D	Um-U	86	86	0.282611005	0.847833014	ns
TOC-mg/l	Lu-D	Lu-U	51	52	0.185383997	1	ns
TOC-mg/l	Sk-D	Sk-U	13	26	0.461256177	1	ns
TOC-mg/l	So-D	So-U	59	62	0.002242927	0.062801961	ns
TOC-mg/l	Um-D	Um-U	86	86	0.165848744	1	ns
TotP- µmol/l	Lu-D	Lu-U	60	60	0.548236694	1	ns
TotP- µmol/l	Sk-D	Sk-U	14	25	0.006191926	0.173373921	ns
TotP- µmol/l	So-D	So-U	59	62	0.102598469	1	ns
TotP- µmol/l	Um-D	Um-U	86	86	0.824202884	1	ns
TotN- µmol/l	Lu-D	Lu-U	60	62	**6.29E-05**	6.29E-04	***
TotN- µmol/l	Sk-D	Sk-U	14	30	0.432089082	1	ns

Appendix D: Letter to the municipalities

Sample letter sent to 17 municipalities along the Gulf of Bothnia

Till: Vakin, Umeå Kommun

Hej,

Mitt namn är Helen Mkandawire, och jag gör under vårterminen 2022 master-examensarbete vid Institutionen för Ekologi Miljö och Geovetenskap (EMG), Umeå universitet. Examensarbetet utförs inom ramen för ett projekt finansierat av Naturvårdsverket, ” Närsalter och övergödning i Bottniska viken” (Programmet för ”Syntesanalyser om avloppsvatten och övergödning, Miljöforskningsanslaget). Projektledare är professor Agneta Andersson, EMG. Syftet med mitt examensarbete är att undersöka hur utläppsvatten från reningsverk påverkar närsaltskoncentrationer och deras stökiometri i recipientvatten. Jag avser att syntetisera redan existerande mätdata. De ämnen jag är intresserad av är kol (C), kväve (N) och fosfor (P), som mätts inom ramen för Recipientkontrollprogrammen (SRK).
Har läst att Öns reningsverk är VAKINS största reningsverk med över 100 000 personer anslutna. Jag skulle därför vilja ta med Öns reningsverk i mitt examensarbete.
Jag är intresserad av att få information om närsaltskoncentrationer ovanför och nedanför utsläppsspunkten från Öns reningsverk. Jag undrar därför:

1. Om ni har data lagrade inom er organisation eller om ni skickar alla data vidare till den nationella datavärden (Recipientkontroll (SRK och RK) | Externwebben (slu.se), Miljödata MVM - Search (slu.se)?
2. Hur frekvent ni tar prover i recipienten och hur långa mätserier som finns?
3. Hur jag bäst kan få tillgång till data från olika mätstationer, tidpunkter och tidsserier?

Eftersom jag inte är svenskspråkig vore jag tacksam om ni kunde skicka svar på engelska, alternativt svara på svenska till min handledare. Då jag har begränsad projekttid, ber jag att få svar inom 2 veckor.

Vänliga hälsningar,

Appendix E: Total data collected for the study

Municipalities along the Gulf of Bothnia and their respective monitoring stations for wastewater where data was collected for this study and location of data collected from recipient stations.

Municipality	Stations	Downstream station	Data Source
Umeå	Umeälven, Vännäs Vattenverk (U7 (U1)	Umeälven, Sydspetsen Öhn (U8 (U5)	Municipality & SLU
	Ume älv Stornorrfors**(NÖ2 (U8/PMX)		SLU
	Vindelälven, Vännäsby, ovan bro(V5 (V5/U2)		SLU
Luleå	L5 - Gråsjälfjärden	L4 - Sandöfjärden	Municipality & smhi
Söderhamn	K338 (Soderhamnfjärden	Lötån, nedströms våg (48028)	smhi
	Söderhamnsån, söderh (48030)		SLU
Örnsköldsvik	A (130)Veckefjärden		Municipality
	B Moälven		Municipality
	C Örnsköldsviksfjärden		Municipality
	D Dekarsöfjärden		Municipality
	E (600) Nötbolandsfjärden		Municipality
	1 Moälven (Nouryon, Domsjö, 2 Miva, Sekab)		Municipality
	2 Moälven/ Örnsköldsviksfjärden (Nouryon, Domsjö, Sekab)		Municipality
	3 Örnsköldsviksfjärden (Domsjö)		Municipality
	4 Örnsköldsviksfjärden (Knorthem, Miva)		Municipality
	5 Dekarsöfjärden (Bodum, Miva)		Municipality
	6 Örnsköldsviksfjärden (Övik Energi AB)		Municipality
Kramfors	Bollstafjärden kontroll 1		Municipality
	Bollstafjärden kontroll 2		Municipality
	Kramforsfjärden		Municipality
	Älandsfjärden		Municipality
	Älandsfjärden kontroll 2		Municipality
	Södra sundet kontroll		Municipality
Gävle	K619		smhi
	K643		smhi
	K627		smhi
	K506		smhi
Piteå	P90		smhi

	P80		Smhi
	P70		Smhi
	P100		Smhi
	P250		smhi
Sundsvall/Timrå	1 (S coastal waters of the high coast)		Municipality & smhi
	50		Municipality & smhi
	135 (Alnösundet)		Municipality & smhi
	175 (Alnösundet)		Municipality & smhi
	320 (Sundsvall Fjärden)		Municipality & smhi
	575 (Draget)		Municipality & smhi
	630 (Svartvikfjärden)		Municipality & smhi
Kalix/Haparanda	Ka 15		Municipality
Nordmaling		NF1	smhi
		NF13	smhi
Skellefteå	S (Skellefteälven, Risön)	S1(Skellefteälven, Ursviksfjärden)	smhi & SLU
	S2 (Skellefteälven, Kvistforsen)		Smhi & SLU
	S3 (Skellefteälven, Renströmsbron)		smhi
Hudiksvall	Ho60 (Hornån empties into Hudiksvallfjärden)		smhi
Nordanstig			No response/No data
Härnösand			No response/No data
Robertsfors			No response/No data

Appendix F: Total data summary

Downstream stations	Year	original # data	Month #	Total months	Upstream Stations	Year	original # data	Month #	Total months
Um-D	2006	8	5,6,8,10	4	Um-U	2006	6	4,5,6,8,10,12	5
Um-D	2007	14	2,4,5,6,8,10,12	7	Um-U	2007	6	2,4,5,6,8,10	5
Um-D	2008	14	2,4,5,6,8,10,12	8	Um-U	2008	8	2,4,5,6,7,8,10, 12	5
Um-D	2009	16	2,4,5,6,8,10,12	7	Um-U	2009	7	2,4,5,6,8,10,12	5
Um-D	2010	9	2,5,6,8,10	5	Um-U	2010	5	2,5,6,8,10	5
Um-D	2011	10	2,5,6,8,10	5	Um-U	2011	5	2,5,6,8,10	5
Um-D	2012	10	2,5,7,8,10	5	Um-U	2012	5	2,5,6,9,10	5
Um-D	2013	10	3,5,6,8,10	5	Um-U	2013	5	2,6,8,10	5
Um-D	2014	10	3,5,6,8,10	5	Um-U	2014	5	3,5,6,8,10	5
Um-D	2015	10	3,5,6,8,10	5	Um-U	2015	5	3,5,6,8,10	5
Um-D	2016	10	3,5,6,8,10	5	Um-U	2016	5	3,5,7,8,10	5
Um-D	2017	10	3,5,6,8,10	5	Um-U	2017	5	3,5,6,8,10	5
Um-D	2018	10	3,5,6,8,10	5	Um-U	2018	5	3,5,6,8,10	5
Um-D	2019	10	3,5,6,8,10	5	Um-U	2019	5	3,5,6,8,10	5
Um-D	2020	10	3,5,6,8,10	5	Um-U	2020	5	3,5,6,8,10	5
Um-D	2021	10	3,5,6,8,10	5	Um-U	2021	5	3,5,6,8,10	5
Lu-D	2006	11	3,6,8,10	4	Lu-U	2006	12	3,6,8,10	4
Lu-D	2007	11	3,6,8,10	4	Lu-U	2007	12	3,6,8,10	4
Lu-D	2008	11	3,6,8,9	4	Lu-U	2008	12	3,6,8,9	4
Lu-D	2009	12	3,6,8,9	4	Lu-U	2009	16	2,3,6,8,9	5
Lu-D	2010	11	3,6,8,10	4	Lu-U	2010	12	3,6,8,10	4
Lu-D	2011	12	3,6,8,9	4	Lu-U	2011	12	3,6,8,9	4
Lu-D	2012	12	3,6,8,9	4	Lu-U	2012	12	3,6,8,9	4
Lu-D	2013	12	3,6,8,9	4	Lu-U	2013	12	3,6,8,9	4
Lu-D	2014	12	3,6,8,9	4	Lu-U	2014	12	3,6,8,9	4
Lu-D	2015	12	3,6,8,9	4	Lu-U	2015	11	3,6,8,9	4
Lu-D	2016	11	3,6,8,9	4	Lu-U	2016	12	3,6,8,9	4
Lu-D	2017	12	3,6,8,9	4	Lu-U	2017	12	3,6,8,9	4
Lu-D	2018	12	4,6,8,9	4	Lu-U	2018	12	4,6,8,9	4
Lu-D	2019	12	3,6,8,9	4	Lu-U	2019	12	3,6,8,9	4
Lu-D	2020	10	3,6,7,8	4	Lu-U	2020	10	3,6,7, 8	4
So-D	2006	8	1,7,8,10	4	So-U	2009	6	3,5,6,8,9,11	6
So-D	2007	8	2,7,8,10	4	So-U	2010	3	3,5,6	3

So-D	2008	8	2,7,8,10	4	So-U	2011	6	3,5,6,8,9,11	6
So-D	2009	8	2,7,8,10	4	So-U	2012	5	3,5,6,9,11	5
So-D	2010	8	2,7,8,10	4	So-U	2013	6	3,5,6,8,9,11	6
So-D	2011	8	2,7,8,10	4	So-U	2014	6	3,5,6,8,9,11	6
So-D	2012	10	2,3,6,7,8	5	So-U	2015	6	3,5,6,8,9,11	6
So-D	2013	10	2,3,6,7,8	5	So-U	2016	6	3,5,6,8,9,11	6
So-D	2014	10	2,3,6,7,8	5	So-U	2017	6	3,5,6,8,9,11	6
So-D	2015	10	2,3,6,7,8	5	So-U	2018	6	3,5,6,8,9,11	6
So-D	2016	10	2,3,6,7,8	5	So-U	2019	6	3,5,6,8,9,11	6
So-D	2017	10	2,3,6,7,8	5	So-U	2020	6	3,5,6,8,9,11	6
So-D	2018	10	2,3,6,7,8	5	So-U	2021	6	3,5,6,8,9,11	6
Sk-D	2016	6	3,4,5,8, 10	5	Sk-U	2008	24	1,7,9,12	4
Sk-D	2017	6	3,5,6,8,10	5	Sk-U	2009	12	6,8,10	3
Sk-D	2018	4	3,5,8	3	Sk-U	2010	14	3,6,8	3
					Sk-U	2011	18	3,6,8	3
					Sk-U	2012	16	1,6,8	3
					Sk-U	2013	24	3,6,8	3
					Sk-U	2014	14	2,3,6,8	4
					Sk-U	2015	12	3,6,8	3
					Sk-U	2016	12	3,6,8	3
					Sk-U	2020	4	8	1
					Sk-U	2021	8	2,8	2