LAND-SEA INTERACTIONS IN THE COASTAL-MARINE SYSTEM OF THE BALTIC SEA UNDER HYDRO-CLIMATIC VARIABILITY

YUANYING CHEN

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Division of Resources, Energy and Infrastructure
Department of Sustainable Development, Environmental Science and Engineering (SEED)
School of Architecture and the Built Environment (ABE)
Royal Institute of Technology (KTH)
SE-100 44 STOCKHOLM, Sweden

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SUMMARY IN SWEDISH

Denna avhandling undersöker den fullständiga transportprocessen av näringsämnen från land till hav, genom olika viktiga komponener, inklusive näringsbelastningens karaktäristika, strömning- och transportdynamik i havet och slutligen hur dessa faktorer från land (näringsbelastningens karaktäristika) och hav (trasportdynamik och nätverket för vattenkvalitet) tillsammans kontrollerar näringstransporten och vattenkvaliteten i havet.

Näringskällorna längsmed den svenska kusten identifierades och separerades. De flesta avrinningsområden domineras av kvardröjande, äldre källor av näringsämnen och koncentrationsnivåerna från dessa källor ökar från norr till söder, eftersom både andelen jordbruksmark och befolkningstätheten är större i södra, jämfört med i norra Sverige. I ett fåtal avrinningsområden domineras näringsbelastningen av aktiva källor eller utgörs av blandade källor och där är det mer troligt att koncentrationsnivåerna sjunker med tiden, än i de avrinningsområden där kvarvarande källor dominerar.

Sett till riktningen på massflödet mellan de större havsområdena har Östersjön en stabil strömningsstruktur, även under varierande hydrologi och klimat. Däremot påverkas storleksordningen på massflödet mellan havsområdena av klimat och hydrologi, och vinden är den drivande faktor som har störst påverkan. Lösta ämnen som sprids från två tydligt olika kustområden i Östersjön resulterar i samma spridningsmönster och föroreningsgrad, trots att signifikanta skillnader finns i kustområdenas strömningsdynamik och transportmönster. Strömningsmönstren i havet kan framförallt kopplas till och kontrolleras av näringsbelastningens storlek. Vattenkvaliteten i Himmerfjärden, en vik av Östersjön, påverkas i olika grad både av landbaserade och havsbaserade processer. Kalla och torra förhållanden leder till störst förbättring av vattenkvaliteten, vilket innebär förbättrad eller oförändrad ekologisk status jämfört med andra underökta förhållanden.

SUMMARY IN ENGLISH

This thesis investigates the complete processes of nutrient loadings from land to sea, through different important component processes, including the nutrient loading characters from land, the flow and transport dynamics in the sea, and finally how these factors from land (the nutrient loading conditions) and the sea (transport dynamics and water quality network) together determine the fate of nutrients and the water quality in the sea.

The source conditions of nutrient loads from the Swedish watersheds along the coast are identified and distinguished. Most of the watersheds are dominated by subsurface legacy sources, and the concentration levels from subsurface legacy sources show an increase pattern from the northern parts of Sweden to the southern parts where there is a larger agriculture land share and greater population density. Some watersheds have dominant current surface sources or mixed sources and are more likely to have decrease trends in the concentration levels than the subsurface legacy sources dominated watersheds.

The Baltic Sea has a stable flow structure under different hydro-climatic conditions when considering the flux directions between marine basins. However, regarding the flux magnitudes between the basins, wind is the predominant driver that significantly influences the water flux. Solute released from two distinct coast locations of the Baltic Sea results in similar spreading patterns in the sea with the same released amounts, even though their coastal dynamics and transport patterns are significantly different. The spreading patterns of the solute concentration in the sea are mainly related and determined by the released amounts of solute. Water quality in the Himmerfjärden bay of the Baltic Sea is influenced by both land-based and sea-based factors to different degrees. The dry-cold hydro-climatic condition is the most favorable for improving water quality, as better or equally good ecological statuses are reached for the water quality components under the dry-cold condition

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Stockholm, January 26th, 2020.

TABLE OF CONTENTS

LIST OF PAPERS

I. **Chen, Y**., Vigouroux, G., Bring, A., Cvetkovic, V., & Destouni, G., 2019. Dominant Hydro-Climatic Drivers of Water Temperature, Salinity, and Flow Variability for the Large-Scale System of the Baltic Coastal Wetlands. *Water*, 11(3), 552. https://doi.org/10.3390/w11030552

II. **Chen, Y**., Cvetkovic, V., & Destouni, G., 2019. Scenarios of Nutrient-Related Solute Loading and Transport Fate from Different Land Catchments and Coasts into the Baltic Sea. *Water*, 11(7), 1407. https://doi.org/10.3390/w11071407

III. **Chen, Y**., Prieto, C., Goldenberg, R., Cvetkovic, V., & Destouni, G. Distinguishing nutrient contributions from legacy and active sources along the Swedish coast. *Submitted to Sustainability.*

IV. Vigouroux, G., **Chen, Y.**, Jönsson, A., Cvetkovic, V., & Destouni, G., Simulation of nutrient management and hydroclimatic effects on coastal water quality and ecological status - The Baltic Himmerfjärden Bay case. *Submitted to Ocean and Coastal Management.*

AUTHOR'S CONTRIBUTIONS TO PAPER I-IV

I. Chen, Y. contributes to study design, building up the model, performing simulations, analyzing results, writing the original draft and final version of the paper, reviewing the paper. Destouni, G. contributes to study design, analysis approach and writing the final version of the paper. Cvetkoivc, V. contributes to model selection and application, simulation set-up. Vigouroux, G. and Bring, A. contribute to scenario selection and data compilations. All the coauthors contribute to analyzing results and reviewing the paper.

II. Chen, Y. contributes to study design, setting up the model, performing simulations, analyzing results, writing the original draft of the paper and final version of the paper, reviewing the paper. Destouni, G. and Cvetkovic, V. contribute to study design, supervision, analyzing results, writing the final version of the paper and reviewing the paper. Cvetkovic, V. contributes to model set up.

III. Chen, Y. contributes to study design, data processing, calculations, data analysis, writing the original draft and final version of the paper, reviewing the paper. Destouni, G. contributes to study design, data analysis, writing the original draft and final version of the paper, and reviewing the paper. Prieto, C. and Goldenberg, R. contribute to data processing and reviewing the paper.

IV. Chen, Y. contributes to the Baltic Sea hydrodynamic simulations, the Himmerfjärden hydrodynamics model set up, data processing and results analysis, and reviewing the paper. Destouni, G., Vigouroux, G. and Cvetkovic, V. contribute to study design. Destouni, G. and Vigouroux, G. contribute to results analysis and writing the paper. Vigouroux, G. contributes to the coastal hydrodynamic and water quality models setup, data processing and simulations. Jönsson, A. contributes to the Himmerfjärden hydrodynamics and water quality model setup. All co-authors contribute to reviewing the paper.

LIST OF ABBREVIATIONS

Chl_a	Chlorophyll a
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus
FVCOM	Finite-Volume Community Ocean Model
GCS	Good Component Status
GOTM	General Ocean Turbulence Model
SM	Supplementary Materials
TN	Total Nitrogen
TP	Total Phosphorus
WF	Water Formation

ABSTRACT

This thesis investigates a few important component processes for understanding and quantifying eutrophication in the Baltic Sea, that include characterization of nutrient loadings from land, water flow in the sea under changing climate conditions and transport of solutes originating from different locations along the coast. Furthermore, this study aims to improve our understanding on how processes from land (the nutrient loading conditions) and the sea (transport dynamics and water quality) couple to determine the fate of nutrients in the sea and the water quality in a selected localized coastal area, the Himmerfjärden Bay.

Comprehensive data are compiled as a basis for numerical simulations. An open source tool for oceanographic studies FVCOM is used to simulate flow and transport processes in the Baltic Sea. Hydrodynamic simulations are verified in terms of temperature, salinity and water level for the year 2005. Results show that most of the investigated Swedish watersheds along the coastline are dominated by subsurface legacy sources, the loads of which are positively and linearly correlated with river discharges. Moreover, subsurface legacy sources are less likely to decrease over time compared with the current surface sources. The Baltic Sea has a stable flow structure considering flux directions between basins, while the flux magnitudes between basins are mainly determined by different wind conditions. The spreading patterns in the sea with solute released from different coastal areas are similar when the released amounts are comparable, even though different cases have different source input and water flow conditions. The overall spreading patterns in the sea are generally dominated by the total mass of released solute. Local transport dynamics and patterns around the coast differ greatly for different cases and are determined by the local flow conditions. Different water quality indicators are influenced by different land-based or sea-based measures for water quality improvement. The dry-cold hydro-climatic condition is the most favorable for improving the water quality and elevating the ecological status in the Himmerfjärden Bay.

Based on this investigation, varying hydro-climatic factors impose important influence on the different component processes of nutrient loading from land to the sea. For example, the change of river discharges from land in the future would influence the total load into the sea from subsurface legacy sources, and finally influence the general spreading patterns of nutrients in the sea. The change of wind conditions would affect the flow and transport dynamics at local scale and flow fluxes magnitudes between marine basins at the sea scale. Change towards a dry-cold condition would be beneficial for the water quality and lead to improvement of coastal water quality, while the change towards a wet-warm condition will be generally unfavorable for improving the water quality. Clearly more comprehensive studies are needed based on the component processes considered in this thesis, for mapping water quality and eutrophication long-term trends in the Baltic Sea with confidence that is sufficient for effective mitigation measures and policies.

Key words: Baltic Sea, nutrient loads, hydro-climatic variability, hydrodynamics, solute transport, water quality.

1. INTRODUCTION

Eutrophication becomes a serious environmental issue in many water bodies over the world (Nixon, 1995; Conley et al., 2009); it can lead to severe environmental consequences by threatening ecosystems, such as hypoxia zones (also called 'dead zones') in the sea (Meier et al., 2011). The exponentially increase of hypoxia or dead zones in the costal oceans since 1960s has been observed, and such a spreading of dead zones have resulted in serious ecosystem problems (Diaz and Rosenberg, 2008). Anthropogenic nutrient loadings from land are important driving factors for hypoxia and eutrophication in coastal areas and the sea (Meier et al., 2011, Diaz and Rosenberg, 2008). This human impact is especially severe for semi-enclosed sea areas, which receive relatively large amounts of nutrient loads from land and at the same time have slow water renewal due to small water exchange with outside (Vigouroux et al., 2019). The Baltic Sea, with its relatively small water exchange with the North Sea through the narrow Danish Strait and receiving considerable nutrient loads (HELCOM, 2011) from its large surrounding catchment area of 1,739,400 km^2 (Hannerz and Destouni, 2006), is an example of a semi-eclosed water areas with considerable hypoxia or anoxia zones (Conley et al., 2009, 2011) under stress from anthropogenic nutrient loads (Conley et al., 2009).

1.1. Nutrient loads from land into the Baltic Sea

The Baltic Sea is an integral part of northern Europe and is an important water environment for the surrounding countries. The total freshwater discharge from its large surrounding catchment areas (Hannerz and Destouni, 2006) is around 480 km^3/year (HELCOM, 2011), which brings notable nutrient loads from land into the sea. Of all the nutrient loads into the Baltic Sea, around 75% of nitrogen and more than 95% of phosphorus are waterborne input through river discharges, or direct discharges such as municipal waste water treatment plants (HELCOM, 2011).

To control the eutrophication process and protect the sea environment, countries around the Baltic Sea have agreed on the Baltic Sea Action Plan, which aims at international collaborations in nutrient load reductions to the sea (HELCOM, 2007). In addition, the European Union also introduced the Water Framework Directive (WFD) for protecting the water quality by an integrated river basins management approach (European Commission, 2000). However, even after adopting the Baltic Action Plan and the first management cycle of EU Water Framework Directive, both of which aim at reducing nutrient loads, the nutrient loads from land, such as those from the large parts of the Swedish catchments which drain into the Baltic Sea (Destouni et al., 2017), are still too high. Sweden is one of the countries with the highest contribution of nutrient loads into the Baltic Sea, for both nitrogen and phosphorus (HELCOM, 2011). The mitigation efforts are not satisfying in nutrient loads for the Swedish catchments (Destouni et al., 2017, Arheimer and Brandt, 2000), some of which may be dominated by subsurface legacy sources (Destouni and Jarsjö, 2018). The subsurface legacy sources, which slower the water quality response to the mitigation efforts (Van Meter and Basu, 2015; McCrackin et al., 2018, Sharpley et al., 2013), post a great challenge for appropriate management methods over longer time (Haygarth et al., 2014; McCrackin et al., 2018). Therefore, effective management approaches with practical and efficient mitigation plans based on a more comprehensive understanding of the source conditions and characteristics of the loads are greatly needed.

1.2. Hydrodynamic and Transport processes in the Baltic Sea

The Baltic Sea is a semi-enclosed shallow water body with relatively small water exchange with the North Sea (Leppäranta and Myrberg, 2009) and relative long exchange time of around 30 years (Stigebrandt, 2001). It can be viewed as divided into different sub-basins according to its overall topography characteristics (Leppäranta and Myrberg, 2009; Fonselius, 1996, HELCOM, 2013).

Physical conditions and dynamics of the Baltic Sea system have been extensively studied from different aspects (Lehmann and Hinrichsen, 2002; Lehmann and Hinrichsen, 2000; Meier and Kauker, 2003). The Baltic Sea has persistent circulation patterns over the long term period (Placke et al.,2018; Meier, 2007; Lehmann et al., 2002). It is a highly stratified shallow water system. Furthermore, some researches have discussed the variability that is inherent in the Baltic Sea physical characteristics and the possible mechanisms leading to those variabilities (Lehmann and Hinrichsen, 2002, Meier and Kauker, 2003). The variability of fluxes between basins is dominated by prevailing atmospheric conditions (Lehmann and Hinrichsen, 2002). Decadal variability of the salinity in the Baltic Sea is caused by decadal variations of freshwater inflow and the wind (Meier and Kauker, 2003). However, in terms of the general flow patterns in the sea, more specific research is needed to quantify the variabilities brought by the external forcings and identify their key drivers.

Pathways and transport patterns of nutrient loads released from different parts of the coasts and the sea have also investigated (Pastuszak et al., 2005; Radtke et al., 2012; Corell and Döös, 2013; Engqvist et al., 2006; Döös and Engqvist, 2007; Delpeche-Ellmann and Soomere, 2013; Myrberg and Andrejev, 2006). Water retention time and particle tracking methods have been used for studying the local transport features of different areas (Corell and Döös, 2013; Engqvist et al., 2006; Döös and Engqvist, 2007; Delpeche-Ellmann and Soomere, 2013; Myrberg and Andrejev, 2006). However, few studies cover the whole range of transport process from land though coastal areas to the whole sea (Jönsson et al., 2004; Vigouroux et al., 2019).

1.3. Water quality studies of the Baltic Sea

Water quality and biogeochemical processes in the Baltic Sea are widely discussed (Conely et al., 2009, Zillén et al., 2008, Vigouroux et al., 2019) from the aspects of nutrient budgets and cycles (Voss et al., 2005; Savchuk and Wulff, 2009), as well as biogeochemical and ecosystem modelling of the sea (Meier et al., 2012; Vahtera et al., 2007; Neumann, 2000; Vigouroux et al., 2019).

Biogeochemical models are usually combined with hydrodynamic models for better understanding of the water quality and biochemical processes of the sea (Vigouroux et al, 2019, Neumann and Schernewski, 2008). Those models are used to explain the eutrophication status and dynamics in the sea (Neumann and Schernewski, 2008; Neumann et al., 2002). Mechanism for ecosystem status and change is complicated in the Baltic Sea, not only related to nutrient loads, but also driven by external forcings, such as wind (Neumann and Schernewski, 2008).

Different nutrient load reduction scenarios have also been investigated in order to quantify possible effects on improving the ecosystem status of the Baltic Sea (Neumann et al., 2002; Kiirikki et al., 2001). These studies have shown that the response of ecosystems to the load reductions is complex and non-linear (Neumann et al., 2002). However, for the coastal areas, better ecological status at the sea could be also important and effective on coastal water quality improvement as the land mitigation effort on the overall nutrient load.

Therefore, for better understanding and managing the water quality and ecological status of the Baltic Sea and its coastal areas, further discussion of different mitigation efforts on the water quality and ecosystem status of the sea are needed.

2. AIM AND SCOPE

This thesis investigates the processes related to nutrient loads and transport in the Baltic Sea, specifically the characterization of nutrient loadings from land, the flow and transport dynamics in the sea, and finally how these factors from land (the nutrient loading conditions) and the sea (transport dynamics and water quality network) are coupled to determine the fate of nutrients in the sea and the water quality in the coastal areas of the sea.

In this thesis, the anthropogenic nutrient loads from land to the Baltic Sea (from the Swedish coast side) and their sources are first analyzed and distinguished (Paper III). The basic water flow patterns of the Baltic Sea and their variability under different hydro-climatic conditions are then discusses (Paper I). Next, examples of nutrient-related solute releases from two different coast locations in the Baltic Sea are considered to study the resulting transport patterns in the coastal areas and further into the Baltic Sea (Paper II). Finally, one example of the water quality condition changes under different land-based and sea-based management scenarios for the Himmerfjärden Bay of the Baltic Sea is discussed (Paper IV).

3. MATERIALS AND METHODS

3.1. Study Cases

3.1.1. The Swedish Coast

The Swedish coast extends from north to south and bounds the west part of the Baltic Sea. The Swedish rivers and small streams receive fresh water and associated nutrient loads from the Swedish watersheds discharging them into the Baltic Sea. Observation stations monitoring nutrient concentration and water discharge are set into the rivers and streams. In our study, we selected 37 coastal concentration stations along the Swedish coast from Destouni et al. (2017). 19 of these stations have associated water discharge measurements sufficiently close to the concentration measurements (red circle, Figure 1a) and are denoted as the Load set of measurements. For the rest of the 18 stations (green triangle, Figure 1a) water discharge data was obtained by estimating the discharge at the outlet from suitable upstream measurements (blue star, Figure 1a) and are denoted as the Load-est set of measurements.

3.1.2. The Baltic Sea

The Baltic Sea is an important water environment in the Northern Europe, lying between 10° E - 30° E in longitude and 53° N - 66° N in latitude. It is a brackish water system surrounded by 9 countries with the total catchment area of 1,739,400 km^2 (Hannerz and Destouni, 2006). The total freshwater discharge from its large surrounding catchment areas (Hannerz and Destouni, 2006) is around 480 km^3/year (HELCOM, 2011), which brings notable nutrient loads from land into the sea. The nutrient loads are greatly related with the discharge magnitude (Destouni et al., 2017) and its change influenced by hydro-climatic factors (Bring et al., 2015).

Furthermore, the sea water exchange of the Baltic Sea and the North Sea through the narrow Danish Straits is relatively small (Dargahi et al., 2017) and hence the Baltic Sea has a long renewal time of around 30 years (Stigebrandt, 2001). Due to the small exchange of sea water and relative long renewal time, the freshwater discharges and waterborne nutrient loads from land greatly influence water quality in the isolated Baltic Sea.

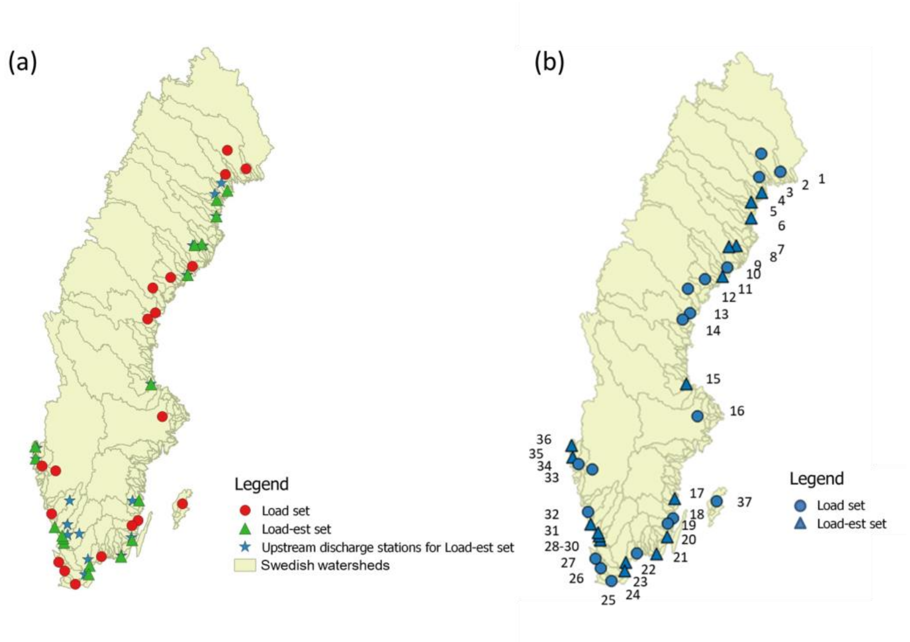


Figure 1. (a) Locations and (b) numbering of the most near-coastal stations from Destouni et al. (2017) considered in the present source analysis. In (a), both nutrient concentration and related water discharges are measured in the Load set of stations (red circles), while only nutrient concentrations are measured directly at the stations included in the Load-est set (green triangles). For the latter, a more upstream discharge station (blue stars) is instead available and used to estimate nutrient load (product of concentration and discharge) (Paper III).

3.1.3. The Kalmar County coast and the Vistula River coast

The Kalmar County coast is at the western part of the Baltic Sea and the Vistula River coast is at the southern Baltic Sea. They are selected for comparison because of their different hydro-climatic, geomorphological and hydrodynamic characteristics.

The freshwater discharges distributed along the Kalmar County coast are relatively small and diffuse. Furthermore, a narrow strait (the Kalmar Strait) is framed parallel to the coast by the island of Öland to its east, which blocks the interaction of the local coastal flow and the main currents in the sea.

The Vistula River, with its estuary in northern Poland, discharges a large amount of water as the second largest river of the Baltic Sea. It has a more open coastal area facing the Gulf of Gdansk compared with the Kalmar County coast.

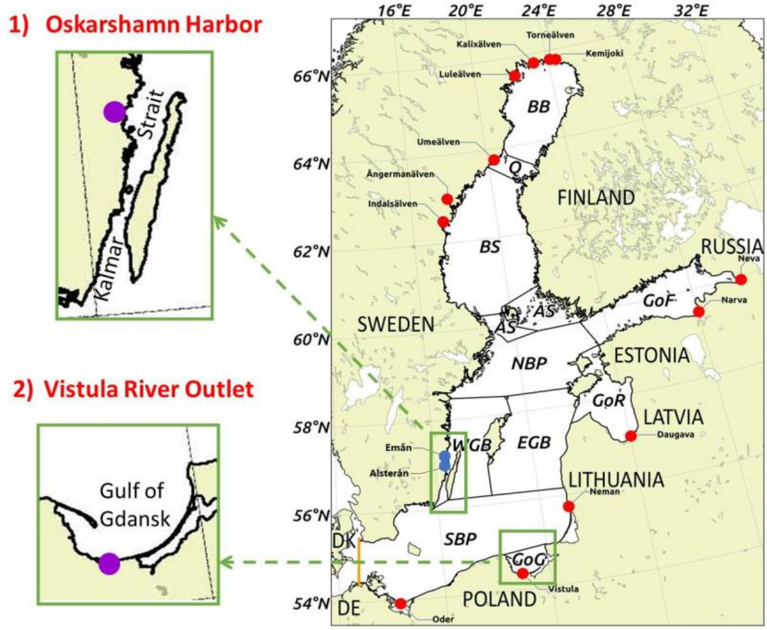


Figure 2. Main marine basins of the Baltic Sea, with the discharge points of 13 main rivers along the Baltic coast (red filled circles) and two local rivers at the Kalmar County coast (blue filled circles), and illustration of the two simulated coastlines and respective solute source release locations (purple filled circles) (modified from Paper I and Paper II).

The two cases also have different hydro-climatic conditions on land. The Kalmar County belongs to the district of Southern Baltic Proper in the Swedish water management district classification, which has an average annual precipitation of around 744 mm/year and runoff (discharge per catchment area) of 242 mm/year. By comparison, the Vistula River catchment has an annual average precipitation of 550–650 mm/year for the most parts of the associated catchments. Additionally, it has an average runoff of around 167 mm/year. Hence on average the Vistula River originates from drier areas.

3.1.4. The Himmerfjärden Bay

The Himmerfjärden Bay is situated in the west coast of the Baltic Sea in Sweden. There are two main freshwater discharges accounting for 68% of all the freshwater discharges into the bay: One is from the Södertälje canal, flowing from the lake Mälaren to the Igelstaviken water formation and the other is the Trosa river to the Trosafjärden water formation. Of all the nutrient loadings from point source, riverine source and air deposition into the bay, over 50% are from freshwater runoff; and around 40% are from point sources (Paper IV). The Himmerfjärdsverken wastewater treatment plant (WWTP) is the major contributor to the point source loadings.

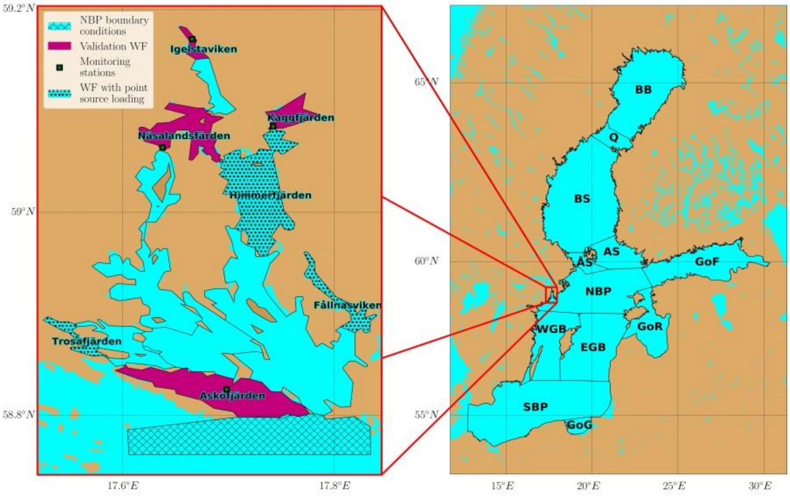


Figure 3: Left: Delimitation of different Water Formations (WFs) in the Himmerfjärden Bay; Right: The Himmerfjärden Bay location in the Baltic Sea and its marine basin Northern Baltic Proper (NBP) that forms the coastal boundary to the open sea. The right panel also outlines the other main marine basins (with associated acronyms) of the Baltic Sea (Paper IV).

The bay connects with the open sea at its southern part. The retention time for the bay, which is usually over 50 days, is relatively long (Engqvist, 1996). With the nutrient loadings from land and the relatively long retention time, there is a need to study and better understand the water quality dynamics in the Himmerfjärden bay.

3.2. Methods and simulation models

3.2.1. Dominant sources classification

Nutrient sources are classified based on the theoretical model developed by Destouni and Jarsjö (2018). The linear relationship of the total load L and water discharge Q are further developed and investigated in this study based on the model of Destouni and Jarsjö (2018), and used as a criteria to distinguish the different sources for the nutrient loads based on available data sets. Detailed derivations and equations are given in Paper III.

Case I: Dominant subsurface legacy sources

Based the quantification of legacy source contributions $C_{out\text{-}L}$ of each watershed by Destouni and Jarsjö (2018), the total coastal load L_{out} with dominant subsurface legacy sources can be expressed as:

$$L_{out} \approx L_{out\text{-}L} = C_{out\text{-}L}\, Q_{out} \approx \alpha Q_{out} \tag{1}$$

α in the above equation represents the subsurface legacy source concentration. In terms of a general linear function, the relation (1) can be expressed as $L_{out}=A\,Q_{out}+B$, with slope $A=\alpha$ and B=0, thus

$$L_{out} = A\,Q_{out} = \alpha Q_{out} \tag{2}$$

The linear relationship of the nutrient load L and water discharge Q is shown in Figure 4 (brown line). All the watersheds with similar L-Q relations are considered to have dominant subsurface legacy sources.

On the other hand, when the above linear relationship between nutrient loads L and water discharge Q exists only after an activation discharge Q_0, . the watersheds with sources resulting in such a L-Q relationship are considered as Case Ib, which is a special case of Case Ia, with the linear relationship between L and (Q-Q_0), as shown in Figure 4 (blue line). The existence of Case Ib watersheds based on available observed data shows the need of further considering other processes such as biogeochemical processes and the mass transfer and transport processes in the present model.

Case II: Dominant current surface sources

According to Destouni and Jarsjö (2018), loads dominated by current surface sources can be expressed as

$$L_{out} \approx L_{out\text{-}C} = C_{out\text{-}C}\, Q_{out} = \beta \tag{3}$$

β in the above equation is introduced to represent the loads contributed by current surface sources.

In terms of a general line function of $L_{out} = A\, Q_{out} + B$, we have the slope A=0 and intercept B=β:

$$L_{out} \approx L_{out\text{-}C} = B = \beta \tag{4}$$

Therefore, according to equation (3), watersheds with a similar L-Q linear pattern where the slope is close to zero (green line, Figure 4) are considered to have dominated current surface sources of nutrients.

Case III: Mixed subsurface legacy and current surface sources

According to Destouni and Jarsjö (2018), the loads contributed by mixed subsurface legacy and current surface sources can be expressed as

$$L_{out}=(1-\gamma)\, L_{out\text{-}L}+\gamma L_{out\text{-}C}\approx (1-\gamma)\alpha Q_{out}+\gamma\beta=AQ_{out}+B \tag{5}$$

i.e., the total load L_{out} is a linear function of water discharge Q_{out}, with slope $A = (1-\gamma)\alpha$ and intercept $B = \gamma\beta$. γ is a dimensionless contribution fraction quantifying the relative contributions of loads from current surface sources to the total load L_{out}; it varies between 0 and 1. Watersheds with a linear L-Q relationship with positive intercepts are considered to have mixed subsurface legacy and current surface sources (purple line, Figure 4).

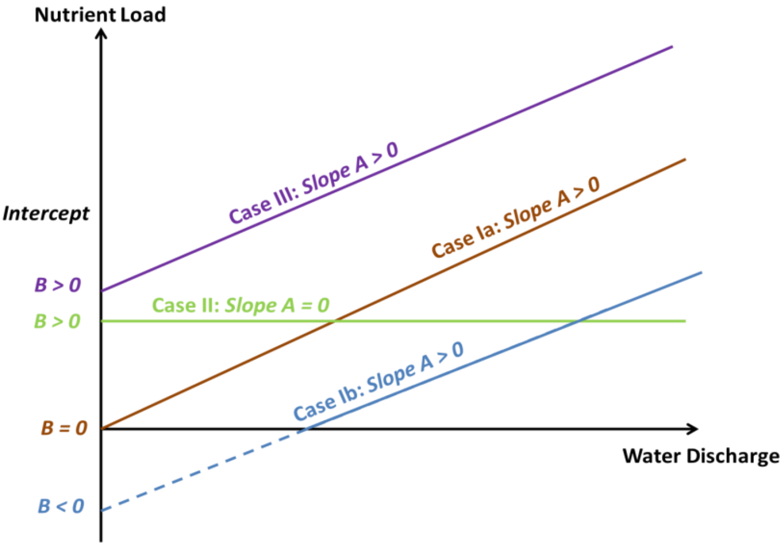


Figure 4. Schematic illustration of the principal regression line cases for the temporal data of nutrient load versus water discharge in each watershed to indicate: dominant subsurface legacy sources (Case Ia) with solute release at all discharge values, and Case Ib with solute release activated at discharges greater than some threshold value Q_0; dominant currently active surface sources (Case II); or a mixture of contributing legacy and currently active sources (Case III) (Paper III).

3.2.2. FVCOM model

The three-dimensional model Finite-Volume Community Ocean Model FVCOM (Chen et al., 2003), which is based on the primitive equations of momentum for free-surface water motion simulation, was used to simulate the hydrodynamic and transport processes of the Baltic Sea and its coastal areas.

Mellor and Yamada turbulence closure model (Mellor and Yamada, 1982; Galperin et al., 1988) is used in the model for vertical turbulence calculation and Smagorinsky eddy parameterization method is used for the horizontal turbulence mixing (Chen et al., 2003).

Finite volume method is used in the model for discretization to ensure mass conservation. In the horizontal direction, an unstructured triangular grid is used for better descriptions of complicated coastlines, and in the vertical direction, sigma layers are used to better capture the shapely changing bathymetry in the sea.

A wide range of coastal and ocean water cases use FVCOM model for simulation and have gained a great success in application (Chen et al., 2009; Chen et al., 2011; Beardsley et al., 2013; Wei et al., 2014). In the thesis work, we built up the FVCOM model for the Baltic Sea. Specifically, it uses triangular grid horizontally with a resolution of 10 km and has 20 uniform sigma layers vertically. The open boundary is set at Skanör (orange boundary line, Figure 2) for the simulation domain, connected to Kattegat and the North Sea.

Available observation-based data for external forcings are used to drive the Batlci Sea model. More specifically, we use water level, water temperature flux, and water salinity flux at/through the open boundary at Skanör (SMHI, 2016a and 2016b). We also select the 13 largest rivers, which contribute to approximately 65% of the total discharge from rivers into our Baltic Sea simulation domain (SMHI, 2012; GRDC, 2015). We apply wind and heat flux data over the sea (ECMWF, 2016; WHOI, 2016; ISCCP, 2016).

The model was validated against observed water temperature, water salinity variations with depth and from a time series for 3 stations distributed from south to north in the sea, and observed water elevation in time series for 2 stations at the south and the north of the sea, for the year 2005 (paper I, Supplementary Materials SM). Moreover, the general flow patterns are compared with previous hydrodynamic studies of the Baltic Sea (Lehmann et al., 2002; Meier, 2007) and show consistency.

For the comparison study between tracer sources in Kalmar County coast and Vistula River coast of paper II, the horizontal resolution at the coastal local zones of Kalmar Strait and Gulf of Gdansk is downscaled to 2 km, and increases gradually to 10 km at the main Baltic Sea. Two main local rivers for the Kalmar coast, whose discharges equal to around 0.5% of those of the 13 largest rivers, are added to better capture the local hydrodynamics and transport patterns.

For the Himmerfjärden Bay, an independent coastal hydrodynamic model is set up with a horizontal resolution between 0.1 km^2 and 1 km^2 adapted to its complicated coastlines and 11 uniform sigma layers in the vertical direction. Open boundary is set at the south of the model domain and receives external forcings including water level, water temperature and water salinity from the measured data (SMHI, 2016c and 2018). The FVCOM model is further coupled with the General Ocean Turbulence Model GOTM (Burchard et al., 1999, Chen et al., 2013) for calculating vertical turbulence for the coastal hydrodynamics of the bay. The coastal model is validated against two summer measurements of water salinity and water temperature for each of the years 2008 and 2009 at six stations in the Himmerfjärden Bay (paper IV, SM).

3.2.3. Water quality model

The water quality analysis is based on a simple biogeochemical model based on organic carbon mineralization to CO_2 in the sediment process (Kiirikki et al., 2001, 2006) applied on each marine basin and each layer (2 in that case) (Vigouroux et al., 2019). The model consists of an ecosystem module and a sediment module (Vigouroux et al., 2019). The ecosystem module takes into account the biogeochemical processes/circulations for the following variables: phytoplankton (the nitrogen-fixing cyanobacteria and the other phytoplankton), dissolved inorganic nitrogen DIN, dissolved inorganic phosphorus DIP, detritus nitrogen, detritus phosphorus and detritus carbon (Kiirikki et al., 2001; Kiirikki 2006; Vigouroux et al.,2019), based on the model of Tyrrell (1999). The sediment module considers nitrogen, phosphorus and carbon, and Iron-bound phosphorous in volatile (easily mobilized) sediments (Kiirikki 2006), but ignores the stabile pool that cannot be mobilized (Vigouroux et al., 2019). The ecosystem variables circulation among the basins is based on advective transport depending on the simulated water velocities.

The coastal water quality model for the Himmerfjärden Bay also includes anoxic areas and the iron-bound phosphorous variable is partitioned between its oxic and anoxic state, and is calibrated for the period 2002-2009 against data for the year 2015 having higher temporal resolution (Paper IV and its SM) and validated for four coastal water formations (WFs) for the summers of years 2008 and 2009 (Paper IV).

3.3. Cases classification and scenario settings

3.3.1. Three dominant cases for nutrient loadings

Nutrient loads L and water discharge Q at each watershed (station) are normalized with their mean values respectively. Linear L-Q regressions are fitted for the normalized L and Q data for each watershed (station). Watersheds with different source conditions are distinguished according to equations (1)-(5) and three approaches. The first approach takes into consideration the normalized shortest distance from the origin point to the fitted line; the second and third approaches consider the intercept of fitted line with the L axis or with the Q axis, respectively. Detailed information of the three approaches and classification criteria are given in Paper III and its Supplementary Materials.

Classification results are shown in Figure 5 and Figure 6 for watersheds with different dominant sources. Of all the 37 watersheds, 33 watersheds are identified to have dominant subsurface legacy sources (Case Ia and Case Ib) for both TN and TP, respectively. Besides, 1 watershed has dominant current surface source (Case II) and 3 have mixed subsurface legacy sources and current surface sources (Case III) for TN; while for TP, the remaining 4 watersheds all have mixed sources (Case III).

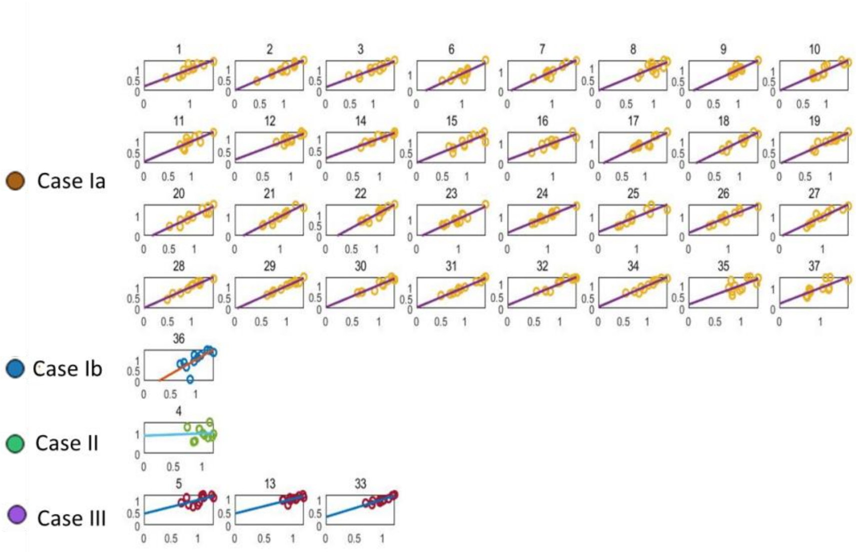


Figure 5. Resulting source case classification according to Figure 4, based on the best fit regression lines to the available data for normalized load (L, vertical axis) of total nitrogen (TN) versus normalized water discharge (Q, horizontal axis) at each station in the Load and Load-est station sets (Figure 1). The load L and discharge Q values are normalized with their respective mean values for each station (Paper III).

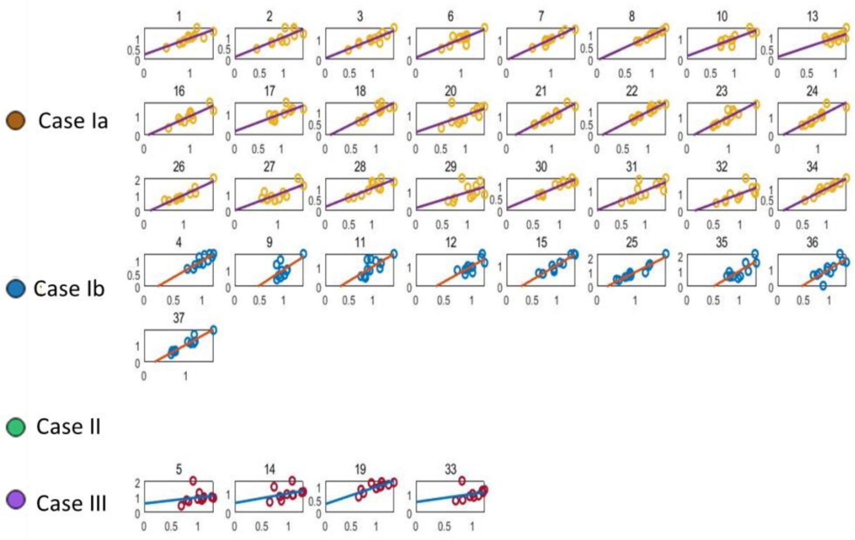


Figure 6. Resulting source case classification according to Figure 4, based on the best fit regression lines to the available data for normalized load (L, vertical axis) of total nitrogen (TP) versus normalized water discharge (Q, horizontal axis) of each station in the Load and Load-est station sets (Figure 1). The load L and discharge Q values are normalized with their respective mean values for each station (Paper III).

3.3.2. Three hydro-climatically distinct cases and management scenarios for the water quality simulation

To understand the influence of different hydro-climatic conditions on the hydrodynamics of the Baltic Sea (paper I), and further the hydrodynamics and water quality conditions in the Himmerfjärden Bay (paper IV), three different cases are chosen characterized by their river discharges into the sea (R, m^3/s) and net heat flux over the sea (denoted as T in Paper I and as H in Paper IV, W/m^2) based on the available data from 2000 to 2009, as described in Table 1.

To categorize the cases, the river discharges and net heat fluxes of each case are compared with the corresponding value that is averaged from 2000 to 2009. A case with larger/smaller river discharges than average is defined as with wet/dry condition. Similarly, a case with larger/smaller net heat fluxes than average is defined as with warm/cold condition. As the Himmerfjärden Bay is influenced by the Baltic Sea through the its open boundary linking to the sea, the conditions defined for the bay consider both the hydro-climatic conditions at the bay and also at the sea.

Table 1: Hydro-climatic condition-year classification based on hydrodynamic forcing conditions for the Baltic Sea and the Himmerfjärden Bay, using data for river discharges (R) and net heat flux (denoted as T for the Baltic Sea and H for the Himmerfjärden Bay) (modified from Paper I and Paper IV).

	Baltic Sea				**Himmerfjärden Bay**			
Cases	**R+,T-**	**R+,T++**	**R--,T+**	Period average	**R-,H-**	**R++,H++**	**R--,H+**	Period average
Year/Period	2005	2000	2003	2000-2009	2005	2000	2003	2000-2009
River Discharge (m^2/s)	9842	10162	6159	8617	11.6	20.1	9.8	14.5
Net heat flux ($W \cdot m^{-2}$)	-4.84	16.66	7.37	2.58	4.9	19.1	6.2	3.3

It should be noticed that the wet/dry condition may not be consistent for the cases with a same year but different region scales, which also holds for the warm/cold condition. Take year 2005 as an example. The case considering the total discharge in to the sea is a normal case. However, when comparing the discharges of the 13 largest rivers to the 10-years average value, it is a wet case. When comparing only the rivers discharging into Himmerfjärden Bay, it is a dry case. Therefore, year 2005 is characterizes as a wet case denoted by "R+" for the Baltic Sea scale and a dry case denoted by "R-" for the Himmerfjärden Bay scale. Moreover, year 2005 is relatively cold for the Baltic Sea, therefore it is denoted as "T–". The net heat flux at the local scale for the Himmerfjärden Bay is slightly higher than average. However, the cold condition of the sea for the year 2005 has relatively strong influence on the bay condition through the open boundary, therefore year 2005 is denoted as a cold case "H–" for the Himmerfjärden Bay.

The year of 2000 characterizes a wet and particularly warm case "R+,T++" for the sea, and a particularly wet and particularly warm case "R++,H++" for the bay. Therefore, the year 2000 can be considered as a typical example of wetter and warmer conditions, which might happen in the future, for both the sea and the bay. Similarly, the year 2003 characterizes a particularly dry and relatively warm case "R– –,T+" for the sea, and a particularly dry and warm case "R– –,H+" case for the bay, which can be seen as the possible conditions of drier summer in the future. Hydrodynamic simulations for the Baltic Sea are done with each of the hydro-climatic settings for the three cases "R+,T-", "R+,T++", "R- -,T+" respectively until they reached the quasi-steady state for case "R- -,T+", "R+,T++", or the water temperature has gone below zero for case "R+,T-" (see further description in Paper I).

Moreover, in the water quality simulations of the Himmerfjärden Bay, different management scenarios are set representing different possible mitigation approaches. Simulations are done under all the scenarios for 30 years with repeating the forcing data for each of the hydro-climatic cases until the results have reached steady state. Consequently, the short-term transient effects of the processes are removed. Thus, the steady state results point out the directions, towards which the considered variables may change in the future under the different corresponding management scenarios.

The management scenarios consist of a base case scenario (S_0), three scenarios reflecting the possible mitigation efforts from land (S_{PS}, S_R, and S_{PS+R}) (called land mitigation scenarios), one scenario (S_{Sea}) reflecting possible mitigation effort to attain good ecological status at the sea (called sea mitigation scenario), and one scenario ($S_{PS+R+Sea}$) reflecting the combined mitigation efforts from land and sea (called combined land and sea mitigation scenario). For example, S_0 represents the current management conditions; S_{PS} and S_R represent the cases of a reduction of total nitrogen and total phosphorus loads by 50% of the loads from point sources, and those reductions are made from point sources loads (S_{PS}) or from riverine loads (S_R), respectively. S_{PS+R} represents the combined reductions from both point sources S_{PS} and riverine loads S_R. S_{Sea} represents the situation with good ecological status that are attained in the sea influencing the coastal water quality condition in the bay through the coastal-marine boundary conditions, and $S_{PS+R+Sea}$ represents the combined mitigation efforts of S_{PS+R} and S_{Sea}.

3.3.3. Two coastal study cases and three release scenarios

The Kalmar County coast and the Vistula River coast are selected for comparisons because they have different hydro-climatic, geomorphological and hydrodynamic characters.

The freshwater discharge from the Kalmar County coast to the sea is relatively small and diffuse. To represent this type of loading along the

Kalmar County coast, Oskarshamn Harbor at the north of the coast (Figure 2) is selected as an example location. In this Kalmar County coast case, the small freshwater discharge from the coast first joins into a coastal flow that move mainly towards the south along the Kalmar Strait (red arrow, coast 1 in Figure 7), and further into a main marine current moving mainly southwestwards along the west coast of the Baltic Sea (blue arrow, coast 1 in Figure 7).

Compared to the Kalmar County coast case, the freshwater discharge from the Vistula River is large for the Vistula River coast case. The large river input enters a more open coastal gulf (Gulf of Gdansk) and meets with a circulating coastal flow (red arrow, coast 2 in Figure 7), and finally joins into a main marine current that goes northwards (blue arrow, coast 2 in Figure 7).

Moreover, the Kalmar County belongs to the district of Southern Baltic Proper in the Swedish water management district, which has an average annual precipitation of around 744 mm/year and runoff (discharge per catchment area) of 242 mm/year. Compared to the Kalmar County, the Vistula River catchment has annual average precipitation of 550-650 mm/year in most of parts of it. In addition, its annual average runoff is around 167mm/year, which is smaller than that of the Kalmar County. Therefore, on average the Vistula River originates from drier areas.

Three scenarios are selected for comparison of the different transport processes from different coast cases and also the influence of different loading conditions from land.

In the solute transport simulations, a solute source that locates at Oskarshamn Harbor for the Kalmar coast case is released over the whole depth of the water. The concentration of the source is set to be constant, normalized to be 1, and assumed to be dimensionless. For the sake of comparison study, in the Vistula River coast case, different amounts of solute are released as a mass flux from the boundary, such that the proportions of the released amounts between the two cases are consistent with the settings in different scenarios. The detailed explanations are as follows.

In the equivalent release scenario, an equal amount of solute load is released from the Vistula River outlet into the sea as the Kalmar County coast case.

Regarding the total nutrient scenario, the total annual averaged nutrient loads released into the sea are considered. The total nutrient loads released in the Vistula case are 35.6 times for TN and 55.1 times for TP greater than those in the Kalmar case, respectively, based on the annual average total TN and TP loads from these two cases (Kustvattenkommitten, 2001; Länsstyrelsen i Kalmar län, 2000; Stålnacke et al., 1999).

For the per-capita nutrient scenario, the annual averaged nutrient loads contributed by per person in the area are considered. More specifically, the average contributions per person are calculated by the population (Statistiska Centralbyrån, 2019; Nilsson, 2006) and the corresponding loads released from the areas (Kustvattenkommitten, 2001; Länsstyrelsen i Kalmar län, 2000; Stålnacke et al., 1999). Based on the average contributions per person, the released solute in the Vistula case is set such that the per-capita TN is 4.3 times smaller than that of the Kalmar case. Similarly, the per-capita TP in the Vistula case is 2.7 times smaller than that of the Kalmar case.

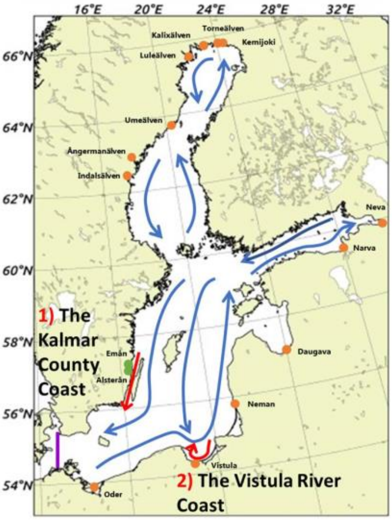


Figure 7. The Baltic Sea locations of the (1) Kalmar County and (2) Vistula River coastal cases are shown with the associated main coastal (red arrows) and marine (blue arrows) water flows; orange dots show the locations of the 13 largest river outlets along the whole Baltic coast and green dots show the outlet locations of two relatively small local rivers at the Kalmar coast (modified from Paper II).

4. RESULTS AND DISCUSSION

4.1. Nutrient concentration distribution from different sources on land for the Swedish coast

Spatial distributions of watersheds with different source types are shown in Figure 8a for TN and Figure 9a for TP, according to the classification in Figures 5 and 6, together with the corresponding subsurface legacy source concentration α, current surface source concentration β/Q_{out} and contribution fraction γ for the watersheds of different cases (Figures 8 and 9).

The legacy source concentrations of both TN and TP show spatial patterns of increasing from the north to the south, where the agriculture land share and the population density are also larger.

Current surface source concentrations are calculated by the intercepts β in Eqs. (4) and (5) divided by the annual average water discharge of the watersheds Q_{out}. Current surface source concentrations (Figures 8c and 9c) are smaller compared with the subsurface legacy source concentrations (Figures 8b and 9b), and the variations of concentration levels are much smaller compared to those of the legacy source concentration.

Contribution fractions γ for the mixed sources cases (Case III) are relatively large (larger than 0.6) for both TN and TP (Figures 8d and 9d) indicating the relatively large contribution from the current surface sources to the mixed sources cases.

Change trends of concentration levels over the years differ among different cases according to the statistics shown in Figure 10. For TN, the watershed of Case II has the largest decreasing trend in percentage per year of all the watersheds; all the 3 watersheds for Case III have a decreasing trend while the trends of watersheds in Case I alter around 0 with more or less equal proportions for increase or decrease. For TP, the medians of Case I and Case III watersheds both have a slight decreasing trend (Figure 10b). If we further count the proportion of the watersheds with a decreasing trend in terms of concentration, the result shows 19 cases out of 33 for Case I watersheds, while it is 3 cases out of 4 for Case III water sheds. It indicates that the TP concentrations of watersheds in Case III are more inclined to decrease compared with those of Case I.

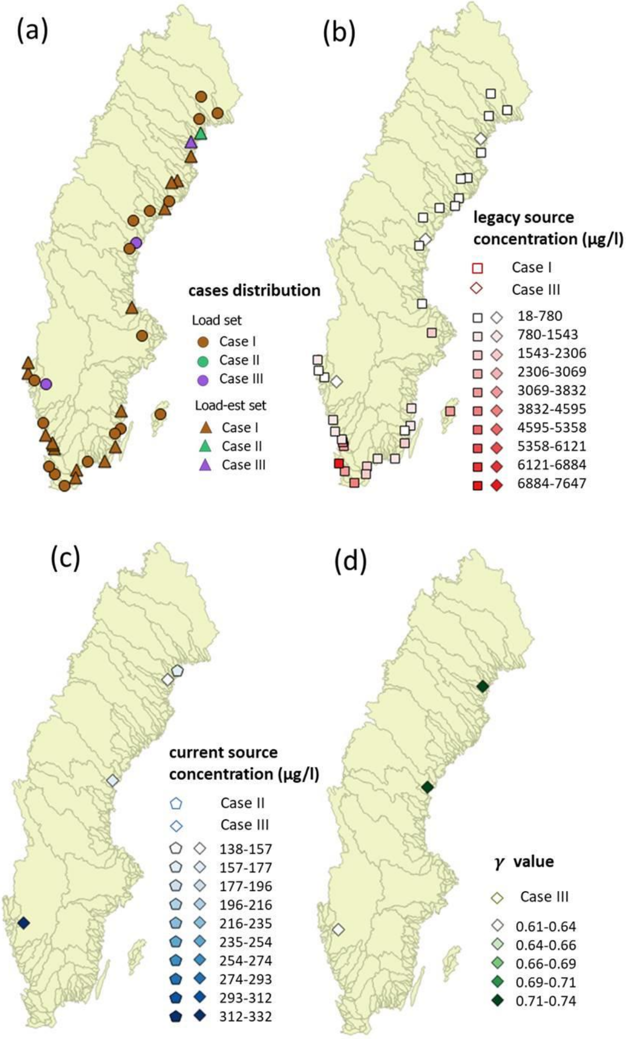


Figure 8. (a) Geographic distribution of the stations of different source cases according to Figure 4 with regard to total nitrogen (TN; Figure 5). Calculated TN source concentrations for (b) Case I and Case III subsurface legacy sources and (c) Case II and Case III current surface sources, and (d) contribution fractions (γ) for the latter in Case III stations (Paper III).

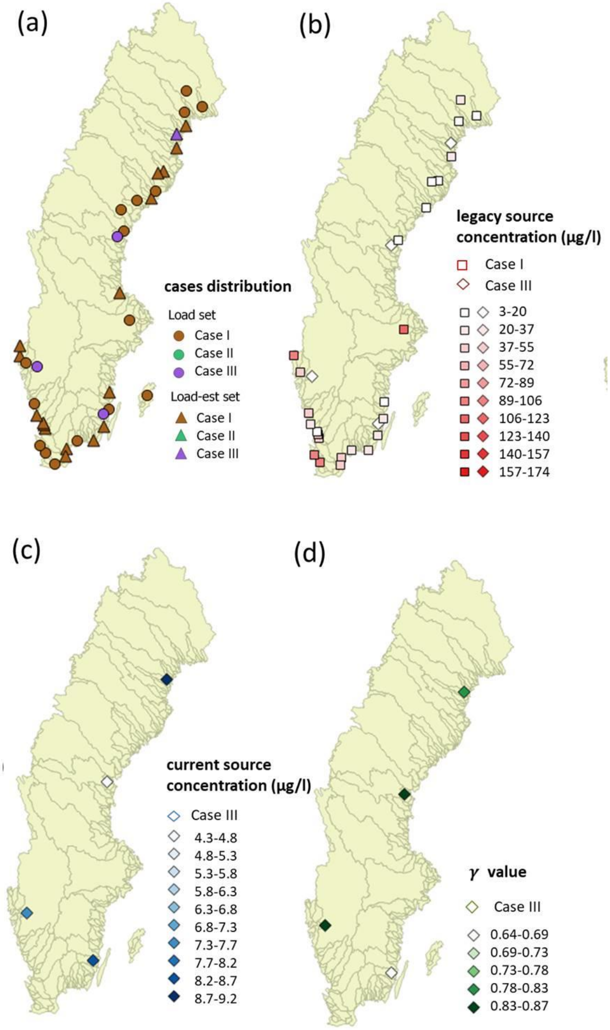


Figure 9. (a) Geographic distribution of the stations of different source cases according to Figure 4 with regard to total phosphorus (TP; Figure 6). Calculated TP source concentrations for (b) Case I and Case III subsurface legacy sources and (c) Case III current surface sources, and (d) contribution fractions (γ) for the latter in Case III stations (Paper III).

Nutrient concentrations in Case I watersheds, which have dominant subsurface legacy sources, are more difficult to mitigate compared with the concentration from current surface sources, as the concentrations of subsurface legacy sources stay within the watersheds with continuously mostly stable concentrations released into the water. These subsurface sources cannot be easily removed by current mitigation efforts; instead, they will have long-lasting effects on the water quality even though no new nutrient loads are added to the watersheds (Van Meter et al., 2018). This explains why Case I watersheds are less likely to have decreasing trends compared with other cases. While the nutrient concentrations from Case II and Case III watersheds, with dominant current surface sources or mixed sources, are considerably easier to mitigate with suitable mitigation methods.

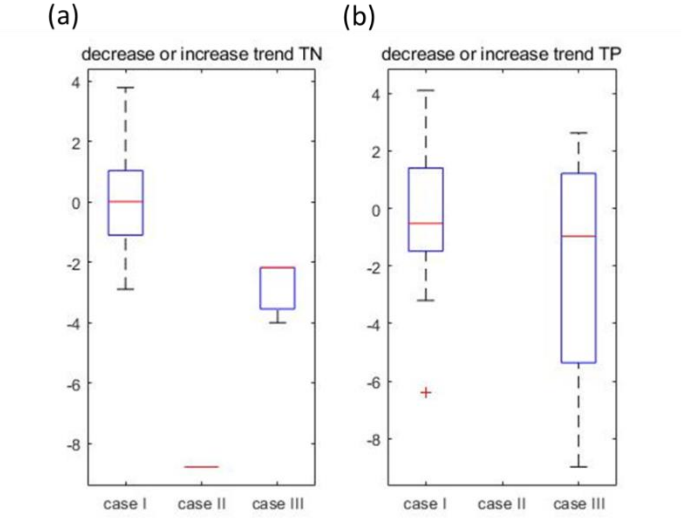
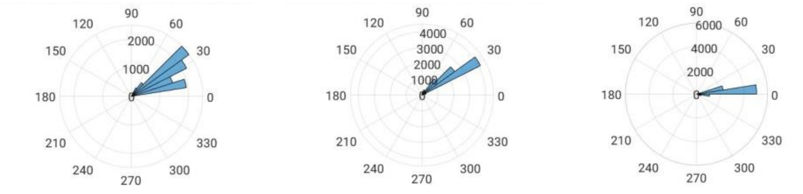


Figure 10. Statistics of change trends (percentage per year) at the stations of different source cases (Figure 4) for (a) the concentration values of total nitrogen (TN, left) and (b) total phosphorus (TP, right) in the discharges to the coast over the study period 2003-2013 (Paper III). The boxplots show the median (line) and associated interquartile (box) and total (whiskers) ranges, and the red + symbol in (b) shows an outlier value.

4.2. Flow patterns and its predominant drivers in the Baltic Sea

Hydrodynamic simulations were done with hydro-climatic settings of three cases “R+,T-”, “R+,T++”, “R- -,T+” (see Section 3.3.2) until they reached the quasi-steady state for case “R+,T++”, “R- -,T+” or the water temperature has gone below zero for case “R+,T-” (see further description in Paper I).

Besides the difference of freshwater runoff and net heat flux characteristics among the three cases, their wind directions are also different. Figure 11 shows the yearly average wind directions (the wind blows towards) at each simulation cell for the three cases. Case “R+,T-” has similar directions towards the northeast for most of the areas as Case “R+,T++”; while in Case “R- -,T+”, winds in most of the area are blowing towards the east.



(a) (b) (c)

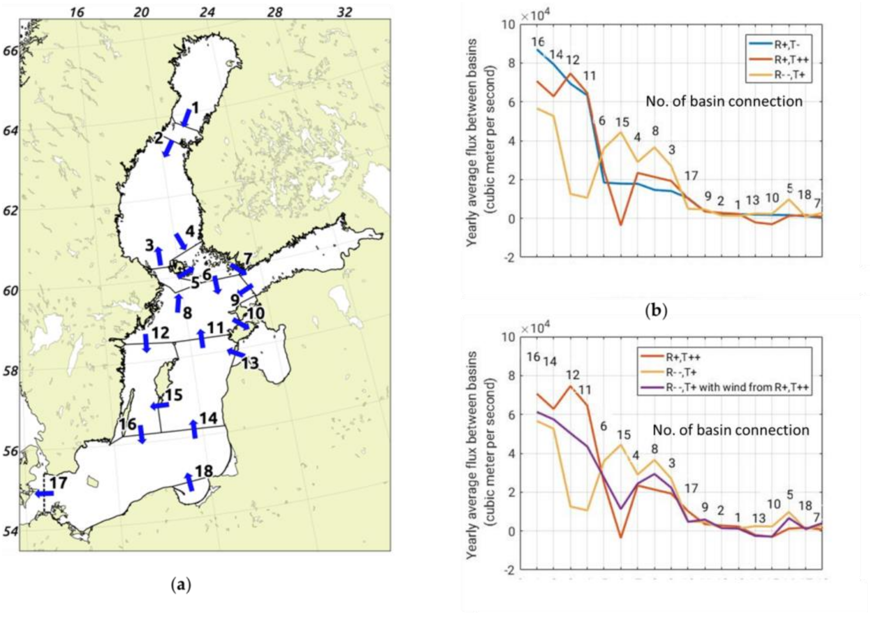
Figure 11. Yearly average wind direction for the simulation cases: (a) “R+,T-“, (b) “R+,T++”, (c) “R- -,T+”(Supplementary Materials, Paper I).

Circulation in the Baltic Sea is the basic factor to further determine the nutrient spreading and transport, and hence influence the water quality and biogeochemical process of the sea. With all the different hydro-climatic drivers/factors, we would like to investigate which factors are the most important for the basic flow structure in the Baltic Sea considering the fluxes direction and magnitude between basins (panel a, Figure 12), and to which extend the basic flow structure is influenced by these hydro-climatic driver(s).

Simulation results show that the flow structure of the two wet cases “R+,T-” and “R+,T++” have similar patterns. By comparison, the dry case “R- -,T+” is different with the fluxes through basin connections No.12 and

No.11 much smaller than the other two cases, while the flux through some other basin connections is larger, such as basins No.15 and No.8. However, with respect to flux direction between basins, the circulation patterns are quite stable among the three cases in spite of the relatively significant differences in the hydro-climatic conditions. Flux directions are the same for most of the basin connections with a large flux; some fluxes may alter their directions across the hydro-climatic cases, such as the fluxes going in and out of the Gulf of Riga (basins No. 10 and No. 13) which change directions for Case "R+,T++".

Furthermore, an additional test was simulated to test how wind can determine the flow structure of the Baltic Sea, with the basic hydro-climatic settings of the dry case "R- -,T+" and changing the wind conditions to the case "R+,T++". Results show that the flow structure of the wind-modified dry case "R- -,T+' (purple line, Figure 12c) is significantly different from the original dry case "R- -,T+" (yellow line, Figure 12c), while have more similarity with the wet case "R+,T++" considering the magnitude of the flux even though there is a great difference in the wetness between the cases. This additional test, together with the effects of wind compared above on the three cases, shows that the wind is the prevailing driver controlling the flow field of the Baltic Sea. With regard to the flow directions, the main flux directions are quite stable across all the cases, whereas the flux magnitude is essentially controlled by the wind field.



(a)

(b)

(c)

Figure 12. Yearly average flows between the marine basins of the Baltic Sea at a quasi-steady state (end-of-simulation period for each case). (a) Basin connection locations and flow directions for the simulation case "R+,T-". (b) Comparison of the resulting cross-basin flows for the three simulation cases: "R+,T-" (blue), "R+,T++" (red), and "R- -,T+" (yellow). (c) Comparison of resulting cross-basin flows for the simulation cases: "R+,T++" (red), "R- -,T+" (yellow), and a modified "R- -,T+" case with wind conditions from "R+,T++" (purple). Negative flows in panels b-c imply changed flow directions from the directions in panel a, for the case "R+,T-"(Paper I).

4.3. Solute transport pattern influenced by the land and sea factors

4.3.1. Land factors – three solute release scenarios

Two different coast locations are selected for comparison of the nutrient-related solute spreading patterns, both locally along the coast and further into the sea. The two cases, Kalmar County coast and Vistula River coast, represent different hydro-climatic conditions on land with drier condition for the Vistula River catchment. Moreover, they have different types of discharge of freshwater into the sea. Specifically, the Kalmar County coast discharge is characterized by relatively small and diffuse sources, while the Vistula River discharge is characterized by a large water river input. Comparisons between the two cases are made with the equivalent loadings from the two locations. Furthermore, nutrient-proportional loading scenarios are simulated for the two cases, with the nutrient loadings from the Vistula River coast proportional to those of the Kalmar County coast regarding total nutrient loadings and per-capita loadings, respectively. These scenarios are included for comparisons between the two cases, also for comparison of the relationship between different amounts of loadings and the transport patterns.

Results with equivalent release scenario are shown in Figure 13. The solute first accumulates at the coastal areas for the two cases, and then spreads into the sea, following the main current patterns of the Baltic Sea in Figures 7 and 12. Concentration levels are quite different at the coastal areas for the two release cases due to their different freshwater and nutrient discharge conditions. With the same loading, the Kalmar County coast with its relatively small and diffuse release, has a much higher concentration at the source and therefore higher concentration level in the coastal water. By comparison, the Vistula River coast, with a large river water discharge and thus lower associated concentration in order to maintain the same total loading as the Kalmar County release, results in lower concentration in the coastal water.

However, the global spreading patterns in the sea are quite similar between the two cases even though there are great differences with source input conditions from land and concentration levels at the local coastal areas. As shown in Figure 13, the two cases, with solute released from different locations, have similar spreading patterns with comparable concentration levels at similar places or similar distances from the sources in the sea.

Different amounts of solute are released at the Vistula River coast proportional to total average annual loads (Figure 14) and per capita released loads (Figure 15) of TN and TP compared with the Kalmar county case. In the total nutrient scenario, the TN and TP loads from the Vistula catchment are 35.6 times and 55.1 times higher than from the Kalmar County, and therefore have much higher and further spreading patterns into the Baltic Sea (Figure 14b and 14c) compared with the Kalmar County results as a baseline (Figure 14a). Converse results are obtained in the per capita nutrient release scenario, in which the released loads from Vistula catchment are 4.3 and 2.7 times lower for TN and TP respectively, compared to those from the Kalmar County. Therefore, the per capita loadings from the Vistula River coast case have resulted in a much smaller spreading and impact in the sea (Figure 15).

Irrespective of whether we compare the two cases within the same scenario, or across the three scenarios for the Vistula River release case, it is obvious that the total amount of loadings from land, has the dominant importance for determining the concentration level and its spreading distance in the sea from the source.

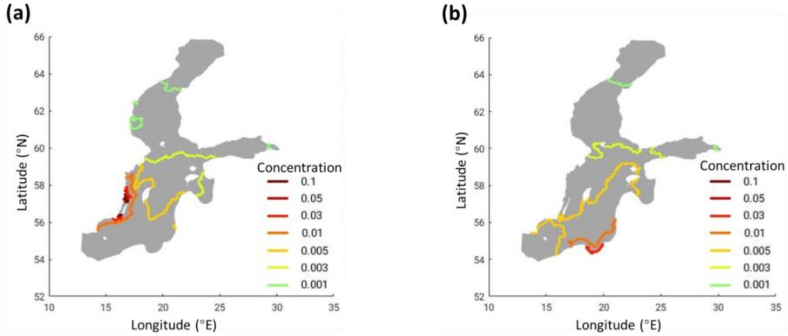


Figure 13. Isolines of maximum solute concentration over the simulation period in the equivalent release scenario. (a) Kalmar County coast case; (b) Vistula River coast case (Paper II).

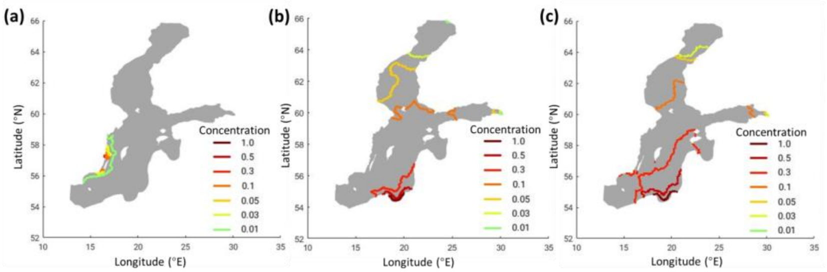


Figure 14. Isolines of maximum solute concentration over the simulation period for the total nutrient release scenario. (a) Kalmar County coast case with standard solute release; (b) Vistula River coast case with total nitrogen (TN)-proportional 35.6 times higher solute release; (c) Vistula River coast case with total phosphorus (TP)-proportional 55.1 times higher solute release (Paper II).

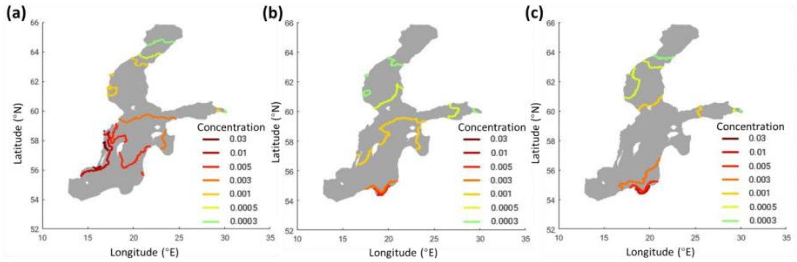


Figure 15. Isolines of maximum solute concentration over the simulation period for the per-capita nutrient release scenario. (a) Kalmar County coast case with standard solute release; (b) Vistula River coast case with TN-proportional 4.3 times lower solute release; (c) Vistula River coast case with TP-proportional 2.7 times lower solute release(Paper II).

4.3.2. Sea factors – two coastal cases with different coastal flows and marine flows

The impact of sea factors on the two cases are discussed under the equivalent release scenario. With the same release amount, the solute concentrations show different patterns at the local coastal areas. Nine observation points for each study case are selected (as shown in Figure 1c, Paper II) to show the hydrodynamics and concentration patterns at the coastal areas.

As Figures 16a and 17a show, the two cases have very different coastal flow fields: The Kalmar County coast case has a simple flow mainly towards the south through the Kalmar Strait (Figure 16a), while the Vistula River coast case has a more complicated flow circulating in the gulf with the flow direction altering a few times (Figure 17a). This results in the greatly different solute concentration distributions in the respective coastal waters. In the Kalmar County coast case, the concentration is much higher at the south than the north since the flow brings the solute towards the south; moreover, a distance effect is obvious in this case of mainly southwards flow with higher concentration at the closer distance to the source (Figure 16b). In the Vistula River coast case, with its circulating coastal flows, the distance effect is not clear; here, the lowest concentration is at the middle observation points and higher concentrations are observed at the fringe (Figure 17b). This is because the water in the middle parts mixes with the main marine currents from the sea (Figure 7), receiving fresh water from these currents which reduces the concentration. Further tests examined by power spectral density PSD and Magnitude-squared coherence also show that the two cases have different drivers and influence chains of their solute transport patterns due to the different hydrodynamic conditions in the sea.

One thing to note is that the concentration level is much higher at the Kalmar County case than the Vistula River case, which is due to the different ways of solute discharge or release from the land as stated above in section 4.3.1.

Power spectral density PSD and Magnitude-squared coherence results show that the two cases have different influence chains of the solute transport patterns at the coastal areas (see further details in paper II). For the Kalmar county coast case, (negative) northwards wind drives the flow both in northwards (negative) and eastwards directions, and finally determine the solute transport patterns at the local areas. By comparison, for the Vistula River coast case, solute transport patterns are influenced by the costal flow in the areas that are dominated by the costal flow; whilst at the areas with more interactions with the stable marine currents, such an influence from the local wind or flow conditions on the solute transport patterns does not exists or is very limited.

For the global spreading patterns in the sea, solutes in the two cases are following different marine currents because of their different released locations (Figure 7). Solute released at the Kalmar county coast are further transported to the south part of the sea following the southwards marine currents parallel to the coast and then northwards to the whole Baltic Sea, after it passes the narrow strait (Figure 7). While for the Vistula River coast case, solute mainly follows the northwards marine currents that meet with the local circulating flow at the bay and spread northwards to the whole sea from the south (Figure 7). However, from the global point of view regarding the general spreading patterns in the sea, the two cases exhibit similarity considering the comparable concentration levels at similar locations in the sea.

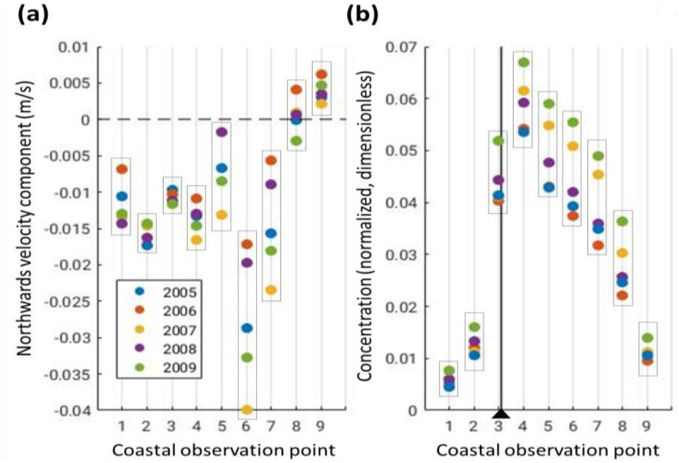


Figure 16. (a) Temporal average northwards velocity component (m/s). (b) Temporal average solute concentration (normalized, dimensionless). Results are for the Kalmar County coast and the symbol ▲ in panel (b) indicating the solute source location along this coastline (Paper II).

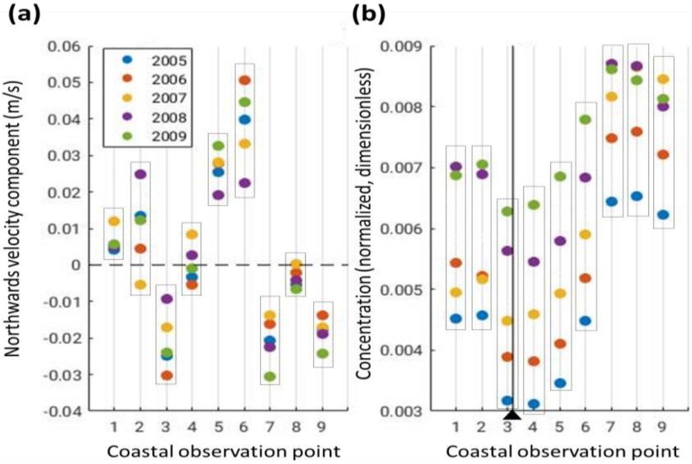


Figure 17. (a) Temporal average northwards velocity component (m/s). (b) Temporal average solute concentration (normalized, dimensionless). Results are for the Vistula River coast with the symbol ▲ in panel (b) indicating the solute source location along this coastline (Paper II).

4.4. Water quality conditions influenced by the land-based and sea-based factors

Simulations of water quality at the Himmerfjärden Bay of the Baltic Sea with different mitigation efforts of land-based, sea-based or combined land and sea mitigation scenarios are compared to the base case scenario (S_0) with the current mitigation condition under different hydro-climatic cases. This aims to compare the effectiveness of different mitigation efforts from land and from the sea, and also reflect on how and to which extend the land-based and sea-based factors will influence the coastal water quality.

Figure 18 show the proportion of water formations (WFs) that have reached the Good Component Status (GCS) for DIN, DIP and summer Chl_a, respectively. This proportion is used as an indicator to show how effective the mitigation efforts are for the coastal water quality. Detailed information about the calculation and classification of GCS are given in Paper IV.

As shown in Figure 18a, land-based mitigation efforts have more impact on the DIN than the sea-based effort. The land-based scenario S_{PS+R} and the combined land and sea scenario $S_{PS+R+Sea}$ have the most impact on improving the water quality conditions, especially for the dry-cold hydro-climatic case. By comparison, for the sea-based scenario the proportions of WF with good DIN status are worse.

For DIP (Figure 18b), the sea-based effort is more effective and has more impact on the water quality status, with more than 80% of all the WFs reaching good status for all the hydro-climatic cases. Land-based factors also have some influence on the water quality status, though not as much as the sea-based factor. In the dry-cold hydro-climatic case, all the land-based efforts result in an improvement over the DIP status.

For the summer Chl_a (Figure 18c), it is also the sea-based effort which yields more impact on the water quality improvement compared with the land-based efforts, and some improvements are also gained by the land-based scenario S_{PS+R} for the dry-warm and wet-warm hydro-climatic cases.

Overall, for the DIN condition in the bay, land-based factors with load reductions from land has the most impact on the coastal water; in contrast, for the DIP and summer Chl_a conditions, a better ecological status in the sea is more important for reaching a good water quality status in the coastal water. Combined land and sea mitigation efforts are effective for all those three water quality components of DIN, DIP and Chl_a.

With all the different hydro-climatic settings, the dry and cold condition is overall more favorable for improving water quality status for DIN, DIP and Chl_a for most of the scenarios compared with the other two cases. Dry-warm case comes the second, and the wet-warm case condition is generally the most unfavorable for reaching good status for the three water quality components.

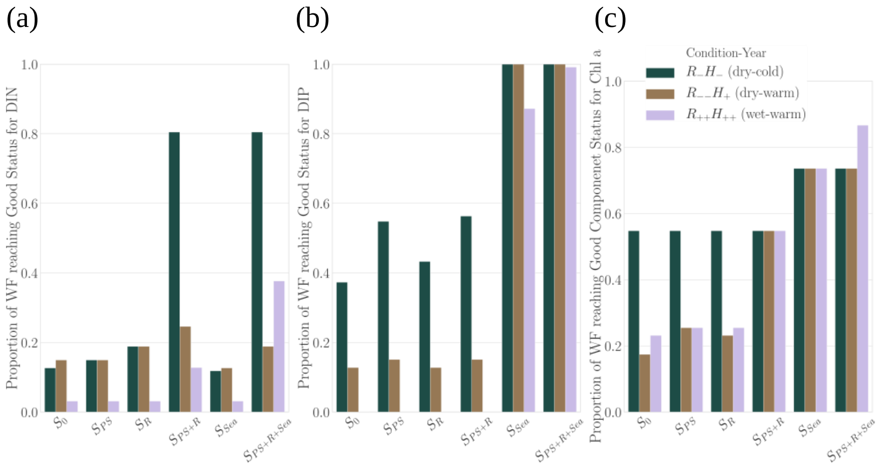


Figure 18: Proportion of coastal Water Formation area reaching Good Component Status for (a) DIN, (b) DIP, and (c) Chl a under main investigated scenarios (S_0, S_{PS}, S_R, S_{PS+R}, S_{Sea}, $S_{PS+R+Sea}$). (modified from Paper IV).

5. SUMMARY

This thesis focuses on the land and sea characteristics of the Baltic Sea system, considering the different sources and patterns of riverine nutrient loads from land and basic flow patterns in the sea under distinct hydro-climatic conditions. Further discussion about the land-based and sea-based effect on the transport patterns of the nutrient loadings at the local coastal scale and global scale of the sea are made by two different coast cases and three different scenarios. Moreover, impacts from the land and sea factors on the coastal water quality status are simulated and compared under different land-based and sea-based mitigation scenarios.

The Baltic Sea receives nutrient loadings from the Swedish coast (the west coast for the Baltic Sea), most of which are dominated by subsurface legacy sources. The subsurface legacy source loads are characterized by the linear-proportional relations of the total loads and the water discharge. Loads with this type of source are more difficult to mitigate compared with those from the current surface sources. The concentrations are quite stable for loads dominated by subsurface legacy sources, while the total amount of loads will change according to the volume of freshwater discharge.

The Baltic Sea has a quite stable flow structure considering the flux directions between basins. Most of the directions of large fluxes between marine basins will not change under distinct hydro-climatic cases, but the magnitude of the fluxes will change a lot depending on the wind field.

Nutrient loads released from different coasts on land to the Baltic Sea show different transport patterns in local coastal areas due to the site-specific coastal hydrodynamic conditions, but result in similar spreading patterns in the sea with comparable concentration levels at similar locations or distance from the sources in the sea, even though they follow different pathways transported by different marine currents. The global spreading patterns in the sea appear to be more influenced and determined by the amount of released loads from land than by the marine currents in the sea.

Water quality conditions at the coastal waters are influenced both by land-based and sea-based factors. Load reduction from combined sources from land has more impact on the DIN status than the improving sea environment, while sea ecological status can change the DIP and Chl_a status of the coastal water greatly. Dry-cold conditions are most favorable for improving the water quality status while the wet-warm conditions are generally most unfavorable.

The above investigation also shows that varying hydro-climatic factors have important impacts on the different component processes of nutrient loading from land to the sea. For example, the change of river discharges from land would influence the total load that comes from subsurface legacy sources into the sea, and eventually influences the spreading of nutrients in the sea; the change of wind conditions would influence flow and transport dynamics at local scale, and the flow fluxes between marine basins at the sea scale. The change towards a dry-cold condition could benefit the water quality, whilst the change towards a wet-warm condition will be generally unfavorable for water quality improvements. More comprehensive studies are needed based on the component processes considered in this thesis, for mapping water quality and eutrophication long-term trends in the Baltic Sea with confidence that is sufficient for effective mitigation measures and policies.

6. FUTURE WORK

Future work that builds on the results of this thesis could be done in the following three directions to further improve our understanding of the coastal-marine system of the Baltic Sea:

- to quantify the influence of loads from the Swedish coast to the Baltic Sea, with comparison under different freshwater discharge scenarios of climate change.
- to combine the tracer model with water quality model, considering all relevant transformations of the nutrients along flow paths, rather than using a passive tracer.
- to combine the hydrodynamic model, water quality model and the ecological model for a more comprehensive ecological simulation of different coastal areas in the Baltic Sea.

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