UPTEC W07013
Examensarbete 20 p
Juni 2007

Salt, water and nutrient fluxes to Himmerfjärden bay

Maria Khalili

Abstract
Salt, water and nutrient fluxes to Himmerfjärden bay

Maria Khalili

The Swedish Environmental Protection Agency has ranked eutrophication as the most severe threat to the Baltic Sea. The strategy to combat the eutrophication in the Baltic has been to reduce antrophogenous emissions of phosphorus and nitrogen from point and diffuse sources. Many scientists argue that the primary production in the Baltic proper is primarily limited by nitrogen which is why Sweden and other countries have implemented an ambitious and expensive program of advanced nitrogen removal in sewage treatment plants. Other experts argue that reduced nitrogen load to the Baltic Sea is either pointless or even harmful.

In the light of these fundamentally different views and the very opposite management strategies they imply, this study aims to more bring clarity to which measures should be taken to reduce eutrophiction by investigating the area of Himmerfjärden. Himmerfjärden is often used as an example of successful removal of nitrogen and the area has been intensively monitored since the 1970's.

This work used a process-based dynamic mass balance model for salt to calculate water retention times in Himmerfjärden. Water and nutrient flows to and from the bay have been calculated. It was shown that the contribution of nutrients to Himmerfjärden from the treatment plant is small compared to the contribution from the Baltic Sea.

This study showed by reviewing literature on Himmerfjärden that there are good reasons to question the hypothesis of Himmerfjärden being nitrogen limited in the long-run. The findings of this study will be used in future mass balance modelling of phosphorus, nitrogen and cyanobacteria in Himmerfjärden.

Keywords: Himmerfjärden, Baltic Sea, eutrophication, nitrogen, phosphorus, mass balance modelling.

Department of Earth Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala
ISSN 1401-5765

Referat
Flöden av salt, vatten och närsalter till Himmerfjärden

Maria Khalili

Naturvårdsverket rankar övergödningen som det allvarligaste hotet mot Östersjön. Strategin för att bekämpa övergödningen i Östersjön har varit att reducera antropogena utsläpp av fosfor och kväve från punktkällor och diffusa källor. Många forskare anser att primärproduktionen i egentliga Östersjön huvudsakligen är begränsad av kväve varför Sverige har infört ett ambitiöst och kostsamt program för avancerad kväverening på reningsverk. Andra experter hävdar istället att reducerade kväveutsläpp är meningslösa eller rent av skadliga.

I ljuset av dessa fundamentalt olika åsikter och de helt motsatta strategier de innebär syftar denna studie till att försöka klargöra vilka åtgärder som borde vidtas för att minska övergödningen genom att undersöka området Himmerfjärden som ofta används som ett exempel på lyckad kväverening. Området har också studerats intensivt sedan 1970-talet.

Detta arbete har använt en processbaserad dynamisk massbalansmodell för salt för att beräkna vattenutbytestider i Himmerfjärden. Flöden av vatten och näringsämnen till och från fjärden har beräknats och det har visats att bidraget av kväve och fosfor till Himmerfjärden från reningsverket är mycket marginellt jämfört med bidraget från Östersjön.

Denna studie har också genom att granska litteratur och mätdata från Himmerfjärden visat att det finns goda skäl att ifrågasätta hypotesen om att primärproduktionen i Himmerfjärden skulle vara långsiktigt begränsad av kväve. Resultaten av denna studie kommer att användas i framtida massbalansmodelleringar av fosfor, kväve och cyanobakterier i Himmerfjärden.

Nyckelord: Himmerfjärden, Östersjön, övergödning, kväve, fosfor, massbalansmodellering.

Preface

This master thesis work was done for the Aquatic Environmental Analysis Research Group at the Department of Earth Sciences, Uppsala University and it is a part of a M.Sc. Education in Aquatic and Environmental Engineering. Supervisor has been Andreas Bryhn and the subject reviewer was Professor Lars Håkanson, both from the Aquatic Environmental Analysis Research Group at the Department of Earth Sciences, Uppsala University.

I would like to thank Andreas, Lars and also Dan Lindgren (from the same research group) for their patience, help and foremost inspiration.

Much love goes out to my sista gal, Sofia and to the love of my life, Bobo.

UPTEC W07 013, ISSN 1401-5765
Printed at the Department of Earth Sciences, Geotryckeriet, Uppsala University, Uppsala, 2007.

KVÄVERENINGEN I HIMMERFJÄRDSVERKET – ETT KOSTSAMT EXPERIMENT?

Naturvårdsverket rankar övergödningen som det allvarligaste hotet mot Östersjön. Ett av de mest studerade områdena i Sverige när det gäller övergödning är Himmerfjärden, en fjärd som sträcker sig mellan Södertälje hamn och Askö. Speciellt med Himmerfjärden är dels att området har studerats intensivt sedan 1970-talet och dels att man ett reningsverk, Himmerfjärdsverket, som har använts för att genomföra och utvärdera storskaliga utsläppsexperiment.

Många forskare anser att primärproduktionen i Egentliga Östersjön huvudsakligen är begränsad av kväve varför Sverige har infört ett ambitiöst och dyrt (hittills runt tio miljarder) program för avancerad kväverening på reningsverk. Andra experter hävdar istället att reducerade kväveutsläpp är meningslösa eller rent av skadliga och att insatserna enbart bör läggas på fosforrening.

Tidigare forskning om Himmerfjärden har huvudsakligen utgått ifrån att Himmerfjärdsverkets utsläpp är av sådan betydelse för näringshalterna i fjärden att förändringar i utsläppsmängder påverkar den totala övergödningen i Himmerfjärden. Förändringar i klorofyll- och näringshalter har kopplats till reningsverkets utsläppsmängder av framför allt kväve. Tolkningar och slutsatser har ofta gjorts och dragits utifrån oorganiska fraktioner av fosfor och kväve.

Jag har i mitt examensarbete använt en processbaserad dynamisk massbalansmodell för salt för att beräkna vattenutbytestider i Himmerfjärden. Denna har använts för att kvantifiera och rangordna olika flöden till Himmerfjärden. Flöden av vatten och näringsämnen till och från fjärden har beräknats och det har visats att bidraget av kväve och fosfor till Himmerfjärden från reningsverket i själva verket är mycket marginellt jämfört med bidraget från Egentliga Östersjön.

För att förstå vad som händer i Himmerfjärden måste man genomföra massbalansmodellering av fosfor i fjärden och data är idag inte väl lämpade för det. Idealiskt skulle man utforma provtagningsprogrammet så att man utesluter en del stationer och istället lägger till en mätstation mellan Askö och Torö. Dessutom vore det önskvärt med fler noggranna vertikalt insamlade data från de stationer man mäter ifrån. Idag anges bara att proven är tagna på 0-10 m och t ex 20-30 m intervall och endast ett prov tas per tillfälle från de två olika lagren.

Mitt examensarbete har också visat, genom att granska litteratur om Himmerfjärden, att det finns goda skäl att ifrågasätta hypotesen om att produktionen i Himmerfjärden skulle vara långsiktigt begränsad av kväve. Dessutom har jag visat att data på oorganiska fraktioner av fosfor och kväve är olämpliga som mått på näringshalter i vatten om man vill göra förutsägelser om algproduktion och algbiomassa. Deras variabilitet är stor och de samvarierar dåligt med klorofyll som är ett vanligt mått på just algbiomassa.

Slutsatsen av mitt examensarbete är att kvävereningen i Himmerfjärdsverket är kostsam och ineffektiv eller rentav kontraproduktiv. Lokala åtgärder ”drunknar” i tillflödet från Östersjon och för att minska övergödningen i Himmerfjärden krävs åtgärder som minskar övergödningen i egentliga Östersjön.

TABLE OF CONTENTS

1 INTRODUCTION

Eutrophication is ranked as the most severe threat to the Baltic Sea (Savage *et al*. 2002, Bernes 2005). Eutrophication means that a water body becomes excessively loaded with nutrients over time. The negative effects that follow overloaded nutrient-rich waters are excessive algal growth and bottom oxygen depletion. This often leads to toxic algal blooms, low levels of oxygen in sediments and numerous other harmful effects (Elmgren 1989, Forsberg 1991, Rönnberg and Bonsdorff 2004).

The Baltic Sea is especially sensitive to pollution in general due to the brackish water causing the ecosystem to adjust to an environment that is neither marine nor fresh. The organisms living in the Baltic Sea originate from marine or fresh water environments and they adjust to the brackish water by regulating their osmotic processes. This is causing stress to the organisms and makes them less resistant to eutrophication (Kautsky 1993). Another sensitivity factor is the narrow threshold connecting the Baltic Sea to the North Sea, preventing a dynamic water exchange (Håkanson 1993).

In order to decrease eutrophication, one needs to understand how nutrients impact and support the eutrophication process. Fighting eutrophication is indeed a challenge but necessary to save and restore the Baltic Sea for future generations.

Many scientists agree about the benefits of decreasing phosphorus emissions to the Baltic Sea although the situation today is that the sources of phosphorus in Sweden are diffuse and small compared to the phosphorus emissions from the Baltic countries and Poland (Boesch *et al*. 2006).

Researchers disagree regarding the role of which nitrogen plays in the eutrophication process. Sweden has spent about ten billion Swedish kronor (Svenska Dagbladet 2006) on limiting nitrogen emissions to the Baltic Sea since the early 1990s (Elmgren and Larsson 1997) but the benefits of these efforts have recently been increasingly questioned (Boesch *et al*. 2006, Svenska Naturskyddsföreningen 2006, Dagens Nyheter 2007).

1.1 OBJECTIVE

The aim of this work and coming studies is to investigate the eutrophication in Himmerfjärden (Figure 1) by performing mass-balance modelling of salt, phosphorus and nitrogen. Himmerfjärden was chosen as study area because it has been studied intensively since 1976 and long data series on nutrient levels and water quality variables are available. There has been no proper mass-balance modelling of the bay before this study.

Elmgren and Larsson (1997) and Larsson *et al*. (2006) stressed the importance of performing a mass-balance modelling study of Himmerfjärden to determine flows and water retention times in the bay. The same report also asked for an evaluation of the sampling program used in Himmerfjärden. This study provides both and will hopefully help in understanding how to decrease eutrophication in the bay more effectively.

This work starts with a literature study and a review on previous eutrophication research in Himmerfjärden. The research includes four large-scale nutrient regulation tests by means of a treatment plant, Himmerfjärdsverket, discharging its effluents to Himmerfjärden. The results from Himmerfjärden are often cited and used to motivate the benefits of nitrogen emission reductions. This has been questioned and the debate has been lively (Rabalais 2002, Rönnberg and Bonsdorff 2004, Howarth and Marino 2006). Also from this perspective the conditions in the bay are interesting.

The study continues with an analysis of the morphology of Himmerfjärden using geographical information systems (GIS) and ends with a dynamic mass balance modelling of salt in the bay. The GIS mapping and the salt modeling describe the flow dynamics in the bay and they will constitute the foundation of further mass balance modelling of Himmerfjärden.

Based on this work, future mass-balance modelling of phosphorus and nitrogen aims to evaluate previous measures to decrease eutrophication and will attempt to predict future changes in the trophic status of the bay.

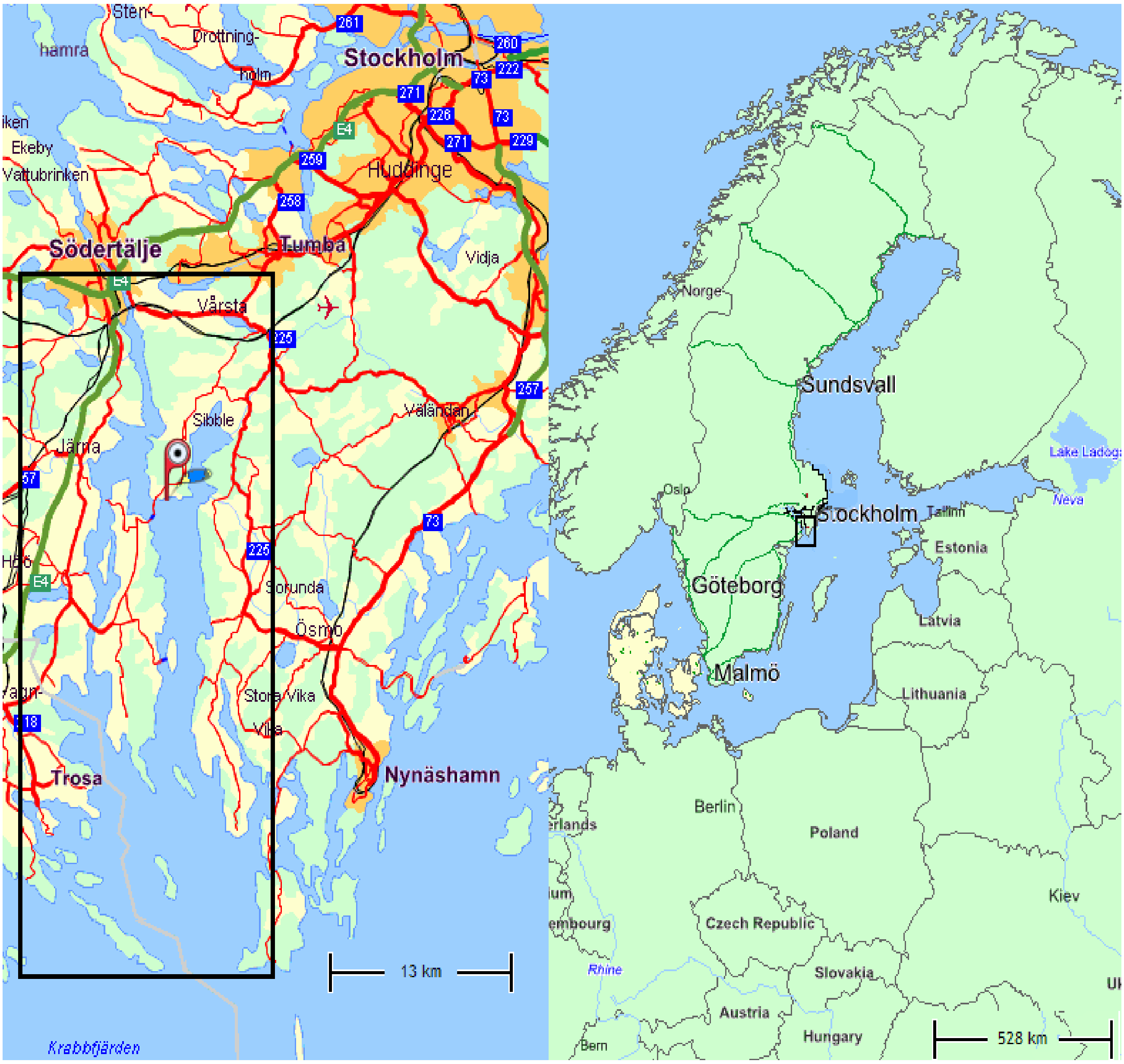


Fig. 1 Location of Himmerfjärden (from www.hitta.se).

2 LITERATURE REVIEW OF HIMMERFJÄRDEN

This literature study focuses on research on Himmerfjärden during the past ten years and it takes off from a comprehensive study of the bay requested by the Swedish Environmental Protection Agency (Naturvårdsverket) (Elmgren and Larsson 1997). In that study, several recommendations and predictions were made on how Himmerfjärden would respond to nitrogen emission regulations. The results of the ambitious nitrogen removal implemented in the late 1990s were evaluated in a second report requested by Naturvårdsverket in 2006 (Boesch *et al*. 2006).

Elmgren and Larsson (1997) found it questionable to generalize results from Himmerfjärden since they stressed that the knowledge of water flows to, within and from the bay was limited. They argued that generalizations could be made from general relationships such as between nutrient concentrations and the biological effects in water and on macro algal communities. The example of Himmerfjärden has been generalized to other areas and is often cited in the literature (Rabalais 2002, Rönnberg and Bonsdorff 2004, Howarth and Marino 2006).

2.1 EUTROPHICATION

An aquatic system exposed to increased inputs of nutrients responds by increased bioproduction. The ecological effects are most evident on the microbiological level where algae and bacteria support all levels of life. The primary producers take up nutrients available in the water and grow with sunlight as the energy source. The level of their photopigment concentration (chlorophyll *a*) is used as a measure of eutrophication (Paerl *et al*. 2003).

These phytoplankton react to increased nutrient concentrations in the water by intensified growth. Primary producers bloom in spring when the temperature rises, light increases and storms mix deep water with surface water fertilizing the upper layer with nutrients. These colonies collapse as nutrients run out and dead algae settles to the bottom (Forsberg 1991, Kautsky 1993).

The amount of organic matter falling onto the bottom areas is sometimes so great that bottom microbes run out of oxygen leading to anaerobic conditions where nitrate and sulphate replaces oxygen in the microbial respiration. In the Baltic Sea, this oxygen depletion is widespread due to high nutrient loading combined with low water exchange rates especially in deep parts of the Baltic. Anoxic conditions in the bottom sediments release phosphorus to the water causing more production and increasing eutrophication (Forsberg 1991, Kautsky 1993).

The growth in the summer is limited by low levels of nutrients in the water. The spring bloom in the Baltic Sea reduces the dissolved nitrogen in the water and this gives an advantage to blue-green algae, also referred to as cyanobacteria. Their ability to fix nitrogen from the air makes them independent of nitrogen levels in the water and they bloom in late summer causing much irritation amongst vacationing bathers and sailors. These algae can also constitute a health risk since several forms are toxic like the infamous foaming species *Nodularia spumigena*. The decline of the cyanobacteria bloom releases nitrogen to the water and stimulates a fall bloom when storms mix deep water rich in phosphorus with surface water (Forsberg 1991, Kautsky 1993).

Recent research suggests a revision of the traditional view on the eutrophication status of the Baltic Sea. Håkanson and Bryhn (2007) suggested that the Baltic Sea is in fact oligotrophic to mesotrophic and that the main source of phosphorus to the sea is not anthropogenic but emanates from the land uplift. By modelling fluxes of phosphorus they also demonstrated that the diffusion rate, the amount sedimenting and the total amount of phosphorus in the water are fairly constant throughout the year thus challenging the traditional view of the eutrophication in the Baltic Sea.

2.1.1 Limiting nutrient

Growth of phytoplankton depends on sunlight, carbon dioxide and available nutrients. Shortage of any of those will control growth and limit the production. Phosphorus and nitrogen are known to act as the main limiting nutrients of primary production in aquatic environments (Forsberg 1991, Elmgren and Larsson 1992).

It has long been assumed that phosphorus limits cyanobacterial growth but iron and molybdenum have also been suggested as important micro elements (Larsson 2005).

Redfield *et al*. (1963) showed that phytoplankton on average contains about seven times as much (by mass) nitrogen as phosphorus. A generally accepted rule is that nutrient limitation is decided by the Redfield ratio, R, estimated from

$$R = \frac{TN}{TP} or \frac{DIN}{DIP} \qquad (1)$$

TN = concentration of total nitrogen
TP = concentration of total phosphorus
DIN = concentration of dissolved inorganic nitrogen
DIP = concentration of dissolved inorganic phosphorus

If $R<7.2$, the water body is said to be limited by nitrogen and if $R>7.2$ it is said that phosphorus is the limiting nutrient. It has also been demonstrated that there is an increased risk of cyanobacterial growth if $R<15$ (Håkanson *et al*. 2007).

2.1.2 DIN/DIP vs TN/TP

Dodds (2003) showed that concentrations of inorganic nutrients in the water can be low also when the supply is high. The turnover rate of bioavailable nutrients is high and low levels of dissolved inorganic nutrients can be found even in highly productive waters. Dodds (2003) suggested that only when the levels of DIN are much higher than the levels of DIP (e.g, 100:1), it is unlikely that DIN is limiting and only if $DIN/DIP<<1$ it is unlikely that P is the limiting nutrient. He concluded that DIN and DIP are poor predictors of nutrient status in aquatic systems compared to TN and TP.

Another reason why DIN and DIP are unsuitable as predictions of nutrient limitation in the water is their inherent uncertainty demonstrated by high coefficients of variation in comparison to TN and TP (Håkanson *et al*. 2007). Table 1 shows the coefficients of variation of DIN, DIP and TN, TP from Himmerfjärden.

Tab. 1 Mean coefficients of variation calculated from all individual data from 1997 to 2006 in Himmerfjärden.

	CV Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
TN	0.13	0.11	0.14	0.16	0.15	0.12	0.10	0.09	0.10	0.11	0.14	0.24	0.13
DIN	0.30	0.26	0.47	1.49	1.20	1.52	1.27	1.50	1.39	0.99	0.59	0.42	0.95
TP	0.10	0.10	0.15	0.24	0.23	0.18	0.16	0.13	0.21	0.28	0.24	0.19	0.18
DIP	0.10	0.12	0.47	0.92	0.58	0.51	0.68	0.61	0.90	0.63	0.30	0.20	0.54

Table 2 shows the number of samples of different fractions of N and P needed to estimate the annual mean with an error of 15 percent in Himmerfjärden, calculated from Equation 1.

Tab. 2 Number of samples required to estimate the mean with an error of 15 percent using data from Himmerfjärden.

	CV	n
TP	0.18	6
DIP	0.54	50
TN	0.13	3
DIN	0.95	154

2.2 HIMMERFJÄRDEN

Himmerfjärden bay, situated about 60 km south of Stockholm at 59° 00' N, 17° 45', is a narrow bay divided into four sub-basins (Boesch *et al*. 2006). The basins are separated by thresholds and just outside the outer basin, to the south, is the area Hållsfjärden. Hållsfjärden is commonly used as a reference area for Himmerfjärden and holds a reference station called B1. There are five sampling stations in Himmerfjärden, called H2 to H6. Himmerfjärden is connected to Lake Mälaren in the north but the freshwater inflow to the bay is limited to a few short periods when water levels in the lake are high (Elmgren and Larsson 1997).

Himmerfjärden has been monitored since the middle of the 1970s when sewage water from the area south-west of Stockholm was redirected from Lake Mälaren to Himmerfjärden. In 1974 sewage water discharges from the treatment plant in Himmerfjärden began with a substantial phosphorus removal (96% on average). The treatment plant initially served about 90 000 people but the population increased rapidly, causing an increase in primarily nitrogen fluxes. Today the plant serves 240 000 people (Boesch, *et al*. 2006). Extensive nitrogen removal has been implemented since the late 1990's reaching about 90 percent in 1998 (Larsson and Elmgren 2001). Figure 2 shows the location of all sampling stations and the location of the Himmerfjärden sewage treatment plant.

It must be stressed that it has been assumed that the emissions from the sewage treatment plant contributes with flows of nitrogen of such significance that the regulation of emissions would have a clear effect on the eutrophication status in Himmerfjärden. This assumption was mainly based on the fact that total nitrogen concentration and inorganic concentrations of nitrogen before the spring bloom at station H4 correlated well ($r^2 = 0.69$, $n = 16$) with the load from the sewage treatment plant. Changes in eutrophication status have consequently been interpreted mainly as results of treatment plant regulatory measures (Elmgren and Larsson 1997, Elmgren and Larsson 2001, Larsson and Elmgren 2001).

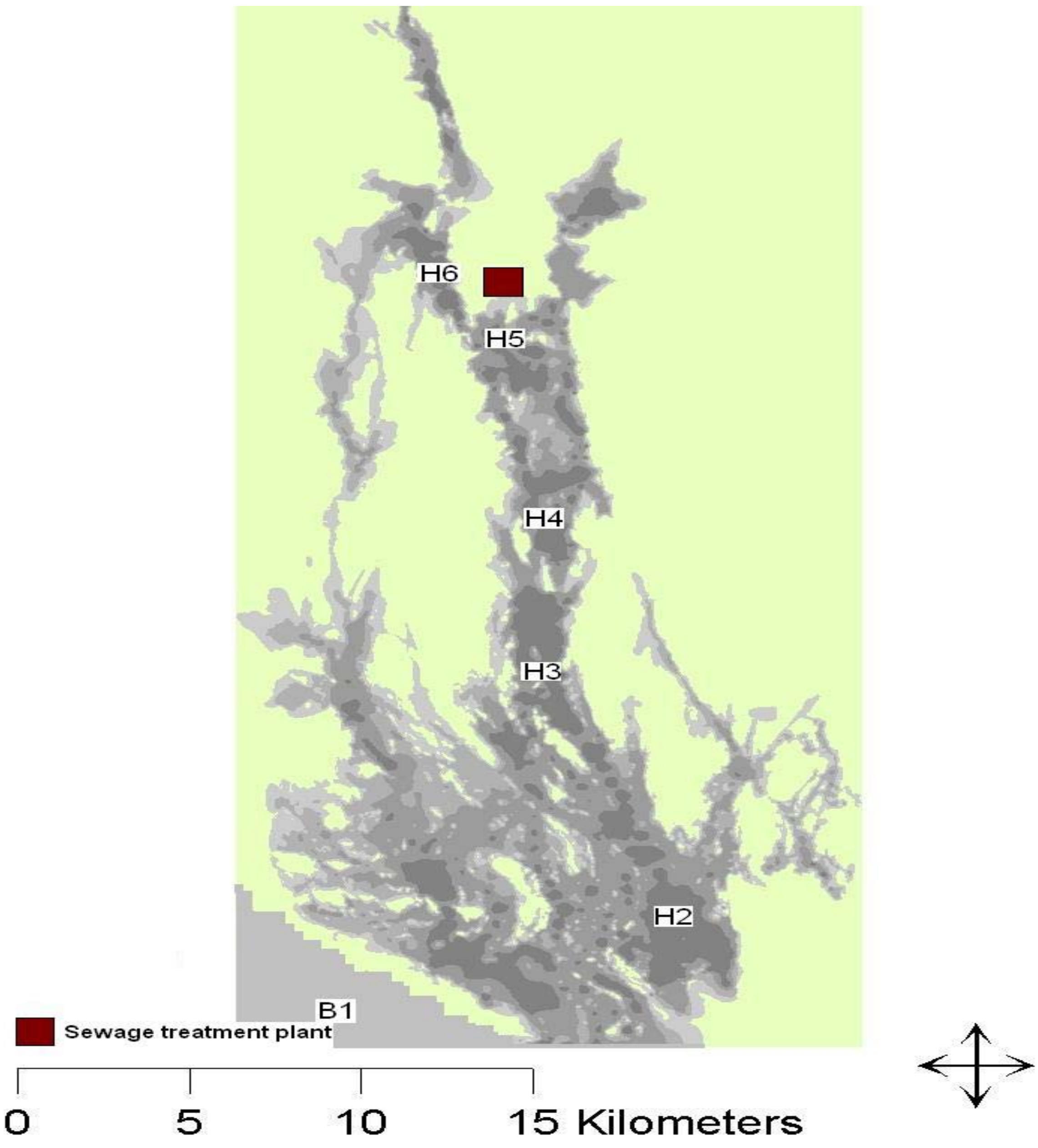


Fig. 2 Himmerfjärden with the locations of sampling stations and treatment plant.

2.2.1 Limiting nutrient

The argumentation in favor of extensive nitrogen removal from the treatment plant in Himmerfjärden is evidently based on the assumption that primary production in Himmerfjärden is limited by nitrogen (Elmgren and Larsson 1997, Elmgren and Larsson 2001, Larsson and Elmgren 2001).

Elmgren and Larsson (1997) showed that the mean input of DIN from the sewage treatment plant correlated well with the mean concentration of DIN in surface water in winter and that the mean concentration of DIN in the winter in the surface water correlated well (r^2=0.57, n>60) with maximum concentration of chlorophyll *a* during the spring bloom.

Larsson and Elmgren (2001) showed that annual means of TN from stations H2 to H6 and station B1 outside Himmerfjärden using data from over 18 years correlated well with Secchi depth and with chlorophyll *a* ($r^2 = 0.64$ and $r^2 = 0.89$ respectively). The correlations with the annual means of TP were weaker ($r^2 = 0.51$ for Secchi depth and chlorophyll not shown). Elmgren and Larsson (2001) also interpreted the annual exhaustion of DIN after the spring bloom as evidence of nitrogen limitation in Himmerfjärden.

Figure 3 shows theTN/TP-ratio and the Redfield ratio based on data of total concentrations in Himmerfjärden and it suggests that phosphorus is the main nutrient regulating primary production. Figure 4 shows the DIN/DIP ratio based on inorganic concentrations in Himmerfjärden and suggests nitrogen as the main limiting nutrient in Himmerfjärden. These two very different results have major implications on how to regulate emissions of N and P and the next section discusses the two alternative ratios.

.

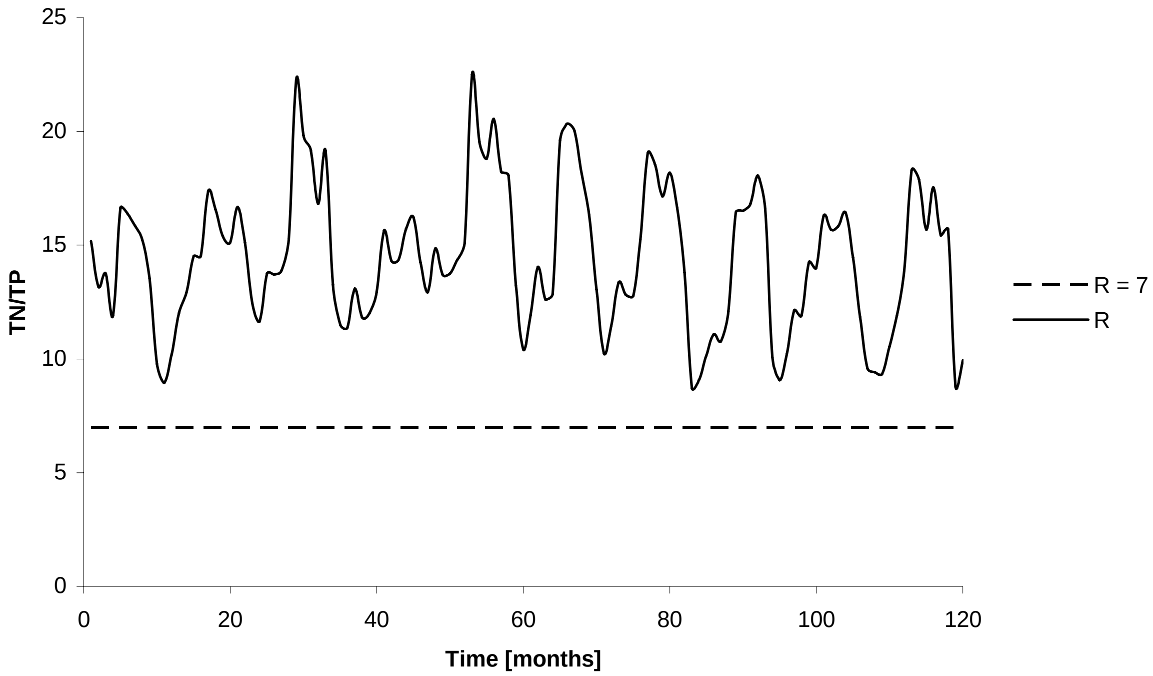


Fig. 3 Redfield ratio based on monthly medians of total concentrations of nitrogen and phosphorus from 1997 to 2006.

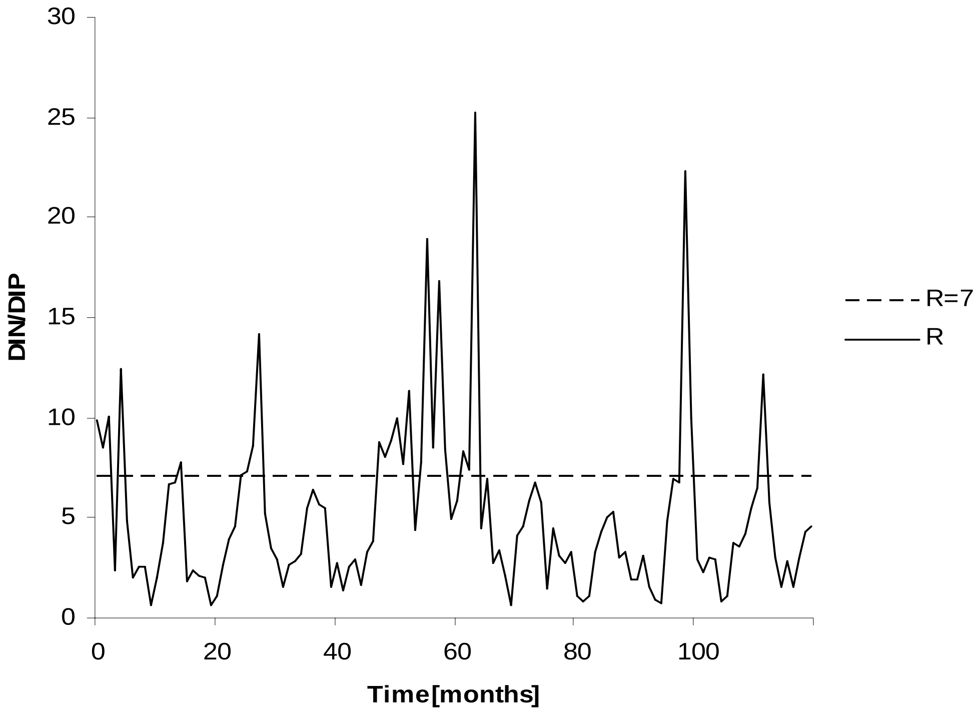


Fig. 4 Redfield ratio based on monthly medians of inorganic concentrations of nitrogen and phosphorus from 1997 to 2006.

2.2.2 Increased phosphorus emissions – 1983 to 1984

The first large-scale experiment in Himmerfjärden was performed in 1983 when the concentration of phosphorus in the treatment plant discharge was allowed to increase to about fourfold. According to Elmgren and Larsson (1997), no increase in primary production was observed following this increase in phosphorus but a slight increase in heterocytes (the nitrogen fixing cells in cyanobacteria) was noted and this increase concurred mainly at station B1 in the reference area possibly implying that blue-green algae growth in Himmerfjärden reflects growth in the adjacent sea.

2.2.3 Varying nitrogen load – 1985 to 1992

The second large-scale experiment started in 1985 when the treatment plant increased its capacity and began receiving sewage from Eolshälls treatment plant resulting in increased emissions of nitrogen to Himmerfjärden. The increase was followed by a successive decrease when nitrogen reduction processes were introduced and became more and more efficient reaching about 50 percent in 1992. As in the case with the first experiment no increase in primary production occurred following increasing nitrogen inputs to the bay. Elmgren and Larsson (1997) suggested that phosphorus at this time was the main limiting nutrient in Himmerfjärden and that the excess nitrogen was exported to the adjacent sea instead causing increased eutrophication in the outside sea.

As mentioned before, Elmgren and Larsson (1997) found no significant correlation between eutrophication indicator variables, such as chlorophyll *a,* phytoplankton production (biomass) or Secchi depth, and varying loads of nitrogen and phosphorus from the sewage treatment plant following the two first large-scale experiments. They concluded that further removal of phosphorus by the treatment plant would not be meaningful since the emissions from the treatment plant constitute a small fraction of total loading of phosphorus. They recommended to increase nitrogen removal efficiency from treatment plant discharge and the arguments brought forward in favor of further nitrogen removal were as listed below:

- the primary production is limited by nitrogen and reduced concentrations will reduce total production.
- since no increase in production was noted following the decrease in Redfield ratio in 1983-1984, due to increased phosphorus emissions, then no increase should occur when decreasing the ratio by decreasing nitrogen emissions.
- nitrogen emissions from the treatment plant have a direct impact on the maximum level of chlorophyll *a* during spring bloom.
- the risk of increased cyanobacterial growth is low even at extensive nitrogen removal.

Elmgren and Larsson (1997) predicted that a nitrogen removal of 70 percent from sewage water would yield annual means of total nitrogen of 350 mg/m^3 and of chlorophyll *a* of 3.6 mg/m^3 in the surface layer in Himmerfjärden (0-10 m). They also predicted that the Secchi depth would be about 5.5 m and that increased risk of cyanobacterial growth would be stimulated first at a removal rate greater than 70 percent.

2.2.4 Increased nitrogen emissions – 2001 to 2002

Following the recommendations from Elmgren and Larsson (1997) extensive nitrogen removal (about 90 percent) began in 1998. A third large-scale experiment was performed in 2001-2002 when emissions of nitrogen were deliberately doubled. As in the previous cases no increase in chlorophyll *a* levels was observed by the increase in nitrogen from the sewage treatment plant (Boesch *et al*. 2006).

According to Boesch *et al*. (2006) both the experiment 1983 and the two experiments with increased nitrogen emissions appear to have been too small and or to short to result in changes in primary production.

2.2.5 Evaluation of the efforts to remove nitrogen from treatment plant emissions

There has been a decrease in chlorophyll *a* levels since the late 1990s until 2004 (except for 2001 to 2002) at H4 (Figure 4) but no statistically significant increase in Secchi depth (Boesch *et al*. 2006). There is a lively debate over whether this decrease is due to the removal of N from the sewage treatment plant or a consequence of the shift towards warmer climate that coincided with the start of the nitrogen removal (Boesch *et al*. 2006). The importance of climatic variation was also stressed by Elmgren and Larsson (1997) as data fluctuations in Himmerfjärden often concurred with data from the reference station, B1. There seems to be a need of finding a way of estimating the impact of climatic variations when evaluating data from Himmerfjärden.

Figures 5 to 7 show the actual values of chlorophyll *a*, TN, Secchi depth as annual medians from station H4 (0-10 m) from 1997 to 2006 and the levels predicted by Elmgren and Larsson (1997). The predicted levels were calculated for 70 percent removal of nitrogen from sewage plant emission but the actual removal rate was 90 percent. The time serie also includes the experiment in 2001 to 2002 with increased nitrogen emissions from the treatment plant.

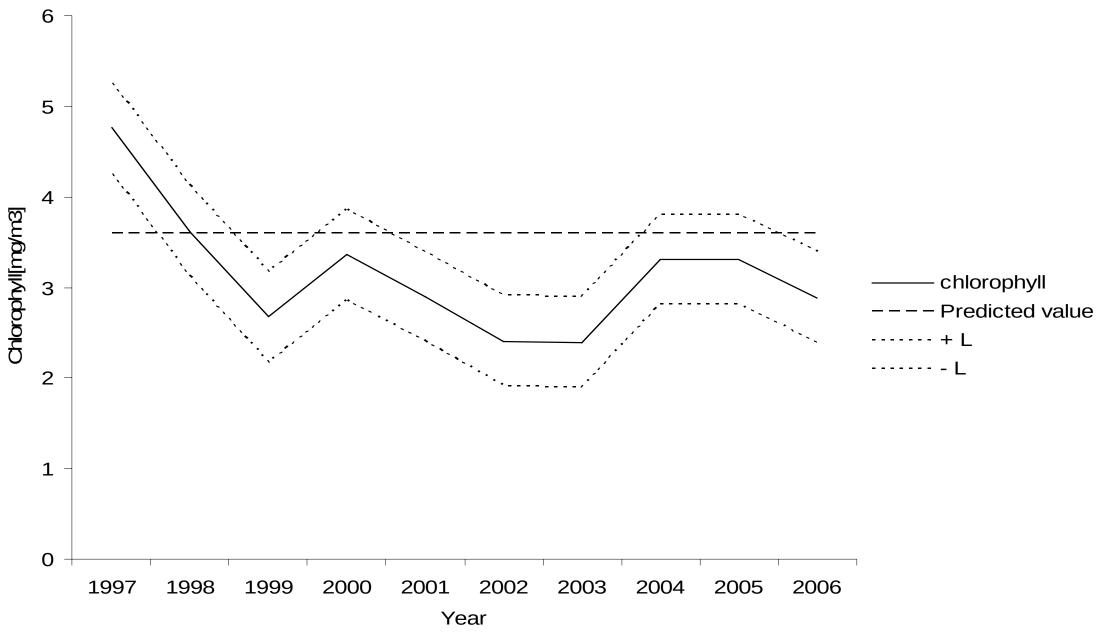


Fig. 5 Levels of chlorophyll as annual medians with confidence intervals estimated from the error of the mean, L, from H4 (0-10 m).

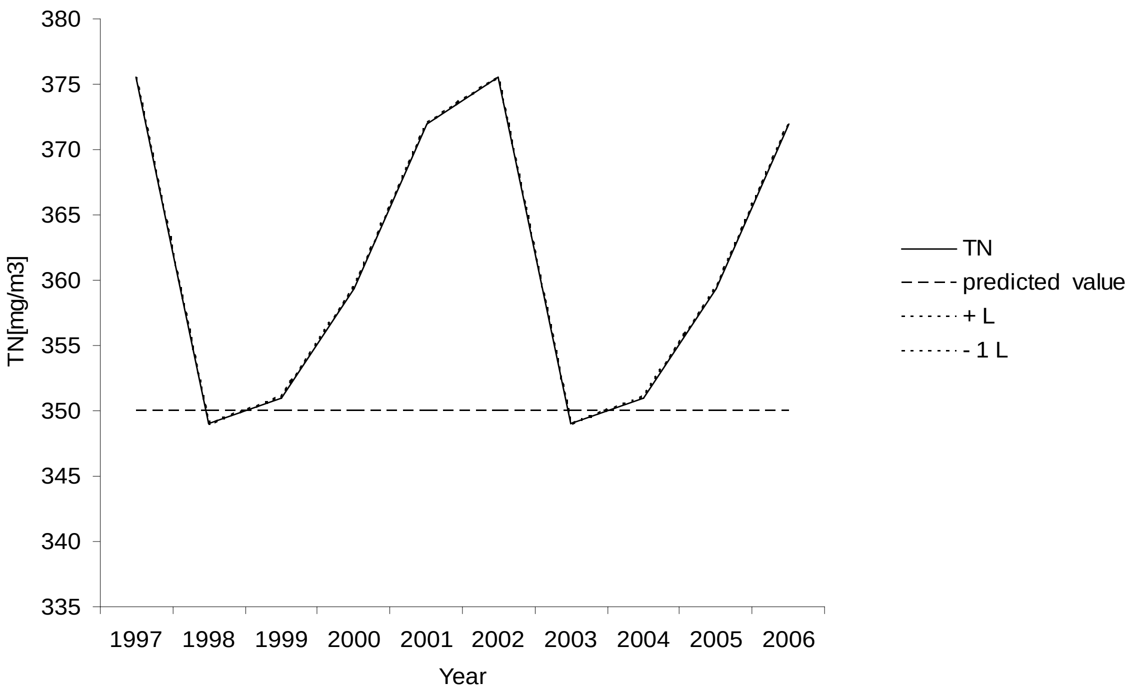


Fig. 6 Levels of TN as annual medians with confidence intervals estimated from the error of the mean, L, from H4 (0-10 m).

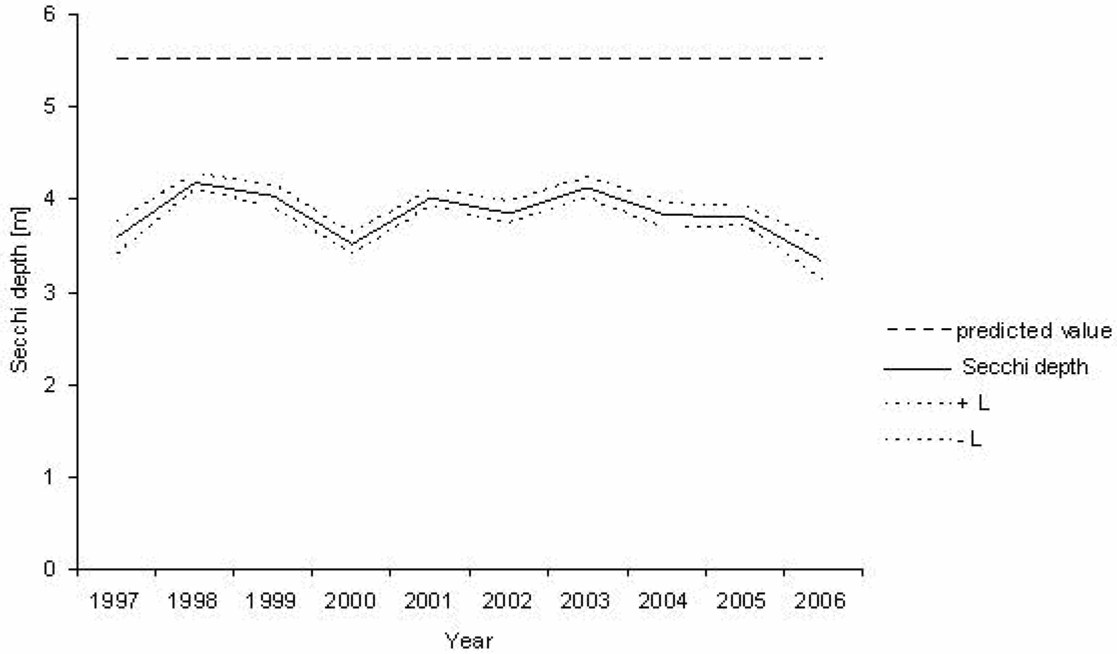


Fig. 7 Levels of Secchi depth as annual medians with confidence intervals estimated from the error of the mean, L, from H4 (0-10 m).

The growth of cyanobacteria has increased substantially in Himmerfjärden since the middle of the 1990's as displayed in Figure 8.

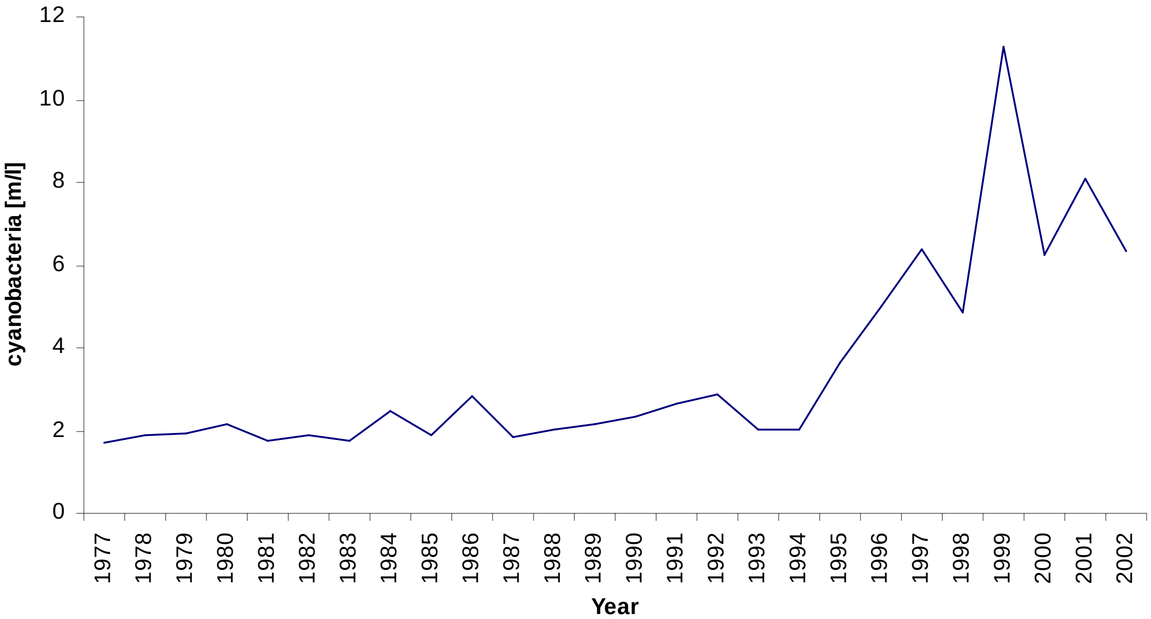


Fig. 8 Cyanobacterial growth in Himmerfjärden as amount *Aphanizomenon* yearly mean june-sept. Units are meters of filament per liter of water. Modified from Boesch *et al*. (2006).

2.2.6 Arguments for nitrogen removal

Suggestions were made that even if total annual biomass would not decrease following extensive nitrogen removal there would still be benefits since the spring bloom would be smaller relative to the summer bloom and this would decrease total annual sedimentation and improve oxygen levels at the bottom (Larsson and Elmgren 2001, Elmgren 2001).

It has also been argued that continued extensive nitrogen removal would help in restoring Himmerfjärden to its original state of phytoplankton production being limited by nitrogen (Bianchi *et al*. 2000, Elmgren 2001). Furthermore, it has also been argued that reducing phosphorus alone would worsen eutrophication in the outside sea since excess nitrogen would be exported from the phosphorus limited coastal areas to the nitrogen limited open sea (Elmgren and Larsson 1997, Larsson and Elmgren 2001).

2.2.7 Arguments against nitrogen removal

One argument brought forward by nitrogen removal skeptics is that the sewage plant contributes about 54 per cent of land based inputs of N as estimated by Savage *et al*. (2002). There is no good estimate of diffuse source N input but it is assumed to be considerable. If nitrogen load from the treatment plant is relatively insignificant compared to total load then it would be hard to justify the expensive strategy of removing 90 percent of nitrogen from the sewage water (Elmgren and Larsson, 2001).

Another argument is that a decrease in nitrogen might be compensated by the increased nitrogen fixation by cyanobacteria that thrive in nitrogen poor waters. The long-term production would then be limited by phosphorus even if phytoplankton would be mainly nitrogen limited in the short-run, as indicated by bioassays including inorganic nutrient addition experiments (Hellström 1998, Eilola and Stigebrandt 1999, Savchuk and Wulff 1999). This in addition to the unpleasant and sometimes toxic nature of the cyanobacterial blooms has been brought forward as a strong argument against extensive nitrogen removal in the Baltic Sea.

2.2.8 Mass balance modelling

The flow of nutrients and water in different sub basins of Himmerfjärden have earlier been estimated by a mass-balance model based on salinity, temperature and hydro-dynamical equations (Elmgren and Larsson 1997). They found that the net export of TN was about 25 percent of the total load and that the net export of TP was about 50 percent of the total load. Surface water retention times were found to vary between about 30 to 140 days for different sub-basins within Himmerfjärden.

Elmgren and Larsson (1997) also estimated the vertical fluxes of nutrients in Himmerfjärden estimating the rates of resuspension, sedimentation and denitrification from differences in net export and total load. They proceeded to estimate vertical fluxes aided by empirical values on sedimentation rates and proportion of resuspended material in sediment traps.

Maximum sedimentation rates of phosphorus were found to vary between 3.5 to 1.0 tons/month in different sub-basins in Himmerfjärden. Maximal rates of diffusion of phosphorus were estimated to about 3.2 to 0.42 tons/month (Elmgren and Larsson 1997).

Maximum sedimentation rates of nitrogen were found to vary between 26 to 5.5 tons/month in four different sub-basins in Himmerfjärden. Maximal rates of diffusion of nitrogen were estimated to be about 9.8 to 2.5 tons/month. Total nitrogen fixation rate was estimated to be about 100 tons/year in the whole bay. Later studies have suggested that the annual amount of nitrogen added to Himmerfjärden through nitrogen fixation may be about 450 tons based on estimates of fixation rates in the Baltic Proper (Larsson *et al*. 2001, Wasmund *et al*. 2005).

Total denitrification, in sub-basins H4 and H5 as displayed in Figure 18, was estimated to be about 300 to 600 tons/year (Elmgren and Larsson 1997).

About 50 percent or more on average, of the settling particulate matter (SPM) found in sediment traps at 15 m depth was resuspended material as estimated by Blomqvist and Larsson (1994). They also found that SPM in Himmerfjärden had a phosphorus content of about 0.15 percent.

Elmgren and Larsson (1997) estimated that emissions from the treatment plant constituted about 25 percent of total load of nitrogen to basins H4 and H5 (see Figure 17). Corresponding fraction for phosphorus was found to be about 7 percent.

The mass-balance model for phosphorus, CoastMab (Håkanson and Eklund 2007), which will be used in future research, may provide more accurate estimates on the rates and flows than those published by Elmgren and Larsson (1997). This is due to the fact that CoastMab includes equations of sedimentation, resuspension, diffusion and biouptake instead of estimating their magnitudes.

3 METHODS

The mass-balance modelling of salt performed in this study will constitute the basis of future mass-balance modelling of phosphorus since it yields necessary information on water retention times and describes flows to and from the area. The methods used in this work include a GIS-analysis, statistical analyses and mass-balance modelling.

3.1 GIS-ANALYSIS

There are many ways to classify and describe coastal areas. In this study, Himmerfjärden was classified according to the feature classes described in Lindgren and Håkanson (2007). The classification limits are listed in Appendix I. By means of geographical information systems (GIS) the morphometrical features of Himmerfjärden were calculated and displayed and geographical model driving variables were identified and compared to values published in the literature.

The dynamic mass balance model used in this study requires that the study area is defined according to the topographical bottle-neck model described in Pilesjö *et al.* (1999).

3.1.1 The Topographical Bottle-Neck Method

The topographical bottle neck method defines size and form parameters for ecosystems in a general and objective way. The borderline towards the open sea area are drawn at the topographical bottle-neck, i.e. where the exposure of the coast from winds and waves is minimized (Håkanson 2000). To minimize the exposure, the border line should be drawn to minimize the section area towards the open sea. The section area, At, in Figure 9, is the vertical area through which the water exchange between the coast and the sea occurs and a 3D-approach should be considered to find the optimal delimitation.

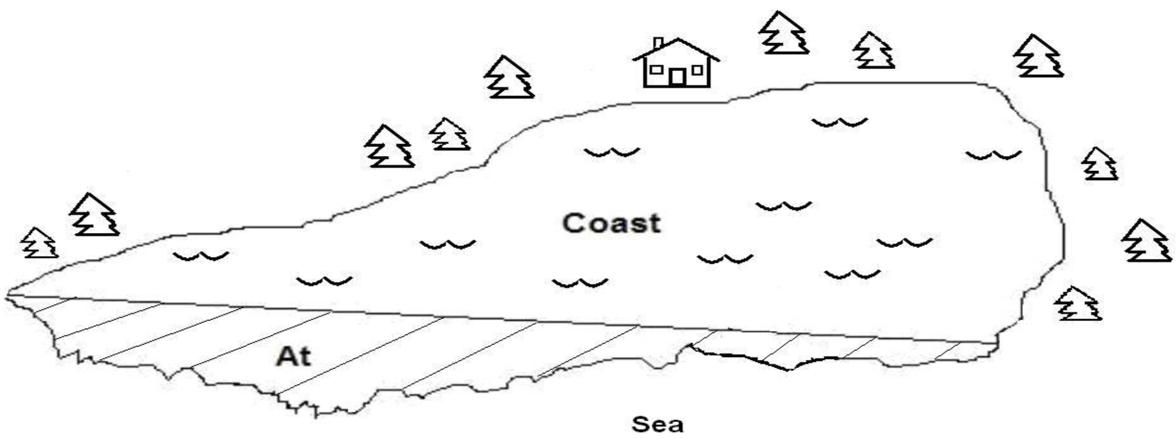


Fig. 9 Section area, At, according to the topographical bottle neck method.

Exposure (Ex [%]) quantifies the topographical openness to the outside sea and the equation reads

$$Ex = 100 At / Area \qquad (2)$$

Area = total area

Calculating surface retention time is a way to estimate the extent to which local efforts to reduce nutrient loads will have an effect on the local receiving waters. A short retention time means that water in the coastal area is quickly exported to the adjacent sea and local emissions will not determine water quality. Longer retention times suggest that local emissions can increase local pollutant concentrations.

3.1.2 GIS mapping

There are many ways to calculate size and form parameters with GIS-software. Nautical maps over Himmerfjärden were digitized in ArcMap by creating a polygon shapefile which covered the extent of the coastal area and a line shapefile containing depth curves. The shapefiles were transformed into a raster file through interpolation and the resulting raster file was converted to a triangulated irregular network file (TIN) in ArcScene and areas and volumes at different depths were calculated.

The nautical maps were unsuitable for calculations of total water surface area since the area of Trosa port was missing from the maps. Instead a digital map covering the total area of Himmerfjärden was downloaded from Lantmäteriet (2007). The total water surface area was calculated from this map and not from the constructed raster file.

The hypsographic curve and the volume curve were constructed and the results from the GIS mapping of Himmerfjärden were compared to values on area, volume and cross section areas estimated by SMHI (2003).

According to Pilesjö *et al*. (1999) several parameters necessary for simulating water dynamics are easy to calculate. These parameters include maximum depth (D_{max}, [m]), water surface area (Area, [km^2]), water volume (Vol, [km^3]) and mean depth (D_{mean}, [m]).

D_{max} was estimated by searching the raster data file for the maximum depth value in the bathymetric GIS map.

The mean depth was estimated from

$$D_{mean} = \frac{Vol}{Area} \tag{3}$$

The form factor describes the shape of the coastal area and the equation reads

$$Vd = 3 \times \frac{D_{mean}}{D_{\max}} \tag{4}$$

The dynamic ratio describes the depth conditions of the coastal area and it is calculated from

$$D_R = \frac{\sqrt{Area}}{D_{mean}} \tag{5}$$

The insulosity describes the island density and influences retention times and the equation reads

$$Ins = \frac{A_{islands}}{Area} \tag{6}$$

$A_{islands}$ = area of islands

3.2 DATA

Data were collected, analyzed and statistically treated to be used in the mass balance model.

3.2.1 Collection of data

Data were collected from many different sources. A comprehensive set of data, including nutrient levels, Secchi depths, chlorophyll *a*, temperatures and salinities, was available for seven measuring stations from 1997 until 2006 at a web site managed by the Department of Systems Ecology at Stockholm University (SESU) (Himmerfjärden 2007). The web site also gives information on sewage treatment plant emissions for that same time period. The data are available on the web site as graphs as displayed in Figure 10.

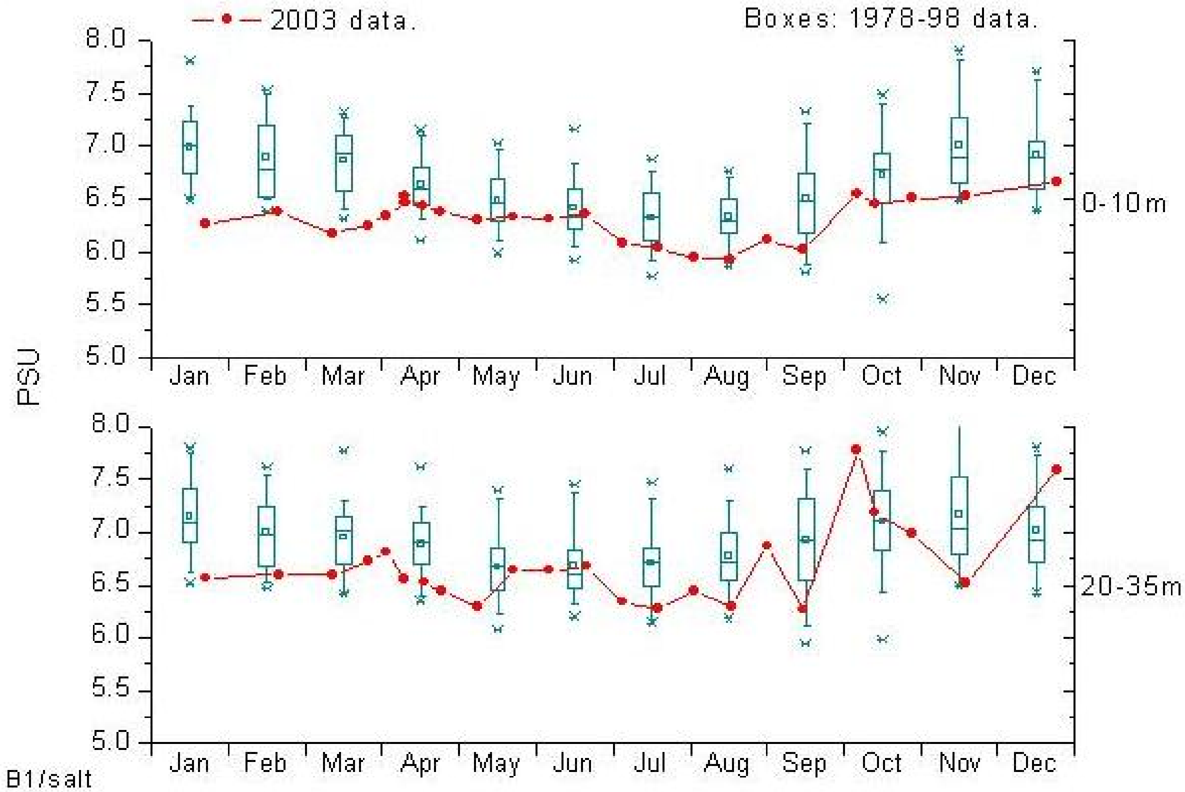


Figure 10. Example of data for salinity at station B1 from 2003 available at Himmerfjärden (2007).

To extract numerical values, the graphs were digitized and numerical values were extracted with GetData, a computer software program.

Data of annual total flow of fresh water to Himmerfjärden from 1977 until 1992 were taken from Elmgren and Larsson (1997) and averaged into one typical year. The data are listed in Appendix I in Table A1A.

3.2.2 Statistical data analysis

The empirical data sets were examined statistically in order to determine their variability and to find the data set that best represents the characteristic conditions in Himmerfjärden. The coefficients of variation used in the sensitivity analysis were calculated from median values instead of the mean to eliminate potential effects from outliers.

$$CV = \frac{SD}{MV} \quad (7)$$

CV = coefficient of variation
SD = standard deviation
MV = mean

More representative sets of data on monthly median values on salinity and temperature were created by dividing Himmerfjärden into sub areas. The areas were delimited according to the topographical bottle-neck method for each new basin holding a measuring station. The surface areas of the sub-basins and new area weighted statistics for Himmerfjärden were calculated.

The data sample that represented the greatest area in Himmerfjärden, H2, was smaller than the other data sets from the other stations. Data on salinity and temperature were generally, except for 1997, 1998 and 2000, only available for the growing season. In order not to underestimate salinity in Himmerfjärden, the area weighted monthly medians used in the modelling were calculated from all available data per month ($M50_{ind}$) instead of averaging each year's monthly medians (M50) into one typical year.

When evaluating the model results, CVs calculated from M50 instead of $M50_{ind}$ were used to compare modelled values to empirical data since the model simulates concentrations over a year. CV_{M50ind} values also include inter annual variations but CV_{M50} only include variations within a year.

Empirical data on salt and temperature in and outside of Himmerfjärden have been and are continuously measured by SESU at varying unspecified depths. The surface layer is generally defined at 0 to 10 meters while the deep water layer mostly is defined at 20 to about 40 meters. The model used in this study defined the surface water compartment as the water volume above the theoretical wave base.

3.2.3 Data sampling evaluation

The measuring stations were examined in order to find out how well each station reflects the conditions in the whole bay. The purpose of the investigation was to find out if any of the measuring stations were redundant and if perhaps there would be a better and more cost effective way of monitoring water chemistry variables in Himmerfjärden.

Monthly salinity medians from stations H2 to H6 from year 2000 were compared with the area weighted monthly median values for that same year to find out which station that best represents the conditions in the whole bay. Data were found to be normally distributed and the maximum error of the mean reads

$$L = \frac{t_{\alpha/2} \times CV}{\sqrt{n}} \tag{8}$$

L = Maximum error of estimate
$t_{\alpha/2}$ = t distribution
CV = Coefficient of variation
n = Number of samples.

The error of the mean is at most L with probability (1-α) and the level of significance was set to $\alpha = 0.05$ so that $t_{\alpha/2} = 1.96$ (Johnson 1994).

The relative errors were calculated for different combinations of measuring stations. The magnitudes of the different errors were evaluated to suggest which combination of stations would return the most cost effective data sampling solution.

3.3 MASS-BALANCE MODEL FOR SALT

The model used in this study (from Håkanson *et al*. 2007) uses ordinary differential equations to quantify salt and water flows on a monthly basis. The model also yields information on water retention times, cross sectional area water velocity and rates on diffusion and mixing between deep and surface water in Himmerfjärden. This dynamic description of Himmerfjärden will constitute the foundation for further mass-balance studies of the bay.

Salt is a conservative substance and it is the substance that contributes the most to variations of density in the water. The salinity of a coastal area is determined by the water retention times. Mass-balance calculations of salt are therefore a reliable way of determining water retention times (Elmgren and Larsson 1997).

A simplified flowchart of the salt mass-balance is found in Figure 11. The complete set of model equations is found in Appendix I.

Simplified salt mass balance abbreviations

SW = Surface water compartment
DW = Deep water compartment
Q_{inSW} = Total inflow to surface water compartment
Q_{outSW} = Total outflow from surface water compartment
$F_{DiffDWSW}$ = Flow from diffusion from deep water to surface water
$F_{MixSWDW}$ = Flow from mixing from surface water to deep water
$F_{MixDWSW}$ = Flow from mixing from deep water to surface water
Q_{inDW} = Total inflow to deep water compartment
Q_{outDW} = Total outflow from deep water compartment.

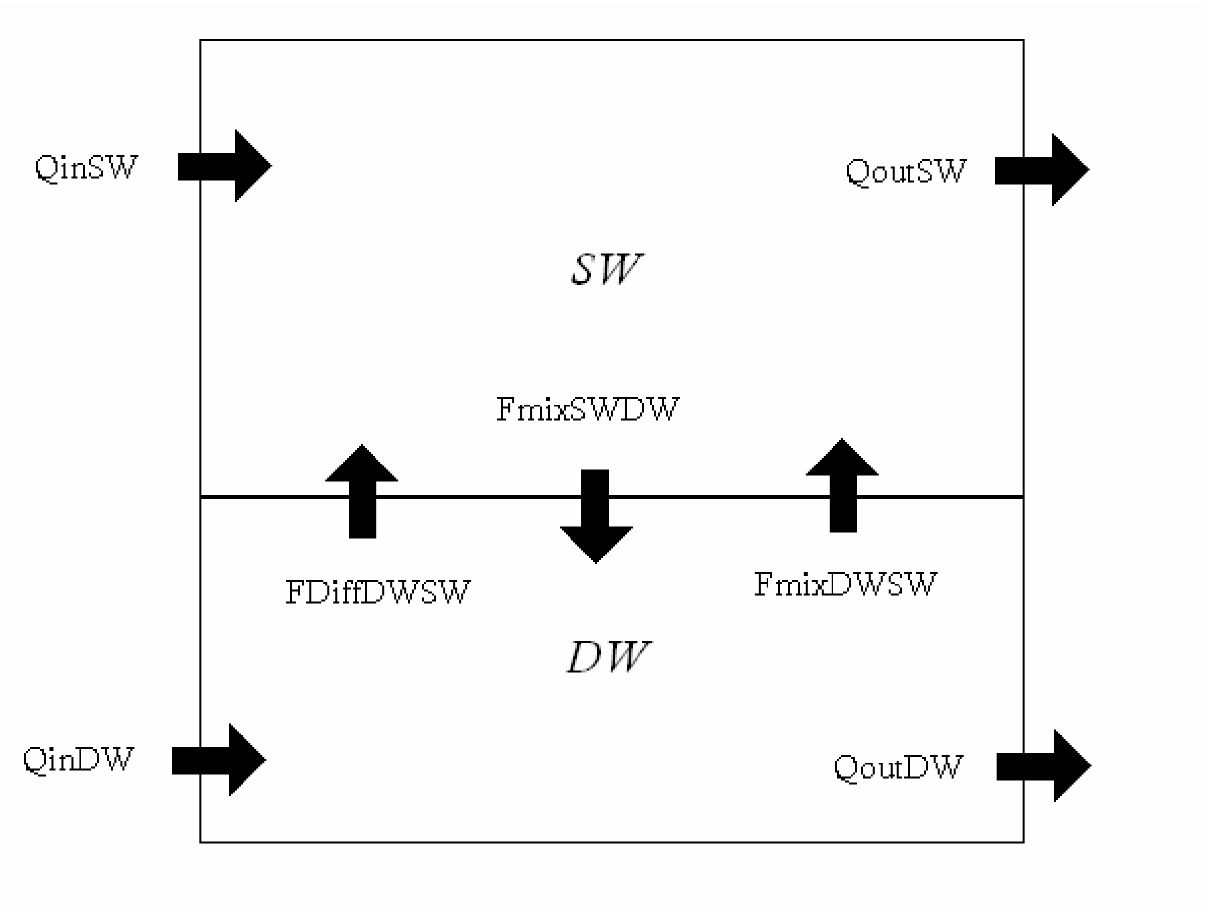


Fig. 11 Simplified salt mass balance model.

In order to run the model the following driving variables need to be defined:

A = Total area of Himmerfjärden
D_{mean} = Mean depth
D_{max} = Maximum depth
V_{DW} = Deep water volume
At = Section area according to the topographical bottleneck method
A_{WB} = Area beneath the wave base
ADA = Area of drainage area
DC_{SWDW} = Distribution coefficient of total inflow from the sea
Q_{intoHi} = Total inflow to Himmerfjärden through cross section area
Lat = Latitude
Prec = Annual rain
Q_{riv} = Annual flow from rivers
Q_{STP} = Annual flow from sewage treatment plant.

Empirical data on salinity in surface water at station B1
Empirical data on salinity in deep water at station B1
Empirical data on temperature in surface water in Himmerfjärden
Empirical data on temperature in deep water in Himmerfjärden

The simulations were made with the time step one month to include seasonal variations in temperature. Data on salinity in the sea outside Himmerfjärden and temperature in Himmerfjärden from year 1997 until 2006 were averaged by month into monthly medians of one typical year. These values were used as input data to the model together with the morphological data obtained by the GIS mapping.

The following abbreviations are used to describe model components. F for flow of salt [kg/month], R for rate [1/month], C for concentration of salt [‰=psu=kg/m^3], DC for distribution coefficients [dimensionless], M for mass [kg], Y for dimensionless moderator, D for depth [m], A for area [m^2], V for volume [m^3], T for temperature [°C]. Flow from one compartment [e.g. DW] to another [e.g. SW] is written F_{DWSW}. Q is water flow [m^3/month]. Baltic Proper is abbreviated as BP.

3.3.1 Theoretical wave base

The model differentiates between deep and surface water and the limit between those is generally drawn at the theoretical wave base. Wind and wave energy do not normally reach below the theoretical wave base thus which demarks the limit between accumulation areas and areas where erosion and transportation of fine cohesive material occur. The wave base in Himmerfjärden was calculated from the equation used for lakes and it reads

$$Dwb = \frac{45.7 \times \sqrt{Area}}{21.4 + \sqrt{Area}} \text{ [m]} \qquad (9)$$

Dwb = depth of wave base

This was a necessary compromise so that the empirical data could be used but ideally, with better suited data, one would have used a different equation tested for coastal areas found in Håkanson and Lindgren (2007).

3.3.2 Section area velocity

The model calculates a value of the section area flow velocity that can be compared to empirical values from other coastal areas to evaluate the accuracy of the modelling result. Håkanson *et al*. (1986) showed that there is a correlation between cross sectional velocity (u_p) and exposure (Ex) and that cross sectional area velocities typically lie within 0.5 to 20 cm/s.

The model calculation is based on the total inflow through half the cross section area (Håkanson and Lindgren 2007).

$$u_p = 100 \times Q_{intoHi}/(0.5 \times At \times 60 \times 60 \times 24 \times 30) \text{ [cm/s]} \qquad (10)$$

3.3.3 Water retention time

From the bathymetric map of Himmerfjärden the mass-balance for salt, water retention time was calculated.

$$T_{SW} = V_{SW}/(Q_{MixDWSW} + Q_{intoHi} + Q_{prec} + Q_{riv}) \qquad (11)$$

V_{SW} = Surface water volume
$Q_{MixDWSW}$ = Flow from mixing from deep water to surface water
Q_{prec} = Inflow from rain
Q_{riv} = Inflow from rivers

Håkanson *et al*. (1986) presented an equation that calculates surface water retention time from exposure and it reads

$$T_{SW} = e^{3,49 - 4,33\sqrt{Ex}} \tag{12}$$

Figures on surface water retention time for different basins in Himmerfjärden were also available from Elmgren and Larsson (1997) and Engqvist *et al*. (1999) and they were compared to the value obtained from the modelling in this study.

3.3.4 Rainfall, evapotranspiration and fresh water point sources

Rainfall, evapotranspiration and fresh water flows to Himmerfjärden from Mälaren, Trosaån, Fitunaån, Moraån and from the treatment plant all represent zero flows of salt to the bay. The monthly inflow of fresh water to Himmerfjärden from rivers has a seasonal pattern that can be modelled. The seasonal distribution model uses a dimensionless moderator (Y_Q) to adjust the annual average value to realistic monthly values mimicking seasonal variations for a typical year. The model utilizes latitude, annual rainfall and the area of the drainage area (ADA) as input variables.

$$Q_{riv} = (Q_{riv,\ annual}/12)\times Y_Q \tag{13}$$

Data on average annual rainfall divided by 12 was used as monthly rainfall since the variation of rain is too stochastic to model.

$$Q_{prec} = A\times Prec_{annual}\times 0.001/12 \tag{14}$$

$Prec_{annual}$ = annual rainfall = 460 mm (Elmgren and Larsson 2001)

It was assumed that 90 percent of the flow from rain evapotranspirates (see Monitor 1988).

$$Q_{eva} = 0.9\times Q_{prec} \tag{15}$$

Q_{eva} = Flow due to evapotranspiration

The size of the inflow from the treatment plant was set to be the median flow over 25 years. The treated sewage is currently discharged at a depth of 25 m. The plume of treated sewage water immediately rises to a depth of 15 m or less (Elmgren and Larsson 1997).

$$Q_{STP} = 35\times 10^6 \tag{16}$$

Q_{STP} = flow from Himmerfjärden treatment plant

3.3.5 Flows to and from the Baltic proper

The total flow from the outside sea into Himmerfjärden (Q_{intoHi}) and the distribution inflow coefficient of salt between deep and surface water (DC_{SWDW}) were the only unknown parameters in the model and they were calibrated so that the modelled values would best fit the empirical values ± two standard deviations. The total outflow from Himmerfjärden must be equal to the total inflow since there is no salt added or lost by riverine input, precipitation, evapotranspiration. Flows from rain and rivers were assumed to flow out from Himmerfjärden as surface water.

DC_{SWDW}

Q_{intoHi}

$Q_{inSW} = DC_{SWDW} \times Q_{intoHi}$ (17)

$Q_{inDW} = (1 - DC_{SWDW}) \times Q_{intoHi}$ (18)

$Q_{outSW} = Q_{inSW} + Q_{prec} + Q_{riv} - Q_{eva}$ (19)

$Q_{outDW} = (Q_{inSW} + Q_{inDW} + Q_{riv} + Q_{prec}) - (Q_{outSW} + Q_{eva})$ (20)

3.3.6 Diffusion

The diffusion process is governed by the salt gradient between the deep water and the surface water compartments. The direction of the flow is from saltier water to less salty water, i.e. from the deep water to the surface water. The rate of diffusion is determined by the salt difference so that the larger the difference the higher the rate. The equation describing the diffusion rate holds a boundary condition so that the diffusion rate will be zero if the water should be saltier in the surface water than the deep water.

$F_{DiffDWSW}$ = if $M_{DW} \times R_{DiffSWDW} \times DiffC < 0$ then 0 else $M_{DW} \times R_{DiffSWDW} \times DiffC$ (21)

DiffC = Diffusion coefficient

$R_{DiffSWDW}$ = if $C_{SW} > C_{DW}$ then 0 else $C_{DW} - C_{SW}$ (22)

$DiffC = 0.5 \times 0.01/12$ (23)

3.3.7 Mixing

The mixing process is driven by the temperature difference between surface water and deep water. The mixing rate will be high when the difference in temperature between deep water and surface water is less than 4 °C and low when the difference is more than 4 °C. The mixing rate is also controlled by the difference in salt between the deep and the surface water so that the mixing rate decreases with increasing stratification (Håkanson and Eklund, 2006).

$F_{MixDWSW} = M_{DW} \times R_{MixSWDW} \times V_{SWDW}$ (24)

$V_{SWDW} = V_{SW}/V_{DW}$ (added to achieve equal water transport through the two water layers)

$F_{MixSWDW} = M_{SW} \times R_{MixSWDW}$ (25)

$R_{MixSWDW}$ = if $C_{DW} > C_{SW}$ then $R_{Mixdefault} \times 1/(1+(C_{DW}-C_{SW}))$
else $R_{mixdefault}$ (26)

$R_{mixdefault} = 1 \times Strat \times A_{ET}/12$ (27)

$A_{ET} = (A - A_{WB})/A$ (28)

Strat = if $|T_{SW}-T_{DW}|<4$ then $1+(1+|T_{SW}-T_{DW}|)$
else $1/(|T_{SW}-T_{DW}|)$ (29)

V_{SWDW} = if $V_{SW}/V_{DW}>30$ then 30
else V_{SW}/V_{DW} (30)

3.3.8 Uncertainty test

In order to determine how uncertainties in different selected input variables influence model results, a sensitivity test was performed using the Monte Carlo technique. The standard deviation of each variable was estimated or calculated and then the variables were allowed to vary randomly within their assigned confidence intervals during a time period of 100 years. The resulting coefficient of variation based on the median gave the total uncertainty of the modeled values.

Running the simulation again but with one variable excluded at a time returned the excluded variable's contribution to the total uncertainty of the model.

4 RESULTS

The results from the GIS-mapping, the data analyses and the modelling are listed below.

4.1 GIS-ANALYSIS

Figure 12. shows three alternative delimitations for Himmerfjärden according to the topographical bottle-neck method.

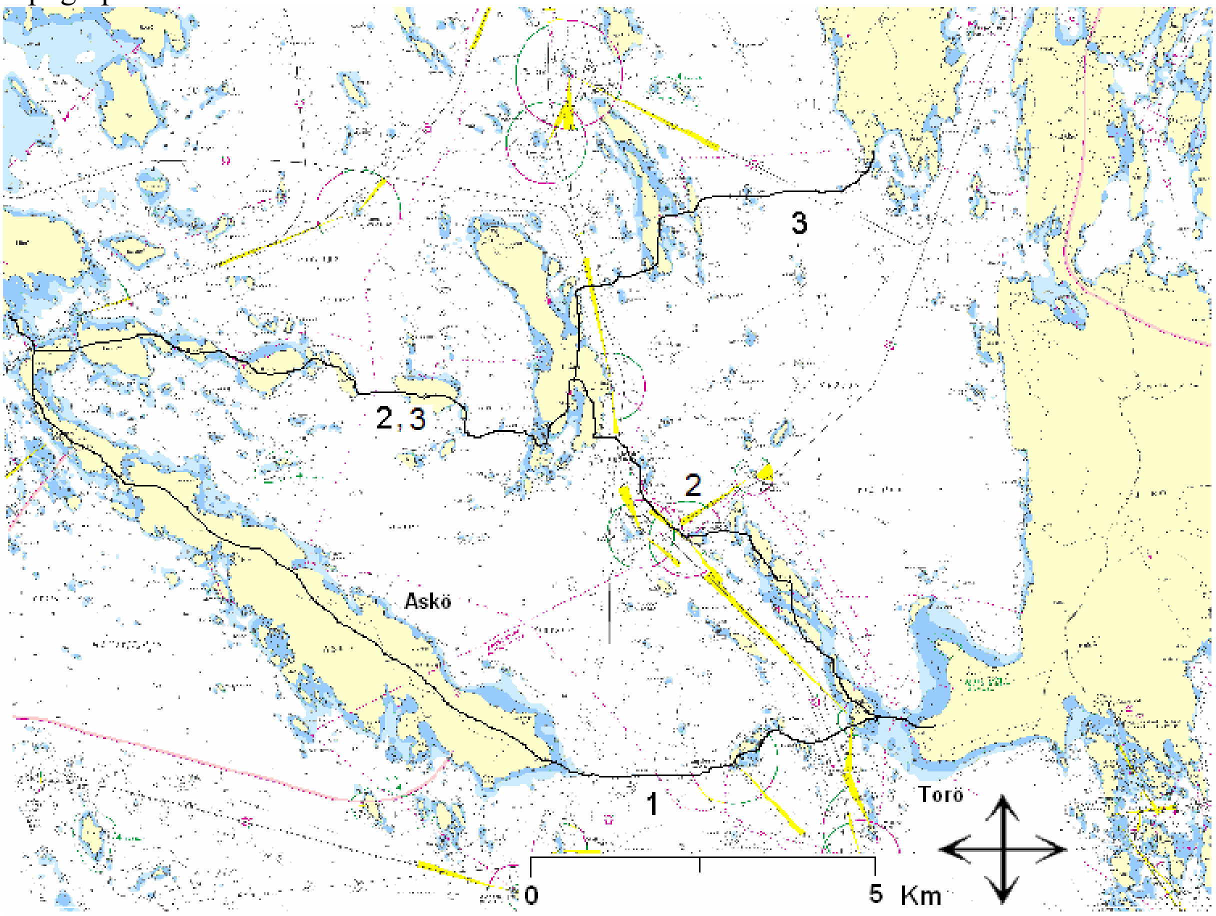


Fig. 12 Three different delimitations of Himmerfjärden.

Table 3 displays the calculated exposures for the three alternative delimitations.

Tab. 3 Exposure results for alternative delimitations.

Delimitation number	Exposure [%]
1	0.019
2	0.045
3	0.071

Figure 13 shows the depth profile from the main section area delimiting Himmerfjärden from the outside sea.

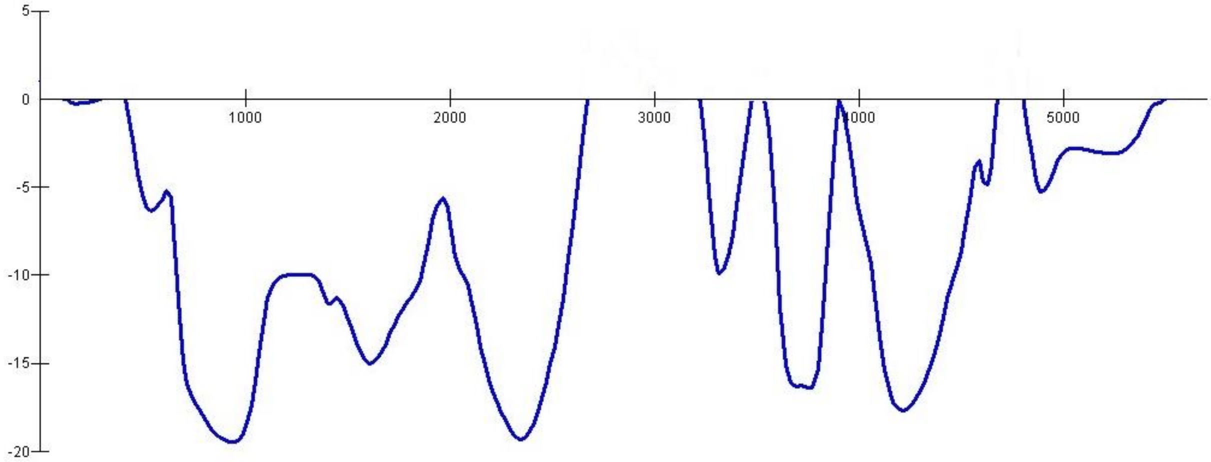


Fig. 13 Section area profile between Askö-Torö.

$A_{nautical} = 244.56$ km^2
A = 234.30 km^2
$A_{SMHI} = 237$ km^2(excluding half of the area of Dragfjärden)
$V_{nautical} = 2.934$ km^3
$V_{SMHI} = 2.913$ km^3 (excluding half of the volume of Dragfjärden)
$D_{max} = 52$ m
At = 45150 m^2

$$D_{mean} = \frac{Vol}{Area} = 12.5 \text{ m}$$

$$Vd = 3 \times \frac{D_{mean}}{D_{\max}} = 0.72$$

$$Ex = \frac{100At}{Area} = 0.019\ \%$$

$$\mathrm{DR} = \frac{\sqrt{Area}}{D_{mean}} = 1.22$$

$$Ins = \frac{A_{islands}}{Area} = 32\ \%$$

$T_{SW} = 18$ days

Himmerfjärden is a semi-enclosed system of intermediate size and depth according to the morphometric classification presented by Lindgren and Håkanson (2007). The bay is more influenced by winds and waves than by slope processes and erosion. The bathymetry is slightly convex and the insulosity is high.

$$Dwb = \frac{45.7 \times \sqrt{Area}}{21.4 + \sqrt{Area}} = 19 \text{ m}$$

Figure 14 shows the TIN file represented by the blue colours and the original raster file in black colours (used when creating the TIN) copied from ArcScene. Figure 15 shows the raster file created from the original nautical maps and it displays the bathymetry of Himmerfjärden.

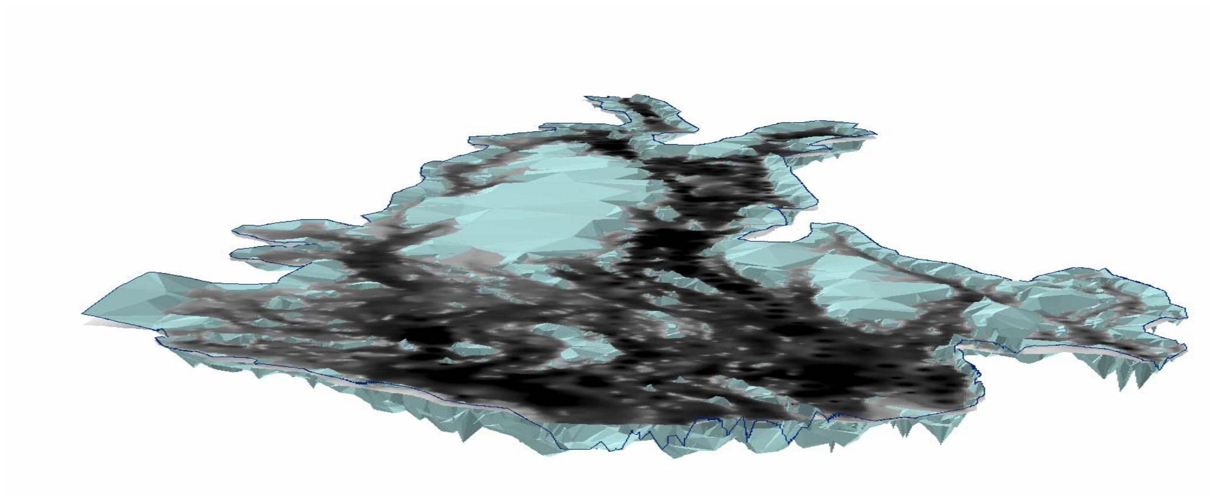


Fig. 14 TIN and raster file of Himmerfjärden imported from ArcScene.

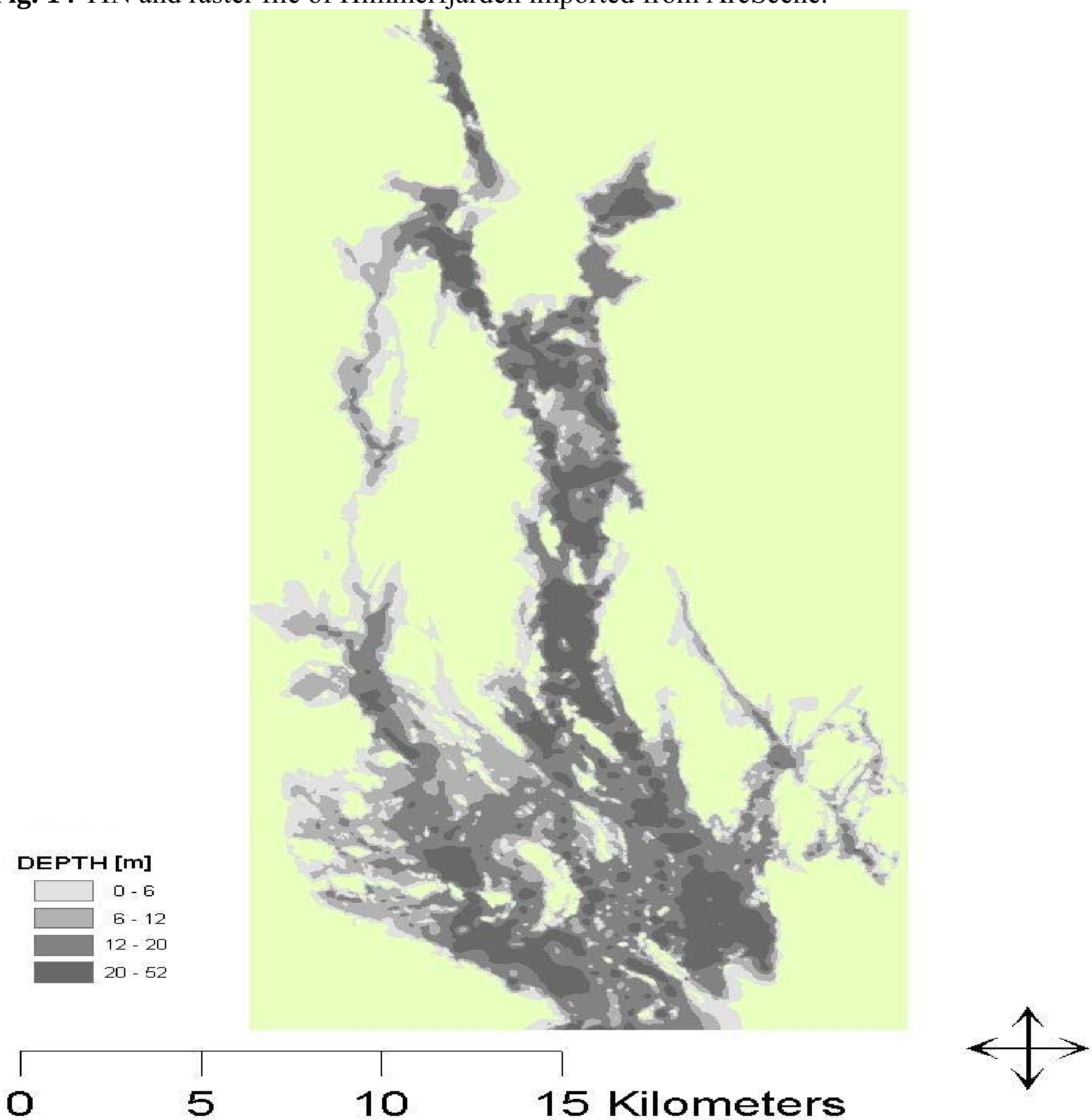


Fig. 15 Bathymetric map (raster) of Himmerfjärden.

.

Figure 16 is a hypsograph showing that the area below the theoretical wave base is 46 km^2 and Figure 17 is a volume curve displaying the volume beneath the wave base, V_{wb} = 0.236 km^3.

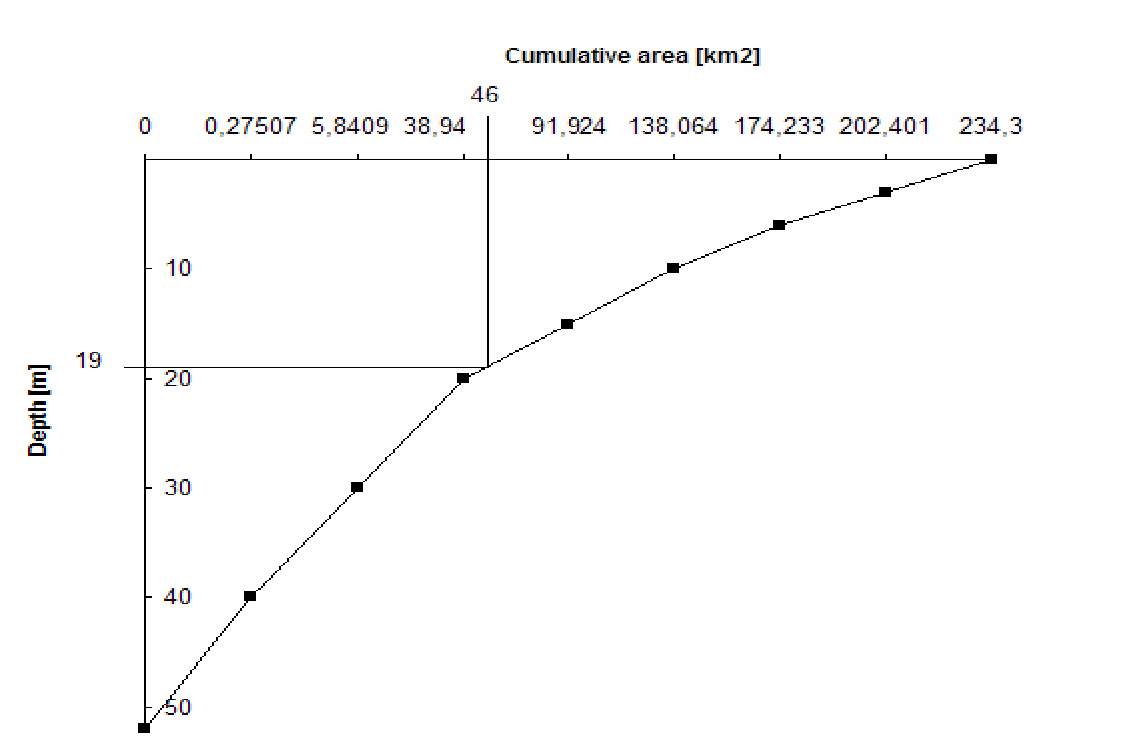


Fig. 16 Hypsograph with water area outlined below D_{wb}=19 m.

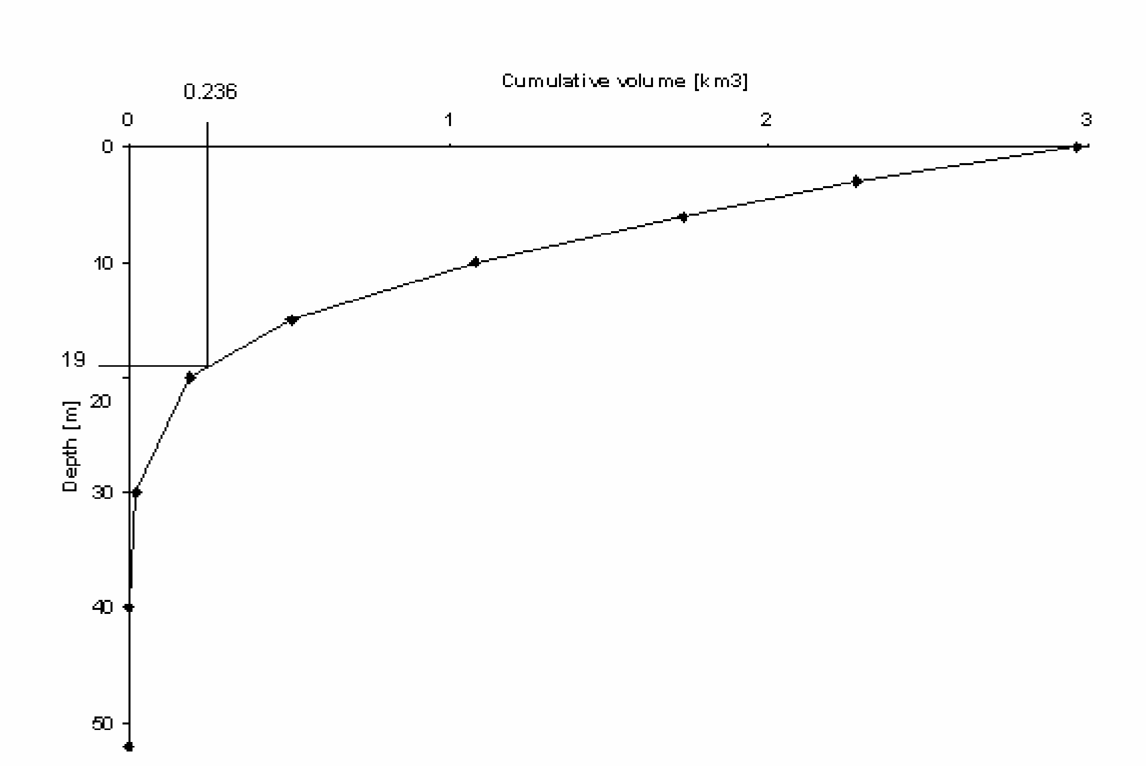


Fig. 17 Volume curve with water volume outlined below D_{wb}=19 m.

4.2 DATA

Table 4 shows the monthly means, medians, area weighted medians and standard deviations, all from individual data by month and coefficients of variation calculated from median values from all individual data (CV_{M50ind}) and from monthly medians year by year averaged into one typical year (CV_{M50}) from stations H2-H6 in Himmerfjärden.

Tab. 4 Statistics for empirical values on salinity in Himmerfjärden.

Salinity [psu]	H2-H6	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SW	**Mean**	5.907	5.991	5.969	5.922	5.802	5.709	5.700	5.626	5.644	5.738	5.874	5.798
	Median	5.934	6.050	6.023	5.902	5.800	5.759	5.703	5.671	5.678	5.715	5.8935	5.994
	Area weighted median	6.410	6.212	6.295	6.235	5.990	5.903	5.861	5.768	5.820	6.049	6.20418	6.195
	SD	0.477	0.460	0.399	0.427	0.396	0.352	0.310	0.290	0.338	0.411	0.382	0.615
	CV_{M50ind}	0.080	0.076	0.066	0.072	0.068	0.061	0.054	0.051	0.060	0.072	0.065	0.103
	CV_{M50}	0.051	0.053	0.048	0.044	0.046	0.047	0.050	0.054	0.056	0.056	0.052	0.050
DW	**Mean**	6.327	6.423	6.400	6.302	6.212	6.165	6.176	6.242	6.344	6.437	6.258	6.216
	Median	6.314	6.438	6.446	6.361	6.242	6.154	6.154	6.286	6.286	6.455	6.289	6.264
	Area weighted median	6.686	6.595	6.529	6.446	6.368	6.309	6.331	6.316	6.369	6.580	6.564	6.333
	SD	0.338	0.403	0.305	0.321	0.275	0.276	0.261	0.238	0.310	0.391	0.391	0.366
	CV_{M50ind}	0.053	0.063	0.047	0.050	0.044	0.045	0.042	0.038	0.049	0.061	0.062	0.058
	CV_{M50}	0.027	0.028	0.020	0.020	0.019	0.027	0.030	0.027	0.035	0.040	0.036	0.035

Statistics for the empirical temperature in Himmerfjärden is found in Appendix I in Table A1B.

4.2.1 Data sampling analysis

Table 5 shows the relative error, L, obtained from combining data from different stations with n kept constant.

Tab. 5 Median errors of different sampling station combinations.

Stations	Salt L, n=100 Year 2000	TP L, n=100 Year 2000	TN L, n=100 Year 2000
H3	0.01	0.04	0.01
All stations	0.02	0.05	0.04
H3,H2,H4 and H5	0.01	0.05	0.03
H3,H2 and H4	0.01	0.04	0.03
H3 and H4	0.01	0.04	0.02
H3 and H5	0.01	0.05	0.03
H3 and H6	0.02	0.05	0.05

Figure 18 shows the sub basin delimitation chosen according to the topographical bottle-neck method for the area weighted set of data and Table 6 lists sizes of the calculated sub areas.

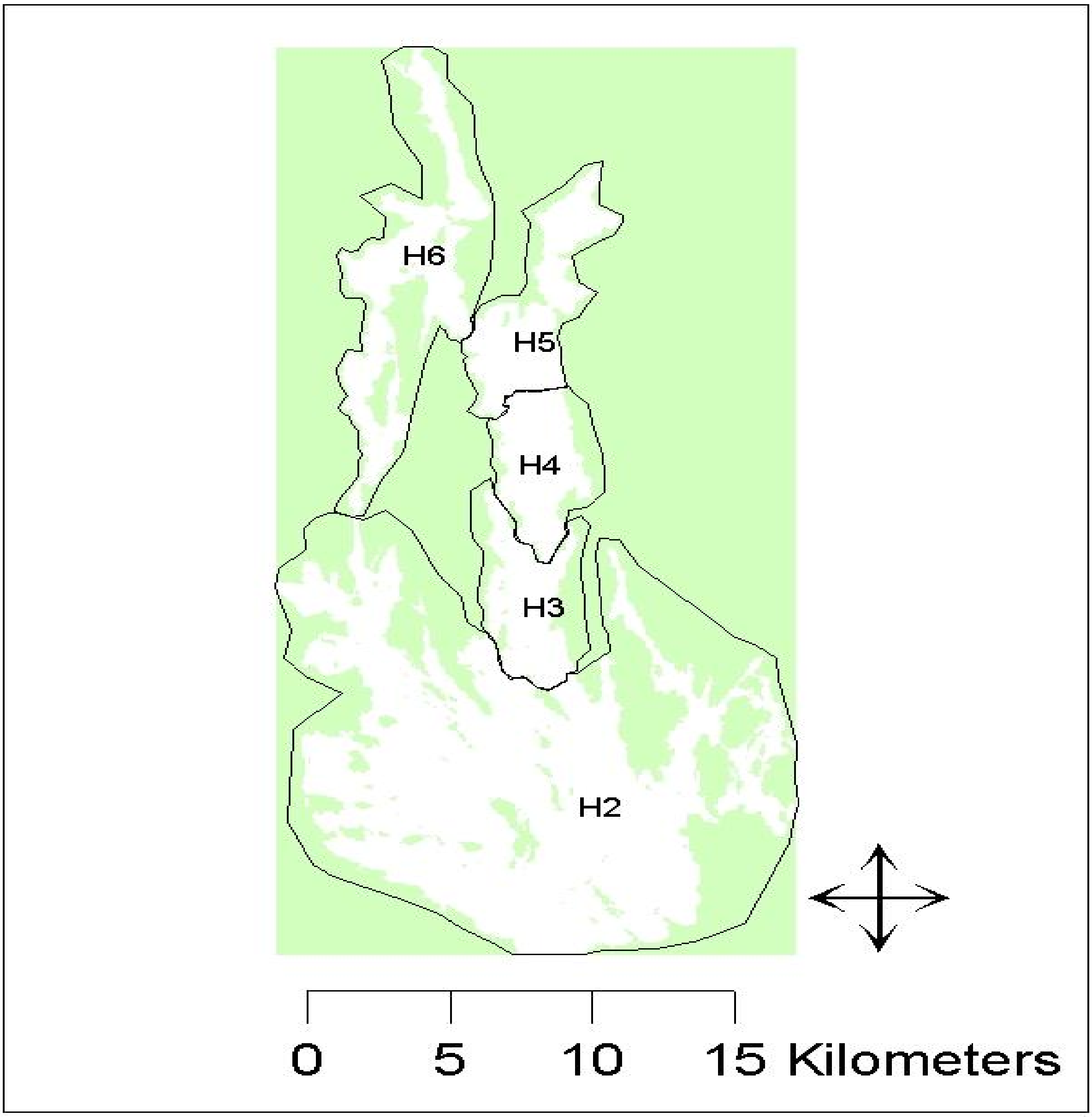


Fig. 18 Sub-areas of Himmerfjärden.

Tab. 6 Size of sub-areas.

Sub-area	**Area [km^2]**
H2	157
H3	15
H4	15
H5	28
H6	19

4.3 MASS-BALANCE MODEL FOR SALT

Figure 19 shows the modeled salinity in Himmerfjärden simulated over one year after steady-state has been reached with the 95 percent confidence interval calculated from empirical data.

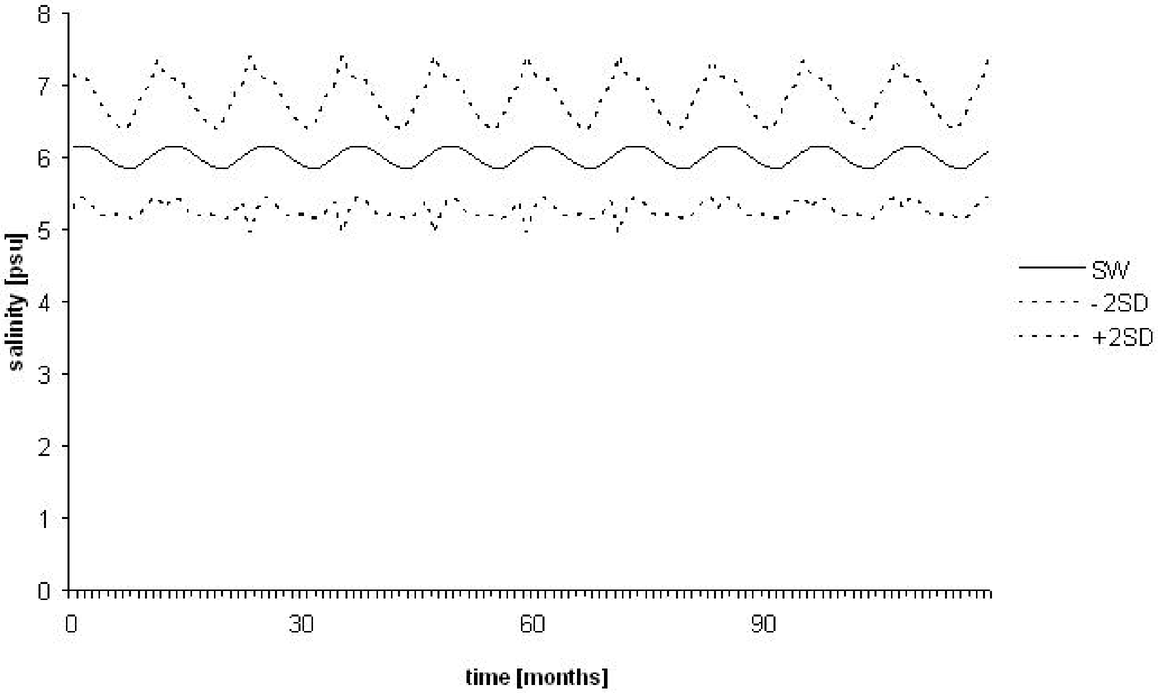


Fig. 19 Results from modelling with DC_{SWDW} = 0.90 and $Q_{intoHi} = 3950\times10^{6}$ m^3/month for surface water.

$T_{SW} \approx 0.7$ months = 21 days
up = 6.73 cm/s

Figures 20 and 21 show the error functions for the modeled values with the default setting versus the area weighted median empirical data on salinity in Himmerfjärden. The graphs show the modelled values deviation from the empirical values. If the values are identical the error function equals zero.

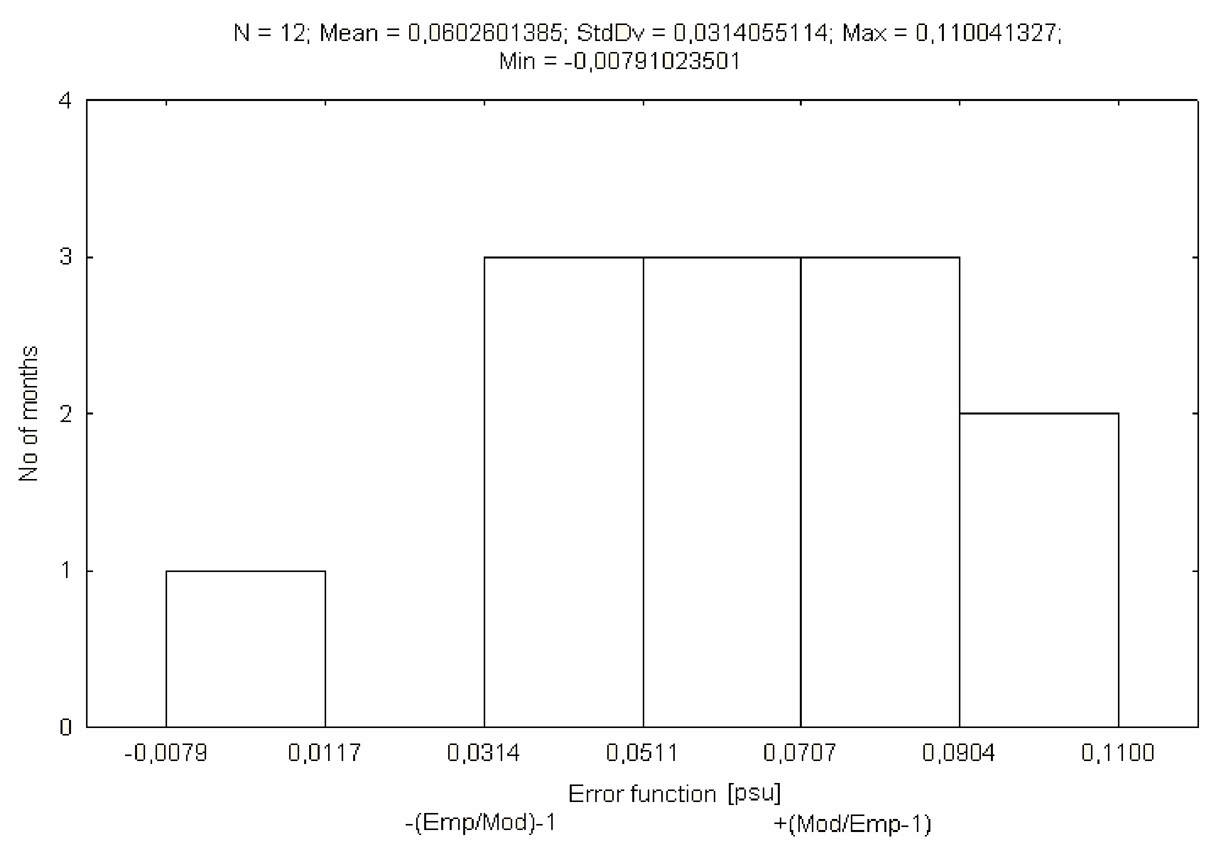


Fig. 20 Empirical values versus modeled values, surface water.

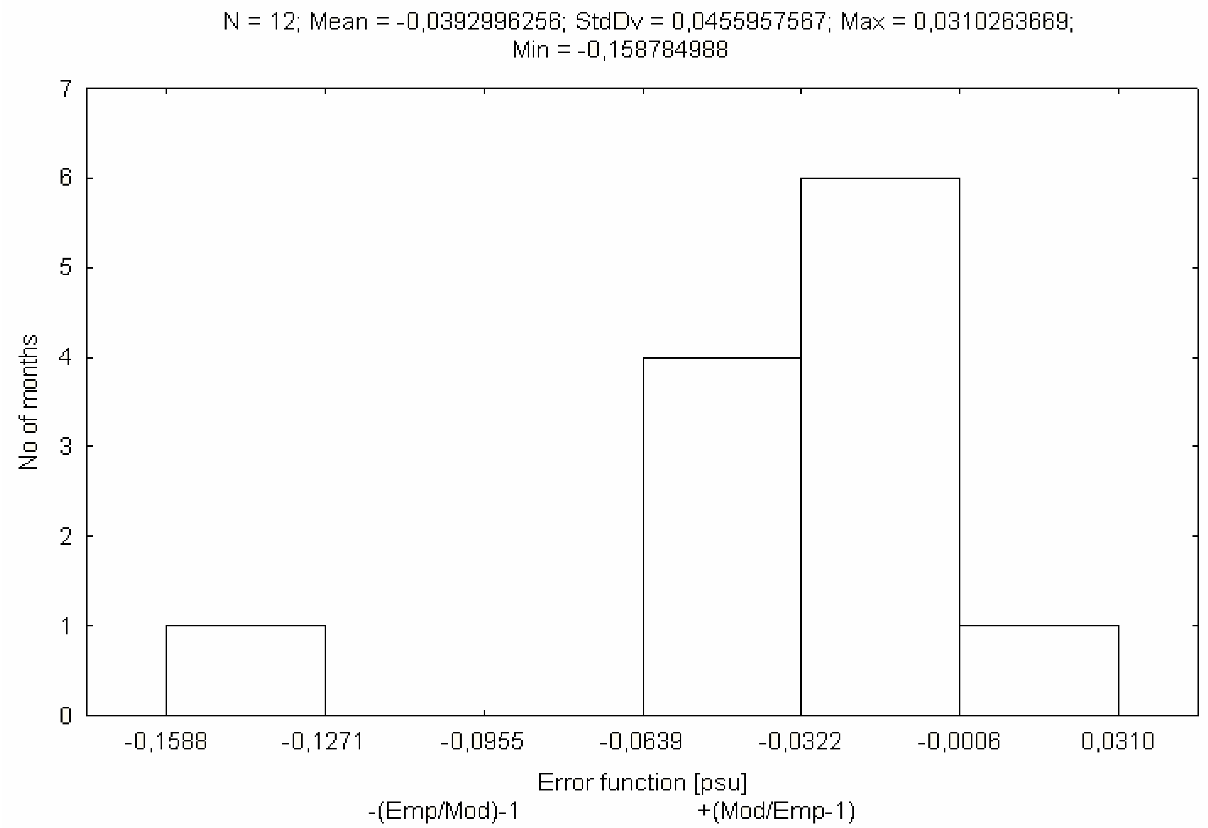


Fig. 21 Empirical values versus modeled values, deep water.

The resulting mean errors when comparing empirical values to modeled values from different values on DC_{SWDW} and Q_{intoHi} are displayed in Table 7 for the surface water compartment. The table also contains information on the section area velocity.

Tab. 7 Results from varying the model inputs DC_{SWDW} and Q_{intoHi} for surface water.

Month	Empirical Salinity SW	Default DC_{SWDW}=0.90 Q_{intoHi}=3950×10^6 m³	DC_{SWDW}=0.90, Q_{intoHi}=2000×10^6 m³	DC_{SWDW}=0.90, Q_{intoHi}=5000×10^6 m³	DC_{SWDW}=0.90, Q_{intoHi}=3000×10^6 m³
1	6.07	6.36	6.36	6.36	6.36
2	5.94	6.53	6.38	6.58	6.47
3	5.88	6.56	6.41	6.58	6.51
4	5.82	6.47	6.39	6.48	6.45
5	5.78	6.32	6.29	6.31	6.32
6	5.88	6.34	6.3	6.35	6.32
7	6.08	6.35	6.32	6.36	6.34
8	6.20	6.34	6.31	6.35	6.33
9	6.41	6.46	6.39	6.49	6.43
10	6.23	6.49	6.41	6.51	6.46
11	6.28	6.46	6.37	6.48	6.43
12	6.25	6.59	6.45	6.63	6.54
Error mean		0.06	0.05	0.06	0.06
u section area		6.73	3.41	8.51	5.11

The resulting errors when comparing empirical values to modeled values from different values on DC_{SWDW} and Q_{intoHi} are displayed in Table 8 for the deep water compartment. The table also contains information on the section area velocity.

Tab. 8 Results from varying the model inputs DC_{SWDW} and Q_{intoHi} for deep water.

Month	Empirical Salinity DW	Default DC_{SWDW}=0.90 Q_{intoHi}=3950×10^6 m³	DC_{SWDW}=0.90, Q_{intoHi}=2000×10^6 m³	DC_{SWDW}=0.90, Q_{intoHi}=5000×10^6 m³	DC_{SWDW}=0.90, Q_{intoHi}=3000×10^6 m³
1	6.39	5.77	5.77	5.77	5.77
2	6.33	6.41	6.16	6.48	6.31
3	6.32	6.48	6.3	6.52	6.42
4	6.32	6.39	6.3	6.39	6.37
5	6.33	6.22	6.2	6.22	6.22
6	6.42	6.12	6.09	6.13	6.12
7	6.58	6.06	6.03	6.07	6.05
8	6.54	5.98	5.97	5.97	5.98
9	6.69	6	5.96	6.01	5.99
10	6.60	6.23	6.11	6.28	6.18
11	6.54	6.4	6.26	6.43	6.35
12	6.47	6.53	6.38	6.56	6.48
Error mean		-0.03	-0.05	-0.04	-0.04
u section area		6.73	3.41	8.51	5.11

Figure 22 shows the water flow sizes to and from Himmerfjärden calculated by the model.

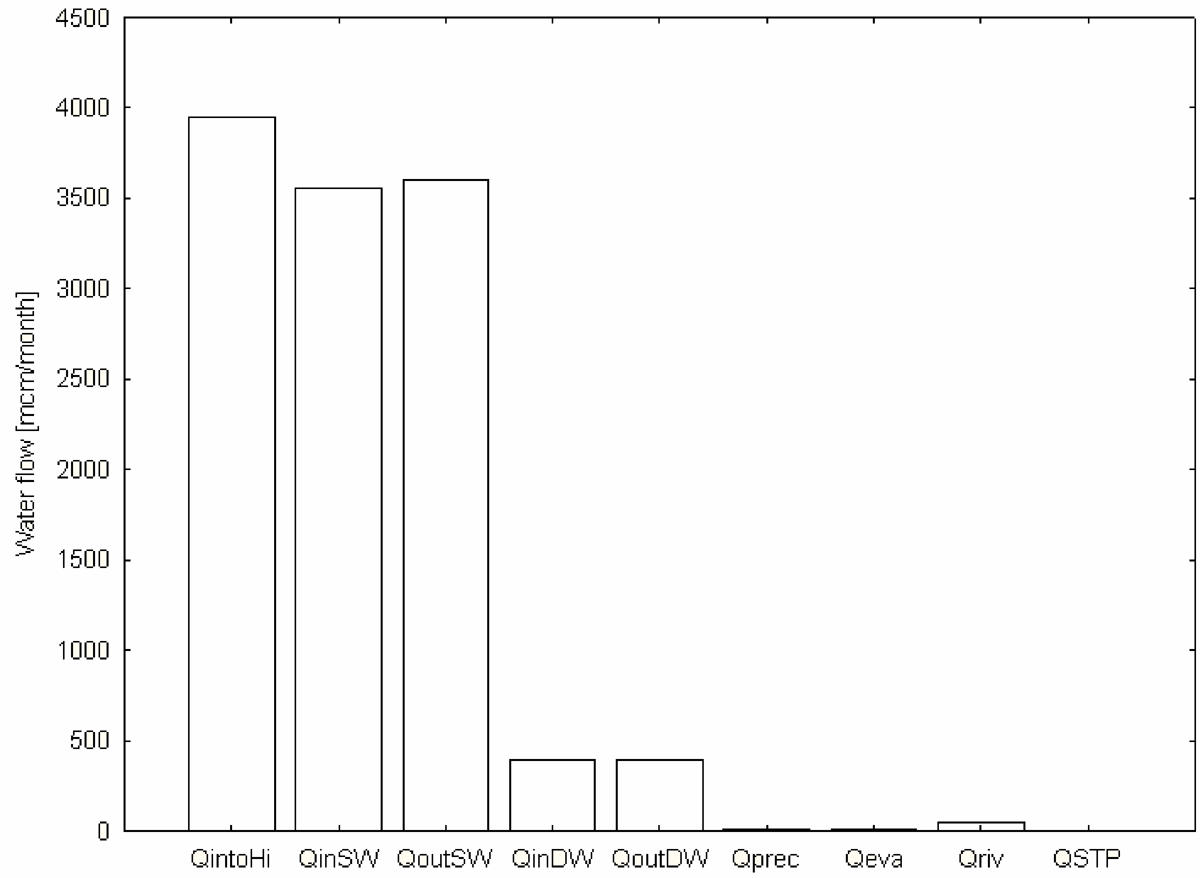


Fig. 22 Water flows to and from Himmerfjärden.

Table 9 displays the load of phosphorus and nitrogen to Himmerfjärden from different sources.

Tab. 9 Annual load as tons/year to Himmerfjärden from different sources.

Year	TN BP	River	STP	N fix	TP BP	River	STP
2006	12743	505	336	450	1265	19	18
1997	12743	505	450	450			

Figures 23 and 24 show the flows of P and N to Himmerfjärden from the Baltic Proper (BP), rivers, sewage treatment plant (STP) and from nitrogen fixing cyanobacteria.

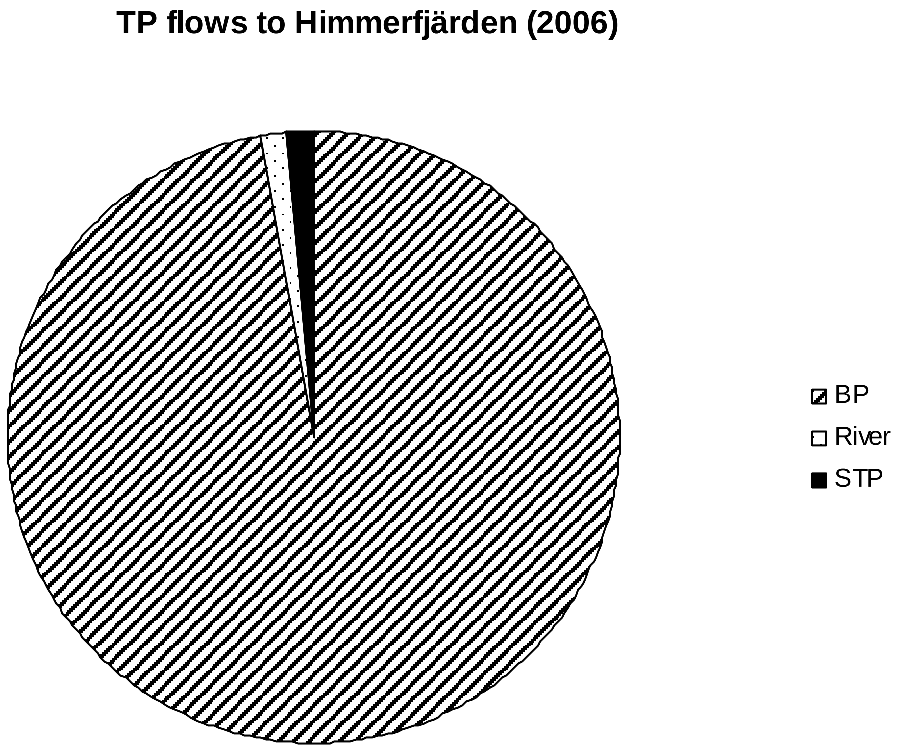


Fig. 23 Load from different sources of phosphorus to Himmerfjärden from 2006.

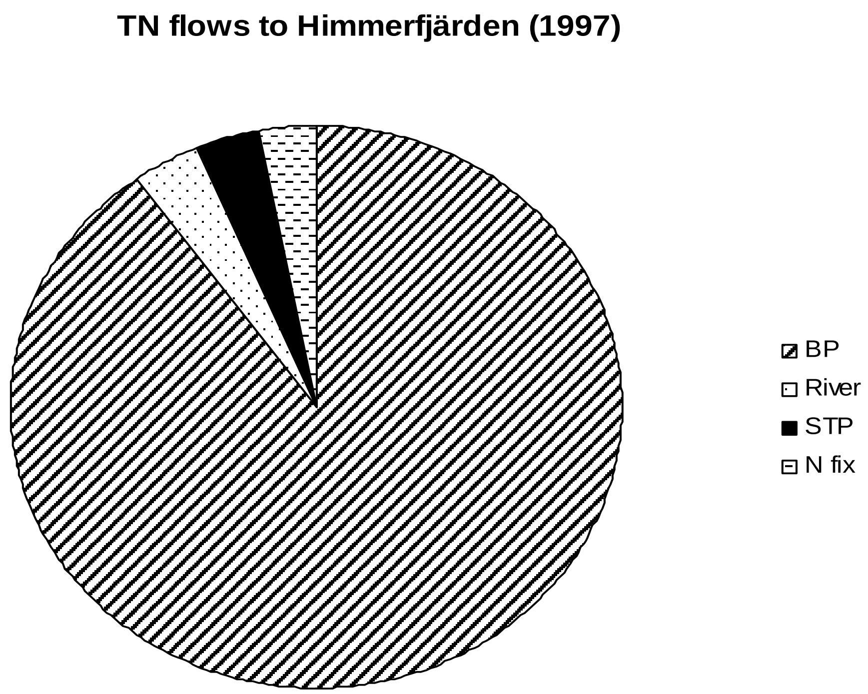


Fig. 24 Load from different sources of nitrogen to Himmerfjärden from 2006.

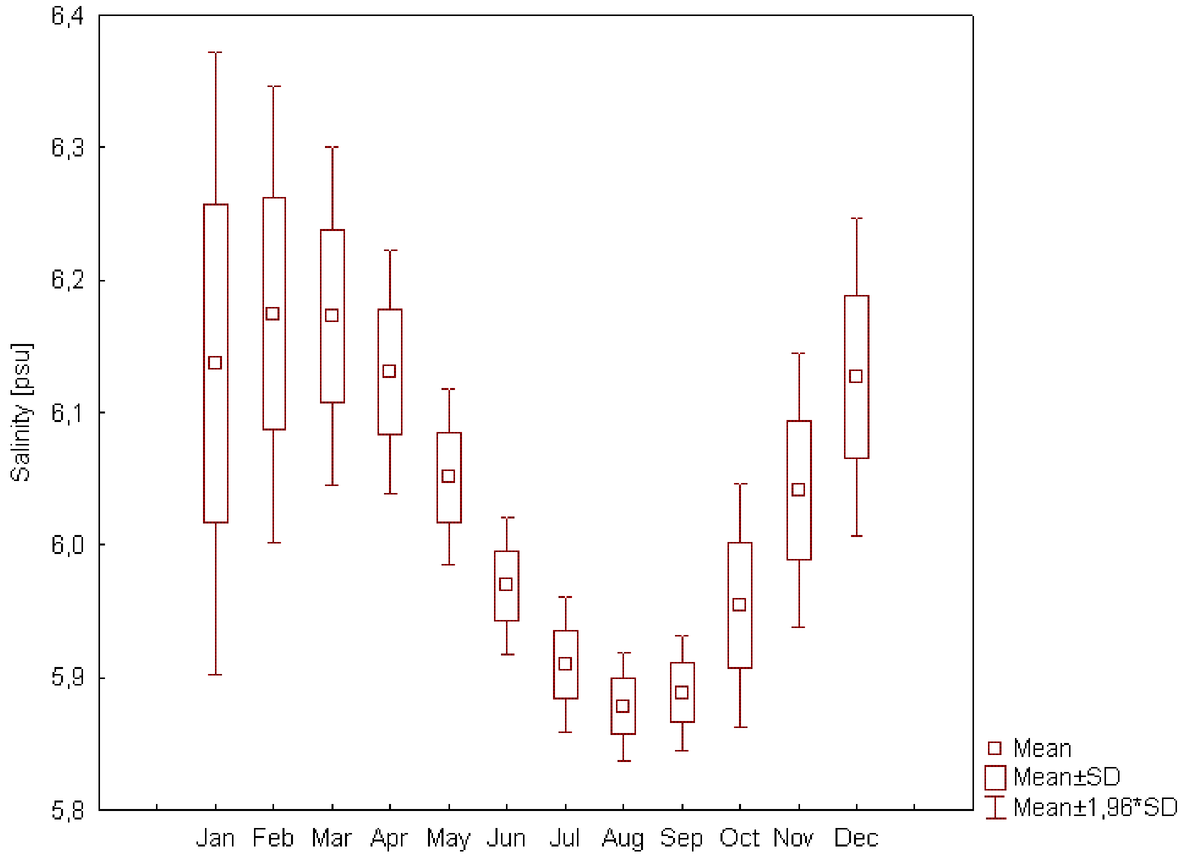
4.3.1 Uncertainty test

Table 10 shows the characteristic CV values used in the uncertainty test including all variables. CV for the morophometric variables were estimated to 0.01 (Håkanson 1999), CV for salinity and temperature were calculated from empirical data and CV for DC_{SWDW} and Q_{intoHi} were set to 0.025 (Håkanson 1999).

Tab. 10 Characteristic coefficients of variations used in the uncertainty test.

Variable	Coefficient of variation
$\mathbf{DC_{SWDW}}$	0.025
$\mathbf{Q_{intoHI}}$	0.025
At	0.010
$\mathbf{V_{DW}}$	0.010
A	0.010
$\mathbf{A_{WB}}$	0.010
Dmean	0.010
ADA	0.010
$\mathbf{C_{SWBP}}$	0.070
$\mathbf{C_{DWBP}}$	0.050
$\mathbf{T_{SW}}$	0.250
$\mathbf{T_{DW}}$	0.280

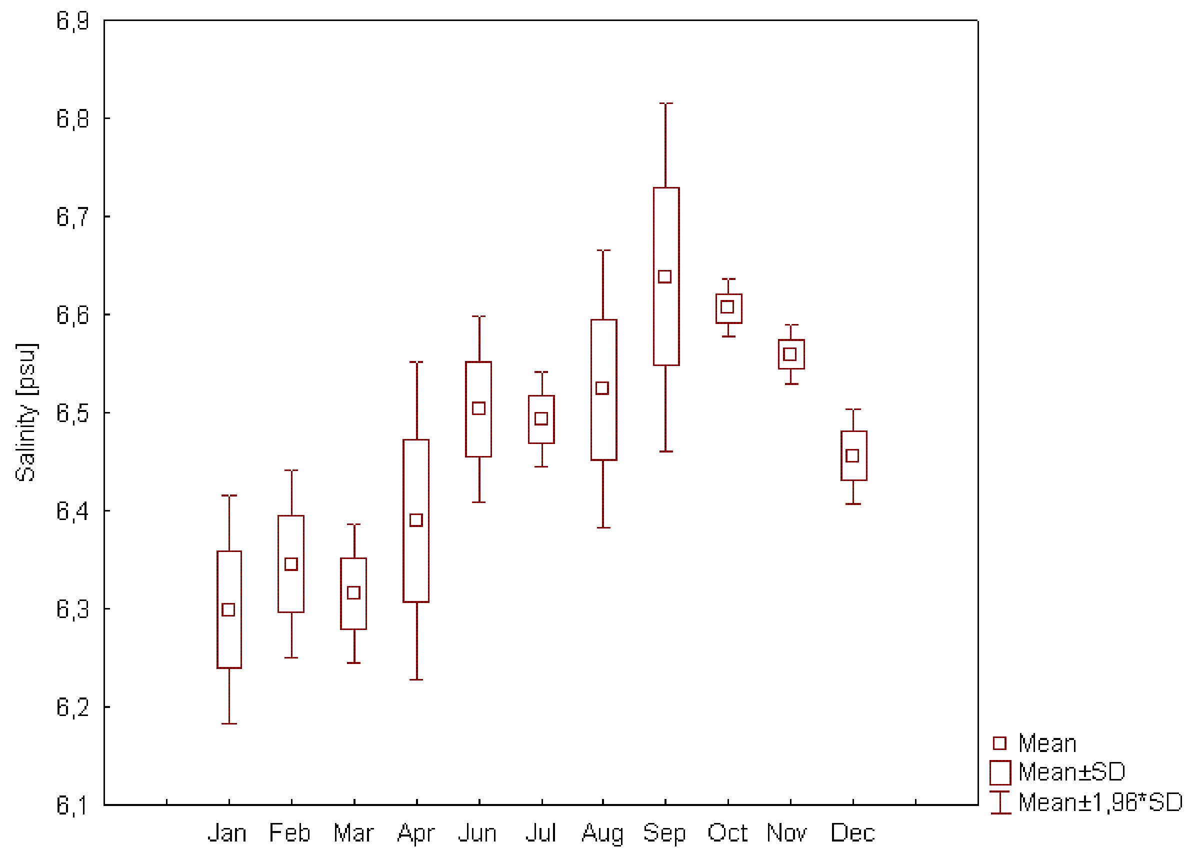
Figure 25 displays the results from the uncertainty test for surface water with total model uncertainty by month displayed in the graph and with total followed by individual input variable contributions to the uncertainty by month displayed in the table.



Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total uncertainty	0.020	0.014	0.011	0.008	0.006	0.004	0.004	0.004	0.004	0.008	0.009	0.010	0.008
DS_{SWDW}	0.020	0.014	0.010	0.008	0.006	0.004	0.004	0.004	0.004	0.008	0.009	0.010	0.008
Qin	0.020	0.014	0.010	0.008	0.006	0.004	0.004	0.003	0.004	0.008	0.009	0.010	0.008
At	0.020	0.014	0.011	0.008	0.006	0.004	0.004	0.004	0.004	0.008	0.009	0.010	0.008
SWBP	0.020	0.014	0.011	0.008	0.006	0.004	0.003	0.002	0.002	0.002	0.003	0.003	0.004
DWBP	0.020	0.014	0.011	0.008	0.006	0.005	0.005	0.004	0.004	0.008	0.009	0.011	0.008
V_{DW}	0.020	0.014	0.010	0.008	0.006	0.004	0.004	0.004	0.004	0.008	0.009	0.010	0.008
A_{wb}	0.020	0.014	0.011	0.008	0.006	0.005	0.005	0.004	0.004	0.008	0.009	0.010	0.008
$Temp_{SW}$	0.020	0.014	0.011	0.008	0.006	0.004	0.004	0.004	0.004	0.008	0.008	0.010	0.008
$Temp_{DW}$	0.020	0.014	0.011	0.008	0.006	0.005	0.005	0.004	0.004	0.008	0.009	0.010	0.008
A	0.013	0.010	0.007	0.006	0.004	0.004	0.005	0.004	0.004	0.008	0.009	0.010	0.006
ADA	0.020	0.014	0.011	0.008	0.006	0.005	0.005	0.004	0.004	0.008	0.009	0.010	0.008
D_{mean}	0.013	0.010	0.007	0.006	0.004	0.004	0.005	0.004	0.004	0.008	0.009	0.010	0.006

Fig. 25 Coefficients of variation for all x-variables, surface water.

Figure 26 displays the results from the uncertainty test for deep water with total model uncertainty by month displayed in the graph and with total and individual input variable contributions to the uncertainty by month displayed in the table.



Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total uncertainty	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.005	0.003	0.010	0.012	0.005
DS_{SWDW}	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.005	0.003	0.010	0.012	0.005
Qin	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.005	0.003	0.010	0.012	0.005
At	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.005	0.003	0.010	0.012	0.005
SWBP	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.005	0.003	0.010	0.012	0.005
DWBP	0.010	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
V_{DW}	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.005	0.003	0.010	0.012	0.005
A_{wb}	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.006	0.003	0.010	0.012	0.005
$Temp_{SW}$	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.005	0.003	0.010	0.012	0.005
$Temp_{DW}$	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.006	0.003	0.010	0.012	0.005
A	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.006	0.003	0.010	0.012	0.005
ADA	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.005	0.003	0.010	0.012	0.005
D_{mean}	0.010	0.001	0.003	0.005	0.005	0.002	0.002	0.010	0.006	0.003	0.010	0.012	0.005

Fig. 26 Coefficients of variation for all x-variables, deep water.

5 DISCUSSION

5.1 LITERATURE REVIEW

Naturvårdsverket, in cooperation with Stockholm University, has started a new large-scale experiment in Himmerfjärden. The hope is that the experiment will bring clarity to the controversy about the benefits of removing nitrogen from sewage effluents. In January 2007 the Himmerfjärden treatment plant turned off its nitrogen removal process and unless there is a clear negative environmental effect it will stay turned off during the next two years and the effects will be closely monitored. Another planned experiment is to change the release point of the sewage effluent from the deep water to the top surface water (Dagens Nyheter, 2007).

This literature study has revealed that there are good reasons to question the management strategy of the treatment plant in Himmerfjärden. Much of the arguments brought in favour of the extensive nitrogen removal policy are based on believes and assumptions that might be false. The main question is whether Himmerfjärden is limited by nitrogen or not.

One problem with the interpretation of data from Himmerfjärden is that it is based on the inorganic fractions of nitrogen and phosphorus. As shown in Table 1 the CV values for DIN and DIP and TN and TP in Himmerfjärden are 0.95 and 0.54 and 0.13 and 0.18 respectively. For DIN this means that the standard deviation almost equals the mean and the table also shows that the CV values are greatest during the growing season. Much of the motivation for nitrogen removal in Himmerfjärden falls apart if one accepts that there are problems involved in using these fractions as a measure of nutrient status of waters.

It is interesting to note that the Redfield ratio based on DIN/DIP is lower than the ratio based on TN/TP. This implies that the fraction of dissolved inorganic nitrogen is smaller relative TN than the fraction of inorganic phosphorus relative TP.

Another obvious problem is that Himmerfjärden has not responded to the removal of nitrogen as predicted by Elmgren and Larsson (1997). The decrease of chlorophyll *a* could be due to the removal of nitrogen or it could be caused by the shift in climate towards mild winters and warmer summers with prolonged periods of stratification that decrease total mixing and depress chlorophyll *a* levels. The increase in cyanobacteria is very dramatic and may be a consequence of the ambitious nitrogen removal from treatment plant emissions. Another possibility is that the increase is not a local phenomenon and that the increase only reflects an increase in cyanobacterial growth in the Baltic proper.

It will be interesting to follow the development of especially chlorophyll *a* and cyanobacterial growth in Himmerfjärden now that nitrogen is not removed from treatment plant emissions.

5.2 GIS-ANALYSIS

The results of the GIS-mapping of Himmerfjärden show that the area calculated from the digital map (A = 234.3 km^2) was very close to the area calculated by SMHI (2003) (A = 237 km^2), implying that the area is probably accurately estimated. The area calculated from the nautical maps was about 10 km^2 larger than the result from the digital map in spite of the fact that Trosa port was not included. This is probably due to the fact that calculating area from a raster created by interpolation is associated with large errors in shallow parts of the bay. The GIS-program will interpret some of the land areas as water when interpolating and the area will be overestimated.

The volume calculated from the raster file (V = 2.93 km^3) was very close to the volume calculated by SMHI (2003) (V = 2.91 km^3). The larger volume that follows the interpolation error is small because of the shallow depth in the areas where the area is overestimated and this small addition seems to make up for the missing volume of Trosa port.

The calculated value on the greatest section area between Askö and Torö by delimitation number 1 (Figure 12 At = 43510 m^2) was also compared with a value calculated by SMHI (2003) (At = 43950 m^2). The area, volume and section area all correlated well with data from SMHI (2003) and therefore figures that were used in the modelling may be considered quite reliable.

Morphological data from Himmerfjärden suggest that the surface water retention time in the whole bay is about 18 days. Data on surface water retention times from different basins in Himmerfjärden were available in Elmgren and Larsson (1997) and Engqvist (1999). They estimated surface-water retention times that varied from 30 days to about 140 days in different areas in Himmerfjärden.

The value on section area flow velocity, *up* = 6.73 cm/s, calculated from the mass-balance for salt lies well within the expected 0.5 to 20 cm/s.

5.3 DATA

The area weighted data on salinity in Himmerfjärden differ slightly (about 3 percent higher) from the non area weighted medians. The standard deviation of empirical data for salinity is about 0.5 psu thus the inherent uncertainty overshadows the area weighting. The area weighted data set was still used in the model as it represents a saltier sample that probably lies closer to the true conditions in the bay since it also accounts for each station's location.

The data sampling analysis shows that station H3 is the station that best reflects the conditions in the bay based on salinity, phosphorus and nitrogen. Excluding sampling stations would not increase the error of the mean. In order to understand which sources of nutrient that affect eutrophication in Himmerfjärden, a mass balance modelling for phosphorus needs to be performed. The data sampling program in Himmerfjärden is unfortunately not optimally suited for this purpose.

Future mass-balance research on eutrophication in Himmerfjärden would be helped by adding a sampling station in the area between Askö and Torö. Previously data from B1 have been used to describe the water flowing into Himmerfjärden (Elmgren and Larsson 1997). This is not at all ideal and B1 might not be very representative for the water flowing into Himmerfjärden.

The data set from Himmerfjärden would also be improved by taking more samples from each station at more and specified depths. This could be done without increasing the sampling program cost by excluding redundant stations like H2, H6 and perhaps H4 or H5.

5.4 MASS-BALANCE MODEL FOR SALT

The modelled values lie well within the 95 percent confidence interval of the empirical data. Different values on Q_{intoHi} and DC_{SWDW} were tested thoroughly and it was shown that the selected values yield the minimum error when correlating modelled values with empirical data. The error functions show that the modelled results are very close to the empirical data. The model is prone to calculating values that are insignificantly smaller than the empirical data and the error varies around zero.

The model calculates a value on surface water retention time that is about 18 days which lies very close to the value calculated from the morphology (21 days). The surface water retention time for all of Himmerfjärden calculated in this work is shorter than previous calculations on surface water retention times in different parts of the bay. No value was available on retention time for the whole bay previous to this study but the correleation between the value calculated form morphology and the value calculated by the mass balance modelling implies that a surface retention time of about 20 days is a quite reliable estimate.

The main flow to Himmerfjärden's deep and surface water is from the adjacent sea (about 91 percent of total water inflow). The levels of pollutants in the bay are thus to a very large extent dependent on the levels in the outside sea and this assumption was also supported by the sensitivity analysis. It is most evident that the sewage treatment plant has little to do with nutrient input to Himmerfjärden when studying Figures 23 and 24. Figure 23 is based on data from 2006 and is shows that the overwhelming contribution of phosphorus to Himmerfjärden originates from the Baltic Proper. Figure 24 is even more interesting in the light of the nitrogen debate. It is based on data from 1997 before the ambitious nitrogen removal program and it clearly shows that the emissions from the sewage treatment plant are completely overshadowed by the contribution from the Baltic Proper.

The findings from the mass-balance modelling of salt contradicts the calculations made by Elmgren and Larsson 1997 who calculated the nitrogen load from the treatment plant to be about 25 percent of total nitrogen load to sub basins H4 and H5. This work suggests that the load of nitrogen from the sewage treatment plant only constitutes 2 percent of total nitrogen load to the bay today and that it constituted about 3 percent in 1997.

The uncertainty test points out the salinity in the surface water in the adjacent sea, total area and the mean depth of Himmerfjärden to be the main variables that most affect the model uncertainty in the surface water. Total model coefficient of variation varies throughout the year from 0.004 to 0.02 which is of a smaller magnitude than the coefficients of variation of empirical data (about 0.05).

The uncertainty in model results for surface water has its minimal values during summer. This is probably due to the inflow of water with stable salinity during summer when mixing is minimal and the water is stratified.

The uncertainty test points out the salinity in the deep water in the outside sea to be the main variable that most affect the modelling uncertainty in the deep water. Total model coefficient of variation varies throughout the year from 0.002 to 0.01 which is of a much smaller magnitude than the coefficients of variation for the empirical data (about 0.05).

The uncertainty in model results for deep water varies more stochastically but reaches maximum values during spring and fall when storms help increase mixing and the temperature difference between deep and surface water is small.

The fact that the salinity in the outside sea contributes the most to the model's uncertainty support the importance of sampling accurate data on the water that flows into Himmerfjärden from the Baltic Proper.

6 CONCLUSIONS

The literature study performed in this work suggests that there is much room for further research on Himmerfjärden. Many questions remain unanswered despite of long data series and more than 30 years of area specific research. There have been assumptions made in the past on the significance of sewage treatment plant emissions to Himmerfjärden that is not supported by the results from the mass-balance of salt performed in this study. The findings of this work imply that the sewage treatment plant emissions of nitrogen and phosphorus are small compared to the contributions from the outside sea. This study and further mass-balance modelling may provide new answers and help bring clarity to the controversy about the management of Himmerfjärden.

This study has in spite of Himmerfjärden's enclosed morphometry and in spite of the lack of available data suited for mass-balance modelling succeeded in creating a realistic model of Himmerfjärden that generates values on salinity that lie within the uncertainty bands of the empirical data.

This work has also shown that the method of collecting data is poorly suited for the purpose of doing mass-balance calculation to understand eutrophication at ecosystem level. It is suggested in this study to decrease the number of sampling stations and to make more detailed measurements on water quality variables and to measure more frequently from those fewer stations. This work has also shown the need for a sampling station somewhere between Askö and Torö. Accurate data on the inflowing water from the sea is of great importance since it describes the single most important flow into Himmerfjärden.

The main task of this study has been accomplished and the modelling has provided a basic understanding of the water dynamics in Himmerfjärden. Further mass-balance modelling of phosphorus, nitrogen and cyanobacteria may be based on the results of the mass-balance for salt and it may provide a new perspective on the eutrophication status and its causes in Himmerfjärden.

References

Bernes, C., 2005. Förändringar under ytan – Sveriges havsmiljö granskad på djupet. Monitor 19. Naturvårdsverket.

Bianchi, S. T., Engelhaupt, E., Westman, P., Andrén, T., Rolff, C., Elmgren, R., 2000. Cyanobacterial blooms in the Baltic Sea: Natural or human-induced? Limnol. Oceanogr., 45: 716-726.

Boesch, D., Hecky, R., O'Melia, C., Schindler, D., Seitzinger, S., 2006. Eutrophication of Swedish Seas. Report 5509. Naturvårdsverket.

Blomqvist, S. and Larsson, U., 1994. Detrital bedrock elements as tracers of settling resuspended particulate matter in a coastal area of the Baltic Sea. Limnol. Oceanogr., 39: 880-896.

Dagens Nyheter, Ökat utsläpp av kväve kan minska algblomning, 2007-01-09

Dodds, K. W., 2003. Misuse of inorganic N and soluble reactive P concentrations to indicate nutrient status of surface waters. J. N. Am. Benthol. Soc., 22: 171-181.

Eilola, K. and Stigebrandt, A., 1999.On the seasonal nitrogen dynamics of the Baltic Proper biogeochemical reactor. J. Mar. Sci., 57: 693-713.

Elmgren, R., 1989. The etrophication status of the Baltic Sea: input of nitrogen and phosphorus, their availability for plant production, and some management implications. Baltic Sea environment proc., 30: 12-31. ISSN-0357-2994.

Elmgren R., 2001. Understanding human impact on the Baltic Ecosystem: Changing views in recent decades. Ambio Vol. 30., No. 4-5.

Elmgren, R. and Larsson, U., 1992. Östersjöns gödning och övergödning. Annual report 1992. Swedish Natural Science Research Council.

Elmgren, R., Larsson, U. (editors)., 1997. Himmerfjärden. Förändringar i ett näringsbelastat kustekosystem i Östersjön. Naturvårdsverket.

Elmgren, R. and Larsson, U., 2001. Nitrogen and the Baltic Sea: Managing Nitrogen in Relation to Phosphorus. The Scientific World 1, p. 371-377.

Engqvist, A., 1999. Coasts and seas. Report 4910. Naturvårdsverket.

Forsberg, C., 1991. Eutrophication in the Baltic Sea. The Baltic Sea University. Uppsala University.

Hellström, T., 1998. Why nitrogen is not the limiting nutrient in the seas around Sweden. Effects of nitrogen in the aquatic environment. KVA report 1: 11-22.

Himmerfjärden, 2007. www2.ecology.su.se/dbhfj/

Håkanson, L., 1993. Physical Geography of the Baltic. The Baltic Sea University. Uppsala University.

Håkanson, L., 1999. Water pollution – methods and criteria to rank, model and remediate chemical threats to aquatic ecosystems. Backhuys Publishers, Leiden, p. 299.

Håkanson, L., 2000. Modelling radiocesium in lakes and coastal areas – a new approach for ecosystem modelers. Kluwer Academic Publishers.

Håkanson, L. and Bryhn, A.C., 2007. A process-based mass-balance model for phosphorus/eutrophication including a climate change scenario, as exemplified for the Baltic Proper. Manuscript, Dept. of Earth Sci., Uppsala Universtity.

Håkanson, L. and Eklund, J., 2006. A dynamic mass balance for phosphorus fluxes and concentrations in coastal areas. Ecol Res., 22: 296-320.

Håkanson, L., Bryhn, A.C., and Hytteborn, J.A., 2007. On the issue of limiting nutrient in aquatic systems and predictions of bluegreen algae. Sci. Tot. Env., 379: 89-108.

Håkanson, L., Kvarnäs, H., Karlsson, B., 1986. Coastal morphometry as regulator of water exchange – a Swedish example. Est. Coast. and Shelf Science., 23: 873-887.

Håkanson, L. and Lindgren, D., 2007 Impact of climate change on the salinity in the Baltic Sea – simulations using a mass-balance modelling approach. Manuscript, Dept. of Earth Sci., Uppsala Universtity.

Howarth, R. W. and Marino, R., 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. Limnol. Oceanogr. 51: 364-376.

Johnson, A. R., 1994. Miller & freund's probability & statistics for engineers. Prentice-Hall, Inc.

Kautsky, L., 1993. Life in the Baltic Sea. The Baltic Sea University. Uppsala University.

Lantmäteriet, 2007. https://geoimager.lantmateriet.se/digibib/index_s.html

Larsson, U., 2005. Varför ökar inte kvävet när fosforn ökar? Årsrapport Östersjön, Naturvårdsverket.

Larsson, U. and Elmgren, R., 2001. Eutrphication in the Baltic Sea area. Integrated coastal management issues. Sci. Int. Coast. Man. pp. 15-35. Dahlem University Press, Berlin.

Larsson, U., Hajdu, S., Walve, J., Elmgren, R., 2001. Baltic Sea nitrogen fixation estimated from the summer increase in upper mixed layer total nitrogen. Limnil. Oceanogr., 46: 811-820.

Larsson, U., Hajdu, S., Walve, J., Andersson, A., Larsson, P., Edler, L., 2006. Bedömningsgrunder för kust och hav. Växtplankton, näringsämnen, klorofyll och siktdjup. 2006.

Lindgren, D. and Håkanson, L. 2007. Functional classification of coastal areas as a tool in ecosystem modelling and management. Manuscript. Uppsala University.

Monitor, 1988. Sweden´s Marine Environment – Ecosystem under Pressure. Swedish Environmental Protection Agency. p. 207

Paerl, H., Valdes M. L., Pinckney, L.J., Piehler, F. M., Dyble, J., Moisander, H. P., 2003. Phytoplankton Photopigments as Indicator of Estuarine and Coastal Eutrophication. Bioscience., 53: 953-964.

Pilesjö, P., Persson, J., Håkanson, L., 1999. A digitizing method for determination of morphometric parameters for coastal management. Submitted in the doctoral thesis "On the role of morphometry in coastal ecosystem modelling and management by Persson, J. 1999. Uppsala University.

Rabalais, N. N., 2002. Nitrogen in aquatic ecosystems. Ambio., 31: 102-112.

Redfield, A.C., Ketchum, B.H. and Richards, F.A., 1963. The influence of organisms on the composition of seawater. In: Hill, N. (ED.), The sea2. Interscience, New York, p. 26-77

Rönnberg, C. and Bonsdorff, E., 2004. Baltic sea eutrophication: area-specific ecological consequences. Hydrobiologia., 514: 224-241.

Savage, C., Elmgren, R., Larsson, U., 2002. Effects of sewage-derived nutrients on an estuarine macrobenthic community. Mar. Ecol. Prog. Ser., 243: 67-82.

Savchuk, O. and Wulff, F., 1999. Modelling regional and large-scale response of Baltic Sea ecosystems to nutrient load reductions. Hydrobiologia., 393: 35-43.

SMHI, 2003. Djupdata för havsområden 2003. Svenskt vattenarkiv. Vol 73. SMHI

Svenska Naturskyddsföreningen, 2006. Från friskt hav till algsoppa. Svensk natur. Vol 3.

Svenska Dagbladet, Vinden vårt hopp mot algblomningen, 2006-07-18.

Wasmund, N., Nausch, G., Schneider, B., Nagel, K, Voss, M., 2005. Comparisation of nitrogen fixation rates determined with different methods: a study in the Baltic Proper. Mar. Ecol. Prog. Ser. Vol., 297: 23-31.

Appendix I

A1. Salt mass balance model equations and variables

F for flow [kg/month], R for rate [1/month], C for concentration [‰=psu=kg/m^3], DC for distribution coefficients [dimensionless], M for mass [kg], D for depth [m], A for area [m^2], V for volume [m^3]. Flow from one compartment [e.g. DW] to another [e.g. SW] is written F_{DWSW}. Q is water discharge [m^3/month]. L is load [kg]. Baltic Proper is abbreviated as BP. AV is short for averaging function.

Deep water

$M_{DW}(t) = M_{DW}(t - dt) + (F_{MixSWDW} + F_{InDW} - F_{MixDWSW} - F_{DiffDWSW} - F_{OutDW}) \times dt$ [kg]

Inflows:
$F_{MixSWDW} = M_{SW} \times R_{MixSWDW}$ [kg /month]
$F_{InDW} = Q_{inDW} \times C_{DWBP}$ [kg /month]

Outflows:
$F_{MixDWSW} = M_{DW} \times R_{mixSWDW} \times DC_{VSWDW}$ [kg /month]
$F_{DiffDWSW}$ = if $M_{DW} \times Diff_{SWDW} \times DiffC < 0$ then 0 else $M_{DW} \times Diff_{SWDW} \times DiffC$ [kg /month]
$F_{outDW} = Q_{outDW} \times C_{DW}$ [kg /month]

Surface water

$M_{SW}(t) = M_{SW}(t - dt) + (F_{MixDWSW} + F_{Riv} + F_{Prec} + F_{DiffDWSW} + F_{InSW} - F_{OutSW} - F_{MixSWDW} - F_{Eva}) \times dt$ [kg]

Inflows:
$F_{MixDWSW} = M_{DW} \times R_{MixSWDW} \times V_{SWDW}$ [kg /month]
$F_{riv} = Q_{riv} \times C_{riv}$ [kg /month]
$F_{Prec} = Q_{prec} \times C_{prec}$ [kg /month]
$F_{DiffDWSW}$ = if $M_{DW} \times Diff_{SWDW} \times DiffC < 0$ then 0 else $M_{DW} \times Diff_{SWDW} \times DiffC$ [kg /month]
$F_{InSW} = Q_{inSW} \times C_{SWBP} + Q_{STP}$ [kg /month]

Outflows:
$F_{OutSW} = Q_{outSW} \times C_{SW}$ [kg /month]
$F_{MixSWDW} = M_{SW} \times R_{MixSWDW}$ [kg /month]
$F_{Eva} = Q_{eva} \times C_{eva}$ [kg /month]

Equations, rates and constants

$ADA = 1268 \times 10^{\wedge 6}$ [m^2]
$Q_{riv,annual} = 1 \times 491.6 \times 10^{\wedge 6} - Q_{STP}$ [m^3/year]
$A = 239 \times 10^{\wedge 6}$ [m^2]
$A_{wb} = 46 \times 10^{\wedge 6}$ (area beneath the wave base) [m^2]
$AF = (500000)/(Q_{prec,annual} \times (Lat \times ADA)^{\wedge 0.25})$
$C_{eva} = 0$ [kg/m^3]
$C_{prec} = 0$ [kg/m^3]
$C_{riv} = 0$ [kg/m^3]

$DiffC = 0.5\times0.01/12$
$DC_{SWDW} = 0.3$ (ratio of inflow from BP)
$Diff_{SWDW}$ = if $C_{SW} > C_{DW}$ then 0 else $(C_{DW}-C_{SW})$ [kg/m^3]
$D_{max} = 52$ [m]
D_{wb} = Wave_base
ET= $(A-A_{Dwb})/A$ (Area of ET bottoms) [m^2]
$Ex = (100\times At\times10^{\wedge(-6)})/(A\times10^{\wedge(-6)})$ [%]
$Q_{STP} = 35\times10^{\wedge6}$ [m^3/year]
Lat = 59
D_{mean}= 12.3 [m]
$R_{MixSWDW} = 1\times$(if $C_{DW}>C_{SW}$ then Mix_rate_default$\times(1/(1+C_{DW}-C_{SW}))^{\wedge \text{Mix_rate_exp}}$ else Mix_rate_default) [1/month]
$Mix_{SWDW}= Mix_{SWDW}/C_{SW}$
Mix_rate_const = 1 [1/month]
Mix_rate_default= $1\times$Stra$\times A_{ET}/12$ [1/month]
Mix_rate_exp = 2
$Q_{riv} = (Q_{riv,annual}/12)\times Y_Q$
$Prec_{,annual}$= 650 [mm/year]
$Q_{eva} = 0.9\times Q_{prec}$ [m^3/month]
$Q_{inDW} = Q_{intoHI}\times(1-DC_{SWDW})$ [m^3/month]
Qin_from_morf_HI = $365\times(V_{SW})$/TSW_days_H_from_morfI [m^3/month]
$Q_{inSW} = DC_{SWDW}\times_{QintoHI}$ [m^3/month]
$Q_{intoHI} = 1800\times10^{\wedge6}$ [m^3/month]
$Q_{mixDWSW} = Mix_{DWSW}/C_{DW}$ [m^3/month]
$Q_{outDW}= (Q_{inSW}+Q_{inDW}+ Q_{riv} +Q_{prec}+ Q_{STP}/12)-(Q_{outSW}+Q_{eva})$ [m^3/month]
$Q_{outSW} = Q_{in\_SW}+Q_{prec}+ Q_{riv} -Q_{eva}$ [m^3/month]
$Q_{prec} = A\times Q_{prec,annual} \times0.001/12$ [m^3/month]
$C_{DW} = M_{DW}/V_{DW}$ [kg/m^3]
$C_{SW}= M_{SW}/V_{SW}$ [kg/m^3]
At= 45310 [m^2]
Strat = if $ABS(T_{SW}-T_{DW}) < 4$ then 1+Mix_rate_const/(1/Mix_rate_const+$ABS(T_{SW}-T_{DW})$) else $1/ABS(T_{SW}-T_{DW})$
T_{DW}months = $V_{DW}/(Q_{inDW}+Q_{mixDWSW})$ [months]
Tmonths = $V/(Q_{intoHI}+Q_{prec}+ Q_{riv})$ [months]
TsalDWyr = $M_{DW}/(F_{inDW}+F_{MixSWDW})$ [year]
Tsalyr = $(M_{DW}+M_{SW})/(F_{inDW} +F_{inSW}+ F_{prec} + F_{riv})$ [year]
TsalSWyr = $M_{SW}/(F_{DiffDWSW}+F_{inSW}+F_{MixDWSW} + F_{prec} + F_{riv})$ [year]
TSWmonths = $V_{SW}/(Q_{mixDWSW}+Q_{prec}+ Q_{riv} +Q_{inSW})$ [months]
TSW_days_H_from_morfI = $(EXP(3.49-4.33\times Ex^{\wedge0.5}))$ [days]
u_section_area_cms = $100\times(Q_{intoHi})/(0.5\times At\times60\times60\times24\times30)$ [cm/s]
$V_{DW} = 236\times10^{\wedge6}$ [m^3]
$V = A\times D_{mean}$ [m^3]
$V_{SW} = (V-V_{DW})$ [m^3]
$V_{SWDW} = V_{SW}/V_{DW}$ [m^3]
$WB = (45.7\times(A\times10^{\wedge(-6)})^{\wedge0.5}/(21.4+(A\times10^{\wedge(-6)})^{\wedge0.5}))$ [m]
$Y_Q = 1+0.526\times((Lat-35)^{\wedge2.18}/35^{\wedge2.18}\times$Seas_norm_Latmax$+(1-(Lat-35)^{\wedge2.18}/35^{\wedge}2.18)\times$Seas_norm_Latmin$)+0.265\times((Q_{riv,annual}/(60\times60\times24\times365))^{\wedge0.22}/5000^{\wedge0.22}\times$Seas_norm_Qmax$+(1-Q_{riv,annual}/(60\times60\times24\times365))^{\wedge0.22}/5000^{\wedge0.22})\times$Seas_norm_Qmin)
Seas_norm_Latmax = GRAPH(MOD(time. 12))

(1.00. -1.00). (2.00. -1.00). (3.00. -1.00). (4.00. -1.00). (5.00. 2.17). (6.00. 2.51). (7.00. 0.63). (8.00. 0.24). (9.00. 0.05). (10.0. -0.03). (11.0. -0.66). (12.0. -0.92)
Seas_norm_Latmin = GRAPH(MOD(time. 12))
(1.00. 1.04). (2.00. 1.37). (3.00. 0.56). (4.00. 0.38). (5.00. -0.29). (6.00. -0.23). (7.00. -0.62). (8.00. -0.71). (9.00. -0.79). (10.0. -0.74). (11.0. -0.28). (12.0. 0.32)
Seas_norm_Qmax = GRAPH(MOD(time. 12))
(1.00. -0.71). (2.00. -0.48). (3.00. -0.17). (4.00. -0.17). (5.00. 0.62). (6.00. 1.74). (7.00. 0.52). (8.00. 0.09). (9.00. -0.16). (10.0. -0.2). (11.0. -0.63). (12.0. -0.44)
Seas_norm_Qmin = GRAPH(MOD(time. 12))
(1.0. 0.58). (2.00. 0.81). (3.00. 0.84). (4.00. 1.58). (5.00. -0.1). (6.00. -1.00). (7.00. -1.00). (8.00. -1.00). (9.00. -0.82). (10.0. -0.56). (11.0. 0.11). (12.0. 0.54)

A2. Tables

Table A1A. Flow and nutrient load to Himmerfjärden.

	Flöde[mcm/year]				TN[tonnes/year]				TP[tonnes/year]			
Year	A+B	Treatment plant	Trosa	Mälaren	A+B	Treatment plant	Trosa	Mälaren	A+B	Treatment plant	Trosa	Mälaren
1977	264	25	209	219	377	550	150	167	22	9	8	5
1978	188	23	137	135	270	504	118	108	15	10	6	2
1979	178	24	124	140	336	531	101	96	18	13	5	3
1980	199	25	115	135	358	585	136	77	26	6	7	3
1981	217	27	139	128	271	667	169	95	26	9	9	4
1982	183	26	130	161	224	747	147	125	10	7	8	4
1983	127	25	89	121	161	613	116	82	8	9	6	3
1984	197	29	106	547	265	718	128	409	16	31	9	15
1985	193	41	155	267	247	886	139	200	14	14	7	8
1986	192	43	138	234	258	898	142	190	13	18	7	7
1987	186	46	127	138		854	123	86	14	14	7	4
1988	170	49	131	136	238	848	160	98	14	18	8	4
1989	95	43	79	108	138	777	102	89	5	16	5	7
1990	206	46	117	183	358	797	155	120	17	19	9	9
1991	164	41	116	137	243	678	146	82	17	12	8	5
1992	179	38	84	129	292	531	99	74	12	13	5	5
1993						506			15	13	7	5
1994						607				10		
1995			123			630				11		
1996						744				10		
1997						449		92		10		6
1998		34				178				18		
1999		34				143				17		
2000		34				179				17		
2001		34				374				19		
2002		35				333				20		
2003		35				158				20		
2004		36				210				20		
2005		35				321				20		
2006		35				290				20		

Table A1B. Statistics for empirical values of temperature in Himmerfjärden.

Temp [°C]	H2-H6	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SW	**Mean**	1.168	0.772	1.086	3.247	8.379	13.186	16.444	17.815	14.915	10.230	7.414	4.374
	Median	0.974	0.654	0.929	3.084	8.615	13.265	16.505	17.811	14.610	10.848	7.468	3.896
	Area weighted median	1.255	0.700	1.084	2.955	8.036	12.550	16.056	17.985	14.548	10.781	7.545	4.337
	SD	0.950	0.502	0.673	1.454	2.602	2.469	2.367	2.967	2.647	1.776	1.508	1.752
	CV_{M50}	0.975	0.768	0.724	0.471	0.302	0.186	0.143	0.167	0.181	0.164	0.202	0.450
DW	**Mean**	1.759	1.008	0.920	1.804	3.567	5.578	7.189	7.907	8.084	8.201	7.292	4.443
	Median	1.106	0.947	0.893	1.793	3.684	5.707	7.353	7.663	8.033	8.000	7.182	4.076
	Area weighted median	2.144	1.265	1.221	2.323	4.000	5.890	7.506	8.293	7.950	8.061	7.126	4.338
	SD	1.621	0.501	0.502	0.829	1.156	1.414	1.467	1.600	1.473	1.304	1.264	1.602
	CV_{M50}	1.465	0.529	0.562	0.462	0.314	0.248	0.199	0.209	0.183	0.163	0.176	0.393

A3. Coastal classification tables from Lindgren and Håkanson (2007)

Table A3A. Classification criteria for openness (exposure) of coastal areas.

Ex	Openness	Typical systems
0-0.002	Enclosed, very enclosed systems	Most coastal lagoons
0.002-1.3	Semi-enclosed systems	Bays, fjords, archipelago
> 1.3	Open systems	Open coasts (cliff, sand, rock, man-made, etc.)

Table A3B. Morphometric classification for aquatic systems based on the form factor, Vd.

Form of lake or coastal area	Class name	Vd
Very convex	VCx	0.05-0.33
Convex	Cx	0.33-0.67
Slightly convex	SCx	0.67-1.00
Linear	L	1.00-1.33
Concave	C	1.33-2.00

Table A3C. Classes for the dynamic ratio.

Class	DR	Description
1 Very deep	< 0.064	Areas dominated by slope processes and erosion and transport processes for fine particle
2 Deep	0.064-0.25	Areas influenced by slope

		processes were erosion, transport and accumulations for fine particles occur
3 Intermediate	0.25-4.1	Areas more influenced by wind and wave processes were erosion, transport and accumulations for fine particles occur
4 Shallow	> 4.1	Area dominated by wind and wave processes and erosion and transport processes for fine particles

Table A3D. Surface area classification.

Surface area [km^2]	**Class name**
> 10000	Very large
1000-10000	Large
100-1000	Intermediate
10-100	Small
<10	Very small