

This file contains:

- 1. A point-by-point response to the referees, including a list of relevant changes**
- 2. A marked up manuscript version, thus, the manuscript including trackchanges.**

Response o referees

2016-06-30

First we would like to thank the two reviewers for their helpful and thoughtful comments. In our response we repeat the comments/questions followed by our response/changes. We refer to page + line numbers in the revised manuscript in which “track changes” are included, if suited.

RC-Referee comment

AR-Author reply

Response to referee #1

RC: My main issue is the lack of discussion of the results with respect to the wider literature. This is probably due to the choice of format that merge the Results with Discussion. A comparison of retention capacity with previous studies is provided (e.g. Figure 14) but the authors should provide a deeper discussion of their results and their implications. This would benefit their study and the audience of Biogeosciences.

AR: We have deepened the discussion of the results and their implications in the revised manuscript. We have also, with a wider perspective, again searched the scientific literature for similar model exercises to which our results have been compared.

RC: Nutrient load decrease during the study which lead to uncertainties in the interpretation of the results. Could the author calculate retention for specific periods (in addition to the 1990-2012 period), i.e. in the earlier and later period of the study, in order to remove the uncertainty about the system not being at steady state? or provide a retention time series for 1990-2012, as in Figure 15? This would also provide information about the change in the system over this period.

AR: Retention time series for 1990-2012 are now included. Since we think that there are enough numbers of figures, which is also commented by referee #2 we have compromised and re-made figure nr 10. The new figure shows the total external nutrient load as well as the nutrient retention in the entire Stockholm Archipelago.

The results which are not already discussed will be included in the discussion to improve the interpretation, P14 L1-3.

RC: Specific comments

RC: P5L4: missing words, "which is why"?

AR: This section is re-organized and sentence above is removed.

RC: P8L21: (2009; 2011)

AR: This is changed. P6L10

RC: P9L3-5: Not clear, does that mean that for each observation you calculate the most limiting nutrient (N or P) and infer the non limiting nutrient with respect to Redfield?

AR: This section is now rewritten, see P8L22-29 in the revised manuscript. The external inorganic nutrient loads are added as DIN and DIP from the forcing as they are in the model. The bioavailability and the composition (dissolved or particulate) of the organic

nitrogen and phosphorus loading from land are generally not known. In the present model configuration the part of organic nutrient loads following the Redfield ratio are assumed to be bioavailable. The nutrient supply that fulfils the Redfield ratio is therefore added to the detritus pool in the model while the remaining fractions of nutrient loads are treated as conservative tracers in the model.

RC: P9 L21: why is there a plus/minus symbol in front of the square root?

AR: We have removed the plus/minus symbol, it is not needed in Eq. 2 in the revised manuscript, P9L13

RC: P12L3-5: Is this first sentence needed?

AR: The sentence is removed in the revised manuscript.

RC: P12L6: suggestion: "good agreement" or "agrees well" rather than "good results"

AR: The suggestion is accepted and the sentence is re-written. See P13L3-4 in the revised manuscript.

RC: P12L21: Please rephrase for clarity (and remove "described")

AR: The paragraph is now re-written, see P13L17-21 in the revised manuscript. What we intend to describe is that the local conditions of stations where data are observed are very important as they can vary due to the positions of the stations. When analyzing model results and interpreting validation results it is important to be aware that the model integrates over a large area, while observations are sampled only at one position that possibly is not representative for the average conditions.

RC: P13L3-5: Why choosing this station?

AR: This station was chosen because the observation data set is largest at this station. This is now added in the revised manuscript, P13L28-30.

RC: P13L8-10: Unless there is primary production in summer.

AR: We did a check of the observation data during summer and there are no significant over saturation of oxygen due to primary production. A sentence discussing the reason is now added since there were only measurements from November (with quite high temperatures) and February. See P14L13-17 in the revised manuscript.

RC: P13L22: "surface nutrients".

AR: The word "surface" is added. See P14L30 in the revised manuscript.

RC: P13L25-29: Why not move this higher up, before you describe the first station. Also, change "parameters" to "state variables" (or else), also L31.

AR: This paragraph is now moved upwards in the revised manuscript and "parameters" is changed to "state variables" in all places, P14L1-6.

RC: P15L4-5: This is already mentioned above.

AR: This is now removed in the revised manuscript.

RC: P15L5-20: Discuss more the implications of the different estimates.

AR: An extended discussion is now included in the revised manuscript, P16.

RC: P15L31: suggestion: "during the simulated period" or "over the 1990-2012 period".

AR: The word "simulated" is added. See P17L11 in the revised manuscript.

RC: P15L31-P16L2. Could you be more specific about the importance of the import of nutrients?

AR: This paragraph is now changed in the revised manuscript, P17L11-16.

RC: Also this statement sounds strange, you say that the effect of nutrient transport has not been studied and will be studied in the future. Then what is this mentioned at all?

AR: We agree and have removed this sentence.

RC: P17L2-4: please rephrase for clarity.

AR: This sentence is not needed and a description on what residence time and how it was calculated is moved to the method section 2.4. See P12L4-7 in the revised manuscript.

RC: P18L7: "by" instead of "with"

AR: Done. This section, describing the reduction scenario was also moved to section 2.4.1. See P12L9-26 in the revised manuscript.

RC: P18L29: Replace with "This implies that under the 2010 conditions, all the total P load..."

AR: Done. See P20L29-30 in the revised manuscript.

RC: P20L5: Suggestion: change to "overall, model results agree with observations"

AR: Done. See P23L4-5 in the revised manuscript.

RC: P20L15: Suggestion: start sentence with However.

AR: The sentence starts now with "Thus". See P23L15 in the revised manuscript.

RC: P20L20: Space before N.

AR: Done.

RC: P20L27-28: Doesn't the retention capacity increases for N on short time scales?

AR: Yes, but not for P. This is now clarified in the revised manuscript, P23L27-28.

Response to referee #2

RC: The model study of Almroth-Rosell et al. presents a sound model approach to improve our understanding of the nutrient retention in the archipelago of the city of Stockholm. Through a combination of different models the authors estimate the retention capacities of nitrogen and phosphorous in different basins from nutrient sources to the Baltic Sea. The models which are combined here and the validation of the model is logical and well done, the results may be relevant for managers. The critical aspect here is the lack of a significant increase of our mechanistic understanding of processes leading to retention or the factors impacting retention. Moreover, the processes behind the retention are not clearly described and thus it remains difficult to fully understand how the retention works in this approach. The processes described are burial and for nitrogen also the process of microbial denitrification in sediments (probably also water column, when oxygen goes to depletion). Clarification of these aspects is required and some detailed comments for improvement are given below.

AC: We thank the referee for the detailed and positive review as well as for the suggested improvements. In the revised manuscript we describe and discuss the different retention

processes in more detail and how they are affected by e.g. oxygen depletion/reoxygenation.

RC: The introduction needs more clarity and focus. The text jumps from general statements to specific Baltic Sea aspects e.g. hypoxia in the Gulf of Mexico is mentioned and next loads of nutrients to the Baltic Sea (p3 lines 8-14) or global eutrophication and loads to the Baltic Sea (p3 lines 18-22).

AC: The aim of the introduction is to put the retention question and the eutrophication problem in a global perspective. We have reorganized the introduction to first introduce the global perspective on eutrophication and coastal nutrient retention with both Gulf of Mexico and the Baltic Sea as examples in some cases. Thereafter we describe the Baltic Sea and the model study in the Stockholm archipelago that is used as an example for more detailed discussions about the processes affecting nutrient retention. Specific information about the Stockholm Archipelago is moved to the Method chapter (chapter 2), in the study site section (section 2.1).

RC: I also did not understand why this example on retention (of nitrogen?) by plants is chosen (p4)?

AC: To be able to calculate the retention in an area the definition of the word need to be discussed. Plants are assimilating nutrients, leading to a removal of the dissolved nutrients from the water mass, which however is not permanent. The transformation of dissolved nutrients into organic material might lead to another exposure of the nutrients for other biogeochemical processes e.g. higher degree of burial. This is clarified in the revised manuscript, P3L25-27, and also more extensively discussed in section 3.2.2.

RC: Why is the expression river outlet preferred over estuary (p4 line 18)?

AC: It was not our intention to choose one expression over another. We have changed to “estuary” in the revised manuscript, P4L11.

RC: The description of the archipelago (p4 lines 23-27) is very brief and general. The more detailed description follows later. This should be combined or at least the reader should be referred to the later text.

AC: We have re-organized the text and moved unnecessary details about the study site from the introduction to the methods in the revised manuscript. In the introduction we now refer to the study site paragraph (section 2.1) for more details about the Stockholm Archipelago.

RC: Further below the reduction of sewage is mentioned however again without details (line 31, reduction of how much N?).

AC: We have included a more extensive description in the revised manuscript and also reorganized the text and moved unnecessary details about the study site from the introduction to the methods (section 2.1).

RC: The classification is mentioned (unsatisfactory eutrophic) but what is that really?

AC: We agree that a clarification of the expression was needed. This section is now extended to include short information about the classification in the revised manuscript, P6L1-7.

RC: What are high nutrient loads (p5 line 4)?

AC: After a reorganization of the introduction parts of the text is moved to the study site section. This sentence is not needed anymore and was therefore removed.

RC: On p.6 (lines 16-19) continue with somewhat vague site descriptions. Please add data on nutrient release over time and what the improvement of the treatment really means in concentration and load changes. Here again a combination of the text in the introduction with the study site description is would be better.

AC: We have included a more extensive description on the nutrient reductions in the revised manuscript, section 2.1.

RC: What is the overall intention of this study – is it a retention estimate for managers, or are processes considered and their regulation by natural settings and anthropogenic impact? These are two different foci which impact the model set-up and the description of results. To me it seems that the authors mix both aspects with the results that neither aspect receives sufficient attention.

AC: The aim is to investigate the filter efficiency of the coastal zone along the land to sea continuum, which is described in the aim-paragraph in the end of the introduction. The aim is also to discuss the processes affecting the nutrient retention in the coastal areas as well as to discuss the concept of retention. We have rephrased and rewrote necessary parts to prevent the focus from being lost in the revised manuscript.

RC: The model description is well done and clear in most cases. Minor requests for clarification are: The conversion of hydrogen sulfide into negative oxygen concentrations is sometimes used but seems not correct since it does not include the conversion of sulfate into hydrogen sulfide. What is the justification for this?

AC: We agree that this needed some clarification, which is done in the revised manuscript, P7L17-19. The conversion of sulfate into hydrogen sulfide is included in the “negative oxygen”. Sulfate is assumed to be reduced according to the model formulations but instead of stating the amount of hydrogen sulphide produced, the term "negative oxygen" is used, corresponding to the amount of oxygen needed to oxidise the hydrogen sulphide. The cited reference in the manuscript is changed to: Fonselius, S. H.: Hydrography of the Baltic deep basins III, 1969.

RC: How is the amount of N and P stored in sediments calculated (p 8 line 1)?

AC: This is better described in the revised manuscript, P7L19-22. The sediment layer in the present model is described by one vertically integrated bulk sediment parameterization (level 3 in Soetaert et al, 2000). The organic material sinking to the sediment is divided into one nitrogen pool and one phosphorus pool described by the state variables NBT and PBT, respectively. The sediment module includes burial and aggregated process descriptions for oxygen and temperature dependent nutrient regeneration and denitrification.

Reference: Soetaert, K., Middelburg, J.J., Herman, P.M.J., Buis, K., 2000. On the coupling of benthic and pelagic biogeochemical models. *Earth-Science Reviews* 51, 173–201.

RC: How is nitrification and denitrification modelled (line 8)?

AC: Nitrification and denitrification are oxygen dependent processes that occur both in the pelagic and benthic parts of the model. The processes are described in detail in the paper by Eilola et al. 2009, (referred to in the manuscript). We agree that these processes may need a more extensive description since especially the denitrification is an important retention process. But we will in this paper not repeat details about processes descriptions. Instead we focus on the relative impact of different processes on the nutrient retention and which is now more discussed in section 3.2.2.

- RC:** Better focus the text lines 10-21 on the critical variables for this study, burial, remineralisation – assimilation and nitrogen fixation are less important.
- AC:** This is a brief general description how the model works to help the reader, if not used to models, to understand that these processes are included. The paragraph does not aim to describe the processes in details.
- RC:** Is the atmospheric deposition indeed significant and deserves this much attention throughout the text (see line 24)?
- AC:** We believe that the reader should be informed about the forcing that drives the model. However, in the revised manuscript we have changed the order of the different forcing variables so that the atmospheric deposition of nutrients is the terminative variable in the sentence, P8L13-15. Understanding the relative importance of the different drivers we consider as important as well. Atmospheric deposition is one even though it is not a dominant source of nutrients in the inner archipelago. However, in the outer archipelago, which has a large area, the atmospheric input of nutrients actually is the dominant external source.
- RC:** Rivers hardly every supply nutrients with a N:P ratio of 16, usually the ratio is much higher (see p9 line 3-5). May be I misunderstand the calculation of the loads, but this needs conversion to true input ratios and concentration.
- AC:** Thank you for pointing out this shortcoming of the description. The external inorganic nutrient loads are added as DIN and DIP from the forcing as they are in the model. This is better described in the revised manuscript, P8L22-29. The bioavailability and the composition (dissolved or particulate) of the organic nitrogen and phosphorus loading from land are generally not known. In the present model configuration the part of organic nutrient loads following the Redfield ratio are assumed to be bioavailable. The nutrient supply that fulfils the Redfield ratio is therefore added to the detritus pool in the model while the remaining fractions of nutrient loads are treated as conservative tracers in the model.
- RC:** The retention calculation (p11) is crucial for the manuscript. Please improve the description and explain R tot better, so that equation 4 becomes clearer.
- AC:** We agree that this is a very important paragraph for the understanding of the study, and have improved the description in the revised manuscript, section 2.4. Also, a supplement 2 is created where different retention calculations are defined.
- RC:** I could not understand the sentence p.12 line 22-23 about the validation of results and how representative stations are.
- AC:** The paragraph is now re-written; see P13L17-21 in the revised manuscript. What we intend to describe is that the local conditions of stations where data are observed are very important as they can vary due to the positions of the stations. When analyzing model results and interpreting validation results it is important to be aware that the model integrates over a large area, while observations are sampled only at one position that possibly is not representative for the average conditions.
- RC:** Where are the cost functions from which are mentioned (p.13 line 25)?
- AC:** Thank you for the remark. We have included cross-reference to Eq. 2 for the correlation coefficient and to Eq. 3 for the cost function value. The paragraph is also moved upwards in the text in the revised manuscript, P14L1-6, which also led to a re-organization of figures 6-8.

RC: In case oxygen is not very well simulated by the model, then denitrification estimates cannot properly work in the model. How well is oxygen represented and how does that impact the results of the denitrification estimates?

AC: Thank you for the comment. The capacity of the model to simulate oxygen is acceptable at all stations except for basin “Sandöfjärden” where the vertical summer profile shows not good results. This can be seen in figure 6 (circles) in the revised manuscript. However, the impact of changed oxygen conditions is discussed more in detail in the section 3.2.2.

RC: In this context the retention time of the water also plays a crucial role since longer retention times should lead to decreasing oxygen concentrations in the water. It would be good to dedicate a paragraph to the linkage of these variables and discuss the model results in relation to findings at the representative stations.

AC: Thank you for the comment! We have included a discussion of this in the revised manuscript, section 3.2.2. The largest sensitivity of denitrification rates to changes in oxygen concentrations occur at concentrations below 4-5 ml/l in the model. The maximum denitrification rate is obtained at an oxygen concentration of about 1 ml/l while denitrification halts under anoxic conditions. We also made a model experiment in which we investigated in which areas of the archipelago the model denitrification may be most sensitive to changes of the oxygen concentrations.

RC: In the present text the retention is qualitatively mentioned but quantifications are lacking (see paragraph 3.2.2).

AC: Quantification of the modelled retention are described and discussed in section 3.2.1. Quantifications of retention in other studies are shown in fig. 14 in section 3.2.2. In the revised manuscript we discuss in more detail the different types of coastal areas and their retention capacities. We have also added quantification on how water depth and residence time and mean bottom water oxygen concentrations affect the modelled nutrient retention.

RC: The paragraph on reduction scenarios is a pure description of model results but lacks aspects of a discussion – this would therefore need drastic shortening.

AC: The description of the setup of scenarios is moved to the methods chapter (section 2.4.2) in the revised manuscript. The discussion is in the revised manuscript more focused and more related also to the discussions about processes affecting retention.

RC: It would be nice to significantly reduce number of figures.

AC: Yes, we are aware that the number of figures is high. However, referee nr 1 actually wanted additional one figure. We compromised and re-made figure nr 10. The new figure shows the total external nutrient load in the entire Stockholm archipelago and in addition the nutrient retention in the entire Stockholm Archipelago. We also removed fig. nr 13 in the original manuscript, since the results are shown also in fig. 14. The text and the figure numbers are adjusted to fit the changes in the revised manuscript.

RC: Overall - as already mentioned above – the study would profit by a comparison of own results with other such model exercises.

AC: We have searched the scientific literature and have so far only found a few model studies for the coastal zone, there are however many model studies on lakes and catchment areas. There are a few empirical retention calculations which we discuss and e.g. Nielsen et al

(2001) performed a retention study using a 2-layer hydrodynamic channel model in Randers Fjord, Denmark.

RC: Although I understand why the paper was submitted to Biogeosciences it may be better placed in a model journal. As the paper stands now it does not explain the processes of nutrient retention or relate them to environmental processes (except the nutrient reduction scenario).

AC: In the revised manuscript we have overall improved the discussion of the nutrient retention processes and the impact from e.g. oxygen changes. We also think that the study has its main interests in the coastal zone as a filter, and the retention processes and not only as a modelling paper, even though we use a model as a tool.

For instance, the importance of permanent relative to temporal retention needs a clarification of the processes involved that can only be quantified and explained from dynamic model results including the pools of nutrients both in the water and in the sediment as in the present study. Also the impact from changing environmental conditions such as anticipated nutrient load reductions may best be explained from model experiments. These results are already quite substantial but we embrace the criticism from the reviewer and have put more emphasis on trying to explain the environmental factors that impact on the processes causing nutrient retention. We have also tried to better discuss how our findings relate to other studies found in the literature.

Additional changes:

We have also noticed that we in the figures used different units, which has been changed in the revised manuscript.

A definition of the retention parameters and way of calculating them are included as a supplement and the text is changed according to these definitions where suited.

Modelling nutrient retention in the coastal zone of an eutrophic sea - a model study

Elin Almroth-Rosell^{*1}, Moa Edman¹, Kari Eilola¹, H.E. Markus Meier^{2,1}, Jörgen Sahlberg¹

¹Swedish Meteorological and Hydrological Institute, Norrköping, Sweden

²Leibniz Institute for Baltic Sea Research Warnemünde, Rostock, Germany

*Corresponding author:

Elin Almroth-Rosell

Swedish Meteorological and Hydrological Institute

Sven Källfelts gata 15, SE-426 71 Västra Frölunda, Sweden.

Tel: +46(0)31 7518969. E-mail: elin.almroth.rosell@smhi.se

Keywords: Nutrient retention, phosphate, nitrogen, eutrophication, biogeochemistry, coastal zone, Baltic Sea

Abstract

The Swedish Coastal zone Model (SCM) was used at a test site, the Stockholm Archipelago located in the northern part of the central Baltic Sea, to study the capacity of the coastal filter on nitrogen (N) and phosphorus (P). The SCM system is a NPDZ-type model coupled to a horizontally integrated, physical model in particular suitable for estuaries. In this study the Stockholm Archipelago consisting of 86 sub-basins was divided into three sub-areas: the inner, the intermediate and the outer archipelago. An evaluation of model results with observations showed that the modelled freshwater supply and the nutrient, salinity and temperature dynamics in the SCM model are of good quality. Further, the analysis showed that the Stockholm Archipelago works as a filter for nutrients that enter the coastal zone from land, but the filter efficiency is not effective enough to take care of all the nutrients. However, at least 65 % and 72 % of the P and N, respectively, are retained. Highest total amounts of P and N are retained in the outer archipelago where the surface area is largest. The area specific

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1 retention of P and N, however, is highest in the smaller inner archipelago and decreases
2 towards the open sea. A major part of the retention is permanent, which for P means burial.
3 For N almost 92 % of the permanent retention is represented by benthic denitrification, less
4 than 8 % by burial, while pelagic denitrification is below 1 %. A reduction scenario of the
5 land loads of N and P showed that the filter efficiencies of N and P increase and the export of
6 N from the archipelago decreases. About 15 years after the reduction the export of P changes
7 into an import of P from the open sea to the archipelago.

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Borttaget: retention capacities

1 Introduction

The worldwide increase of coastal eutrophication and anoxia has spread exponentially since the 1960s. Coastal oxygen depletion is associated with dense population areas and large river loads of nutrients (Diaz and Rosenberg, 2008). The use of industrially produced fertilizer started in the late 1940s and has since then been contributing to the anthropogenic fertilization of the global marine system (Galloway et al., 2008). The river load of nutrients originating from agriculture activities has been shown to be controlled by the size of the river flow, e.g. the flow from the Mississippi River has a large impact on the oxygen conditions in the northern Gulf of Mexico, which suffers from severe hypoxia with “dead zones” as a result (Rabalais et al., 2002).

With ambition to diminish eutrophication there has been a lot of efforts around the world to reduce the land load of nutrients to sea, but the expected results of a healthier environment have not been accomplished in all places (Kemp et al., 2009). The responses of eutrophication and the extent of hypoxic area for changes in nutrient loads are different in different types of systems. Also changes in climatic and hydrodynamic conditions might lead to a non-linear recovery (Kemp et al., 2009). Nutrients transported from land to sea first enter the coastal zones and are then further transported towards the open sea. However, not all of the supplied nutrients reach the open sea as the coastal zone acts as a filter (McGlathery et al., 2007). Nutrients are involved in coastal chemical, physical and/or biological processes (e.g. denitrification, burial, algae and plant assimilation) and are, thus, retained in coastal areas (Duarte and Cebrián, 1996; Voss et al., 2005). The retention and filter efficiency of the coastal zone might be of large importance for the water quality in open waters.

Retention capacity is, however, not well defined. Johnston (1991) discussed that retention processes are of different magnitudes and irreversibility, e.g. plant uptake and litter decomposition provide short- to long-term retention of nutrients. The importance of temporary retention depends on the release rates, translocations, and the longevity of plants, which affects the permanent retention. Billen et al. (2011) and Nixon et al. (1996) defined retention as the net effect of temporary and permanent removal from the water phase through different biogeochemical processes (e.g. biological uptake, burial and denitrification). The net effect of nutrients on the water quality of an area can be studied by the simple method of subtracting the output of nutrients from the input (Johnston, 1991). This simple method of calculating the retention capacity of nitrogen (N) and phosphorus (P) has been used in a

Borttaget: The enhanced land load of nutrients to the Baltic Sea (Fig. 1) located in northern Europe, during the period 1950-1980 (Gustafsson et al., 2012) has led to eutrophication and consequently increased frequency and intensity of cyanobacterial blooms, expanding bottom hypoxia and dead bottom zones (e.g. Bergström et al., 2001; Conley et al., 2009; Diaz and Rosenberg, 2008; Vahtera et al., 2007). Actually, the largest anthropogenically induced hypoxic area in the world is found in the Baltic Sea (Carstensen et al., 2014), where it varied between 70000 and 80000 km² during year 2010-2014 (Hansson and Andersson, 2014).

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1 number of studies (e.g. Eilola et al., 2014; Hayn et al., 2014; Karlsson et al., 2010; Nixon et
 2 al., 1996; Sanders et al., 1997) for different areas of the world. The retention capacity has
 3 been discussed to be related to the residence time and depth in different water systems (Balls,
 4 1994; Hayn et al., 2014; Nixon et al., 1996). Hence, the longer a water parcel and its nutrient
 5 content stays within a system, the larger the containing nutrients are affected by the internal
 6 transformation and retention processes. Filter efficiency is in the present study referred to as
 7 the capacity of the studied area to retain the local nutrient loads from land and atmosphere
 8 (see Section 2.4). There are not enough estimates of nutrient retention in different coastal
 9 zones around the world to evaluate and understand its effect on the environmental status of
 10 coastal seas. Quantification of the filter efficiencies in different coastal ecosystems as
 11 estuaries, archipelagos, lagoons and embayments would increase the understanding and the
 12 knowledge necessary for managing the coastal zone. Numerical models have been used to a
 13 larger extent for studies in lakes and freshwater catchment areas (e.g. Ahlgren et al., 1988;
 14 Hejzlar et al., 2009) than for retention and filter efficiency studies in coastal areas where only
 15 a few studies seem to exist in the literature (see discussions below).

16 The Baltic Sea (Fig. 1), located in northern Europe, is an example where the enhanced land
 17 load of nutrients to the sea (Gustafsson et al., 2012) has led to eutrophication and
 18 consequently increased frequency and intensity of cyanobacterial blooms, expanding bottom
 19 hypoxia and dead bottom zones (e.g. Bergström et al., 2001; Conley et al., 2009; Diaz and
 20 Rosenberg, 2008; Vahtera et al., 2007). Actually, the largest anthropogenically induced
 21 hypoxic area in the world is found in the Baltic Sea (Carstensen et al., 2014), where it varied
 22 between 70000 and 80000 km² during year 2010-2014 (Hansson and Andersson, 2014). In the
 23 Baltic Sea, most of the coastal zones and the open sea still suffer from eutrophication in spite
 24 of reduced nutrient loads since the 1990s (HELCOM, 2010).

25 The aim with this study is to quantify the filter efficiency in the eutrophic Stockholm
 26 Archipelago (see section 2.1) of N and P and to discuss the relative importance of different
 27 physical and/or biological processes using the Swedish Coastal zone Model (SCM). In
 28 addition, changes in the filter efficiency along the land-sea continuum, from the inner
 29 archipelago, through the intermediate and outer archipelago to the open Baltic Sea, will be
 30 studied in order to evaluate the effect of the size of the archipelago on the filter efficiency,
 31 After a description of the model system (Section 2) and an evaluation of the results of SCM
 32 (Section 3.1), the filter efficiency of the coastal zone is calculated and the effects of a reduced
 33 land load of N and P are analyzed (Section 3.2). Conclusions finalize the study (Section 4).

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Borttaget: The Stockholm Archipelago is the largest archipelago in Sweden and the second largest in the Baltic Sea. Signs of eutrophication in the Stockholm Archipelago have been observed as increased ratio of laminated sediments from the 1930s (Jonsson et al., 2003) and the eutrophication status in the inner Stockholm Archipelago were in the early 1970s classified as highly eutrophic (Lännergren et al., 2009). ¶

An implemented P reduction in the sewage treatment facilities in the 1970s led to some improvements of the marine environment (Brattberg, 1986), but in the 1990s the areas were still eutrophic with poor bottom water oxygen conditions (Jonsson et al., 2003; Rosenberg and Diaz, 1993). The reduction of the N load from the sewage treatment facilities in the mid-1990s led to further improvement of the eutrophication status. In 2008 the bottom oxygen conditions had clearly improved in the deeper parts and only enclosed bays, such as e.g. Stora Värtan, suffered still from anoxia (Karlsson et al., 2010 and references therein). However, the annual monitoring status report of the environmental status of the inner Stockholm Archipelago in 2014 still classified the area as unsatisfactory eutrophic (Lücke, 2015). ¶

The large river Norrström supplies high nutrient loads to the inner part of the archipelago why this area is suitable for retention calculations. C

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1 2 Methods

2 2.1 Study site

3 The brackish archipelago of Stockholm (Fig. 1), located at the east coast of Sweden, is the
4 largest archipelago in Sweden and the second largest in the Baltic Sea. The archipelago is a
5 continuation of the river Norrström with an average discharge of about $160 \text{ m}^3 \text{ s}^{-1}$ from Lake
6 Mälaren (Lindh, 2013). The river outflow carries about 2600 metric tons (t) of N and 120 t of
7 P annually to the coastal basin “Strömmen” in the inner archipelago (Lännergren, 2010). The
8 rocky islands in the archipelago are surrounded by basins of different sizes and depths which
9 are connected by straits. In this study the archipelago has been divided into three areas: the
10 inner, intermediate and outer archipelagos. Several large islands form a natural border
11 between the inner and the intermediate archipelagos and the limited water exchange occurs
12 through five narrow sounds with shallow sills. The outflow from the inner to the intermediate
13 archipelago passes through the sounds in the surface layer, while inflows of more saline water
14 mainly occur at larger depths. The border between the intermediate and the outer archipelagos
15 follows the chain of islands in north-south direction with several connections between the
16 areas (Fig. 1).

17 Fig. 1.

Flyttad (infogning) [1]

18 The largest point sources of nutrients to the inner archipelago originate from waste water
19 treatment facilities of Stockholm, which is situated at the outlet of the Lake Mälaren. Signs of
20 eutrophication in the Stockholm Archipelago have been observed as increased ratio of
21 laminated sediments from the 1930s (Jonsson et al., 2003) and the eutrophication status in the
22 inner Stockholm Archipelago was in the early 1970s classified as highly eutrophic
23 (Lännergren et al., 2009). In the 1970s the sewage treatment facilities in Stockholm started to
24 chemically precipitate P, which reduced their P load from about 600 t yr^{-1} to about 100 t yr^{-1}
25 (Fig. 3 in Lücke, 2014). The reduction led to some improvements of the marine environment
26 (Brattberg, 1986), but in the 1990s the areas were still eutrophic with poor bottom water
27 oxygen conditions (Jonsson et al., 2003; Rosenberg and Diaz, 1993). In the mid-1990s there
28 was a further reduction of the P to about 25 t yr^{-1} and the sewage treatment facilities started to
29 reduce the N as well, from about 3000 t yr^{-1} to 1250 t yr^{-1} (Fig. 3 in Lücke, 2014), which led
30 to further improvement of the eutrophication status. In 2008 the bottom oxygen conditions
31 had clearly improved in the deeper parts and only enclosed bays, such as e.g. Stora Värtan,
32 suffered still from anoxia (Karlsson et al., 2010 and references therein). However, the annual

[monitoring status report of the environmental status of the inner Stockholm Archipelago in 2014 still classified the area as unsatisfactory eutrophic \(Lücke, 2015\) according to the national directives by the Swedish Environmental Protection Agency and the Swedish Agency for Marine and Water Management \(Naturvårdsverket, 2007; HaV, 2013\) based on the EU Water Framework Directive. The area still suffered from reduced water transparency, high concentrations of phytoplankton chlorophyll and areas without any bottom fauna due to low oxygen concentrations.](#)

Borttaget: The chemical and biological treatment removing P was implemented in the early 1970s and was further developed in the 1990s to remove also N. ¶

Flyttad uppåt [1]: Fig. 1.

2.2 Model description

The Swedish Coastal zone Model (SCM) is a multi-basin 1D-model based on the equation solver PROgram for Boundary layers in the Environment (PROBE; Svensson, 1998), coupled to the Swedish Coastal and Ocean Biogeochemical model (SCOBI; Eilola et al., 2009; Marmefelt et al., 1999). The model system was developed to calculate physical and biogeochemical states in Swedish coastal waters. The inner, intermediate and outer Stockholm archipelagoes (Fig. 1) are represented by 16, 44 and 26 sub-basins, respectively (see figure in Supplement 1).

2.2.1 PROBE

The physical model PROBE calculates horizontal velocities, temperature and salinity profiles (Svensson, 1998; Omstedt, 2015). The surface mixing is calculated by a $k-\varepsilon$ turbulence model and the bottom mixing is a parameterization based on the stability in the bottom water. Light transmission, as well as ice formation growth and decay, are also included in the model. The vertical grid resolution is half a meter in the uppermost layers, one metre from 4-70 m, and two metres between 70-100 m. The general differential equation of the PROBE solver is formally written as

$$\frac{\partial \phi}{\partial t} + \frac{\partial}{\partial x_i} u_i \phi = \frac{\partial}{\partial z} \left(\Gamma_\phi \frac{\partial \phi}{\partial z} \right) + S_\phi \quad (1)$$

Here ϕ is the dependent variable, t time, z vertical coordinate, x_i horizontal coordinates, u_i horizontal velocities, Γ_ϕ vertical exchange coefficient, and S_ϕ source and sink terms. Vertical advection (and moving surface) is included accounting for vertical transport in sub-basins due to in and outflows. The sources and sinks determined by the ecosystem model are added to S_ϕ .

1 The water exchange between the sub-basins is controlled by the baroclinic pressure gradients.
2 The net flow through the sounds will be the same as the river discharge from land in order to
3 preserve volume. Inflowing water to a sub-basin is interleaved into its density level without
4 any entrainment, and heavy surface water in one sub-basin may thus reach the bottom level in
5 an adjacent basin. The sea level variations outside the boundary are of minor importance for
6 the SCM results and are therefore not included in the forcing. The water exchange across the
7 boundary between the coastal zone and the open sea is assumed to be in geostrophic balance,
8 since this boundary is open with a width greater than the internal Rossby radius. A time step
9 of 600 seconds was used in the present simulations.

10 2.2.2 Biogeochemical model (SCOBI)

11 The SCOBI model describes the biogeochemistry of marine waters in the Baltic Sea and
12 Kattegat (Eilola et al., 2009). Nine pelagic and two benthic variables (Fig. 2) are described in
13 the SCM-SCOBI model. In the pelagic zone three different phytoplankton groups (diatoms,
14 flagellates and others, and cyanobacteria), one zooplankton group, one pool for detritus and
15 three inorganic nutrients pools (nitrate, ammonium and phosphate) are represented. The
16 model also calculates oxygen and hydrogen sulfide concentrations, of which the latter are
17 represented by “negative oxygen” equivalents ($1 \text{ ml H}_2\text{S l}^{-1} = -2 \text{ ml O}_2 \text{ l}^{-1}$) and includes the
18 conversion of sulfate into hydrogen sulfide (Fonselius, 1969). Thus, the negative oxygen
19 corresponds to the amount of oxygen needed to oxidise the hydrogen sulfide. The sediment in
20 the present model is parameterized by one vertically integrated bulk sediment layer (level 3 in
21 Soetaert et al, 2000). Organic material that sinks to the sediment is divided into one benthic
22 nitrogen pool (NBT) and one benthic phosphorus pool (PBT). SCOBI has been used and
23 validated in several studies, both coupled to the basin scale Baltic Sea model PROBE-Baltic
24 (e.g. Marmefelt et al., 1999) and to the three dimensional Rossby Center Ocean model (RCO;
25 e.g. Meier et al., 2011).

26 In the model the processes of phytoplankton assimilation, mortality and nitrogen fixation,
27 zooplankton grazing, excretion of detritus and dissolved inorganic nitrogen (DIN) and
28 phosphorus (DIP), the oxygen and temperature dependent mineralization of detritus, benthic
29 N and benthic P, nitrification and denitrification are described. Phytoplankton assimilates
30 carbon (C), N and P according to the Redfield molar ratio (C:N:P=106:16:1) and the biomass
31 is represented by chlorophyll (Chl) according to a constant carbon to chlorophyll mass (mg)
32 ratio (C:Chl=50:1). Light attenuation depends on background attenuation due to water and

Borttaget: and Valderrama

Borttaget: 2003

Borttaget: For the benthic layer the amounts of stored N and P are calculated.

1 humic substances and a variable attenuation caused by particulate organic matter
2 (phytoplankton, zooplankton and detritus). All particulate variables sink downward through
3 the water column. Predation is used as a closing term to parameterize interactions with higher
4 trophic levels in the ecosystem and move matter from zooplankton to the detrital and inorganic
5 pools. Resuspension of sediment that is important in the open Baltic Sea (Almroth-Rosell et
6 al., 2011) has not yet been implemented in this SCOBI version, but the sediment releases
7 dissolved inorganic nutrients back to the water mass, with the release of phosphate being
8 redox dependent. Some fractions of benthic N and P are assumed to be buried in the sediment
9 as a permanent sink, and are hence removed from the system. For further details of the
10 SCOBI model the reader is referred to Eilola et al. (2009; 2011).

11 Fig. 2.

12 2.2.3 Forcing

13 The SCM-SCOBI model system is forced by weather, the conditions in the sea outside the
14 archipelago, point sources, discharge of freshwater and nutrients from land and atmospheric
15 deposition of nutrients. The initial values for both the pelagic zone and the sediment are
16 derived from spin-up simulations.

17 There are two types of land derived forcing; discharge of water and nutrients from both rivers
18 and surface run-off from the drainage area given by the S-HYPE model (Lindström et al.,
19 2010) and point sources representing sewage plants and industries. The run-off is added to the
20 surface water of each basin and no reduction of river nutrients due to precipitation at river-
21 mouths is assumed in this model setup. The point sources of nutrient loads are assigned to the
22 depth levels mostly resembling the actual depth of the discharge. The inorganic riverine
23 nutrient loads are added as DIN and DIP to the SCM. The organic nutrients in the land loads
24 are calculated from the difference between total nitrogen (TN) and DIN, and total phosphorus
25 (TP) and DIP, respectively. The bioavailability and the composition (dissolved or particulate)
26 of the organic nitrogen and phosphorus loading from land are generally not known. In the
27 present model configuration the fraction of organic nutrient loads that follows the Redfield
28 ratio are assumed to be bioavailable and will be added to the detritus pool in the model, while
29 the remaining fractions of nutrient loads are treated as conservative tracers in the model.

30 The weather forcing consists of solar insolation, air temperature, wind, relative humidity and
31 cloudiness. The insolation and all the radiation and heat fluxes across the water-air interface
32 are calculated by the PROBE model. The weather variables are taken from a gridded database

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Borttaget: atmospheric deposition of nutrients,

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Borttaget: The organic N and P that is in balance according to Redfield ratio

Borttaget: part is regarded as not bioactive dissolved organic nutrients

1 developed at the Swedish Meteorological and Hydrological Institute (SMHI), using 3-hourly
 2 meteorological synoptic monitoring station data, and the depositions of nitrogen species
 3 (NHX and NOX) are calculated by the MATCH model (Robertson et al., 1999). For the
 4 deposition of phosphate, a literature value of $0.5 \text{ kg m}^{-2} \text{ month}^{-1}$ is used (Areskoug, 1993).
 5 The boundary conditions to the open Baltic Sea is set by vertical mean profiles calculated by a
 6 one dimensional PROBE setup for each Baltic open water area and assimilation of monitoring
 7 data. The monitoring data used in the assimilation are extracted from the stations MS4, US5B,
 8 SR5, BY31 and BY29 (Fig. 1) depending on depth and time, to get the best representation of
 9 the open sea's influence on the SCM model domain.

Borttaget: different

10 2.3 Evaluation strategy

11 To quantify the fit between modelled values and observations a correlation coefficient, r , was
 12 calculated (Eq. 2).

$$13 \quad r = \frac{\sum_{i=1}^n (P_i - \bar{P})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (P_i - \bar{P})^2 \sum_{i=1}^n (O_i - \bar{O})^2}} \quad 2$$

14 where P is model value, O is observation of the analyzed parameter, i is the data number and n
 15 is the total number of data points. Two series of observations and model values that are
 16 identical will lead to an r value equal to one, while uncorrelated data result in a r value close
 17 to zero. In addition to the r value, the average cost function (C) values (Eq. 3) for the different
 18 parameters were used in the evaluation of the SCM results.

19

$$20 \quad C = \frac{\sum_{i=1}^n \left| \frac{P_i - O_i}{sd(O_i)} \right|}{n} \quad 3$$

21 A cost function describes the proximity of model results and observations by normalizing the
 22 difference between them with the standard deviation (sd) of the observations. If average
 23 model results fall within the standard deviation of observations, C is below one which is
 24 regarded as good. Results that are within two standard deviations will be regarded as to be on
 25 an acceptable level. The corresponding simulation levels, good and acceptable, for the
 26 correlation coefficient are achieved when r is higher than two thirds (0.66) and one third

1 (0.33), respectively. This approach using r and C has been used in earlier studies (Edman and
2 Omstedt, 2013; Edman and Anderson, 2014) and is based on methods by Oschlies (2010).

3 The outflow from Lake Mälaren is three orders of magnitude larger than the sum of all other
4 S-HYPE fresh water components to the inner Stockholm Archipelago. The output from S-
5 HYPE of fresh water and nutrient loads from Mälaren to the Stockholm Archipelago was
6 therefore used in the evaluation of the fresh water forcing to SCM. Observations of freshwater
7 discharge were retrieved from the Baltic Environmental Database (BED, 2015) at the Baltic
8 Nest Institute, Stockholm University. The correlation between monthly mean of observed and
9 simulated discharge for the period (1990-2012) was then calculated.

Borttaget: r value

10 In the evaluation of the results of the SCM in different basins, the long term averages (1990-
11 2012) of the vertical distribution of salinity, DIN, DIP and oxygen during winter (November-
12 February) and summer months (May-August) were compared to corresponding observations
13 for the whole modelled period. Further, the correlation r and the mean cost function C of the
14 vertical distribution of observations and model output were calculated. Also the long term
15 averages of the seasonal variations in surface temperature, DIN, DIP and bottom water
16 oxygen concentrations were used in the evaluation by calculating the corresponding r and C
17 values.

18 Observations from the Stockholm Archipelago (Fig. 3) were provided by Stockholm City and
19 Stockholm University. For the quantitative validation described above the quality of
20 observations from each site (Table 1) had to fulfil three requirements to be used in the
21 validation process; 1) period coverage: 80% of the years sampled; 2) annual coverage: at least
22 7 of the 12 months sampled; and 3) vertical data coverage: at least 5 depth levels frequently
23 measured over the full depth of the basin. In addition at least 3 months with observations were
24 required for the evaluation of winter and summer conditions. Average values were then
25 calculated for periods and depth levels with dense data distribution. The model output was
26 used in the same way as observations, and the modelled averages were calculated for the same
27 time intervals and depth ranges.

28 *Fig. 3.*

29 *Table 1.*

2.4 Calculation of retention

The retention of P and N in a region can be calculated as the difference between the load and the outflow (Almroth-Rosell et al., 2015; Hayn et al., 2014; Johnston, 1991; Meier et al., 2012). The input of nutrients is the sum of inflows from outer areas, rivers, land runoff, point sources and atmospheric load, while the outflow of nutrients is the export from the area to outer seas (Fig. 4). N₂-fixation is another process that needs to be taken into account as it is a source of bioavailable N to the system. Retention in the present study can be temporal or permanent. A build-up of the pelagic and benthic active pools of P and N are referred to as temporal retention processes. Permanent retention removes the nutrients permanently from the modelled system. For modelled P burial is the only retention process that permanently removes P, while for N also benthic and pelagic denitrification are considered as permanent sinks.

The different processes affecting retention (burial, denitrification, benthic and pelagic nutrient pool changes) have been calculated separately, as they are included in the biogeochemical model SCOBI. Total retention (R_{tot}) is the sum of both permanently and temporally retained P and N (see supplement 2 for retention definitions). The area specific retention, R_{AS} , is the retention normalized to the area and is calculated from eq. 4:

$$R_{AS} = \frac{R_{tot}}{A} \quad 4$$

where A is the size of the area. R_{AS} can be used to compare the retention in basins of different sizes. The filter efficiency, F_{eff} , is calculated from eq. 5:

$$F_{eff} = \frac{R_{tot}}{Nu_{land}} \times 100 \quad 5$$

where Nu_{land} is the sum of the nutrient load from land and the deposition from air. The F_{eff} is an estimate of the proportion (%) of the nutrients from land and atmosphere that is retained within the area. Similarly the retention efficiency (R_{eff}) can also be calculated, defined as the proportion of the total nutrient load (sum of all sources, including import from surrounding waters) that is retained within the area (supplement 2). In the present study, however, the focus is on the filter effect and filter efficiency.

The total retention and the filter efficiency were calculated for the entire Stockholm Archipelago, and also separately for the inner, intermediate and outer archipelagos in order to

Flyttad (infogning) [2]

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Borttaget: A build-up of the pelagic and benthic active pools of N and P are regarded as temporal retention processes. N₂-fixation is another process that needs to be taken into account as it is a source of bioavailable N to the system. In the present study the focus has been on the retention of the external nutrient load from land and atmosphere.

Borttaget: retention

Borttaget: affecting retention

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Flyttad uppåt [2]: Burial is the only retention process for modelled P that permanently removes P from the model system, while for N also benthic and pelagic denitrification has to be considered as permanent sinks. A build-up of the pelagic and benthic active pools of N and P are regarded as temporal retention processes. N₂-fixation is another process that needs to be taken into account as it is a source of bioavailable N to the system.

Borttaget: retention (or sink)

Formaterat: Teckensnitt: Kursiv

Borttaget: R_{TOT} (%), of the sum of nutrient load from land and deposition from air (Nu_{in}) has been calculated according to eq. 4:

Borttaget: 4

Borttaget: retention

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1 investigate the spatial gradient of retention capacity from the inner coastal zone towards the
2 open Baltic Sea.

3 *Fig. 4.*

4 The residence time is defined as the average time water or a dissolved substance spends
5 within a particular basin. In the present study the fresh water residence time is calculated as
6 the water volume of a group of basins divided by the fresh water inflow received from land
7 (Bolin and Rodhe, 1973; Monsen et al., 2002).

9 **2.4.1 Reduction scenario of the nutrient land load**

10 The SCM is also used to investigate the effect of a reduction of the nutrient load from land to
11 the Stockholm Archipelago. The loads of P and N from sewage treatment facilities depend on
12 their size, i.e. the number of person equivalents (pe) for which they were built. Estimates of
13 realistic minimum discharge concentrations of P and N from sewage treatment facilities used
14 in the SCM reduction scenario, which are based on technical feasibility but not on economic
15 or resource sustainability, are given in Table 2 (Kerstin Rosén Nilsson, County
16 Administrative Board of Stockholm, personal communication). The reductions of P and N
17 from land runoff, e.g. due to decreased nutrient load from agriculture and increased use of
18 small sized sewage treatment plants by individual households where these are not connected
19 to a municipal sewage treatment facility are set to 10 % and 15 % for P and N, respectively.
20 Also point sources from different industries are assumed to decrease their discharge of N and
21 P with 10 % as well. The reductions result in a total decrease of P and N load by 12 and 20 %,
22 respectively, to the entire Stockholm Archipelago.

23 A SCM model spin-up run period of 45 years with river and weather forcing from year 2010
24 provides the steady state initial conditions used for the reduction experiment. After the spin-
25 up period the reductions of the nutrient loads are implemented, according to Table 2.

26 Table 2.

27

3 Results and discussion

3.1 Validation

The variability of the modelled discharge of water and nutrients by the S-HYPE model agrees well with observations (Fig. 5 and Table 3) for the simulated period (1990-2012). A clear relationship between the magnitude of river outflow (Q_F) and the nutrient loads is observed both for monthly observations and S-HYPE output (Fig. 5). The model seems to slightly underestimate the spring discharge and overestimate low flow regimes. However, overall it captures a realistic annual variation of the discharge, which is reflected in high correlation coefficients (Eq. 2) for all evaluated parameters (Table 3). Highest correlation coefficients are found for Q_F and TN, compared to the slightly lower values for TP, DIP and DIN, which is in accordance with previous studies (Grimvall et al., 2014; Strömquist et al., 2012). An extensive validation is also available in Sahlberg et al. (2008).

- Borttaget:** The load of freshwater to the model is an important forcing component, which needs to be of good quality since the coastal zone is strongly influenced by the land load of freshwater and nutrients.
- Borttaget:** is
- Borttaget:** compared to
- Borttaget:** ion
- Borttaget:** with good results (Fig. 5 and Table 2)
- Borttaget:** (Table Table 2)

Fig. 5.

Table 3.

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Datasets from eight stations (Table 1) fulfilled the requirements of good data availability and were used in the evaluation of the SCM model results. There are aspects that are important to have in mind when comparing model results and observations. In the model the state variables are horizontally averaged in each basin, while observations are measured at one station at a certain location. The Stockholm Archipelago has relatively large spatial salinity gradients and the representativeness of a station when compared to model results can be somewhat limited if e.g. the position of the station is close to an out- or inlet of the basin. Observations may in general also be influenced by local conditions, e.g. sewage effluents, high sediment fluxes or stagnant conditions, which are smeared out in the average results of the model. Still we assume for the present study that the station data are good enough for the quantitative model validation and give a background for discussions about model strengths and weaknesses. As an example, validation results are shown for one of the basins where the number of observations is large enough both during summer and winter periods to be included in the validation process. The example is from station Blockhusudden (Position G in Fig. 3), where the largest data set of observations was found. The station is situated at the boundary between the innermost basin Strömmen and the next adjacent sub-basin.

- Borttaget:** T
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- Borttaget:** the innermost basin Strömmen, which is
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1 The objective correlation coefficients (Eq. 2) and the cost function value (Eq. 3) for the
2 different state variables implied correspondingly that the model manage to simulate the
3 average vertical winter and summer profiles with good or acceptable skills in the basin
4 Strömmen (Fig. 6g), except for the average seasonal value of DIN that was described as not
5 good. The differences between model results and observations of DIN may be a result of the
6 location of the monitoring station.

7 The long term average summer depth profiles of modelled salinity and oxygen in the basin
8 Strömmen correlate well with observations, while the winter values of salinity were too low,
9 especially in the surface layers (Fig. 7a,b). This difference is partly due to the fact that the
10 salinity of a station at the entrance to the basin is more reflecting the boundary conditions of
11 the downstream basin than the mean conditions in Strömmen. The surface winter
12 concentrations of oxygen were too high, but decreased with depth and became too low in the
13 lower layers (Fig. 7b). It might be expected that winter surface oxygen concentrations in
14 observations should be higher than in summer because of the temperature effect on oxygen
15 saturation concentrations as seen from the model results. However, the number of
16 observations during winter are limited and occurred mostly in November and February, which
17 may influence the average values of the observations.

18 The results indicate that there is an impact from local conditions at the monitoring station that
19 are not captured by the model setup. The modelled DIN depth profiles show higher values at
20 about 15 m depth during both winter and summer (Fig. 7c), while the DIP profiles values
21 seems to be satisfactory at all depth and periods (Fig. 7d). Also the individual observations
22 show higher concentrations of both DIN and DIP around 15 m depth which is where the
23 halocline has its largest vertical gradient. This depth level corresponds to the depth where two
24 sewage water treatment plants relieve their sewage water in the model. The winter
25 stratification was stronger in the model because of the lower surface salinity. This hampers
26 the vertical transports of oxygen and has an influence on the winter oxygen conditions in the
27 deep water that were lower in the model compared to the observations from the more well
28 ventilated entrance area.

29 The average seasonal variation of the surface temperature and the bottom water oxygen
30 concentrations was captured by the model, but not the increase of surface nutrients, especially
31 DIN, during autumn (Fig. 8). The surface salinity was overall somewhat low, which probably
32 is a result of the location of the monitoring station, as described above.

Borttaget: . E

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1 In the other basins used in the evaluation (vertical and seasonal profiles are not shown) of the
2 SCM state variables during winter, summer and season were simulated with good or
3 acceptable skills, except for the average vertical summer profiles of DIN in the basin
4 Solöfjärden (Fig. 6c) and oxygen concentration in the basin Sandöfjärden (Fig. 6a). The
5 combined model skills, which were calculated as the average of the individual *r* and *C* values,
6 were good in six of the eight evaluated basins (purple cross in Fig. 6). In the remaining two
7 basins the skills were considered as acceptable.

8 Fig. 6

9 Fig. 7

10 Fig. 8

11 3.2 Retention of nutrients in the Stockholm Archipelago

12 During the period 1990-2012 on average 174 t P yr⁻¹ and 5846 t N yr⁻¹ entered the inner
13 archipelago, mainly from the Lake Mälaren. That is a major part of the 217 t P yr⁻¹ and
14 8288 t N yr⁻¹ which entered the entire Stockholm Archipelago (Fig. 9). The P load from point
15 sources was clearly lower than the river load (Fig. 10). However, the N load from point
16 sources was higher than the river load in the beginning of the studied period (Fig. 10b), but
17 decreased in the middle of the 1990s due to the implementation of a more effective method to
18 remove N in the waste water treatment facilities. The P supply to the intermediate archipelago
19 mainly originated from runoff from land, while for N there were also some point sources that
20 contributed to the land load on the same level. In the outer archipelago the nutrient load from
21 land was almost negligible and most of the nutrients were deposited from the atmosphere.

22 Fig. 9.

23 Fig. 10.

24 Largest amounts of P and N were retained in the outer archipelago compared to the
25 intermediate and inner archipelago (Fig. 9). The retention of all supplied P and N, including
26 the net import from upstream areas, within the inner, intermediate and outer Stockholm
27 archipelagos amounts to 18 %, 23 % and 48 % for P, respectively, and 14 %, 26 % and 60 %
28 for N, respectively. The area of the three zones increases from inner (109 km²), to the
29 intermediate (759 km²) and to the outer archipelago (2360 km²) and thus, the retention of
30 nutrients seems to increase with increased area. On the other hand, the average of the area
31 specific retention of P and N was for the simulation period highest in the inner archipelago,

Borttaget: The objective correlation coefficients and the cost function value for the different parameters implied correspondingly that the model managed to simulate the average vertical winter and summer profiles with good or acceptable skills in the basin Strömmen (Fig. 8g), except for the average seasonal value of DIN that was described as not good. The differences between model results and observations of DIN may be due to similar reasons as described for salinity above.

Borttaget: all parameters

Borttaget: Fig. 8

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Borttaget: ¶
Fig. 8. ¶

Borttaget: in the inner archipelago

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Borttaget: (Fig. 10 b)

Borttaget: (Fig. 10 e)

Borttaget: (Fig. 10 c, f)

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Borttaget: amount

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Borttaget: per area unit (km⁻²)

1 and decreased towards the open sea (Fig. 11). The permanent retention was during the
2 simulated period on a stable level, while fluctuations in the temporal retention reflects the
3 effect of varying rivierine nutrient input (Fig. 10c,d). The water depth and the residence time
4 are affecting the retention of nutrients, which will be further discussed in Section 3.2.2. The
5 largest part of the total retention in the entire Stockholm Archipelago was permanent, which
6 for P means burial. For N benthic denitrification represented as much as almost 92 % of the
7 permanent retention, burial for less than 8 % and pelagic denitrification was below 1 %.

8 *Fig. 11.*

9 Karlsson et al. (2010) found in their empirical study for 1982-2007 that about 15 % of the
10 total input of N and 10 to 13% of the total input of P were retained in the inner Stockholm
11 Archipelago. However, their numbers are based on the total input, thus both the land load and
12 an estimated input from outer areas, i.e. the intermediate Stockholm Archipelago. A
13 recalculation from the given numbers in their study, resulted in a filter efficiency of about 25
14 and 24 % for N and about 21 and 30 % for P of the nutrient load from land and atmosphere
15 for the periods 1982-1995 and 1996-2007, respectively. These numbers of the filter efficiency
16 are higher than the numbers in the present model study. To be able to compare the numbers a
17 recalculation of the filter efficiency in the SCM for the latter period (1996-2007) in the inner
18 archipelago was performed, but did not change the SCM results considerably. The largest
19 difference between the two studies is caused by the calculation of net exchange of nutrients
20 through the sounds. The transport through the sounds was in Karlsson et al. (2010) calculated
21 from average volume flows estimated from mass balance calculations for salt together with
22 budget calculations using observations of average nutrient concentrations. In the present study
23 the exchange of nutrients between the inner and the intermediate archipelago was part of the
24 dynamic model calculations in the SCM. The SCM net outflow from the inner archipelago for
25 N and P was about 11 % and 8 %, respectively, larger compared to the net outflow of the
26 nutrients in the Karlsson et al. (2010) study. Another difference between the two studies was
27 the land load of P, which was about 8 % lower in the SCM. The difference in land load of N
28 was only about 1 %. Thus, calculations from an empirical model based on Knudsen's
29 relations (Knudsen, 1900) and calculations using long term average values resulted in about
30 10 % higher retention efficiency values compared to the calculations from SCM, a coupled
31 numeric physical-biogeochemical model with high vertical resolution and small time step. In
32 spite of the difference in models the result are surprisingly close.

Borttaget: In the inner Stockholm Archipelago about 14 % and 18 % of the external N and P supply, respectively, were retained within the area.

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1 The temporary retention in SCM is negative in all three parts of the archipelago for both P and
2 N (Fig. 9 and Fig. 10). The reason for negative temporary retention is mainly a decrease in the
3 benthic nutrient pools during the period (Fig. 12). The largest decrease (29 %) is found in the
4 pelagic pool of N in the inner archipelago, which coincides with the decrease in N load from
5 point sources (Fig. 10). In the intermediate and outer Stockholm archipelagos the pelagic pool
6 of N remains on about the same level through the whole simulation period. The large
7 decreases in the benthic pools of N and P (14-18 %) occur in the intermediate and outer
8 archipelagos, while there are only small changes in the pelagic and benthic pools of P in the
9 inner archipelago. Because of the nutrient retention there is a reduced net transport of N and P
10 from the inner archipelago towards the intermediate and outer archipelagos and further to the
11 open sea during the simulated period (Fig. 9). In addition to the net export of nutrients to outer
12 areas, there is also an extensive circulation of nutrients between the coast and the open sea.
13 The importance of imported nutrients into the coastal zones from sea has been discussed in
14 earlier studies (e.g. Humborg et al., 2003) in which it was concluded that many estuaries has a
15 net import of DIN and DIP from sea, e.g. Chesapeake Bay (Boynton et al. 1995). Thus, in
16 these cases the import is larger than the export as also discussed in section 3.2.3.

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Borttaget: However, the effect of nutrient transports from the open sea into the coastal zone on coastal retention has not been studied before and will be addressed in more detail in future studies.

17 Fig. 12.

18 3.2.1 The coastal filter

19 From the present results it can be concluded that the Stockholm Archipelago works like a
20 filter for nutrients that enter the coastal zone from land and atmosphere. However, a rather
21 large area of the archipelago is needed to effectively retain the nutrients. About 82 and 86 %
22 of P and N supplies, respectively, pass the small inner archipelago and are exported to the
23 intermediate archipelago. In the intermediate and the outer archipelago all local supplies of
24 nutrients from land and atmosphere are retained together with a fraction of the nutrients
25 imported from the inner archipelago. The filter efficiencies increase with increased coastal
26 area from land to the sea continuum (Fig. 13). However, the filter efficiency of the entire
27 Stockholm Archipelago is not effective enough to take care of all the nutrients that enter the
28 system from land and the atmosphere, but still, at least 65 % and 72 % of the supplied P and
29 N, respectively, are retained. The total retention numbers (permanent and temporary)
30 correspond to 141 t P yr⁻¹ and 5954 t N yr⁻¹ (Fig. 9). Since Stockholm Archipelago is the
31 largest archipelago in Sweden it might be that most of the other Swedish coastal areas with a
32 large run-off from land would be less effective as coastal filters and, thus, contribute to a
33 larger extent to the eutrophication in the open sea. This is one question in focus of an on-

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1 going study where the entire Swedish coastal area will be evaluated similarly to the present
2 study.

3 3.2.2 Processes affecting retention

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4 The present study was performed in an area characterised as an eutrophic archipelago in an
5 inland sea with basins having oxic, hypoxic and anoxic bottom waters. The results of the
6 retention are in agreement with results from previous studies (Billen et al., 2011; Hayn et al.,
7 2014; Nielsen et al., 2001; Nixon et al., 1996), but with somewhat lower values in the entire
8 and inner plus intermediate archipelagos (Fig. 13). Their studies were performed in various
9 types of systems: coastal lagoons, drowned river estuaries, coastal embayments, and inland
10 seas in North America and in Europe. Those systems varied from being relatively pristine to
11 systems with large point sources (eutrophic), and they also varied between oxic to hypoxic
12 and/or anoxic conditions. Nixon et al. (1996) showed that the retention of P and N correlated
13 to the log scale of the ratio between the average depth and the residence time of the study
14 areas, which is confirmed by the results from the studies by Billen et al. (2011), Hayn et al.
15 (2014) and Nielsen et al. (2001) as well as by the present study (Fig. 13).

Borttaget: Fig. 14

15 In shallow areas
16 larger parts of the sinking particulate organic material may reach all the way down to the sea
17 floor where it can be exposed to retention processes such as burial and denitrification. On the
18 other hand, in a much deeper area a larger part of the organic material may become re-
19 mineralised within the water column on its way down to the sea floor. The nutrients can then
20 be re-used by phytoplankton and/or be further transported out from the system. Long
21 residence times in a system increase the time of exposure for biogeochemical transformation
22 processes and sedimentation within the system and larger parts of the nutrients may be
23 retained. These two parameters therefore affect the retention of nutrients (Fig. 13) and the
24 correlation implies that the retention occurs mostly in the sediment due to processes such as
25 burial and denitrification, which is the case in the present model study. However, in the
26 present study no clear relation was found between the average depth (10-20 m for all three
27 areas) and the filter efficiency. Actually, also Nixon et al. (1996) discussed this and concluded
28 that including the depth in the analyze of the retention vs residence time did not much
29 improve the regression. The filter efficiency in the present study did, however, increase with
30 4-5 % yr⁻¹ as the fresh water residence time increased in the land to sea continuum.

Borttaget: Fig. 14

Borttaget: However, it is not clear for all the mentioned studies above how the residence time was calculated, why it is possible that the results are not completely comparable. In the present study the residence time is calculated as the volume of the study area divided by the fresh water inflow from land.

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31 Fig. 13.

1 The denitrification process has an oxygen dependency and the largest sensitivity of the
2 denitrification rates to changes in oxygen concentrations in the model occur at concentrations
3 below 180-220 $\mu\text{mol l}^{-1}$ (~4-5 ml/l). The maximum denitrification rate is obtained at an
4 oxygen concentration of about 45 $\mu\text{mol l}^{-1}$ (~1 ml/l) while denitrification halts under anoxic
5 conditions. Also P is affected by oxygen since P has an oxygen dependent adsorption
6 behaviour on particulate iron(III)oxyhydroxides (Mortimer, 1941). The adsorption of P on
7 particles can lead to higher burial rates during oxic conditions compared to anoxic conditions
8 when the release rate of P from the sediment is higher (Viktorsson et al., 2012; Almroth-
9 Rosell et al., 2015). The effect of the oxygen concentration was studied in an experiment
10 where the oxygen concentrations were manually reduced in the model. As a result the hypoxic
11 areas increased with 49 km^2 (300 %) and the anoxic area increased with 13 km^2 (360 %) in the
12 entire Stockholm Archipelago. Further, the total retention of N increased with 780 t yr^{-1}
13 (14 %), while the total retention of P decreased with 49 t yr^{-1} (28 %). The inner archipelago
14 had the largest increase of hypoxic and anoxic areas and also the largest changes in retention
15 of N and P. The N retention increased there with 243 t yr^{-1} (29 %) and the P retention
16 decreased with 9 t yr^{-1} (38 %). Thus, a reduced oxygen concentration led to increased N
17 retention due to increased denitrification. The denitrification not only increased as a number it
18 also increased its proportion of the permanent retention from 92 % to 94 %, while burial
19 correspondingly decreased its proportion. The decreased P retention was due to higher release
20 of P from the sediment.

21 Denitrification has in earlier studies been shown to increase in areas with longer residence
22 times (Nixon et al., 1996, Finlay et al., 2013). This is confirmed also in a study with a two-
23 layer hydrodynamic channel model used in the Randers Fjord (Nielsen et al., 2001). The
24 residence time was only on average six days and the filter efficiencies of N and P were
25 estimated to 10 % and 9 %, respectively, which were lower compared to in the Stockholm
26 Archipelago with a residence time in the inner archipelago of about 110 days. The denitrified
27 proportion of the permanent retained N was also lower, about 60 % compared to in the
28 Stockholm Archipelago (92 %). Waters with longer residence times are less ventilated at the
29 sediment interface. While this is certainly true for stratified and enclosed coastal regions it
30 should, however, be remembered that in other regions a well-mixed water volume can be
31 ventilated from the atmosphere. Benthic primary producers and benthic fauna are also
32 important factors for the retention of nutrients in shallow coastal ecosystems (McGlathery et
33 al., 2007; Norkko et al., 2012). Assimilation of nutrients by algae does not directly change the

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1 pools of nutrients, but transfer the nutrients into organic material. Plant uptake can e.g. lead to
2 increased burial and also influence on the oxygen dependent biogeochemical processes in the
3 sediment due the plant metabolism (McGlathery et al., 2007). These processes are not yet
4 implemented in the SCM, and therefore not included in the present study.

5 It is also important to know whether a system is in balance with the nutrient loads or not since
6 it would affect the retention capacity. In this study the temporary retention is negative for both
7 N and P in all three areas of the Stockholm Archipelago which implies that the system is not
8 in a steady state. This imbalance is however expected since there are reductions of the nutrient
9 loads in the first part of the simulation period (Fig. 10a, b). However, the possibility that the
10 results may be influenced by unknown initial conditions of sediment concentrations should
11 not be excluded. There are only few observations available and the knowledge about the
12 amount of sediment nutrients involved in biogeochemical cycles is poor.

13 **3.2.3 Response to reduction scenario of the nutrient land load**

14 The fastest response in the nutrient load reduction experiment is seen in the pelagic pool of N
15 which rapidly decreases, but reaches a steady state after about three years with reduced loads
16 (Fig. 14). The pelagic pool of P decreases in the inner archipelago but increases slightly in the
17 outer areas. The changes in P pools are slower compared to those in N pools. The large and
18 fast decrease of pelagic N in the inner archipelago, results in a decreased N:P ratio (Table 4),
19 as well as (not shown) lower chlorophyll concentrations, reduced sedimentation, and
20 increased export of P from the inner archipelago to the outer areas and the Baltic proper. Also
21 the anoxic areas decrease with about 30% as a result of the lower deposition of organic
22 material on the sea floor (not shown). The changes in the benthic pools of N and P occur over
23 a longer time period, and the benthic P pool does not reach a steady state until about 40 years
24 after the reduction.

25 In the reduction scenario the transport of N to the open sea from the Stockholm Archipelago
26 decreases by 62% within four years (Table 4). The filter efficiency of N in the entire
27 archipelago increases at the same time from 79 % to 90 % as a result of the load reduction.

28 The longer response time of P compared to N is observed also in the filter efficiency (Fig. 14).

29 The filter efficiency of P at the end of the spin-up run is about 100 %. This implies that under
30 the 2010 conditions, all the P land load is retained in the Stockholm Archipelago when the
31 system is in steady state. This is not the case when the original model forcing is used, which
32 implies that the Stockholm archipelago is still adjusting to the load reductions already

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Borttaget: The SCM is used to investigate the effect of a reduction of the nutrient load from land to the Stockholm Archipelago. The loads of P and N from sewage treatment facilities depend on their size, i.e. the number of person equivalents (pe) for which they were built. Estimates of realistic minimum discharge concentrations of P and N from sewage treatment facilities used in the SCM reduction scenario, which are based on technical feasibility but not on economic or resource sustainability, are given in Table 4 (Kerstin Rosén Nilsson, County Administrative Board of Stockholm, personal communication). The reductions of P and N from land, e.g., due to decreased nutrient load from agriculture and increased use of small sized sewage treatment plants by individual households where these are not connected to a municipal sewage treatment facility are set to 10 % and 15 % for P and N, respectively. Also the point sources from different industries are assumed to decrease their discharge of N and P with 10 % as well. The reductions result in a total decrease of P and N load with 12 and 20 %, respectively, to the entire Stockholm Archipelago. Largest impact from the load changes occurs in the inner archipelago, where most of the nutrient load enters the sea.¶

A SCM model spin-up run period of 45 years with river and weather forcing from year 2010 provides the steady state initial conditions used for the reduction experiment. After the spin-up period the reductions of the nutrient loads are implemented, according to Table 4. ¶

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Table 3. ¶

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1 implemented. Thus, the coastal region might under present conditions continue to improve
2 without further actions.

3 The filter efficiency of P decreases to 74 % during the first years after the reduction,
4 coinciding with the large decrease in the N pelagic pool and the decrease in N/P ratio. After
5 the initial decrease, the filter efficiency slowly increases to 106 % at the end of the simulation
6 period, i.e. retention is larger than the land and atmospheric load of P. As a consequence the
7 export of P from the archipelago to the Baltic proper decreases with time, and about 18 years
8 after the load reduction the direction of the transport changes. This coincides with the time
9 when the filter efficiency again reached 100 %. Thereafter the archipelago begins to import P
10 from the open sea. Thus, with the contemporary boundary conditions used at the open sea, P
11 from the Baltic proper becomes retained within the archipelago. For coastal management this
12 indicates the importance of the open sea nutrient conditions when effects of load reductions
13 are evaluated.

14 From these experiments it seems that local nutrient load abatements can improve the
15 environmental state of a semi-enclosed coastal site (the inner archipelago) that is locally
16 impacted by humans. The results also imply that for the first 5-15 years, increased nutrient
17 concentrations might locally be expected, but the effect of this will largely depend on which
18 nutrient that limit the seasonal phytoplankton production initially, and also the water
19 residence time.

20 However, for the more open coastal zone, represented in the present study by the intermediate
21 and outer archipelago, the response to further nutrient load reductions was minor. This
22 exemplifies that for many coastal areas the interactions between the open sea and the nutrient
23 cycling in the coastal zone is probably more important than the land-sea connection. For the
24 Baltic Sea this could mean that continued cooperation between the Baltic Sea countries will
25 be an important factor for the environmental development of many coastal sites. Some of the
26 coastal areas that are more open and influenced by the open water properties may have a less
27 problematic environmental state to begin with, mainly due to better ventilation of deeper
28 waters, and also less anthropogenic interference. Some other locations may be affected e.g. by
29 large blooms of harmful algae that thrive in nutrient rich waters.

30 The present study can conclude that even the eutrophicated Stockholm Archipelago can, after
31 further nutrient load abatements, act as a sink for open water phosphorous. Similar behaviour
32 was found in the Chesapeake Bay (Boynton et al. 1995), which acts as a sink for the total load
33 of P, thus, P from land, atmosphere and from the open sea.

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1 4 Conclusion

2 Archipelagos are complex areas with many basins and several shallow sounds, which affect
3 the transport of water and the dissolved and particulate nutrients. For the first time the SCM
4 model was used to study the capacity of the coastal filter of nutrients. An evaluation showed
5 that overall, model results agree with observations.

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6 We focused our study to the northern Baltic proper and investigated retention of N and P in
7 the Stockholm Archipelago. The main findings are described below.

- 8 • The coastal zone works as an efficient filter for the land loads of nutrients. Under
9 prevailing conditions 65 % and 72 % of P and N supplied from land, respectively, are
10 retained.
- 11 • A sensitivity experiment reducing the land load of nutrients showed that the retention
12 capacity of N and P increased. In this case the export of N from the archipelago
13 decreased and P was imported from the open sea.
- 14 • The average filter efficiency is dependent on the spatial dimensions of the coastal area.
15 Thus, nutrient retention per area is largest in the inner archipelago and decreases
16 towards the open sea.
- 17 • Average water depth and water residence time regulate the retention of nutrients that
18 occurs mostly in the sediment due to processes such as burial and denitrification.
- 19 • The pools of nutrients in the water and in the sediment changes with nutrient loads on
20 different time scales and affects the temporal nutrient retention in the area. N has a
21 rather short response time of about three years while it takes about 40 years for P to
22 reach balance in a system with constant forcing. Changing N:P ratios in the
23 archipelago due to the different response time scales also have an impact on the
24 nutrient retention capacity on decadal time scales.
- 25 • Coastal management needs to take the aspects of time and balance between nutrient
26 loads and pools into account in the assessment of impacts from nutrient load
27 abatements. On shorter timescales the retention capacity of P might be less effective
28 when the nutrient load from land decreases.

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13

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7 Figures

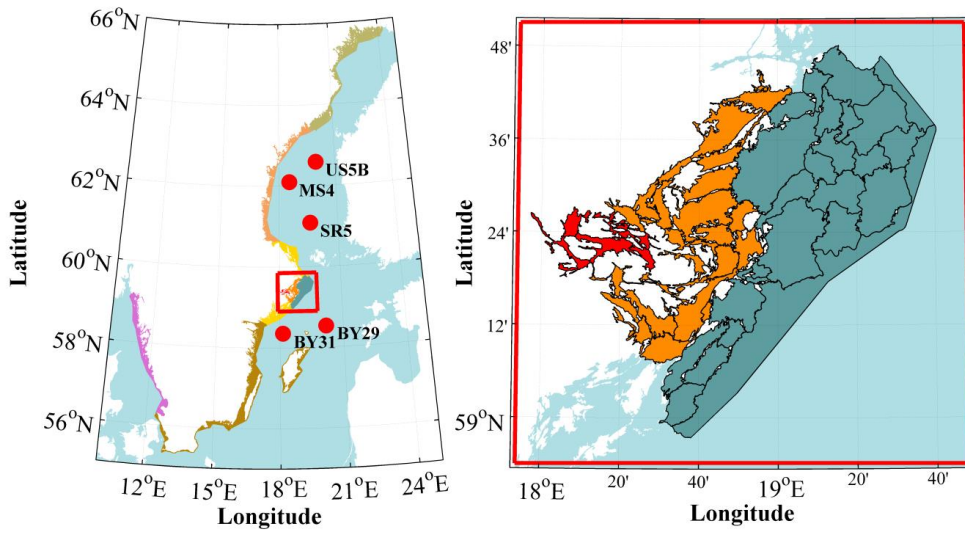


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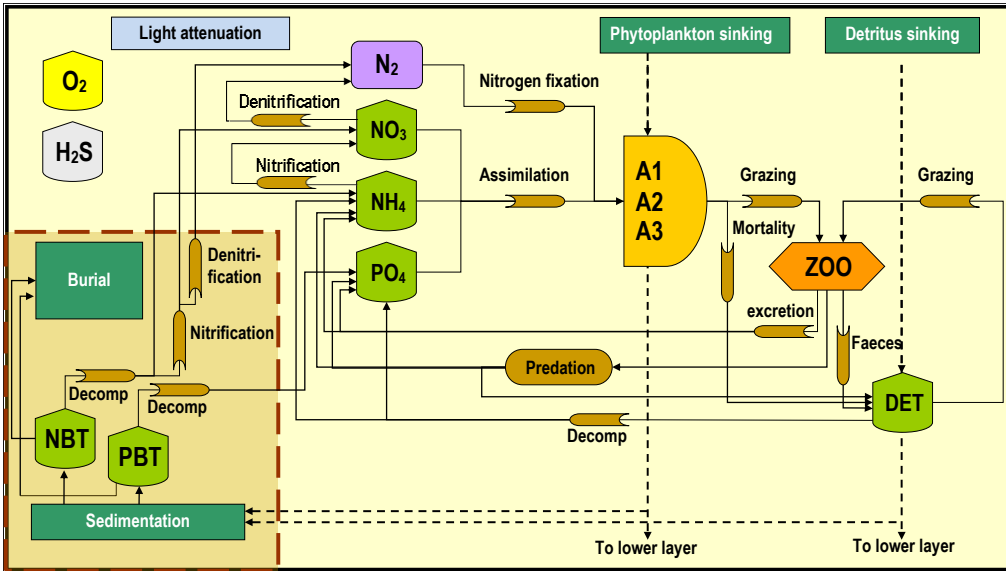


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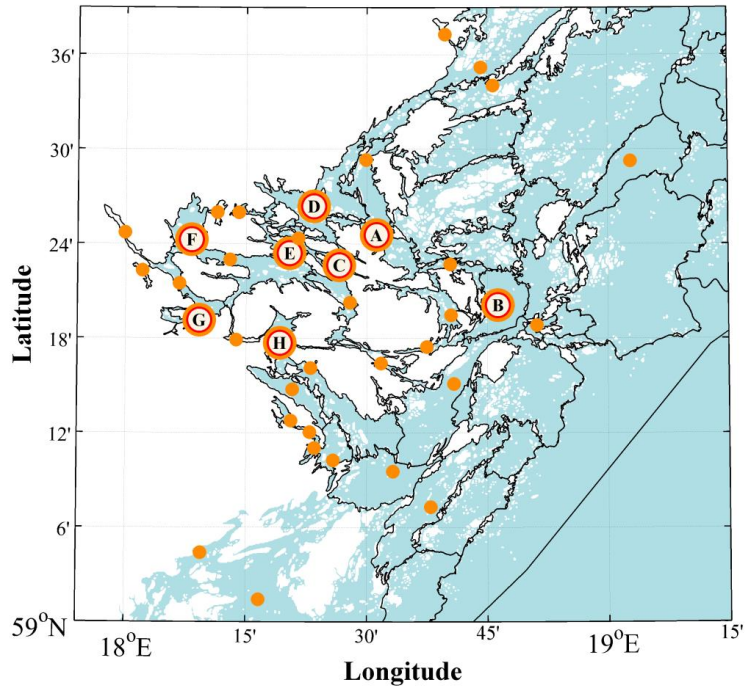


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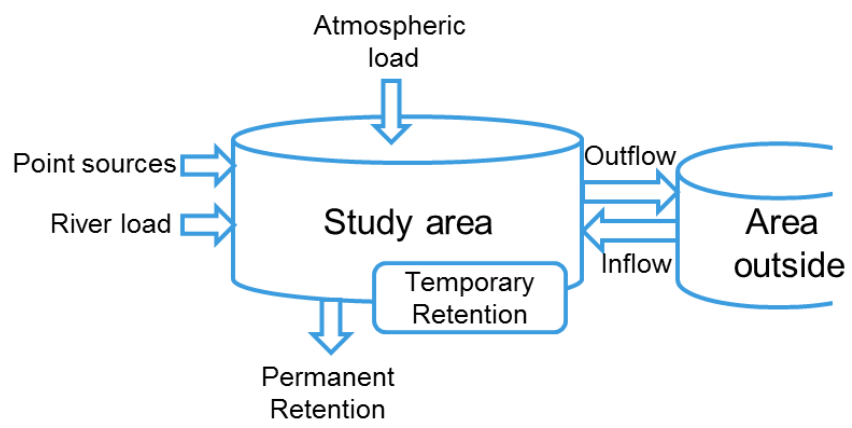


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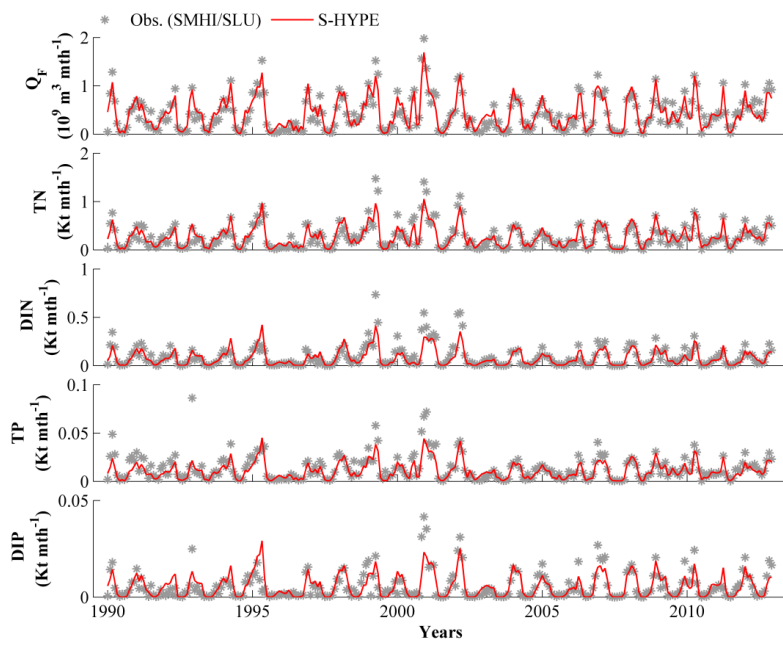


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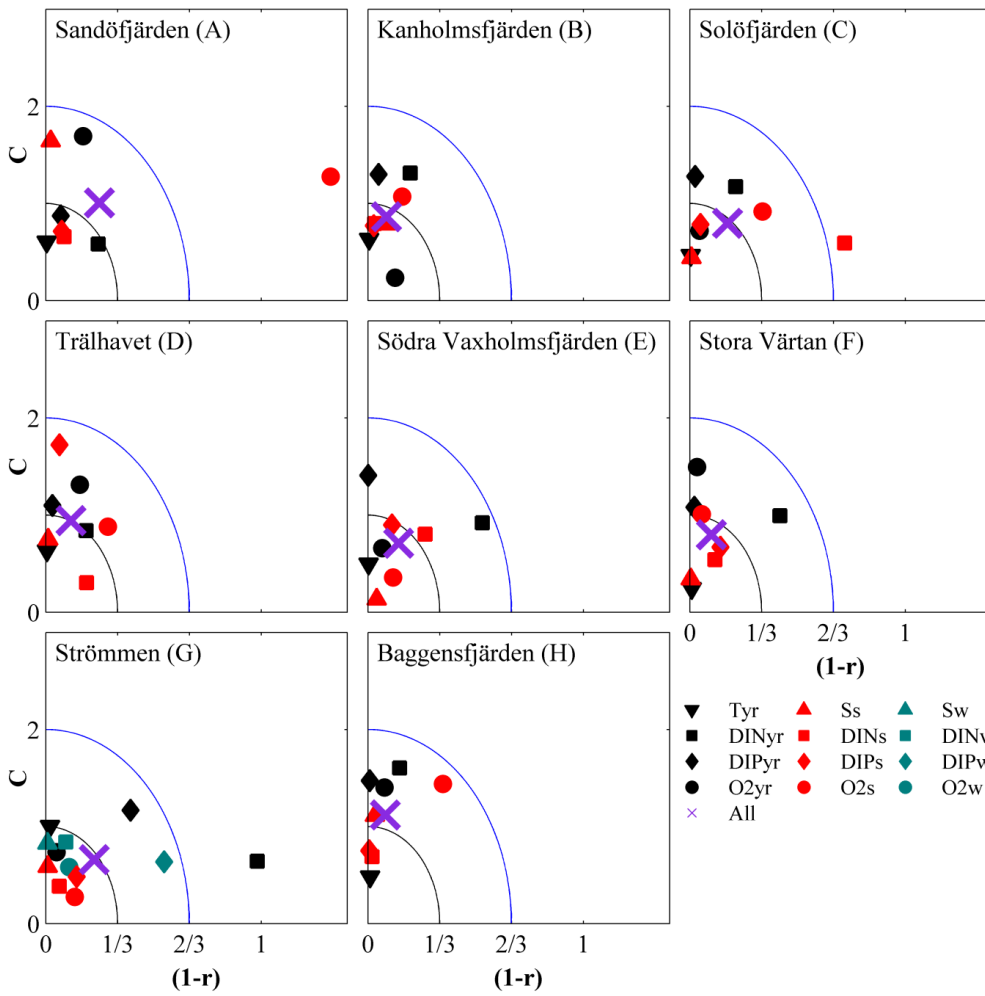


Fig. 6.

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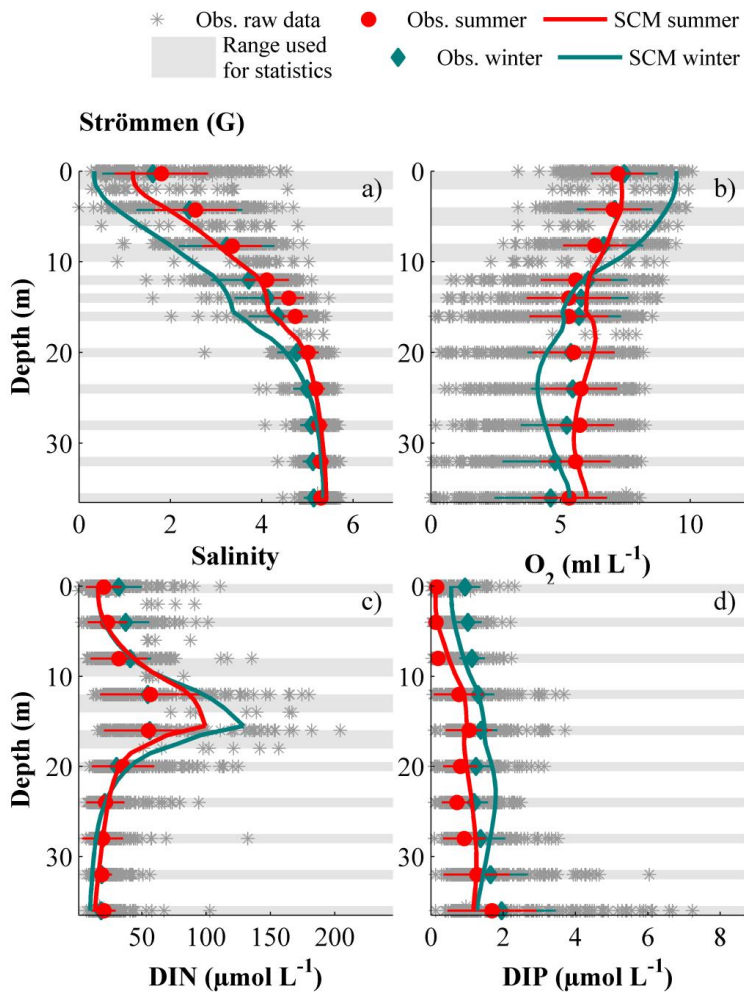


Fig. 7.

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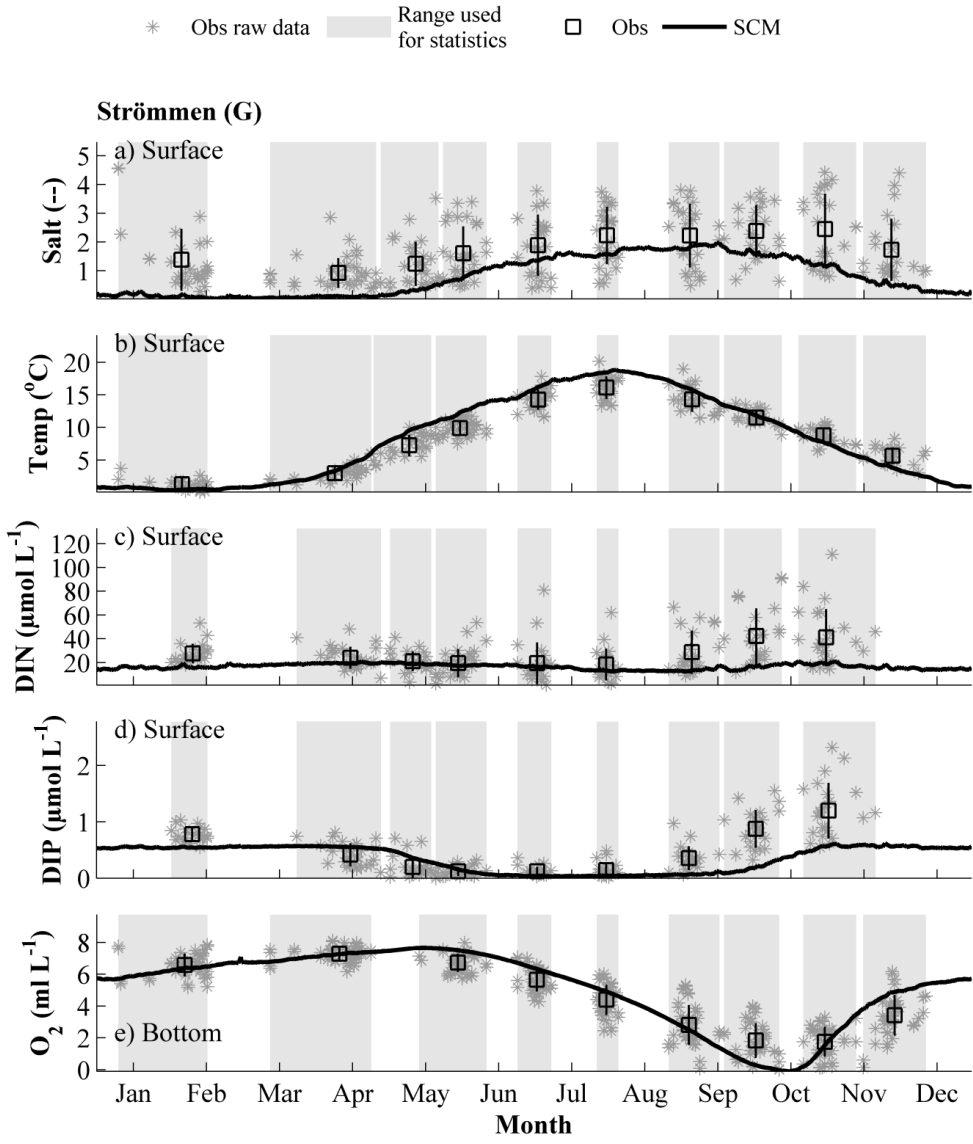
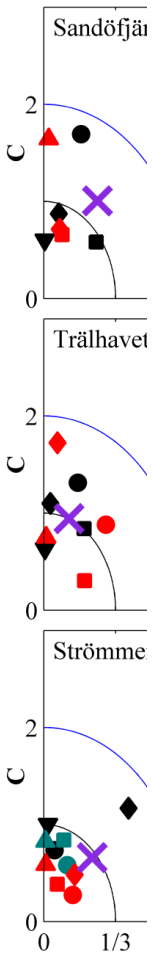


Fig. 8.

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Flyttad uppåt [3]:
Fig. 8.4

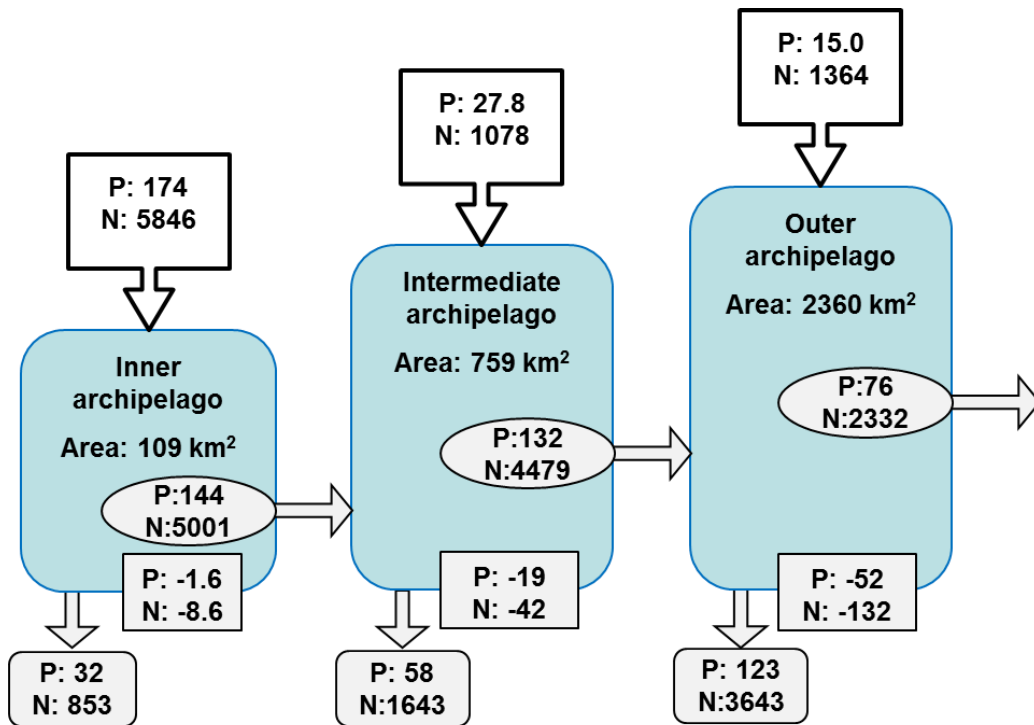


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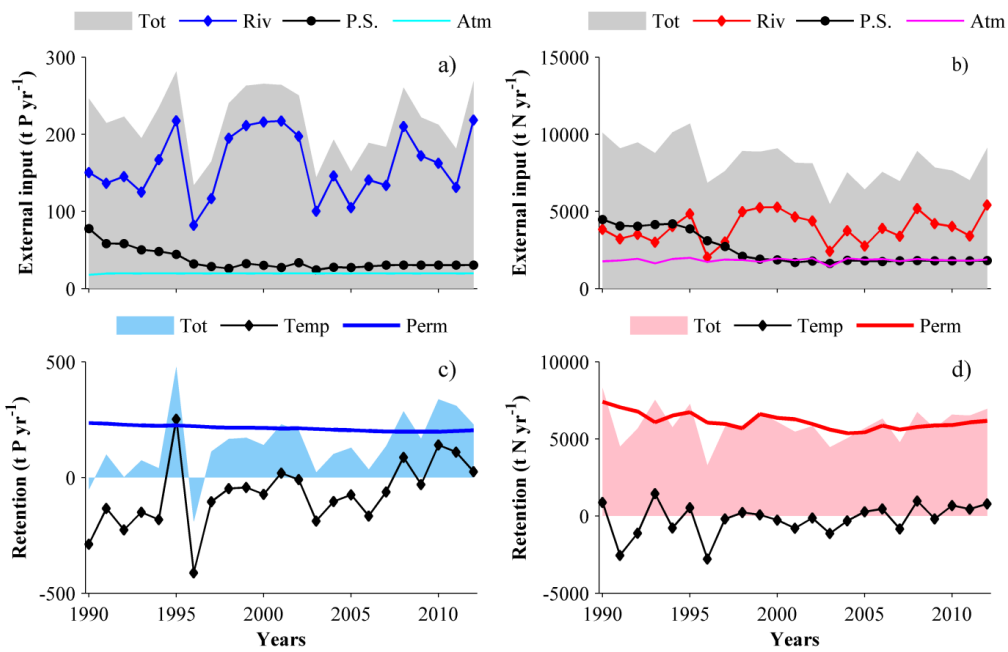
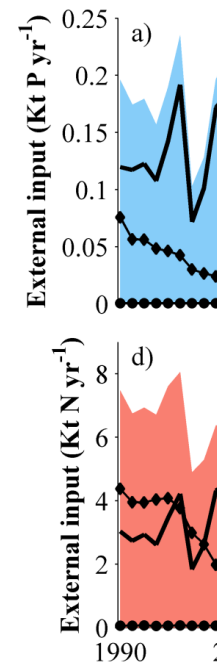
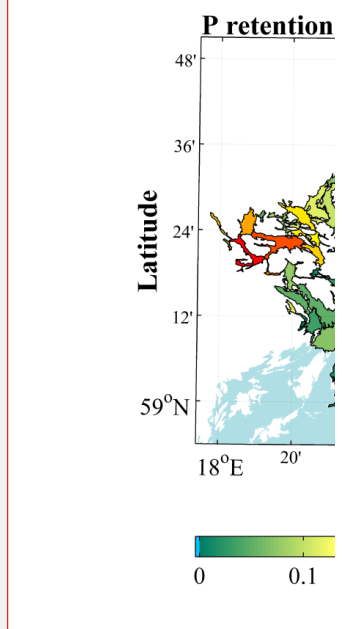
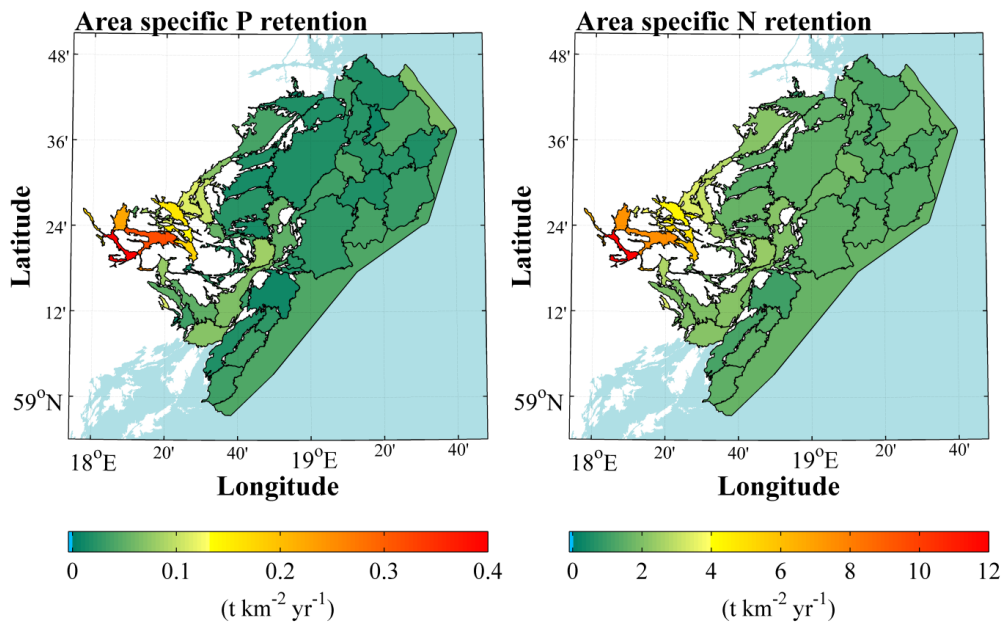


Fig. 10.



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Fig. 11.

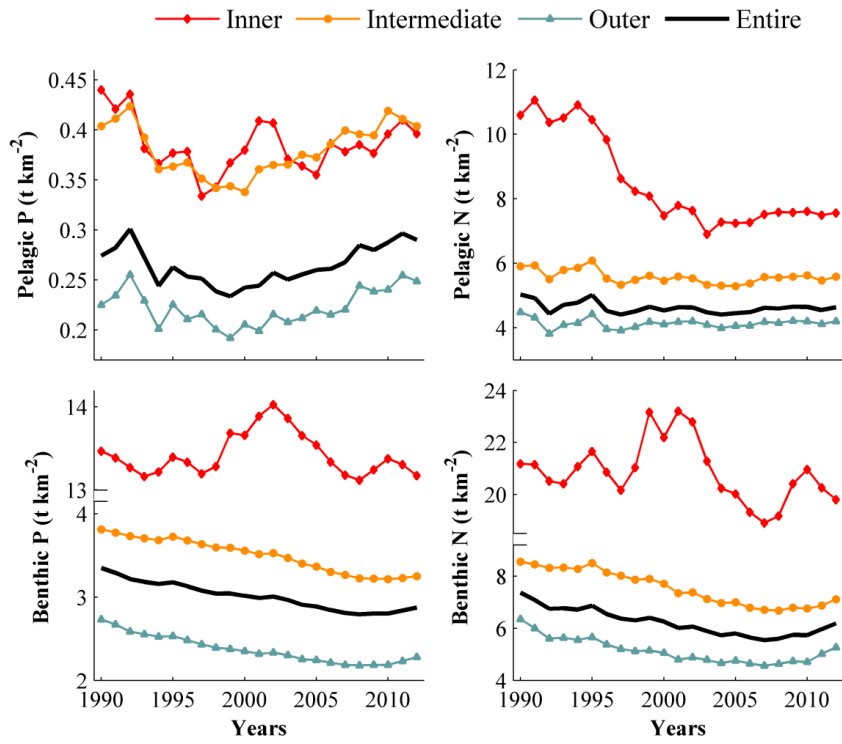
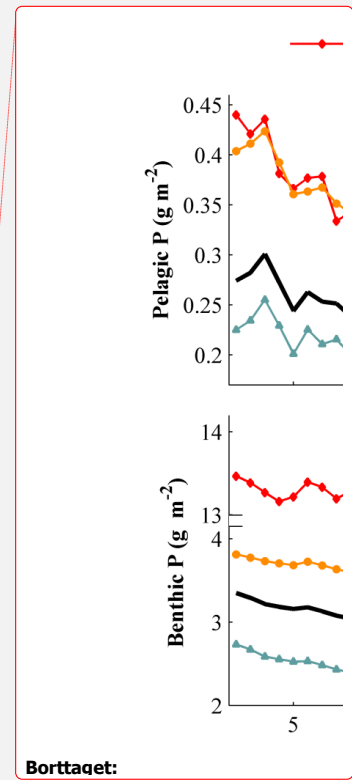


Fig. 12.



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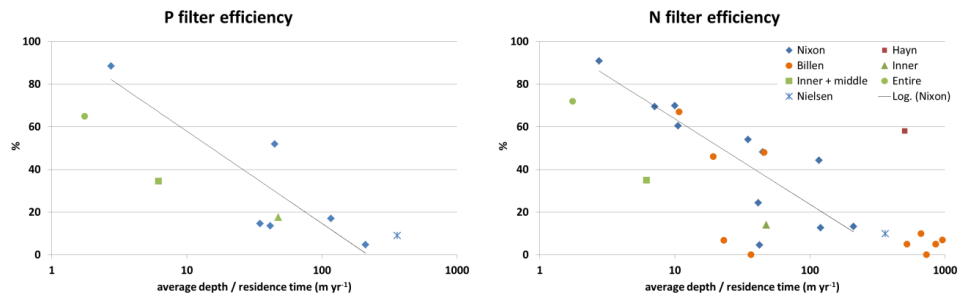
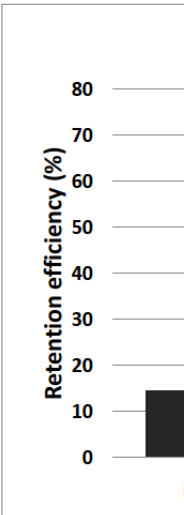


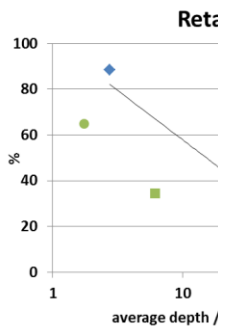
Fig. 13



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Fig. 13

Sidbrytning



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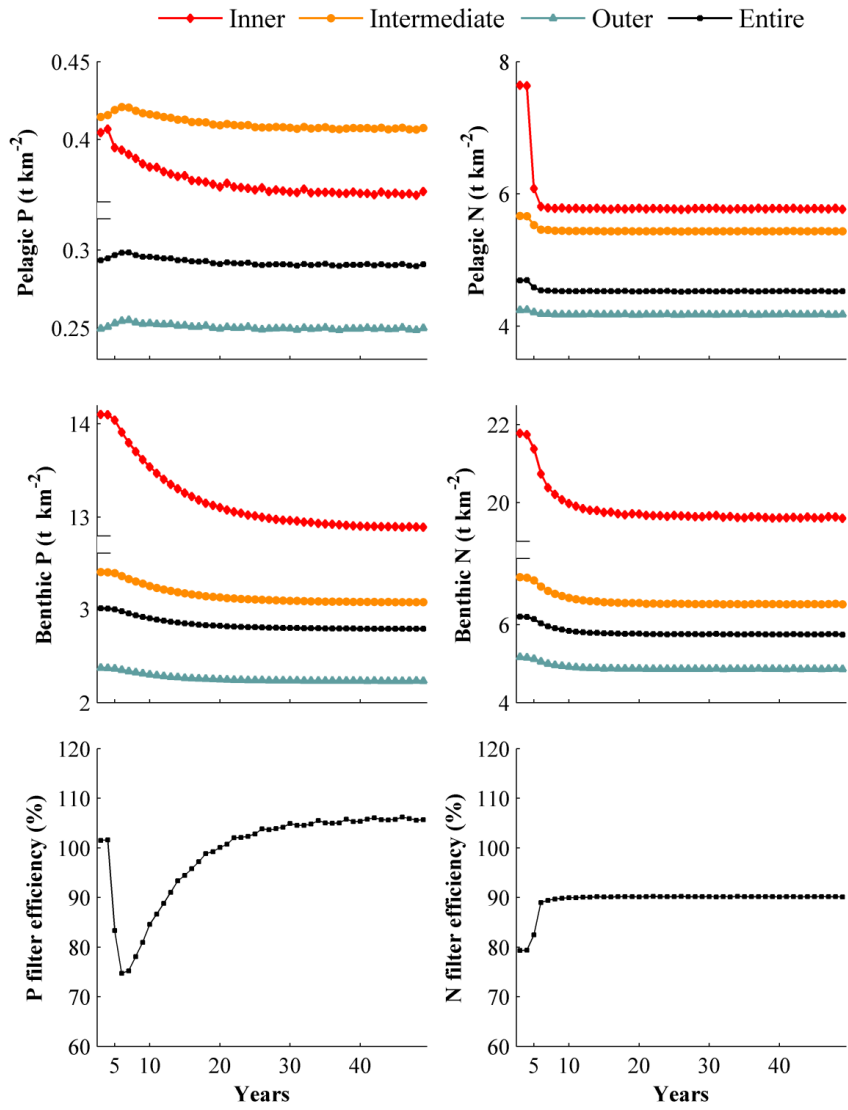
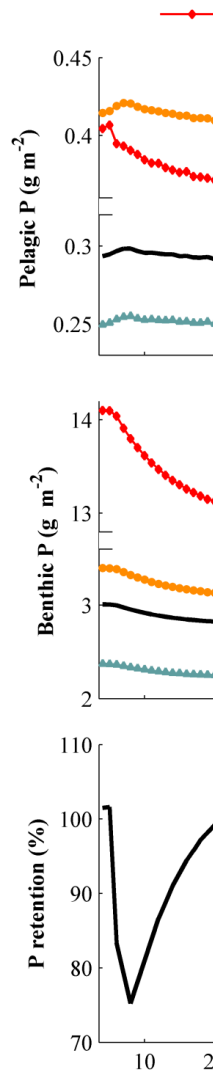


Fig. 14



Borttaet:

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8 Figure captions

Fig.1. The Swedish Coastal zone Model can be used in different areas along the Swedish coast stretching from the Norwegian border in the West to the Finnish border in the North (different colours, left). In the present study the SCM model covers the northern Baltic proper (marked with a red square) and has been used to estimate the coastal filter efficiency of nutrients in the Stockholm inner (red), intermediate (orange) and outer (blue) archipelagos (right). The outlet of river Norrström is marked with a black arrow and the different basins are shown by the black contours.

Borttaget: retention capacity

Fig.2. Schematic figure of the Swedish Coastal and Biogeochemical model, SCOBi. Oxygen and hydrogen sulphide are simplified for clarity.

Fig.3. Available locations with observations (circles and dots) in the Stockholm Archipelago. Model evaluation of temperature, salinity, DIN, DIP and bottom water oxygen concentration was performed at selected stations (circles marked with letters), which are described in Table 1.

Fig.4. The calculation scheme of retention in the study area.

Fig.5. Observed (stars) and modelled (line) monthly outflow (Q_F) and nutrient loads from Lake Mälaren, through Norrström to basin Strömmen for the modelled period (1990-2012). DIN is the sum of nitrate and ammonium.

Fig.6. Average cost function (C) and correlation coefficients, adjusted (1-r) to the range 0-1, for an overview of the model skill at the eight different validation sites (A-G). The individual skills of the different parameters, average seasonal variation (black) and/or the vertical summer (red) and winter (turquoise) profiles of temperature (T), DIN, DIP and oxygen concentrations (O_2) are shown, as well as the combined model skills for all variables (purple cross). Variables within the inner quarter circle and between the two quarter circles are considered to be good and acceptable, respectively, while variables that are outside the quarter circles are not well simulated.

Flyttad (infogning) [4]

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Flyttad uppåt [4]: Fig.8. Average cost function (C) and correlation coefficients, adjusted (1-r) to the range 0-1, for an overview of the model skill at the eight different validation sites (A-G). The individual skills of the different parameters, average seasonal variation (black) and/or the vertical summer (red) and winter (turquoise) profiles of temperature (T), DIN, DIP and oxygen concentrations (O_2) are shown, as well as the combined model skills for all variables (purple cross). Variables within the inner quarter circle and between the two quarter circles are considered to be good and acceptable, respectively, while variables that are outside the quarter circles are not well simulated.

Fig.7. The SCM modelled (lines) and observed (circle and diamond) vertical average profiles (1990-2012) of salinity (a) and concentrations of oxygen (O_2), b), DIN (c) and DIP (d) in the basin Strömmen during winter (turquoise) and summer (red) months. Depth layers with dense number of observations (grey stars) determined the vertical depth intervals (grey shaded area) used in the profile calculations. The standard deviations (horizontal lines) were calculated for the summer and winter values of the observations.

Fig.8. Simulated (lines) and observed averages (squares) of the seasonal variation and the standard deviation (vertical lines) of the observations in the basin Strömmen (1990-2012) of surface temperature (Temp), salinity, DIN and DIP and of the bottom water oxygen concentrations. Time periods with dense number of observations (grey stars) determined the time intervals (grey shaded area) used in the calculations.

Fig.9. Transport scheme of N and P ($t\ yr^{-1}$) from land and atmosphere (top boxes), and the net exchange from the inner, intermediate and outer archipelago (ellipse) towards the open sea. Total retention is the sum of temporary retention (square) and permanent retention (square with round corners). For P burial is the only process that leads to permanent retention, while for N also denitrification removes N. Negative values for the temporary retention means a decrease in the benthic and/or pelagic pools of nutrients.

Borttaget: total

Borttaget: (coloured area)

Borttaget: load ($t\ yr^{-1}$)

Borttaget: and

Borttaget: solid line

Borttaget: diamonds

Borttaget: filled circles

Fig.10. The external annual load and retention ($t\ yr^{-1}$) of P (a, c) and N (b, d) in the entire Stockholm Archipelago for the period 1990-2012. Total load (shaded area) and the contributions from the different sources: rivers and land run off (diamonds), point sources (circles) and atmosphere (solid line) is shown on the top row. The total retention (shaded area) as a sum of permanent retention (solid line) and temporary retention (diamonds) (c, d) is shown on the bottom row.

Borttaget: to the inner (a, d), intermediate (b, e) and outer (c, f) Stockholm Archipelago during the period 1990-2012.

Fig. 11. The retention per area unit ($t\ km^{-2}\ yr^{-1}$) of P (left) and N (right) in each basin of the Stockholm Archipelago.

Fig. 12. The total content ($g\ m^{-2}$) of the pelagic (top) and benthic (bottom) P (left) and N (right) in the inner (diamonds), intermediate (circles), outer (triangles) and entire (black line) Stockholm archipelagos.

Fig. 13. The filter efficiency of P (left) and N (right) versus the logarithmic ratio between the average depth and the freshwater residence time of the study areas ($month\ yr^{-1}$). Data from other studies are from Billen et al. (2011), Hayn et al. (2014), Nielsen et al. (2001) and Nixon et al. (1996). The straight line shows the logarithmic regression for the data from Nixon et al. (1996).

Fig. 14. Pelagic (upper) and benthic (middle) pools of P (left) and N (right) in the inner (red), intermediate (orange), outer (turquoise) and entire (black) Stockholm Archipelago. The filter efficiencies (%) of the nutrient load from land and atmosphere are shown for the entire Stockholm Archipelago (lower), where the small peaks derive from leap years.

Borttaget: Fig. 13. The retention efficiency (%) of P (blue) and N (black) from river, land run-off and atmosphere in the inner archipelago towards the open sea by adding the next area and its input to the calculation. ¶

Borttaget: 4

Borttaget: retention

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9 Tables

Table 1. Number of sampling occasions (Occ) during the number of years, number of months during each year, and number of depths levels that was frequently sampled at the different stations used for validation of model results. The position of the stations can be seen in Fig. 3.

ID	Station name	Basin name	Occ	Years*	Months	Depths**
A	Nyvarp	Sandöfjärden	209	23	8	14
B	Kanholmsfjärden	Kanholmsfjärden	206	23	9	13
C	Solöfjärden	Solöfjärden	213	23	8	14
D	TrälhavetII	Trälhavet	215	23	9	13
E	S. Vaxholmsfjärden	S. Vaxholmsfjärden	131	23	7	8
F	Blomskär	Stora Värtan	141	23	8	9
G	Blockhusudden	Strömmen	249	23	11	16
H	Baggensfjärden	Baggensfjärden	173	20	9	10

* Entire period is 23 years; **Sampled at least half of the sample occasions

Table 2. The maximum concentrations of P and N (mg l^{-1}) in the discharge from sewage treatment plants of different size (person equivalents, pe) and the reduction of P and N loads from rivers and industries (%) in the scenario run with the SCM.

<u>Sewage treatment facilities (pe)</u>	<u>P</u> <u>(mg l^{-1})</u>	<u>N</u> <u>(mg l^{-1})</u>
<u>>50 000</u>	<u>0.1</u>	<u>4</u>
<u>10 000-50 000</u>	<u>0.1</u>	<u>6</u>
<u><10 000</u>	<u>0.15</u>	<u>10</u>
<u>Decrease in land load</u>	<u>(%)</u>	<u>(%)</u>
<u>Industries</u>	<u>10</u>	<u>10</u>
<u>River load</u>	<u>10</u>	<u>15</u>

Table 3. The correlation coefficients (r) between observations (obs) and model results (S-HYPE), and the long term (1990-2012) averages of river outflow (QF) and nutrient loads from Lake Mälaren.

<u>Variable</u>	<u>Units</u>	<u>Average</u> <u>obs</u>	<u>Average</u> <u>S-HYPE</u>	<u>r</u>
Q _F	$10^6 \text{ m}^3 \text{ month}^{-1}$	421	422	0.94
TN	t month^{-1}	270	271	0.93
DIN	t month^{-1}	83	76	0.86
TP	t month^{-1}	13	11	0.87
DIP	t month^{-1}	5.7	5.7	0.79

Borttaget: 2

Table 4. The total land load (rivers, land run-off and atmosphere) of P and N ($t\ yr^{-1}$) to the Stockholm Archipelago, the size of the benthic and pelagic N and P pools (t), the export from the area ($t\ yr^{-1}$) and the filter efficiency (F_{eff}) before and after the nutrient reductions, as well as their percentage changes. The system is in both cases in steady state, thus the benthic and pelagic pools are in balance with the nutrient load.

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	Unit	Initial values	End of period	Change (%)	
P	Total load	$t\ yr^{-1}$	213	186	-13
	Pool*	T	10661	9952	-7
	Export	$t\ yr^{-1}$	-3.5	-11	-207
	F_{eff}	%	101	106	
N	Total load	$t\ yr^{-1}$	7690	6164	-20
	Pool*	T	35196	33216	-6
	Export	$t\ yr^{-1}$	1585	609	-62
	F_{eff}	%	79	90	
N:P**	Molar ratio		42	35	-16

Borttaget: Retention
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Borttaget: Retention

*The sum of benthic and pelagic pools. ** In the inner archipelago.

Borttaget: ¶

¶
Table 4. The maximum concentrations of P and N (mg l⁻¹) in the discharge from sewage treatment plants of different size (person equivalents, pe) and the reduction of P and N loads from rivers and industries (%) in the scenario run with the SCM. ¶

Sewage treatment facilities (pe)

