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

*Elin Almroth-Rosell[*1], Moa Edman[1], Kari Eilola[1], H.E. Markus Meier[2,1], Jörgen Sahlberg[1]*

[1]Swedish Meteorological and Hydrological Institute, Norrköping, Sweden

[2]Leibniz 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

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

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

The Baltic Sea (Fig. 1), located in northern Europe, is an example where the enhanced land load of nutrients to the sea (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 km^2 during year 2010-2014 (Hansson and Andersson, 2014). In the Baltic Sea, most of the coastal zones and the open sea still suffer from eutrophication in spite of reduced nutrient loads since the 1990s (HELCOM, 2010).

The aim with this study is to quantify the filter efficiency in the eutrophic Stockholm Archipelago (see section 2.1) of N and P and to discuss the relative importance of different physical and/or biological processes using the Swedish Coastal zone Model (SCM). In addition, changes in the filter efficiency along the land-sea continuum, from the inner archipelago, through the intermediate and outer archipelago to the open Baltic Sea, will be studied in order to evaluate the effect of the size of the archipelago on the filter efficiency.

After a description of the model system (Section 2) and an evaluation of the results of SCM (Section 3.1), the filter efficiency of the coastal zone is calculated and the effects of a reduced land load of N and P are analyzed (Section 3.2). Conclusions finalize the study (Section 4).

2 Methods

2.1 Study site

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

Fig. 1.

The largest point sources of nutrients to the inner archipelago originate from waste water treatment facilities of Stockholm, which is situated at the outlet of the Lake Mälaren. 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 was in the early 1970s classified as highly eutrophic (Lännergren et al., 2009). In the 1970s the sewage treatment facilities in Stockholm started to chemically precipitate P, which reduced their P load from about 600 t yr^{-1} to about 100 t yr^{-1} (Fig. 3 in Lücke, 2014). The reduction 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). In the mid-1990s there was a further reduction of the P to about 25 t yr^{-1} and the sewage treatment facilities started to reduce the N as well, from about 3000 t yr^{-1} to 1250 t yr^{-1} (Fig. 3 in Lücke, 2014), which 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) 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 transparancy, high concentrations of phytoplankton chlorophyll and areas without any bottom fauna due to low oxygen concentrations.

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-ε 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

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

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.

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

2.2.2 Biogeochemical model (SCOBI)

The SCOBI model describes the biogeochemistry of marine waters in the Baltic Sea and Kattegat (Eilola et al., 2009). Nine pelagic and two benthic variables (Fig. 2) are described in the SCM-SCOBI model. In the pelagic zone three different phytoplankton groups (diatoms, flagellates and others, and cyanobacteria), one zooplankton group, one pool for detritus and three inorganic nutrients pools (nitrate, ammonium and phosphate) are represented. The model also calculates oxygen and hydrogen sulfide concentrations, of which the latter are represented by "negative oxygen" equivalents (1 ml H_2S l^{-1} = −2 ml O_2 l^{-1}) and includes the conversion of sulfate into hydrogen sulfide (Fonselius, 1969). Thus, the negative oxygen corresponds to the amount of oxygen needed to oxidise the hydrogen sulfide. The sediment in the present model is parameterized by one vertically integrated bulk sediment layer (level 3 in Soetaert et al, 2000). Organic material that sinks to the sediment is divided into one benthic nitrogen pool (NBT) and one benthic phosphorus pool (PBT). SCOBI has been used and validated in several studies, both coupled to the basin scale Baltic Sea model PROBE-Baltic (e.g. Marmefelt et al., 1999) and to the three dimensional Rossby Center Ocean model (RCO; e.g. Meier et al., 2011).

In the model the processes of phytoplankton assimilation, mortality and nitrogen fixation, zooplankton grazing, excretion of detritus and dissolved inorganic nitrogen (DIN) and phosphorus (DIP), the oxygen and temperature dependent mineralization of detritus, benthic N and benthic P, nitrification and denitrification are described. Phytoplankton assimilates carbon (C), N and P according to the Redfield molar ratio (C:N:P=106:16:1) and the biomass is represented by chlorophyll (Chl) according to a constant carbon to chlorophyll mass (mg) ratio (C:Chl=50:1). Light attenuation depends on background attenuation due to water and humic substances and a variable attenuation caused by particulate organic matter (phytoplankton, zooplankton and detritus). All particulate variables sink downward through the water column. Predation is used as a closing term to parameterize interactions with higher tropic levels in the ecosystem and move matter from zooplankton to the detrital and inorganic pools. Resuspension of sediment that is important in the open Baltic Sea (Almroth-Rosell et al., 2011) has not yet been implemented in this SCOBI version, but the sediment releases dissolved inorganic nutrients back to the water mass, with the release of phosphate being redox dependent. Some fractions of benthic N and P are assumed to be buried in the sediment as a permanent sink, and are hence removed from the system. For further details of the SCOBI model the reader is referred to Eilola et al. (2009; 2011).

Fig. 2.

2.2.3 Forcing

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

There are two types of land derived forcing; discharge of water and nutrients from both rivers and surface run-off from the drainage area given by the S-HYPE model (Lindström et al., 2010) and point sources representing sewage plants and industries. The run-off is added to the surface water of each basin and no reduction of river nutrients due to precipitation at river-mouths is assumed in this model setup. The point sources of nutrient loads are assigned to the depth levels mostly resembling the actual depth of the discharge. The inorganic riverine nutrient loads are added as DIN and DIP to the SCM. The organic nutrients in the land loads are calculated from the difference between total nitrogen (TN) and DIN, and total phosphorus (TP) and DIP, respectively. 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 fraction of organic nutrient loads that follows the Redfield ratio are assumed to be bioavailable and will be added to the detritus pool in the model, while the remaining fractions of nutrient loads are treated as conservative tracers in the model..

The weather forcing consists of solar insolation, air temperature, wind, relative humidity and cloudiness. The insolation and all the radiation and heat fluxes across the water-air interface are calculated by the PROBE model. The weather variables are taken from a gridded database developed at the Swedish Meteorological and Hydrological Institute (SMHI), using 3-hourly meteorological synoptic monitoring station data, and the depositions of nitrogen species (NHX and NOX) are calculated by the MATCH model (Robertson et al., 1999). For the deposition of phosphate, a literature value of 0.5 kg m^{-2} $month^{-1}$ is used (Areskoug, 1993).

The boundary conditions to the open Baltic Sea is set by vertical mean profiles calculated by a one dimensional PROBE setup for each Baltic open water area and assimilation of monitoring data. The monitoring data used in the assimilation are extracted from the stations MS4, US5B, SR5, BY31 and BY29 (Fig. 1) depending on depth and time, to get the best representation of the open sea's influence on the SCM model domain.

2.3 Evaluation strategy

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

$$r = \frac{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)\left(O_i - \overline{O}\right)}{\sqrt{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2 \sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}} \qquad 2$$

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

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

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

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

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

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

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

Fig. 3.

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). N_2-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 investigate the spatial gradient of retention capacity from the inner coastal zone towards the open Baltic Sea.

Fig. 4.

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

2.4.1 Reduction scenario of the nutrient land load

The SCM is also 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 2 (Kerstin Rosén Nilsson, County Administrative Board of Stockholm, personal communication). The reductions of P and N from land runoff, 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 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 by 12 and 20 %, respectively, to the entire Stockholm Archipelago.

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 2.

Table 2.

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; Strömqvist et al., 2012). An extensive validation is also available in Sahlberg et al. (2008).

Fig. 5.

Table 3.

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.

The objective correlation coefficients (Eq. 2) and the cost function value (Eq. 3) for the different state variables implied correspondingly that the model manage to simulate the average vertical winter and summer profiles with good or acceptable skills in the basin Strömmen (Fig. 6g), 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 a result of the location of the monitoring station.

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

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

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

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

Fig. 6.

Fig. 7.

Fig. 8.

3.2 Retention of nutrients in the Stockholm Archipelago

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

Fig. 9.

Fig. 10.

Largest amounts of P and N were retained in the outer archipelago compared to the intermediate and inner archipelagos (Fig. 9). The retentions of all supplied P and N, including the net import from upstream areas, within the inner, intermediate and outer Stockholm archipelagos amounts to 18 %, 23 % and 48 % for P, respectively, and 14 %, 26 % and 60 % for N, respectively. The area of the three zones increases from inner (109 km^2), to the intermediate (759 km^2) and to the outer archipelago (2360 km^2) and thus, the retention of nutrients seems to increase with increased area. On the other hand, the average of the area specific retention of P and N was for the simulation period highest in the inner archipelago, and decreased towards the open sea (Fig. 11). The permanent retention was during the simulated period on a stable level, while fluctuations in the temporal retention reflects the effect of varying rivierine nutrient input (Fig. 10c,d). The water depth and the residence time are affecting the retention of nutrients, which will be further discussed in Section 3.2.2. The largest part of the total retention in the entire Stockholm Archipelago was permanent, which for P means burial. For N benthic denitrification represented as much as almost 92 % of the permanent retention, burial for less than 8 % and pelagic denitrification was below 1 %.

Fig. 11.

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

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

Fig. 12.

3.2.1 The coastal filter

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

3.2.2 Processes affecting retention

The present study was performed in an area characterised as an eutrophic archipelago in an inland sea with basins having oxic, hypoxic and anoxic bottom waters. The results of the retention are in agreement with results from previous studies (Billen et al., 2011; Hayn et al., 2014; Nielsen et al., 2001; Nixon et al., 1996), but with somewhat lower values in the entire and inner plus intermediate archipelagos (Fig. 13). Their studies were performed in various types of systems: coastal lagoons, drowned river estuaries, coastal embayments, and inland seas in North America and in Europe. Those systems varied from being relatively pristine to systems with large point sources (eutrophic), and they also varied between oxic to hypoxic and/or anoxic conditions. Nixon et al. (1996) showed that the retention of P and N correlated to the log scale of the ratio between the average depth and the residence time of the study areas, which is confirmed by the results from the studies by Billen et al. (2011), Hayn et al. (2014) and Nielsen et al. (2001) as well as by the present study (Fig. 13). In shallow areas larger parts of the sinking particulate organic material may reach all the way down to the sea floor where it can be exposed to retention processes such as burial and denitrification. On the other hand, in a much deeper area a larger part of the organic material may become re-mineralised within the water column on its way down to the sea floor. The nutrients can then be re-used by phytoplankton and/or be further transported out from the system. Long residence times in a system increase the time of exposure for biogeochemical transformation processes and sedimentation within the system and larger parts of the nutrients may be retained. These two parameters therefore affect the retention of nutrients (Fig. 13) and the correlation implies that the retention occurs mostly in the sediment due to processes such as burial and denitrification, which is the case in the present model study. However, in the present study no clear relation was found between the average depth (10-20 m for all three areas) and the filter efficiency. Actually, also Nixon et al. (1996) discussed this and concluded that including the depth in the analyze of the retention vs residence time did not much improve the regression. The filter efficiency in the present study did, however, increase with 4-5 % yr^{-1} as the fresh water residence time increased in the land to sea continuum.

Fig. 13.

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

Denitrification has in earlier studies been shown to increase in areas with longer residence times (Nixon et al., 1996, Finlay et al., 2013). This is confirmed also in a study with a two-layer hydrodynamic channel model used in the Randers Fjord (Nielsen et al., 2001). The residence time was only on average six days and the filter efficiencies of N and P were estimated to 10 % and 9 %, respectively, which were lower compared to in the Stockholm Archipelago with a residence time in the inner archipelago of about 110 days. The denitrified proportion of the permanent retained N was also lower, about 60 % compared to in the Stockholm Archipelago (92 %). Waters with longer residence times are less ventilated at the sediment interface. While this is certainly true for stratified and enclosed coastal regions it should, however, be remembered that in other regions a well-mixed water volume can be ventilated from the atmosphere. Benthic primary producers and benthic fauna are also important factors for the retention of nutrients in shallow coastal ecosystems (McGlathery et al., 2007; Norkko et al., 2012). Assimilation of nutrients by algae does not directly change the pools of nutrients, but transfer the nutrients into organic material. Plant uptake can e.g. lead to increased burial and also influence on the oxygen dependent biogeochemical processes in the sediment due the plant metabolism (McGlathery et al., 2007).These processes are not yet implemented in the SCM, and therefore not included in the present study.

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

3.2.3 Response to reduction scenario of the nutrient land load

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

In the reduction scenario the transport of N to the open sea from the Stockholm Archipelago decreases by 62% within four years (Table 4). The filter efficiency of N in the entire archipelago increases at the same time from 79 % to 90 % as a result of the load reduction. The longer response time of P compared to N is observed also in the filter efficiency (Fig. 14).

The filter efficiency of P at the end of the spin-up run is about 100 %. This implies that under the 2010 conditions, all the P land load is retained in the Stockholm Archipelago when the system is in steady state. This is not the case when the original model forcing is used, which implies that the Stockholm archipelago is still adjusting to the load reductions already implemented. Thus, the coastal region might under present conditions continue to improve without further actions.

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

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

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

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

Table 4.

Fig. 14.

4 Conclusion

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

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

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

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7 Figures

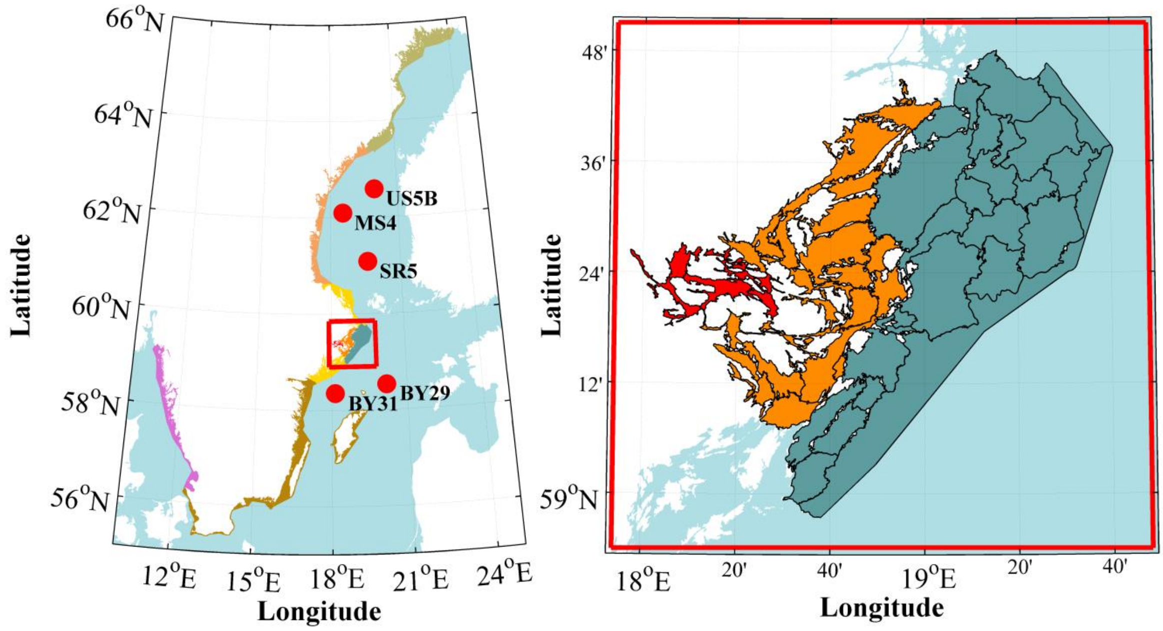


Fig. 1.

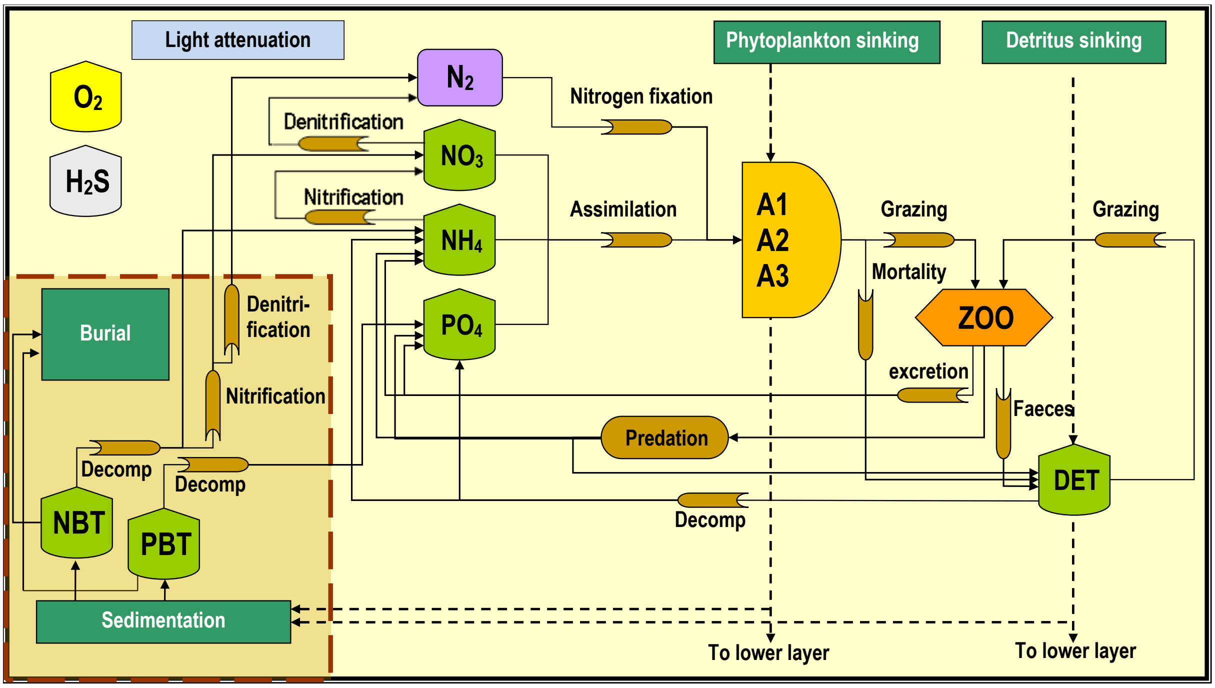

Light attenuation
Phytoplankton sinking
Detritus sinking
O2
H2S
N2
NO3
NH4
PO4
Nitrogen fixation
Denitrification
Nitrification
Assimilation
A1
A2
A3
Grazing
Grazing
Mortality
ZOO
excretion
Faeces
Predation
DET
Decomp
Burial
Denitri-
fication
Nitrification
Decomp
Decomp
NBT
PBT
Sedimentation
To lower layer
To lower layer

Fig.2.

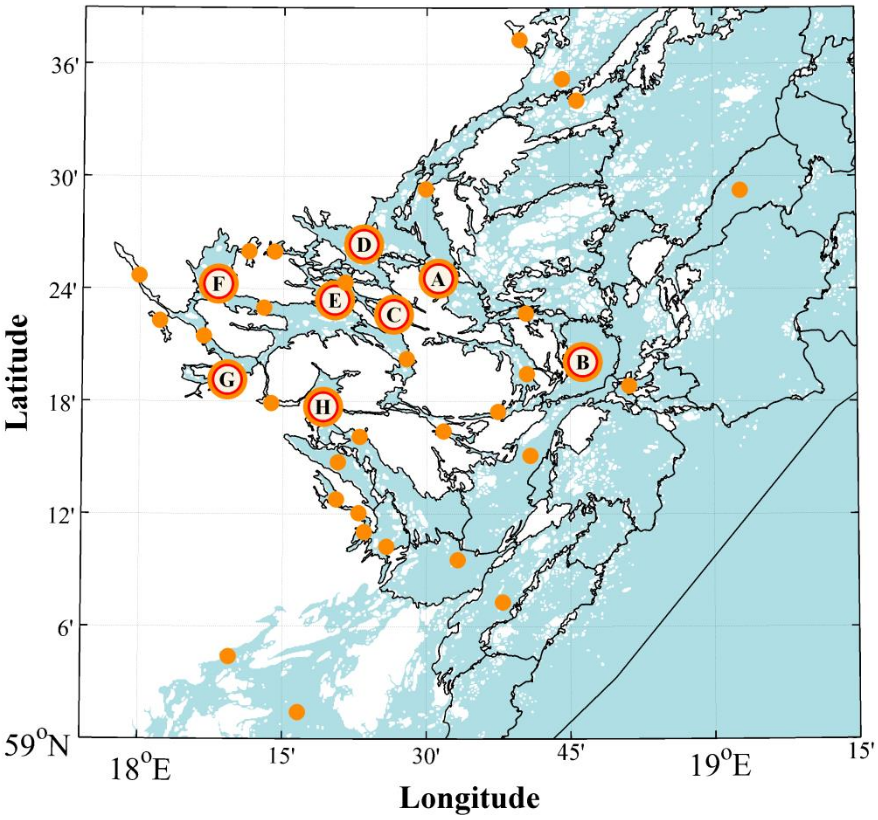

36'
30'
24'
18'
12'
6'
59°N
18°E
15'
30'
45'
19°E
15'
Latitude
Longitude
A
B
C
D
E
F
G
H

Fig. 3.

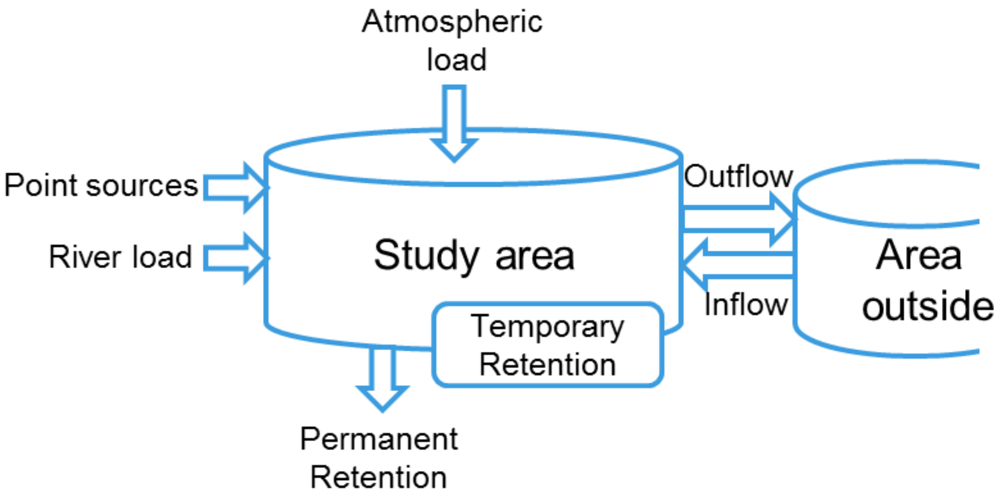

Atmospheric load
Point sources
River load
Study area
Outflow
Inflow
Area outside
Temporary Retention
Permanent Retention

Fig. 4.

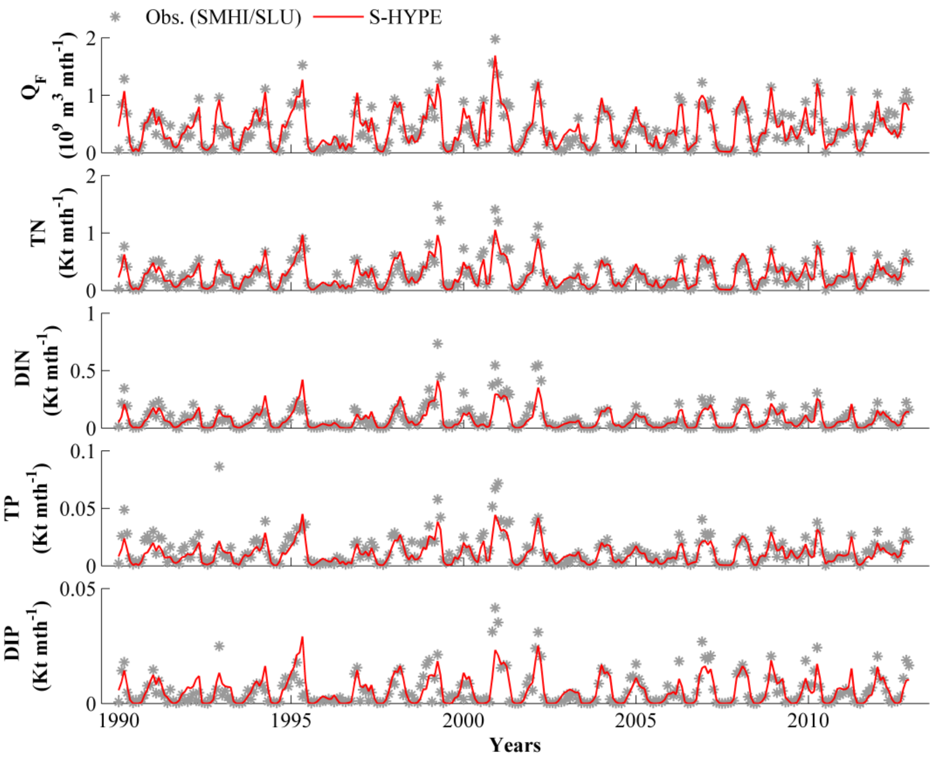

Obs. (SMHI/SLU)
S-HYPE
Q_F (10^9 m^3 mth^{-1})
TN (Kt mth^{-1})
DIN (Kt mth^{-1})
TP (Kt mth^{-1})
DIP (Kt mth^{-1})
Years

Fig. 5.

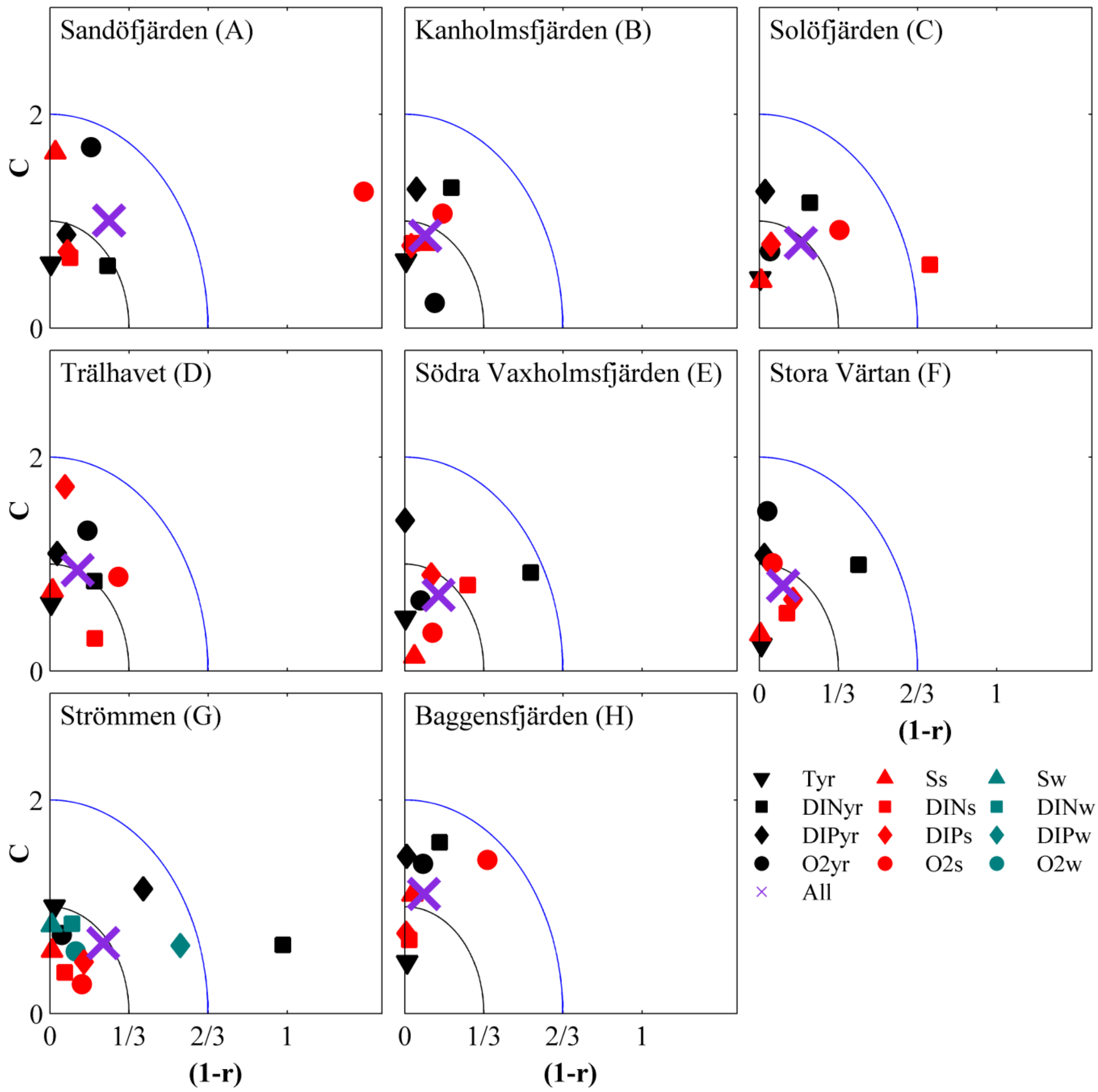

Sandöfjärden (A)
Kanholmsfjärden (B)
Solöfjärden (C)
Trälhavet (D)
Södra Vaxholmsfjärden (E)
Stora Värtan (F)
Strömmen (G)
Baggensfjärden (H)
C
0
2
0
1/3
2/3
1
(1-r)
Tyr
DINyr
DIPyr
O2yr
All
Ss
DINs
DIPs
O2s
Sw
DINw
DIPw
O2w

Fig. 6.

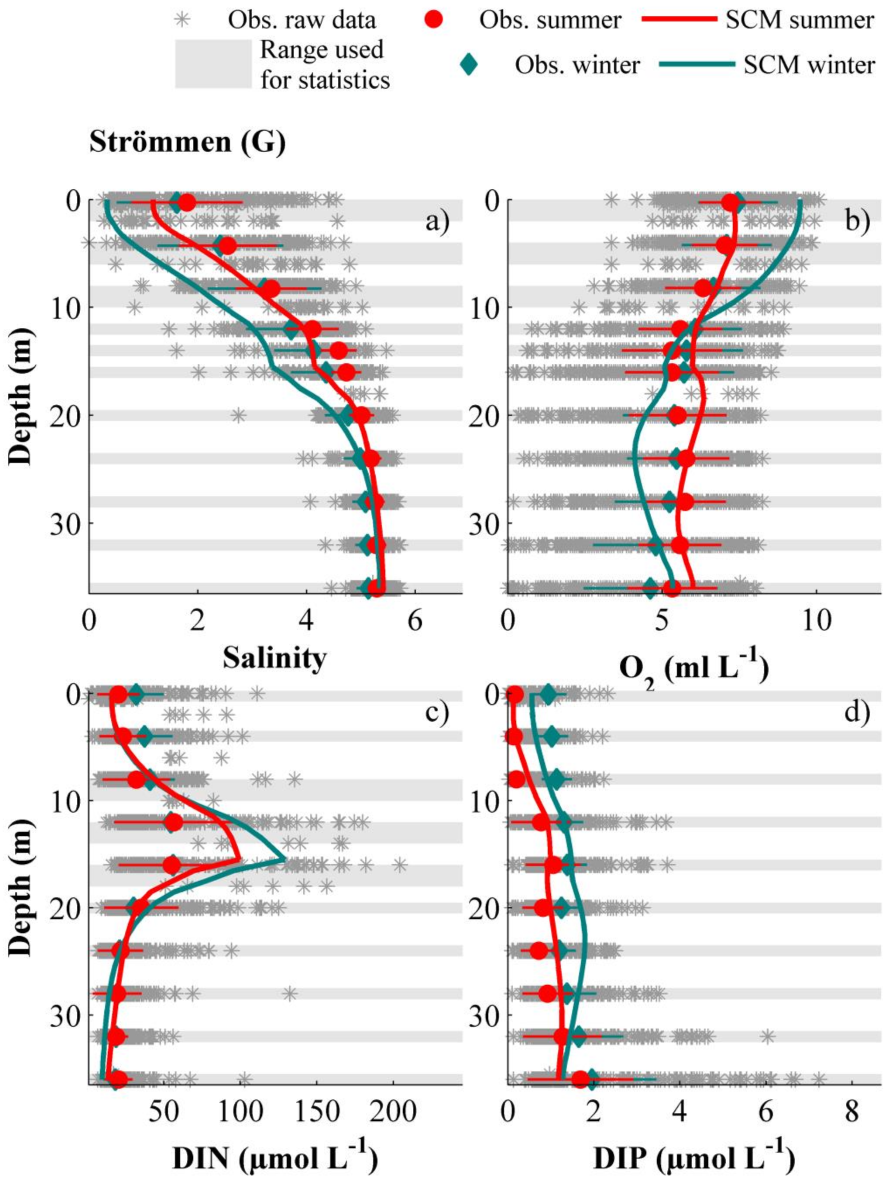

Obs. raw data
Obs. summer
SCM summer
Range used for statistics
Obs. winter
SCM winter
Strömmen (G)
a)
b)
c)
d)
Depth (m)
Salinity
O2 (ml L-1)
DIN (µmol L-1)
DIP (µmol L-1)

Fig. 7.

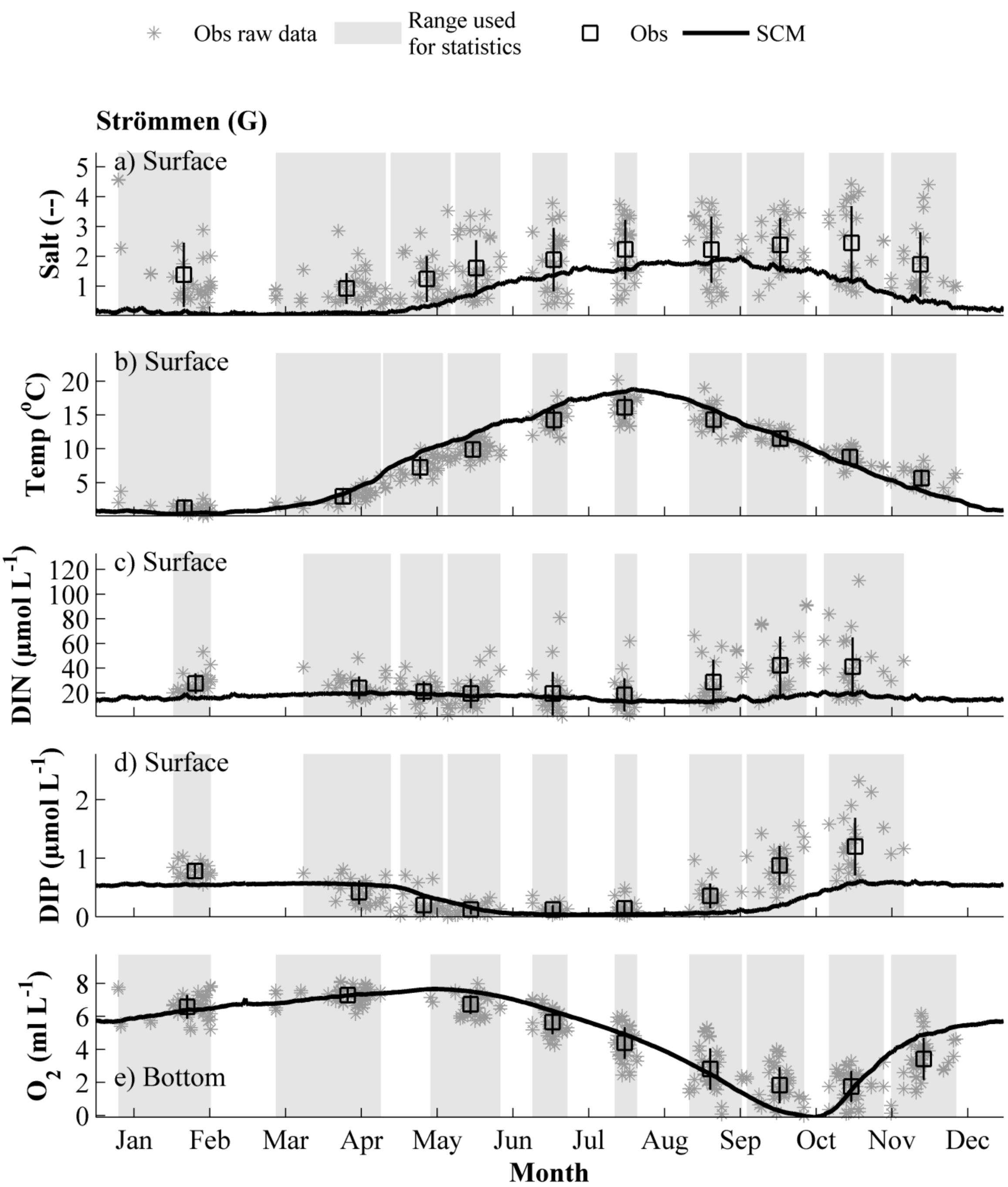
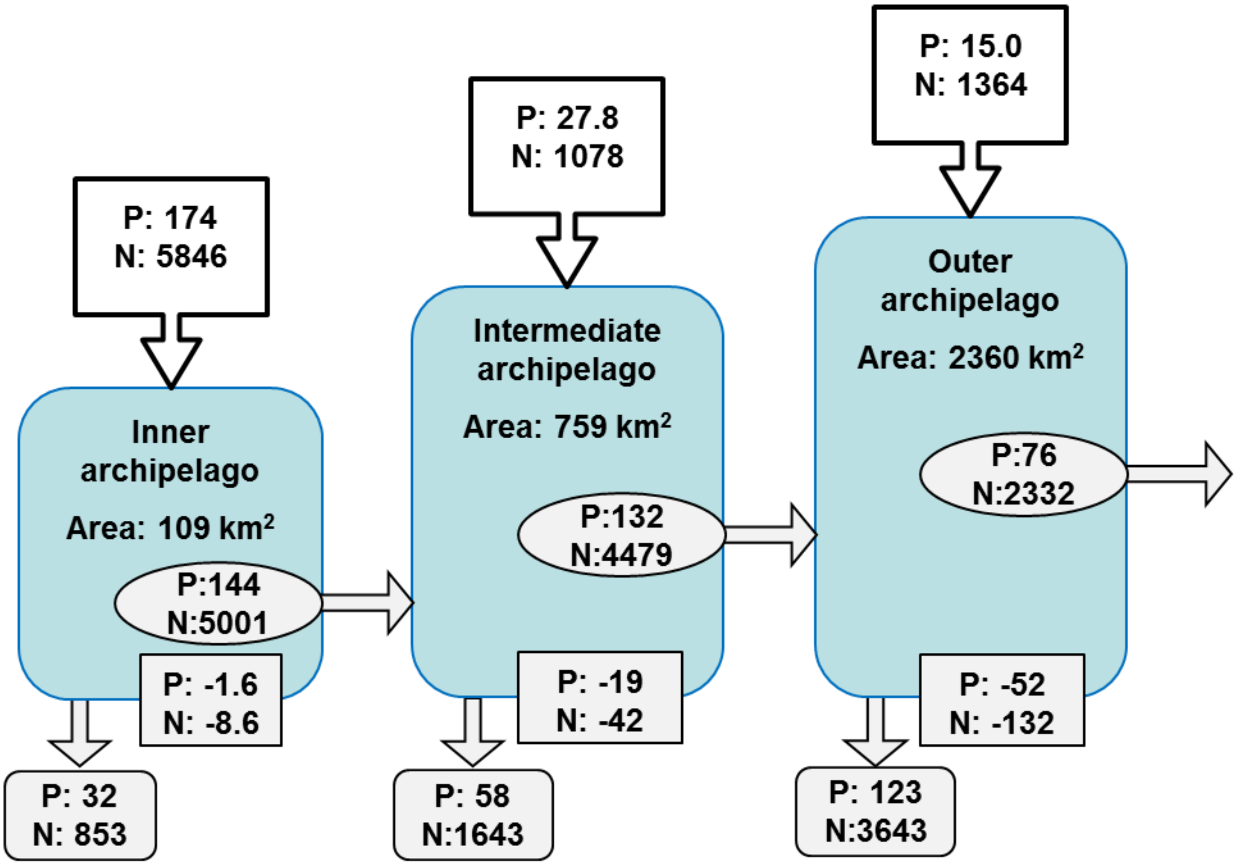
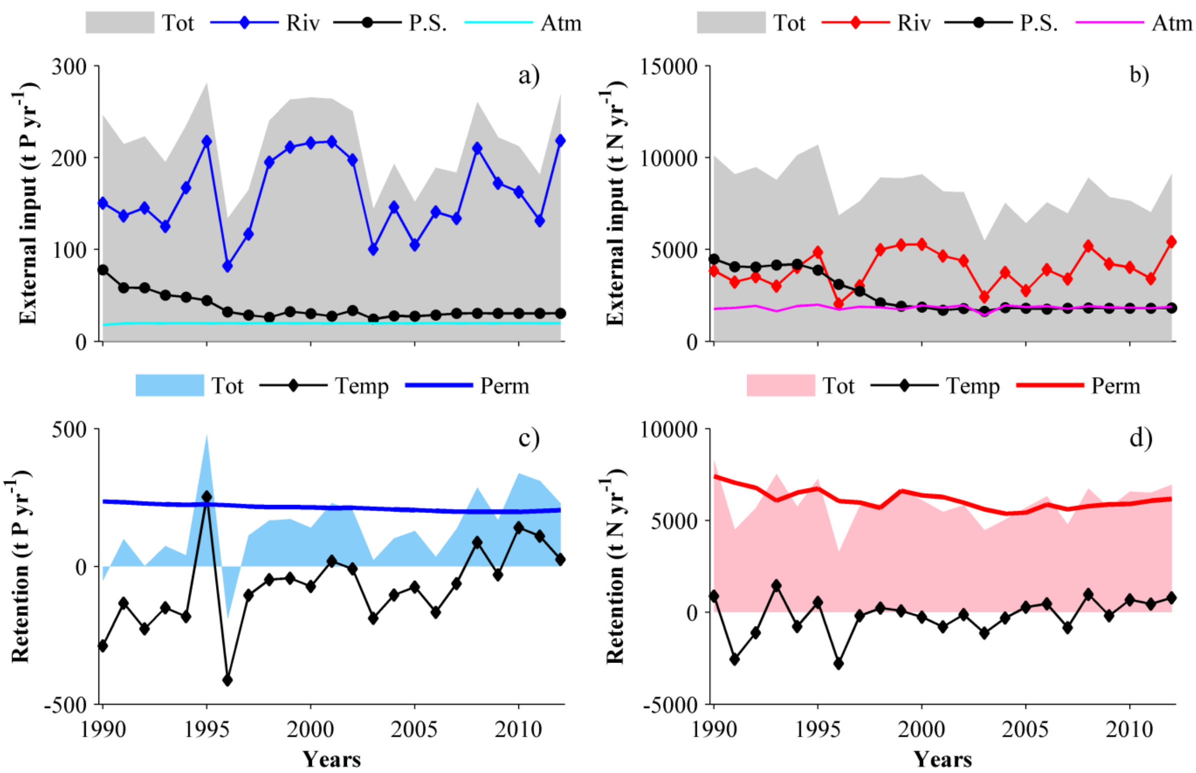

Obs raw data
Range used for statistics
Obs
SCM
Strömmen (G)
a) Surface
Salt (--)
b) Surface
Temp (°C)
c) Surface
DIN (µmol L-1)
d) Surface
DIP (µmol L-1)
e) Bottom
O2 (ml L-1)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

Fig. 8.



P: 174
N: 5846
P: 27.8
N: 1078
P: 15.0
N: 1364
Inner archipelago
Area: 109 km²
Intermediate archipelago
Area: 759 km²
Outer archipelago
Area: 2360 km²
P:144
N:5001
P:132
N:4479
P:76
N:2332
P: -1.6
N: -8.6
P: -19
N: -42
P: -52
N: -132
P: 32
N: 853
P: 58
N:1643
P: 123
N:3643

Fig. 9.



Tot
Riv
P.S.
Atm
a)
b)
External input (t P yr-1)
External input (t N yr-1)
300
200
100
0
15000
10000
5000
0
Tot
Temp
Perm
c)
d)
Retention (t P yr-1)
Retention (t N yr-1)
500
0
-500
10000
5000
0
-5000
1990
1995
2000
2005
2010
Years

Fig. 10.

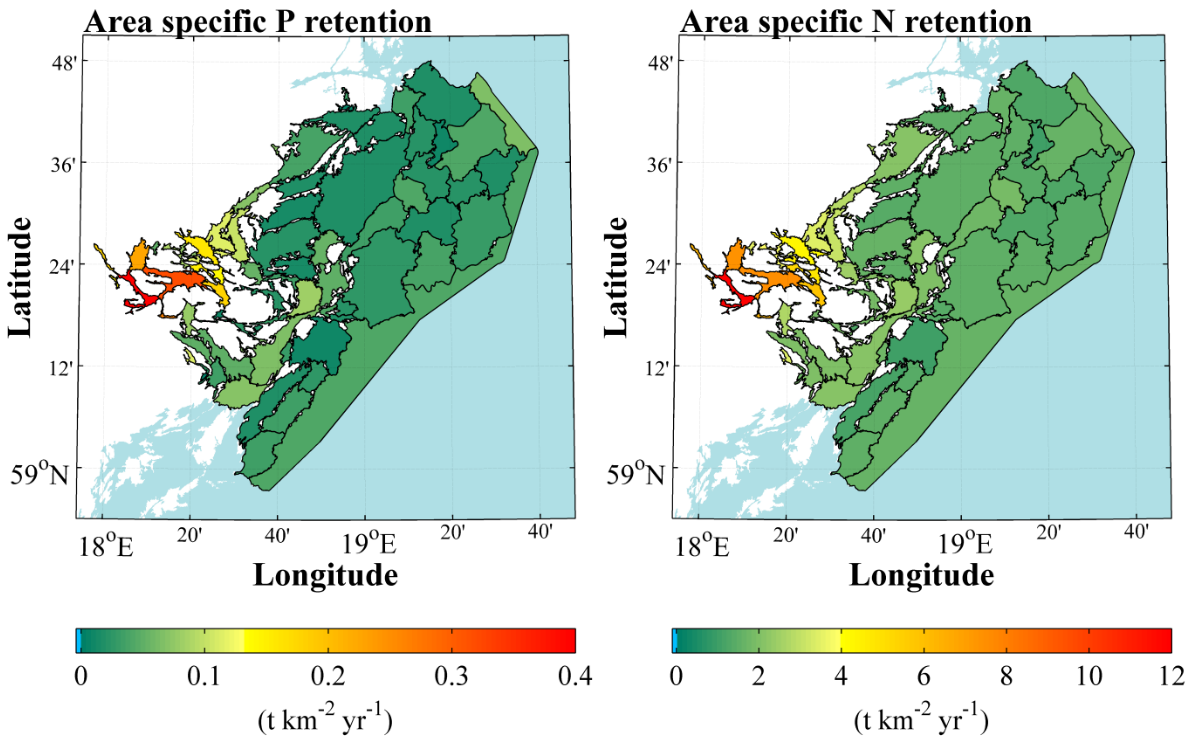
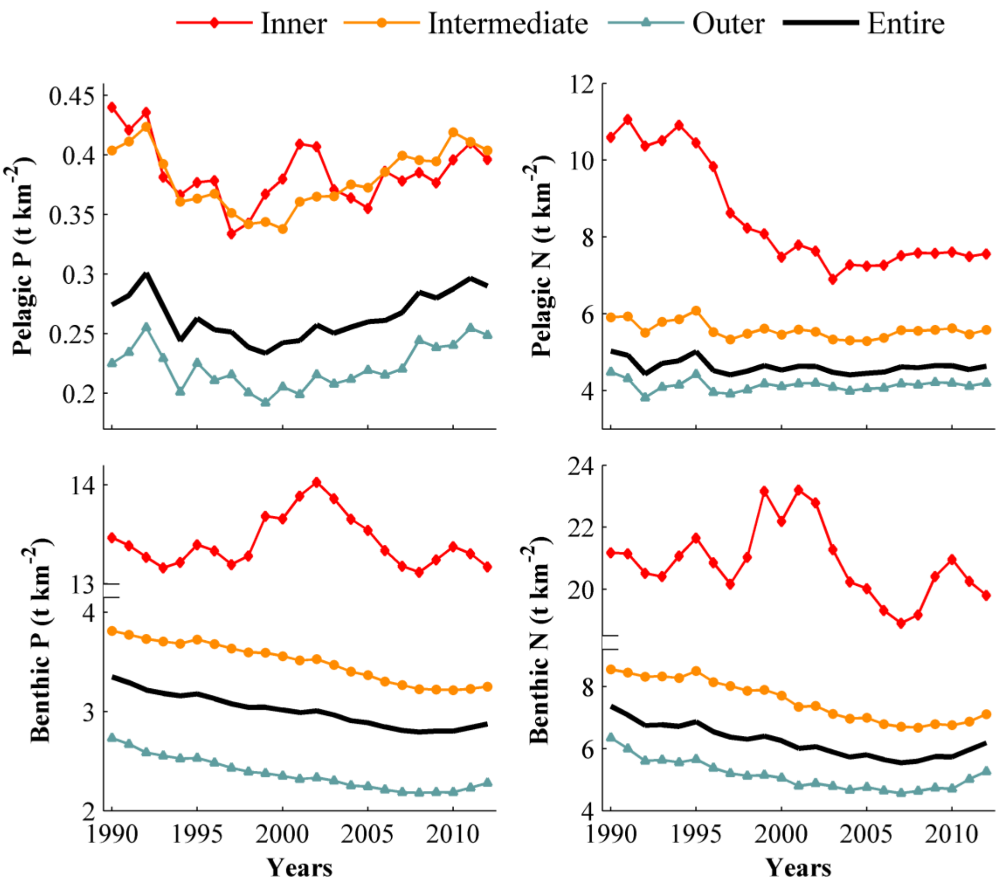

Area specific P retention
Area specific N retention
Latitude
Longitude
48'
36'
24'
12'
59°N
18°E
20'
40'
19°E
0
0.1
0.2
0.3
0.4
2
4
6
8
10
12
(t km-2 yr-1)

Fig. 11.



Inner
Intermediate
Outer
Entire
Pelagic P (t km-2)
Pelagic N (t km-2)
Benthic P (t km-2)
Benthic N (t km-2)
Years
Years

Fig. 12.

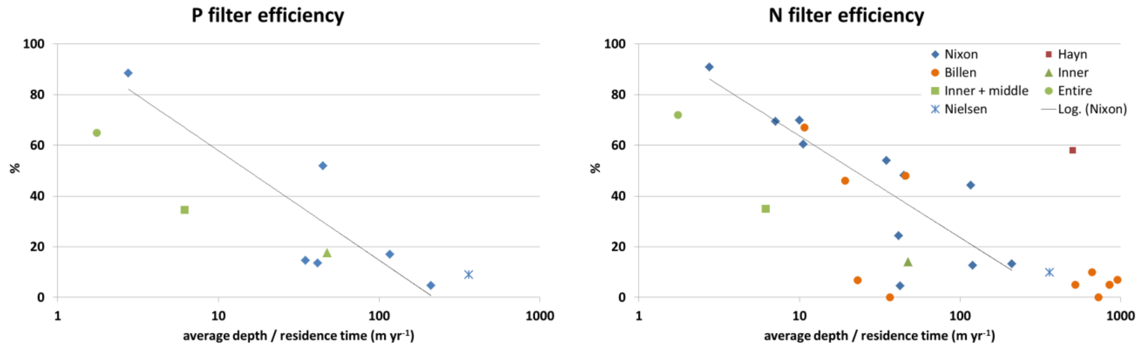

P filter efficiency
N filter efficiency
%
average depth / residence time (m yr-1)
Nixon
Billen
Inner + middle
Nielsen
Hayn
Inner
Entire
Log. (Nixon)
100
80
60
40
20
0
1
10
100
1000

Fig. 13.

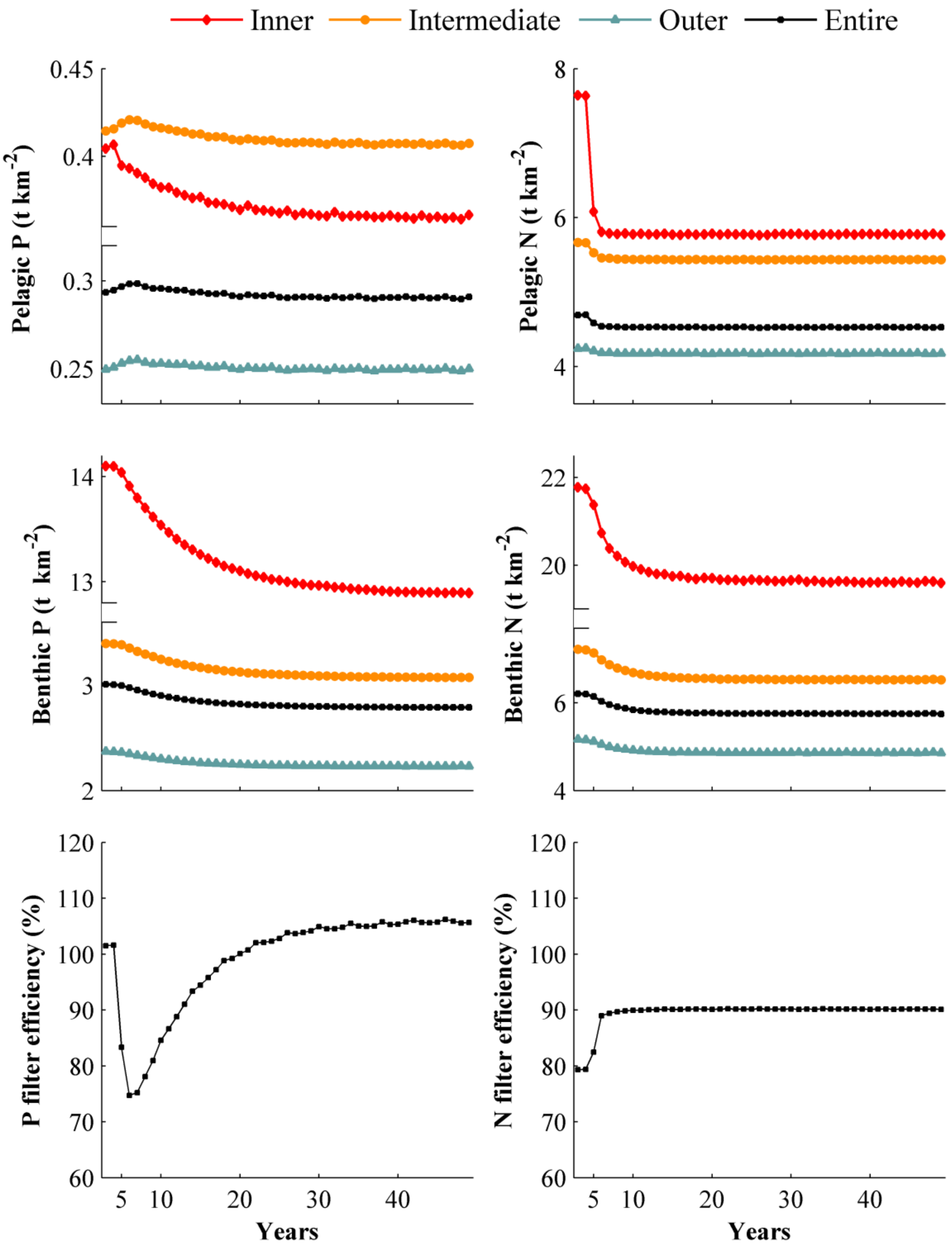

Inner
Intermediate
Outer
Entire
Pelagic P (t km^{-2})
0.45
0.4
0.3
0.25
Pelagic N (t km^{-2})
8
6
4
Benthic P (t km^{-2})
14
13
3
2
Benthic N (t km^{-2})
22
20
6
4
P filter efficiency (%)
120
110
100
90
80
70
60
N filter efficiency (%)
5
10
20
30
40
Years

Fig. 14

8 Figure captions

Fig.1. The Swedish Coastal zone Model can be used in different areas along the Swedish coast streching 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 northen 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.

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.

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 deviaton (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.

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.

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.

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.

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

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.

Variable	**Units**	**Average obs**	**Average S-HYPE**	**r**
Q_F	10^6 m³ $month^{-1}$	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

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.

		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

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