The eutrophication in the Kattegat has recently been evaluated by an international group of experts. They recommended that Sweden should focus on reductions in nitrogen loading. The aim of this work is to present nutrient fluxes to, within and from the Kattegat as a basis for remedial actions. Important nutrient fluxes to the bioproductive surface-water layer in the Kattegat emanate from the Baltic Sea, which is evident by looking at the catchment area for the entire Baltic Sea in relation to the relatively small catchment area draining directly into the Kattegat. This book motivates an “optimal” strategy to reduce eutrophication in the Kattegat. The costs for this strategy would be about 400 million euro per year if this is done in a cost-effective manner, which means a focus on reducing 10,000 tons per year of phosphorus discharged by rivers to the most polluted coastal areas in the Baltic Sea. The costs to reduce 15,000 tons per year of phosphorus and 133,000 tons per year of nitrogen according to the Baltic Sea Action Plan, which was signed by the Baltic States in November 2007, would be about 3300 million euro per year. That is, 2900 million euro per year higher than the strategy advocated in this work to reach the goal that the water clarity in the Baltic Sea including the Kattegat would return to what it was 100 years ago.
Modeling Nutrient Fluxes to, within and from the Kattegat to Find an Optimal, Cost-Efficient Swedish Remedial Strategy

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### Introduction and aim

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### Water, SPM, nutrient and bioindicator modeling

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Abstract in English
An international group of experts have recently evaluated the eutrophication in the Kattegat and recommended that Sweden should focus on reductions in nitrogen loading and on measures to reduce atmospheric deposition of N (Boesch et al., 2008). The aim of this work is first to give background information on the conditions in the Kattegat, e.g., on the morphometry including the criteria to define the limit for the surface-water layer (from the theoretical wave base). Chapter 3 presents the water fluxes to, within and from the Kattegat. These fluxes are important for the quantification of all fluxes of salt, phosphorus, nitrogen and SPM (suspended particulate matter) regulating the concentrations of these substances. Chapter 3 also gives approaches to predict chlorophyll-a concentrations and Secchi depths from light conditions and dynamically modeled values of P, N, SPM and salinity. The water fluxes determined from the CoastMab-model (a general, dynamic, process-based mass-balance model) for salt are used throughout this modeling. It has been demonstrated that CoastMab for P, which prior to this work has been validated for many independent aquatic systems and been demonstrated to predict very well, also predicts P-, N-concentrations in water and sediments, and also the target bioindicators in the Kattegat well. Many tests have been carried out to lower the eutrophication in the Kattegat. Significant nutrient fluxes to the bioproductive surface-water layer in the Kattegat emanate from the Baltic Sea, which is evident by looking at the catchment area for the Baltic Sea, including the Baltic States, parts of Russia, Belarus and Germany, Poland, Finland and Sweden in relation to the catchment area draining directly into the Kattegat (from SW Sweden and parts of Denmark). The dominating deep-water fluxes to the Kattegat come from the Skagerrak. A reduced eutrophication implies a lowering of the primary production, which will lead to reduced secondary production, including zooplankton and fish; it would likely also increase acidification (since this is related to primary production); and it could increase concentrations of organic toxins in fish – “in the clearest waters swim the most toxic fish”. The strategy that one should ask for should also concur with some practical constraints, e.g., it is not realistic to reduce all anthropogenic P- or N-discharges. For countries where major investments in nutrient reductions have already been made, it will be increasingly expensive to reduce the remaining tons. In the “optimal” scenario, about 10,000 t/yr of P is being reduced and also N-reductions. It should, however, be noted that it is not possible to provide scientifically relevant predictions how the Baltic Sea system would respond to reductions in nitrogen loading since there are major uncertainties related to the quantification of atmospheric N-fixation, wet and dry deposition of N, the algorithm regulating the particulate fraction for N and hence also sedimentation of particulate N and denitrification. For the Kattegat, however, atmospheric N-fixation has been neglected because there are no significant amounts of N-fixating cyanobacteria in this system; the atmospheric deposition used in this modeling comes from the OSPAR-model (SMHI) and should be reliable in terms of order-of-magnitude values; denitrification is uncertain and has been treated as a residual term in the mass-balance for N. No such calibrations have been done in the mass-balances for P (i.e., CoastMab is used directly without any tuning) or SPM. The costs for the “optimal” strategy would likely be about 400 million euro/yr if this is done in a cost-effective manner, which means a focus on P-reductions connected to the most polluted coastal areas in the Baltic Sea (the “hotspots”). Evidently, there would be major differences in these costs depending on country, method to reduce P and N, etc. To achieve cost-efficiency, the money allocated for Swedish nutrient reductions should preferably go to building sewage treatment plants in the Baltic countries and Poland. The costs to reduce 15,016 t/yr of P and 133,170 t/yr of N according to HELCOM would be 3300 million/yr. That is 2900 million euro/yr higher than the “optimal” strategy advocated in this work.
Kort sammanfattning på svenska

En internationell expertgrupp (Boesch et al., 2008), som arbetat på uppdrag av Naturvårdsverket för att utvärdera kunskapsläget vad gäller övergödningen i Kattegatt och ge förslag på lämpliga åtgärder för att förbättra situationen, har rekommenderat att Sverige i första hand bör försöka minska kvävetransporter från svensk jordbruksmark och den atmosfäriska kvävedeposition till Kattegatt, Skagerrak och svenska Västkusten. I detta arbete har en generell, validerad massbalansmodell (CoastMab), som tidigare inte testats för Kattegatt, använts. Validerad betyder att denna modell testats i ett 30-tal kustområden av olika storlek och karaktär (allt från Svarta havet, Atlantkusten till Bottenhavet) och vid dessa tester, som gjorts utan områdesspecifika kalibreringar ("tuning"), visat sig prediktera bl.a. fosforkoncentrationer, suspenderat partikulärt material (SPM), sedimentation, klorofyll och sikttdjup, mycket väl, ofta inom det intervall som ges av osäkerheten i de empiriska kontrollvärdena. För kväve finns ingen motsvarande generellt användbar, validerad processbaserad massbalansmodell. Det beror bl.a. på att för kväve finns flera viktiga substansspecifika transportprocesser för vilka inga generella värdestade ekvationer finns.

De figurer i detta arbete som presenterar de olika årsbudgeterna för vatten, salt, fosfor, suspenderat partikulärt material och kväve visar att mycket stora följen av vatten och närsalter till Kattegatts bioproduktiva ytlager (0-40 m) kommer från Östersjön. Detta borde vara enkelt att förstå eftersom allt vatten från hela Östersjöns mycket stora avrinningsområde, som omfattar Finland, delar av Ryssland, Baltikum, Polen, delar av Tyskland, Vitryssland, Danmark och Sverige, rinner ut i Kattegatt, och detta avrinningsområde är många gånger större än de delar av sydvästra Sverige och Danmark, som direkt avvattnas till Kattegatt. Detta betyder i detta sammanhang, liksom i alla liknande sammanhang, att man i första hand måste åtgärda de största tillflödena för att åstadkomma de mest genomgripande förändringarna.

Utifrån massbalansberäkningarna redovisas en ”optimal” åtgärdsstrategi för att minska övergödningen i Kattegatt. Detta är det förslaget skiljer sig från expertgruppens förslag och innebär att resurserna bör fokuseras mot att reducera främst fosforflödena till Östersjöns mest eutrofierade områden (dvs Finska viken, Rigabukten, kustområdet utanför Kaliningrad och Oders och Wistulas mynningsområden) med totalt ca 10,000 t fosfor per år (och inte med 15,000 ton fosfor per år, som anges i ”Baltic Sea Action Plan”). Det är inte möjligt för närvarande att på ett vetenskapligt ansvarsfullt sätt förutsäga hur Östersjöen skulle svara på kvävereduktioner. Men om man antar att en stor del av fosforreductionerna skulle kunna genomföras så att de även medför kvävereduktioner och också reduktioner i tillförseln av suspenderat partikulärt material (SPM), då redovisas hur Kattegatt skulle svara på sådana förändringar. Den totala kostnaden för att reducera 15,016 ton fosfor per år och 133,170 ton kväve per år enligt ”Baltic Sea Action Plan” har angetts till 3300 miljoner euro per år. Det är 2900 miljoner euro per år dyrare än den strategi som presenteras i detta arbete. Med den strategi som presenterats här skulle övergödningsläget i Östersjön inklusive Kattegatt återgå till förhållandena som de var mellan 1900 och 1920 innan de stora förändringarna ägde rum mellan 1920 och 1980. Det skall noteras att mycket små förändringar också skett i Kattegatt de senaste 10 till 15 åren. På det hela taget gäller att de pengar som allokeras enligt BSAP för att minska närsaltsbelastningen från Sverige skulle göra mer nytta (större reduktion i kg per insatt krona) för att minska övergödningen i Östersjön inklusive Kattegatt om pengarna främst kanaliserades till kostnadseffektiva forsförreductioner i första hand i Polen och de Baltiska staterna.
1. Introduction
1.1. Background and aim of the study

An international group of experts have recently evaluated the eutrophication in the Kattegat and recommended to the Swedish Environmental Protection Agency that Sweden should focus remedial efforts on reductions in nitrogen loading from agricultural areas and on measures to reduce atmospheric deposition of nitrogen and they also stressed the importance of international co-operations to combat the eutrophication in the Baltic Sea including the Kattegat (Boesch et al., 2008). Boesch et al. (2008) also gave a literature review related to the conditions in the Kattegat and this will not be repeated in this work. The international group of experts also concluded from their literature review that there were major uncertainties on the nutrient fluxes to and from the Kattegat/Skagerrak system and this is one of the reasons why this work was initiated.

Nitrogen reductions related to agricultural practices are generally very expensive with prices in the range from 4 to 15 euro per kg (Elofsson and Gren, 2004). According to Håkansson (2007), the Kattegat receives annually about 41.4 kt nitrogen from Swedish rivers including 20.8 kt from agriculture. Eilola and Sahlberg (2006) have presented a scenario where 35% of Swedish tributary N-fluxes are reduced and this would cost from 54 to 220 million euro per year and they also showed that this would cause only marginal effects on the Kattegat-Skagerrak system. Those calculations were done using the OSPAR-model (see also Håkansson, 2007), which is basically an "oceanographic" model applied in this context for the entire Kattegat-Skagerrak system including several coastal areas treated as separate and communicating basins. In this work, a different modeling approach will be used since different modeling approaches may have different strong and weak points. Fig. 1.1 gives nutrient budgets for nitrogen and phosphorus from the OSPAR-modeling for the Kattegat-Skagerrak system. The results presented in this work using the CoastMab-model (see Håkanson and Bryhn, 2008a) may be compared with the results in fig. 1.1. Note, however, that this work will only discuss the nutrient fluxes to, within and from the Kattegat, so several of the presuppositions and fluxes given in fig. 1.1 are not directly comparable with the results that will be presented in this work.

It should be stressed that fig. 1.1 does not inform about:

- How much of the inflowing water from the North Sea that is transported as a surface-water flux and/or deep-water flux.
- Sedimentation, resuspension, diffusion, mixing, biouptake or any internal transport processes for nitrogen; and only burial for phosphorus.
- Inflow and outflow (to and from) the Kattegat-Skagerrak system and the North Sea and the Baltic Sea, only net annual inflow, which means that this figure does not provide information so that the fluxes from land that may be reduced by remedial actions can be put in a proper context where all fluxes to the system are shown.

The international experts (Boesch et al., 2008) did not base their advice on results from validated mass-balance models but more on general analogies with results and data from other systems. Validated process-based mass-balance models are - categorically - the only tool to quantify fluxes, concentrations and amounts and to make predictions of how concentrations would change in response to reductions in...
The aim of this work has been to:
1. Apply the CoastMab-model to the Kattegat directly and without any “tuning” to quantify the nutrient fluxes to, within and from the system.
2. Define the driving variables related to the morphometry of the Kattegat system and also the basic structure of the model (i.e., how the water and sediment compartments are defined).
3. Present the driving variables related to salinity conditions, water temperatures, water discharges and nutrient concentrations and also trend analysis for these variables for the study period (1995 to 2008).
4. When the presuppositions have been defined, several remedial scenarios will also be given, which are meant to demonstrate how the Kattegat would likely respond to changes in tributary P- and N-loading directly to the Kattegat, from the Baltic Sea and from the Skagerrak.
5. Finally, based on those results, recommendations will be given for a remedial strategy to reduce the eutrophication in the Kattegat.

The transport processes quantified in this model are general and apply for all substances in most aquatic systems, but there are also substance-specific parts (e.g., related to the particulate fraction, criteria for diffusion and denitrification). This is not a model where the user should make any tuning, calibrations or change model constants. The idea is to have a model based on general and mechanistically correct algorithms describing the monthly transport processes (sedimentation, resuspension,
Introduction and aim

diffusion, mixing, etc.) at the ecosystem scale (i.e., for entire defined basins) and to calculate the role of the different transport processes and how a given system would likely react to changes in inflow related to natural changes and anthropogenic reductions of water pollutants.

It should also be stressed that the conditions in the open-water areas of the Kattegat influence the smaller coastal archipelago systems very much; typical water retention times for the surface-water in smaller coastal areas along the Swedish coastline is about 5 days (see Håkanson et al., 1986). This means that also for relatively enclosed coastal areas deep in archipelago areas with water retention times of about 15 days, the entire surface-water volume is exchanged two times every month. This also means that "one cannot save coastal areas unless one first saves the sea". The coastal areas are often regarded as "nurseries and pantries" for the sea. So, the conditions in the sea outside a given coastal area influence the transport of water pollutants to and from coastal areas, also in estuaries. The coastal area, the outside sea and adjacent coastal areas should be regarded as series of interrelated, communicating basins.

For persons not familiar with the Baltic Sea system, fig. 1.2 gives a geographical overview and the names of the main basins. The salinity decreases from over 30 psu in the Skagerrak to about 3 psu in the northern part of the Bothnian Bay. It is easy to imagine the enormous water dynamics of the system which is responsible for the inflow of salt water from the south (Kattegat and Skagerrak), the freshwater outflow and the rotation of the earth (the Coriolis force), the variations in winds and air pressures that causes the necessary mixing and water transport causing this salinity gradient. These salinities demonstrate that the Baltic Sea system including the Kattegat is a very dynamic system. The catchment area of the entire Baltic Sea system is many times larger than the Swedish and Danish areas draining directly into the Kattegat and the water from the entire Baltic Sea system will eventually also flow into the Kattegat.

1.2. Outline of the study

The basic structure of this work and some of the main features of the CoastMab-model are illustrated in fig. 1.3.

First (at level 1), CoastMab, i.e., the process-based coastal mass-balance model for salt, which is explained in detail in Håkanson and Bryhn (2008a) for the Baltic Sea basins, will be used to quantify the water fluxes to, within and from the vertical layers in the Kattegat, including mixing and diffusion. The main results will be given in chapter 3. It should be stressed that the CoastMab-modeling has been tested in many coastal areas and lakes and also discussed in Håkanson and Bryhn (2008a, c). This model calculates the water fluxes needed to explain the measured salinities. This means that data on salinities in the inflowing water to the Kattegat from the Baltic Sea and the Skagerrak are needed to run the model and in the following simulations, data from the period 1995 to 2008 (supplied by SMHI) will be used. This modeling also needs morphometric data (mean depth, volume, form factor, dynamic ratio, etc.) and the hypsographic curve and those data are discussed in chapter 2. The size and form of a given aquatic system, i.e., the morphometry, influences the way in which the system functions, since the depth-characteristics influence resuspension and internal loading of nutrients, the nutrient concentrations regulate the primary production, which in turn
regulates the secondary production, including zooplankton and fish (see Håkanson and Boulion, 2002).

![Map of the Baltic Sea](image)

**Fig. 1.2. Location map of the Baltic Sea.**

At level 2, CoastMab for phosphorus is used. This version of the CoastMab-model for phosphorus is modified as compared to the model presented by Håkanson and Bryhn (2008a). The main reason for this is that this work does not use a regression predicting the concentrations of suspended particulate matter (SPM) from modeled concentrations of total phosphorus (TP). Instead, the dynamic CoastMab-model for SPM (layer 3) is used. One should note that many of the algorithms to quantify the transport processes for phosphorus, salt and nitrogen are also valid for SPM, e.g., inflow to the Kattegat to the Baltic Proper, sedimentation of particulate phosphorus and SPM, mixing, diffusion of salt and dissolved phosphorus and nitrogen, resuspension of particulate phosphorus, nitrogen and SPM, and burial of P, N and SPM. There are also specific transport processes for nitrogen, such as atmospheric deposition, gas transport (nitrogen also appears in a gaseous phase), atmospheric N$_2$-fixation and denitrification. Nitrogen modeling is included in this work and data from Eilola and Sahlberg (2006) have been used for the atmospheric N-deposition.

At level 3, CoastMab for SPM (suspended particulate matter) is used. This means that the inflow, production, sedimentation, burial and mineralization of suspended particulate matter are quantified on a monthly basis (see Håkanson, 2006). Sedimentation is important for the oxygen consumption and oxygen status of the system, and especially for the oxygen conditions in the deep-water layer below the theoretical wave base and for the diffusion of phosphorus from sediments to water.
Introduction and aim

At level 4, general regression models are used to predict how the two key bioindicators, the Secchi depth (a standard measure of water clarity and the depth of the photic zone) and the concentrations of chlorophyll-a (a key measure of both primary phytoplankton production and biomass and also the driving variable for the foodweb model, CoastWeb; see appendix 8.2) would likely change in relation to changing phosphorus and nitrogen concentrations, salinities, SPM-values, temperature and light conditions. This will be explained in chapter 3.

Linked to these mass-balance models (CoastMab), there is also a more comprehensive dynamic foodweb model for 10 functional groups (CoastWeb, see Håkanson and Gyllenhammar, 2005; Håkanson and Bryhn, 2008b; Håkanson and Lindgren, 2007), used in this work to calculate biouptake and retention of phosphorus and nitrogen in biota. Using the CoastWeb-model means that one can also ask questions like: How will the fish production change if, e.g., costly remedial measures are taken to reduce eutrophication in the Kattegat and if less intensive fishing would be carried out? However, the focus of this work is not on the foodweb modeling but on the mass-balance modeling.

Any dynamic (time dependent) model can be tuned so that it describes empirical data well in a given system. However, errors in models are often - if not always - revealed when models are blind tested against independent data from new systems. So, validations are fundamental in ecosystem modeling in disclosing deficiencies in models and hence also in the modeler’s understanding of how natural systems work. There are at least four criteria by which ecosystem models can be critically evaluated:

- By the predictive power revealed by validations.
• By the relevance of the target y-variables in disclosing fundamental ecosystem structures, functional aspects of aquatic ecosystems and threshold values related to operationally applied guidelines in water management.
• By the applicability and generality of the model, i.e., by the width of the model domain, and
• By the accessibility of the driving variables needed to make simulations.

Evidently, there exist many models for marine systems. At a first glance, such models may look the same, but there can also be fundamental differences between seemingly similar models because the basic structures, the equations and model constants may be different. CoastMab is relatively new and no other models use the same sedimentological criteria as CoastMab to define fundamental model structures, e.g., the surface-water compartment, the deep-water compartment, the sediment compartment for ET-areas (erosion and transport areas for cohesive fine material; where there is resuspension) and the accumulation-area compartment (where there is no wind/wave-induced resuspension of fine sediments). This also means that key transport processes, such as sedimentation, resuspension and mixing, are quantified differently in this approach compared to most other models. All approaches to quantify the transport processes cannot be most relevant from a mechanistic point of view. Such a ranking of models cannot be done by arguments, only from critical validations using reliable data from many systems. No dynamic models that provide seasonal variations for variables such as phosphorus, suspended particulate matter and salinity based on other structures have been validated for so many different coastal areas in terms of size, depth conditions, salinity ranges and nutrient loading and given results even close to what has been reported for CoastMab (Håkanson and Bryhn, 2008a, c).

In fact, the generality and predictive power of models for radionuclides, nutrients, metals, organics and suspended particulate matter (SPM) have increased in a way that was inconceivable ten years ago. This new generation of dynamic mass-balance models predict as well as one can measure - if one measures well! And yet, they are driven by readily available driving variables and have a general structure that applies to most types of substances in aquatic systems. The major reason for this development is, ironically, the Chernobyl accident. Large quantities of radiocesium (\(^{137}\text{Cs}\)) and radiostrontium (\(^{90}\text{Sr}\)) were released in April/May 1986 as a pulse. To follow the pulse of these radionuclides through ecosystem pathways has meant that important fluxes and mechanisms, i.e., ecosystem structures have been revealed. It is important to stress that many of these new structures and equations are valid not just for radionuclides, but for most types of contaminants, e.g., for nutrients. This means that the CoastMab-model, which is based on these new developments in radioecology, should be of great interest also to other ecosystem modelers, e.g., interested in eutrophication. When the initial version of the model was blind-tested against independent data from a wide domain of systems, (357 empirical data from 23 different European lakes), the coefficient of determination (\(r^2\)) was 0.96 and the slope 0.98. This is almost like an analytical solution (see Håkanson, 2000).

Meteorological data on winds and oceanographic data on directions and speeds of currents at individual sites have been omitted in this modeling, since CoastMab has a focus on monthly predictions at the ecosystem scale and during one month winds can generally blow from many directions and with many velocities.
2. Basic information on the Kattegat

As a background to this work, figures 2.1 and 2.2 show maps related to the areal variations in two of the target bioindicators discussed in this work, the concentration of chlorophyll-a (a standard measure of phytoplankton biomass) and the Secchi depth (a standard measure of water clarity directly reflecting the amount of suspended particulate matter causing the scattering of light; see Håkanson, 2006). These two maps provide a good overview of the areal distribution patterns related to the eutrophication in the Kattegat and the Baltic Sea, and from these maps one can identify “hotspots”, i.e., areas with high algal biomasses expressed by the chlorophyll-a concentrations and areas with turbid water and low Secchi depths, which should be targeted in remedial contexts related to eutrophication. And vice versa, these maps also provide key information related to areas where reductions in anthropogenic nutrient input should not have a high priority. One can note that the conditions in the Kattegat are significantly better than in, e.g., the Gulf of Finland, the Gulf of Riga and the estuaries of Oder and Vistula. However, this does not imply that nothing should be done to improve the eutrophication in the Kattegat.

From fig. 2.1, one can note that chlorophyll-a concentrations in the Baltic Sea and parts of the North Sea lower than 2 μg/l (oligotrophic conditions) are found in the northern parts of the Bothnian Bay and the outer parts of the North Sea, while values higher than 20 μg/l (hypertrophic conditions) more are often found in, e.g., the Vistula and Oder lagoons. The hotspots shown in the map outside the British coast may be a result of data from situations when algal blooms are over-represented. This map shows that at water depths smaller than 10 m, the Baltic Sea has typical chlorophyll concentrations between 2 and 6 μg/l during the growing season (May to September), which correspond to the mesotrophic class.

Fig. 2.2 shows that several areas with low Secchi depths can be observed, e.g., in the Gulf of Riga and along the North Sea coasts of Holland, Belgium and Germany. However, some of the observed patchiness may be a result of the interpolation method rather than a true patchiness.

2.1. Introduction and aim

First, the utilized morphometric data for the Kattegat will be presented. This section will also explain why and how the given morphometric parameters are important for the mass-balance calculations. This has been discussed in more detail for lakes by Håkanson (2004). The idea here is to provide a background illustrating how morphometric parameters are used in the CoastMab-model.

Second, compilations of data on salinities, phosphorus, nitrogen, temperature, oxygen concentrations, Secchi depths and concentrations of chlorophyll-a will be given (all these data come from SMHI). The water fluxes will be presented in the next chapter. Those data are used in quantifying the transport of the nutrients.

The dynamic mass-balance model for suspended particulate matter (CoastMab for SPM) quantifying sedimentation will also be used. SPM causes scattering of light in the water and influences the Secchi depth and hence the depth of the photic zone.
Fig. 2.1. Areal distribution of chlorophyll-a in the Baltic Sea and parts of the North Sea during the growing season (May-September) in the upper 10 m water column for the period from 1990 to 2005 (from Håkanson and Bryhn, 2008a).

Fig. 2.2. Average yearly Secchi depths in the Baltic Sea and parts of the North Sea in the upper 10 m water column during 1990 to 2005 (Håkanson and Bryhn, 2008a).
SPM also influences the bacterial decomposition of organic matter, and the oxygen situation and the conditions for zoobenthos, by definition an important food source for benthivorous fish.

This chapter will give trend analyses concerning all the studied water variables for the period 1995 to 2008.

An important aspect of this modeling concerns the use of hypsographic curves (i.e., depth/area-curves for defined basins) to calculate the necessary volumes of water of the given vertical layers. This information is essential in the mass-balance modeling for salt, phosphorus, nitrogen and SPM. If there are errors in the defined volumes, there will also be errors in the calculated concentrations since, by definition, the concentration is the mass of the substance in a given volume of water.

This chapter also presents an approach to define and differentiate between the surface-water and the deep-water layers. Traditionally, this is done by water temperature data, which defines the thermocline, or by salinity data, which defines the halocline. CoastMab uses an approach which is based on the water depth separating areas where sediment resuspension of fine particles occurs from bottom areas where more continuous sedimentation is likely to happen. The depth separating areas with discontinuous sedimentation (the T-areas) from areas with more continuous sediment accumulation (the A-areas) of fine materials is called the theoretical wave base. This is an important concept in mass-balance modeling of aquatic systems (see Håkanson, 1977, 1999, 2000). The theoretical wave base will also be used to define algorithms (1) to calculate concentrations of matter in the given compartments, (2) to quantify sedimentation by accounting for the mean depths of these compartments, (3) to quantify internal loading via advection/resuspension as well as diffusion (the vertical water transport related to concentration gradients of dissolved substances in the water), (4) to quantify upward and downward mixing between the given compartments and (5) to calculate outflow of substances from the given compartments.

Empirical monthly values of the salinity for the period 1995 to 2008 have been used to calibrate the CoastMab-model for salt and those calculations provide data of great importance for the mass-balances for phosphorus, nitrogen and SPM, namely:
1) The fluxes of water to and from the defined compartments.
2) The monthly mixing of water between layers.
3) The basic algorithm for diffusion of dissolved substances in water.
4) The water retention rates influencing the turbulence in each compartment, and hence also
5) The sedimentation of particulate phosphorus, nitrogen and SPM in the given compartments.

So, this chapter will provide and discuss the data necessary to run CoastMab.

2.2. Morphometric data and criteria for the vertical layers
Basin-specific data are compiled in table 2.1 and will be briefly explained in this section. This table gives data on, e.g., total area, volume, mean depth, maximum depth and the depth of the theoretical wave base (D_{wb} in m), the fraction of bottoms areas dominated by fine sediment erosion and transport (ET-areas) above the theoretical wave base, the water transport between the Kattegat and the Baltic Proper (see
Håkanson and Bryhn, 2008a), sediment characteristics (water content and organic content = loss on ignition; mainly based on data supplied by prof. Ingemar Cato, SGU, Uppsala) and latitude.

Table 2.1. Basic data (and abbreviations) for the three basins discussed in this work. Bolded values are used in the modeling.

<table>
<thead>
<tr>
<th>Area (A) (km²)</th>
<th>Kattegat (KA)</th>
<th>Skagerrak (SK)</th>
<th>Baltic Proper (BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical wave base (D_wb) (m)</td>
<td>39.9</td>
<td>40.9</td>
<td>43.8</td>
</tr>
<tr>
<td>Area above WB (ET-areas) (km²)</td>
<td>18,684</td>
<td>13,190</td>
<td>87,600</td>
</tr>
<tr>
<td>Area below WB (A-areas) (km²)</td>
<td>3134</td>
<td>3510</td>
<td>123,500</td>
</tr>
<tr>
<td>ET-areas (ET) (%)</td>
<td>86</td>
<td>79</td>
<td>47</td>
</tr>
<tr>
<td>Max. depth (D_max) (m)</td>
<td>91 (130)</td>
<td>-</td>
<td>459</td>
</tr>
<tr>
<td>Volume (V) (km³)</td>
<td>522.7</td>
<td>-</td>
<td>13,055</td>
</tr>
<tr>
<td>Volume above WB (ET-areas) (km³)</td>
<td>487.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Volume below WB (A-areas) (km³)</td>
<td>35.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean depth (D_MV) (m)</td>
<td>23.96</td>
<td>-</td>
<td>61.8</td>
</tr>
<tr>
<td>Form factor (Vd) (-)</td>
<td>0.79</td>
<td>-</td>
<td>0.40</td>
</tr>
<tr>
<td>Dynamic ratio (DR) (-)</td>
<td>6.16</td>
<td>-</td>
<td>7.43</td>
</tr>
<tr>
<td>Water transport from Kattegat to Baltic Sea (Q) (km³/yr)</td>
<td>29</td>
<td>33.2</td>
<td>250</td>
</tr>
<tr>
<td>Water transport to Kattegat from Baltic Sea (Q) (km³/yr)</td>
<td>889</td>
<td>33.2</td>
<td>250</td>
</tr>
<tr>
<td>A-sediment water content (W, 0-10 cm) (%ww)</td>
<td>70</td>
<td>-</td>
<td>75</td>
</tr>
<tr>
<td>Fresh sediment water content (W) (%ww)</td>
<td>85</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A-sediment organic content (IG, 0-10 cm) (%dw)</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fresh sediment organic content (IG) (%dw)</td>
<td>15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Old sediment organic content (IG) (%dw)</td>
<td>7.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Latitude (°N)</td>
<td>57</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

There are more than 15,000 measurements on water temperature, salinity, TN- and TP-concentrations and chlorophyll and about 14,000 data on Secchi depths and oxygen concentrations for the period from 1995 to 2008 used in this work from the entire Kattegat.

The theoretical wave base is defined from the ETA-diagram (see fig. 2.3; erosion-transport-accumulation; from Håkanson, 1977), which gives the relationship between the effective fetch, as an indicator of the free water surface over which the winds can influence the wave characteristics (speed, height, length and orbital velocity). The theoretical wave base separates the transportation areas (T), with discontinuous sedimentation of fine materials, from the accumulation areas (A), with more continuous sedimentation of fine suspended particles. The theoretical wave base ($D_{wb}$ in m) is at a water depth of 39.9 m in the Kattegat. This is calculated from eq. 2.1 (Area = area in km²):

$$D_{wb} = \frac{45.7 \times \sqrt{\text{Area}}}{\sqrt{\text{Area}} + 21.4}$$ (2.1)
Basic information on the Kattegat

**Effective fetch (km)**

![Diagram showing the relationship between effective fetch, water depth, and potential bottom dynamic conditions.](image)

$\text{DTA} = \frac{45.7 \cdot \text{EF}}{\text{EF} + 21.4}$

It should be stressed that this approach to separate the surface-water layer from the deep-water layer has been used and motivated in many previous contexts for both lakes (Håkanson et al., 2004), smaller coastal areas in the Baltic Sea (Håkanson and Eklund, 2007) and for the sub-basins in the Baltic Sea (Håkanson and Bryhn, 2008a, c). This approach gives one value for the wave base related to the area of the system.

The relevance of this approach for the Kattegat is demonstrated in fig. 2.4A for the salinity, fig. 2.4B for the oxygen concentration, fig. 2.5 for the TN/TP-ratio (TN = total nitrogen; TP = total phosphorus). From fig. 2.4A, it may be noted that the surface-water (SW) salinity is clearly different from the deep-water (DW) salinity. The mean SW-salinity is 24.6 psu (see table 2.2, which also gives monthly mean values and coefficients of variation, CV) whereas the mean DW-salinity is 33.3 (the CV-value is very low, 0.02; $\text{CV} = \text{SD} / \text{MV}$; SD = standard deviation, MV = mean value). Tables 2.2 and 2.3 give mean monthly values and coefficients of variations not just for salinity but also for water temperatures, oxygen concentrations, phosphate, TP, nitrite, nitrate, ammonium and TN, and table 2.2 gives the corresponding data for PON (particulate organic nitrogen), POC, chlorophyll and Secchi depth. The aim of the modeling is to describe these empirical salinities as close as possible and to predict the given TP, TN, chlorophyll concentrations and Secchi depths as close as possible. Note that the basic aim is to predict the mean annual values rather than the monthly data because (1) annual and not monthly nutrient fluxes from the Baltic Proper are used in this modeling and (2) annual and not monthly nutrient fluxes from land (from HELCOM, 2000) are used.
Fig. 2.4. The relationship between (A) water depth and salinity in the Kattegat and (B) between water depth and oxygen concentrations. The two figures also show the theoretical wave base at about 40 m in the Kattegat. Data from SMHI. The statistical analyses given in fig. B demonstrate that the theoretical wave base at 40 m is also the threshold depth for the oxygen concentrations.

So, in this modeling, the Kattegat (KA) has been divided into two depth intervals:
(1) The surface-water layer (SW), i.e., the layer above the theoretical wave base.
(2) The deep-water layer (DW) is defined as the volume of water beneath the theoretical wave base.

It should be stressed that the theoretical wave base describes average conditions. During storm events, the wave base will be deeper (see Jönsson, 2005) and during calm periods at shallower depths. The wave base also varies spatially within the studied area. From figures 2.4 and 2.5, it is evident that the depth of the wave base describes the conditions in the Kattegat well.
Basic information on the Kattegat

2.2.1. Size and form characteristics of the basin

Fig. 2.6 gives the hypsographic curve for the Kattegat and how the areas above and below the theoretical wave base are defined. One can note that the area below the theoretical wave base (D_{wb}) at 39.9 m in KA is 3134 km² and the total area 21,818 km². The volume of the SW-layer is 487.5 km³ and of the DW-layer only 35.2 km³; the entire volume is 522.7 km³. The maximum depth is 130 m, but from fig. 2.6, one can see that the area below 91 m is very small so 91 m has been used as a functional maximum depth in this modeling.

Among the morphometric parameters characterizing the studied sub-basin, three main groups can be identified (see Håkanson, 2004):

- Size parameters: different parameters in length units, e.g., the maximum depth, parameters expressed in area units, such as water surface area, and parameters expressed in volume units, e.g., total volume and SW-volume.
Table 2.2. Mean monthly values (MV) and coefficients of variation (CV) for variables in the surface-water layer of the Kattegat for the period 1995 to 2008; for surface-water temperature (SWT), salinity (Sal), oxygen concentration (O₂), phosphate (PO₄), total phosphorus (TP), nitrite (NO₂), nitrate (NO₃), ammonium (NH₄), total nitrogen (TN), particulate organic nitrogen (PON), particulate organic carbon (POC) and chlorophyll-a concentrations (Chl).

<table>
<thead>
<tr>
<th>Month</th>
<th>Secchi</th>
<th>SWT</th>
<th>Sal</th>
<th>O₂</th>
<th>PO₄</th>
<th>TP</th>
<th>NO₂</th>
<th>NO₃</th>
<th>NH₄</th>
<th>TN</th>
<th>PON</th>
<th>POC</th>
<th>Chl</th>
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<tbody>
<tr>
<td></td>
<td>(m)</td>
<td>(°C)</td>
<td>(psu)</td>
<td>(ml/l)</td>
<td>(μmol/l)</td>
<td>(μmol/l)</td>
<td>(μmol/l)</td>
<td>(μmol/l)</td>
<td>(μmol/l)</td>
<td>(μmol/l)</td>
<td>(μmol/l)</td>
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</tr>
<tr>
<td>1</td>
<td>5.7</td>
<td>4.4</td>
<td>26.5</td>
<td>0.63</td>
<td>0.88</td>
<td>0.34</td>
<td>7.6</td>
<td>0.71</td>
<td>21.7</td>
<td>2.18</td>
<td>18.8</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5.1</td>
<td>3.4</td>
<td>26.2</td>
<td>0.60</td>
<td>0.89</td>
<td>0.30</td>
<td>9.0</td>
<td>0.69</td>
<td>23.5</td>
<td>2.35</td>
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<td>2.09</td>
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</tr>
<tr>
<td>3</td>
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<td>3.3</td>
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<td>0.39</td>
<td>0.77</td>
<td>0.19</td>
<td>7.5</td>
<td>0.78</td>
<td>24.1</td>
<td>3.94</td>
<td>29.5</td>
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</tr>
<tr>
<td>4</td>
<td>6.4</td>
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<td>23.5</td>
<td>0.28</td>
<td>0.61</td>
<td>0.14</td>
<td>5.6</td>
<td>0.97</td>
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<td>3.69</td>
<td>25.9</td>
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<td>5.9</td>
<td>7.9</td>
<td>23.5</td>
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<td>0.58</td>
<td>0.15</td>
<td>4.9</td>
<td>1.03</td>
<td>21.0</td>
<td>3.36</td>
<td>24.3</td>
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<td>3.40</td>
<td>23.8</td>
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<td>14.8</td>
<td>23.4</td>
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<td>0.50</td>
<td>0.15</td>
<td>2.5</td>
<td>0.88</td>
<td>19.2</td>
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<td>23.8</td>
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<td>6.8</td>
<td>16.6</td>
<td>24.1</td>
<td>0.21</td>
<td>0.53</td>
<td>0.16</td>
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<td>0.82</td>
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<td>15.5</td>
<td>25.9</td>
<td>0.26</td>
<td>0.60</td>
<td>0.22</td>
<td>1.9</td>
<td>0.78</td>
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<td>3.70</td>
<td>22.3</td>
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<td>12.9</td>
<td>24.1</td>
<td>0.31</td>
<td>0.69</td>
<td>0.23</td>
<td>2.6</td>
<td>1.03</td>
<td>19.9</td>
<td>3.14</td>
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<td>0.75</td>
<td>0.31</td>
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<td>3.21</td>
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<td>0.79</td>
<td>0.32</td>
<td>5.5</td>
<td>1.02</td>
<td>21.2</td>
<td>2.26</td>
<td>17.0</td>
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<tr>
<td>MV</td>
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<td>24.60</td>
<td>0.35</td>
<td>0.68</td>
<td>0.22</td>
<td>4.67</td>
<td>0.91</td>
<td>20.92</td>
<td>3.15</td>
<td>22.74</td>
<td>2.32</td>
<td></td>
</tr>
</tbody>
</table>

- Form parameters (based on size parameters) such as mean depth and the form factor.
- Special parameters, for example, the dynamic ratio and the effective fetch.

The CoastMab-model uses several of these variables. They are listed in table 2.1 and will be defined in the following text.

Traditionally, the mean depth (D_MV in m) is defined as the ratio between the water volume (V in m³) and the area (A in m²), or D_MV = V/A. The mean depth is a most informative and useful parameter in aquatic sciences and it is an integral part of the CoastWeb-model.

The volume development, also often called the form factor (V_d, dimensionless), is defined as the ratio between the water volume and the volume of a cone, with a base equal to the water surface area (A in km²) and with a height equal to the maximum depth (D_max in m):

\[ V_d = (A \cdot D_{MV} \cdot 0.001)/(A \cdot D_{Max} \cdot 0.001 \cdot 1/3) = 3 \cdot D_{MV}/D_{Max} \]  

(2.2)
Table 2.3. Mean monthly values (MV) and coefficients of variation (CV) for variables in the deep-water layer (DW) of the Kattegat for the period 1995 to 2008; DW-temperature (DWT), salinity (Sal), oxygen concentration (O2), phosphate (PO4), total phosphorus (TP), nitrite (NO2), nitrate (NO3), ammonium (NH4) and total nitrogen (TN).

<table>
<thead>
<tr>
<th>Month</th>
<th>DWT (°C)</th>
<th>Sal (psu)</th>
<th>O2 (ml/l)</th>
<th>PO4 (µmol/l)</th>
<th>TP (µmol/l)</th>
<th>NO2 (µmol/l)</th>
<th>NO3 (µmol/l)</th>
<th>NH4 (µmol/l)</th>
<th>TN (µmol/l)</th>
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</thead>
<tbody>
<tr>
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<td>4.44</td>
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<td>9.09</td>
<td>0.99</td>
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<td>5.88</td>
<td>34.37</td>
<td>5.88</td>
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<td>33.86</td>
<td>3.62</td>
<td>0.83</td>
<td>0.98</td>
<td>0.42</td>
<td>6.70</td>
<td>0.71</td>
<td>16.45</td>
</tr>
<tr>
<td>10</td>
<td>11.66</td>
<td>34.09</td>
<td>4.26</td>
<td>0.76</td>
<td>0.92</td>
<td>0.26</td>
<td>6.40</td>
<td>0.28</td>
<td>15.27</td>
</tr>
<tr>
<td>11</td>
<td>11.22</td>
<td>33.69</td>
<td>4.85</td>
<td>0.74</td>
<td>0.91</td>
<td>0.40</td>
<td>5.49</td>
<td>0.42</td>
<td>15.00</td>
</tr>
<tr>
<td>12</td>
<td>9.52</td>
<td>33.80</td>
<td>5.47</td>
<td>0.72</td>
<td>0.85</td>
<td>0.43</td>
<td>6.30</td>
<td>0.24</td>
<td>15.30</td>
</tr>
<tr>
<td>MV</td>
<td>7.86</td>
<td>33.31</td>
<td>5.35</td>
<td>0.75</td>
<td>0.90</td>
<td>0.30</td>
<td>7.80</td>
<td>0.69</td>
<td>17.78</td>
</tr>
</tbody>
</table>

The form factor describes the form of the basin. The form of the basin is very important, e.g., for internal sedimentological processes. In basins of similar size but with different form factors, one can presuppose that the system with the smallest form factor would have a larger area above the theoretical wave base, and more of the resuspended matter transported to the surface-water compartment than to the deep-water compartment below the theoretical wave base compared to a system with a higher form factor. This is also the way in which the form factor is used in CoastMab.

The dynamic ratio (DR; see Håkanson, 1982) is defined by the ratio between the squareroot of the water surface area (in km² not in m²) and the mean depth, DMV (in m; DR = √Area/DMV). DR is a standard morphometric parameter in contexts of resuspension and turbulence in entire basins. ET-areas above the theoretical wave base (i.e., areas where fine sediment erosion and transport processes prevail) are likely to dominate the bottom dynamic conditions in basins with dynamic ratios higher than 3.8. Slope processes are known (see Håkanson and Jansson, 1983) to dominate the bottom dynamic conditions on slopes greater than about 4-5%. Slope-induced ET-areas are likely to dominate basins with DR-values lower than 0.052. One should also expect that in all basins there is a shallow shoreline zone where wind-induced waves will create ET-areas, and it is likely that most basins have at least 15% ET-areas. If a basin has a DR of 0.26, one can expect that in this basin the ET-areas would occupy 15% of
the area. If DR is higher or lower than 0.26, the percentage of ET-areas is likely to increase. Basins with high DR-values, i.e., large and shallow system are also likely to be more turbulent than small and deep basins. This will influence sedimentation. During windy periods with intensive water turbulence, sedimentation of suspended fine particles in the water will be much lower than under calm conditions. This is accounted for in the CoastMab-model and the dynamic ratio is used as a proxy for the potential turbulence in the monthly calculations of sedimentation.

![Hypsographic curve for the Kattegat. Based on data from SMHI.](image)

It should be stressed that the form factor and the dynamic ratio provide different and complementary aspects of how the form may influence the function of aquatic systems.

The effective fetch (see the ETA-diagram in fig. 2.3) is often defined according to a method introduced by the Beach Erosion Board (1972). The effective fetch \( L_{ef} \) gives a more representative measure of how winds govern waves (wave length, wave height, etc.) than the effective length, since several wind directions are taken into account. Using traditional methods, it is relatively easy to estimate the effective fetch by means of a map and a special transparent paper (see Håkanson, 1977). The central radial of this transparent paper is put in the main wind direction or, if the maximum effective fetch is requested, in the direction which gives the highest \( L_{ef} \)-value. Then the distance \( x \) in km from the given station to land (or to islands) is measured for every deviation angle \( a_i \), where \( a_i \) is ± 6, 12, 18, 24, 30, 36 and 42 degrees. \( L_{ef} \) may then be calculated from:

\[
L_{ef} = \frac{\sum x_i \cdot \cos(a_i)}{\sum \cos(a_i)} \cdot SC'
\]  

(2.3)
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Σcos(a_i) = 13.5, a calculation constant.
SC' = the scale constant; if the calculations are done on a map in scale
1:250,000, then SC' = 2.5.

The effective fetch attains the highest values close to the shoreline and the minimum values in the central part of a basin. This relationship is important in, e.g., contexts of shore erosion and morphology, for bottom dynamic conditions (erosion-transportation-accumulation), and hence also for internal processes, mass-balance calculations, sediment sampling and evaluations of sediment pollution.

For entire basins, the mean effective fetch may be estimated as √Area (see fig. 2.3). In a round basin, the requested value should be somewhat lower than the diameter (d = 2·r; r = the radius); the area is π·r² and hence d = 1.13·√Area and the mean fetch approximately √Area.

2.2.2. Sediments and bottom dynamic conditions
As stressed in fig. 2.3, the theoretical wave base may also be determined from the ETA-diagram. This approach focuses on the behavior of the cohesive fine materials settling according to Stokes’ law in laboratory vessels:

- Areas of erosion (E) prevail in shallow areas or on slopes where there is no apparent deposition of fine materials but rather a removal of such materials; E-areas are generally hard and consist of sand, consolidated clays and/or rocks with low concentrations of nutrients and other substances.
- Areas of transportation (T) prevail where fine materials (such as the carrier particles for water pollutants) are deposited periodically (areas of mixed sediments). This bottom type generally dominates where wind/wave action regulates the bottom dynamic conditions. It is sometimes difficult in practice to separate areas of erosion from areas of transportation. The water depth separating transportation areas from accumulation areas, the theoretical wave base, is, as stressed, a fundamental component in these mass-balance calculations.
- Areas of accumulation (A) prevail where the fine materials (and particulate forms of water pollutants) are deposited continuously (soft bottom areas).

The generally hard or sandy sediments within the areas of erosion (E) often have a low water content, low organic content and low concentrations of nutrients and pollutants. The A-areas are the areas (the "end stations") where high concentrations of pollutants may appear (see table 2.4).

The conditions within the T-areas are, for natural reasons, variable, especially for the most mobile substances, like phosphorus, manganese and iron, which react rapidly to alterations in the chemical "micro-climate" (given by the redox-potential) of the sediments. Fine materials may be deposited for long periods during stagnant weather conditions. In connection with a storm or a mass movement on a slope, this material may be resuspended and transported up and away, generally in the direction toward the A-areas in the deeper parts, where continuous deposition occurs. Thus, resuspension is a most natural phenomenon on T-areas.

It should also be stressed that fine materials are rarely deposited as a result of simple vertical settling in natural aquatic environments. The horizontal velocity is generally at least 10 times larger, sometimes up to 10,000 times larger, than the
vertical component for fine materials or flocs that settle according to Stokes' law (Bloesch and Burns, 1980; Bloesch and Uehlinger, 1986).

Table 2.4. The relationship between bottom dynamic conditions (erosion, transportation and accumulation) and the physical and chemical character of the surficial sediments. The given data represent characteristic values based on data from 11 Baltic Sea coastal areas (from Håkanson et al., 1984). $ww = \text{wet weight}; \ dw = \text{dry weight}.$

<table>
<thead>
<tr>
<th>PHYSICAL PARAMETERS</th>
<th>Erosion</th>
<th>Transportation</th>
<th>Accumulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content (% $ww$)</td>
<td>$&lt; 50$</td>
<td>$50 - 75$</td>
<td>$&gt; 75$</td>
</tr>
<tr>
<td>Organic content (% $dw$)</td>
<td>$&lt; 4$</td>
<td>$4 - 10$</td>
<td>$&gt; 10$</td>
</tr>
<tr>
<td>NUTRIENTS (mg/g $dw$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>$&lt; 2$</td>
<td>$10 - 30$</td>
<td>$&gt; 5$</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>$0.3 - 1$</td>
<td>$0.3 - 1.5$</td>
<td>$&gt; 1$</td>
</tr>
<tr>
<td>Carbon</td>
<td>$&lt; 20$</td>
<td>$20 - 50$</td>
<td>$&gt; 50$</td>
</tr>
<tr>
<td>METALS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron (mg/g $dw$)</td>
<td>$&lt; 10$</td>
<td>$10 - 30$</td>
<td>$&gt; 20$</td>
</tr>
<tr>
<td>Manganese (mg/g $dw$)</td>
<td>$&lt; 0.2$</td>
<td>$0.2 - 0.7$</td>
<td>$0.1 - 0.7$</td>
</tr>
<tr>
<td>Zinc (μg/g $dw$)</td>
<td>$&lt; 50$</td>
<td>$50 - 200$</td>
<td>$&gt; 200$</td>
</tr>
<tr>
<td>Chromium (μg/g $dw$)</td>
<td>$&lt; 25$</td>
<td>$25 - 50$</td>
<td>$&gt; 50$</td>
</tr>
<tr>
<td>Lead (μg/g $dw$)</td>
<td>$&lt; 20$</td>
<td>$20 - 30$</td>
<td>$&gt; 30$</td>
</tr>
<tr>
<td>Copper (μg/g $dw$)</td>
<td>$&lt; 15$</td>
<td>$15 - 30$</td>
<td>$&gt; 30$</td>
</tr>
<tr>
<td>Cadmium (μg/g $dw$)</td>
<td>$&lt; 0.5$</td>
<td>$0.5 - 11.5$</td>
<td>$&gt; 1.5$</td>
</tr>
<tr>
<td>Mercury (ng/g $dw$)</td>
<td>$&lt; 50$</td>
<td>$50 - 250$</td>
<td>$&gt; 250$</td>
</tr>
</tbody>
</table>

An evident boundary condition for this approach to calculate the ET-areas is that if the depth of the theoretical wave base, $D_{wb} > D_{\text{Max}}$, then $D_{wb} = D_{\text{Max}}$.

In CoastMab, there are also two other boundary conditions for ET (= the fraction of ET-areas in the basin):

If ET $> 0.99$ then ET = 0.99 and if ET $< 0.15$ then ET = 0.15.

ET-areas are generally larger than 15% (ET = 0.15) of the total area since there is always a shore zone dominated by wind/wave activities. For practical and functional reasons, one can also generally find sheltered areas, macrophyte beds and deep holes with more or less continuous sedimentation, that is, areas which actually function as A-areas. So, the upper boundary limit for ET may be set at ET = 0.99 rather than at 1. The value for the ET-areas is used as a distribution coefficient in the CoastMab-model. It regulates whether sedimentation of the particulate fraction of the substance (here phosphorus, nitrogen or SPM) goes to the DW-layer or to the ET-areas.

Sediment data for the Kattegat are compiled in table 2.5. One can note that:

1. Most TP-values from the upper 2 cm of the accumulation areas sediments below the theoretical wave base vary in the range from 0.7 to 1.1 mg TP/g $dw$ (the mean value is close to 0.88 mg/g $dw$; $dw = \text{dry weight}$); the TN-data from 2.1 to 2.8 mg/g $dw$ (MV = 2.4 mg/g $dw$); the organic content is about 10-11 % $ww$ ($ww = \text{wet weight}$).
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Table 2.5. Mean values (MV) and coefficients of variation (CV) for TP, TN and loss on ignition in surficial (0-2 cm) accumulation area sediments (A) and erosion- and transport sediments (ET) in the Kattegat (data from prof. Ingemar Cato, SGU).

<table>
<thead>
<tr>
<th>0-2 cm ET/SW</th>
<th>0-2 cm</th>
<th>TP (mg/g dw)</th>
<th>TN (mg/g dw)</th>
<th>IG (% ww)</th>
<th>Water depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>67</td>
<td>0.99</td>
<td>1.69</td>
<td>9.87</td>
<td>22.6</td>
</tr>
<tr>
<td>MV</td>
<td></td>
<td>0.29</td>
<td>0.46</td>
<td>0.72</td>
<td>0.47</td>
</tr>
<tr>
<td>CV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/DW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>40</td>
<td>0.88</td>
<td>2.43</td>
<td>11.02</td>
<td>52.6</td>
</tr>
<tr>
<td>MV</td>
<td></td>
<td>0.16</td>
<td>0.34</td>
<td>0.30</td>
<td>0.16</td>
</tr>
<tr>
<td>CV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Due to substrate decomposition by bacteria and compaction from overlying sediments, the TP-, TN-concentrations and the organic content (loss on ignition, IG) decrease with sediment depth in the accumulation areas (see Håkanson and Jansson, 1983). In all following simulations, a sediment depth of 0-10 cm will be used and this means that the reference values for the water content, organic content, TP- and TN-concentrations will be adjusted to this. The reference values for the 0-10 cm layer is set to be 33% lower than the P-, and N-values given in table 2.5 for the 0-2 cm layer.

3. The bulk density (d in g/cm³ ww) is between 1.1 and 1.3.

4. The water content (W in % ww) has been set to 70% for the upper 10 cm accumulation areas sediments in the Kattegat (0-10 cm) and to 85% for the newly deposited SPM on the ET-areas.

5. The organic content (= loss on ignition, IG in % dw) is set to 10% for the upper 10 cm accumulation areas sediments in the Kattegat. The IG-value in underlying clays sediments is around 7.5% dw.

   The area of erosion (AreaE) is calculated from the hyposgraphic curve and the corresponding depth given by the ETA-diagram (fig. 2.1). This means that the depth separating E-areas from T-areas is given by:

   \[ D_{ET} = \frac{(30.4 \sqrt{\text{Area}})}{\sqrt{\text{Area}} + 34.2} \]  

   Note that area is given in km² in eq. 2.4 to get \( D_{ET} \) in m. \( D_{ET} \) is 25 m in the Kattegat.

2.2.3. Trends and variations in water variables

This section will present and discuss empirical data in the Kattegat for the period 1995 to 2008 (data from SMHI) as a background to the subsequent modeling. Fig. 2.7 first gives data on the target bioindicators, Secchi depth, oxygen concentrations and concentrations of chlorophyll-a in the surface-water layer in the Kattegat. This figure and the following figures also give statistical trend analyses (regression line, coefficient of determination, \( r^2 \), and number of data, n). From fig. 2.5, one can note:

- There is a very weak trend for these three bioindicators, as revealed by the small slope coefficients (-0.00776 for Secchi depth, -0.0021 for oxygen and -0.0028 for chlorophyll) and the low \( r^2 \)-values (0.21, 0.0052 and 0.0027). So, for this period, the conditions have been rather stable in the Kattegat for these three key variables.
Fig. 2.7. Variations in (A) Secchi depths (m), (B) oxygen concentrations (ml/l) and (C) chlorophyll-a (μg/l) in the SW-layer of the Kattegat in the years 1995 to 2008 (Month 1 is January of 1995). The figure also gives a trend analyses (regression line, coefficient of determination, $r^2$, and number of data, n). Data from SMHI.

- One can also note the clear seasonal pattern for oxygen and that there is no evident seasonal pattern for Secchi depth, and more of an in-between pattern for chlorophyll. One might have expected a more evident seasonal pattern for chlorophyll with peak values in the spring and fall.

The corresponding information is given in fig. 2.8 for surface-water temperatures, salinity, TP- and TN-concentrations and the TN/TP-ratio. The TN/TP-ratio addresses the question about “limiting” nutrient, which is central in aquatic ecology and has been treated in numerous papers and textbooks (e.g., Dillon and Rigler, 1974; Smith, 1979, 2003; Riley and Prepas, 1985; Howarth, 1988; Evans et al., 1996; Wetzel, 2001; Newton et al., 2003; Smith et al., 2006; Håkanson and Bryhn, 2008a, c). The average composition of algae ($C_{106}N_{16}P$) is reflected in the Redfield ratio ($N/P = 7.2$ by mass). So, by definition, algae need both nitrogen and phosphorus and one focus of coastal eutrophication studies concerns the factors limiting the phytoplankton growth and biomass, often expressed by chlorophyll-a values in the water. Note that the actual phytoplankton biomass at any given moment in a system is a function of...
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the bioavailable nutrient concentrations, light and predation on phytoplankton by herbivorous zooplankton minus the death of phytoplankton regulated by the turnover time of the phytoplankton (see Håkanson and Boullion, 2002).

Based on data from surface-water layer

$$y = 0.0125x + 8.30; r^2 = 0.013; n = 23375$$

Fig. 2.8. Variations in (A) temperatures (°C), (B) salinities (psu), (C) TP, (D) TN and (E) in the TN/TP-ratio in the SW-layer of in the years 1995 to 2008 (Month 1 is January of 1995). The figure also gives a statistical trend analyses (regression line, coefficient of determination, $r^2$, and number of data, n). Data from SMHI.
From fig. 2.8, one can note:

- All trends are weak. The strongest is the decrease in TN-concentrations; the increase in temperature is also interesting in these days when global warming is on the agenda; the changes in salinity, TP and TN/TP are very small. It should be stressed that all these changes are statistically significant because the number of data is so large. These data support the conclusion that there have been no major changes in the Kattegat system during the last 13 years.

\[ y = -0.0064x + 1047; r^2 = 0.0005; n = 6574; p = 0.068 \]

**Fig. 2.9.** The temporal variation in monthly tributary water discharge from Swedish rivers entering the Kattegat in the period 1985 to 2002. The figure also gives a statistical trend analyses (regression line, coefficient of determination, \( r^2 \), and number of data, \( n \)). Data from SMHI.

Fig. 2.9 gives the temporal (monthly) trend in tributary water discharge from Swedish rivers entering the Kattegat. Here, one can see a characteristic seasonal variation with high water discharge in spring. The trend is weak.

- Fig. 2.10 illustrates another problem related to the concept of “limiting” nutrient. Using data from the Baltic Proper, this figure gives a situation where the chlorophyll-a concentrations show a typical seasonal “twin peak” pattern with a pronounced peak in April. The higher the primary production, the more bioavailable nitrogen (nitrate, ammonium, etc.) and phosphorus (phosphate) are being used by the algae (the spring bloom is mainly diatoms) and eventually the nitrate concentration drops to almost zero and the primary production decreases - but the important point is that the primary production, the phytoplankton biomass and hence also the concentration of chlorophyll-a remain relatively high during the entire growing season!

2.2.5. The dilemma related to cyanobacteria in the Kattegat

Fig. 2.11 illustrates this dilemma. The figure gives the TN/TP-ratio on the y-axis and the surface-water temperature on the x-axis. It has been demonstrated by analyses of empirical data from many systems that there exist a threshold value for blooms of cyanobacteria when the TN/TP-ratio is lower than 15 and when the SW-temperatures are higher than 15 °C (see Häkanson et al., 2007). Based on this, one should expect that the conditions in the Kattegat would favor cyanobacteria in about 20% of the time (fig. 2.11). But cyanobacteria do not seem to appear in Kattegat but they
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Fig. 2.10. Variations in chlorophyll-a concentrations, phosphate and nitrate in the Baltic Sea (using data from the Gotland deep between 1993 to 2003; data from SMHI, Sweden).

Fig. 2.11. The relationship between the TN/TP-ratio and SW-temperatures in the Kattegat in the years 1995 to 2008. The figure also illustrates threshold temperatures and TN/TP-ratios (both at values of 15) for cyanobacteria. Data from SMHI.

certainly appear in the Baltic Sea (see Håkanson and Bryhn, 2008a, c). In hypertrophic lakes, the biomass of cyanobacteria can be very high with concentrations of about 100 mg/l (Smith, 1985). Howarth et al. (1988a, b) found no data on N-fixing planktonic species in estuaries and coastal seas, except for the Baltic Sea and the Pell-Harvey estuary, Australia. Also results from Marino et al. (2006) support this general lack of N-fixing cyanobacteria in estuaries. There are more than 10 nitrogen fixating cyanobacteria species in the Baltic Proper (Wasmund et al., 2001). A field study in the Baltic Sea (Wasmund, 1997) indicated that in this brackish environment cyanobacteria have the highest biomass at 7 – 8 psu and that the blooms in the Kattegat and Belt Sea are more frequent if the salinity is below
11.5 psu (see also Sellner, 1997). A laboratory experiment with cyanobacteria from the Baltic Sea supports the results that the highest growth rate was at salinities in the range between 5 and 10 psu (Lehtimäki et al., 1997). So, the lack of cyanobacteria in the Kattegat may be related to the relatively high SW-salinity of about 25 psu in this system.

This also means that in this mass-balance modeling for nitrogen, there is no atmospheric nitrogen fixation.

2.2.6. The reasons why this modeling is not based on dissolved nitrogen or phosphorus

At short timescales (seconds to days), it is evident that the causal agent regulating/limiting primary production is the concentration of the nutrient in bioavailable forms, such as DIN (dissolved inorganic nitrogen) and DIP, nitrate, phosphate and ammonia. Short-term nutrient limitation is often determined by measuring DIN- and DIP-concentrations, or by adding DIN and/or DIP to water samples in bioassays. However, information on DIN and DIP from real coastal systems often provide poor guidance in management decisions because:

- DIN and DIP are quickly regenerated (Dodds, 2003). For example, zooplankton may excrete enough DIN to cover for more than 100% of what is consumed by phytoplankton (Mann, 1982). In highly productive systems, there may even be difficulties to actually measure nutrients in dissolved forms because these forms are picked up so rapidly by the algae. Dodds (2003) suggested that only when the levels of DIN are much higher than the levels of DIP (e.g., 100:1), it is unlikely that DIN is limiting and only if DIN/DIP < 1, it is unlikely that P is the limiting nutrient. He also concluded that DIN and DIP are poor predictors of nutrient status in aquatic systems compared to TN and TP.
- Phytoplankton and other primary producers also take up dissolved organic N and P (Huang and Hong, 1999; Seitzinger and Sanders, 1999; Vidal et al., 1999).
- DIN and DIP are highly variable in most aquatic systems including the Kattegat (see Håkanson and Bryhn, 2008a, c and tables 2.2 and 2.3) and are, hence, very poor predictors of phytoplankton biomass and primary production (as measured by chlorophyll concentrations; see fig. 2.12).
- Primary production in natural waters may be limited by different nutrients in the long run compared to shorter time perspectives (see Redfield, 1958; Redfield et al., 1963). Based on differences in nutrient ratios between phytoplankton and seawater, Redfield (1958) hypothesized that P was the long-term regulating nutrient, while N deficits were eventually counteracted by nitrogen fixation. Schindler (1977, 1978) tested this hypothesis in several whole-lake experiments and found that primary production was governed by P inputs and unaffected by N inputs, and that results from bioassays were therefore irrelevant for management purposes. Redfield's hypothesis has also been successfully tested in modeling work for the global ocean (Tyrrell, 1999) and the Baltic Proper (Savchuk and Wulff, 1999). However, Vahtera et al. (2007) have used a "vicious circle" theory to suggest that both nutrients should be abated to the Baltic Sea since they may have different long-term importance at different times of the year.
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Fig. 2.12. Empirical data from the Baltic Sea, Kattegat and Skagerrak on mean monthly chlorophyll-a concentrations (logarithmic data) versus empirical data (log) on DIN and DIP, respectively. The figure also gives the equations for the regressions and the corresponding $r^2$-values (from Håkanson and Bryhn, 2008a).

So, the concentrations of the bioavailable fractions, such as DIN and DIP in μg/l or other concentration units, cannot as such regulate primary phytoplankton production in μg/(l·day) (or other units), since primary production (as revealed by chlorophyll data) represents a flux including a time dimension and the nutrient concentration is a concentration without any time dimension. The central aspect has to do with the flux of DIN and DIP to any given system and the regeneration of new DIN and DIP related to bacterial degradation of organic matter containing N and P. The concentration of DIN and DIP may be very low and the primary phytoplankton production and biomass can be high as in fig. 2.10 because the regeneration and/or inflow of DIN and DIP are high. The regeneration of DIN and DIP concerns the amount of TN and TP available in the water mass, i.e., TN and TP represent the pool of the nutrients in the water, which can contribute with new DIN and DIP. It should be stressed that phytoplankton has a typical turnover time of about 3 days and bacterioplankton has a typical turnover time of slightly less than 3 days (see Håkanson and Boulion, 2002). This means that within a month there can be 10 generations of phytoplankton, which would need both DIN and DIP and in the proportions given by the Redfield ratio (7.2 in grams).

2.2.7. The reasons why it is difficult to model nitrogen

There are four highlighted spots with question marks in fig. 2.13 indicating that for many coastal systems, it is very difficult to quantify some of the most important transport processes in a general manner for nitrogen. Three of them are denitrification, atmospheric wet and dry deposition and nitrogen fixation, e.g., by certain forms of cyanobacteria. Fig. 2.13 also highlights another major uncertainty related to the understanding of nitrogen fluxes in coastal systems, the particulate fraction, which is necessary for quantifying sedimentation. Atmospheric nitrogen fixation may very important in contexts of mass-balance calculations for nitrogen.
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(see Rahm et al., 2000) and in this modeling for the Kattegat, the same value for atmospheric nitrogen deposition has been used as used in the OSPAR-model by SMHI. The data on atmospheric nitrogen deposition for the Kattegat should be reasonable in terms of order-of-magnitude values. Without empirically well-tested algorithms to quantify nitrogen fixation, crucial questions related to the effectiveness of the remedial measures to reduce nutrient discharges to aquatic systems cannot be properly evaluated, since costly nitrogen reductions may be compensated for by nitrogen fixation by cyanobacteria. However, this is a problem in many systems, such as the Baltic Sea, but not in the Kattegat where there seem to be no significant amounts of cyanobacteria.

Fig. 2.13. Overview of important transport processes and mechanisms related to the concept of “limiting” nutrient (from an illustration for the Baltic Sea from Håkanson and Bryhn, 2008a).

The two remaining question marks in fig. 2.13, denitrification and the particulate fraction, will be discussed in the next chapter.

2.3. Comments and conclusions

Traditional hydrodynamic or oceanographic models to calculate water fluxes to, within and out of coastal areas generally use water temperature data (the thermocline) or the salinity (the halocline) to differentiate between different water layers. This chapter has motivated another approach, the theoretical wave base as calculated from process-based sedimentological criteria, to differentiate between the surface-water layer and lower vertical layers and this approach gives one characteristic value for each basin. Morphometric data for the Kattegat and the hypsographic curve have been used in the CoastMab-modeling. The basic aim of this chapter has been to present empirical data
Basic information on the Kattegat

from the Kattegat on total phosphorus (TP), total nitrogen (TN), chlorophyll, Secchi depth, water temperature, oxygen and salinity. The empirical data from the Kattegat show:

1. All water variables in the SW-layer of the Kattegat have been fairly stable in the period between 1995 and 2008.
2. There is a small increase in surface-water temperatures in the Kattegat (compare global warming).
3. The salinities have also been fairly stable since 1995.
4. The seasonal pattern in monthly median chlorophyll-a concentrations is relatively obscure.
5. The water column has been divided into two layers, separated by the theoretical wave base. This describes the conditions very well.
Chapter 2
3. Water, SPM, nutrient and bioindicator modeling

3.1. Water exchange and water transport

3.1.1. Background on mass-balances for salt and the role of salinity

The salinity is of vital importance for the biology of coastal areas influencing, e.g., the number of species in a system (Remane, 1934), and also the reproductive success, food intake and growth of fish (Rubio et al., 2005; Nissling et al., 2006). Furthermore, a higher salinity increases the flocculation and aggregation of particles (Håkanson, 2006) and hence affects the rate of sedimentation, which is of particular interest in understanding variations in water clarity within and among coastal areas. The saltier the water, the greater the flocculation of suspended particles. This does not only influence the concentration of particulate matter, but also the concentration of any substance with a substantial particulate phase such as phosphorus and nitrogen. The salinity also affects the relationship between total phosphorus (TP), total nitrogen (TN) and primary production/biomass (chlorophyll-a; Håkanson and Bryhn 2008a, c). These relationships are shown in figures 3.1 and 3.2 and they are used in this work to calculate chlorophyll-a from dynamically modeled salinities, phosphorus and nitrogen concentrations and from information on the number of hours with daylight (see table 3.1). The salinity is easy to measure and the availability of salinity data for the Kattegat is very good.

\[
\begin{align*}
\text{For salinity } < 10: & \quad (\text{Chl/TN})^{0.5} = -0.014\text{abs}(\text{salinity}-10)^{0.5}+0.145; \quad r^2 = 0.05; \quad n = 263; \quad p = 0.0004 \\
\text{For salinity } > 10: & \quad (\text{Chl/TN})^{0.5} = -0.0122\text{abs}(\text{salinity}-10)^{0.5}+0.145; \quad r^2 = 0.21; \quad n = 358; \quad p < 0.0001
\end{align*}
\]

Fig. 3.1. Scatter plot of data relating the ratio Chl/TN to salinity (psu). The figure also gives two regressions for salinities either below (crosses) or higher than the threshold value of 10 (circles) (from Håkanson and Bryhn, 2008a). Note that for the Kattegat, the surface-water (SW) salinity is about 25 psu; if TN is 300 μg/l, this gives Chl ≈ 3 μg/l. The scatter around the given regression partly depends on light, uncertainties in data and uncertainties in the particulate fraction for nitrogen.
Table 3.1. Daylight table giving average number of hours and minutes with daylight different months at different latitudes on the northern hemisphere.

<table>
<thead>
<tr>
<th>Month</th>
<th>Equator</th>
<th>10°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
<th>50°</th>
<th>60°</th>
<th>70°</th>
<th>80°</th>
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<td>10:24</td>
<td>9:37</td>
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<td>0:00</td>
<td>0:00</td>
</tr>
<tr>
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<td>11:49</td>
<td>11:21</td>
<td>11:10</td>
<td>10:42</td>
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<td>9:11</td>
<td>7:20</td>
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<tr>
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<td>14:22</td>
<td>15:22</td>
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<td>22:13</td>
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</tr>
<tr>
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<td>11:42</td>
<td>11:28</td>
<td>11:10</td>
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<td>9:03</td>
<td>5:10</td>
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</tr>
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<td>11:12</td>
<td>10:40</td>
<td>10:01</td>
<td>9:06</td>
<td>7:37</td>
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<td>11:32</td>
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</tbody>
</table>

From: http://encarta.msn.com/media_701500905/Hours_of_Daylight_by_Latitude.html

Fig. 3.2. Box-and-whisker plot (showing medians, quartiles, percentiles and outliers) illustrating the Chl/TP-ratio for 10 salinity classes. The statistics give the median values, the coefficients of variation (CV) and the number of data in each class (from Håkanson and Bryhn, 2008a). Note that for the Kattegat, the surface-water (SW) salinity is about 25 psu; if TP is 20 μg/l, this gives Chl \approx 3 μg/l. The scatter around the given regression partly depends in light and uncertainties in data.

So, figures 3.1 and 3.2 illustrate the role of salinity in relation to the Chl/TP and Chl/TN-ratios. The figures give the number of data in each salinity class, the box-and-whisker plots give the medians, quartiles, percentiles and outliers, and the table below.
the diagram provides information on the median values, the coefficients of variation (CV = SD/MV; SD = standard deviation; MV = mean value) and the number of systems included in each class (n). These results are evidently based on many empirical data from many systems covering a wide salinity gradient. An interesting aspect concerns the pattern shown in the figure. One can note:

• The median value for the Chl/TP-ratio for lakes is 0.29, which is almost identical to the slope coefficient for the key reference model for lakes (0.28 in the OECD-model; see OECD, 1982).
• The Chl/TP-ratio changes in a wave-like fashion when the salinity increases. It is evident that there is a minimum in the Chl/TP-ratio in the salinity range between 2 and 5. Subsequently, there is an increase up to the salinity range of 10-15, and then a continuous decrease in the Chl/TP-ratio until a minimum value of about 0.012 is reached for the hypersaline systems.

From the relationship between the Chl/TN-ratio and salinity, one can identify differences and similarities between the results for the Chl/TP-ratio.

• At higher salinities than 10-15, there is a steady decrease also in the Chl/TN-ratio (note that there are no data on TN from the hypersaline systems).
• The Chl/TN-ratio attains a maximum value for systems in the salinity range between 10-15, and significantly lower values in lakes and brackish systems.
• The median Chl/TN-values vary from 0.0084 (for lakes), to 0.017 for brackish systems in the salinity range between 10 and 15, to very low values (0.0041) for coastal systems in the salinity range between 35 and 40.

The water exchange in the Kattegat is calculated using the CoastMab-model for salt. This chapter will present monthly budgets for water and salt in the Kattegat.

Mass-balance models have long been used as a tool to study lake eutrophication (Vollenweider, 1968; OECD, 1982) and also used in different coastal applications (see Håkanson and Eklund, 2007; Håkanson and Bryhn, 2008c). Mass-balance modeling makes it possible to predict what will likely happen to a system if the conditions change, e.g., a reduced discharge of a pollutant related to a remedial measure. Mass-balance modeling can be performed at different scales depending on the purpose of the study. A large number of coastal models do exist, all with their pros and cons. For example, the 1D-nutrient model described by Vichi et al. (2004) requires meteorological input data with a high temporal resolution, which makes forecasting for longer time periods than one week ahead problematic. The 3D-model used by Schernewski and Neumann (2005) has a temporal resolution of 1 minute and a spatial resolution of 3 nm (nautical miles), which means that it is difficult to find reliable empirical data to run and validate the model. Several water balance studies have also been carried out in the Kattegat and the Baltic Sea, see, e.g., Jacobsen (1980), HELCOM (1986, 1990), Bergström and Carlsson (1993, 1994), Omstedt and Rutgersson (2000), Stigebrandt (2001), Rutgersson et al. (2002), Omstedt and Axell (2003), Omstedt et al. (2004) and Savchuk (2005). The result of such mass-balance calculations for salt or for other substances, depend very much on how the system is defined and how the model is structured.

Within the BALTEX program (BALTEX, 2006; BACC, 2008), the water and heat balances are major research topics and estimates on the individual terms in the water balance are frequently being revised (e.g., Bergström and Carlsson, 1993, 1994; Omstedt and Rutgersson, 2000; Rutgersson et al., 2002). The major water balance
components in the Baltic Sea are the in- and outflows at the entrance area, river runoff and net precipitation (Omstedt et al., 2004). Change in water storage needs also to be considered at least for shorter time periods. The different results depend on the time period studied and the length of the period. Several studies have also divided the Baltic Sea into sub-basins and from the water and salt balances estimated the flows (e.g., Omstedt and Axell, 2003; Savchuk, 2005).

The necessary empirical data on salinity to run the CoastMab-model have been obtained from SMHI (the Swedish Hydrological and Meteorological Institute) and data from the period 1995 to 2008 have been used in this work.

There are inter-annual and seasonal variations in both net precipitation and riverine water input to the Kattegat (HELCOM, 1986; Bergström and Carlsson, 1993, 1994; Winsor et al., 2001) as well as in the exchange of water with the Kattegat and the salinity of this water (Samuelsson, 1996). This work has focused on a period when there is access to comprehensive data for the mass-balances for salt, but also for this period there are inherent uncertainties in the data. This is shown by the CV-values in tables 2.2 and 2.3.

The fluxes and retention rates for the different sub-basins and compartments of the Kattegat, as defined in this mass-balance modeling for salt, will be used in the following mass-balance modeling for phosphorus, nitrogen and SPM. The basic structuring of this model (CoastMab) enables extensions not just to other substances than salt, but also to other systems than the Baltic Sea and the Kattegat.

### 3.1.2. Water fluxes

Fig. 3.3 illustrates the basic structure of the model with its two water compartments (SW and DW in the Kattegat) and also results of the modeling for water fluxes. Note that this modeling is done on a monthly basis to achieve seasonal variations, which is important in the mass-balance models for phosphorus, nitrogen and SPM. All the water fluxes in fig. 3.3 are, however, given in km$^3$/yr to get an overview. This figure also shows water fluxes from Swedish plus Danish rivers, precipitation and evaporation. For the tributary fluxes data from SHMI for the period 1995-2008 have been used (see table 3.2).

The salinities in the inflowing surface-water and deep-water from Skagerrak have been calculated from the data (from SMHI) given in tables 3.3 and 3.4.

The model quantifies the fluxes needed to achieve steady-state concentrations for the salinity that correspond as closely as possible to the empirical monthly salinities in the two compartments. All equations have been given by Håkanson and Bryhn (2008a) and the basic equations are compiled in table 3.5.

One can note from fig. 3.3 that the greatest water fluxes into the Kattegat are the deep-water (DW) flux from Skagerrak (SK) (20,700 km$^3$/yr), the surface-water (SW) flux from the Baltic Proper (BP) (890 km$^3$/yr); the tributary inflow, precipitation and deep-water inflow from the Baltic Proper are relatively small (37, 47 and 43 km$^3$/yr, respectively). Since this is mass-balance for salt, the fluxes out of the system should be equal to the inflow at steady state. These fluxes provide a very important interpretational framework for the other mass-balances (for phosphorus, nitrogen and SPM).
Mass-balance modeling in the Kattegat

**Fig. 3.3.** Characteristic annual water fluxes to, from and within the Kattegat for the period 1995-2008.

**Table 3.2.** Mean monthly values (MV) and coefficients of variation (CV) for the tributary water discharge from Sweden and Denmark for the period 1995 to 2008.

<table>
<thead>
<tr>
<th>Month</th>
<th>Q (m³/s), Swed.</th>
<th>Q (m³/s), Denm.</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>1477</td>
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</tr>
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<td>2</td>
<td>1473</td>
<td>256</td>
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<tr>
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<tr>
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<td>MV</td>
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<td>183</td>
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<td>0.53</td>
</tr>
<tr>
<td>MV</td>
<td>0.43</td>
<td>0.48</td>
</tr>
</tbody>
</table>
Table 3.3. Mean monthly values (MV) and coefficients of variation (CV) for variables in the surface-water layer of Skagerrak for the period 1995 to 2008 for Secchi depth, surface-water temperature (SWT), salinity (Sal), total phosphorus (TP) and total nitrogen (TN).

<table>
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<tr>
<th>Month</th>
<th>Secchi (m)</th>
<th>SWT (°C)</th>
<th>Sal (psu)</th>
<th>TP (μg/l)</th>
<th>TN (μg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.8</td>
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</table>

From the fluxes of water and salt (the mass-balance for salt is given in fig. 3.4), one can also define the associated retention times (T) and retention rates (1/T; fig. 3.5 gives the water retention rates in the compartments in the Kattegat). The retention rates for water may be used in mass-balance models for, e.g., nutrients since these rates indicate the potential turbulence in the given compartment, and the turbulence regulates the settling velocity for suspended particles – the higher the potential turbulence, the lower the settling velocity for particulate phosphorus (Håkanson and Bryhn, 2008a). The retention time for water in each compartment is defined from the total inflow of water (m³/month) and the volume of the compartment (m³).

Empirical salinity data are compared to modeled values in fig. 3.6A. The inherent empirical uncertainties in the mean monthly salinity values (the CV-values) are small, about 0.28 in the SW-layer and very small in the DW-layer, 0.02 (see tables 2.2 and 2.3). The excellent results shown in fig. 3.6A is not a result of a blind test, rather a result achieved after many calibrations.
Mass-balance modeling in the Kattegat

Table 3.4. Mean monthly values (MV) and coefficients of variation (CV) for variables in the deep-water layer of Skagerrak for the period 1995 to 2008 for deep-water temperature (DWT), salinity (Sal), total phosphorus (TP) and total nitrogen (TN).

<table>
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<th>Month</th>
<th>DWT (°C)</th>
<th>Sal (psu)</th>
<th>TP (μg/l)</th>
<th>TN (μg/l)</th>
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<td>0.30</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>0.02</td>
<td>0.25</td>
<td>0.23</td>
</tr>
<tr>
<td>MV</td>
<td>0.17</td>
<td>0.02</td>
<td>0.27</td>
<td>0.22</td>
</tr>
</tbody>
</table>

3.1.3. Comments
To understand how the Kattegat system, or any aquatic system, responds to changes in, e.g., loading of toxins, salt or nutrients, it is imperative to have a dynamic process-based perspective quantifying the factors and functions regulating inflow, outflow and internal transport processes and retention rates. This section has demonstrated that this modeling using the theoretical wave base rather than traditional temperature data to define the surface-water and deep-water compartments can give excellent correspondence between empirical and modeled data for the salinity. It is often stressed in contexts of marine eutrophication that it is important to develop practically useful general dynamic mass-balance models based on the ecosystem perspective to be able to give realistic evaluations of how systems will respond to changes in nutrient loading or other remedial actions (see Smith, 2003) and this modeling is meant to do that.

The basic aim of this section has been to present data on the fluxes of water and the theoretical retention times for water and salt since those values give fundamental information on how the system reacts to changes in, e.g., nutrient loading. The idea with this modeling, and the results presented in this work, is that these water fluxes, water retention rates and the algorithms to quantify vertical mixing and diffusion among the defined layers should be structured in such a manner that the model can be used to
Table 3.5. A compilation of basic equations in the mass-balance model for salt (CoastMab) for the Kattegat (KAt. Abbreviations: F for flow (kg/month), R for rate (1/month), C for concentration (psu), DC for distribution coefficients (dimensionless), M for mass (kg salt), D for depth in m, A for area in m², V for volume in m³; flow from one compartment (e.g., SW) to another compartment (e.g., MW) is written as $F_{SWMW}$; mixing flow is abbreviated as $F_{xWMW}$; Q is water discharge (m³/month),

Surface-water (SW)

$M_{SW,K}(t) = M_{SW,K}(t - dt) + \left( F_{DWSW,K} + F_{trib,K} + F_{prec,K} + F_{idWSW,K} + F_{SWBP,K} + F_{SWSK,K} - F_{xSW,DW,K} - F_{eva,K} - F_{SWKA, BP} - F_{SWKA, SK} \right) \cdot dt$

INFLOWS:

- $F_{DWSW,K} = M_{DW,K} \cdot Rx_{K} \cdot V_{SW,K}/V_{DW,K}$; mixing flow from DW to SW in KA (kg/months)
- $F_{trib,K} = Q_{trib,K} \cdot C_{trib,K}$; tributary inflow to KA (kg/months)
- $F_{prec,K} = Q_{prec,K} \cdot C_{prec,K}$; flow to KA from precipitation (kg/months)
- $F_{idWSW,K} = M_{DW,K} \cdot R_{idWSW,K} \cdot Constdiff$; diffusive flow DW to SW in KA (kg/months)
- $F_{SWBP,K} = Q_{SWBP,K} \cdot C_{SWBP}$; SW-flow from BP to KA (kg/months)
- $F_{SWSK,K} = Q_{SWSK,K} \cdot C_{SWSK}$; SW-flow from SK to KA (kg/months)

OUTFLOWS:

- $F_{xSW,DW,K} = M_{DW,K} \cdot Rx_{K}$; mixing flow from SW to DW in KA (kg/months)
- $F_{eva,K} = M_{SW,K} \cdot Q_{eva,K} \cdot 0$; evaporation from BP (kg/months)
- $F_{SWKA, BP} = Q_{SWKA, BP} \cdot C_{SWKA}$; SW-flow from KA to BP (kg/months)
- $F_{SWKA, SK} = Q_{SWKA, SK} \cdot C_{SWKA}$; SW-flow from KA to SK (kg/months)

Deep-water (DW)

$M_{DW,K}(t) = M_{DW,K}(t - dt) + \left( F_{ASDW,K} + F_{MWBP,K} + F_{DWSK,K} - F_{xDSW,DW,K} - F_{DW, SK} \right) \cdot dt$

INFLOWS:

- $F_{ASDW,K} = M_{SAW,K} \cdot Rx_{K}$; mixing flow from SW to DW in KA (kg/months)
- $F_{MWBP,K} = Q_{MWBP,K} \cdot C_{MWBP}$; DW-flow from BP to KA (kg/months)
- $F_{DWSK,K} = Q_{DWSK,K} \cdot C_{DWSK}$; DW-flow from SK to KA (kg/months)

OUTFLOWS:

- $F_{xDSW,DW,K} = M_{DW,K} \cdot Rx_{K} \cdot V_{SW,K}/V_{DW,K}$; mixing flow from DW to SW in KA (kg/months)
- $F_{xDSW, SK} = M_{SAW,K} \cdot Rx_{K} \cdot V_{SW,K}/V_{DW,K}$; mixing flow from SW to DW in KA (kg/months)
- $F_{DW, SK} = R_{DW, SK} \cdot M_{DW, SK} \cdot Constdiff$; diffusive flow DW to SK in KA (kg/months)
- $F_{DW, SK} = Q_{DW, SK} \cdot C_{DW, SK}$; DW-flow from KA to SK (kg/months)

quantify also fluxes of phosphorus, nitrogen and SPM. This places certain demands on the structure of this model, which are different from oceanographic models, e.g., in quantifying resuspension, mixing and diffusion and in the requirements regarding the accessibility of the necessary driving variables.

The crucial element(s) of this salt budget for the Kattegat, mainly concern the uncertainties in the forcing data (river-water fluxes, precipitation, etc.).
3.2. Phosphorus dynamics in the Kattegat

3.2.1. Background on CoastMab for phosphorus

A central aspect of this work concerns the practical application of this modeling as a tool to find the most appropriate remedial strategy to combat the eutrophication in the Kattegat. In that context, it is fundamental to try to identify the anthropogenic contributions to the nutrient loading. HELCOM (see table 3.6) has presented very useful data regarding the natural, diffuse and point source discharges of phosphorus and nitrogen to the Kattegat. Evidently, the natural nutrient fluxes should not be reduced,
Fig. 3.6. Empirical data versus modeled values in the Kattegat. (A) salinities, (B) modeled TP-concentrations in the surface-water (SW) layer versus plus/minus 1 standard deviation (SD) of the mean empirical value, (C) modeled TP-concentrations in the deep-water (DW) layer versus ± 1 SD, (D) modeled dissolved fractions of phosphorus in the SW-layer versus the PO₄/TP-ratio, (E) modeled dissolved fractions of phosphorus in the DW-layer versus the PO₄/TP-ratio, (F) modeled TN in SW-layer versus ± 1 SD, (G) modeled TN in DW versus ± 1 SD, (H) modeled dissolved fractions of N in SW versus the DIN/TN-ratio, (I) modeled dissolved fractions of N in DW versus DIN/TN.
Table 3.6. Transport of phosphorus and nitrogen from land to the Kattegat in the year 2000 (t; from HELCOM, 2000).

<table>
<thead>
<tr>
<th>Nutrient (%)</th>
<th>Natural</th>
<th>Diffuse</th>
<th>Point sources</th>
<th>Total load</th>
<th>From Sweden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus</td>
<td>363</td>
<td>1063</td>
<td>387</td>
<td>1813</td>
<td>46.8</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>13,561</td>
<td>53,661</td>
<td>6452</td>
<td>73,674</td>
<td>54.3</td>
</tr>
</tbody>
</table>

Table 3.7. Required nutrient reductions according to the Baltic Sea Action Plan (BSAP; see HELCOM (2007a, b)).

<table>
<thead>
<tr>
<th></th>
<th>Phosphorus (t)</th>
<th>Nitrogen (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>16</td>
<td>17,210</td>
</tr>
<tr>
<td>Estonia</td>
<td>220</td>
<td>900</td>
</tr>
<tr>
<td>Finland</td>
<td>150</td>
<td>1200</td>
</tr>
<tr>
<td>Germany</td>
<td>240</td>
<td>5620</td>
</tr>
<tr>
<td>Latvia</td>
<td>300</td>
<td>2560</td>
</tr>
<tr>
<td>Lithuania</td>
<td>880</td>
<td>11,750</td>
</tr>
<tr>
<td>Poland</td>
<td>8760</td>
<td>62,400</td>
</tr>
<tr>
<td>Russia</td>
<td>2500</td>
<td>6970</td>
</tr>
<tr>
<td>Sweden</td>
<td>290</td>
<td>20,780</td>
</tr>
<tr>
<td>Transboundary pool</td>
<td>1660</td>
<td>3780</td>
</tr>
<tr>
<td>Sum:</td>
<td>15,016</td>
<td>133,170</td>
</tr>
</tbody>
</table>

only a certain part of the anthropogenic fluxes from point sources and diffuse emissions.

As a background to the discussion to find the best possible remedial strategy to mitigate the eutrophication in the Baltic Sea, table 3.7 shows central aspects of the strategy proposed by HELCOM (2007b), which was also accepted by the Baltic States in November 2007.

The yearly cost of the Baltic Sea Action Plan has been estimated at 3.3 billion euro/yr (HELCOM and NEFCO, 2007). According to calculations by the Swedish Department of Agriculture, N-reductions, which Sweden has agreed to undertake in the Baltic Sea Action Plan, cannot be fulfilled unless a large part of the agricultural sector in the country would be permanently shut down, an option which would eliminate tens of thousands of jobs. Sweden, which is presently a net exporter of grain, could have to become a yearly net importer of millions of tons of grain (Swedish EPA, 2008), which would be associated with additional environmental pressure and transportation costs. Based on costs for building water treatment plants in the Baltic States and the St. Petersburg area (20,000 euro per ton P; HELCOM and NEFCO, 2007), the action alternative motivated in Håkanson and Bryhn (2008a; about 10,000 tons phosphorus per year) would cost 0.2-0.4 billion euro per year, or about 10% of the cost of the Baltic Sea Action Plan.

In the requested budgets for nitrogen and phosphorus for the Kattegat, it is essential to include all major transport processes in order to understand the situation, and especially to know how remedial measures reducing nutrient loading to the system would likely change nutrient concentrations in water and sediments. The importance of the internal fluxes and the transport between basins compared to the anthropogenic
nutrient input from land has also been shown by Christiansen et al. (1997) in a study of parts of the Kattegat.

### 3.2.2. Phosphorus modeling in CoastMab

The transport processes (sedimentation, resuspension, burial, diffusion, mixing, biouptake, etc.) for phosphorus, nitrogen and SPM quantified in the CoastMab-model are general and apply for all substances in all/most aquatic systems (see fig. 3.7), but there are also substance-specific parts (mainly related to the particulate fraction, the criteria for diffusion from sediments and the fact that nitrogen appears with a gaseous phase). So, these processes have the same names for all systems and for all substances:

- **Sedimentation** is the flux from water to sediments or to deeper water layers of suspended particles and nutrients attached to such particles.
- **Resuspension** is the advective flux from sediments back to water, mainly driven by wind/wave action and slope processes.
- **Diffusion** is the flux from sediments back to water or from water layers with high concentrations of dissolved substances to connected layers with lower concentrations. Diffusion is triggered by concentration gradients, which would often be influenced by small-scale advective processes; even after long calm periods, there are currents related to the rotation of the earth, the variations of low and high-pressures, temperature variations between day and night, etc.; it should be noted that it is difficult to measure water velocities lower than 1-2 cm/s in natural aquatic systems.
- **Mixing** (or large-scale advective transport processes) is the transport between, e.g., surface-water layers and deeper water layers related to changes in stratification (variations in temperature and/or salinity).
- **Mineralization** (and regeneration of nutrients in dissolved forms) is the decomposition of organic particles by bacteria.
- **Primary production** is creation of living suspended matter from sunlight and nutrients.
- **Biouptake** is the uptake of the substance in biota. In the CoastMab/CoastWeb-model, one first calculates biouptake in all types of organisms with short turnover times (phytoplankton, bacterioplankton, benthic algae and herbivorous zooplankton) and from this biouptake in all types of organisms with long turnover times (i.e., fish, zoobenthos,

---

**Fig. 3.7. Illustration of transport processes (= fluxes) and the structure of CoastMab for phosphorus, nitrogen, salinity and suspended particulate matter. Atmospheric nitrogen fixation and deposition and denitrification are not shown in this figure.**

- Diffusion is the flux from sediments back to water or from water layers with high concentrations of dissolved substances to connected layers with lower concentrations. Diffusion is triggered by concentration gradients, which would often be influenced by small-scale advective processes; even after long calm periods, there are currents related to the rotation of the earth, the variations of low and high-pressures, temperature variations between day and night, etc.; it should be noted that it is difficult to measure water velocities lower than 1-2 cm/s in natural aquatic systems.
- Mixing (or large-scale advective transport processes) is the transport between, e.g., surface-water layers and deeper water layers related to changes in stratification (variations in temperature and/or salinity).
- Mineralization (and regeneration of nutrients in dissolved forms) is the decomposition of organic particles by bacteria.
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- Biouptake is the uptake of the substance in biota. In the CoastMab/CoastWeb-model, one first calculates biouptake in all types of organisms with short turnover times (phytoplankton, bacterioplankton, benthic algae and herbivorous zooplankton) and from this biouptake in all types of organisms with long turnover times (i.e., fish, zoobenthos,
Mass-balance modeling in the Kattegat

predatory zooplankton, jellyfish and macrophytes) to account for the fact that phosphorus circulating in the system will be retained in these organisms and the retention times for phosphorus in these organisms are calculated from the turnover times of the organisms.

- Burial is the sediment transport of matter from the biosphere to the geosphere often of matter from the technosphere.
- Outflow is the flux out of the system of water and everything dissolved and suspended in the water.

3.2.2.1. New features in the phosphorus modeling

3.2.2.1.1. The dynamic SPM-model replaces the SPM-regression

In the previous version of the CoastMab-model for the Baltic Sea (Håkanson and Bryhn, 2008a, c), the concentrations of suspended particulate matter, SPM, was calculated from modeled TP-concentrations from the following regression:

\[ \log(\text{SPM}) = 1.56 \cdot \log(\text{TP}) - 1.64 \]  
\[ (r^2 = 0.90; n = 51 \text{ system with salinities } < 15 \text{ psu}; p < 0.001) \]  

It should be stressed that this approach works quite well for the conditions in the surface-water (SW) layer (see Håkanson and Bryhn, 2008a), but less well for predictions of SPM in deep-water (DW) layers, where the total concentrations of phosphorus generally are high because the fraction of dissolved phosphorus would be high. The true SPM-value in the DW-layers can be expected to be lower than predicted by this regression and SPM should be better estimated using the dynamic SPM-model, which has been used in this work.

So, the first new feature in this modeling concerns the replacement of eq. 3.1 to predict SPM with a dynamic SPM-model, which will be explained later in this chapter.

3.2.2.1.2. Calculations of burial

This modification is also related to the change in SPM-modeling and it has to do with the quantification of burial \( (F_{\text{Bur}}) \), which is the transport of substances from surficial A-sediments to sediment layers deeper than 10 cm. It was previously given by:

\[ F_{\text{Bur}} = M_{\text{TPADW}} \cdot \left( \frac{1.386}{\text{Age}_{\text{ADW}}} \right) \]  

Where 1.386 is the half-life constant and \( M_{\text{TPADW}} \) is the mass (g) of TP in the given sediment compartment. The half-life constant (which is generally used in radioecology in contexts related to physical half-lives of radionuclides) has been replaced in this modeling by 1 (one) so that the burial rate is given by \( 1/T \) rather than \( 1.386/T \). The age of TP in the given compartment was calculated from the sedimentation of particulate phosphorus. This approach also includes two boundary conditions. If there is very little sedimentation, e.g., 0.01 cm/yr, and the calculated age of the 0-10 cm sediment layer is 1000 years, the TP in the sediments could not be available for diffusive upward transport for such a long time. An upper boundary age of 30 years has been used and if the age of the A-sediments is shorter than 1 year, a second boundary age of 12 months has been utilized in this modeling.
In the new approach, sedimentation is calculated automatically by the dynamic SPM-model and not indirectly from sedimentation of phosphorus. The half-life constant (1.386) has been replaced by one (1). This means that burial for phosphorus is:

\[ F_{\text{Bar}} = M_{\text{TPADW}} \left( \frac{1}{\text{Age}_{\text{TPADW}}} \right) \]  

(3.3)

The age of phosphorus in the sediments, \( \text{Age}_{\text{TPADW}} \), is given by:

If \( \text{Age}_{\text{TPADW}} > 360 \) months, \( \text{Age}_{\text{TPADW}} = 360 \) else \( \text{Age}_{\text{TPADW}} \)

If \( \text{Age}_{\text{TPADW}} < 12 \) months, \( \text{Age}_{\text{TPADW}} = 12 \) else \( \text{Age}_{\text{TPADW}} \)  

(3.4)

Where \( \text{Age}_{\text{SPMADW}} \) is the age (in months) of SPM (calculated from the dynamic SPM model). \( \text{Age}_{\text{SPMADW}} \) is given by

\[ \text{Age}_{\text{SPMADW}} = 12 \cdot \frac{10}{\text{Sed}_{\text{SPMADW}}} \]  

(3.5)

This means that if, e.g., the annual sedimentation (\( \text{Sed}_{\text{SPMADW}} \)) is 0.25 cm/yr, a rather typical value for the Kattegat (see later in this chapter), \( \text{Age}_{\text{SPMADW}} = 40 \cdot 12 = 480 \) months and \( \text{Age}_{\text{TPADW}} \) regulating burial of TP is set to the boundary age of 360 months. This approach is also used for the nitrogen modeling.

### 3.2.2.1.3. Boundary conditions and improved algorithm for the particulate fraction

In the previous version of the model, there were no defined boundary conditions for the particulate fraction (PF) for phosphorus in water, and hence no limits for the dissolved fraction of phosphorus (DF = 1 – PF). However, it is evident that all phosphorus in the water phase cannot appear in dissolved form. If this were the case there would be no sedimentation of particulate phosphorus and the TP-concentration in the sediments would approach zero. Since long, it is well known that phosphorus can appear in sediments in many different forms (see Håkanson and Jansson, 1983) and that the TP-concentration in Baltic Sea glacial clays seldom are lower than 0.3-0.5 mg/g dw (see Cato, 1977; Emelyanov, 1986, 1988; Jonsson et al., 1990; Jonsson, 1992). This means that there should be a boundary condition for the PF-value in water and in all following simulation, it has been put at 0.99, i.e., DF should always be ≥ 0.01.

In this modeling, an algorithm for the PF-value for phosphorus based on three principles has been used: (1) the PF-value should increase when phosphorus in dissolved form is being taken up by and retained by plankton, (2) the PF-value should increase with increased resuspension of particulate phosphorus and (3) the PF-value should increase with increased SPM-concentrations, which are modeled separately from TP-fluxes by CoastMab for SPM. The improved algorithm for the PF-value will be described in more detail later in this chapter.

### 3.2.2.1.4. Calculations of biouptake and retention in biota

Since the modeling presented in this work includes a foodweb model (CoastWeb; see appendix 8.2; table 3.8 gives an overview of commonly used abbreviations), it is possible to account also for the biouptake and retention of phosphorus (and nitrogen) in all the functional groups within the framework of a comprehensive and tested mass-
Mass-balance modeling in the Kattegat

balance modeling approach including all major abiotic transport processes. Preliminary calculations of the uptake and retention of phosphorus (and nitrogen) in all functional groups in the Kattegat have been carried out and those calculations indicate that there are basically only very small changes in predicted phosphorus (or nitrogen) concentrations in water and sediments between those more complicated calculations and simplified calculations where one would only differentiate between nutrient uptake and retention in organisms with long turnover times (i.e., fish, zoobenthos, predatory zooplankton, jellyfish and macrophytes) and in organisms with short turnover times (i.e., phytoplankton, bacterioplankton, herbivorous zooplankton and benthic algae). In the following, results based on the simplified approach will be presented, since this will not substantially influence either the calculated TP-concentrations or the production and foodweb characteristics related to the functional groups. This is one of several simplifications needed to keep the model as small as possible.

To calculate the TP-uptake and retention first in biota with short turnover times, this modeling uses a similar approach as presented by Håkanson and Boulión (2002). This means that the uptake and retention in biota is given by:

\[
M_{TPBioS}(t) = M_{TPBioS}(t - dt) + (FTPBioS - FTPBioSret) \cdot dt \tag{3.6}
\]

\(M_{TPBioS}(t)\) is the mass (amount) of TP in organisms with short turnover times (g). The uptake of TP in these organisms (g/month) is calculated using:

1. The dimensional moderator for the influence of the light conditions \((Y_{DayL})\) as given by Håkanson and Bryhn (2008a, c), see eq. 3.9.
2. The biouptake rate is given by the inverse of the mean turnover time for organisms with short turnover time \((1/T_{BioS})\), see eq. 3.10.
3. The dissolved fraction of phosphorus in the surface-water layer \((DF_{SW} = 1 - PF_{SW};\) see later section).

This means that the biouptake of phosphorus by these organisms is given by:

\[
FTPBioS = M_{TPSW} \cdot Y_{DayL} \cdot (365/(12 \cdot T_{BioS})) \cdot DF_{SW} \tag{3.7}
\]

The flux of TP out of this compartment is given by:

\[
FTPBioSret = M_{TPBioS} \cdot (365/(12 \cdot T_{BioS})) \tag{3.8}
\]

The dimensional moderator based on the number of hours with daylight \((HDL;\) see table 3.1) each month is \(Y_{DayL}\).

\[
Y_{DayLBB} = HDL/12 \tag{3.9}
\]
The average turnover time of the organisms with short turnover times ($T_{\text{BioS}}$ in days) is calculated from the individual turnover times ($T_{\text{BA}}$, $T_{\text{PH}}$, $T_{\text{BP}}$ and $T_{\text{ZH}}$; BA = benthic algae; PH = phytoplankton; BP = bacterioplankton; ZH = herbivorous zooplankton) adjusted to the biomasses calculated by the CoastWeb-model. That is:

$$T_{\text{BioS}} = T_{\text{BA}} \cdot (M_{\text{BA}}/M_{\text{Stot}}) + T_{\text{PH}} \cdot (M_{\text{PH}}/M_{\text{Stot}}) + T_{\text{BP}} \cdot (M_{\text{BP}}/M_{\text{Stot}}) + T_{\text{ZH}} \cdot (M_{\text{ZH}}/M_{\text{Stot}})$$

(3.10)

Table 3.8. Abbreviations and dimensions of the most commonly used concepts and variables in this modeling. Note that as simple and self-explanatory abbreviations as possible have been used. Greek letters have been banned.

**A. Organisms**
- BA = Benthic algae
- BE = Zoobenthos
- BP = Bacterioplankton
- JE = Jellyfish
- MA = Macrophytes
- PD = Predatory fish
- PH = Phytoplankton
- PY = Prey fish
- ZH = Zooplankton, herbivores
- ZP = Zooplankton, predators

**B. Driving variables**
- Area = Coastal area ($m^2$)
- $D_{\text{av}}$ = Mean depth (m)
- $D_{\text{max}}$ = Maximum depth (m)
- SWT = Surface-water temperature ($°C$)
- Sal = Salinity (psu)

**C. Foodweb interactions**
- BM = Biomass (kg ww), e.g., $BM_{BP}$
- CON = Consumption (kg ww/month), e.g., $CON_{PHZH}$
- CR = Actual consumption rate (1/month), e.g., $CR_{ZPPY}$
- EL = Elimination (kg ww/month), e.g., $EL_{ZP}$
- ER = Erosion (kg ww/month), e.g., $ER_{BA}$
- Fish = Fishing, total (kg ww/month), e.g., $Fish_{FD}$
- IPR = Initial production (kg ww/month), e.g., $IPR_{ZHZ}$
- NBM = Normal biomass (kg ww), e.g., $NBM_{BE}$
- NCR = Normal consumption rate (1/month)
- MER = Metabolic efficiency ratio (dim. less), e.g., $MER_{PYPD}$
- NR = Number of first order food choices (dim. less)

**D. Mass-balance (= CoastMab)**
- $A_{\text{Sec}}$ = Area above Secchi depth (m)
- BL = Biota with long turnover times
- BS = Biota with short turnover times
- C = Concentration, e.g., of phosphorus $C_{TP}$(μg/l)
- DF = Dissolved fraction of phosphorus (dim. less)
- DP = Dissolved phosphorus (μg/l)
- DR = Dynamic ratio (dim. less)
- ET = Areas of fine sediment erosion & transport (dim. less)
- F = Flux (g/month), e.g., $F_{ETSW}$ (from ET to SW)
- M = Mass (g), e.g., $M_{ET}$
- PF = Particulate fraction (dim. less)
- R = Rate (1/month)
- SW = Surface water
- DW = Deep water
- SWT = SW temperature ($°C$)
- DWT = DW temperature ($°C$)
- TP = Total phosphorus (μg/l)
- TN = Total nitrogen (μg/l)
- $V_f$ = Volume development (= form factor, dim. less)
- $Y$ = Dimensionless moderator

**E. Other abbreviations**
- Chl = Chlorophyll-a concentration (μg/l)
- dw = Dry weight
- IG = Sediment organic content (= loss on ignition, % dw)
- PrimP = Primary phytoplankton production
- Prec = Mean annual precipitation (mm/yr)
- Sec = Secchi depth (m)
- SPM = Suspended particulate matter (mg/l)
- W = Sediment water content (% ww)
- ww = Wet weight
Where \( M_{BA}, \ M_{PH}, \ M_{BP} \) and \( M_{ZH} \) are the calculated monthly biomasses (kg ww) of the given planktonic organisms and \( M_{Slo} \) is the total biomass of these organisms (= \( M_{BA} + M_{PH} + M_{BP} + M_{ZH} \)).

The biouptake and retention of phosphorus (or nitrogen) in organisms with long turnover times is calculated from their consumption of the organisms with short turnover times. This is given by:

\[
M_{TPBioL}(t) = M_{TPBioL}(t - dt) + (F_{TPBioSL} - F_{TPBioLSW}) \cdot dt \quad (3.11)
\]

\( M_{TPBioL}(t) \) is the mass (amount) of TP in organisms with long turnover times (g). The uptake of TP in these organisms (g/month) is calculated from:

\[
F_{TPBioSL} = M_{TPBioS} \cdot \left(365/(12 \cdot T_{TPBioL})\right) \quad (3.12)
\]

The flux of TP out of this compartment to the surface-water layer is given by:

\[
F_{TPBioLSW} = M_{TPBioL} \cdot \left(365/(12 \cdot T_{TPBioL})\right) \quad (3.13)
\]

The average turnover time of the organisms with long turnover times (\( T_{BioL} \) in days) is calculated in the same manner as for the organisms with short turnover times, i.e.:

\[
T_{TPBioL} = \left(T_{MA} \cdot (M_{MA}/M_{Lot}) + T_{PY} \cdot (M_{PY}/M_{Lot}) + T_{PD} \cdot (M_{PD}/M_{Lot}) + T_{ZB} \cdot (M_{ZB}/M_{Lot}) + T_{JE} \cdot (M_{JE}/M_{Lot}) + T_{ZP} \cdot (M_{ZP}/M_{Lot}) \right) \quad (3.14)
\]

The total biomass of these organisms is given (\( M_{Lot} = M_{MA} + M_{PY} + M_{PD} + M_{JE} + M_{ZP}; \ MA = \) macrophytes; \( PY = \) prey fish; \( PD = \) predatory fish; \( JE = \) jellyfish; \( ZP = \) predatory zooplankton).

### 3.2.2.1.5. Calculations of TP-concentrations in sediments

To use the dynamic SPM-model also means that one can define and predict the TP-concentrations in the accumulation area sediments (\( TP_{Ased} \)) in a more direct and mechanistically correct way from dynamically modeled TP-amounts in A-sediments (\( M_{TPAced} \)) and dynamically modeled SPM-amounts in A-sediments (\( M_{SPMAced} \)) as:

\[
TP_{Aced} = M_{TPAced}/M_{SPMAced} \quad (3.16)
\]

This approach also opens up an important avenue to critically control model predictions; if both \( M_{TPAced} \) and \( M_{SPMAced} \) are correctly modeled, if all TP-concentrations in water are correctly modeled (which will be tested against empirical data) and if all SPM-concentrations in water are correctly modeled (which will be tested against mainly Secchi depth data), also the TP-concentrations in A-sediments should be correctly modeled, i.e., fall in the critical range between 0.5 and 0.68 mg TP/g dw.

### 3.2.2.1.6. The turbulence in the deep-water layer

Since the water exchange in the DW-later in the Kattegat is very intense because the DW-volume is small and the DW-inflow from the Skagerrak large, this modeling has
applied a boundary condition for the default mixing rate \( R_{MixDef} \) between the two layers so that the mixing should be higher than in more normal situations when the DW-retention time is longer than the SW-retention time. This is given by:

\[
\text{If } T_{DW} < T_{SW} \text{ then } R_{MixDef} = R_{mixdef} \left( \frac{T_{SW}}{T_{DW}} \right)^{1.2} \text{ else } R_{MixDef} = R_{Mixdef} \quad (3.17)
\]

This means that the mixing rate increases in a non-linear way when \( T_{DW} \) becomes smaller than \( T_{SW} \). Mixing is still a relatively small for salt in the Kattegat; about 30,000 kt/yr compared to the DW-inflow from Skagerrak of about 710,000 kt/yr (see fig. 3.4). This approach for mixing is also applied for salt, nitrogen and SPM.

### 3.2.2.1.7. The salinity moderator

The salinity of the water influences the settling velocity - the higher the salinity, the greater the aggregation, the bigger the flocs and the faster the settling velocity (Kranck, 1973, 1979). This is expressed by a dimensionless moderator for the salinity \( Y_{Sal} \) operating on the default settling velocity: If the salinity < 1 psu then \( Y_{Sal} = 1 \) else \( Y_{Sal} = (1 + 1 \cdot (\frac{Sal}{1 - 1}) = Sal \). This means that for systems with a salinity of 36 psu, the settling velocity increases by a factor of 36 as compared to freshwater systems.

### 3.2.2.2. Empirical data versus modeled values

Figures 3.6B and C present the modeled TP-concentrations in SW and DW-water against the corresponding empirical data. The results in fig. 3.6 are well within the uncertainty bands given by ± one standard deviation for the empirical data (see tables 2.2 and 2.3) and one cannot expect better results given the fact that there have been no calibrations and that the transport from the Baltic Proper is based on the mean annual value. The modeled TP-concentrations in A-sediments (0-10 cm) are given in fig. 3.8A and also these modeled values fall within the requested empirical range (0.5 to 0.68 mg TP/g dw).

### 3.2.2.3. Phosphorus fluxes

The annual fluxes of phosphorus are shown in fig. 3.9. These fluxes give information of fundamental importance related to how the Kattegat likely reacts to changes in phosphorus loading.

It should be noted that the phosphorus fluxes to and from organisms with short turnover times (BS) are large compared to all other fluxes, but the amounts of TP found in biota is small compared to what is found in some other compartments. This illustrates the classical difference between “flux and amount”. In the ranking of the annual fluxes for the Kattegat from fig. 3.9, it is evident that the most dominating fluxes are the ones to and from biota with short turnover times (about 480 kt/yr), whereas the average monthly amount of TP in all types of plankton is just about 3.9 kt. Most phosphorus is found in A-sediments (95 kt), on ET-areas (4 kt) and in the SW-layer (7 kt). Looking at the TP-fluxes to the Kattegat, the DW-flux from Skagerrak is the dominating one (440 kt/yr), followed by the SW-inflow from the Baltic Proper (18 kt/yr), followed by DW-inflow from the Baltic Proper (5 kt/yr), SW-inflow from the Skargerrak (1.9 kt/yr), tributary inflow (1.8 kt/yr) and atmospheric precipitation (0.1 kt/yr). Sedimentation in the SW-layer is also important, 0.7 kt/yr to the DW-layer and
4.0 kt/yr to the ET-sediments. Sedimentation in the DW-layer is 3 kt/yr; about 60% of the phosphorus in the SW-layer and about 90% in the DW-layer appear in dissolved forms (see table 3.7 and fig. 3.6D and E). Figures 3.6D and E give a comparison between modeled dissolved fractions and empirical ratios between phosphate and total phosphorus. It should be stressed that the dissolved fraction (DF) as defined in the model from the particulate fraction (DF = 1 – PF) is not the same thing as phosphate. There are several different dissolved forms of phosphorus often abbreviated as DP (DIP + DOP), and figures 3.6 D and E illustrate that the correspondence between modeled DF and the ratio between phosphate and TP in the Kattegat is reasonable.

Fig. 3.8. Empirical data versus modeled values in the Kattegat. (A) modeled TP-concentrations in the accumulation area sediments (0-10 cm) versus maximum and minimum reference values (B) modeled TN-concentrations in the accumulation area sediments (0-10 cm) versus empirical maximum and minimum values, (C) modeled Secchi depths versus plus/minus 1 standard deviation (SD) of the mean empirical value, (D) empirical mean monthly concentrations of chlorophyll, modeled chlorophyll concentrations based on only TP, on only TN and on both TP and TN (bolded), (E) modeled sedimentation based on the water content of recently deposited matter and on the mean water content in sediments from the upper 10 cm sediment layer and compared to the mean annual reference sedimentation in the Baltic Proper, and (F) modeled SPM-concentrations in the SW-layer and in the DW-layer in the Kattegat.
Together with the relatively high oxygen concentrations in the entire Kattegat, this also implies that diffusion of phosphorus from the A-sediments is small in the Kattegat (only 0.006 kt/yr). The diffusive flux in the water from the DW-compartment to the SW-compartment is also very small (0.03 kt/yr). Burial, i.e., the transport of TP from the sediment biosphere to the sediment geosphere is 3 kt/yr.

### 3.2.2.5.1. The particulate fraction for phosphorus

A very important part of most mass-balance models for chemical substances, including nutrients, is the distribution coefficient. Traditionally (see Santschi and Honeyman 1991; Erel and Stolper, 1993; Benoit et al., 1994; Warren and Zimmerman, 1994; Wehyenmeyer, 1996; Gustafsson and Gschwend, 1997), the $K_d$-concept is used in these contexts; $K_d$ is the ratio between the particulate ($C_{Par}$ in g/kg dw) and the dissolved ($C_{Diss}$ in g/l) phases, i.e., $K_d = C_{Par}/C_{Diss}$. $K_d$ is often given in l/kg. This means that the dissolved fraction can be written:

$$D_{Diss} = 1/(1 + K_d \cdot SPM \cdot 10^{-6})$$

(3.18)

**Fig. 3.9.** Characteristic annual phosphorus fluxes to, from and within the Kattegat (kt/yr). Note that the net inflow of phosphorus from the Baltic Proper is 15 kt/yr, SMHI (Håkansson, 2007; the OSPAR assessment) gives 14 kt/yr.
Mass-balance modeling in the Kattegat

Where SPM is the amount of suspended particulate matter in the water in mg/l. It is essential to distinguish between the dissolved and the particulate fractions for all substances. It is especially important to do so for the key nutrients in water management since phytoplankton take up the dissolved fractions and only the particulate fractions can settle out by gravity. This means that there are different transport routes for the two fractions. From eq. 3.18, it is evident that the SPM-concentration influences the distribution of the nutrients into these two fractions. The settling velocity for the particulate fraction in m/time may be turned into a sedimentation rate (dimension l/time) by division with the mean depth of the system or a defined part of the system. The sedimentation rate regulates sedimentation, and hence also internal loading in the given system.

The particulate TP-fraction in the SW-compartment \( (PF_{SW}) \) depends on and increases with the biouptake of dissolved phosphorus from the water (i.e., with the mass of phosphorus bound to plankton, \( M_{TPBio} \)); and \( PF_{SW} \) increases with increasing resuspension \( (DC_{resSW}) \), which supplies particulate phosphorus to the system; and \( PF \) increases with increased SPM-concentrations in the water. This is given by:

\[
PF_{SW} = Y_{SPMPFSW} \cdot (DC_{ResTPSW} + (M_{TPBio}/(M_{TPSW}+M_{TPBio})))
\]  

If Strat > 1 then \( PF_{DW} = Y_{SPMPFDW} \cdot DC_{ResTPDW} \) else

\[
PF_{DW} = Y_{SPMPFDW} \cdot DC_{ResTPDW} \cdot (Strat/DWT)^{0.5}
\]  

The Strat-value (Strat for stratification) is 1 when the system is homothermal. When the temperature difference between the SW-compartment and the DW-compartment is higher than 4°C, i.e., when the system is stratified and there is reduced oxygenation of the DW-layer, \( PF_{DW} \) should decrease and this is given by this equation. The resuspended fraction is calculated in the same manner in the SW- and DW-compartments. For the SW-compartment, we have:

\[
DC_{ResTPSW} = F_{TPETSW}/(F_{TPw}+F_{TPETSW}+F_{TPSWPK}+F_{TPSWSS}+F_{TPp}+F_{XPDSW}+F_{DTPDSW})
\]  

This is simply the resuspension flux \( (F_{TPETSW}) \) in relation to all other fluxes into the SW-layer. The resuspended fraction in the DW-layer is then given by:

\[
DC_{ResTPDW} = (F_{TPETDW})/(F_{DTPADW}+F_{TPETDW}+F_{TPDWPK}+F_{TPDWSS}+F_{TPSWDW}+F_{TPSWD})
\]  

The algorithm quantifying the increase in PF for phosphorus from increased SPM-concentrations is given by:

\[
Y_{SPMPF} = (1+0.15 \cdot (SPM/3 – 1))
\]  

The norm-value in this dimensionless moderator is 3 (mg/l); this is also the normal value for the Baltic Sea according to Pustelnikov (1977) and the same value is used for the Kattegat. The amplitude value of 0.15 gives the range for how variations in SPM
influence the PF-value. If, e.g., SPM is 5 mg/l, $Y_{SPM,PF}$ is 1.1 and the PF-value 10% higher than in situations when SPM is 3 mg/l. Note that this dimensionless moderator has been applied in the same manner for all PF-values in both layers and that the corresponding SPM-concentrations have been calculated by the dynamic CoastMab-model.

It is well established from empirical data from many systems that the PF-value for phosphorus in mainly the surface water in many aquatic systems is about 0.56 (see Håkanson and Bryhn, 2008a, c). This means that the monthly PF-values for the Kattegat may be compared to and controlled against this empirical reference value in terms of order of magnitude values. The calculated PF-values, or rather the dissolved fractions, the DF-values (DF = 1-PF) may also be compared with the empirical PO$_4$/TP-ratios given in tables 3.9 and 3.10. Those results are shown in fig. 3.6. One can note that:

1. The modeled DF-values in the SW-layer generally vary around 0.5-0.6.
2. The modeled values in the DW-layer are higher than in the SW-layer. This means that there should be a relatively low sedimentation of particulate phosphorus, and hence fairly low concentrations of TP in sediments. This is also evident if one looks at the empirical data. The TP-concentrations in these sediments are about 0.5-0.6 mg/g dw, which should be compared to a characteristic TP-concentration in older sediments (e.g., glacial clays) of about 0.5 mg/g dw. So, the diffusion of TP from these sediments should be low because the pool of phosphorus available for diffusion is small and related to the difference between 0.5-0.6 and 0.5 (mg/g dw).

Table 3.9. Mean monthly values (MV) for the surface-water layer of Kattegat for the period 1995 to 2008 for the ratios between phosphate (PO$_4$) and total phosphorus (TP), dissolved inorganic nitrogen (DIN = NO$_2$+NO$_3$+NH$_4$) to total nitrogen (TN) and the ratio between these two ratios.

<table>
<thead>
<tr>
<th>Month</th>
<th>PO$_4$/TP</th>
<th>DIN/TN</th>
<th>(DIN/TN)/(PO$_4$/TP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.72</td>
<td>0.40</td>
<td>0.55</td>
</tr>
<tr>
<td>2</td>
<td>0.68</td>
<td>0.42</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>0.50</td>
<td>0.35</td>
<td>0.70</td>
</tr>
<tr>
<td>4</td>
<td>0.45</td>
<td>0.30</td>
<td>0.70</td>
</tr>
<tr>
<td>5</td>
<td>0.47</td>
<td>0.29</td>
<td>0.61</td>
</tr>
<tr>
<td>6</td>
<td>0.34</td>
<td>0.22</td>
<td>0.64</td>
</tr>
<tr>
<td>7</td>
<td>0.36</td>
<td>0.18</td>
<td>0.51</td>
</tr>
<tr>
<td>8</td>
<td>0.40</td>
<td>0.15</td>
<td>0.39</td>
</tr>
<tr>
<td>9</td>
<td>0.43</td>
<td>0.15</td>
<td>0.36</td>
</tr>
<tr>
<td>10</td>
<td>0.46</td>
<td>0.19</td>
<td>0.43</td>
</tr>
<tr>
<td>11</td>
<td>0.52</td>
<td>0.26</td>
<td>0.50</td>
</tr>
<tr>
<td>12</td>
<td>0.64</td>
<td>0.32</td>
<td>0.51</td>
</tr>
<tr>
<td>MV</td>
<td>0.48</td>
<td>0.26</td>
<td>0.54</td>
</tr>
</tbody>
</table>
Table 3.10. Mean monthly values (MV) for the deep-water layer of Kattegat for the period 1995 to 2008 for the ratios between phosphate (PO$_4^-$) and total phosphorus (TP), dissolved inorganic nitrogen (DIN = NO$_2^-+$NO$_3^-+$NH$_4^+$) to total nitrogen (TN) and the ratio between these two ratios.

<table>
<thead>
<tr>
<th>Month</th>
<th>PO$_4$/TP</th>
<th>DIN/TN</th>
<th>(DIN/TN)/(PO$_4$/TP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.72</td>
<td>0.40</td>
<td>0.55</td>
</tr>
<tr>
<td>2</td>
<td>0.84</td>
<td>0.53</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>0.86</td>
<td>0.56</td>
<td>0.65</td>
</tr>
<tr>
<td>4</td>
<td>0.86</td>
<td>0.54</td>
<td>0.62</td>
</tr>
<tr>
<td>5</td>
<td>0.84</td>
<td>0.55</td>
<td>0.66</td>
</tr>
<tr>
<td>6</td>
<td>0.84</td>
<td>0.51</td>
<td>0.60</td>
</tr>
<tr>
<td>7</td>
<td>0.86</td>
<td>0.52</td>
<td>0.61</td>
</tr>
<tr>
<td>8</td>
<td>0.87</td>
<td>0.50</td>
<td>0.57</td>
</tr>
<tr>
<td>9</td>
<td>0.84</td>
<td>0.48</td>
<td>0.57</td>
</tr>
<tr>
<td>10</td>
<td>0.83</td>
<td>0.45</td>
<td>0.55</td>
</tr>
<tr>
<td>11</td>
<td>0.82</td>
<td>0.42</td>
<td>0.52</td>
</tr>
<tr>
<td>12</td>
<td>0.85</td>
<td>0.46</td>
<td>0.54</td>
</tr>
<tr>
<td>MV</td>
<td>0.83</td>
<td>0.49</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Only when the PF-values are high can there be a high sedimentation of particulate phosphorus, and vice versa. The data given on the DF (or PF) values may in many ways be seen as an interpretational key to the transport processes for phosphorus, and there are several ways to check the validity of the data. The first and foremost criteria is to see how well the modeled TP-concentrations using these algorithms for the particulate fraction correspond to the measured data of phosphorus in water and sediments. It should also be stressed again that the dissolved forms as defined here from the particulate fraction is not the same thing as phosphate.

3.3. Production and sedimentation of particles – CoastMab for SPM

The dynamic SPM-model (CoastMab for SPM) has been described by Håkanson (2006). That book also presented results of blind tests, sensitivity and uncertainty analyses and comparisons between empirical and modeled values. The model gave very good results for the tested 17 different Baltic Sea coastal areas. The mean error when empirical data on sedimentation (from sediment traps) were compared to modeled values was 0.075, the median error was – 0.05, the standard deviation was 0.48 and the corresponding error/uncertainty for the empirical data was 1.0, as given by the coefficient of variation. This means that the uncertainties in the empirical data set the limit for further improvements of model predictions. The error for the modeled values was defined from the ratio between modeled and empirical data minus 1, so that the error is zero when modeled values correspond to empirical data.

However, the CoastMab-model for SPM has not been used before for such large systems and such high-salinity areas as the Kattegat. This section will describe the model.
3.3.1. Basic model structure
The structure of the dynamic model for basins with two water compartments, such as the Kattegat, is shown in fig. 3.10. There are four main compartments: surface water, deep water, areas where processes of fine sediment erosion and transport dominate the bottom dynamic conditions (ET-areas) and the accumulation areas with continuous deposition of fine materials. There are different sources for SPM:
1. Primary production, which causes increasing biomasses for all types of plankton (phytoplankton, bacterioplankton and herbivorous zooplankton) influencing SPM in the water.
2. Inflow of SPM to the surface-water layer in the Kattegat from the Baltic Proper and the Skagerrak.
3. Inflow of SPM to the deep-water layer (i.e., from Baltic Proper and/or the Skagerrak).
4. Tributary inflow.

The amount of matter deposited on ET-areas may be resuspended by, e.g., wind/wave action or slope processes, so resuspension is an important internal process influencing the SPM-flux in coastal areas. The resuspended matter can be transported either back to the surface water ($F_{SPM_{ETSW}}$) or to the deep water ($F_{SPM_{ETDW}}$). How much that will go in either direction is regulated by a distribution coefficient calculated from the form ($V_d = \text{the form factor} = 3 \cdot D_{MV}/D_{Max}; D_{MV} = \text{the mean depth}; D_{Max} = \text{the max. depth}$) of the coastal area. Other internal processes are mineralization, i.e., the bacterial decomposition of organic SPM-particles in water and sediments. Since the CoastWeb-model calculates the biomass of bacterioplankton, mineralization is calculated in a new way using model-predicted values of bacterioplankton biomass, as will be explained below. The model also accounts for mixing, i.e., the transport from deep water to surface water or from surface water to deep water.

All equations are compiled in appendix 8.1 and table 3.8 gives an overview of abbreviations.

3.3.2. Primary production of SPM
Calculating the bioproduction is a focal issue in aquatic sciences and many authors have discussed primary production. Generally, chlorophyll-a concentrations are predicted from light conditions (or water temperatures) and nutrient concentrations (e.g., Dillon and Rigler, 1974; Smith, 1979; Riley and Prepas, 1985; Evans et al., 1996). The equation to quantify the amount of SPM generated on a monthly basis in a given system used here comes from Håkanson and Boullion (2002). In this approach, total SPM-production is calculated from chlorophyll-a, accordingly:

$$F_{prod} = (30.6 \cdot \text{Chl}^{0.927}) \cdot 0.45 \cdot 30 \cdot \text{Area} \cdot 2 \cdot \text{Sec} \cdot 0.001 \cdot \frac{((\text{SWT}+0.1)/9) \cdot (BM_{PL}/BM_{PH})}{(BM_{PL}/BM_{PH})} \quad (3.24)$$

Chl = The mean monthly chlorophyll concentration ($\mu g/l$); the expression $(30.6 \cdot \text{Chl}^{0.927})$ transforms Chl into phytoplankton production (in $\mu g \text{ C}/l$·d). The factor 0.45 is a standard transformation to change $g \text{ C}$ to $g \text{ dw}$. Multiplication with 0.001, 30 days, lake area (Area) and the mean monthly value of the depth of the photic zone (= two times the Secchi depth = 2·Sec in m) give the biomass of phytoplankton produced per month (g dw per month).
The structure of the dynamic SPM model for coastal areas (CoastMab)

MSPMSW

Tributary inflow

FSMtrib

Inflow to SW from the Baltic Proper and Skagerrak

FSWSPMKBKA FSWSPMSKKA

From primary production to SW

FSPMPP

Mix SW to DW

FxSPMDWSW

Sed from SW to DW

FSPMSWDW

Mineralization in DW

FSPMminDW

Sed on A-areas

FSPMminADW

Mineralization in A

FSPMminADW

Burial (FBur)

MA

Outflow from SW to the Baltic Proper and Skagerrak

FSMPSWKABP FSMPSWKASK

Mineralization in SW

FSPMminSW

Resuspension from ET to SW

FSPMETS

Sed on ET areas

FSMPETSW

Resusp from ET to DW

FSPMETS

Outflow from DW to Skagerrak

FSPMDWKASK

Mineralization in ET

FSPMminET

Inflow to DW from the Baltic Proper and Skagerrak

FSPMDWBKA FSPMDWSKKA

Mineralization in DW

FSPMminDW

Sed on ET areas

FSMPETSW

Fig. 3.10. A general outline of the structure of the CoastMab-model for suspended particulate matter (SPM) for basins (such as the Kattegat, KA) with two water compartments (SW and DW).

BM_{PL}/BM_{PH} = The average ratio between the biomass of all sorts of plankton (phytoplankton, bacterioplankton zooplankton, etc.; BM_{PL}) to the calculated biomass of phytoplankton (BM_{PH}). This ratio gives that the total biomass of bacterioplankton plus zooplankton plus phytoplankton is a factor of about 2.5 higher than the phytoplankton biomass and this value has also been used in this modeling. There is generally a marked temporal variability around this mean value from seasonal changes in surface-water temperatures. This is quantified by the dimensionless moderator for SWT in eq. 3.24.

SWT = Mean monthly surface-water temperatures (°C); this modeling uses empirical data on SWT (from SMHI). By dividing SWT with a reference temperature of 9 °C (related to the duration of the growing season; see Håkanson and Boullon, 2002), this approach accounts for seasonal variations in SWT in a dimensionless manner. The moderator is (SWT+0.1)/9. The constant 0.1 is used since SWT may approach 0 °C during the winter and since there is also production under the ice.
Sec = Secchi depth (in m); values on Secchi depth have been derived from a model described later in this chapter from the model based on dynamically modeled salinities and SPM-values (from Håkanson, 2006).

3.3.3. Inflow of SPM from the sea and from tributaries

The inflow of SPM to the surface water from the Baltic Proper and the Skagerrak to the Kattegat is calculated from the two surface water flows ($Q_{SWBPKA}$ and $Q_{SWSKA}$ in m³/month), which are derived from the mass-balance for salt and the concentrations of SPM in the SW-layer in the Baltic Proper (SPM$_{SWBP}$ mg/l = g/m³) and in the Skagerrak (SPM$_{SWSK}$). The SPM$_{SWSK}$-values have been calculated from the same model as used to calculate Secchi depths from SPM and salinities, since empirical data on Secchi depths are available for the Skagerrak and also reliable empirical data on SW-salinities in the Skagerrak (see table 3.2). The SPM$_{SWBP}$-data for the Baltic Proper emanate from Håkanson and Bryhn (2008a) and they are (in mg/l):

<table>
<thead>
<tr>
<th>Month</th>
<th>1 Jan</th>
<th>2 Feb</th>
<th>3 Mar</th>
<th>4 Apr</th>
<th>5 May</th>
<th>6 Jun</th>
<th>7 Jul</th>
<th>8 Aug</th>
<th>9 Sep</th>
<th>10 Oct</th>
<th>11 Nov</th>
<th>12 Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>2.19</td>
<td>2.31</td>
<td>2.46</td>
<td>2.57</td>
<td>2.57</td>
<td>2.53</td>
<td>2.32</td>
<td>2.05</td>
<td>1.75</td>
<td>1.60</td>
<td>1.78</td>
<td>2.00</td>
</tr>
</tbody>
</table>

This means that the SW-inflow of SPM from the Baltic Proper is given by:

$$F_{SPMSWBPKA} = Q_{SWBPKA} \cdot SPM_{SWBP} \quad (3.25)$$

The relatively small deep-water inflow of SPM from the Baltic Proper is quantified in the same way:

$$F_{SPMDWBPKA} = Q_{DWBPKA} \cdot SPM_{DWBP} \quad (3.26)$$

Using the following data (note that these DW-data emanate from the dynamic SPM-model used for the Baltic Proper; this is the same model as used in this work for the Kattegat):

<table>
<thead>
<tr>
<th>Month</th>
<th>1 Jan</th>
<th>2 Feb</th>
<th>3 Mar</th>
<th>4 Apr</th>
<th>5 May</th>
<th>6 Jun</th>
<th>7 Jul</th>
<th>8 Aug</th>
<th>9 Sep</th>
<th>10 Oct</th>
<th>11 Nov</th>
<th>12 Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>1.85</td>
<td>2.04</td>
<td>2.24</td>
<td>2.33</td>
<td>2.03</td>
<td>1.51</td>
<td>1.17</td>
<td>0.95</td>
<td>0.83</td>
<td>0.86</td>
<td>1.22</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Since there are no available reliable DW-data on SPM in the Skagerrak or in the tributaries to the Kattegat, those data have been estimated in the following manner from SPM$_{SWSK}$-values and empirical TN- and TP-concentrations in the SW- and DW-layers in the Skagerrak (from tables 3.2 and 3.3):

$$SPM_{DWSK} = SPM_{SWSK} \cdot ((TP_{DWSK}+TN_{DWSK})/(TP_{SWSK}+TN_{SWSK})) \quad (3.27)$$

There are no SPM-data from the tributaries entering the Kattegat and those SPM-values have been estimated from the TP-inflow or the TN-inflow. Generally, in systems highly influenced by anthropogenic nutrient loading, one can assume that the TP-concentration is 1-2 mg/g dw of SPM (see Håkanson, 2006). Based on empirical TP-concentrations in recently deposited sediments in the Kattegat (see table 2.4) this TP-
concentration has been set to 1 mg/g dw, and hence the SPM-concentration in the inflowing tributary water has been set to 1000 times the TP-concentration.

### 3.3.4. Sedimentation

Sedimentation of SPM depends on:

1. A default settling velocity, \( v_{\text{Def}} \), which is set to 72 m/yr for planktonic materials, SPM and the carrier particles for the particulate fraction for phosphorus in highly productive systems (Håkanson, 2006; Håkanson and Bryhn, 2008a). The default settling velocity is changed into a rate (1/month) by division with the mean depth of the surface-water layer (\( D_{SW} \)) for sedimentation in this layer and by the mean depth of the deep-water layer (\( D_{DW} \)) for sedimentation in this layer.

2. The SPM-concentration will also influence the settling velocity - the greater the aggregation of suspended particles, the bigger the flocs and the faster the settling velocity (Kranck, 1973, 1979; Lick et al., 1992). This is expressed by a dimensionless moderator (\( Y_{\text{SPM}} \)).

3. The salinity of the water will also influence the settling velocity - the higher the salinity, the greater the aggregation, the bigger the flocs and the faster the settling velocity (Kranck, 1973, 1979). This is expressed by a dimensionless moderator for salinity (\( Y_{\text{Sal}} \)) operating on the default settling velocity.

4. Burban et al. (1989, 1990) have demonstrated that changes in turbulence are very important for the fall velocity of suspended particles. Generally, there is more turbulence, which keeps the particles suspended, and hence causes lower settling rates, in the surface water than in the calmer deep-water compartment. The turbulence is also generally greater in large and shallow basins (with high dynamic ratios, DR) compared to small and deep basins. In this modeling, two dimensionless moderators (\( Y_{TDW} \) and \( Y_{DR} \)) related to the theoretical water retention time and the dynamic ratio are used to quantify how turbulence is likely to influence the settling velocity in the SW- and DW-compartments. Since there is generally no ice cover in the Kattegat, the influence of ice on the turbulence and sedimentation has been set to 1 (no effects) in the following simulations.

5. The settling velocity also depends on the amount of resuspended matter. The resuspended particles have already been deposited and aggregated and they have also generally been influenced by benthic activities, which will create a "gluing effect", and they have a comparatively short distance to fall after being resuspended (see Håkanson and Jansson, 1983). The longer the particles have stayed on the bottoms, the larger the potential gluing effect and the faster the settling velocity if the particles are resuspended. The resuspended fraction is calculated in the model and the resuspended particles settle out faster. This is expressed by another dimensionless moderator (\( Y_{\text{Res}} \)).

Sedimentation from the SW-compartment to the ET-areas (\( F_{\text{SPMSWET}} \)) is given by:

\[
F_{\text{SPMSWET}} = M_{\text{SPMSW}} \cdot ((v_{\text{Def}} \cdot Y_{\text{SPMSW}} \cdot Y_{\text{SalSW}} \cdot Y_{\text{ResSW}})/D_{SW}) \cdot ET \cdot ((1-DC_{\text{ResSW}})+Y_{\text{ResSW}} \cdot DC_{\text{ResSW}}) \tag{3.18}
\]

- \( M_{\text{SPMSW}} \) = The mass of SPM in the SW-compartment (g); calculated automatically in the CoastMab-model using Euler’s method.
- \( V_{\text{Def}} \) = The default settling velocity (6 m/month).
$Y_{SPM_{SW}}$ = The dimensionless moderator expressing how SPM-concentrations in SW influence aggregation and sedimentation of SPM.

$Y_{Sal_{SW}}$ = The dimensionless moderator expressing how the salinity in the SW-layer influences aggregation and sedimentation of SPM.

$Y_{T_{crit}}$ = The dimensionless moderator expressing temperature criteria for how the ice would influence the turbulence and hence also sedimentation of SPM.

$ET$ = The fraction of ET-areas ($ET = \text{Area}_{ET}/\text{Area}$), i.e., a dimensionless measure of the area above the theoretical wave base.

$DC_{Res_{SW}}$ = The distribution coefficient for the resuspended SPM-fraction.

$Y_{Res_{SW}}$ = The dimensionless moderator expressing how much faster the resuspended matter will settle out compared to the primary material (which have not been resuspended).

These expressions will be explained in the following text.

### 3.3.4.1. SPM influences on sedimentation

The higher the concentration of suspended particles in the water (SPM in mg/l), the faster the settling velocity. This is given by the following dimensionless moderator, which is used for both layers:

$$Y_{SPM} = (1 + 0.75 \cdot (\text{SPM}/50 - 1))$$

(3.19)

The amplitude value (0.75) quantifies how changes SPM influence the settling velocity. If, e.g., SPM changes by a factor of 10, e.g., from 2 mg/l (which is a typical value for relatively low-productive systems) to 20 mg/l (which is typical for highly productive systems), this will cause a change in the settling velocity by a factor of 2. The borderline value for the moderator is 50 mg/l, since it is unlikely that marine systems (entire coastal areas on a monthly time scale) will have higher mean monthly SPM-values than that. In this modeling, SPM has a default settling velocity of 72 m/yr in systems with SPM-values of 50 mg/l, and in systems with lower SPM-concentrations the fall velocity is lower, as expressed by eq. 3.19.

In traditional mass-balance models, one would multiply an amount (kg) by a rate (1/month) to get a flux (i.e., amount-rate). In this modeling, one multiplies kg\cdot(1/month)\cdot Y (= amount-rate-moderator), where Y is a dimensionless moderator quantifying how an environmental variable (like SPM) influences the given flux (e.g., sedimentation). Instead of building a large mechanistic sub-model for how environmental factors influence given rates, this technique uses a simple, general algorithm for the moderator. Empirical data can be used for the calibration and test of the moderator. The dimensionless moderator defined by eq. 3.19 uses a borderline value, i.e., a realistic maximum value of SPM = 50, to define when the moderator, $Y_{SPM}$, attains the value of 1. For all SPM-values smaller than the borderline value, $Y_{SPM}$ is smaller than unity. One can also build normal-value moderators in such a way that the $Y_{SPM}$ is 1 for the "normal" value and higher or lower than 1 for SPM-values higher and lower than the defined normal value (e.g., SPM = 5; see Håkanson and Peters, 1995). The amplitude value regulates the change in $Y_{SPM}$ when the actual SPM-value differs from the borderline value and/or the normal value.
3.3.4.2. Influences of salinity on sedimentation
The salinity influences the aggregation and sedimentation of suspended particulate matter, including particulate phosphorus. The dimensionless moderator for salinity (Y_{Sal}) was discussed in section 3.2.2.1.7.

3.3.4.3. Influences of the potential turbulence on sedimentation
The dimensionless moderator for the dynamic ratio (DR; the potential turbulence), Y_{DR}, is given by:

If DR < 0.26 then Y_{DR} = 1 else Y_{DR} = 0.26/DR \tag{3.20}

Basins with a DR-value of 0.26 (see Håkanson and Jansson, 1983) are likely to have a minimum of ET-areas (15% of the area) and the higher the DR-value, the larger the area relative to the mean depth and the higher the potential turbulence and the lower the settling velocity.

The dimensionless moderator expressing how the ice would influence the turbulence of the system, Y_{T_{crit}}, is defined by:

If SWT < 0.9 °C (the monthly boundary temperature criteria for the ice effects) then:

Y_{T_{crit}} = ((5-SWT)/(SWT+0.5)) \cdot Y_{DR} else Y_{T_{crit}} = Y_{DR} \tag{3.21}

For example, for the Kattegat DR is 6.16 and hence Y_{DR} is 0.042, which is 6.16 times lower than in a system with a DR-value of 0.26. This also means that the settling velocity is 6.16 times lower, if everything else is constant. Eq. 3.21 gives a successive increase in the settling rate with increasing ice cover and when the monthly SWT-value is zero, the equation gives a factor of 10 higher sedimentation rate due to the reduction in wind-generated wave turbulence from a full ice cover. In situations when here are several consecutive months with ice cover, or with SWT lower than 0.9 °C, this should influence the settling of SPM and particulate nutrients substantially, and this is what this algorithm is meant to quantitatively describe. So, the potential turbulence should be related to the wind/wave activity, and large and shallow systems with high dynamic ratios should have higher waves, more turbulence, which will keep the particles suspended in water for longer periods of time. One can compare sedimentation in a bottle in the laboratory under calm conditions when the bottle rests on a table (as this is described by Stokes’ law) compared to sedimentation in the bottle when it is shaken.

The high turbulence in the DW-layer in Kattegat will also influence the settling velocity of SPM in this layer. This is calculated from the theoretical deep-water retention times by:

If T_{DW} < 30 (days) then Y_{TDW} = \sqrt{30}/1 else Y_{TDW} = (\sqrt{T_{DWBP}/1})^{0.5} \tag{3.22}

This means that if T_{DW} is 100 days Y_{TDW} is 10 and sedimentation of SPM a factor of 1.8 faster as compared to a situation when the theoretical DW water retention time is 30
days or less (as in Kattegat); when $T_{DW}$ is 365 days, $Y_{TDW}$ is 19.2 and sedimentation of SPM a factor of 3.5 faster than when $T_{DW} < 30$ days.

3.3.4.4. The resuspended fraction

Resuspended particles generally settle out more rapidly than particles originating directly from primary autochthonous or allochthonous sources. The resuspended fraction of SPM in the SW-compartment is calculated by means of the distribution coefficient ($DC_{ResSW}$), which is defined by the ratio between resuspension from ET-areas to surface water relative to all fluxes to the SW-compartment. Since these fluxes are calculated automatically in the CoastMab-model, $DC_{ResSW}$ is also calculated automatically.

The dimensionless moderator expressing how much faster resuspended particles settle compared to primary particles is given by:

$$Y_{Res} = ((12/Strat)+1)^{0.5}$$ (3.23)

Where $((12/Strat) +1)^{0.5}$ is a dimensionless expression equal to $T_{ET}/1$, where $T_{ET}$ is the mean retention time (the mean age = $T_{ET}$) of and SPM on the ET-areas in months and 1 is a reference age (1 month). When the system is homothermal and Strat is 1, $T_{ET}$ = $Y_{Res}$ is 3.6 months and the resuspended particles settle out 3.6 times faster than the primary materials. When the system is stratified, Strat can approach 0.1 (a highly stratified system) and the $T_{ET}$-value can approach 12 months, which means that resuspended particles which have stayed that long on the bottom would be more consolidated (including gluing effects from zoobenthos) and would settle out 3.3 (12/3.6) times faster than under homothermal conditions.

3.3.5. Resuspension

By definition, the materials settling on ET-areas will not stay permanently where they were deposited but will be resuspended by mainly wind/wave activity. If the age of the material ($T_{ET}$) is set to a very long period, e.g., 10 years, these areas will function as accumulation areas; if, on the other hand, the age is set to 1 week or less, they will act as erosion areas.

Resuspension of SPM back to surface water from ET-areas, $F_{ETSW}$ (g SPM/month), is given by:

$$F_{SPMETSW} = M_{SPMET} \cdot R_{Res} \cdot (1-V_d/3)$$ (3.24)

If $SWT < 0.9$ °C (the boundary condition for the ice effects) then:

$$R_{Res} = (SWT+0.2) \cdot 1/((12/Strat)) \text{ else } R_{Res} = 1/(12/Strat)$$ (3.25)

There may be resuspension from current activities and slope processes also under ice, so the monthly resuspension rate, $R_{res}$, should not be zero. With this approach, the resuspension is a factor of 5 lower under ice, when $SWT = 0$, compared to situations when monthly SWT-values are higher than 0.9 °C.
Resuspension from ET-areas to DW-areas below the theoretical wave base areas, \( F_{ETSWDW} \), is given by:

\[
F_{SPMETDW} = M_{SPMET} \cdot R_{Res} \cdot \left( V_d / 3 \right)
\]  

(3.26)

\( M_{SPMET} \) is the total amount of resuspendable matter on ET-areas (g). \( V_d \) is the the form factor. Note that \( V_d / 3 \) is used as a distribution coefficient to regulate how much of the resuspended material from ET-areas that will go the surface water or to the DW-compartment. If the basin is U-shaped, \( V_d \) is about 3 (i.e., \( D_{Max} \approx D_{MV} \)) and all resuspended matter from ET-areas will flow to the deeper areas. If, on the other hand, the basin is shallow and \( V_d \) small, most resuspended matter will go to the surface-water compartment. \( R_{Res} \) is the resuspension rate (1/month) related to the age of the material on the ET-areas.

The ordinary differential equation describing the fluxes of SPM to and from the ET-areas is given below:

\[
M_{SPMET}(t) = M_{SPMET}(t - dt) + (F_{SPMSWET} - F_{SPMETDW} - F_{SPMETSW}) \cdot dt
\]  

(3.27)

The three monthly SPM-fluxes are:

1. \( F_{SPMSWET} \) = Sedimentation of SPM from from SW to ET.
2. \( F_{SPMETDW} \) = Resuspension flux from ET to DW.
3. \( F_{SPMETSW} \) = Resuspension from SW to ET.

The bulk density of A-sediments (d in g ww/cm\(^3\)) is calculated in the CoastMab-model using a standard formula (from Håkanson and Jansson, 1983) based on the water content (W) and IG (in % ww; abbreviated as IG*). That is:

\[
d = 260/(100 + 1.6 \cdot (W + IG^* \cdot ((100 - W)/100)))
\]  

(3.28)

The water content in the top decimeter of accumulation area sediments in the Kattegat is set to 70% ww as a default value and the IG-value to 10% dw (see table 2.5).

3.3.6. SPM mixing

To quantify mixing, i.e., the upward and downward advective transport of SPM between the SW- and DW-layers, empirical data on water temperatures (from SMHI) and dynamically modeled salinities are used. Since this is modeling on a monthly basis, and since the circulation in the Kattegat should increase if the surface water becomes colder than the DW-layer in the winter, this modeling accounts for how such temperature variations regulate mixing. The greater the difference in mean monthly temperatures between the two layers, the smaller the advective mixing. This is quantified by the following approach exemplified for the upward mixing (in kg/months) between DW and SW:

\[
F_{SPMDWSW} = M_{SPMDW} \cdot R_{ASWDW} \cdot V_{SW} / V_{MW}
\]  

(3.29)
The downward mixing transport of SPM from SW to DW is then given by:

\[ F_{\text{SPM SW to DW}} = M_{\text{SPM SW}} \cdot R_{\text{SW to DW}} \] (3.30)

\[ M_{\text{SPM SW}} = \text{The mass of SPM (g) in the SW-layer.} \]
\[ M_{\text{SPM DW}} = \text{The mass of SPM (g) in the DW-layer.} \]
\[ V_{\text{SW}} / V_{\text{DW}} = \text{The ratio between the volume (m^3) of the SW-layer and the DW-layer. This ratio is included in eq. 3.29 to obtain the same water transport in both directions across the depth of the theoretical wave base.} \]
\[ R_{\text{SW to DW}} = \text{The mixing rate for SW to DW (1/month).} \]

The salinity (Sal) also affects the density of the water and hence also stratification and mixing. The influences of salinity (Sal_{DW} and Sal_{SW} are the salinities in psu in the SW- and DW-layers) on the mixing rate is given by:

If Sal_{DW} > Sal_{SW} then
\[ R_{\text{SW to DW}} = R_{\text{Mix def}} \cdot \left( \frac{1}{1 + Sal_{DW} - Sal_{SW}} \right)^{R_{\text{Mix exp}}} \]
else
\[ R_{\text{SW to DW}} = R_{\text{Mix def}} \] (3.31)

\[ R_{\text{Mix exp}}, \text{the mixing rate exponent is set to 2 as a general default value (the larger the value of this exponent, the smaller the mixing, and vice versa); } R_{\text{Mix def}} \text{ is the default mixing rate (1/month), which is calculated from the fraction of erosion plus transport areas for fine sediments (ET, dimensionless; see eq. 3.32) – it is assumed that systems with large ET-areas (i.e., systems dominated by resuspension) should be more turbulent with more mixing. } R_{\text{Mix def}} \text{ is also influenced by the temperature stratification, which is calculated from the difference in monthly temperatures between the two layers. ET is defined from:} \]

\[ ET = \frac{(\text{Area} - \text{Area}_{\text{DWB}})}{\text{Area}} \] (3.32)

\[ \text{Area} = \text{The total water surface area of the system (m}^2\text{).} \]
\[ \text{Area}_{\text{DWB}} = \text{The area below the theoretical wave base (m}^2\text{).} \]

The monthly temperature-dependent stratification is calculated from:

\[ \text{Strat} = \text{if } \text{ABS(SWT} - \text{DWT)} < 4 \text{ °C then} \]
\[ \text{Strat} = (\frac{1}{1/R_{\text{Mix const}} + \text{ABS(SWT} - \text{DWT)})} \text{ else } \text{Strat} = 1/\text{ABS(SWT} - \text{DWT}) \] (3.33)

Where the mixing rate constant, \( R_{\text{Mix const}} \), is set to 1 as a default value. SWT is the SW-temperature in °C. This means that the default mixing rate is given by:

\[ R_{\text{Mix def}} = \text{Strat} \cdot ET / 12 \] (3.34)

The value of 1 for the general mixing rate constant \( R_{\text{Mix const}} \) has been derived from calibrations. One can see that if the difference between the SW- and DW-temperatures is, e.g., 6 °C, the value for Strat is 2/7 = 0.29; if the temperature difference is 3 °C, Strat is 0.5 and there is more mixing in the system; if the temperature difference is zero, Strat is 2 and there is intensive mixing in the system. \( R_{\text{Mix def}} \) is defined by eq. 3.17.
3.3.7. Mineralization

Mineralization is the loss of the organic degradable fraction of SPM by bacterial decomposition. The value used for the mineralization rate, $R_{\text{Min}}$, regulates the total amount of SPM being lost each month in a given compartment. Bacteria can be found in the entire water mass, although the highest bacterial biomasses often appear in the sediments, close to the bottom and near the water surface (Håkanson and Jansson, 1983).

The bacterial degradation is a function of the temperature ($\text{SWT} = \text{surface-water temperature in °C}$ and $\text{DWT} = \text{deep-water temperature in °C}$). The loss of SPM from mineralization in surface water is:

$$F_{\text{MinSPMSW}} = M_{\text{SPMSW}} \cdot R_{\text{Min}} \cdot Y_{\text{ET}} \cdot (\text{SWT}/9)^{1.2}$$ (3.35)

Where 9 °C is a reference temperature related to the duration of the growing season (see Håkanson and Boulion, 2002); the mineralization rate ($R_{\text{Min}}$) used in all model simulations utilizes modeled values on the biomass of bacterioplankton (from the CoastWeb-model) and is given in eq. 3.36. The ratio SWT/9 is used as a simple dimensionless moderator and the exponent 1.2 stresses the non-linear temperature dependence of bacterial decomposition (see, e.g., Törnblom and Rydin, 1998). $Y_{\text{ET}}$ is a dimensionless moderator quantifying in a simple manner a more complicated phenomenon related to the fact that resuspended particles are older and more likely to have been mineralized and have a lower organic content than primary particles (see Håkanson, 2006). The mass (= amount) of SPM in the surface water ($M_{\text{SPMSW}}$) is calculated automatically by the CoastMab-model.

$$R_{\text{Min}} = \left(\frac{M_{\text{BP}}}{N_{\text{BM BP}}}\right) \cdot 0.01$$ (3.36)

The mineralization constant, 0.01 (1/month), is generally used in CoastMab and has been derived from calibrations. $M_{\text{BP}}$ is the actual, modeled biomass of bacterioplankton (kg ww) in the given basin and $N_{\text{BM BP}}$ is the corresponding norm-value (the normal biomass of bacterioplankton; see appendix 8.2). The higher the actual bacterioplankton biomass as compared to the norm-value, the higher the potential mineralization.

The organic content is generally highest in the material collected in the surface-water sediment traps (dominated by primary materials) and lowest in the sediment samples, where the sediments have been decomposed (mineralized) to a larger extent. This demonstrates that bacterial decomposition is important in understanding changes in SPM-values and that resuspended matter should be expected to have a lower organic content than primary materials. Håkanson (2006) has also shown that there is a statistically significant cross-systems correlation between the relative extent of ET-areas and the organic content of accumulation area sediments ($\text{IG} = \text{loss on ignition}$) — the higher the ET-value, the lower the organic content. That information lies behind the dimensionless moderator $Y_{\text{ET}}$, which is meant to quantify that the mineralization rate should be higher for systems dominated by primary materials and lower for systems dominated by resuspension and SPM, which has already been mineralized. In CoastMab, $Y_{\text{ET}}$ is defined by:
\[ Y_{ET} = \frac{0.99}{ET} \]  

This means that \( Y_{ET} = 1 \) for basins dominated by resuspension (\( ET = 0.99 \)) and \( Y_{ET} = 6.6 \) in systems with a minimum of resuspension (\( ET = 0.15 \)). For such basins, the mineralization rate is also 6.6 times higher.

The mineralization loss from the deep-water compartment is then:

\[ F_{MinSPMDW} = M_{SPMDW} R_{Min} Y_{ET} (DWT/9)^{1.2} \]  

The basic idea in settling the mineralization rate for sediments is to make sure that there is a realistic relationship between sedimentation and burial in all sediment compartments. The difference should be regulated by the substrate decomposition from mineralization and losses of matter released from gas ebullition in the sediments. In systems where much SPM emanate from primary production, the fraction of degradable organic matter should be relatively high and hence also the difference between sedimentation and burial, and vice versa for systems where SPM includes more minerogenic materials. These rather complicated processes have been handled in a simple manner in this modeling. Several alternative approaches have been tested. The following alternative is used for all sediment compartments.

Mineralization in the two sediment compartments is given by:

\[ F_{MinSPMsed} = M_{SPMA} R_{Minsed} \]  

Where \( M_{SPMA} \) is the mass of SPM (in this case from the A-sediments), \( R_{Minsed} \) is given by the default the mineralization constant (i.e., 0.01) times a general constant of 30 for sediments (since there are more bacteria in the sediments than in the water.)

3.3.8. SPM outflow

Outflow and inflow of SPM are treated in similar ways. The outflow of SPM from the surface water is calculated from the SW-flows (\( Q_{SWKABP} \) or \( Q_{SWKASK} \) in m³/month). These water fluxes are derived from the mass-balance for salt and the concentration of SPM in the SW-layer in the Kattegat (SPM\(_{SW}\) mg/l = g/m³) is calculated from CoastMab for SPM. This means that the SW-outflow to the Skagerrak is given by:

\[ F_{SPMSWKASK} = Q_{SWKASK} SPM_{SW} \]  

The deep-water outflow of SPM to the Skagerrak is quantified in the same way:

\[ F_{SPMDWKASK} = Q_{DWKASK} SPM_{DW} \]  

3.3.9. The panel of driving variables

Table 3.8 gives a compilation of all abbreviations used in this modeling and table 3.11 gives the panel of driving variables for the dynamic SPM-model. These are the coastal-
area specific variables needed to run the dynamic SPM-model. No other parts of the model should be changed.

**Table 3.11. Panel of driving variables for the dynamic SPM-model.**

A. Morphometric parameters:
1. Hypsographic curve

B. Chemical variables:
2. Data on salinity, TP-, TN-concentrations, Secchi depths and/or SPM-concentrations in the inflowing water to the coastal area from the outside sea
3. Data and tributary inflow of TP, TN and SPM

C. Other variables:
4. Tributary water discharge or latitude and annual precipitation and evaporation

3.3.10. Testing model predictions
First, it should be stressed that the basic SPM-model has been extensively tested for smaller coastal areas in the Baltic Sea and provided excellent predictions, generally within the uncertainty bands of the empirical data (see Håkanson, 2006).

The modeled SPM-concentrations are given in fig. 3.8F. One can note that the mean value for the entire surface-water layer in the Kattegat is about 5 mg/l. A default value of 3 mg/l (from Pustelnikov, 1977) has often been used for SPM in the Baltic Sea. Håkanson and Eckhell (2005) presented a rather comprehensive empirical study on SPM-variations in the Baltic Proper under different wind situations, at different sampling depths and under stratified and non-stratified conditions. The mean and median values were both 2.3 mg/l, with a coefficient of variation (CV) of 0.67, a very high value.

It should be stressed that SPM-concentrations generally vary very much and appear with high CV-values in most aquatic systems. This implies that many samples are needed to obtain a reliable mean value (see eq. 3.42). Håkanson (2006) gave a compilation of CV-values for SPM from different aquatic systems and e.g., the mean CV for UK rivers was 1.71. This means that 1124 measurements are needed to calculate the mean SPM-concentration with an error smaller than 10% of the mean. The general sampling formula is given by (from Håkanson, 1984):

\[
n = (t \cdot CV/L)^2 + 1\]

(3.42)

Where \( t \) = Student's t, which specifies the probability level of the estimated mean (usually 95%; strictly, this approach is only valid for variables from normal frequency distributions), and \( CV \) = coefficient of variation within a given ecosystem. \( L \) is the level of error accepted in the mean value. For example, \( L = 0.1 \) implies 10% error so that the measured mean will be expected to lie within 10% of the expected mean with the probability assumed in determining \( t \). Since one often determines the mean value with 95% certainty (\( p = 0.05 \)), the \( t \)-value is set to 1.96.
In the archipelago areas in the Kattegat, one should expect a relatively high sedimentation (e.g., Cato, 1977; Dave and Nilsson, 1994; Thorsen et al., 1995). Measurements of sedimentation at individual sites in the open Kattegat (Dave and Nilsson, 1994; Thorsen et al., 1995) have indicated that sedimentation is generally around 0.1-0.5 cm/yr. Fig. 3.8E presents results from the calculations using the dynamic SPM-model. One can see that these results are close to the empirical data: the mean value for sedimentation in the 0-10 cm DW-layer is about 0.2 cm/yr; the value is about 0.4 for more recently deposited materials with a higher water content; the reference value of 0.1 applies for the Baltic Sea. Given the relatively high oxygen concentrations in the DW-layer (fig. 2.3B), one should expect a marked bioturbation in the A-sediments, which would create a mixing of older and recently deposited matter so the average age of the sediments from sediment cores should be older than the value given by the sedimentation rate in cm/yr (Håkanson and Jansson, 1983).

So, these results are in good overall agreement with empirical data considering the problems related to the time- and area-comparability of the sediment data. It should be stressed that one must expect major differences in sedimentation (= deposition) of matter within the Kattegat. The rule is that the net sedimentation should vary from zero at the theoretical wave base, increase with water depth (sediment focusing), and show an areal distribution pattern reflecting the dominating hydrological flow pattern (Håkanson and Jansson, 1983). Note that there may be large variations among years related to storms and changes in run-off.

Fig. 3.11. Characteristic annual SPM-fluxes to, from and within the Kattegat for the period 1995-2008.
3.3.11. SPM-fluxes
Fig. 3.11 shows the annual SPM-fluxes to, within and from the Kattegat. It is evident that the most dominating abiotic SPM-inflow is DW-inflow from the Skagerrak (about 113,000 kt/yr), followed by SW-inflow from the Baltic Proper (1940 kt/yr), tributary inflow (1820 kt/yr), SW-inflow from the Skagerrak (650 kt/yr) and DW-inflow from the Baltic Proper (95 kt/yr). Sedimentation in the SW-layer is also important with 3060 kt/yr. Sedimentation of SPM from the SW to the DW-layer is 510 kt/yr. The flux related to internal loading (resuspension) is 480 kt/yr from ET-areas to the SW-layer and 170 kt/yr to the DW-layer. Burial, i.e., the transport of SPM from the sediment biosphere to the sediment geosphere is about 2000 kt/yr. The total SPM-production is 8600 kt/yr.

3.3.12. Comments
Previous knowledge regarding the SPM-concentration, its variation and the factors influencing variations among and within sites was very limited for the Kattegat. The results discussed here represent a step forward in understanding and predicting SPM in the Kattegat and also in other similar systems. Evidently, it would have been preferable to have access to a large database on SPM, but it is very demanding (in terms of costs, manpower, ships, etc.) to collect such data, especially under storms.

It should also be noted that bioturbation, fish movements (Meijer et al., 1990), currents (Lemmin and Imboden, 1987) and slope processes (Håkanson and Jansson, 1983) might influence the SPM-concentrations and how SPM varies among and within sites as well as boat traffic, trawling and dredging. These factors have, however, not been accounted for in this modeling, which does not concern sites but entire basins.

3.4. Predicting chlorophyll-a concentrations
Values of chlorophyll-a concentrations in the surface-water layer drive the secondary production (including the production of zooplankton and fish), which means that it is very important to model chlorophyll as accurately as possible. This section will first describe the approach used to model chlorophyll and then present results describing how well modeled values correspond to measured data.

Typical chlorophyll-a concentrations for the Kattegat and parts of the North Sea are shown fig. 1.3. Values lower than 2 μg/l (oligotrophic conditions) are found in the northern parts of the Bothnian Bay and the outer parts of the North Sea, while values higher than 20 μg/l (hypertrophic conditions) are often found in, e.g., the Vistula and Oder lagoons.

Concentrations of chlorophyll-a represent one of the most important bioindicators related to eutrophication. Håkanson and Bryhn (2008a, c) discussed several approaches to predict chlorophyll in the surface-water layer:
(1) From regressions based on empirical TN-concentrations and light conditions (see, e.g., fig. 3.12).
(2) From regressions based on modeled or empirical TP-concentrations (see, e.g., fig. 3.13), light, salinity and boundary conditions related to surface-water temperatures.

Approaches applied in this work are also given in table 3.12.
Table 3.12. Compilation of regressions for predicting (A) concentrations of chlorophyll-a in the surface layer from TP- and TN-concentrations and salinities using a comprehensive data-base from 493 coastal systems from many parts of the world and using data from the growing season (see Håkanson and Bryhn, 2008a), (B) TP-concentrations in the SW-layer from TN-concentrations and surface-water salinities using the same comprehensive data-base, (C) TN-concentrations in the surface-water from TP-concentrations and surface-water salinities using the same data-base. F > 4 in all cases.

<table>
<thead>
<tr>
<th></th>
<th>Step</th>
<th>x-variable</th>
<th>Model</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>TP</td>
<td>log(Chl) = 1.17·log(TP)-0.94</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>TN</td>
<td>log(Chl) = 0.66·log(TP) +0.73·log(TN)-2.16</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Sal</td>
<td>log(Chl) = 0.67·log(TP)+0.57·log(TN)-0.02·abs(Sal-12)-1.62</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>TN</td>
<td>log(TP) = 0.923·log(TN)-0.012</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Sal</td>
<td>log(TP) = 1.011·log(TN) +0.2245·log(1+Sal)-1.478</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>TN</td>
<td>log(TN) = 0.70·log(TP)+1.668</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Sal</td>
<td>log(TN) = 0.668·log(TP) -0.0092·Sal+1.830</td>
</tr>
</tbody>
</table>

Fig. 3.12. Scatter plot between chlorophyll and TN. The figure also gives regressions for the actual data and log-transformed data for the 618 data points covering a wide range of coastal systems (from Håkanson and Bryhn, 2008a).
To obtain seasonal/monthly variations, the following calculations will use three approaches, which will be compared to empirical data:

1. Chl from TP, TN and salinity. This is the approach given in table 3.12A, which have provided an $r^2$-value ($r^2 = \text{coefficient of determination}$) of 0.76 and it is based on empirical data from 493 systems from many parts of the world. The relationship between TN and TP-concentrations for these data is shown in fig. 3.14 and the results shown in this figure are important in contexts of remedial strategies, since the figure demonstrates that there is generally a significant co-variation between TN- and TP-concentrations and this indicates that one would often reduce also TP-concentrations in receiving water systems if remedial measures focus on nitrogen reductions, and vice versa. To achieve a realistic seasonal patterns, the dimensional moderator ($Y_{\text{DayL}} = \text{HDL}/12$) based on the number of hours with daylight each month (from table 3.1) has also been applied in all the following predictions using the regression in table 3.12A.

2. Chl from TP and salinity. This approach uses the results shown in fig. 3.2 and also modeled values on the dissolved fraction of phosphorus, since this is the only fraction that can be taken up by phytoplankton and since values of the dissolved fraction of phosphorus in the SW-layer ($\text{DF}_{\text{TPSW}}$; dim. less) are automatically calculated by the CoastMab-model for phosphorus and are thus available for predicting chlorophyll. This modeling also uses a boundary condition related to low water temperatures given by:

\[
\text{Chl} = 0.30 \times \text{TP} - 2.00; \quad r^2 = 0.73 \\
\log(\text{Chl}) = 1.12 \times \log(\text{TP}) - 0.87; \quad r^2 = 0.61
\]

### Figure 3.13
Scatter plot between median surface-water concentrations of chlorophyll and total-P (TP) for the growing season from 10 sub-groups constituting a salinity gradient. The figure also gives regressions for the actual data and log-transformed data for the 533 data points (from Håkanson and Bryhn, 2008a).
If SWT > 4 °C then \( Y_{\text{SWT}} = 1 \) else \( Y_{\text{SWT}} = (\text{SWT} + 0.1)/4 \) \hspace{1cm} (3.43)

This water-temperature moderator will not influence modeled chlorophyll values when the surface-water temperature is higher than 4 °C, but it will lower predicted chlorophyll values during the winter time, and since there is also primary production under ice, the constant 0.1 is added. This moderator has been used and motivated before (see Håkanson, and Eklund, 2007).

This means that using this approach Chl (μg/l) is predicted from:

\[
\text{Chl}_{\text{Mod}} = \text{TP}_{\text{SW}} \cdot \text{DF}_{\text{TPSW}} \cdot Y_{\text{DayL}} \cdot Y_{\text{Sal}} \cdot Y_{\text{SWT}} \hspace{1cm} (3.44)
\]

\( \text{TP}_{\text{SW}} \) = TP-concentration in SW-water in μg/l.
\( Y_{\text{Sal}} \) = Y4 a dimensionless moderator for the influence of salinity on chlorophyll calculated from:

\[
Y_1 = \begin{cases} 
0.20 - 0.1 \cdot (\text{Sal}/2.5 - 1) & \text{if Sal < 2.5 psu} \\
0.20 + 0.02 \cdot (\text{Sal}/2.5 - 1) & \text{else} 
\end{cases}
\]

\[
Y_2 = \begin{cases} 
0.28 - 0.1 \cdot (\text{Sal}/12.5 - 1) & \text{if Sal < 12.5} \\
0.20 - 0.1 \cdot (\text{Sal}/12.5 - 1) & \text{else} 
\end{cases}
\]

\[
Y_3 = \begin{cases} 
0.06 - 0.1 \cdot (\text{Sal}/40 - 1) & \text{if Sal > 40} \\
Y_2 & \text{else} 
\end{cases}
\]

\[
Y_4 = \begin{cases} 
0.012 & \text{if Y3 < 0.012} \\
Y_3 & \text{else} 
\end{cases}
\]

---

**Fig. 3.14. Scatter plot between concentrations of total-P (TP) and total-N (TN) for the growing season from 9 sub-groups constituting a salinity gradient. The figure also gives regressions for the actual data and log-transformed data for the 495 data points (from Håkanson and Bryhn, 2008a).**
(3) Chl from TN. This approach is similar to the algorithm given in eq. 3.44 but the basic relationship between Chl, TN and salinity is the one given in fig. 3.1.

Fig. 3.8D compares the modeled values using the three approaches with the mean monthly empirical chlorophyll values from the Kattegat for the period 1995 to 2008 (from SMHI; see table 2.2). There is generally relatively good correspondence between the modeled values and the empirical data and in all following simulations, the regression based on both TP and TN will be used. It should be stressed that the empirical chlorophyll values from the Kattegat are quite uncertain; the average monthly CV-value is as high as 1.08 (see also fig. 2.5C), so all model predictions are well within ± 1 standard deviation of the empirical mean values.

3.5. Predicting water clarity and Secchi depth

The Secchi depth is an important variable since the water clarity defines the depth of the photic zone. In all the following calculations, the depth corresponding to two Secchi depths is used to define the entire depth of the photic zone (see Håkanson and Peters, 1995).

There exists a close relationship between SPM, Secchi depth and salinity (see Håkanson, 2006) – the higher the salinity, the higher the aggregation of suspended particles, the larger the particles and the higher the water clarity. An SPM-concentration of 5 mg/l, would imply turbid conditions in a freshwater system, but clearer water in a saline system. This is illustrated in fig. 3.15 (the curves in the figure are calculated from eq. 3.45). The relationship between Secchi depth (Sec in m), SPM_{sw} (mg/l) and salinity (Sal_{sw} in psu) is given by:

$$
Sec = 10^{a - (10^{0.15 \cdot \log(1+Sal_{sw}+0.3)}1+0.5)\cdot(\log(SPM_{sw}+0.3)/2+10^{0.15 \cdot \log(1+Sal_{sw}+0.3)}-1))}
$$

(3.45)

Fig. 3.15. Illustration of the relationship between Secchi depth, SPM in the surface-water layer and surface-water salinities typical in the Kattegat. Note that small changes or uncertainties in SPM-values in the Kattegat would influence Secchi depths relatively much.
The SPM-concentrations in the SW-layer (SPM$_{sw}$ in mg/l) are predicted from the dynamic SPM-model. It should be noted that this approach is also used to predict SPM-concentrations in the SW-layer in the Skagerrak from empirical data on Secchi depth in the Skagerrak (and from empirical salinities, as already explained).

The results of these model predictions for the Secchi depth in the Kattegat are compared to measured data in fig. 3.8C. The modeled values are close to the empirical values and within the uncertainty band given by ± 1 standard deviation for the empirical data.

These results give further empirical support to the general validity and predictive power of the CoastMab-modeling.

### 3.6. Dynamic modeling of nitrogen

The dynamic modeling of the nitrogen fluxes uses the same CoastMab-model and the same water fluxes (to, within and from the Kattegat), and the same mixing rates and diffusion rates, as given by the CoastMab-model for salinity; it uses the same algorithms for sedimentation, resuspension, biouptake and retention in biota as the CoastMab-model for phosphorus. However, for nitrogen, the following substance-specific modifications have been applied:

1. The particulate fraction of nitrogen (PN) in the SW-layer is calculated using the same basic algorithm as used for phosphorus except that for the dissolved fraction of nitrogen in the SW-compartment, the monthly correction factors given in table 3.9 have been used (i.e., the (DIN/TP)/(PO$_4$/TP) data have been multiplied with the monthly modeled DF-value for phosphorus). These modeled values are compared to the empirical DIN/TN-values in fig. 3.6H and there is a good general agreement.

2. The particulate fraction of nitrogen in the DW-layer in the Kattegat is calculated using the same approach. Table 3.10 gives the monthly correction factors (i.e., (DIN/TP)/(PO$_4$/TP)). The modeled values are compared to the empirical DIN/TN-values in fig. 3.6L and also these values are in relative good agreement with the measured DIN/TN-values.

3. Since there are no or very small amounts of nitrogen-fixating cyanobacteria in the Kattegat, N$_2$-fixation is not accounted for in this modeling. This is also in agreement with the OSPAR-modeling carried out by SMHI.

4. The nitrogen inflow from Skagerrak utilizes the same water fluxes as used for the salinity, phosphorus and SPM; the empirical data for the SW-layer in Skagerrak are given in table 3.3; and for the DW-layer in table 3.4.

5. The nitrogen inflow from the Baltic Proper uses the same empirical data (TN in μg/l) for the SW-layer (from HELCOM, 2007a, b) as presented and used by Håkanson and Bryhn (2008a), i.e.:

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<tbody>
<tr>
<td>298.7</td>
<td>292.1</td>
<td>292.8</td>
<td>280.5</td>
<td>264.7</td>
<td>273.2</td>
<td>270.4</td>
<td>266.9</td>
<td>265.5</td>
<td>283.7</td>
<td>278.8</td>
<td>305.7</td>
</tr>
</tbody>
</table>

For the DW-inflow from the Baltic Proper to the Kattegat, the following mean annual value has been used (also from HELCOM, 2007a, b): 314 μg/l.
6. The tributary inflow of nitrogen to the Kattegat is based on the values from HELCOM given in table 3.6.
7. The denitrification in the Kattegat (in water and sediments) has been calculated as a residual term to satisfy the mass-balance for nitrogen. This means that denitrification is the SW-layer has been calculated by:

$$F_{\text{denitSW}} = \text{Const}_{\text{SW}} \cdot (\text{SWT}/9.33) \cdot M_{\text{TNSW}} \cdot V_{\text{SW}}/V$$  \hspace{1cm} (3.46)

Where the SW-calibration constant (Const_{SW}, a denitrification rate for the SW-layer with the dimension 1/month) has been derived from tests and set to zero. In these tests, denitrification was assumed to be temperature dependent (SWT) and 9.33 is the mean annual temperature and SWT/9.33 is a dimensionless temperature moderator; $M_{\text{TNSW}}$ is the mass (amount) of TN in the SW-layer (g); $V_{\text{SW}}$ is the SW-volume and V is the total volume ($m^3$) so $V_{\text{SW}}/V$ is a dimensionless moderator for the SW-layer.

Denitrification is the DW-layer is given by:

$$F_{\text{denitDW}} = \text{Const}_{\text{DW}} \cdot (\text{DWT}/9.33) \cdot M_{\text{TNDW}} \cdot V_{\text{DW}}/V$$  \hspace{1cm} (3.47)

Also Const_{SW} has been set to zero. This means that the model does not calculate denitrification losses for the two water compartments in the Kattegat. For the ET-sediments, denitrification has been calculated from:

$$F_{\text{denitET}} = \text{Const}_{\text{ET}} \cdot M_{\text{TNET}} \cdot (\text{SWT}/9.33)$$  \hspace{1cm} (3.48)

Const_{ET} has also been set to zero in all following model simulations; $M_{\text{TNET}}$ is the mass (amount) of TN in the ET-sediments (g).

Denitrification is the A-sediments (0-10 cm) is given by:

$$F_{\text{denitA}} = \text{Const}_{\text{A}} \cdot (\text{DWT}/9.33) \cdot M_{\text{TNA}}$$  \hspace{1cm} (3.49)

Model calibrations have indicated that Const_{A} should be set to 0.003 (1/month) for the denitrification in the accumulation area sediments. It should be stressed again that the denitrification constants are determined from calibrations to satisfy the mass-balance for nitrogen and they are not based on general, tested, algorithms which have been proven to work well in many coastal systems. This means that the predictions using the mass-balance model for nitrogen are more uncertain than the predictions of salt, phosphorus and SPM.

The diffusion of dissolved nitrogen from the deep-water layer to the surface-water layer is small in the Kattegat because the concentration gradient of DIN is small; the diffusion is calculated with the same algorithm as used for salinity and phosphorus.

The predictions for the TN-concentrations in the surface-water and deep-water layers in the Kattegat are compared to empirical monthly data in figures 3.6F and G. Since these modeled values are based on calibrated denitrification rates, the modeled values are close to the empirical data.
3.6.1. Nitrogen fluxes
Annual fluxes of nitrogen are shown in fig. 3.16. These fluxes give important information of how the Kattegat system likely reacts to changes in nitrogen loading. It should be noted that also the nitrogen fluxes to and from organisms with short turnover times (BS) are large compared to most other fluxes, but the amounts of TN found in biota is small compared to what is found in other compartments. In the ranking of the annual fluxes to the Kattegat, the most dominating abiotic fluxes are the TN-flux to DW-layer from the Skagerrak (4200 kt/yr), followed by the SW-inflow from the Baltic Proper (200 kt/yr), tributary inflow (74 kt/yr), SW-inflow from the Skagerrak (25 kt/yr), atmospheric precipitation (17 kt/yr) and DW-inflow from the Baltic Proper (14 kt/yr). Sedimentation in the SW-layer is 17 kt/yr to the DW-layer and 100 kt/yr to the ET-sediments. Sedimentation in the DW-layer is 29 kt/yr; about 25% of the nitrogen in the SW-layer and about 50% in the DW-layer (see tables 3.9 and 3.10) of the nitrogen appears in dissolved form. Figures 3.6H and I give a comparison between modeled dissolved fractions and empirical ratios between DIN and TN. It should be stressed that the dissolved form (DF), as defined in the model from the particulate fraction (DF = 1 – PF), is not the same thing as DIN. Fig. 3.6 shows that the overall correspondence between modeled DF and the ratio between DIN and TN in the Kattegat is good.

From fig. 3.16 one can note that the diffusion of nitrogen from sediments to water and from the DW-layer to the SW-layer is zero. Denitrification, on the other hand, is 7 kt/yr from A-sediments and zero from water and ET-sediments. Burial of TN from the A-sediments is 22 kt/yr.

3.7. Conclusions
To understand how the Kattegat system, or any aquatic system, responds to changes in, e.g., loading of toxins or nutrients, it is imperative to have a dynamic process-based perspective quantifying the factors and functions regulating inflow, outflow and internal transport processes and retention rates. This chapter has demonstrated that this modeling approach, using the theoretical wave base rather than traditional temperature and/or salinity data to define the surface-water and deep-water compartments, can give excellent correspondence between empirical and modeled data on the salinity.

This chapter has presented budgets for water, salt, TP, TN and SPM in the Kattegat. This process-based mass-balance modeling has used empirical data (from SMHI) for the period 1995 to 2008.

An aim of the first part of this chapter was to present data on the fluxes of water and the theoretical retention times for water and salt in the defined sub-basins of the Kattegat since those values give fundamental information on how the system reacts to changes in, e.g., nutrient loading. This also places certain demands on the structure of this model, which differs from oceanographic models, e.g., in quantifying resuspension, mixing and diffusion and in the requirements regarding the accessibility of the necessary driving variables.
Fig. 3.16. Characteristic annual nitrogen fluxes to, from and within the Kattegat for the period 1995-2008. Note that the net inflow of nitrogen from the Baltic Sea is 189 kt/yr, SMHI (Håkansson, 2007; the OSPAR assessment) gives 190 kt/yr.

This chapter has also discussed empirically-based models, which have been added to the process-based dynamic CoastMab-model. These are the sub-models for Secchi depth and chlorophyll-a concentrations. When tested against empirical data for the Kattegat, there was good overall correspondence between predicted values for Secchi depth and chlorophyll-a concentrations and the dynamic SPM-model predicts sedimentation, SPM-concentrations and burial in accordance with existing, but rather scattered, data.
4. Management scenarios for the Kattegat

This chapter will present four scenarios, which are meant to focus on key problems related to a sustainable management of the trophic state of the Kattegat. The last scenario will put the results together and discuss an “optimal” management plan for the Kattegat related to realistic nutrient reductions to lower the eutrophication. The first scenario is logical in the sense that the main focus is on two large nutrient fluxes to the surface-water in the Kattegat discussed in the Baltic Sea Action Plan. If very costly remedial actions reducing 10,000 to 100,000 t nutrients (P and N, respectively) annually to the Baltic Sea including the Kattegat are asked for at a yearly cost in the range of 1000-3000 million euro/yr, the model should be able to predict the expected changes in the surface-water layer (the bioproductive layer) not just for the nutrient concentrations but also for key bioindicators of eutrophication, such as the Secchi depth and the concentration of chlorophyll-a. So, scenario 1 is the first logical step in an attempt to find an “optimal” abatement plan to reduce the eutrophication of the Kattegat. Comprehensive analyses based on very large data-sets on the conditions in the Kattegat have shown (in chapter 2) that the anthropogenic nutrient emissions have not altered the eutrophication in the Kattegat markedly during the last 10-15 years. It is, however, well documented (see, e.g., a compilation of data and literature references in Håkanson and Bryhn, 2008a, c) that the eutrophication in the Baltic Sea increased significantly in the period between 1920 and 1980.

The second and third scenarios will focus specifically on phosphorus and nitrogen reductions in the catchments of the rivers entering the Kattegat. The Baltic Sea Action Plan (see table 3.7), which the governments the Baltic countries agreed upon in November 2007, implies that 15,000 t of phosphorus and 133,000 t of nitrogen of the total riverine nutrient fluxes to the entire Baltic Sea (including the Kattegat) should be reduced annually; including 290 t/yr of phosphorus and 20,780 t/yr of nitrogen from Sweden. The second and third scenarios will address how such reductions would likely influence the Kattegat system.

The fourth scenario will be based on the results from the three first scenarios and on the results presented in this work on the water fluxes, salt fluxes, nutrient fluxes and fluxes of suspended particulate matter to, within and from the Kattegat as well as the results related to how the two key bioindicators (Secchi depth and chlorophyll) would likely respond to changes in nutrient concentrations in surface-water of the Kattegat. The basic idea is that this scenario should motivate an “optimal” remedial strategy to reduce the eutrophication in the Kattegat.

Nutrient reductions are ultimately related to political decisions. One can safely assume that it is practically impossible to remediate all human emissions of nutrients to the Baltic Sea. The 15,000 t/yr suggested by HELCOM (2007b) represent a reduction of 50% of the 30,000 t/yr of phosphorus transported via rivers/countries to the Baltic Sea. From countries that have already carried out costly measures to reduce nutrient discharges to the Baltic Sea, only a smaller part of the remaining anthropogenic nutrient fluxes can realistically and cost-efficiently be reduced.
The costs for nutrient reductions are difficult to establish but one can give a few examples to highlight possible order-of-magnitude values. Malmaeus et al. (2007) have shown that the costs to reduce phosphates in detergents are less than 0.4 euro/kg P, advice related to P-reductions in agriculture would cost 5-100 euro/kg P, reduced P in feed for animals 5-7 euro/kg P and cultivation and harvesting of mussels/clams about 35 euro/kg P. The point here is that there are major differences among the different options and that it is beyond the aim of this work to scrutinize the various alternatives and recommend the alternative that would be most cost-efficient for the Baltic Sea and the Kattegat. The point here is that such work is really important and that the CoastMab-model can be a useful complementary tool in such contexts to address the “benefit” side of the cost-benefit analysis. The target benefit should not be the reductions in nutrient input from countries or tributaries related to a given remedial action, neither the reductions in nutrient concentrations in the Kattegat system, but rather the change in the target bioindicators in the system: How would a certain remedial strategy for reducing X tons of phosphorus for Y euro in river Z change the water clarity, the Secchi depth, reduce the risks of blooming of cyanobacteria (e.g., in the Baltic Proper) and reduce the maximum concentration of chlorophyll-a in the Baltic Proper and/or the Kattegat? To address such issues, one needs a validated, process-based mass-balance model. No such model is at present available for nitrogen, but the CoastMab-model presented in this work may be used to address the target issues related to how the Kattegat would likely respond to changes in phosphorus input and also, with the given reservations, for nitrogen in the Kattegat, and for the key bioindicators, and this will be demonstrated in this chapter.

4.1. Scenario 1. Reductions in tributary phosphorus loading to the Baltic Sea
This scenario is based on the following two key arguments:
• The focus is set on dominating fluxes to the surface-water layer in the Kattegat. That is on the nutrient fluxes from the Baltic Proper (see the annual budgets presented in fig. 3.9 for phosphorus and in fig. 3.16 for nitrogen). Very significant nutrient fluxes to the bioproductive surface-water layer in the Kattegat comes from the Baltic Proper, which should be evident just by looking at the catchment area for the entire Baltic Sea, including the Baltic States, parts of Russia, Belarus and Germany, Poland, Finland and Sweden in relation to the relatively small catchment area draining directly into the Kattegat (from south-western Sweden and parts of Denmark).
• The focus will also be set on phosphorus and not on nitrogen because:
  1. It is not possible to provide scientifically relevant predictions how the Baltic Sea system would respond to reductions in nitrogen loading since there are several major uncertainties related to the quantification of nitrogen fixation, wet and dry deposition of nitrogen, the algorithm regulating the particulate fraction for nitrogen and hence also sedimentation of particulate nitrogen and denitrification. For the Kattegat, on the other hand, atmospheric nitrogen fixation is neglected in this modeling because there are no significant amounts of N-fixating cyanobacteria in this system; the atmospheric deposition used in this modeling for the Kattegat comes from the OSPAR-model (SMHI) and should be reliable in terms of order-of-
magnitude values. Quantifying denitrification is uncertain also in the Kattegat and it has been treated as a residual term in the mass-balance for nitrogen so that the modeled concentrations in the surface-water layer, the deep-water layer, in the ET-sediments and the A-sediments should correspond to empirical data. No such calibrations have been done in the mass-balance calculations for phosphorus (i.e., the basic, validated CoastMab-model is used directly without any tuning) or for the mass-balance calculations for SPM.

2. In the Baltic Sea, and especially in the Baltic Proper, nitrogen reductions are likely to favor the blooming of harmful algae (cyanobacteria), and such events should be avoided. This means that reductions in tributary nitrogen loading to the Baltic Sea may, in fact, even increase the nitrogen concentration in the water (see Håkanson and Bryhn, 2008a).

3. So, there are no general, process-based mass-balance models for nitrogen, neither for the Baltic Sea basins, the Kattegat or for any other coastal areas in the world, which have been tested (validated) for independent coastal systems and been demonstrated to yield good predictive power, as far as this author is aware.

4. In spite of the fact that costly measures have been implemented to reduce nitrogen transport from agriculture, urban areas (e.g., from water purification plants) and industries, the nitrogen concentrations in the surface-water in the Kattegat have remain largely constant for the last 15-20 years.

So, the focus is set on the mass-balance modeling of phosphorus in scenario 1.

Fig. 4.1 gives the results from three simulations (sensitivity tests):

(1) When half of the total phosphorus reductions have been carried out (i.e., a reduction of 7500 t TP/yr) for the tributaries to the Baltic Proper (as if 7500 t TP/yr were suddenly reduced from Polish rivers entering the Baltic Proper) and all other factors influencing the system have been held constant. Evidently, it is not realistic to implement such large and sudden reductions. These simulations illustrate the dynamic response of the Kattegat system to such a sudden P-reduction into the Baltic Proper delivering its water to the Kattegat.

(2) When 9775 t TP/yr from the tributaries entering the Baltic Sea have been (suddenly) reduced. Many tests have been presented by Håkanson and Bryhn (2008a) to try to find an optimal strategy for Baltic Sea management. Such a strategy should also concur with some evident practical constraints. For example, it may be very difficult and costly and maybe damaging for agriculture, urban development and industry, to reduce more than 60-70% of the anthropogenic point source and diffuse discharges of TP in the East Baltic countries, which have had much less investment in remedial measures than, e.g., countries like Finland, Sweden and Germany. For this management strategy a limit was set to 60% TP-reductions in the anthropogenic emissions to the Gulf of Finland, the Gulf of Riga and from Poland, and a 30% reduction in the anthropogenic TP-emissions from Sweden, Finland and Germany in seeking the optimal strategy. There was also a focus on the conditions in the “hotspots”, i.e., the Gulf of Finland, the Gulf of Riga and the Baltic Proper, and not on smaller coastal areas, and not on the oligotrophic basins (i.e., the Bothnian Bay and the Bothnian Sea). From these presuppositions, an “optimal” strategy, which concerns a total reduction of 9775 t/yr of phosphorus
and of these reductions 6625 t/yr (48% of anthropogenic emissions) are removed from the countries/rivers adding nutrients to the Baltic Proper, 2725 t/yr from the rivers entering the Gulf of Finland (corresponding to 60% of the anthropogenic input) and 425 t/yr of TP to the Gulf of Riga (or 46% of the anthropogenic input to this basin). This would give an average Secchi depth of 7 m in the Gulf of Finland and this is what the Secchi depth was in the Gulf of Finland before 1920. It would also give a Secchi depth of almost 10 m (9.7 m) in the Bothnian Sea, of about 8 m in the Bothnian Bay, 5.6 m in the Gulf of Riga and almost 8 m (7.9 m) in the Baltic Proper.

(3) When 15,000 has been reduced according to the Baltic Sea Action Plan. One can estimate that this would create a mean annual TP-concentration in the surface-water of the Baltic Proper of about 12 μg/l, as compared to the default value today of about 20 μg/l. Case one (a reduction of 7500 t TP/yr) would give an annual mean
Management scenarios for the Kattegat

TP-concentration of 15.2 μg/l; case two (when 9775 t TP/yr are being reduced as described) would give a mean annual value of 13.6 μg/l in the surface-water layer of the Baltic Proper (see Håkanson and Bryhn, 2008a).

From fig. 4.1, one can note clear reductions in the TP-concentration (fig. 4.1A) in the SW-layer in the Kattegat if these remedial actions were carried out; see also table 4.1, which gives the corresponding mean annual values for the Secchi depth, chlorophyll-, TP- and TN-concentrations in the surface-water layer in the Kattegat. In these simulations, it is assumed that reductions in TP-loading would also imply reductions in SPM-loading and TN-concentrations in the Baltic Proper. This may not be the case if the TP-reductions would mainly relate to the building of water treatment plants, which could target specifically on phosphorus removal. If that would be the case, the improvements in SPM-concentrations and the related improvements in water clarity (figures 4.1B and C) would be smaller. This would also affect the predicted changes in chlorophyll-a concentrations, but to a lesser extent. So, the results would depend on the way in which the remedial actions are carried out and the results shown in fig. 4.1 and table 4.1 are meant to represent what one would “normally” expect.

Table 4.1. Mean annual values for Secchi depth, chlorophyll-a, TP- and TN-concentrations in the surface-water layer in the Kattegat related to scenario 1.

<table>
<thead>
<tr>
<th>Reductions (t phosphorus per year to the Baltic Sea)</th>
<th>Default</th>
<th>7500</th>
<th>9775</th>
<th>15,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secchi depth (m)</td>
<td>6.2</td>
<td>6.5</td>
<td>6.6</td>
<td>6.7</td>
</tr>
<tr>
<td>Chlorophyll (μg/l)</td>
<td>2.9</td>
<td>2.6</td>
<td>2.6</td>
<td>2.5</td>
</tr>
<tr>
<td>TP (μg/l)</td>
<td>23</td>
<td>21</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td>TN (μg/l)</td>
<td>283</td>
<td>283</td>
<td>284</td>
<td>284</td>
</tr>
</tbody>
</table>

One can also note from table 4.1 that the TN-concentrations should increase slightly (from 283 to 284 μg/l) as a consequence of the reductions in SPM-concentrations and the related increases in Secchi depths (from 6.2 to 6.7 m); the lower SPM-concentrations would decrease the settling velocities for particulate nutrient forms (nitrogen and phosphorus).

One can conclude from this scenario (and the following scenarios) that no other realistic actions would likely improve the eutrophication in the Kattegat more than reductions in phosphorus loading to the Baltic Sea. This is, in fact, evident from looking at the phosphorus fluxes (fig. 3.9) to the surface-water layer in the Kattegat, since this action addresses the largest direct TP-flux to the SW-layer in the Kattegat.

4.2. Scenario 2. Reductions in tributary phosphorus loading to the Kattegat from Sweden

From fig. 3.9, one can also see that the total Swedish contribution from diffuse sources corresponds to 500 t/yr or 2.3% of the total external TP-inflow to the SW-layer in the Kattegat; and that the TP-contribution from Swedish point source emissions amount to 180 t/yr, or 0.85% of the total annual direct external TP-inflow to the SW-layer (21,800 t/yr). So, what could one expect if half the Swedish BSAP-
quota of 145 t/yr or if all of the Swedish quota (290 t/yr) would be directed (rather unrealistically) to the catchment areas of the Swedish rivers entering the Kattegat; evidently not very much, as shown in fig. 4.2. This is not an effective strategy to reduce the eutrophication in the Kattegat.

Fig. 4.2. Scenario 2. Curves 1 give the default conditions; curves 2 the modeled response when 145 t/yr (half the Swedish BSAP quota) of the tributary TP-inflow to the Kattegat have been removed; and curves 3 the modeled response when 290 t/yr of the tributary TP-inflow to the Kattegat have been removed.

A. TP-concentrations in the surface-water (SW) of the Kattegat (KA).
B. The corresponding SPM-concentrations in the surface-water (SW) of the Kattegat.
C. Gives the probable changes in Secchi depth in the Kattegat.
D. Gives the corresponding likely changes in chlorophyll-a concentrations in the Kattegat.

It should be stressed that more or less the same results as shown in fig. 4.2 would be obtained if 145 or 290 t phosphorus per year would be reduced from any inflow to the Kattegat system, whether this is from Sweden, Denmark, the Skagerrak or the Baltic Proper.

4.3. Scenario 3. Reductions in tributary nitrogen loading to the Kattegat from Sweden

Fig. 3.16 gives the annual budget for nitrogen and fig. 4.3 shows three simulations (sensitivity tests) in analogy with the results for phosphorus in fig. 4.2. As an important background, one can note that the total contribution from Swedish diffuse sources corresponds to 29,100 t TN/yr or 9.2% of the total nitrogen external inflow to the SW-layer (mixing excluded); and that the TN-contribution from point sources amount to 3500 t/yr, or 1.1% of the total external annual TN-inflow the SW-layer (316,000 t/yr). If half of the Swedish BSAP-quota of 10,390 t/yr or the entire
Management scenarios for the Kattegat

Swedish quota (20,780 t/yr) were (hypothetically) reduced from the tributaries or other inflows to the Kattegat, the environmental gain would be very small, as shown in fig. 4.3A. The improvements for the Secchi depth and for the phytoplankton biomass (the chlorophyll-a concentration) would also be very small indeed. This is also evident by looking at the nitrogen fluxes to the Kattegat in fig. 3.16.

4.4. Scenario 4. An “optimal” management to reduce the eutrophication in the Kattegat

How would a more “optimal” remedial scenario for the Kattegat look? Many alternatives have been tested during the course of this work and it seems clear from the results already given that the first focus should be on phosphorus reductions in the rivers entering the Baltic Proper. The second focus could be on remedial

![Fig. 4.3. Scenario 3. Curves 1 give the default conditions; curves 2 the modeled response when 10,390 t/yr (half the Swedish BSAP quota) of the tributary TN-inflow to the Kattegat have been removed; and curves 3 the modeled response when 20,780 t/yr of the tributary TN-inflow to the Kattegat have been removed.
A. TN-concentrations in the surface-water (SW) of the Kattegat (KA).
B. The corresponding TP-concentrations in the surface-water (SW) of the Kattegat.
C. Gives the probable changes in Secchi depth in the Kattegat.
D. Gives the corresponding likely changes in chlorophyll-a concentrations in the Kattegat.](image)

actions for phosphorus that would also reduce the nitrogen transport to the Baltic Proper, although it is difficult to predict how such nitrogen reductions would actually change the nitrogen concentrations in the Baltic Proper. It is also, evidently, very important to seek remedial measures that would reduce phosphorus and nitrogen emissions in a cost-efficient manner; the costs per removed kg nutrient may vary with a factor of 10-100 depending on the selected approach; and if the same approach is carried out in different Baltic Sea countries; and whether the
reduction concerns the “first kg” or the “last kg” in a long-term remedial strategy removing 10,000 to 100,000 t/yr. It should also be stressed that nutrient reductions in the Baltic Proper would be beneficial for the entire Baltic Sea system, where there are several “hotspots” (e.g., the Gulf of Finland, the Gulf of Riga, the area outside Kaliningrad, the Oder and Vistula estuaries, etc.) with significantly worse conditions than in the Kattegat (see figures 1.3 and 1.4). Reductions in the “upstream” Baltic Sea system would also clearly benefit the Kattegat system.

Fig. 4.4 gives results from simulations (sensitivity tests) when 9775 t TP/yr has been reduced (as described and motivated by Håkanson and Bryhn, 2008a) and when also the average nitrogen concentration in the Baltic Proper has been

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**Fig. 4.4 Scenario 4 – the “optimal” scenario.** Curves 1 give the default conditions, when the mean TP-concentration in the SW-layer in the Baltic Proper is 20 μg/l; curves 2 when the value is 13.6 μg/l corresponding to a reduction in TP-loading of 9775 t/; curves 3 when also the TN-concentration in the SW-layer in the Baltic Proper has been hypothetically reduced by 10% (from 281 to 253 μg/l).

A. TP-concentrations in the surface-water (SW) of the Kattegat (KA).

B. The corresponding TN-concentrations in the surface-water (SW) of the Kattegat.

C. Gives the probable changes in Secchi depth in the Kattegat.

D. Gives the connected changes in SPM in the surface-water layer in the Kattegat.

E. The corresponding likely changes in chlorophyll-a in the Kattegat.
hypothetically lowered by 10% (from 281 μg/l on an annual basis to 253 g/l). This would significantly lower the TP-concentrations in the SW-layer in the Kattegat (fig. 4.4A) and also reduce the TN-concentrations in the SW-layer in the Kattegat (fig. 4.4B) and if those measures would be carried out in a manner that would also reduce SPM-emissions to the Baltic Proper (in a “normal” way), then there would also be clear reductions in the SPM-concentrations in the SW-layer in the Kattegat and corresponding increases in water clarity and lower chlorophyll-a concentrations, as shown in fig. 4.4.

It should be noted again that the modeled changes in TP-concentrations are more reliable and that the reductions in the TN-concentrations in the Baltic Proper in this scenario are hypothetical. If the reductions in TN-concentrations in the Baltic Sea would be even lower than 10% (which is suggested in the Baltic Sea Action Plan) this would create even smaller changes than the already small changes shown for this scenario. “Optimal” in this scenario means that this is probably the best result one could realistically hope for.

4.5. Comments and conclusions
In this section, the wisdom of the HELCOM strategy to reduce the eutrophication in the Baltic Sea (including the Kattegat) has been challenged. Nitrogen reductions may fail to give lower N-concentration in the water because of compensatory increases in the nitrogen fixation by cyanobacteria, especially in the Baltic Proper. The results presented in this chapter indicate that a reduction of 15,000 t/yr of phosphorus would likely create what may well be an undesired oligotrophication of the Baltic Sea system in the sense that the trophic status, as revealed by the operational bioindicators (Secchi depth and chlorophyll), would approach a lower level than Baltic Sea managers should realistically ask for.

An alternative remedial strategy to reduce the eutrophication in the Kattegat based on the following cornerstones have been presented and motivated:
1. Many remedial measures in agriculture, in urban areas or industry, would remove both nutrients and when substance-specific methods are available, they should target on phosphorus removal; less substance-specific methods may reduce both phosphorus and nitrogen and if such remedial measures could be carried out in a cost-efficient manner, it would be advantageous. The effects of nitrogen reductions cannot be predicted with any certainty in the Baltic Proper, but with some certainty in the Kattegat.
2. A remedial strategy where 3180 t/yr of the phosphorus to the Gulf of Finland, 550 t/yr to the Gulf of Riga and 5000 t/yr to the Baltic Proper (and no reductions to the Bothnian Sea and the Bothnian Bay) has been motivated as the most efficient approach to reduce also the eutrophication in the Kattegat system. Evidently, it would take a long time to implement such reductions in the Baltic Sea system (including the Kattegat). The Baltic Sea system could face several changes in that time (e.g., related to climatic variations such as increased water temperatures and reductions in ice cover in the Baltic Sea). This means that these recommendations should be taken with due reservations and that they should be adjusted to such possible future changes. The CoastMab-model applied in this work could be a useful tool in such contexts.
Chapter 4
5. Summary, conclusions and recommendations

To develop scientifically warranted programs of conservation, management and remediation is a great challenge. In this situation, quantitative models are essential to predict, to guide assessment and to direct intervention. The CoastMab-model used in this work should be regarded as a tool for water management. The CoastMab-model has a focus on the ecosystem scale. This is also a very important scale in water management, e.g., in contexts of impact assessment and when remedial measures are discussed. CoastMab also offers an approach to handle “trade-offs” and test working hypotheses concerning aquatic transport processes and interactions. The fact that the CoastMab-model, in spite of its breadth and complexity, may be driven by relatively few readily accessible variables, and that it is based on a general algorithms which may be repeated for different substances gives a certain robustness and attractiveness to the model and provides a framework for its practical usefulness and predictive power, which are essential components in models for aquatic management. It is essential and it is interesting that so much information about complicated transport processes can be obtained from a model based on this structure and so few driving variables.

Chapter 2 gave basic information on the conditions in the Kattegat, e.g., on the morphometry including the criteria to define the limit between the surface-water layer and the deep-water layer from the theoretical wave base. Chapter 3 presented the water fluxes to, within and from the Kattegat system. These water fluxes are important for the quantification of all fluxes of salt, phosphorus, nitrogen and SPM regulating all monthly concentrations. Chapter 3 also gave approaches to predict chlorophyll-a concentrations and Secchi depths from dynamically modeled values of phosphorus, nitrogen, SPM and salinity and monthly light conditions. These approaches are of fundamental importance in the CoastWeb-modeling because the foodweb model is driven by chlorophyll-a concentrations and the Secchi depth is a measure of the depth of the photic layer. The water fluxes determined from the CoastMab-model for salinity are used throughout this modeling. It has been demonstrated that the CoastMab-model for phosphorus, which prior to this work has been validated for many independent aquatic systems and been demonstrated to predict very well, also predicts TP- and SPM-concentrations in the Kattegat very well.

It has been shown how the CoastMab-model predicts TP- and TN-concentrations in water and sediments, and also the two target bioindicators. In fact, the inherent uncertainties in the available empirical data used to run and test the model for salt, phosphorus, SPM and the two target bioindicators set the limit to the predictive power of the model.

It should, however, be noted that it is not possible to provide scientifically relevant predictions how the Baltic Sea system would respond to reductions in nitrogen loading since there are major uncertainties related to the quantification of nitrogen fixation, wet and dry deposition of nitrogen, the algorithm regulating the particulate fraction for nitrogen and hence also sedimentation of particulate nitrogen and denitrification. For the Kattegat, on the other hand, atmospheric nitrogen fixation has been neglected in this modeling because there are no significant
amounts of N-fixating cyanobacteria in this system; the atmospheric deposition used in this modeling for the Kattegat comes from the OSPAR-model (SMHI) and should be reliable in terms of order-of-magnitude values; however, the denitrification is uncertain also in the Kattegat and it has been treated as a residual term in the mass-balance for nitrogen so that the modeled concentrations in the surface-water layer, the deep-water layer, in the ET-sediments and the A-sediments should correspond to empirical data. No such calibrations have been done in the mass-balance calculations for phosphorus (i.e., the basic, validated CoastMab-model is used directly without any tuning) or for the mass-balance calculations for SPM.

It is sub-optimal to give reduction quotas to different countries (such a strategy is based on political considerations rather than science). A more scientific strategy should be based on the identified “hotspots”, so the strategy should rather be to target on basins (generally estuaries) with a high degree of eutrophication and reduce nutrient input to such systems. From the maps given in chapter 2, one can identify the Gulf of Riga, the Gulf of Finland, the Oder and Vistula estuaries and the area outside of Kaliningrad as hotspot areas.

Because of major changes in population structure, agriculture, species composition, fishing/trawling, etc., it is not possible to carry out measures that would bring the Baltic Sea ecosystem including key structural and functional characteristics, functional groups and species back to the conditions as they were, say 100 years ago, but it would be possible to reduce nutrient inputs so that the Secchi depth in the Gulf of Finland could return to about 7 m as it was between 1900 and 1920. To reach such a specific goal, there must also be major nutrient reductions not just in the rivers entering the Gulf of Finland, but also in the rivers entering the Baltic Proper, since the water and nutrient exchange between the Baltic Proper and the Gulf of Finland is intense (which can be seen from the salinity maps for the entire Baltic Sea including the Kattegat).

In this work, a realistic remedial scenario has been presented that would considerably improve the conditions not just in the Kattegat but also in the Gulf of Riga and the Gulf of Finland as well as the Baltic Proper and the entire Baltic Sea.

The default conditions using the CoastWeb-model have been described in detail for water fluxes, salinity, phosphorus, SPM, chlorophyll, Secchi depth and it has been demonstrated that the general approach used here (without any tuning or calibrations for the Kattegat system) also generally showed good correspondence between modeled values and empirical data. The nitrogen modeling also showed good results, but the CoastWeb-model for nitrogen includes calibrations related to denitrification so the results for the mass-balance for nitrogen are not as reliable as the other predictions.

Many tests have been carried out to find a strategy to reach the goal that the eutrophication in the Kattegat system could be reduced. Very significant nutrient fluxes to the bioproductive surface-water layer in the Kattegat come from the Baltic Proper, which should be evident just by looking at the catchment area for the entire Baltic Sea, including the Baltic States, parts of Russia, Belarus and Germany, Poland, Finland and Sweden in relation to the relatively small catchment area draining directly into the Kattegat (from south-western Sweden and parts of
Summary, conclusions and recommendations

Denmark). The final results are given on a monthly basis in fig. 4.4. Evidently, it is not realistic to implement such major reductions in nutrient P-loading suddenly, and these curves are mean to illustrate the relatively fast dynamic response of the Kattegat system in this hypothetical remediation scenario.

One can note from these tests (sensitivity tests), and also from Håkanson and Bryhn (2008a), that a reduction of 15,000 t/yr of phosphorus to the Baltic Sea, as suggested by HELCOM (see table 3.6) and agreed upon by the Baltic States in November 2007, would likely increase the Secchi depth in the Gulf of Finland beyond the mean or median values around the year 1900. This indicates that 15,000 t/yr is likely an “overkill”. A lowering of the primary production in the Baltic Sea and the Kattegat will imply also a reduction in the secondary production, including zooplankton and fish; it would likely increase acidification (since this is related to the primary production); it could also increase the concentration of organic toxins in fish – “in the clearest waters swim the most toxic fish”. This is a well-established fact called biological dilution (see Håkanson, 1999, 2000). It relates to the definition of the average concentration of toxins in fish, C = M/BM, where M is the total mass of a given toxin in fish (in g; e.g., total-PCB, total dioxins, methyl mercury) and BM is the total biomass of the fish (e.g., prey or predatory fish, or a given species of fish, such as cod; in kg). If BM decreases as it does in this oligotrophication scenario, C should increase if there are no simultaneous reductions in the loading of toxins to the system. There is evidently no point to lower the trophic status of the Baltic Sea or the Kattegat system to levels were the environmental drawbacks become larger than the benefits, and every action could potentially include benefits as well as drawbacks.

The strategy that one should ask for should also concur with some evident practical constraints. For example, it is not really realistic to reduce all anthropogenic TP- or TN-discharges. And for countries where major investments in nutrient reductions have already been made, it will become increasingly expensive to reduce the remaining tons. So, a search for an optimal strategy, one could, for example, limit TP-reductions to 60-70% of the anthropogenic emissions to coastal systems where few costly remedial actions have been implemented, and to about 30% reduction in countries such as Sweden, Finland and Germany. So, the wisdom of the HELCOM strategy to reduce the eutrophication in the Baltic Sea may be challenged.

It should also be stressed that given the conditions in the Baltic Proper, nitrogen reductions may fail to give lower N/P-ratios in the water because of compensatory increases in the nitrogen fixation by cyanobacteria (see Håkanson and Bryhn, 2008a, c). If nitrogen reductions lower the N/P-ratios in the surface water, this could increase the competitiveness of cyanobacteria in relation to other algae even more, which is a clearly negative consequence of an expensive remedial strategy implemented to improve rather than worsen the conditions in the Baltic Sea.

In the “optimal” scenario, about 10,000 t/yr of phosphorus is being reduced and also nitrogen reductions that would lower the TN-concentration in the Baltic Proper. The costs for this would likely be about 400 million euro/yr if this is done in a cost-effective manner, which means a focus on phosphorus reductions connected to the
most polluted estuaries and coastal areas. Evidently, there would be major differences in these costs depending on the country, the method to reduce phosphorus and nitrogen, etc. One can assume that most of this would go to the building of water treatment plants in the Baltic countries and Poland. The costs to reduce 15,016 t/yr of TP and 133,170 t/yr of nitrogen according to the HELCOM strategy would be 3300 million euro/yr. That is, 2900 million euro per year higher than the “optimal” strategy suggested in this work.

On the whole, the money allocated for Swedish nutrient reductions according to BSAP would improve the eutrophication in the Baltic Sea including Kattegat more efficiently (a higher nutrient reduction in kg per euro) if the money could primarily go to cost-efficient phosphorus reductions in mainly Poland and the Baltic States.

Acknowledgements

This project has been financed by the Swedish Environmental Protection Agency. Ingemar Cato, SGU, has been very helpful and freely supplied sediment data on nutrient concentrations. Pia Andersson, Kari Eilola and Bertil Håkansson at SHMI, have also been most helpful in supplying the necessary water chemical data, data on tributary discharges and atmospheric nitrogen deposition and they have given constructive comments on the manuscript. Lars Klintwall and Håkan Staaf at the Swedish Environmental Protection Agency have also provided valuable viewpoints on the manuscript. This work has depended very much on the data supplied by SMHI and SGU. I would also like to thank Per Jonsson, who was instrumental to get the project going and to Andreas Bryhn and Magnus Karlsson for many constructive discussions.
6. Sammanfattning på svenska

En internationell expertgrupp (Boesch et al., 2008), som arbetat på uppdrag av Naturvårdsverket för att utvärdera kunskapsläget vad gäller övergödningen i Kattegatt och ge förslag på lämpliga åtgärder för att förbättra situationen, har rekommenderat att Sverige i första hand bör minska kvävetransporterna från svensk jordbruksmark och medverka till att minska den atmosfäriska kvävedeposition till Kattegatt, Skagerrak och svenska Västkusten. Kvävereduktioner inom jordbruket kan dock bli mycket kostsamma med priser från 37 till 151 kr per kg kväve borttaget per år (Elofsson och Green, 2004). Kattegatt tar, enligt Håkansson (2007), årligen emot omkring 41,400 t kväve från Sverige och av detta ca 20,800 t från jordbruk. Eilola och Sahlberg (2006) har presenterat ett scenario där 35% av de svenska N-flödena minskats och detta skulle då innebära en kostnad på från 540 miljoner kr (= 37·1000·0.35·41,400) till 2200 miljoner kr per år men de visade också att miljöförbättringarna på Kattegatt/Skagerrak-systemen skulle bli marginella.

OSPAR-modellen (se Håkansson, 2007) har således redan använts på Kattegatt/Skagerrak-systemet (se Eilola och Sahlberg, 2006) och resultat från den modellen diskuteras också i någon mån av Boesch et al. (2008). Eftersom det således redan finns en rapport från de arbetena (från SMHI) har resultaten från det modelleringsarbetet endast diskuterats mycket kort i denna rapport, främst i anslutning till fig. 1.1. Den diskussionen går ut på att informationen i fig. 1.1 kan ge missvisande signaler till personer som inte arbetar med eller förstår nödvängigheten av massbalansberäkningar (dvs budgetberäkningar). För att förstå hur minskningar i enskilda utsläpp eller transporter av näringsämnen (fosfor och/eller kväve) till Kattegatt från svenska vattendrag eller punktkällor (t.ex. angivet i ton per år eller månad) måste man – kategoriskt – sätta in denna transportreduction i sitt sammanhang där alla andra viktiga flöden till systemet finns realistiskt medräknade och angivna. De helt dominerande transporterna av vatten, fosfor och kväve sker mellan Kattegatt och Skagerrak, å ena sidan, och mellan Kattegatt och Östersjön, å den andra sidan (se kapitel 3). Fig. 1.1 ger här inte information om de stora helt dominerade närsaltsflödena till Kattegatt utan endast nettoflödena i dessa två huvudriktningar. På detta sätt framstår flodintransporten från Sverige som relativt sett större och betydelsefullare än den faktiskt är.

Dessutom är det stora skillnader mellan intransport och uttransport av vatten, salt och närsalter i ytvattnet och djupvattnet. Omfattande data (från SMHI), som presenteras och diskuteras i kapitel 2, demonstrerar detta med all önskvärd tydlighet. Det betyder att om man rätt skall förstå hur Kattegatt reagerar på ändringar i närsaltbelastning bör Kattegatt delas upp åtminstone i ett ytvattnelager och ett djupvattnelager. Dessutom tar inte OSPAR-modelleringen på ett vetenskapligt adekvat sätt hänsyn till flera interna transportprocesser, som reglerar hur Kattegatt svarar på ändringar i närsaltbelastning, t.ex. resuspension av finmaterial och partikulära närsaltsfraktioner från erosions- och transportbottnar ovanför den teoretiska vågbasen, som definierar yt- och djupvattenskikten, eller bioupptag och retention av närsalter i biota (främst växtplankton, bakterioplankton och djurplankton). Man kan således inte direkt jämföra resultaten från OSPAR-
modelleringen med de resultat som presenterats i detta arbete, där CoastMab-modellen används. CoastMab tar hänsyn till alla dessa interna transportprocesser och dessutom bygger massbalansberäkningarna för näsalter på en verklig massbalans för salt, dvs de vattenflöden som beräknas med CoastMab-modellen är de vattenflöden som krävs för att de mycket noggrant uppmätta salthalterna skall kunna förklaras.

I detta arbete har en generell, validerad massbalansmodell (CoastMab; se Håkanson och Bryhn, 2008a, c), som tidigare inte testats för Kattegatt, använts. Validerad betyder att denna modell testats i ett 30-tal kustområden av olika storlek och karaktär (allt från Svarta havet, Atlantkusten till Bottenhavet) och vid dessa tester, som gjorts utan områdesspecifika kalibreringar ("tuning"), visat sig prediktera bl.a. fosforkoncentrationer, suspenderat partikulärt material (SPM), sedimentation, klorofyll och siktjup, mycket väl, ofta inom det intervall som ges av osäkerheten i de empiriska mätvärdena (se t.ex. Håkanson and Bryhn, 2008a, c).

beräknade värden skall stämma med uppmätta värden på kvävekoncentrationerna i vatten och sediment.

Utifrån detta kan man förstå att dessa två modellansatser (OSPAR och CoastMab) bygger på olika modellstrukturer och skall snarast ses som komplement till varandra. Kort kan sägas att OSPAR är mer av en "oceanografisk" modell och CoastMab mer av en modell som bygger på recenta sedimentologiska processer. CoastMab är en generell (allmängiltig) dynamisk processbaserad modell som bygger på ordinära differentialekvationer.

Grundläggande frågor i detta arbete har varit: Hur skulle Kattegatt svara på en minskning i fosfor- och kvävetransporten från olika tillflöden? Hur mycket lägre skulle kvävekoncentrationen bli i systemet om åtgärderna genomfördes enligt den internationella expertgruppens råd i t.ex. de svenska tillflödena till Kattegatt? Hur skulle förändringar i närsaltkoncentrationer i Kattegattsytvatten påverka viktiga bioindikatorer, som siktjupet (ett standardmått på vattnets klarhet) och/eller koncentrationen klorofyll-a (ett standardmått på såväl växtplanktons produktion som biomassa)? Finns det en alternativ åtgärdsstrategi som skulle ge bättre, mer kostnads-effektiva resultat för att minska övergödningen i Kattegatt? Hur skulle i så fall motiven till de alternativa förslagen se ut?

Detta arbete har haft följande uppläggning:

Först (på nivå 1) har CoastMab-modellen för salt använts för att kvantifiera vattenflöden till, inom och bort från Kattegatt. Dessa beräkningar inkluderar omblandning (mellan yt- och djupvatten) och diffusion (dvs transport av lösta ämnen från delar med höga koncentrationer till delar med lägre koncentrationer). Denna typ av modellering har testats för många kustområden och sjöar och förklaras i detalj av Håkanson och Bryhn (2008a, c). Modelleringen innebär att man beräknar de vattenflöden som krävs för att förklara uppmätta (och mycket särskilt) salthalter. Det betyder också att måtdata på salthalter i inflödande vatten från Skagerrak och från Egentliga Östersjön krävs liksom tillförlitliga data på salthalter i Kattegatt. För att göra denna typ av modellering krävs också tillförlitliga morfometriska data (medeldjup, volym, formfaktor, dynamisk kvot, etc.), liksom en hypsografisk kurva (dvs en djup/area-kurva) för Kattegatt. Dessa data presenteras i kapitel 2 och de har tillhandahållits av SMHI. SGU (prof. Ingemar Cato) har utan kostnad tillhandahållit viktiga sedimentdata på kväve och fosfor (som också presenteras i kapitel 2).

På nivå 2 har CoastMab för närsalterna kväve och fosfor använts. Det bör noteras att många av de algoritmer (= ekvationer) som ingår i CoastMab-modellen är generella och kan kvantifiera transportprocesser för både kväve och fosfor, t.ex., inflödena från Egentliga Östersjön och Skagerrak, sedimentation, ombländning, diffusion, resuspension och burial (dvs "begravning" av material från ytliga sedimentlager till mer djupliggande sedimentlager). För kväve, som också uppträder i gasform, föreligger dessutom, som nämnts, speciella transportprocesser, som våt- och torrdeposition, atmosfärisk kvävefixering och denitrifikation. Dessa transportprocesser har hittills inte ingått i CoastMab-modellen och värden på våt- och torrdeposition, har, som nämnts, tagits från OSPAR-modelleringen, värden på flodintransporten av fosfor och kväve bygger på data från HELCOM (2007b). Transporten av närsalter från Östersjön kommer från CoastMab-modellen för
Östersjön (se Håkanson and Bryhn, 2008a). Alla beräkningar sker på månadsbasis, men redovisas oftast på årsbasis, eftersom det inte funnits adekvata månadsdata på flera viktiga transportprocesser utan endast årsdata. 

På nivå 3 har CoastMab använts för att kvantifiera inflöde, produktion, sedimentation, burial och mineralisering av suspenderat partikulärt material (SPM; se Håkanson, 2006). Sedimentationen är viktig för syretäringen och systemets syrestatus, och speciellt för syreförhållanden i djupvattenzonen under den teoretiska vågbasen och därmed för diffusionen av fosfor från dessa sediment tillbaka till vattenfasen. 

På nivå 4 har generella och vältestade regressionsmodeller (dvs statistiska modeller som bygger på empiriska data) använts för att prediktera hur viktiga bioindikatorer som siktdjupet och koncentrationen av klorofyll-a skulle ändras i relation till ändrade närsaltskoncentrationer i vattnet, som i sin tur kan relateras till olika åtgärder på land. 

Det skall noteras att detta arbete har fokuserats till hela Kattegatt (och inte till förhållanden i enskilda vikar/kustområden inom systemet), eftersom förhållanden i hela Kattegatt är av fundamental betydelse för förhållanden också inom de flesta mindre kustområden inom systemet, t.ex., längs den svenska Västkusten.

Resultat från CoastMab-modellen för salt, fosfor, kväve och suspenderat partikulärt material i vatten och sediment, för bestämning av sedimentation och bioupptag av fosfor och kväve, för bestämning av siktdjup och klorofyll-a koncentrationer i ytvatten på månads- och årsbasis har jämförts med empiriska data och dessa jämförelser visar att modellen ger bra resultat, ofta mitt i intervallet som ges av osäkerheten i empiriska mätdata. Kattegatt har vid dessa modelleringsdelats upp i ett ytvattenlager, ovanför 39.9 m, som definieras av den teoretiska vågbasen, och ett djupvattenlager under den teoretiska vågbasen. Ovanför vågbasen förefinner definitionsmässigt erosions- och transportbottnar för finmaterial, dvs på dessa bottnar kan man räkna med att finmaterialet sedimenterar diskontinuerligt (dvs att perioder med sedimentation avlöses av perioder med vind/våg-genererad resuspension). Under vågbasen förefinnas så kallade ackumulationsbottnar (finsedimentbottnar). Detta är en funktionell indelning; under stormperioder kan vågbasen sänkas under 40 m i Kattegatt och under lugnvädersperioder kan den ligga på lägre vattendjup. För modelleringen av transportprocesser betyder detta att vågbasen utgör en så kallad ”kollektiv lösning” där pluseffekter skall vara lika med minuseffekter på månadsbasis så att nettoresultatet skall ge korrekta värden. 

Flera olika tester och simuleringar har presenterats med CoastMab-modellen. De åtgärdsmodelleringarna har fokuserats mot hur olika realistiska reduktioner (scenarier; se kapitel 4) i närsaltsbelastning skulle påverka övergödningssituationen i Kattegatt. Syftet har varit att identifiera hur kvävere dukte skulle påverka systemet, eftersom det är just detta som den internationella expertgruppen har rekommenderat (se Boesch et al., 2008). Idén har varit att försöka komma fram till en ”optimal” och kostnadseffektiv åtgärdsstrategi som kan rekommenderas för det praktiken miljöarbetet. I detta arbete har också ambitionen varit att åtminstone snudda vid det mycket viktiga problemet att försöka få fram realistiska och adekvata kostnader för olika åtgärder, eftersom detta inte gjordes av expertgruppen.
Sammanfattning på svenska

Sammanfattningsvis kan sägas:

• De figurer som presenterar de olika årsbudgeterna för vatten (fig. 3.3), salt (fig. 3.4), fosfor (fig. 3.9), suspenderat partikulärt material (fig. 3.11) och kväve (fig. 3.16) visar entydigt att mycket stora flöden av vatten och närsalter till Kattegatts bioproductiva ytlager (0-40 m) kommer från Östersjön. Detta borde vara enkelt att förstå eftersom allt vatten från hela Östersjöns mycket stora avrinningsområde, som omfattar Finland, delar av Ryssland, Baltikum, Polen, delar av Tyskland, Vitryssland, Danmark och Sverige, rinner ut i Kattegatt, och detta avrinningsområde är många gånger större än de delar av sydvästra Sverige och Danmark, som direkt avvattnas till Kattegatt.

• Utifrån de data som ges i dessa budgetar är det uppenbart att mycket stora ytvattenflödena av fosfor och kväve kommer från Östersjön och det betyder i detta sammanhang, liksom i alla liknande sammanhang, att man i första hand måste åtgärda de största tillflödena för att åstadkomma de mest genomgripande förändringarna/förbättringarna (se scenario 1 i kapitel 4). Närsaltsflödena från de svenska vattendrag som mynnar direkt till Kattegatt är små i sammanhanget och beräkningar genomförda i kapitel 4 (scenarierna 2 and 3) visar klart och entydigt att inte ens om hela Sveriges kvot på närsaltsreduktioner enligt den undertecknade ”Baltic Sea Action Plan” på 290 ton fosfor per år och 20,780 ton kväve per år skulle genomföras i Kattegatts avrinningsområde skulle det ge några påtagligt positiva effekter. Dessa flöden är helt enkelt för små i sammanhanget. Totalt tillförs Kattegatts ytvatten årligen ca 200,000 ton kväve per år från Östersjön, 74,000 t/år från vattendrag, varav ca hälften kommer från Danmark och ca 32,600 ton utgör den totala svenska antropogena belastningen från diffusa källor och punktutsläpp, 25,000 t/år från Skagerrak och det atmosfäriska bidraget är 17,000 t per år. Diffusionen i systemet är liten medan den interna ombländningen relativt stor (240,000 till 270,000 t/år), men inte större än att det mesta av det kväve som rinner in via djupvattnet (4,150,000 t/år) också rinner ut via djupvattnet (4,200,000 t/år). Sedimentationen på erosions- och transportbottnar (100,000 t/år), sedimentation på ackumulationsbottnar (29,000 t/år), burial (22,000 t/år) och den interna resuspensionen (till ytvattnet, 72,000 t/år och till djupvattnet, 26,000 t/år) är relativt viktiga flöden, som påverkar hur Kattegat svarar på ändringar i kvävebelastning (se fig. 3.16).

För fosfor är motsvarande flöden: Total tillförsel till Kattegatts ytvatten ca 18,000 t/år från Östersjön, 1900 t/år från Skagerrak, 1800 t/år från vattendrag, varav ca hälften kommer från Danmark och ca 680 ton från svenska antropogena diffusa källor och punktutsläpp. Diffusionen från djupvattnets är liten (30 t/år) och den interna ombländningen ca 20,000 t/år; det atmosfäriska bidraget är ca 100 t fosfor per år. Sedimentationen är totalt ca 3000 t/år, burial 3000 t/år; den interna resuspensionen till ytvattnet är ca 3000 t/år och till djupvattnet, 1100 t/år (fig. 3.9).

Utifrån dessa resultat från massbalansberäkningarna redovisas en ”optimal” åtgärdsstrategi för att minska övergödningen i Kattegatt i scenario 4 i kapitel 4. Det förslaget skiljer sig från den internationella expertgruppens förslag och innebär att resurserna bör fokuseras mot att reducera främst fosforflödena till Östersjöns mest eutrofierade områden (dvs Finska viken, Rigabukten, kustområdet utanför Kaliningrad och Oders och Wistulas mynningsområden) med total ca 10,000 t.

På det hela taget gäller att de pengar som aviserats enligt BSAP för att minska närsaltsbelastningen från Sverige skulle göra mer nytta (större reduktion i kg per insatt krona) för att minska övergödningen i Östersjön inklusive Kattegatt om pengarna främst kanaliserades till kostnadseffektiva forsforreduktioner i första hand i Polen och de Baltiska staterna.
7. Literature references


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8. Appendices

Appendix 8.1. A compilation of the differential equations for the dynamic SPM-model (CoastMab) using data for the Kattegat (KA) to exemplify the calculation routines. Abbreviations and dimensions are given in table 3.8.

**Surface water (SW)**

\[
\begin{align*}
M_{SPMSWKA}(t) &= M_{SPMSWKA}(t - dt) + (F_{SWSPMBPKA} + F_{xSPMDWSWKA} + F_{SPMETSWKA} + F_{SPMtribKA} - F_{SPMSWKABP} - F_{SPMSWDWKA} - F_{SPMSWETKA} - F_{xSPMSWDWKA} - F_{SPMminSWKA}) \cdot dt \\
M_{SPMSWKA}(t) &= \text{Mass (amount of SPM) in the SW-compartment at time } t \text{ (g)} \\
F_{SWSPMBPKA} &= \text{Flow into the SW-compartment from the Baltic Proper (BP; g/month); see below} \\
F_{SPMETSWKA} &= \text{Flow (resuspension) from ET-areas to the SW-compartment (g/month)} \\
F_{SPMtribKA} &= \text{Flow into the SW-compartment from tributaries (g/month)} \\
F_{SPMSWKABP} &= \text{Flow from the SW-compartment and out to the Baltic Proper (g/month)} \\
F_{SPMSWDWKA} &= \text{Flow (sedimentation) from the SW-compartment to deep-water (DW) compartment (g/month)} \\
F_{SPMSWETKA} &= \text{Flow (sedimentation) from the SW-compartment to ET-areas (g/month)} \\
F_{xSPMSWDWKA} &= \text{Flow from surface water to deep water (downward mixing; g/month)} \\
F_{SPMminSWKA} &= \text{Flow (mineralization) from the SW-compartment (g/month)} \\
M_{SPMETKA}(t) &= M_{SPMETKA}(t - dt) + (F_{SPMSWETKA} - F_{SPMETDWKA} - F_{SPMETSWKA} - F_{SPMminETKA}) \cdot dt \\
M_{SPMETKA}(t) &= \text{Mass (amount of SPM) in the ET-compartment at time } t \text{ (g)} \\
F_{SPMETDWKA} &= \text{Flow (resuspension) from ET-areas to the DW-compartment (g/month)} \\
F_{SPMminETKA} &= \text{Flow (mineralization) from the ET-areas (g/month)} \\
M_{SPMDWKA}(t) &= M_{SPMDWKA}(t - dt) + (F_{SPMSWDWKA} + F_{SPMETDWSWKA} + F_{xSPMSWDWKA} + F_{SPMDBPKA} - F_{xSPMSWDWKA} - F_{SPMDBWA} - F_{SPMDWKABP} - F_{SPMminDWKA}) \cdot dt \\
M_{SPMDWKA}(t) &= \text{Mass (amount of SPM) in the DW-compartment at time } t \text{ (g)} \\
F_{SPMDBPKA} &= \text{Flow into the DW-compartment from the Baltic Proper (g/month)} \\
F_{SPMDBWA} &= \text{Flow (sedimentation) from the DW-compartment to A-areas (ADW; g/month)} \\
F_{SPMDWKABP} &= \text{Flow from the DW-compartment and out to the Baltic Proper (g/month)} \\
F_{SPMminDWKA} &= \text{Flow (mineralization) from the DW-compartment (g/month)} \\
M_{SPMADWKA}(t) &= M_{SPMADWKA}(t - dt) + (F_{SPMDBWA} - F_{BurSPMKA} - F_{SPMminADWKA}) \cdot dt \\
M_{SPMADWKA}(t) &= \text{Mass (amount of SPM) in the ADW-compartment at time } t \text{ (g)} \\
F_{BurSPMKA} &= \text{Flow (burial) from the ADW-compartment (g/month)} \\
F_{SPMminADWKA} &= \text{Flow (mineralization) from the ADW-compartment (g/month)} \\
\end{align*}
\]

**Algorithms for fluxes**

**Inflow**
production (mass of SPM from primary production from the CoastWeb-model)

\[ M_{\text{SPMprod}KA} = (M_{\text{MBPKA}}+M_{\text{MPHKA}}+M_{\text{MZHKA}}) \cdot 1000 \]

Sedimentation

\[ F_{\text{SPMSSWTKA}} = M_{\text{SPMSSWKA}} \cdot \left( \frac{v_{\text{SWKA}}}{D_{\text{SWKA}}} \cdot ET_{KA} \cdot (1-DC_{\text{ResSPMSSWKA}}) + Y_{\text{ResKA}} \cdot DC_{\text{ResSPMSSWKA}} \right) \]

\[ F_{\text{SPMSSWDWKA}} = M_{\text{SPMSSWKA}} \cdot \left( \frac{v_{\text{SWKA}}}{D_{\text{SWKA}}} \cdot (1-ET_{KA}) \cdot (1-DC_{\text{ResSPMSSWKA}}) + Y_{\text{ResKA}} \cdot DC_{\text{ResSPMSSWKA}} \right) \]

\[ F_{\text{SPMDWADWKA}} = M_{\text{SPMDWKA}} \cdot Y_{\text{TKA}} \cdot \left( \frac{v_{\text{DWKA}}}{D_{\text{DWKA}}} \cdot (1-DC_{\text{ResSPMDWKA}}) + Y_{\text{ResKA}} \cdot DC_{\text{ResSPMDWKA}} \right) \]

Burial:

\[ F_{\text{BurSPMKA}} = M_{\text{SMAKA}} \cdot \left( \frac{1}{(\text{Age}_{\text{ADWKA}})} \right) \]

Resuspension

\[ F_{\text{SPMETSWKKA}} = M_{\text{SPMETKA}} \cdot R_{\text{ResKA}} \cdot \left( V_{d_{KA}}/3 \right) \]

\[ F_{\text{SPMETFWDWKA}} = M_{\text{SPMETKA}} \cdot R_{\text{ResKA}} \cdot \left( V_{d_{KA}}/3 \right) \]

Mixing

\[ F_{\text{SPMSWDSWKKA}} = M_{\text{SPMSWKA}} \cdot R_{\text{MixSDWK}} \cdot V_{\text{SWKA}}/V_{\text{DWKA}} \]

\[ F_{\text{SPMDWSDWKKA}} = M_{\text{SPMDWKA}} \cdot R_{\text{MixSDWK}} \cdot V_{\text{SWKA}}/V_{\text{DWKA}} \]

Mineralization

\[ F_{\text{SPMminSWWK}} = M_{\text{SPMSWKA}} \cdot R_{\text{MinSW}} \]

\[ F_{\text{SPMminDWK}} = M_{\text{SPMDWK}} \cdot R_{\text{MinDW}} \]

\[ F_{\text{SPMminETKA}} = M_{\text{SPMETKA}} \cdot R_{\text{Minsed}} \]

Other model variables and algorithms

\[ \text{Area}_{KA} = 16700 \cdot 10^6 \text{ [km}^2\text{]} \]

\[ \text{Area}_{EKA} = 7810 \cdot 10^6/(\text{Area}_{KA} \cdot \text{Area}_{\text{belowDwbKA}}) \text{ [km}^2\text{]} \]

\[ \text{Area}_{\text{areaSKA}} = \text{Area}_{KA} \cdot (1-ET_{KA}) \text{ [dim. less]} \]

\[ \text{Area}_{\text{AboveDwbKA}} = \text{Area}_{KA} \cdot \text{Area}_{\text{belowDwbKA}} \text{ [km}^2\text{]} \]

\[ \text{Area}_{\text{BelowDwbKA}} = 3500 \cdot 10^6 \text{ [km}^2\text{]} \]

\[ \text{Age}_{KA} = \text{If Age}_{\text{TPADW}} > 360 \text{ months, then 360 else Age}_{\text{TPADW}}; \text{ if Age}_{\text{TPADW}} < 12 \text{ months, then 12 else 12-10/Sed}_{\text{TPADW}} \text{ [months]} \]

\[ \text{Age}_{ETKA} = (12/\text{Strat}_{KA}) \text{ [months]} \]

\[ \text{Age}_{\text{ADWKA}} = 12-10/(\text{Sed}_{\text{cm}yr}\text{}/\text{yr}_{KA}) \text{ [months]} \]

\[ \text{Amp}_{\text{Rmig}} = 0.2 \text{ [dim. less]} \]

\[ \text{Amp}_{\text{Trib}} = 0.5 \text{ [dim. less]} \]

\[ C_{\text{HPKA}} = 1000 \cdot M_{\text{HPKA}}/V_{\text{SWKA}} \text{ [conc. bacterioplankton; t/m}^3\text{]} \]

\[ \text{DC}_{\text{ResSPMSDWA}} = F_{\text{SPMSDWSWK}}/((F_{\text{SPMDSWP}})+F_{\text{SPMETDWSWK}})+F_{\text{SPMMSDWA}}+F_{\text{SPMSSDWA}}) \text{ [dim. less]} \]

\[ \text{DC}_{\text{ResSPMDWA}} = (F_{\text{SPMETSWK}})/((F_{\text{SPMSUW}})+F_{\text{SPMETDWSWK}})+F_{\text{SPMPPKA}}+F_{\text{SPMBSHPK}}+F_{\text{SPMDWKA}}+F_{\text{SPMinD}}+F_{\text{SPMSDWSWK}}) \text{ [dim. less]} \]

\[ D_{\text{DWKA}} = (D_{\text{Max}}-D_{\text{wDWA}})/2 \text{ [m]} \]

\[ DF_{\text{SWKA}} = 1 - PF_{\text{SWKA}} \text{ [dim. less]} \]
Appendices

\[ D_{\text{Max}KA} = 91 \text{[m]} \]
\[ D_{\text{WKA}} = (45.7\cdot(\text{Area}_{\text{KA}}\cdot10^{-6})^{0.5}/(21.4+(\text{Area}_{\text{KA}}\cdot10^{-6})^{0.5})) \text{[m]} \]
\[ D_{\text{WKABP}} = D_{\text{WKA}}/2 \text{[m]} \]
\[ D_{\text{WT}_{KA}} = (1.00, 4.29), (2.00, 3.50), (3.00, 3.32), (4.00, 3.26), (5.00, 3.41), (6.00, 3.68), (7.00, 3.76), (8.00, 3.83), (9.00, 3.91), (10.0, 4.02), (11.0, 4.73), (12.0, 5.39) \text{[°C]} \]
\[ E_{\text{T}_{KA}} = (\text{Area}_{\text{KA}} \cdot \text{Area}_{\text{BelowDwbKA}}) / \text{Area}_{\text{KA}} \text{[dim. less]} \]
\[ F_{\text{T}_{\text{tribKA}}} = ((202+582+335)/12) \cdot 10^{6} \cdot Y_{\text{OKA}} \text{[g/month]} \]
\[ \text{Ice limit} = 0.9 \text{[°C]} \]
\[ \text{Lat}_{KA} = 57.7 \text{[°N]} \]
\[ \text{NBM}_{\text{BPKA}} = Y_{\text{SPM}_{\text{KA}}} \cdot 0.001 \cdot V_{\text{SWKA}} \cdot 10^{4} \cdot (0.973-(0.27\cdot\log(\text{Chl}_{KA})+0.19)-0.438) \text{[kg ww]} \]
\[ P_{\text{F}_{\text{SWKA}}} = Y_{\text{SPMFSW}} \cdot (\text{DC}_{\text{RevTFSW}} + (M_{\text{TPBS}}/(M_{\text{TPSW}}+M_{\text{TPbio}})) \text{[dim. less]} \]
\[ Q_{\text{DWKABP}} = Q_{\text{KABP}} \cdot Q_{\text{SWKABP}} \text{[m³/month]} \]
\[ Q_{\text{SWBPKA}} = Q_{\text{BPKA}} \cdot (1-DC_{\text{SWDKWA}}) \text{[m³/month]} \]
\[ Q_{\text{SWKABP}} = Q_{\text{SWBPKA}} + Q_{\text{TribKA}} + (Q_{\text{PercKA}} - Q_{\text{EvKKA}}) \text{[m³/month]} \]
\[ \text{Ref}_{\text{Temp}} = 9 \text{[°C]} \]
\[ R_{\text{MinDWA}} = R_{\text{Min}KA} \cdot (\text{DWT}_{KA}/\text{Ref}_{\text{Temp}})^{1.2} \text{[1/month]} \]
\[ R_{\text{Min}KA} = (\text{M}_{\text{BPKA}} / \text{NBM}_{\text{BPKA}}) \cdot 0.01 \cdot (0.99 / E_{\text{T}_{KA}}) \text{[1/month]} \]
\[ R_{\text{Mixed}} = 0.01 \cdot 30 \]
\[ R_{\text{MinSWKA}} = R_{\text{Min}KA} \cdot ((\text{SWT}_{KA} / \text{Ref}_{\text{Temp}})^{1.2} \text{[1/month]} \]
\[ R_{\text{MinSWDWA}} = (\text{Sal}_{\text{DWKKA}} \cdot \text{Sal}_{\text{SWKA}}) \text{then } R_{\text{MixedKKA}} = (1/(1+\text{Sal}_{\text{DWKKA}} \cdot \text{Sal}_{\text{SWKKA}}))^{2} \text{else } R_{\text{MixedKKA}} \text{[1/month]} \]
\[ R_{\text{MixedKKA}} = \text{if } T_{\text{DW}} < T_{\text{SW}} \text{then } (((T_{\text{SW}}/T_{\text{DWKKA}})^{1.2}) \cdot \text{Strat}_{KA} \cdot E_{\text{T}_{KA}}/12 \text{else Strat}_{KA} \cdot E_{\text{T}_{KA}}/12 \text{[1/month]} \]
\[ R_{\text{ResKKA}} = \text{if } \text{SWT}_{KA} < \text{Ice limit} \text{then } \{(\text{SWT}_{KA} + 0.2) \cdot 1/\text{Age}_{\text{ETKA}} \text{else } 1/\text{Age}_{\text{ETKA}} \text{[1/month]} \]
\[ \text{Seasnorm}_{\text{Lama}} = -1.000, -1.000, -1.000, -1.000, -1.000, -1.000, -1.000, -1.000, -1.000, -1.000, -1.000, -1.000 \text{[dim. less]} \]
\[ \text{Sec}_{KA} = 10^{4} \cdot (z_{KA} + 0.5) \cdot (\log(\text{SPM}_{\text{SWKA}}) + 1/3) + 2/z_{KA}) \text{[m]} \]
\[ \text{Sal}_{\text{DWKKA}} = 10^{4} \cdot F_{\text{SPM}_{\text{DWKKA}}} / (A_{\text{Area}_{\text{KA}}}) \cdot 30 \text{[µg/cm²·d]} \]
\[ \text{SWT}_{KA} = (1.00, 2.00), (2.00, 1.13), (3.00, 0.755), (4.00, 1.76), (5.00, 3.27), (6.00, 4.16), (7.00, 5.11), (8.00, 6.10), (9.00, 12.6), (10.0, 11.1), (11.0, 7.02), (12.0, 7.02) \text{[°C]} \]
\[ \text{SPM}_{\text{DWKKA}} = M_{\text{SPMWKKA}} / V_{\text{DWKKA}} \text{[mg/l]} \]
\[ \text{SPM}_{\text{SWKKA}} = (M_{\text{SPMWKKA}} + M_{\text{SPMprodKKA}}) / V_{\text{SWKKA}} \text{[mg/l]} \]
\[ \text{Temp}_{\text{CritKKA}} = \text{if } \text{SWT}_{KA} < \text{Ice limit} \text{then } \text{Ice limit} / (\text{Ice limit} + \text{SWT}_{KA}) \text{else } Y_{\text{DRKKA}} \]
\[ TP_{\text{Clay}} = 0.5 \text{[mg/g dw]} \]
\[ TP_{\text{AedKKA}} = M_{\text{TPDWA}} / ((10^{4} \cdot V_{\text{AedKKA}} \cdot d_{\text{KA}} \cdot (1-W_{\text{KA}})/100)) \text{[mg/g dw]} \]
\[ TP_{\text{SWKKA}} = 1000 \cdot (M_{\text{TPSWKKA}} + M_{\text{TPbioKKA}}) / V_{\text{SWKKA}} \text{[µg/l]} \]
\[ V_{\text{AedKKA}} = \text{Area}_{\text{BelowDwbKKA}} \cdot 10^{-6} \cdot (V_{\text{DWKKA}}/3 \text{[m³]} \]
\[ V_{\text{CA}} = 3 \cdot D_{\text{MVKKA}} / D_{\text{Max}KA} \text{[dim. less]} \]
\[ V_{\text{DWKKA}} = V_{\text{Def}} \cdot Y_{\text{Sal}_{\text{DWKKA}}} \cdot Y_{\text{SPM}_{\text{DWKKA}}} \text{[m/month]} \]
\[ V_{\text{SWKKA}} = V_{\text{Def}} \cdot Y_{\text{SPM}_{\text{SWKKA}}} \cdot Y_{\text{Sal}_{\text{SWKKA}}} \text{[m/month]} \]
\[ V_{\text{Def}} = 6 \text{[m/month]} \]
\[ Y_{\text{DRKKA}} = \text{if } DR_{\text{KA}} < 0.26 \text{then } DR_{\text{KA}}/0.26 \text{else } 0.26 / DR_{\text{KA}} \]
\[ V_{\text{DWKKA}} = 18 \cdot 10^{4} \text{[m³]} \]
\[ V_{\text{SWKKA}} = 392 \cdot 10^{4} \text{[m³]} \]
\[ W_{\text{KA}} = 70 \% \text{ww} \]
\[ Y_{\text{DayLKA}} = \text{HD}_L / 12 \text{[dim. less]} \]
\[ Y_{\text{DR}} = \text{If } DR < 0.26 \text{then 1 else } 0.26 / DR \text{[calculates how changes in DR and turbulence influence sedimentation]} \text{[dim. less]} \]
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\[ Y_{QKA} = 1 + 0.526 \cdot ((\text{Lat}_{KA} - 35)^{2.18/35^{2.18} \cdot \text{Seasnorm}_{Lat_{max}} + (1-(\text{Lat}_{KA} - 35)^{2.18/35^{2.18} \cdot \text{Seasnorm}_{Lat_{min}})) + 0.265 \cdot \left(\frac{\text{Qemp}_{KA}}{(60 \cdot 60 \cdot 24 \cdot 365)^{0.22/5000^{0.22} \cdot \text{Seasnorm}_{Q_{max}}}} + (1-(\frac{\text{Qemp}_{KA}}{(60 \cdot 60 \cdot 24 \cdot 365)})^{0.22/5000^{0.22} \cdot \text{Seasnorm}_{Q_{min}})} \right) \] [dim. less]

\[ Y_{QSec} = \frac{Q_{MWBPKA} + Q_{SWBPKA}}{Q_{TribKA} + Q_{MWBPKA} + Q_{SWBPKA}} \] [dim. less]

\[ Y_{PFKA} = \frac{F_{TPETSWKA}}{F_{TPrecKA} + F_{TPETSWKA} + F_{TPSBPKA} + F_{TPtribKA} + F_{dTPDWSWKA} + F_{xTPDWSWKA}} \] [dim. less]

\[ Y_{ResKA} = (\text{Age}_{ETA} + 1)^{0.5} \] [calculates how much faster resuspended sediments settle out] [dim. less]

\[ Y_{SalSW} = (1 + 1 \cdot (\text{Sal}_{SW}/1 - 1)^{(\text{Sal}_{SW}^{0.05})}) \] [calculates how changes in salinities > 1 psu influence sedimentation] [dim. less]

\[ Y_{SalDwKA} = (1 + 1 \cdot (\text{Sal}_{Dw}/1 - 1)) \] [dim. less]

\[ Y_{SPMDwKA} = 1 + 0.75 \cdot (\text{SPM}_{DwKA}/50 - 1) \] [dim. less]

\[ Y_{SPMSwKA} = 1 + 0.75 \cdot (\text{SPM}_{SwKA}/50 - 1) \] [dim. less]

\[ Y_{TKA} = \begin{cases} R_{Mixdef} = R_{Mixdef} \cdot (1/T_{DW})^{0.5} & \text{if } T_{DW} < T_{SW} \\ R_{Diff} = R_{Diff} \cdot (1/T_{DW})^{0.5} & \text{else} \end{cases} \] [dim. less]

\[ Y_{JKA} = \begin{cases} Y_{JKA} < 0.012 & \text{else } Y_{JKA} \end{cases} \] [dim. less]

\[ Y_{jKA} = \begin{cases} Y_{jKA} < 0.28 \cdot (\text{Sal}_{Sw_{KA}}/12.5 - 1) & \text{else } (0.20 + 0.02 \cdot (\text{Sal}_{Sw_{KA}}/2.5 - 1)) \end{cases} \] [dim. less]

\[ Y_{TempChl} = \begin{cases} Y_{TempChl} > 4 & \text{then } 1 \text{ else } (\text{SWT}_{KA} + 0.1)/4 \end{cases} \] [dim. less]

\[ z_{KA} = (10^{0.15 \cdot \log(1 + \text{Sal}_{Sw_{KA}}) + 0.3} - 1 \] [dim. less]
Appendix 8.2. A. The first parts of this appendix (A) outlines the CoastWeb-model, the second part (/B) gives all equations.

8.2.1. Outline of the CoastWeb-model.
Modeling predator-prey interactions in marine system is an old tradition (Fleming, 1939). However, many models including functional groups need to be calibrated to suit local conditions. But good calibration results are no guarantee that a model describes natural conditions correctly, since almost any model can be tuned to provide “perfect” correspondence to empirical data in a given system. Only independent validations (= blind tests) yielding high predictive power from a wide range of systems can demonstrate that a given model describes natural conditions in an relevant way (Peters, 1991). The basic model used in this work is intended to be practically useful and it includes ten functional groups. It has also been critically tested for several aquatic systems and proven to yield good results for its target variables, i.e., biomasses and production values for the functional groups included in the model on a monthly basis.

CoastWeb is partially based on LakeWeb (Håkanson and Boulion, 2002) and it quantifies important differences between fresh and saltwater systems. Bacterioplankton physiology differs between freshwater and marine water species, although the work that bacterioplankton performs is virtually the same in both environments (Hobbie, 1988). Marine systems generally have higher zooplankton species diversity than lakes, and this is a key difference between freshwater and marine zooplankton (Lehman, 1988). The biomass of benthic macrofauna covers similar ranges and follows similar patterns in lakes and marine waters (Lopez, 1988), although brackish sediments seem to contain lower biomasses (Josefson and Hansen, 2004). Marine fish biomasses are difficult to predict, but they tend to be positively correlated to nutrient availability and primary productivity. A Soviet database used by Håkanson and Boulion (2002) indicated that primary productivity and fish yield show similar correlations in natural lakes and marine waters. One functional group that is certainly more important in marine systems than in lakes is jellyfish. Jellyfish are highly concentrated at physical discontinuities such as haloclines, thermoclines and at episodes related to tides and turbulent conditions. The general role of jellyfish in foodwebs, i.e., how jellyfish react to changing predation pressure or to increased pollution, has not been thoroughly quantified (Mills, 2001). Jellyfish feed on the same organisms as many species of fish and increases in jellyfish biomass have been attributed to overfishing and eutrophication (Arai, 2001).

Fig. 8.1 shows the general outline of the CoastWeb-model. All functional groups are calculated by a similar set of equations. This appendix will not repeat the motivations and tests of the model. The main aim of the model is to quantitatively describe typical, characteristic foodweb interactions so that production, biomasses and predation can be determined for the functional groups included in the model, the three primary producers: (1) Phytoplankton; as calculated from chlorophyll, which may in turn be calculated from local, regional or general regressions based on either total phosphorus (TP) or total nitrogen (TN), and from light conditions, water temperature, salinity, Secchi depth and morphometry. (2) Benthic algae; calculated from Secchi depth (water clarity), latitude (temperature) and coastal morphometry. (3) Macrophytes (cover, production and biomass) calculated from Secchi depth, latitude and morphometry.

The six secondary producers (consumers of different orders): (4) Herbivorous zooplankton, feeding on phytoplankton and bacterioplankton. (5) Predatory zooplankton, eating only herbivorous zooplankton. (6) Jellyfish, feeding mainly on zooplankton; they generally abound at salinities > 10 psu. (7) Zoobenthos, feeding mainly on sediments (detrivores), benthic algae and macrophytes.
(8) Prey fish, feeding on herbivorous and predatory zooplankton and zoobenthos; and
(9) Predatory fish, eating only prey fish; note that this modeling also calculates predation of fish from man, birds and animals as well as migration in and out of fish, jellyfish and plankton, and that the model calculates net production.
(10). Finally, one decomposer, bacterioplankton, which decomposes suspended organic matter included in SPM (suspended particulate matter).

The functional group “predatory” fish does the work of eating “prey fish”, which does the job of consuming zooplankton and zoobenthos, etc. Other groups of organisms, like benthic bacteria and fungi, are not treated as individual groups but are accounted for in the flux to zoobenthos called “zoobenthos production from sediment sources”. There are many such simplifications in this modeling. They are necessary for several reasons, to keep the model as small as possible (it is still quite extensive), to keep the driving variable as few and as

### CoastWeb

**Fig. 8.1.** An outline of CoastWeb, a model to quantify all important foodweb interactions for functional groups, including biotic/abiotic feedbacks, in a general manner. TP = total phosphorus, Chl = chlorophyll, SPM = suspended particulate matter, Sal = salinity.

accessible as possible (otherwise it might be difficult to use the model in practice) and to be able to critically test the model using empirical data. The idea has not been to include everything in the model but to focus on key functional groups of organisms and fundamental abiotic/biotic relationships. CoastWeb is intended to cover a wide domain of coastal systems: from temperate, boreal and cold zones, large and small systems, shallow and deep systems,
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oligotrophic to hypertrophic conditions and brackish to very salt systems (salinities from 0 to 36 psu).

There are only a few obligatory driving variables in the model. A basic assumption for this modeling is that at the monthly ecosystem scale, one can make important simplifications (thus reducing accumulated uncertainties) and remove weather as a driving variable.

CoastWeb is primarily intended to handle feedbacks among the functional groups. Because biotic/abiotic feedbacks are also of great interest, several such interrelationships are included, one concerns how dynamically modeled TP-concentrations influence chlorophyll and also the SPM-concentration; another how SPM and salinity influences water clarity (Secchi depth), which is important for the production of macrophytes, benthic algae and the volume of the photic zone, a third relates to sedimentation of SPM, which regulates the oxygen concentration in the deep-water zone and hence also diffusion of phosphorus from sediments to water.

Basically, CoastWeb consists of two parts: (A) the foodweb sub-model, which is driven by chlorophyll data, and calculates production (kg ww per week) and biomass (kg ww) of the functional groups (fig. 8.1), and (B) the mass-balance model for nutrients (CoastMab), which is based on transport processes, which appear in most systems and apply for most substances.

In CoastWeb, one can predict chlorophyll from dynamically modeled TP-concentrations using the best available empirical regression (local, regional or general). This is also a standard procedure in lake science (see Vollenweider, 1968; Chapra, 1980; OECD, 1982). It should be stressed that in this modeling, the TP-concentrations affect the coastal foodweb in many ways.

Basically, the consumption rate for any given functional group is related to three factors:

1. The ratio between the actual biomass (BM) and the normal biomass (NBM) of the predator. The higher this ratio, the higher the predation pressure on the given prey.
2. The number of first order food choices (NR). The structure of the model involves several simplifications and there are always either one or two first order food choices. This means that NR is 1 or 2.
3. The inverse of the turnover time ($T_{SU}$) of the predator. Animals with short turnover times create a greater predation pressure on their prey than animals with long turnover times (and a higher value of the actual consumption rate constant, $CR_{SU}$). So, predatory fish will eat a relatively small fraction of the total available biomass of its prey per time unit. Small herbivorous zooplankton, on the other hand, are likely to consume a larger percentage of their prey (such as phytoplankton and bacterioplankton) per unit of time.

Fundamental concepts in CoastWeb are: (1) Consumption rates - “how large fraction of the prey biomass is consumed per time unit by the predator?” (2) Metabolic efficiency ratios for each compartment - “how much of the food consumed will increase the biomass of the consumer?” (3) Turnover or retention rates for each compartment - “how long is the mean, characteristic lifespan of the group?” (4) Food choices - “if there is a food choice, how much is consumed of each food type?” (5) Migration rates for fish - “how large fraction of the fish will leave and enter the system per unit of time?”. The model is based on a general production unit that may be mechanistically understood and repeated for different functional groups of organisms.
8.2.2. Basic equations for the CoastWeb-model for a system with two vertical compartments (here the Kattegat, KA). Abbreviations and dimensions are given in table 3.8.

**Bacterioplankton**

\[
BM_{BPKA}(t) = BM_{BPKA}(t - dt) + (IPR_{BPKA} + MIG_{InBPKA} - CON_{BPZHKA} - EL_{BPKA} - MIG_{OutBPKA}) \cdot dt
\]

\[
IPR_{BPKA} = R_{PRBP} \cdot \left(\frac{SPM_{SWKA}}{1000}\right) \cdot V_{SWKA} \cdot Y_{SWTKA}^{1}
\]

\[
MIG_{InBPKA} = R_{MigPHKA} \cdot NBM_{BPBS}
\]

\[
CON_{BPZHKA} = BM_{BPKA} \cdot CR_{ZHKA}
\]

\[
EL_{BPKA} = BM_{BPKA} / T_{BP}
\]

\[
MIG_{OutBPKA} = R_{MigPHKA} \cdot BM_{BPKA}
\]

**Benthic algae**

\[
BM_{BAKA}(t) = BM_{BAKA}(t - dt) + (IPR_{BAKA} - EL_{BAKA} - CON_{BAZKAB} - ER_{BAKA}) \cdot dt
\]

\[
IPR_{BAKA} = R_{PRBAKA} \cdot Area_{SecKA} \cdot (2 \cdot Sec_{KA}) \cdot Y_{TPKA} \cdot (HDL/12) \cdot Y_{SWTKA}^{1}
\]

\[
EL_{BAKA} = BM_{BAKA} / T_{BA}
\]

\[
CON_{BAZKAB} = BM_{BAKA} \cdot CR_{BAZKAB}
\]

\[
ER_{BAKA} = BM_{BAKA} \cdot R_{EzKA}
\]

**Jellyfish**

\[
BM_{JEKA}(t) = BM_{JEKA}(t - dt) + (IPR_{ZHJEKA} + IPR_{ZPPJEKA} + MIG_{InJEKA} - EL_{JEKA} - MIG_{OutJEKA}) \cdot dt
\]

\[
IPR_{ZHJEKA} = Y_{SalJEKA} \cdot DC_{ZPPtoPHBP} \cdot (1 - DC_{ZPZHJE}) \cdot CON_{ZHJEKA} \cdot MER_{ZP} \cdot Y_{SWTKA}^{0.5}
\]

\[
IPR_{ZPPJEKA} = Y_{SalJEKA} \cdot (DC_{ZPPtoPHBP}) \cdot DC_{ZPZHJE} \cdot CON_{ZHJEKA} \cdot MER_{ZP}
\]

\[
MIG_{InJEKA} = R_{MigPYKA} \cdot NBM_{JEKA} \cdot Y_{SalJEKA}
\]

\[
EL_{JEKA} = BM_{JEKA} / T_{JE}
\]

\[
MIG_{OutJEKA} = R_{MigPYKA} \cdot BM_{JEKA}
\]

**Macrophytes**

\[
BM_{MAKA}(t) = BM_{MAKA}(t - dt) + (IPR_{MAKA} - CON_{MAZKAB} - EL_{MAKA} - Er_{MAKA}) \cdot dt
\]

\[
IPR_{MAKA} = R_{PRMA} \cdot Area_{MAvKA} \cdot MA_{CovKA} \cdot 0.01 \cdot (HDL/12) \cdot Y_{SWTKA}^{1}
\]

\[
CON_{MAZKAB} = BM_{MAKA} \cdot CB_{ZBvMAKA} \cdot 0.001
\]

\[
EL_{MAKA} = BM_{MAKA} / T_{MA}
\]

\[
Er_{MAKA} = BM_{MAKA} \cdot R_{EzKA}
\]

**Predatory fish**

\[
BM_{PDKA}(t) = BM_{PDKA}(t - dt) + (IPR_{PDKA} + MIG_{InPDKA} - FISH_{PDKA} - EL_{PDKA} - MIG_{OutPDKA}) \cdot dt
\]

\[
IPR_{PDKA} = BM_{ERPD} \cdot F_{PYPDKA} \cdot Y_{SWTKA}^{0.25}
\]

\[
MIG_{InPDKA} = R_{MigPDKA} \cdot NBM_{PDKA}
\]

\[
FISH_{PDKA} = BM_{PDKA} \cdot R_{fishKA}
\]

\[
EL_{PDKA} = BM_{PDKA} / T_{PD}
\]

\[
MIG_{OutPDKA} = \text{if } BM_{PDKA} / NBM_{PDKA} > 1 \text{ then } (R_{migPDKA}) \cdot (BM_{PDKA}) \text{ else } 0.5 \cdot (R_{migPDKA}) \cdot (BM_{PDKA})
\]

**Phytoplankton**

\[
BM_{PHKA}(t) = BM_{PHKA}(t - dt) + (IPR_{PHKA} + MIG_{InPHKA} - ELP_{HKA} - CON_{PHZHKA} - MIG_{OutPHKA}) \cdot dt
\]
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IPR_{PHKA} = \text{PrimP}_{KA}
MIG_{inPHKA} = R_{MigPHKA} \cdot NBM_{PHBS}
EL_{PHKA} = BM_{PHKA} \cdot 1/T_{PH}
CON_{PHZHKA} = BM_{PHKA} \cdot CR_{ZHKA}
MIG_{OutPHKA} = R_{MigPHKA} \cdot BM_{PHKA}

**Prey fish**
BM_{PYKA}(t) = BM_{PYKA}(t - dt) + (IPR_{ZHPYKA} + IPR_{ZPPYKA} + IPR_{ZBPYKA} + MIG_{inPYKA} - CON_{PYPDKA} - EL_{PYKA} - FISH_{PYKA} - MIG_{OutPYKA}) \cdot dt

IPR_{ZHPYKA} = DC_{ZHPYKA} \cdot (1 - DC_{ZPYKA}) \cdot \text{MER}_{PY} \cdot CON_{ZHPYKA} \cdot Y_{SWTKA}^{0.25}
IPR_{ZPPYKA} = DC_{ZPPYKA} \cdot DC_{ZPYKA} \cdot CON_{ZPPYKA} \cdot \text{MER}_{PY} \cdot Y_{SWTKA}^{0.25}
IPR_{ZBPYKA} = F_{ZBPYKA} \cdot \text{MER}_{PY} \cdot (1 - DC_{ZPKA}) \cdot Y_{SWTKA}^{0.25}
MIG_{inPYKA} = \text{if BM}_{PYKA}/NBM_{PYBS} > 1 \text{ then } 0.5 \cdot R_{MigPYKA} \cdot NBM_{PYBS} \text{ else } R_{MigPYKA} \cdot NBM_{PYBS}
CON_{PYPDKA} = BM_{PYKA} \cdot CR_{PYKA}
EL_{PYKA} = BM_{PYKA} \cdot 1/T_{PY}
FISH_{PYKA} = BM_{PYKA} \cdot R_{Fish}
MIG_{OutPYKA} = \text{if BM}_{PYKA}/NBM_{PYBS} > 1 \text{ then } R_{MigPYKA} \cdot BM_{PYKA} \text{ else } 0.5 \cdot R_{MigPYKA} \cdot BM_{PYKA}

**Zoobenthos**
BM_{ZKAB}(t) = BM_{ZKAB}(t - dt) + (IPR_{MAZKAB} + IPR_{BAZKAB} + IPR_{SedZKAB} - CON_{ZBPYKA} - EL_{ZKAB}) \cdot dt

IPR_{MAZKAB} = (1 - DC_{MAZKAB}) \cdot CON_{MAZKAB} \cdot \text{MER}_{MA} \cdot Y_{SWTKA}^{0.25}
IPR_{BAZKAB} = DC_{BAZKAB} \cdot \text{MER}_{BA} \cdot CON_{BAZKAB} \cdot Y_{SWTKA}^{0.25}
IPR_{SedZKAB} = M_{SedKA} \cdot DC_{SedBA} \cdot NCR_{ZKAB} \cdot (\text{MER}_{SedKA} \cdot (ET_{KA} + (1 - ET_{KA}) \cdot Y_{Ek1KA} \cdot Y_{EkKA})) \cdot Y_{SWTKA}^{0.25}
CON_{ZBPYKA} = BM_{ZKAB} \cdot CR_{PYKA}
EL_{ZKAB} = BM_{ZKAB} \cdot 1/T_{ZB}

**Herbivorous zooplankton**
BM_{ZHKA}(t) = BM_{ZHKA}(t - dt) + (IPR_{PHZHKA} + IPR_{BPZHKA} + MIG_{inZHKA} - EL_{ZHKA} - CON_{ZHPYKA} - CON_{ZHJEKA} - MIG_{OutZHKA}) \cdot dt

IPR_{PHZHKA} = DC_{PHBPBP} \cdot \text{CON}_{PHZHKA} \cdot \text{MER}_{PHZH} \cdot Y_{SWTKA}^{0.5}
IPR_{BPZHKA} = (1 - DC_{PHBPBP}) \cdot CON_{BPZHKA} \cdot \text{MER}_{BPZH} \cdot Y_{SWTKA}^{0.5}
MIG_{inZHKA} = R_{MigZPKA} \cdot NBM_{ZHBS}
EL_{ZHKA} = BM_{ZHKA} \cdot 1/T_{ZH}
CON_{ZHPYKA} = BM_{ZHKA} \cdot CR_{PYKA}
CON_{ZHJEKA} = BM_{ZHKA} \cdot CR_{ZPKA}
CON_{ZHIEKA} = \text{if BM}_{JEKA} > 1 \text{ then } BM_{ZHKA} \cdot CR_{JEKA} \cdot R_{ProdJE} \text{ else } 0
MIG_{OutZHKA} = R_{MigZPKA} \cdot BM_{ZHKA}

**Predatory zooplankton**
BM_{ZPKA}(t) = BM_{ZPKA}(t - dt) + (IPR_{ZPKA} + MIG_{inZPKA} - CON_{ZPPYKA} - EL_{ZPKA} - CON_{ZJEKA} - MIG_{OutZPKA}) \cdot dt

IPR_{ZPKA} = \text{CON}_{ZHIPZPKA} \cdot \text{MER}_{ZP} \cdot Y_{SWTKA}^{0.25}
MIG_{inZPKA} = R_{MigZPKA} \cdot NBM_{ZPBS}
CON_{ZPPYKA} = BM_{ZPKA} \cdot CR_{PYKA}
EL_{ZPKA} = BM_{ZPKA} \cdot 1/T_{ZP}
CONZPKA = BMZPKA \cdot C_{RIEKA} \cdot R_{prodIE} \\
MIGOnZPKA = R_{MgZPKA} \cdot BMZPKA

**Model variables**

\[ \text{Area}_{KA} = 36260 \cdot 10^6 \]
\[ \text{Area}_{2SecKA} = \text{Area}_{KA} - \text{Area}_{2SecKA} \cdot 10^4 \text{ (=littoral fraction above 2 Secchi depths)} \]
\[ C_{BAKA} = 1000 \cdot BM_{BAKA} / \text{Area}_{KA} \]
\[ C_{BPKA} = 1000 \cdot BM_{BPKA} / V_{SWKA} \]
\[ Chl_{ModKA} = \text{Modeled concentration of chlorophyll-a in KA (μg/L)} \]
\[ CR_{BAZKAB} = (N_{CR_{ZKAB}} + N_{CR_{ZKAB}} \cdot (BM_{ZKAB} / N_{BM_{ZKAB}} - 1)) \]
\[ CR_{ZBMAKA} = (N_{CR_{JEKA}} + N_{CR_{JEKA}} \cdot (BM_{JEKA} / N_{BM_{JEKA}} - 1)) \]
\[ CR_{JEKA} = (N_{CR_{JEKA}} + N_{CR_{JEKA}} \cdot (BM_{JEKA} / N_{BM_{JEKA}} - 1)) \]
\[ CR_{ZPDKA} = Y_{Fish} \cdot (N_{CR_{PDKA}} + N_{CR_{PDKA}} \cdot (BM_{PDKA} / N_{BM_{PDKA}} - 1)) \]
\[ CR_{PYKA} = (N_{CR_{PYKA}} + N_{CR_{PYKA}} \cdot (BM_{PYKA} / NBM_{PYKA} - 1)) \]
\[ CR_{ZHKKA} = (N_{CR_{JEKA}} + N_{CR_{JEKA}} \cdot (BM_{JEKA} / NBM_{JEKA} - 1)) \]
\[ CR_{ZPKA} = (N_{CR_{ZPKA}} + N_{CR_{ZPKA}} \cdot (BM_{ZPKA} / NBM_{ZPKA} - 1)) \]
\[ DC_{BAMA} = (1 - DC_{SedBA}) \cdot 0.75 \]
\[ DC_{SedBA} = 0.75 \]
\[ DC_{PDKABS} = Q_{SWBSKA} / (Q_{SWBSKA} + Q_{SWSBP}) \]
\[ DC_{PYPDKA} = 0.5 \]
\[ DC_{PYPDKA2} = \text{if} \left( \frac{TP_{SWKA}}{TP_{SWKA} + 22} \right)^{0.4} < 0.75 \text{ then } 0.75 \text{ else } \left( \frac{TP_{SWKA}}{TP_{SWKA} + 22} \right)^{0.4} \]
\[ DC_{PYPDKA3} = \text{if } DC_{PYPDKA} > 0.95 \text{ then } 0.95 \text{ else } DC_{PYPDKA} \]
\[ DC_{ZIPPBP} = 0.5 \]
\[ DC_{ZPZB} = 0.65 \]
\[ DC_{ZPZAD} = \text{if } DC_{ZPZB} > 0.9 \text{ then } 0.9 \text{ else } DC_{ZPZB} \]
\[ DC_{ZPHZH} = 0.5 \]
\[ DC_{ZPHZH} = 0.5 \]
\[ ET_{KA} = \text{ET-areas in KA from the CoastMab-model} \]
\[ F_{FishPDKA} = BM_{PDKA} \cdot R_{fishKA} \]
\[ Y_{SalSec} = \left( \frac{Sal_{SWKA}}{12} \right) \]
\[ IG = 10 \]
\[ Lat_{KA} = 57.7 \]
\[ MA_{CovKA} = \text{Litfrac}_{KA} \cdot MA_{Percentage} \]
\[ MER_{MA} = 0.15 \]
\[ MER_{MA} = 0.24 \]
\[ MER_{SedKA} = MER_{MA} + 0.25 \]
\[ MER_{MA} = 0.15 \]
\[ MER_{PD} = 0.25 \]
\[ MER_{PHZH} = 0.24 \]
\[ MER_{PY} = 0.16 \]
\[ MER_{ZP} = 0.32 \]
\[ MSedKA = ((10 - 7.5) / 10) \cdot (IG / 100) \cdot (1 / (1 - W / 100)) \cdot (M_{SPMAKA} + M_{SPMETKA}) \]
\[ NBM_{MAKA} = NPR_{MAKA} \cdot T_{MA} \]
\[ NBM_{BAKA} = NPR_{BAKA} \cdot T_{BA} \]
\[ NBM_{BPKA} = 0.001 \cdot V_{SWKA} \cdot 10^4 \cdot (0.973 \cdot (0.27 \cdot \log(Chl_{ModKA}) + 0.19) - 0.438) \]
\[ NBM_{FishKA} = Y_{ChlKA} \cdot 10^4 \cdot (-6) \cdot ((\text{Area}_{KA} \cdot \text{TP}_{SWKA} \cdot 0.71)) \]
\[ NBM_{JEKA} = NBM_{ZPKA} \cdot 4 \cdot Y_{SalJEKA} \]
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\[ NBMPDKA = (1 - DC_{PYPDKA}) \cdot \text{SMTH}(NBMFishKA, T_{PD}, NBM_{FishKA}) \]
\[ NBMPHKKA = Y_{ChlKA} \cdot (10^{-6}) \cdot (1500 - V_{SecKA}) \cdot (10^{9}) \cdot (30 \cdot TP_{SWKA}^{-1.4}) \]
\[ NBMPYKA = DC_{PYPDKA} \cdot \text{SMTH}(NBMFishKA, T_{PY}, NBM_{FishKA}) \]
\[ NBMZKAB = Y_{ChlKA} \cdot (10^{-6}) \cdot 810 \cdot (TP_{SWKA}^{-0.71}) \cdot \text{AreaKA} \]
\[ NBMZHRKA = Y_{ChlKA} \cdot (DCZHZP) \cdot (10^{-6}) \cdot V_{SWKA} \cdot 38 \cdot TP_{SWKA}^{-0.64} \]
\[ NBMZPKA = Y_{ChlKA} \cdot (1 - DCZHZP) \cdot (10^{-6}) \cdot V_{SWKA} \cdot 38 \cdot TP_{SWKA}^{-0.64} \]
\[ NCRJEKA = N_{JE}/T_{JE} \]
\[ NCRPD = 1/T_{PD} \]
\[ NCRPYKA = N_{PY} \cdot (NCRZPKA \cdot 0.15 + NCRPD \cdot 0.85) \]
\[ NCRZKAB = N_{ZB}/T_{ZB} \]
\[ NCRZHKKA = N_{ZH}/T_{ZH} \]
\[ NCRZPKA = 1/T_{ZP} \]
\[ N_{JE} = 2 \]
\[ NPRBAKA = 0.63 \cdot (A_{Sec/A}) \cdot PR_{PHKA} \]
\[ NPRMAKA = 0.001 \cdot \text{AreaKA} \cdot 1/52 \cdot 10^{(2.472 + 1.028 \cdot \log(MACovKA) - 0.516 \cdot 90/(90 - \text{LatKA}))} \]
\[ NPRZPKA = 0.0759 \cdot F_{PRPHKA}^{-0.84} \]
\[ N_{PY} = 2 \]
\[ N_{ZB} = 2 \]
\[ N_{ZH} = 2 \]
\[ MIGOutPDBS = \text{if } BM_{PDBS} / \text{NBM}_{PDBS} > 1 \text{ then } (R_{MigPDBS})(BM_{PDBS}) \text{ else } 0.5 \cdot (R_{MigPDBS})(BM_{PDBS}) \]
\[ MIGOutPYBS = \text{if } BM_{PYBS} / \text{NBM}_{PYBS} > 1 \text{ then } (R_{MigPYBS})(BM_{PYBS}) \text{ else } 0.5 \cdot (R_{MigPYBS})(BM_{PYBS}) \]
\[ PR_{BAKA} = BM_{BAKA}/T_{BA} \]
\[ PR_{BPKA} = BM_{BPKA}/T_{BP} \]
\[ PrimP_{KA} = \text{if } SecKA > 1 \text{ then } ((10^{-6}) \cdot ((2.13 \cdot ChlmodKA^{0.25} - 0.25) \cdot 4) \cdot (1/0.45) \cdot (1/0.2) \cdot 30.42 \cdot (1500 - V_{SecKA}) \cdot 10^{9}) \text{ else } ((10^{-6}) \cdot ((2.13 \cdot ChlmodKA^{0.25} - 0.25) \cdot 4) \cdot (1/0.45) \cdot (1/0.2) \cdot 30.42 \cdot \text{AreaKA} \cdot (2 \cdot SecKA)^{0.2}) \]
\[ PR_{JEKA} = BM_{JEKA}/T_{JE} \]
\[ PR_{MAKA} = BM_{MAKA}/T_{MA} \]
\[ R_{ProdJE} = 1 \]
\[ PR_{PD} = BM_{PD}/T_{PD} \]
\[ PR_{PH} = BM_{PH}/T_{PH} \]
\[ PR_{PY} = BM_{PY}/T_{PY} \]
\[ PR_{ZKAB} = BM_{ZKAB}/T_{ZB} \]
\[ PR_{ZHKKA} = BM_{ZHKKA}/T_{ZH} \]
\[ PR_{ZPKA} = BM_{ZPKA}/T_{ZP} \]
\[ Q_{SWSKA} = (Q_{cvSKA} + Q_{SWKAS})(-Q_{mibSKA} + Q_{precSKA} + Q_{DWBSKA}) \]
\[ Q_{SWBS} = (1055 \cdot 10^{9})/12 \]
\[ R_{JE} = \text{if } (0.1186 - 0.1338 \cdot \log(MACovKA) + 0.0769 \cdot V_{dKA}) < 0.1 \text{ then } 0.1 \text{ else (0.1186 - 0.1338 \cdot \log(MACovKA) + 0.0769 \cdot V_{dKA})} \]
\[ R_{FishKA} = (BM_{PD}/NBM_{PD}) \cdot Y_{Area ref/KA} \cdot R_{fish} \cdot 12 \]
\[ R_{Fish} = 0.1 \]
\[ R_{PBAKA} = 0.01 \]
\[ R_{Migconst} = 0.1 \]
\[ R_{MigPDBS} = R_{Migconst} \cdot Y_{SeasonKA} / T_{SWKA} \]
\[ R_{MigPHKA} = 1/T_{SWKA} \]
\[ R_{MigPYKA} = R_{MigPDBS} \]
\[ R_{MigZPKA} = 1/T_{SWKA} \]
\[ R_{PRP} = 4.35 \]
\[ RF_{BMA} = 0.025 \cdot (30.42/7) \]
Sal_{SWKA} = Modeled salinity in SW-layer in KA
Sec_{KA} = Modeled Secchi depth in KA
Sec_{LakeKA} = if (10^{(1+0.5)·(log(SPM_{SWKA})+0.3)/2+1}) > Sec_{KA} then Sec_{KA} else (10^{(1+0.5)·(log(SPM_{SWKA})+0.3)/2+1})
Sed_{AKAcmyr} = Modeled salinity in sedimentation in A-areas in KA in cm/yr
smth_{KA} = if Lat_{KA} > 63 then 1 else (63-Lat_{KA})
SPM_{SWKA} = Modeled SPM-concentration in SW-layer in KA
TBA = 4/30.42
TPSWKA = Modeled TP-concentration in SW-layer in KA
TBA = 4/30.42
TPY = 300/30.42
TBP = 2.8/30.42
TMA = 300/30.42
Vd_{KA} = Form factor in KA
Y_{SWKA} = 1067·10^{9}
Y_{Area1/B} = (10^{12}/Area_{B})^{0.5}
Y_{Area2/B} = (Area_{2SecLakeB}/Area_{B})
Y_{ChlKA} = Chl_{modKA}/Chl_{modlakeKA}
Y_{ChlZKAB} = 1/Y_{Area2SecBP}
Y_{EhKA} = if (Sed_{AKAcmyr} > 0.75 (cm/yr) then Y_{Eh1KA} = 0 else Y_{Eh1KA} = 1
Y_{Eh1KA} = if (Sed_{AKAcmyr} < 0.075 (cm/yr) then Y_{Eh1KA} = (1-1·(Sed_{AKAcmyr}/0.075-1))
else Y_{Eh1KA} = 1
Y_{fish1BS} = if Y_{fish1BS} < 0.2 then 0.2 else Y_{fish1BS}
Y_{fish1BS} = if TPSWBS < 30 then (1-2.5·(NBM_{PYTPKA}/NBM_{refPYKA}-1)
else Y_{fish1BS} = (1-0.4·(NBM_{PYTPKA}/NBM_{refPYKA}-1)
YSWTKA = SWT/9
NBM_{PYTPKA} = 10^{(-6)·((Area_{B}·590·TPSWKA)^0.71))
NBM_{refPYKA} = 10^{(-6)·((Area_{B}·590·30)^0.71))
Y_{SalSWKA} = if (Sal_{SW}/1 - 1)^{(Sal_{SW}/0.05))
else if (Y_{SeasonKA} > 0 then ((Y_{SeasonKA}+Y_{Season1KA})/(2)-(Lat_{KA}/63)
else (Y_{Season1KA}+Y_{Season1KA})/(2))-(63/Lat_{KA})
If Lat > 63°N then AV = 1 else AV = (63-Lat_{KA}); AV is an averaging function used in the smoothing function Y_{Season1KA} = SMTH(Y_{SeasonKA}, AV, 1)
Y_{SecZPKA} = if Sec_{KA} < 2 then (1+1·(Sec_{KA}/2-1)) else 1
Y_{TPKA} = (1+0.75·(TPSWKA/10-1))