SMHI

Jörgen Sahlberg

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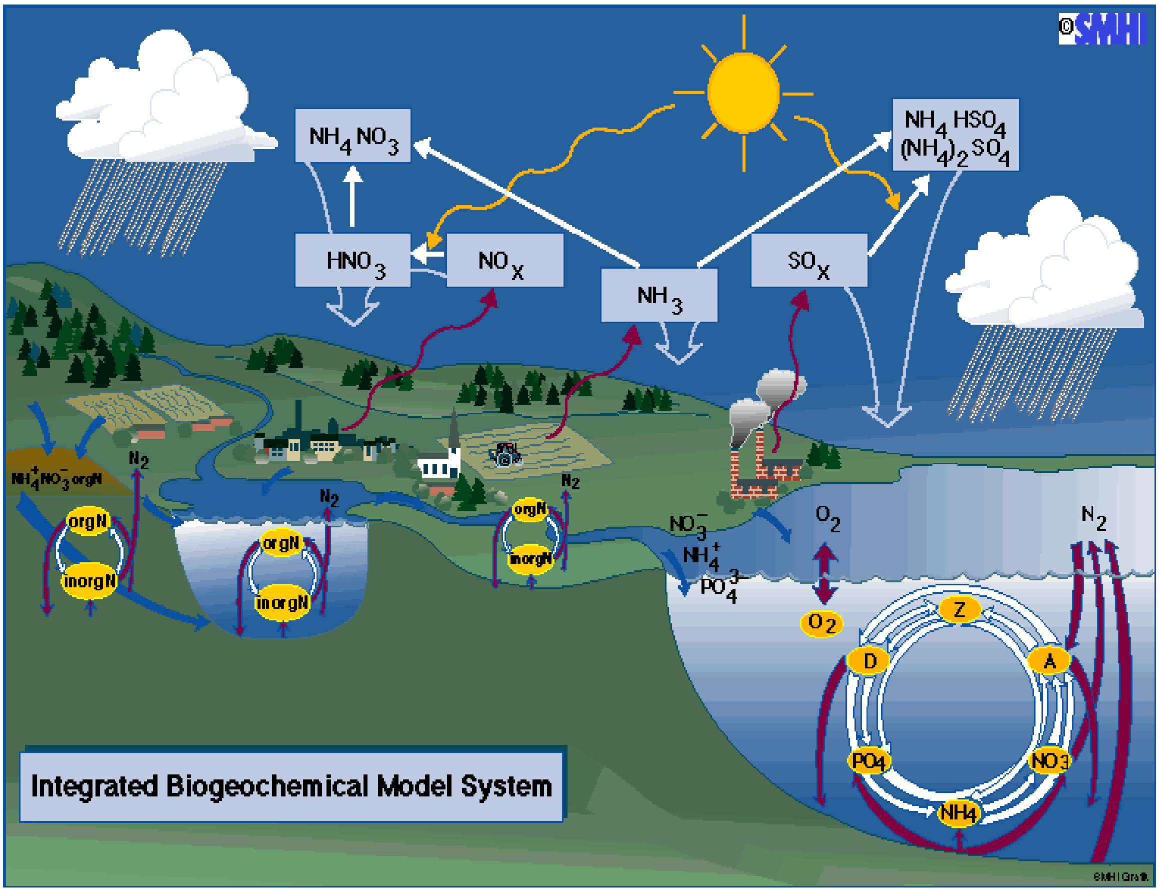
The Coastal Zone Model



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Contents

1 INTRODUCTION

SMHI has developed a model system for water quality calculations on land, in lakes and rivers and in coastal zone waters around Sweden. The system is called HOME Water where HOME stands for Hydrology, Oceanography and Meteorology for the Environment. The focus in this report is to describe the coastal zone model which is the part of the HOME Water system that calculates the state in the coastal zone along the whole Swedish coast.

The coastal zone model is a coupled 1-dimensional physical and biogeochemical model. The physical model is called the Probe model and is fully described by Svensson (1998). It calculates the horizontal velocities, temperature and salinity profiles. The surface mixing is calculated by a $k-\varepsilon$ turbulence model and the bottom mixing is a parameterization based on the stability in the bottom water. Ice formation growth and decay is also included in the model. Probe has a high vertical resolution with a vertical grid cell size of 0.5m in the top 4m. The grid cell size then increases as the depth increases. In the depth interval 4 -70m the cell size is 1.0m, from 70 – 100m it is 2m, from 100-250m it is 5m and if the depth is larger then 250m the grid cell size is 10m. This means that the model calculates the vertical profiles of all its variables and assumes that they are horizontally homogeneous in the studied area. In order to include horizontal variations in a larger area it is divided into several sub-basins. These sub-basins are identical to the defined national water bodies according to the Water Framework Directive (WFD). Each sub-basin is described by the hypsographical curve. Connecting sub-basins exchange water and properties through connecting sounds.

The biogeochemical model is called SCOBI (Swedish Coastal Ocean BIogeochemical model). In SCOBI nine variables are solved where seven are the pelagic variables: zooplankton, phytoplankton, detritus, nitrate, ammonium, phosphate and oxygen. In the bentic layer the model solves for the two variables nitrogen and phosphorus.

2 THE PHYSICAL PROBE MODEL

The Probe model reproduces the temporal variation of stratification and mixing in each sub-basin. PROBE can be classified as an “equation solver for 1-dimensional transient, or two dimensional steady, boundary layers” (Svensson, 1998). PROBE embodies a two-equation turbulence model, one equation for the turbulent kinetic energy (k) and one equation for the dissipation rate of turbulent kinetic energy (ε), and includes a simple parameterisation of deepwater mixing. This model has been used for the description the hydrography of the Baltic Sea where the Baltic and the west coast is divided into 13 sub-basins. This PROBE-Baltic model has been thoroughly tested and validated for longer time periods and includes an ice model. Omstedt & Axell (2003) describe the processes and elements of this model in detail.

The general differential equation of the PROBE solver is formally written as

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

Here ϕ is the dependent variable, *t* time, *z* vertical coordinate, *x* horizontal coordinate, *u* horizontal velocity, Γ_ϕ exchange coefficient, and S_ϕ source and sink terms. For 1-dimensional cases the advection term is not active. Vertical advection (and moving surface) is however included accounting for vertical transport in a sub-basin due to in- and outflows. Boundary conditions may be specified either by the value or by the flux of a variable. The sources and sinks determined by the ecosystem model are added to S_ϕ. Vertical advection and diffusion are excluded for the solution of benthic biogeochemical processes.

The momentum equations read:

$$\frac{\partial \rho U}{\partial t} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\rho}\frac{\partial \rho U}{\partial z}\right) + f\rho V \qquad \text{(Eq. 2)}$$

$$\frac{\partial \rho V}{\partial t} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\rho}\frac{\partial \rho V}{\partial z}\right) - f\rho U \qquad \text{(Eq. 3)}$$

where *t* is time coordinate, *x* and *y* horizontal space coordinates, *z* vertical space coordinate, *U* and *V* horizontal velocities, *p* pressure, *f* Coriolis' parameter, and ρ density. The dynamical effective viscosity, μ_{eff}, is the sum of the turbulent viscosity, μ_T, and the laminar viscosity, μ. Pressure gradients may be treated in several ways, depending on the problem considered.

The surface boundary conditions for the momentum equations are defined as:

$$\frac{\mu_{eff}}{\rho}\frac{\partial \rho U}{\partial z} = \tau_x^a \qquad \text{(Eq. 4)}$$

$$\frac{\mu_{eff}}{\rho}\frac{\partial \rho V}{\partial z} = \tau_y^a \qquad \text{(Eq. 5)}$$

where $\tau_x^a = \rho^a C_d^a U_i^a W_i^a$ and $\tau_y^a = \rho^a C_d^a V_i^a W_i^a$ are the wind stresses. Wind velocities in x- and y-direction are described by U_i^a, V_i^a and the wind vector is W_i^a. C_d is the drag coefficient and ρ^a is the air density. At the lower boundary the condition of zero velocity is used.

The dynamic eddy viscosity is calculated from the turbulent kinetic energy, k, and its dissipation rate, ε, by the Prandtl/Kolmogorov relation :

$$\mu_T = C_\mu \rho \frac{k^2}{\varepsilon} \qquad \text{(Eq. 6)}$$

where C_μ is an empirical constant.

The turbulent kinetic energy, k, is given by,

$$\frac{\partial k}{\partial t} = \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\rho\sigma_k}\frac{\partial k}{\partial z}\right) + P_s + P_b - \varepsilon \qquad \text{(Eq. 7)}$$

where σ_k is the Prandtl/Schmitt number for k. P_s and P_b are production terms due to shear velocity and buoyancy.

The dissipation rate of turbulent kinetic energy, ε , becomes

$$\frac{\partial \varepsilon}{\partial t} = \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\rho\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial z}\right) + \frac{\varepsilon}{k}\left(C_{1\varepsilon}P_s + C_{3\varepsilon}P_b - C_{2\varepsilon}\varepsilon\right) \qquad \text{(Eq. 8)}$$

where σ_ε is the Prandtl/Schmitt number for ε. $C_{1\varepsilon}$, $C_{3\varepsilon}$ and $C_{2\varepsilon}$ are empirical constants.

A full description of the derivation of all turbulence equations and empirical coefficients is found in Rodi (1980) and Svensson (1998).

The bottom water eddy diffusivity, ν_z, is commonly expressed as a function of the stability frequency N^2 (Stigebrandt, 1987; Omstedt, 1990) according to:

$$\nu_z = \alpha N^{-1} \qquad \text{(Eq. 9)}$$

where $N^2 = -\frac{g}{\rho}\frac{\partial \rho}{\partial z}$, g = acceleration of gravity, ρ =water density. Typical values for α is (1-2) x 10^{-7} (Gargett, 1984; Stigebrandt, 1987; Axell, 1998).

Heat equation :

$$\frac{\partial(\rho c_p T)}{\partial t} + W\frac{\partial(\rho c_p T)}{\partial z} = \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\rho\sigma_{eff}}\frac{\partial(\rho c_p T)}{\partial z}\right) + F_{sun}$$

(Eq. 10)

$$F_{sun} = F_s^w (1-\eta) e^{-\beta(D-z)}$$

where T is the water temperature, c_p is the specific heat of water, σ_{eff} effective Prandtl number which is the sum of the laminar and turbulent Prandtl numbers, F_{sun} is a source term due to insolation, F_s^w is that part of the total insolation that penetrates the water surface, η is the fraction of F_s^w absorbed in the upper centimetre close to the water surface, β is an extinction coefficient and D the total water depth (note that the z axel starts at the bottom pointing upwards). If the water is ice covered the short wave radiation that penetrates the water surface is strongly reduced. Equations describing the penetration of short wave radiation through an ice-snow cover are given by Sahlberg (1988).

For the heat equation the surface boundary condition may be formulated as :

$$\frac{\mu_{eff}}{\rho\sigma_{eff}}\frac{\partial\rho c_p T}{\partial z} = F_n \qquad \text{(Eq. 11)}$$

where F_n is the net heat exchange through the water surface. It consists of the sum of four different heat fluxes

$$F_n = F_h + F_e + F_{nl} + \eta F_s^w \qquad \text{(Eq. 12)}$$

where F_h , F_e , F_{nl} are the sensible and latent heat fluxes and net longwave radiation respectively and η is the part of the short wave radiation that is absorbed at the surface. The parameterisation of these fluxes including F_s^w follows from Omstedt & Axell (2003). At the lower boundary a zero flux condition is used, i.e. no sediment heat flux.

In the coastal zone model the water exchange between two sub-basins inside the coastal zone or between a coastal zone sub-basin and the outer sea is described in two different ways.

First the water exchange between two sub-basins within the coastal zone follows from Stigebrandt (1990) where the water exchange is controlled by the sum of the barotropic and baroclinic pressure gradients according to

$$Q = \int_0^H B(z)\sqrt{2\alpha(\Delta P_i - \Delta P_s)/\rho_0}\,dz \qquad \text{(Eq.13)}$$

Q is the water flux (m^3s^{-1}), H is the sill depth of the connecting sound (m), B is the width of the sound (m), α is put constant to 0.4, ΔP_i and ΔP_s are the baroclinic and barotropic pressure differences over the sound (Nm^{-2}) and ρ_0 is the water density (kgm^{-3}).

The baroclinic pressure gradient comes from the density difference between the sub-basins calculated from the surface down to the connecting sill depth, see figure 1.

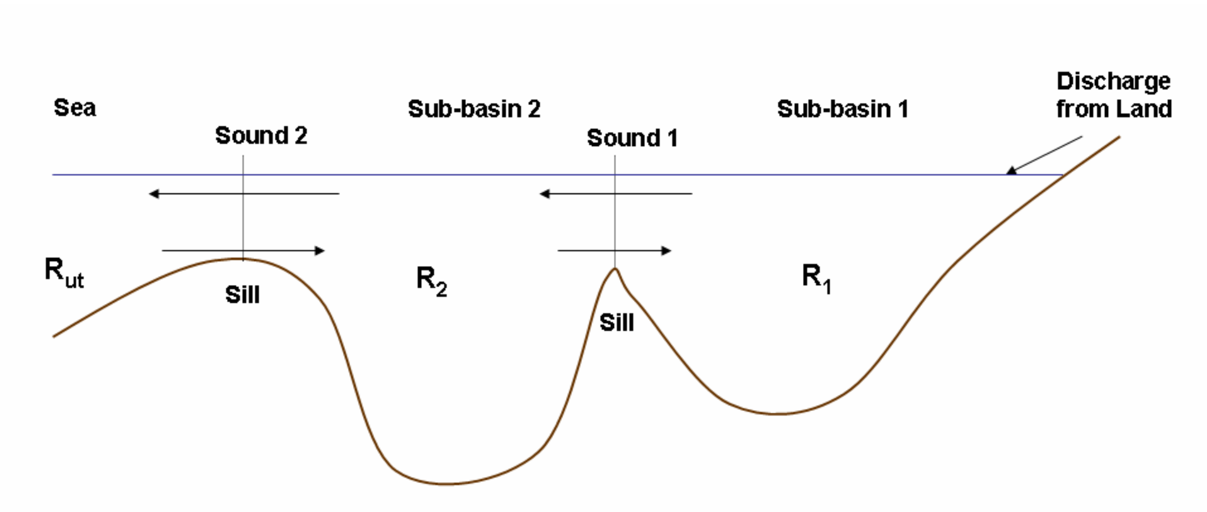


Figure 1. The figure shows the typical water exchange between two sub-basins where sub-basin 1 has a river discharge from land and sub-basin 2 is connected to the sea.

The water density in sub-basin 1, R_1 , is smaller then the water density R_2 in sub-basin 2 and thus there is an outflow at the surface from sub-basin 1 to sub-basin 2 and a deeper inflow to sub-basin1 from sub-basin2. The net flow over the connecting sound 1 will be the same as the river discharge from land in order to preserve the mass continuity.

Inflowing water to one sub-basin seeks there its density level without any entrainment. Heavy surface water in one sub-basin may thus reach the bottom level in the other sub-basin.

In the coastal zone model the barotropic part is excluded from the calculation which means that no water level variation exists in the model. Several tests with the coastal zone model have shown that on the longer time scales (months) it is the baroclinic part that dominates the water exchange between different sub-basins. The reason for excluding the barotropic part is the possibility to use a longer time step when calculating the horizontal water exchange. This will reduce the calculation time.

Second the water exchange over the boundary between the coastal zone and the sea is taken from Omstedt & Axell (2003). Normally this boundary is open with a width greater the internal Rossby radius and the flow is assumed to be in geostrophic balance. The formulation reads

$$Q = \frac{g\beta\Delta SH^2}{2f} \qquad \text{(Eq.14)}$$

Where β is the salinity contraction coefficient, equal to 8 $*10^{-4}$, ΔS is the salinity difference between the deep water and the surface layer and f is the coriolis parameter.

There is also a possibility to include the effect of upwelling or downwelling. This may only be done in those sub-basins that have their boundary towards the sea outside the coastal zone. The effect of upwelling or downwelling t is caused by the wind and if it will be up- or downwelling depends on the wind direction. The wind driven water velocity is a function of depth and is parameterized in the following way,

$$Q_{wind}(z) = u(z) - U \qquad \text{(Eq.15)}$$

where

$$U = \frac{1}{H}\int_0^H u(z)dz \qquad \text{(Eq. 16)}$$

where u(z) is the calculated water velocity, H the water depth and U the calculated mean water velocity. Note that this formulation of the wind driven transport leads to a zero net transport over the boundary.

2.1 The ice model

Ice cover has a great impact on the insolation, heat and momentum exchange between water and atmosphere. In the coastal zone model ice is formed when the temperature of the upper centimetres drops below the freezing point. Then both the momentum transport from the atmosphere to the water surface is cut off together with the heat exchange between water and atmosphere. The heat equation boundary condition is changed from a flux condition to a value condition where the value of the water temperature at the ice-water interface is put to the freezing point which depends on the water salinity.

The initial ice formation can be rather complex with many ice formations and break up events depending on the strength of the heat loss and the wind stress at the surface. This is parameterized in the following simple way (Sahlberg, 1988). If the ice thickness is less the 0.1m and the daily mean value of the wind velocity is greater then 4 ms^{-1}, the ice cover will break up and disappear. When the ice grows thicker then 0.1m the growth continues until the spring melting starts.

The ice growth is calculated using a degree day method,

$$h_{ice} = K_g(\sum \overline{T}_a)^{1/2} \qquad \text{if } \overline{T}_a < 0 \qquad \text{(Eq.17)}$$

where h_{ice} is the ice thickness, K_g a constant with the value 0.024 and $\overline{T}_a$ is the daily mean air temperature. The air temperature summation starts at the ice formation date.

The ice melting formulation is taken from Ashton (1983), where the daily decreasing ice thickness is a linear function of $\overline{T}_a$,

$$\Delta h_{ice} = K_m \overline{T}_a \qquad \text{if } \overline{T}_a > 0 \qquad \text{(Eq.18)}$$

where K_m is put constant to 5.3*10^{-3}.

The snow thickness on the ice is assumed to vary with the ice thickness. During ice growth $h_{snow} = 0.20 * h_{ice}$ and during ice melting $h_{snow} = 0.05 * h_{ice}$.

3 THE BIOGEOCHEMICAL SCOBI MODEL

The Swedish Coastal and Ocean Biogeochemical model, SCOBI (Figure 2) is a process-oriented model that includes marine nitrogen, phosphorous and oxygen dynamics. This report will give a short description of the SCOBI model. For the full description of the first version of SCOBI see Marmefelt et al. (2000) and for the latest model version see Eilola et al. (2009).

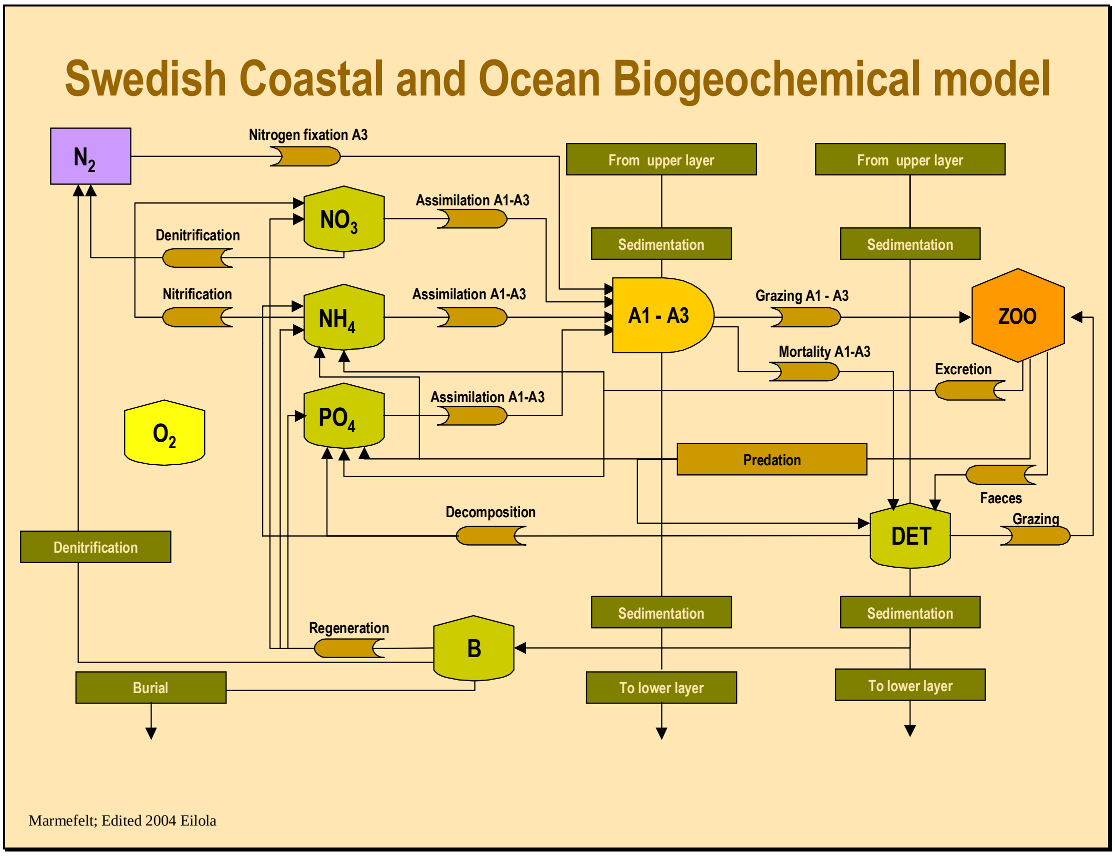


Figure2. The components of the SCOBI model.

In its basic form SCOBI contains 7 pelagic variables, nitrate (NO_3), ammonium (NH_4), phosphate (PO_4), autotrophs (A), zooplankton (ZOO), detritus (DET), and oxygen (O_2). The sediment module (B) in the model includes aggregated process descriptions for nutrient regeneration, denitrification and permanent burial of organic matter. The module contains nutrients in the form of benthic nitrogen (NBT) and phosphorus (PBT) which are comparable to available observations of sediment concentrations.

The vertical light attenuation (Kd), computed by the model, depends on a background attenuation and attenuation due to varying concentrations of phytoplankton. Carbon (C) is used as the constituent representing detritus and zooplankton. Phytoplankton is represented by chlorophyll (Chl) according to a constant carbon to chlorophyll ratio

C:Chl. Nitrogen (N) and phosphorus (P) content of phytoplankton, zooplankton and detritus are obtained from a constant C:N:P ratio, the so called Redfield ratio.

The source terms in equation 1 (Eq.1) for each variable and for each discrete depth layer are described by the equations below. Conversion factors between units are left out for simplicity and clarity. Note that pelagic concentrations are given per unit water volume while the benthic concentrations are given per unit bottom area. The process descriptions of the SCOBI model are mainly taken from ecological models presented in the literature.

Source term for phytoplankton:

$$S_{PHY} = GROWTH_{PHY} + SINKI_{PHY} - SINKO_{PHY} - MORT_{PHY} - GRAZE_{PHY} \qquad \text{(Eq.19)}$$

PHY denotes autotrophs (A). GROWTH is growth of the phytoplankton population with an uptake of inorganic nutrients following the so-called Redfield ratio. SINKI is the influx of sinking phytoplankton from the layer above. SINKO is the outflow of sinking phytoplankton to the sediments and to the layer below. MORT is phytoplankton mortality and GRAZE is grazing by zooplankton.

Source term for zooplankton:

$$S_{ZOO} = GROWTH_{ZOO} - EXCR_{ZOO} - FECAL_{ZOO} - PRED_{ZOO} \qquad \text{(Eq.20)}$$

ZOO denotes zooplankton. GROWTH is the sum of grazing from the pools of detritus and phytoplankton. A fraction EXCR of assimilated food is excreted as inorganic nutrients (ammonium and phosphate) and another fraction FECAL is lost to faeces (detritus). PRED is a closure term representing the predation on zooplankton by higher predators. A fraction (Ω) of PRED becomes detritus and the rest is decomposed and mineralized to inorganic nutrients (ammonium and phosphate).

$$S_{DET} = SINKI_{DET} + MORT_{PHY} + FECAL_{ZOO} + \Omega \cdot PRED_{ZOO} - GRAZE_{DET} - SINKO_{DET} - DCOMP_{DET}$$

(Eq.21)

DET denotes detritus. SINKI is the influx of sinking detritus from the layer above. SINKO is the outflow of sinking detritus to the sediments and to the layer below. MORT is the sum mortality of phytoplankton. FECAL are fecal pellets from zooplankton grazing of phytoplankton. GRAZE is grazing by zooplankton and Ω ·PRED is the fraction of predation that becomes detritus. DCOMP is decomposition and mineralisation of pelagic detritus to inorganic nutrients (ammonium and phosphate.

Source term for phosphate:

$$S_{PO_4} = EXCR_{ZOO} + (1-\Omega) \cdot PRED_{ZOO} + DCOMP_{DET} + \Psi \cdot SEDOUT_{PO_4} - UPTAKE_{PO_4}$$

(Eq.22)

PO_4 denotes inorganic dissolved phosphate. EXCR is excretion from zooplankton,

(1 - Ω) · PRED is the fraction of predation that becomes phosphate. DCOMP is mineralisation of pelagic detritus.Ψ is the ratio between bottom area and water volume. SEDOUT is flux of phosphate from sediments. UPTAKE is the sum of phosphate uptake by the growth of phytoplankton.

Source term for ammonium:

$$S_{NH_4} = EXCR_{ZOO} + (1-\Omega)\cdot PRED_{ZOO} + DCOMP_{DET} + \Psi \cdot SEDOUT_{NH_4} - UPTAKE_{NH_4} - NITFIC_{NH_4}$$

(Eq.23)

NH_4 denotes inorganic dissolved ammonium. EXCR is excretion from zooplankton,

(1 - Ω) · PRED is the fraction of predation that becomes ammonium. DCOMP is mineralization of pelagic detritus. Ψ is the ratio between bottom area and water volume. SEDOUT is flux of ammonium from sediments. UPTAKE is the sum of ammonium uptake by the growth of phytoplankton. NITFIC is pelagic oxidation of ammonium to nitrate (nitrification).

Source term for nitrate:

$$S_{NO_3} = \Psi \cdot SEDOUT_{NO_3} + NITFIC_{NH_4} - UPTAKE_{NO_3} - DENIT_{NO_3} \qquad \text{(Eq.24)}$$

NO_3 denotes inorganic dissolved nitrate.Ψ is the ratio between bottom area and water volume. SEDOUT is flux of nitrate from sediments. NITFIC is pelagic oxidation of ammonium to nitrate (nitrification). UPTAKE is the sum of nitrate uptake by the growth of phytoplankton. DENIT is pelagic denitrification of nitrate to molecular nitrogen.

Source term for Oxygen:

$$S_{O_2} = PROD_{O_2} + DENIT_{NO_3} - DCOMP_{DET} - EXCR_{ZOO} - (1-\Omega)\cdot PRED_{ZOO} - \Psi \cdot RSED_{\Sigma N} - NITFIC_{NH_4}$$

(Eq.25)

O_2 denotes dissolved oxygen. PROD is the sum of oxygen production by the growth of phytoplankton. DCOMP is oxygen consumption due to oxidation of decomposed pelagic detritus. DENIT is reimbursement of oxygen due to anaerobic decomposition of detritus by pelagic denitrification. EXCR is oxygen consumption due to zooplankton respiration. (1-Ω) · PRED is oxygen consumption due to predator respiration. Ψ is the ratio between bottom area and water volume. RSED is oxygen consumption due to the oxygen demand by both the decomposition of benthic detritus and benthic nitrification. NITFIC is oxygen consumption due to pelagic nitrification.

Source term for benthic phosphorus:

$$S_{PBT} = SINKI_{PHY} + SINKI_{DET} - SEDOUT_{PO4} - BURIAL_{PBT} \qquad \text{(Eq.26)}$$

PBT denotes concentration of labile benthic phosphorus per unit bottom area in the upper “active” sediment layer. $SINKI_{PHY}$ and $SINKI_{DET}$ are the fluxes to the sediment of sinking phytoplankton and detritus per unit bottom area. SEDOUT is a redox dependent flux of phosphate from the sediments. BURIAL is permanent burial of phosphorus in layers below the active upper sediment layer.

Source term for benthic nitrogen:

$$S_{NBT} = SINKI_{PHY} + SINKI_{DET} - SEDOUT_{NO3} - SEDOUT_{NH4} - DENIT_{NBT} - SEQN_{NBT} - BURIAL_{NBT} \quad \text{(Eq.27)}$$

NBT denotes labile benthic nitrogen concentration per unit bottom area in the upper “active” sediment layer. $SINKI_{PHY}$ and $SINKI_{DET}$ are the fluxes to the sediment of sinking phytoplankton and detritus per unit bottom area. $SEDOUT_{NO3}$ and $SEDOUT_{NH4}$ are redox dependent fluxes of nitrate and ammonium from the sediments. *DENIT* is benthic denitrification of nitrate to molecular nitrogen. *SEQN* is redox dependent permanent removal of nitrogen due to adsorption of ammonium to sediment particles. *BURIAL* is permanent burial of nitrogen in layers below the active upper sediment layer.

Light attenuation:

$$Kd=Kd_w+Kd_{phy} \quad \text{(Eq.28)}$$

Kd denotes the total light attenuation coefficient. Kd_w is the background light attenuation due to attenuation by water, humic substances and suspended particles. Kd_{phy} depends on the concentration of autotrophs hence accounting for the effects of self-shading into algal growth.

4 BOUNDARY CONDITIONS

4.1 From the atmosphere

The meteorological forcing data, air temperature, wind velocity, cloud cover, relative humidity and precipitation, are extracted from a database at the SMHI. It contains data from the meteorological synoptic network interpolated into a regular grid of 1x1 degree horizontal and 3 hour time resolution, figure 3. The PROBE model computes the momentum transport (Eq.4 and 5), the solar radiation and the heat exchange with the atmosphere (Eq.10 and 11).

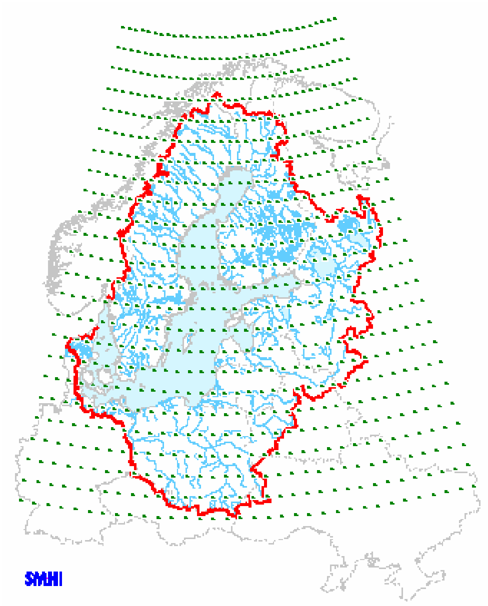


Figure 3. The meteorological database covers the total discharge area of the Baltic Sea, Skagerrak and Kattegat.

Atmospheric deposition of nitrate and ammonium was calculated by the MATCH model, Robertsson & Lagner(1999) and stored in 20x20km squares as monthly mean values. The deposition data used was from the three year period 2001-2003. The atmospheric flux enters as the boundary condition to the variables nitrate and ammonium in the SCOBI model. Since the model perform calculations over the period 1990-2008 it is necessary to extrapolate the deposition data to the whole calculation period. Based on the three years of MATCH data yearly mean deposition values were calculated. Assume that the main deposition occurs during periods with precipitation these yearly mean values are distributed over the different years and months based on weights calculated from monthly precipitation during each year.

There is also a small amount of phosphorus deposition from the atmosphere. The coastal zone model uses a constant value of 0.5kg/m^2/month according to Areskoug(1993) as the boundary condition to the phosphorus equation.

For the oxygen equation there is a flux boundary condition at the air-water interface

$$\frac{\mu_{eff}}{\rho}\frac{\partial O_2}{\partial z} = V_{O_2}(O_2 - O_{2sur}(1 + c_{bu})) \qquad \text{(Eq.29)}$$

Here, O_{2sur} is the saturation oxygen concentration at the surface, which depends on temperature and salinity (Weiss 1970). Stigebrandt (1991) introduced the factor c_{bu} in order to take into account the effects of air bubbles in the surface water. He estimated the value of the “bubble factor” to be c_{bu}=0.025. V_{O_2} is an exchange velocity dependent on wind speed and can be written

$$V_{O_2} = \frac{5.9}{\sqrt{Sc}}(aW + b) \quad \text{(Eq.30)}$$

Here, *Sc* is a temperature dependent Schmidt number for oxygen, *W* is the wind speed and *a* and *b* are empirical constants depending on wind speed, Stigebrandt (1991).

4.2 From the land

One part of the nutrient transport to the coastal zone comes from land. In the HOME Water system the land transport of water and nutrients are calculated by the hydrological HBV-NP model (Andersson et al, 2005). In the HOME Water system the HBV-NP model calculates all discharge from land on daily bases and stores the result on separate data files, one data file for each coastal sub-basin. The nutrient data produced in the HBV-NP model are in the form of organic and inorganic nutrients. The total transport of nutrients from land depends mainly on the size of the water discharge since the nutrient transport is the water discharge multiplied by the nutrient concentration and the water discharge varies much more then the nutrient concentrations over the year. The water calibration in the HBV-NP model is therefore of outmost importance.

In the coastal zone model the calculated transport data enters the upper 1m layer in the coastal sub-basins. Besides these land discharges there are point sources such as industries and sewage plants with discharges directly into the coastal sub-basins. These point sources are also taken into account in the coastal zone model where the discharge depth may be arbitrary.

During the year 2009 tests have been made to introduce the new hydrological model HYPE into the HOME Water system. These tests will continue together with further development of HYPE during the year 2010. The purpose is to replace HBV-NP with HYPE in the near future.

4.3 From the sea

The conditions in the coastal zone are strongly dependent on the conditions in the open sea outside the coastal zone as the transport over the boundary between the coastal zone and the sea is large (Eq.14). Normal values of ΔS and mixing depth H along the Swedish coast lead to boundary water transports between $10^3 – 10^5$ m^3/s which are normally much higher then the water transports from land. But as was mentioned before it is not only the water transport that controls the conditions in the coastal zone but also the transported nutrient concentrations which are normally higher in the land transport compared to the concentrations in the sea transport to the coastal zone.

The water exchange between the boundary sub-basins and the sea transports heat, salinity for the PROBE model and all seven pelagic variables for the SCOBI model. Thus to get reliable model results in the coastal zone area it is important to know the physical and biochemical conditions in the sea. If only measured data should be used to describe these conditions there would be a lack of information on zooplankton, phytoplankton and detritus as phytoplankton is seldom measured and zooplankton and detritus are never measured. Another disadvantage in using measured data is that the measured conditions would be the same for a whole month, as the measuring frequency is one month in the Swedish national environmental surveillance program for the sea, figure 4.

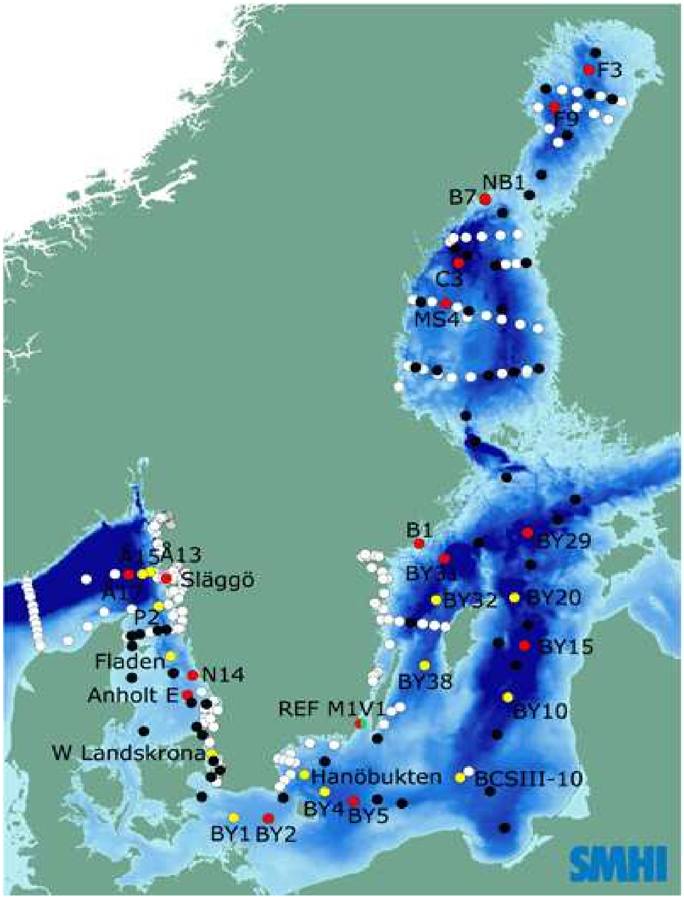
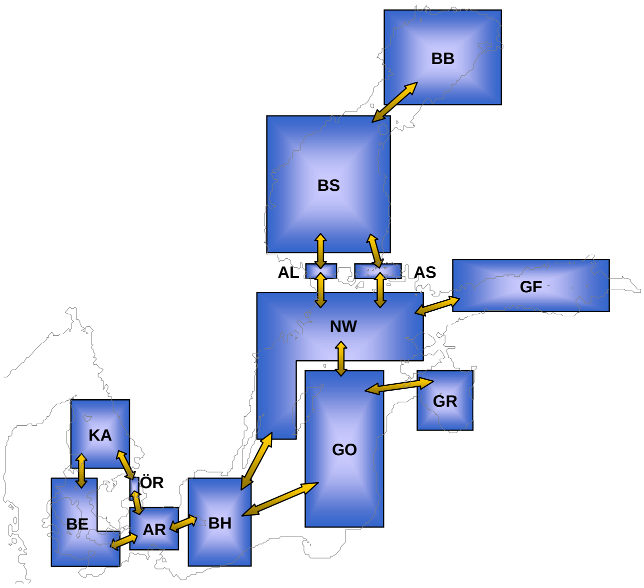


Figure 4. Measuring stations included in the different measuring programs are marked with coloured dots. Red dots mark the national environmental surveillance program(frequency once a month), yellow dots a SMHI program(frequency once a month) and black dots a SMHI winter program(frequency once a year). The white dots are stations which have been closed down.

To solve this problem the Probe-Baltic model is coupled to the SCOBI model and applied to the Baltic Sea and the West coast in thirteen sub-basins, see figure 5.



Figur 5. Schematic picture over the 13 PROBE-Baltic sub-basins.

As the Probe-Baltic / SCOBI model is also a 1-dimensional model, with the same equation solver as the coastal zone model, it calculates horizontal mean values with high vertical resolution in each sub-basin. These values represent the physical and biogeochemical condition in the central part of each sub-basin. But this condition is probably not representative for the water close to the coastal zone boundary as there exist horizontal gradients towards the coast. In order to improve the calculations the model is used with data assimilation of selected measuring stations in the sea close to the coastal zone boundary. The coupled Probe-Baltic / SCOBI model calculated all the nine necessary variables for the different sea areas along the Swedish coast during the whole period 1990-2008. Those data were stored on data files, with a time resolution of one day, and used as the sea boundary condition to the coastal zone model.

5 CALCULATION DETAILS

The Swedish coast is divided into 8 different coastal areas where the coastal zone model (and the HOME Water system) is applied. These eight areas follows the Swedish water districts except for the southern Baltic Proper district which is divided according to the WFD responsibilities of the County Board. Their names and the number of sub-basin in each area are, the Bothnian Bay 108 sub-basins, the Bothnian Sea 62 sub-basins, the northern Baltic Sea 153 sub-basins, the Östergötland coast 45 sub-basins, the Småland coast 54 sub-basins, the Gotland coast 21 sub-basins, the Skåne-Blekinge coast 47 sub-basins and finally the West coast has 122 sub-basins, figure 6.

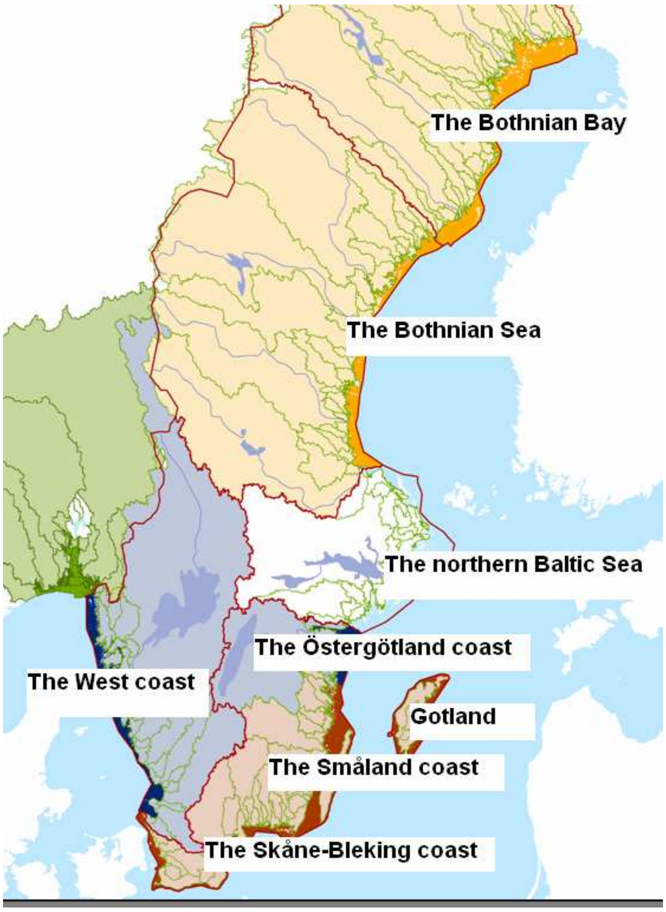


Figure 6. The Swedish coast is divided into 8 different areas where the coastal zone model is applied.

The coastal zone model, together with the HOME Water system, runs on a normal PC with a typical calculation time, of a 100 sub-basin system, is 2-3 hours. The model is rather easy to export to a new coastal zone area as it uses all area specific descriptions as input data files. The time step of the Probe model is 10 minutes while the SCOBI variables and the horizontal water fluxes are calculated once every hour. The normal calculation period should cover the length of 15-20 years. Today the period used is between the years 1990-2006. The reason for using such a long period is that the nitrogen and phosphorus exchange between the water and the sediments have to adjust towards the state of equilibrium. As there are no measurements of the amount of nitrogen and phosphorus in the sediments the initial state of these variables is not known and has to be calculated through several long time calculations where the final result from one calculation is saved as the initial state to the next. These calculations were carried out until there was no drift, on the long time scale, in the amount of nitrogen and phosphorus in the sediment which indicate that the state of equilibrium is reached. At this point the data is saved and used as the final initial condition.

6 EXAMPLE : THE COAST OF SMÅLAND

This chapter illustrates some model results from the coast of Småland which is situated in the south eastern part of Sweden. The coastal zone model set up of Småland is divided into 54 sub-basins, Figure 7. All sub-basin names and connections through sounds to neighbouring sub-basins are shown schematically in Figure 8. The 1-dimensional Probe-SCOBI model is applied to each sub-basin and all variables are calculated in every sub-basin at the same time step. The calculation period is from the year 1990 to 2006.

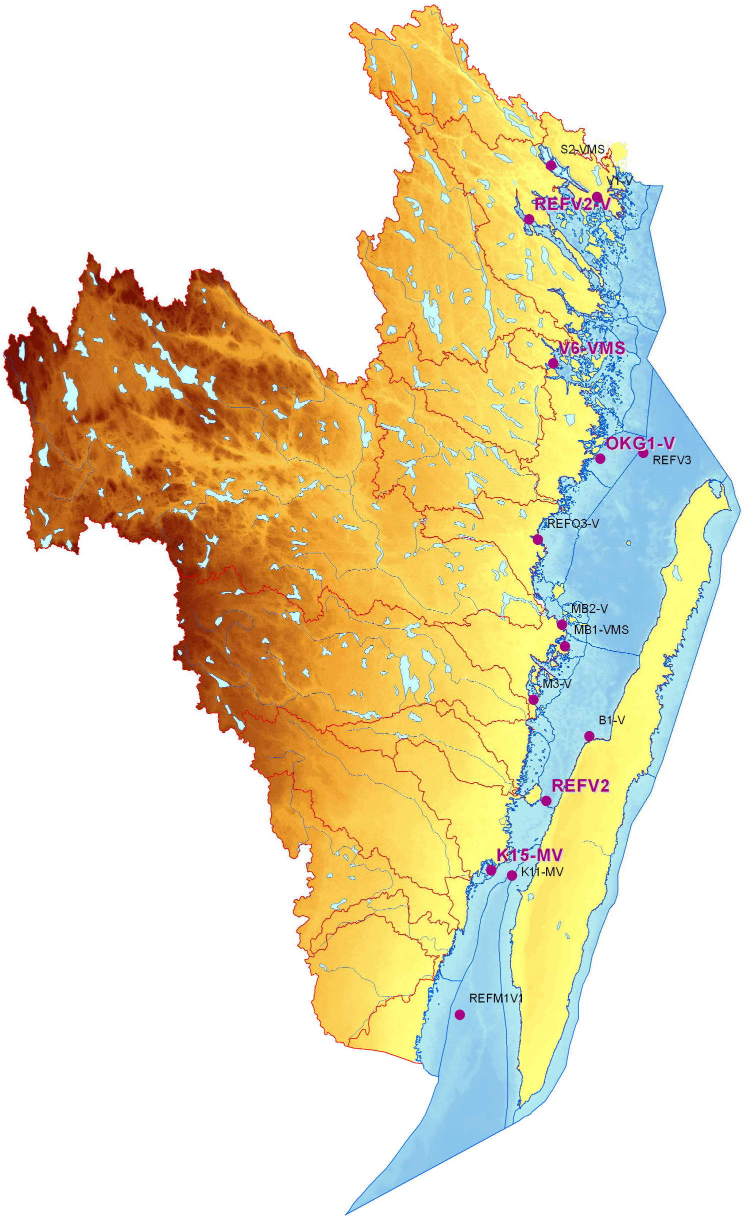


Figure 7. The map shows the coast of Småland and its division into 54 different sub-basins together with the discharge area. The coloured dots are measuring stations use for verification of the model results.

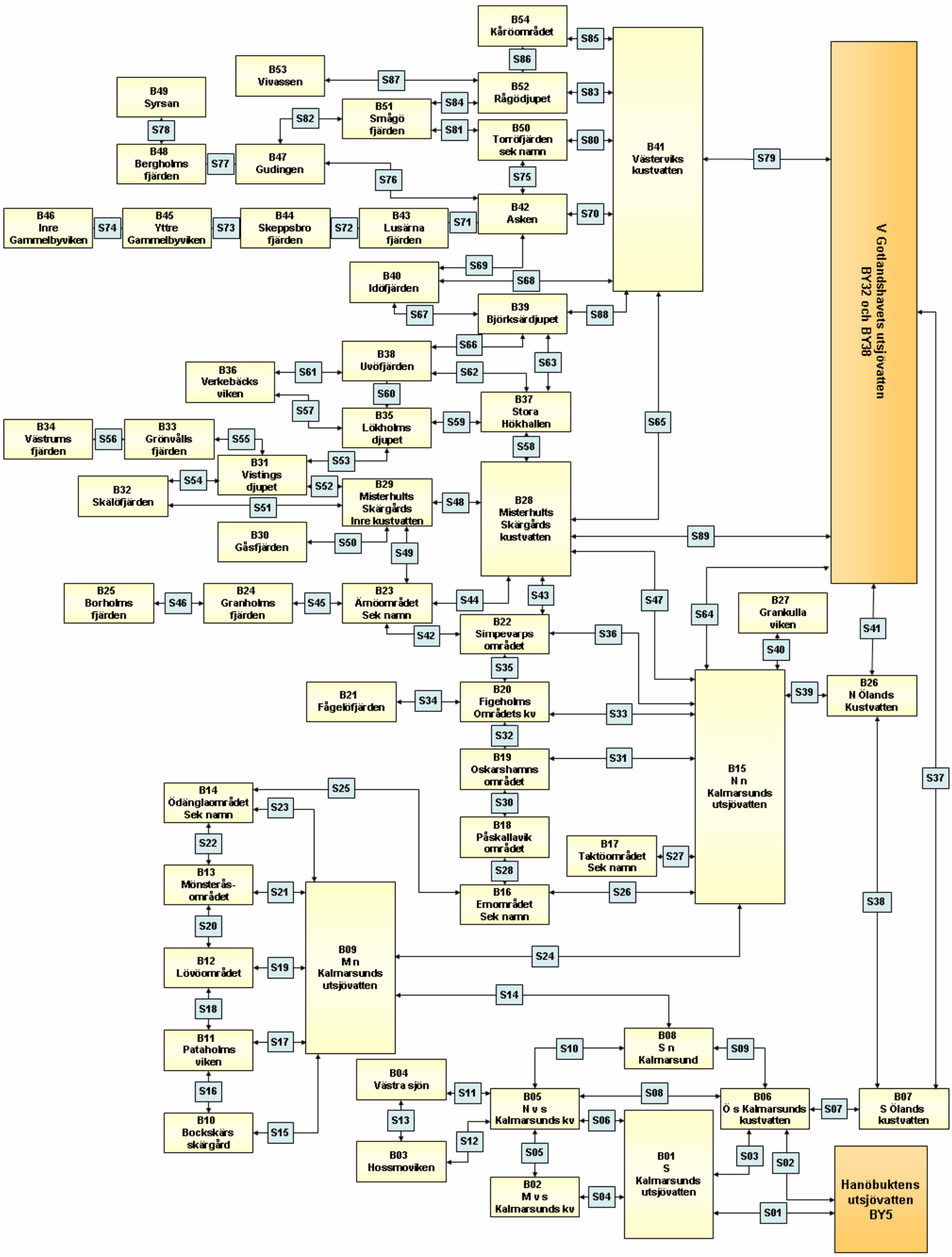


Figure 8. A schematic description of the coastal zone model along the Småland coast

One difficulty in the validation of a 1-dim model is that the model results, which are horizontally homogeneous in a sub-basin, are compared to measured data from a single station in the area. This may not be a problem if the measuring station is placed in the central part of the sub-basin. But normally this is not the case. The measuring stations along the Swedish coast are however often placed in the vicinity of a point source outlet, a river outlet or at a sill between two sub-basin and thus do not describe the mean conditions horizontally.

The model results from the two sub-basins Västra Sjön, in the southern part, and Inre Gamlebyviken, in the northern part of the coast of Småland, will be compared to measured data from station K15-MV and RefV2-V respectively. The two stations are marked in the map in Figure 7. The data to be compared are salinity, temperature, oxygen, nitrate, phosphate and phytoplankton during the whole calculation period 1990-2005, see Figures 9 and 10.

Västra sjön. This sub-basin surface area is 7km^2 with a maximum depth of 6m.The mean discharge from land is only 0.24 m^3/s. Towards the sea the boundary is open without any significant sill that could reduce the horizontal water exchange. With a small discharge from land and an open boundary towards the open sea the state in the sub-basin Västra Sjön will probably be more affected from the open sea than from the land discharge.

The calculated and measured results from the surface and bottom water are presented in Figure 9. The measured salinity show larger variations both at the surface and at the bottom compared to the calculated salinity.

The calculated oxygen condition is normally in good agreement with measurements in the surface water. As Västra Sjön is a shallow sub-basin there are only small differences between the surface and bottom water and thus the measured bottom oxygen is well described in the model.

For nitrate and phytoplankton the agreement is good between calculations and measurements in both surface and bottom water. For phosphate however the measurements show a larger variation compared to the model calculations.

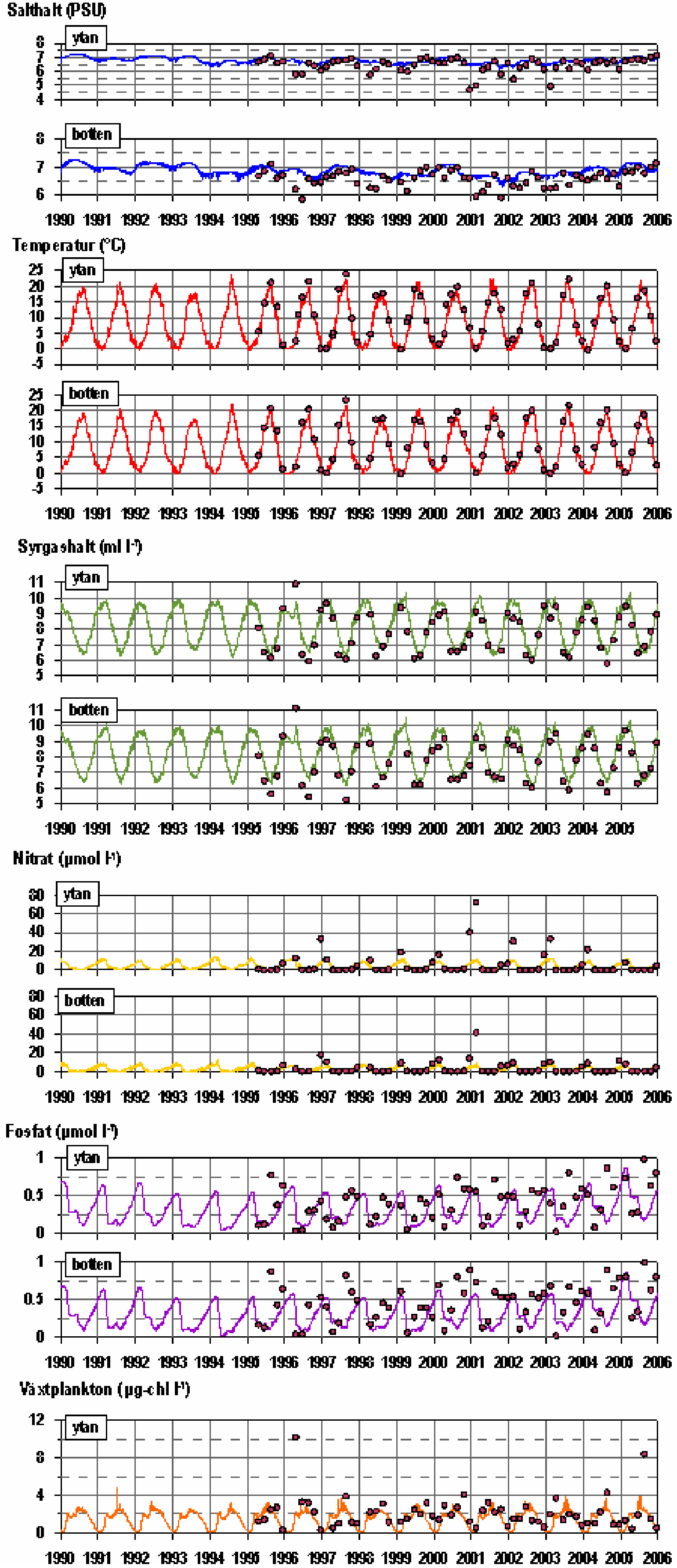


Figure 9.A comparison between calculations and measurements in the sub-basin Västra Sjön.

Inre Gamlebyviken (Figure 10)**.** This sub-basin surface area is 9.3km^2 with a maximum depth of 57m.The mean discharge from land is 1.3m^3/s. The sub-basin is the inner part of a long and narrow bay. It is connected to the sub-basin Yttre Gamlebyviken through a sill with a depth of 5m. Yttre Gamlebyviken is connected to Skeppsbrofjärden through a sound with a sill depth of 10m and Skeppsbrofjärden is connected to Lusärnafjärden through a sound with sill depth of 7m, see Figure 8. This means that the state of the Inre Gamlebyviken will probably be more affected from the land discharge than the open sea water which has a long way through several other sub-basins before it reaches Inre Gamlebyviken.

The measuring station Ref-V2V is situated where the depth is 50m and is therefore assumed to be representative for the whole sub-basin.

The calculated and measured results from the surface and bottom water are presented in Figure 10.

The calculated salinity varies in the same way as the measurements although it is a little to high in both surface and bottom water. The water temperature and oxygen conditions are well described in both surface and bottom water. Calculated nitrate and phosphate values are most of the time in good agreement with the measurements. Deviations occur for nitrate in the surface water during three winters and for phosphate in the bottom water during two winters. The calculated concentration of phytoplankton is lower than measured concentration. Normally the maximum calculated concentration is around 4 mg chl/m^3 while the measured maximum concentration often varies between 4 – 10 mg chl/m^3 with some values even over 20 mg chl/m^3.

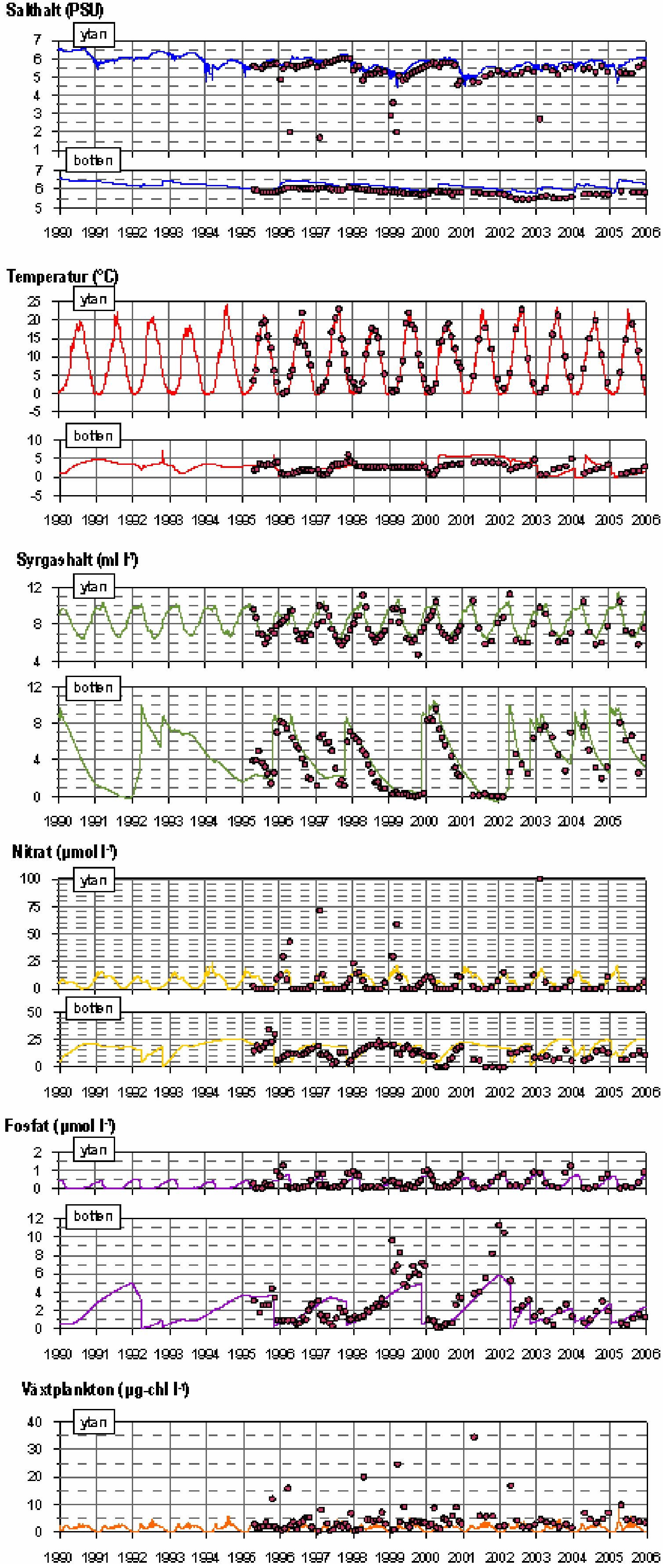


Figure 10. The comparison between calculations and measurements in the basin Inre Gamlebyviken.

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