A dynamic compartment model to predict sedimentation and suspended particulate matter in coastal areas

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Abstract

This paper presents a new dynamic mass-balance model for suspended particulate matter (SPM) and sedimentation in coastal areas handling all important fluxes of SPM to, from and within coastal areas, as such areas can be defined according to the topographical bottleneck method. The model is based on ordinary differential equations and the calculation time (di) is one month to reflect seasonal variations. An important demand, related to the practical utility of the model, is that it should be driven by variables readily accessed from standard monitoring programs or maps. Added to the dynamic core model are several (static) empirical regressions for standard operational effect variables used in coastal management, such as the Secchi depth, the oxygen saturation in the deep water, and chlorophyll-a concentrations. The obligatory driving variables include four morphometric parameters (coastal area, section area, mean and maximum depth), latitude (to predict surface water and deep water temperatures, stratification and mixing) and Secchi depth or SPM-concentrations in the sea outside the given coastal area. The model is based on four compartments: two water compartments (surface water and deep water; the separation between these two compartments is done not in the traditional manner from temperatures but from sedimentological criteria, as the water depth separating transport areas from accumulation areas) and two sediment compartments (ET-areas, i.e., erosion and transportation areas where fine sediments are discontinuously being deposited, and A-areas, i.e., accumulation areas where fine sediments are continuously being deposited). The processes accounted for include inflow and outflow via surface and deep water, input from point sources, from primary production, from land uplift, sedimentation, burial (the transport of matter from surficial A-sediments to underlying sediments), resuspension, mixing and mineralization. The model has been validated with good results (the predictions of sedimentation are within the 95% confidence limits of the empirical data used to validate the model) against data collected by sediment traps placed in 17 Baltic coastal areas of different character. The paper also presents sensitivity and uncertainty tests of the model. The weakest part of the model concerns the sub-model to predict the ET-areas. Many of the structures in the model are general and have also been used with similar success for other types of aquatic systems (mainly lakes) and for other substances (mainly phosphorus, radionuclides and metals). We also present approaches to indicate how the model could be modified for coastal areas other than those included in this study, e.g., for open coasts, estuaries or areas influenced by tidal variations.

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1. Introduction and aim

This work presents a dynamic model to predict sedimentation (deposition in g dw/m² month or cm per year; g dw = gram dry weight). This is the first model
for sedimentation in coastal areas that meet the criteria for practically useful predictive models discussed by Håkanson and Peters (1995):

1. Such models should predict important target variables for water management and science. Sedimentation certainly meets this requirement since sedimentation must be known to calculate burial, i.e., the flux of matter, nutrients, metals, radionuclides or organic toxins from the biosphere to the geosphere. Sedimentation must also be known to calculate the age of sediments and hence also historical and time-related aspects of sediment contamination. Sedimentation also regulates the oxygen concentration/saturation, which in turn influences the survival of zoobenthos, a key functional group, which in turn is of paramount importance as food for fish, etc.

2. Such models should also yield high predictive power when validated against independent empirical data. The validation of the model presented here is a central task of this work.

3. They should also apply over a wide domain, which should be clearly defined. This model will be validated using data from Baltic coastal areas. However, the structure of this model is such that it should apply more generally, although this remains to be demonstrated. The only reason why we have not tested this model for coastal areas from other parts of the world is that we do not have access to relevant data from such areas.

4. The variables needed to run the model (the obligatory driving variables) should be easily accessed, e.g., from standard monitoring programs or maps. This is a very important demand for this model and a key criterion for practical usefulness.

There are also different types of models and modelling approaches for sedimentation and variables influencing sedimentation in coastal areas (see, e.g., Wulff et al., 2001). However, there are major differences among models related to differences in target variables (from conditions at individual sites to mean values over larger areas), modelling scales (daily to annual predictions), modelling structures (from using empirical/regression models to the use of ordinary or partial differential equations) and driving variables (whether accessed from standard monitoring programs, climatological measurements or specific studies). To make meaningful model comparisons is not a simple matter, and this is not the focus of this paper. As far as the present authors are aware, there are no mass-balance models for suspended particulate matter (SPM) and coastal sedimentation of the type presented here accounting for total primary production, point source emissions, fresh water input, surface and deep water exchange processes, land uplift, interannual loading, mixing, etc. in a general manner designed to achieve practical utility and monthly variations. Also the fundamental unit, the defined coastal area, is determined in a way that, to the best of our knowledge, has not been used before in dynamic modelling of sedimentological processes; no comparable models use the topographical bottleneck approach to define the coastal area. This approach also makes it possible to estimate the theoretical surface water and deep water retention times (which are fundamental components in coastal mass-balance modelling) from bathymetric map data.

This is also an effect–load–sensitivity model (ELS-model; Håkanson, 1999). ELS-models are designed for practical utility and are often based on a dynamic (mass-balance) model yielding concentrations of chemical substances in the water and then complemented with regressions between such concentrations and operational variables of ecosystem effects. This dynamic model gives concentrations of suspended particulate matter in the coastal water (SPM in mg/l) and the operational effect variables are the oxygen saturation in the deep water (O₂ Sat in %) and the Secchi depth (in m), a standard measure of water clarity. SPM includes living and dead plankton, all types of humic materials, minerals and aggregated colloids, i.e., all types of carrier particles for water pollutants (Santschi and Hovenman, 1991; Gustafsson and Gschwend, 1997). In spite of this, SPM is not often measured in regular monitoring programs. SPM in a coastal area may originate from several sources and could be divided according to composition into, e.g., organic and inorganic materials or according to sources into: allochthonous, autochthonous, from land uplift and resuspension (Blomqvist, 1992; Håkanson, 1999). The basic aim of this paper is to account for all the important factors regulating SPM in coastal areas and hence also sedimentation.

It should be stressed that SPM regulates the two major transport routes, the dissolved phase and the
following pelagic transport, and the particulate phase and the following sedimentation and benthic route, of all types of materials and contaminants in aquatic ecosystems. To make the differentiation between the two phases a distribution coefficient, \( K_d \), is generally used. \( K_d \) can be determined from investigations of natural waters (e.g., Benoit et al., 1994; Warren and Zimmerman, 1994), from laboratory experiments or model simulations (e.g., Erel and Stolper, 1993).

SPM in the water column is a fundamental component of aquatic ecosystems. It is well known (Wetzel, 1983) that SPM is crucial at lower trophic levels as a source of energy for bacteria and phyto- and zooplankton. The studies of, e.g., Khalid (1974) and Ostappen (1989) have shown that SPM can be considered a fundamental component also at higher hierarchical levels, where SPM influences many tropho-metabolic properties.

The accuracy of a model prediction is strongly influenced by the uncertainty in the empirical data used to run and validate the model (Håkanson and Peters, 1995). Sedimentation is known to display considerable natural variations between years, seasons and/or even between closely located stations (Matteucci and Frascari, 1997; Blomqvist and Larsson, 1998; Heiskanen and Tallberg, 1999). Douglas et al. (2003) have shown that there are large variations in sedimentation even during 36–48 h periods. The empirical sediment trap data used to validate this model have coefficients of variation (CV = S.D./MV; S.D. = the standard deviation, MV = the mean value) of 0.58 for the surface water and 0.50 for the deep water compartment (Wallin et al., 1992).

In models for lakes and/or coastal areas, the surface water compartment is often separated from the deep water compartment by the thermocline (Carlsson et al., 1999), the pycnocline (Abdel-Moati, 1997) or the halocline (Andrew et al., 2002). However, the classic phosphorus model by Vollenweider (1968) does not separate surface and deep water at all and neither does, e.g., De Schmedt et al. (1998) when modelling suspended sediments and heavy metals in the Scheldt estuary. The thermocline, halocline and pycnocline are all gradients, meaning gradual changes, and they can be found over wide ranges of water depths (Håkanson et al., 2003). This means that it is often difficult to find a relevant value separating the surface water compartment from the deep water compartment using, e.g., temperature data. In this work, where we are studying SPM and sedimentation using a mass-balance approach and calculating monthly fluxes, we have chosen not to make the separation in the traditional way using temperature data, but to separate surface and deep water at the “critical water depth”, i.e., the depth below which fine cohesive particles following Stokes’s law are continuously being deposited (Håkanson and Jansson, 1983). This gives one defined critical water depth for each coastal area. From this water depth, it is then easy to calculate requested water volumes and internal loading. This also leads to a relatively simple model structure since the sedimentation of SPM from the deep water, and the deep water alone, ends up on areas of continuous sedimentation (the accumulation areas).

This paper is structured in such a way that after this introduction, we will present the studied coastal areas and the methods and data used to build and test the model. Then, we will present the model and its sub-models. This model uses ordinary differential equations (in an ecosystem perspective, i.e., the model applies for entire coastal areas and not for individual sites in coastal areas). A fundamental requirement for the model is the definition of a coastal area—i.e., how and where to draw the boundary lines toward the sea and/or adjacent coastal areas. For the studied coastal areas, we use the “topographical bottleneck” approach (Pilesjö et al., 1991) to define each coastal area. This means that the boundary lines are drawn so that the exposure (Ex), i.e., the ratio between the section area (At in km²) and the area of the enclosed coastal area (Area in km²) attains minimum values (Ex = 100 × At/Area). This gives the basic unit for which we will determine water volume, mean depth, maximum depth, inflow, outflow and internal fluxes of SPM. For other types of coastal areas, e.g., tidal areas, open coastal areas, estuaries strongly influenced by tributary water, coastal areas from other climatological zones, we will give suggestions how to modify this modelling approach. Then, we will compare modelled data on sedimentation to empirical data, which come from measurements using sediment traps placed at two to four sites in each coastal area (in the surface water and in the deep water, and for two periods of about one week each during the growing season). The fieldwork and the sediment trap data have been presented in detail by Wallin et al. (1992). We will also examine
the results and focus on areas where there are differences between modelled output and empirical data, on critical model tests, mainly sensitivity and uncertainty tests using Monte Carlo techniques according to procedures discussed by Håkanson (1999), and, finally, we will exemplify the practical use of the model in coastal management.

2. Methods and data

This work is based on data from 17 coastal areas located in three different archipelagos in the Baltic Sea. Five of the areas are in the St. Anna archipelago off the Swedish east coast, seven areas are located in the Blekinge archipelago, in the south of Sweden and the remaining five areas in the Åbolands archipelago, SW of Finland, see Fig. 1. The Baltic Sea is brackish with a salinity ranging from 5 to 10% in a north-south gradient. Compared to other seas the Baltic Sea with its mean depth of only 56 m, is shallow. It is almost entirely surrounded by land and the tidal variation is small (~20 cm; see Voipio, 1981). The Åbolands archipelago is the largest archipelago in the Baltic Sea. It reaches from Åland to the Finnish main land. The average depth is low but tectonic faults as deep as 50–60 m do exist. The St Anna archipelago has many islands, the bays are deep and long and several have thresholds towards the sea. The Blekinge archipelago is narrow and the water circulation is generally good (Persson et al., 1994a).

Table 1 gives a compilation of data:

- Area code.
- Latitude; used to calculate surface- and deep-water temperatures with a modified version of the temperature model presented by Ottoisson and Abrahamsson (1998).
- The morphometric parameters, coastal area (Area), maximum depth ($D_{\max}$), mean depth ($D_m$), section area ($A_s$); used to calculate coastal volume ($V = Area \times D_m$) and concentrations of SPM; the morphometric parameters are also used to determine the coastal form, which influences internal fluxes of SPM.
- The measured mean summer concentration of total nitrogen (TN in μg/l); used to calculate primary production.
- The mean surface water salinity, which influences aggregation of suspended particles and sedimentation.
- “Fish production” in Table 1 relates to point source emissions of SPM from fish cage farms. All these data were collected in a project where the environmental impacts of emissions from fish cage farms were studied (Wallin et al., 1992). There are no other major point sources of nutrients or SPM to these areas. All of them are also little influenced by tributaries, which is indicated by the salinities in Table 1.
- The data used to validate the model are given by the columns Sed$_{\text{WH}}$ and Sed$_{\text{SW}}$ (sedimentation in sediment traps placed in the deep water and the surface water); Wallin et al. (1992) and Wallin and Håkanson (1991) have given reports on how, when, where and for how long the sediment traps were deployed. The data used here are the mean values for July, August and September.
- The last column in Table 1 gives the Secchi depths at the sample sites in the section areas closest to the sea (Secchi in m). These data represent mean values
<table>
<thead>
<tr>
<th>Area</th>
<th>Code</th>
<th>Latitude (° N)</th>
<th>Land uplift (mm per year)</th>
<th>Area (km²)</th>
<th>$D_{\text{max}}$ (m)</th>
<th>$D_{\text{m}}$ (m)</th>
<th>$A_{r}$ (km²)</th>
<th>TN (mg/l)</th>
<th>Salinity (‰)</th>
<th>F Wis production (t per year)</th>
<th>Sed$_{\text{DW}}$ (g dw/m² day)</th>
<th>Sed$_{\text{SW}}$ (g dw/m² day)</th>
<th>Secchi Sea (m)</th>
</tr>
</thead>
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<td>Lilla Rimmö</td>
<td>SE1</td>
<td>58</td>
<td>2</td>
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<td>385</td>
<td>6.4</td>
<td>41</td>
<td>20.2</td>
<td>4.2</td>
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<td>125</td>
<td>22.7</td>
<td>11.1</td>
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<td>0.0285</td>
<td>354</td>
<td>6.6</td>
<td>200</td>
<td>18.3</td>
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<tr>
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<td>2</td>
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<td>35.2</td>
<td>8.0</td>
<td>0.0162</td>
<td>334</td>
<td>6.6</td>
<td>300</td>
<td>9.5</td>
<td>3.7</td>
<td>2.0</td>
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<tr>
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<td>3.12</td>
<td>14.3</td>
<td>5.2</td>
<td>0.0067</td>
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<td>6.5</td>
<td>135</td>
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<td>4.2</td>
<td>5.0</td>
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<tr>
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<td>7.05</td>
<td>21.6</td>
<td>7.1</td>
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<td>Sjäppsko</td>
<td>SS6</td>
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<td>5.8</td>
<td>0.0180</td>
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<td>4.3</td>
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<tr>
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<td>2.21</td>
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<td>0.0114</td>
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<td>381</td>
<td>13.4</td>
<td>9.1</td>
<td>2.5</td>
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<tr>
<td>Laxsalma</td>
<td>F4</td>
<td>61</td>
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<td>4.28</td>
<td>18.5</td>
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<td>0.0080</td>
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<td>F5</td>
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<tr>
<td>Min.</td>
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<td>1.4</td>
<td>11.1</td>
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<td>0.0006</td>
<td>256</td>
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<td>10</td>
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<td>1.1</td>
<td>1.2</td>
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<tr>
<td>Max.</td>
<td>61</td>
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<td>14.2</td>
<td>46.9</td>
<td>13.8</td>
<td>0.0285</td>
<td>417</td>
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<td>381</td>
<td>56.4</td>
<td>17.6</td>
<td>5.0</td>
<td></td>
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<tr>
<td>Mean (MV)</td>
<td>58</td>
<td>2.1</td>
<td>5.3</td>
<td>20.7</td>
<td>6.9</td>
<td>0.0151</td>
<td>327</td>
<td>6.6</td>
<td>102</td>
<td>17.7</td>
<td>6.2</td>
<td>3.2</td>
<td></td>
</tr>
</tbody>
</table>
for the larger coastal region where the given coastal areas are located. These data are used to estimate the
inflow of SPM from the sea and/or adjacent coastal areas to the given coastal area \( Q_{SW} \times \text{SPM}_{\text{adj}} \) in \( \text{m}^3 \) per month (g/m² = g per month). \( \text{SPM}_{\text{adj}} \) is calculated from SecMax from a regression given in Table 2.
This regression is based on data from Baltic coastal areas. Evidently, there are strong mechanistic links between SPM causing light scattering and Secchi depth, a reflection of light scattering by suspended particles (Håkanson and Boulton, 2002). The Secchi depth is also an measure of the effective depth of the photic zone influencing primary production.

Table 1 also gives the ranges (minimum and maximum values) for the data and one should note that these ranges give important information about the model domain.

Table 2 gives a compilation of all empirical regressions used in this work.

- The regression between SPM and Secchi depth of the coastal areas (Sec) is used to relate modelled SPM-concentration to coastal Secchi depth, a standard operational effect variable in contexts of water management.
- The regressions under (B) in Table 2 gives the theoretical surface water retention time and the theoretical deep water retention time (\( T_{SW} \) and \( T_{DW} \))

### Table 2

<table>
<thead>
<tr>
<th>Regression</th>
<th>( r^2 )</th>
<th>( n )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ( \log(\text{SPM}_{\text{adj}}) = -0.05\text{SecMax} + 0.85 )</td>
<td>0.81</td>
<td>26</td>
<td>Håkanson and Karlsson (2003)</td>
</tr>
<tr>
<td>Sec ( = -6.45 \log(\text{SPM}) + 15.15 )</td>
<td>0.81</td>
<td>26</td>
<td>Håkanson and Karlsson (2003)</td>
</tr>
<tr>
<td>B ( \text{ln}(T_{SW}) = -4.33(\text{Sec}) + 3.94 )</td>
<td>0.95</td>
<td>14</td>
<td>Persson et al. (1994a)</td>
</tr>
<tr>
<td>( T_{SW} = -251 - 138 \log(\text{At}) + 269 \log(\text{Vd}) )</td>
<td>0.79</td>
<td>15</td>
<td>Håkanson and Karlsson (2003)</td>
</tr>
<tr>
<td>Model domain: 0.002 &lt; Ex &lt; 1.5; 0.0006 &lt; At &lt; 0.08; 0.5 &lt; Vd &lt; 1.5; data from Baltic coastal areas; note that ( T_{SW} ) and ( T_{DW} ) are never permitted to be &lt;1 day and ( T_{DW} ) never &gt;120 days</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C ( \log(\text{Chl}) = (2.78 \log(\text{TN}) - 6.66) )</td>
<td>0.91</td>
<td>22</td>
<td>Håkanson (1999)</td>
</tr>
<tr>
<td>( \text{O}<em>{2}\text{Sat} = 100 \times \exp(2.544 - 0.342 \log(\text{SecMax}) - 0.510 \log(D</em>{\text{sw}}) - 0.236 \log(1 + 100(1 - \text{E}) - 0.393 V_{d} - 0.298 \log(1 + T_{SW})) )</td>
<td>0.87</td>
<td>22</td>
<td>Data from Walfin et al. (1992)</td>
</tr>
<tr>
<td>Model domain: 250 &lt; TN &lt; 420; the model for ( \text{O}_{2}\text{Sat} ) is valid for Baltic coastal areas defined by the ranges given in Table 1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Additional Notes

- Theoretical water retention times \( T_{SW} \) and \( T_{DW} \) are calculated for the coastal area in days. Flow of SPM to and from the coastal area \( F_{SWin}, F_{SWout}, F_{DWin} \) and \( F_{DWout} \).
- To determine the theoretical surface water retention time \( T_{SW} \) for a given coastal area. There are several field methods to do so and they are all costly and demanding (Håkanson, 2003). Measurement of the \( T_{SW} \) is certainly one of the major regulating factors for inflow, outflow and retention of substances in coastal areas. However, \( T_{SW} \) is defined from the net flow of water from the sea and/or adjacent coastal areas and the volume of the surface water \( V_{SW} \), depends on many stochastic processes. This makes it difficult to give a reliable prediction of \( T_{SW} \) at a given time. In any coastal area, \( T_{SW} \) may be indefinitely long on a calm summer day and very short in connection with a storm or a sudden change in air pressure. \( T_{SW} \) is always related to a frequency distribution. This model assumes that the characteristic \( T_{SW} \)-value, the median, is used. There is an evident uncertainty associated with such \( T_{SW} \)-values. We have tested to see how important this uncertainty is relative to other uncertainties for predicting sedimentation, the target variables in this model. As a rule of thumb, one can say that the costs of establishing a frequency distribution of empirical \( T_{SW} \)-values to

\[ Q_{SW} = \text{SPM}_{\text{adj}} \times \text{secMax} \]

\[ T_{SW} = \frac{V_{SW}}{Q_{SW}} \]

\[ T_{DW} = \frac{V_{DW}}{Q_{DW}} \]
determine a reliable median $T_{SW}$ from traditional field measurements (using dye, current meters, etc.) is about US$ 20,000 for one coastal area (Håkanson et al., 1984). It is not very meaningful to build a management model if it is a prerequisite that such extensive field work must first be carried out to determine $T_{SW}$ as a driving variable. This means that it is of great importance that $T_{SW}$ can, in fact, be estimated from one coastal morphometric variable, i.e., the exposure (Ex). This dynamic model uses $T_{SW}$-values (in months) predicted from the regression given in Table 2 and those predicted values agree very well with measured values on $T_{SW}$ ($r^2 = 0.95$). To use this approach, Ex should be between 0.002 and 1.3, and the regression should not be used when the tidal range is $> 20$ cm. In estuaries, the fresh water discharge must also be accounted for. For more open coasts, i.e., when Ex $> 1.3$, $T_{SW}$ may be calculated not by this equation but from a model based on coastal currents (the $u$-formula, see later) and/or from the tidal range (the $dH$-formula, see later).

The same arguments can be given for the deep-water retention time ($T_{DW}$). It is very difficult and costly to determine also $T_{DW}$ with, e.g., the dye method (Persson and Håkanson, 1996). The costs per area are even higher for $T_{DW}$ than for $T_{SW}$, but $T_{DW}$ can also be predicted from readily available morphometric parameters (Table 2). This empirical $T_{DW}$-formula is based on data from Baltic coastal areas.

The second operational effect variable here (after the Secchi depth) is the oxygen saturation of the deep water ($O_2$Sat). The regression for $O_2$Sat in Table 2 will be used as a sub-model. This regression gives mean values of $O_2$Sat for the summer period. Of all the many factors that could, potentially, influence $O_2$Sat, the following have been shown to be most important (Håkanson, 1999):

1. The theoretical deep water retention time ($T_{DW}$); variations in mean $O_2$Sat among coastal areas can be statistically explained to a high degree ($r^2 = 0.46$) by variations in $T_{DW}$; the longer $T_{DW}$, the lower $O_2$Sat. This is logical and mechanistically understandable.

2. The mean depth ($D_m$); the mechanistic reason for this is not so easy to disclose since $D_m$ influences many different factors, e.g., (1) resuspension, (2) the volume and hence all concentrations, (3) stratification and mixing, and (4) the depth of the photic zone and, hence, primary production.

3. The prevailing bottom dynamic conditions in the coastal area (ET);

   In defining the bottom dynamic conditions (erosion, transportation and accumulation), this work uses the following definitions (Håkanson and Jansson, 1985):

   - Areas of erosion (E) prevail where there is no apparent deposition of fine materials but rather a removal of such materials, e.g., in shallow areas or on slopes; E-areas are generally hard and consist of sand, gravel, consolidated clays and/or rocks.
   - Areas of transportation ($T$) prevail where fine materials are deposited periodically (areas of mixed sediments). This bottom type generally dominates where wind/wave action regulates the bottom dynamic conditions. The water depth separating transportation areas from accumulation areas, the critical depth, is a fundamental component of this dynamical model.
   - Areas of accumulation ($A$) prevail where the fine materials are deposited continuously (soft bottom areas). These are the areas (the “end stations”) where high concentrations of pollutants are most likely to appear. The generally hard or sandy sediments within the areas of erosion and transport (ET) often have a low water content, low organic content, and low concentrations of nutrients and pollutants. In connection with a storm or a mass movement on a slope, the material on the ET-area may be resuspended and transported up and away, generally in the direction towards the A-areas in the deeper parts, where continuous deposition occurs. 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 component is generally at least 10 times larger, sometimes up to 10,000 times larger, than the vertical component for fine materials or floc that settle according to Stokes’s law (Bloesch and Burns, 1980; Bloesch and Uehlinger, 1986).

4. Sedimentation on A-areas (Sed); the more oxygen-consuming matter deposited on A-areas, the lower $O_2$Sat. This is the link between the dynamic model and the regression given in Table 2 for $O_2$Sat.
5. The form of the coastal area (Vd); the form of the
coast may be revealed by the mean depth, but even
better by the form factor (Vd) or the relative depth
(Drel; Håkanson, 1999).

3. The dynamic model
3.1. Basic structure

The structure of the dynamic model is shown in
Fig. 2. There are four compartments: surface water,
deep water, areas where processes of erosion and
transport dominate the bottom dynamic conditions
(ET-areas) and accumulation areas (A-areas). The
volumes of the surface and deep water are calculated
from the water depth separating T-areas from A-areas,
the critical depth (DTA, see later). Also note the abbre-
viation: F for fluxes (g per month), C for concentra-
tions (g/m³), R for rates (1 per month), M for masses
(amounts in g). Fluxes from one compartment to
another are denoted, e.g., FSWDW for sedimentation
from surface water (SW) to deep water (DW). Fig. 2
also shows the target variable, sedimentation on
A-areas (FDW). Also note that there are six inflows,
which will be explained in the following sections:
1. Primary production (FPrP) includes all types of
plankton (phytoplankton, bacterioplankton and
zooplankton) influencing SPM in the water.
2. Inflow to surface water from the sea (FSSW).
3. Land uplift (FLU). Land uplift is not a major pri-
mary source of matter in most coastal areas on
Earth, but about 80% of the material deposited on
the A-areas in the open part of the Baltic Sea has
been reported to emanate from land uplift associ-
ated with the latest glaciation (Jonsson, 1992).
4. Direct emissions of SPM from point sources
(FDSSW). We will calculate this input from fish
cage farms.

![Diagram of the coastal model](image-url)

Fig. 2. An outline of the structure of the coastal model. Note that for simplicity we have omitted point source emissions to the deep water compartment in this figure.
5. Tributary inflow (FQ). We will give calculation routines for this inflow, but freshwater inflow is of no or little significance in our coastal areas, and this sub-model is included here to stress the generality of our modelling approach. Inflow of SPM to the deep water from the sea (F\text{SWtoD}).

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 flux of matter in coastal areas. The resuspended matter can be transported either back to the surface water (F\text{ETSWtoM}) or to the deep water (F\text{ETD}). How much that will go in either direction is regulated by a distribution coefficient calculated from the form of the coastal area. Other internal processes are mineralization, i.e., the bacterial decomposition of SPM in the surface water (F\text{SWtoM}) or in the deep water (F\text{ETD}), mixing, i.e., the transport from deep water to surface water (F\text{SWtoM}) or from surface water to deep water (F\text{ETSWtoM}) and burial, i.e., the transport from biologically active A-sediments to deeper (geological) A-sediments with no macrofauna.

All basic equations are compiled in Table 3. In the following, we will first present the inflow sub-models.

3.2. Inflow sub-models

3.2.1. Primary production

Primary production is basically calculated from chlorophyll-a, which in turn is calculated from total-N concentrations from the regression in Table 2 for these Baltic coastal areas. To quantify primary production of SPM, we have used an algorithm presented by Håkanson and Bouillon (2002), which gives:

\[
F_{\text{PP}} = \left( \frac{(SWT + 0.1)}{9} \right) (30.6 \times \text{Chl}^{0.237}) \times 0.45 \\
\times 30 \times \text{Area} \times \text{Sec} \times 0.001 \times \frac{BM_{\text{PL}}}{BM_{\text{d}}} 
\]

SWT = The mean monthly surface water temperature (°C). By dividing SWT with a reference temperature of 9°C (related to the duration of the growing season), 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 primary production under the ice.

Chl = The mean chlorophyll concentration during the growing season (µg/l); the expression \((30.6 \times \text{Chl}^{0.237})\) transforms Chl into phytoplankton production (µg C/day). The factor 0.45 is a standard transformation factor to change g C to g dw. Multiplication with 0.001, 30 days, coastal area (Area) and the effective depth of the photic zone (=the Secchi depth) gives the biomass of phytoplankton produced per month (g dw per month). Note that for these Baltic coastal areas chlorophyll concentrations may be predicted from TN-data. For other coastal areas, e.g., in the Bothnian Bay, chlorophyll concentrations are probably better predicted from total phosphorus concentrations, and for other coastal areas, e.g., in the Black Sea or the Mediterranean, one may have to apply other regressions than the one used here.

\[
BM_{\text{PL}}/BM_{\text{d}} = \text{The ratio between the biomass of all sorts of plankton (phytoplankton, bacterioplankton and zooplankton: BM_{\text{d}})} \text{ to the calculated biomass of phytoplankton (BM_{\text{PL}}) comes from the foodweb model presented by Håkanson and Bouillon (2002). We have used this foodweb model to see if it is possible to}
\]

Table 3

<table>
<thead>
<tr>
<th>Surface water (SW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_{\text{BM}}(t) = M_{\text{BM}}(t-\Delta t) + F_{\text{BM}} + F_{\text{SWBM}} + F_{\text{ETBM}} + F_{\text{BNBM}} - F_{\text{BM}} - F_{\text{BNBM}} - F_{\text{BNBM}} + F_{\text{BM}} + F_{\text{BNBM}} + F_{\text{BNBM}}</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>ET-areas (ET)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_{\text{ET}}(t) = M_{\text{ET}}(t-\Delta t) + (F_{\text{ET}} + F_{\text{ETBM}} - F_{\text{ET}} - F_{\text{ETBM}}) + F_{\text{ET}} + F_{\text{ETBM}}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Active A-sediments (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_{\text{A}}(t) = M_{\text{A}}(t-\Delta t) + (F_{\text{A}} - F_{\text{A}})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sedimentation on A-areas (F_{\text{SWA}}) is the target abiotic variable in this dynamic model.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep (or bottom) water (DW)</td>
</tr>
<tr>
<td>M_{\text{DW}}(t) = M_{\text{DW}}(t-\Delta t) + (F_{\text{DW}} + F_{\text{ETDW}} + F_{\text{BNDW}} + F_{\text{BNBW}} - F_{\text{DW}} - F_{\text{BNDW}} - F_{\text{BNBW}})</td>
</tr>
</tbody>
</table>

All abbreviations are given in the figures.
find a simple general calculation constant for this ratio along a trophic state gradient. Those results are shown in Fig. 3 and one can note that this ratio is on average about 2.5 along the entire gradient. We will assume that this constant can also be used in this model. It means that the total production is a factor of 2.5 higher than the primary phytoplankton production.

Sec = Secchi depth (in m; an estimate of the depth of the photic zone) calculated from modelled values of SPM using the regression in Table 2.

The surface water temperatures (SWT) needed to calculate $F_{sw}$ can either come from measurements, climatological tables or from temperature models. In this work, we have used a modified version of the model presented by Ottosson and Abrahamsson (1998). Since this is a model for coastal water temperatures (see Fig. 4), we have omitted altitude and continentality as driving variables. To predict SWT and deep water temperatures (DWT), and also the mixing rate (from SWT and DWT, see later), one needs data on latitude, coastal area and coastal mean depth (such data are given in Table 1 for our 17 coastal areas). There are several boundary conditions for this sub-model. The coastal waters are not likely stratified if the mean depth is lower than 2 m and if the dynamic ratio (DR = $\sqrt{\text{Area}/D_{om}}$; Area in km$^2$ and $D_{om}$ in m) is larger than 3.8 (Håkanson and Jansson, 1983).

Fig. 5 shows how this sub-model predicts SWT and DWT at four latitudes using data for the coastal area Gravvik (SS4, see Table 1). One can note that there would be a likely ice cover at latitudes 60 and 65 $^\circ$N, but not at latitude 55 $^\circ$N.

3.2.2. Inflow to surface water from the sea

The inflow to the surface water from the sea or adjacent coastal areas ($F_{sw,in}$) is calculated from the surface water flow ($Q_{sw}$), which is calculated from the theoretical surface water retention time ($T_{sw}$, see Table 2) and the concentration of SPM outside the coast (SPM$_{ext}$), which is calculated here from measured regional mean values of Secchi depth close to the section areas (Sec$_{sec}$, see Table 1). Evidently, it would have been preferable to have access to reliable empirical data both on $T_{sw}$ and SPM$_{ext}$, but such data are very hard to get. This means that the inflow of SPM from the sea is given by:

$$F_{sw,in} = Q_{sw} \times \text{SPM}_{ext} = \frac{Q_{sw}}{T_{sw}} \times 10^{-(0.05 \times \text{Sec}_{sec} + 0.85)}$$

(2)

where the surface water volume ($V_{sw}$ in m$^3$) is defined not from water temperatures and stratification (as is generally the case, see Håkanson, 1999), but from the critical depth ($D_{cr}$). There are several reasons for this: (i) $D_{cr}$ can be calculated in a simple, general, relevant and well tested manner (Eq. (3)) and (ii) vertical water temperature profiles for many sites over longer periods (like months) often show a continuous decrease in temperature, and hence no clear thermocline. This means that it is often difficult to define the borderline depth between the surface water and the deep water from water temperature measurements (Håkanson et al., 1984).

1. $D_{cr}$ is first calculated from the mean effective fetch (estimated for entire coastal areas by $\sqrt{\text{Area}}$) using the following equation (from Håkanson and Jansson, 1983):

$$D_{cr} = \frac{45.7}{\sqrt{\text{Area}}} \times 21.4 + \sqrt{\text{Area}}$$

(3)

Note that $\text{Area}$ is given in km$^2$ in this equation. There are several models to predict the critical depth and the percentage of ET-areas for coastal areas (Persson and Håkanson, 1995), but those approaches generally require data on the filter factor or the mean filter factor, i.e., how the conditions...
outside the defined coastal area (islands, etc.) work as an energy filter and reduce the impact of waves from the sea. In this modelling approach, we will omit the filter factor and use an approach presented by Håkanson and Karlsson (2003). This approach can predict \( D_{Ta} \), from the information given in Table 1. The more detailed filter factor can only be determined using digitized bathymetric maps and GIS-techniques (see Pileggi et al., 1991) and has been omitted as obligatory driving variable here to gain simplicity.

2. In the second step to calculate the ET-area (dimensionless), one accounts for coastal form; shallow coasts have larger areas above the critical depth than deep areas, if all else is constant; this calculation is related to the hypsographic form (depth/area-form as given by the form factor, \( Vd = 3D_{max}/D_{max} \); \( D_{max} \) = the mean depth; \( D_{max} \) = the maximum depth; see Håkanson, 1999):

\[
A = 1 - ET = \left( \frac{D_{max} - D_{Ta}}{D_{max} + D_{Ta}^{0.5/Vd}} \right)
\]

3. The larger the exposure (Ex = 100 \times \text{At/Area}), the larger the potential energy impact from the sea
Håkanson, 1995) and the deeper the critical depth. This is accounted for by the following approach:

If Ex < 0.003 then Y_{EA} = 1, else

\[ Y_{EA} = \left( \frac{Ex}{0.003} \right)^{0.25} \]  

(5)

and the other boundary condition for very open coastal areas is:

If Ex > 10 then Y_{EA} = 10 else Y_{EA} = Y_{EA}  

(6)

The value for V_{EA} is multiplied by the value for D_{EA} (from Eq. (3)). This means that when the exposure varies between 0.003 and 10, D_{EA} is increased by the factor (Ex/0.003)^{0.25}. That is, if Ex = 0.1, the factor is 2.4 and D_{EA} likely at a water depth of 2.4D_{EA} m rather than at D_{EA}. This step accounts for the depth and width of the section area, but not for the conditions outside the defined coastal area, which is handled by the next step—"open or closed coast", the OS-factor.

4. We will use the OS-value of 1 as a default value for all coastal areas in the following validation, but also discuss when it may be motivated to change this value.

5. Note that D_{IA} is never permitted to be deeper than 0.99D_{MAX}.

6. For practical purposes, to avoid many time-consuming calculation steps, which are necessary to obtain stable solutions using the calculation routines (Euler or Runge-Kutta) for retention rates greater than about 30 (≈ 30 exchanges per month), there is an "if_then_else" statement in the model, which never allows the surface water retention time to be less than 1 day.

From this, one can calculate the volume of the surface water (V_{SW}) accordingly (see Fig. 6):

\[ V_{SW} = (\text{Area} - \text{Area}_A) \frac{D_{IA}}{3/V_d} + \text{Area}_A \times D_{IA} \]  

(7)

Area A is the area below the critical limit (the accumulation area), which is calculated from Eq. (4) (≡ A × Area). The deep-water volume (V_{DW}) is then given by (V - V_{SW}).

Note that the ET-value from Eq. (4) is used as a dimensionless distribution coefficient. It regulates the sedimentation of SPM either on A-areas or on ET-areas and hence also the amount of matter.

Sub-models for volumes

![Fig. 6. The sub-model for surface and deep water volume.](image-url)
available for resuspension on ET-areas. ET generally varies from 0.15, since there must always be a shallow shore zone where processes of erosion and transport dominate the bottom dynamic conditions, to 1 in large and shallow areas totally dominated by ET-areas. In this modelling approach (see Fig. 7), however, ET is never permitted to become higher than 0.99, since one can assume that in most coastal areas there are deep holes, sheltered areas or macrophyte beds which would function as A-areas. For simplicity, we use this approach also when there is an ice cover (if SWT = 0 °C), because the stratification is weak during the winter time, primary production low and the error in predicting sedimentation with this simplification small.

To stress the generic character of this modelling approach, we will also discuss how this model can be modified for open coasts, tidal coasts and estuaries dominated by freshwater inflow. Note, however, that for the following parts, the given algorithms to calculated water exchange have not been critically tested. They are logical constructs, which need to be tested against empirical data for many coastal areas. Unfortunately, such data are difficult to access and it has been beyond the scope of this work to carry out such studies.
For open coasts, $T_{SW}$ (in months) may be estimated from data on the characteristic coastal current ($u$). Typical values for coastal currents in the Baltic are given in FRP (1978). One can use a default value of 2.5 cm/s ($u_{ad}$, from Håkanson et al., 1984). If the exposure ($Ex$) is smaller than 1.3, the influence of coastal currents is already accounted for by the $T_{SW}$-equation in Table 2. For more open coastal areas, a system of simple operational rules based on the exposure ($Ex$) can be applied; if $Ex > 1.3$, the following dimensionless moderator is first used (from Håkanson, 2000):

$$Y_{Ex} = 1 + 0.5 \left( \frac{Ex}{10} - 1 \right)$$

(8)

where 0.5 is the amplitude value; this value regulates the influence that an increase in the actual exposure ($Ex$) would have relative to the norm-value (here $Ex = 10$) on the $T_{SW}$-value. The norm-value of 10 means that if the exposure is larger than 10, then coastal currents are likely to fully influence the requested $T_{SW}$-value and if the actual $Ex$-value is lower than the norm-value, the coastal currents will not influence the $T_{SW}$-value as much. If $Ex = 2$, $Y_{Ex} = 0.6$ and the theoretical surface water retention time $tPW$ can be seen as 1.67 longer than if $Ex = 10$.

This means that the theoretical surface water retention time from coastal currents ($T_{SWC}$ in months) is given by:

$$T_{SWC} = \frac{V_{SW}}{Y_{Ex} \times u \times 0.01 \times 60 \times 60 \times 24 \times 30 \times 0.5 \times At}$$

(9)

$u =$ The characteristic coastal current; e.g., 2.5 cm/s. 0.5 = It is assumed that 50% of the section area is involved in the active water exchange.

For tidal coasts, $T_{SW}$ can be estimated from (see Håkanson, 2000):

$$T_{SWT} = \frac{V_{SW}}{Area \times dH \times Y_{Ad} \times 0.01 \times k \times 30}$$

(10)

Area = the coastal area in m$^2$; $k =$ a mixing constant; $k \equiv$ 1 means complete mixing. This value can be used as a default assumption if the model is run with $dH = 1$ month; 0.01 = a calculation constant which changes $dH$ in cm per day to m per day; $dH =$ the tidal amplitude in m per month ($=30 \times dH$, if $dH$ is given in m per day).

$Y_{Ad} = Y_{Ex} \times Y_{MFI}$ if $Y_{Ad} > 1$ then $Y_{Ad} = 1$  

(11)

$Y_{Ad}$ is given by Eq. (8) and $Y_{MFI}$, the dimensionless moderator for the mean filter factor is defined (from Håkanson, 2000) as:

$$Y_{MFI} = 1 + 0.5 \left( \frac{MFI - 1}{50} \right)$$

(12)

where 0.5 is the amplitude value; the same amplitude value as in the previous moderator has been used in this case. The denser the outside archipelago, the greater the “energy filter”, the smaller the influence of the coastal current. The selected norm-value of 50 means that if the MFI is larger than 50, then coastal currents (and index) are likely to fully influence the requested $T_{SW}$-value. Note that a filter factor of 100 means an open coast without any topographical obstacles like islands, reefs, etc. If $Ex$ and/or MFI are larger than the norm-values, there is an “if-then else” statement which sets the moderators to 1.

For estuaries the SPM-flow is given by:

$$F_{in} = C_{SPM} \times SR \times ADA \left( \frac{Prec}{mm} \right) \times Y_{Q} \times 60 \times 60 \times 24 \times 30$$

(13)

The tributary load (g/dw per month) is a function of the SPM-concentration in the tributary ($CN_{SPM}$, in g/m$^3$) and the water discharge ($Q$ in m$^3$ per month), which is either empirically determined or estimated from the specific runoff (SR in m$^3$/km$^2$). For Nordic catchment areas, one can often use the value 0.01 as default value for SR (Håkanson and Peters, 1995). ADA is the catchment area (km$^2$). So, the SPM-inflow (in g per month) is calculated from SR times the area of the catchment area (ADA in km$^2$), the ratio between the actual mean annual precipitation (Prec in mm per year) and the reference value for mean annual precipitation (650 mm per year) times a dimensionless moderator for mean monthly water discharge ($Y_{Q}$) to get seasonal/monthly variations; see Table 4) times the SPM-concentration in the tributary.

3.2.3. SPM from land uplift

The amount of suspended particulate matter (SPM) always depends on two main causes, allochthonous inflow and autochthonous production. In the Baltic, however, there is also another source, land uplift (see Voipio, 1981). Thousand-year-old sediments influence the Baltic ecosystem today. When the old bottom areas rise after being depressed by the glacial ice, they
The depth separating T-areas from A-areas ($D_{TA}$ plus $D_{LA}$) is estimated from a similar approach (see Eq. (3)). The area between these two water depths (Area$_T$ - Area$_A$ in m$^2$) may be calculated from Eq. (4). It is also assumed that 50% of the new sediment volume (m$^3$) of glacial clays from land uplift will be accessible for resuspension – these clays have a relatively low water content (about 60% w/w; Håkanson et al., 1984) and are not so easily resuspended, especially not in topographically sheltered areas or close to the wave base. This means that $P_{LU}$ is given by (see Fig. 8):

$$F_{LU} = D_{LR} \times EF(Ae - Ar) \left(1 - \frac{W - 15}{100}\right) \times (d + 0.2)10^6 \quad (15)$$

$W$ is the water content of the sediments lifted above the critical depth. It is assumed that the water content of the compacted glacial clays is 15% lower than the recently deposited sediments and that the bulk density ($d$ in g/cm$^3$) is 0.2 units higher than in the recently deposited sediments.

3.2.4. SPM from point source emissions (fish farms)

The approach to calculate SPM-fluxes from fish cage farms (rainbow trout) has been presented by Håkanson and Bouillon (2002). The inflow is calculated from (1) the annual fish production (AFP in g), (2) the feed coefficient (or feed conversion ratio,
FCR; we will use a default FCR-value of 1.5 in the following simulations; see Wallin et al., 1992 and (3) a seasonal dimensionless moderator ($V_{arm}$), which accounts for the fact that there is generally a typical seasonal pattern in fish growth, fish feeding and emissions of SPM such that high emissions generally occur in the fall, just before the harvest. About 23% of the added feed (Johansson et al., 1998) is likely to be discharged from the farm as SPM. From Håkanson and Boulion (2002), we also assume that 50% of these emissions go to the surface water compartment ($D_{farm}$) and 50% to the deep-water compartment (1 - $D_{farm}$). This means that the discharge of SPM to the surface water from this point source is given by:

$$F_{PSSW} = 0.23 \times AFP \times FCR \times V_{farm} \times D_{farm}$$

(16)

### 3.2.5. Deep water inflow from the sea

The sixth and last inflow is the deep-water inflow ($F_{PSSW}$). This is quantified by the following equation:

$$F_{DW_{in}} = Q_{DW} \times (SPM_{sea} + 2)$$

(17)

$Q_{DW}$ is the deep water inflow ($m^3$ per month), which is given by the ratio between the volume of the deep water ($V_{DW}$ in $m^3$ from Fig. 6) and the theoretical deep water retention time ($T_{DW}$ in months; from Table 2), i.e., $V_{DW}/T_{DW}$. $SPM_{sea}$ is the SPM-concentration in the surface water in the sea outside the coast, as
calculated from Secchi depth measurements (from the regression in Table 2). 2 mg/l are added to get a better estimate of the SPM-concentration in the deep-water value because the SPM-concentration is likely to be higher close to the bottom (Håkanson and Eckhell, 2003).

3.3. Outflow

The outflow from the surface water is given by a flux called \( F_{SWin} \):

\[
F_{SWin} = \frac{M_{SW}}{T_{SW}}
\]

(18)

\( 1/T_{SW} \) is the outflow rate (1 per month); \( T_{SW} \) is the theoretical surface water retention time (Table 2). \( M_{SW} \) is the modelled amount of SPM in the surface water (g).

The deep water outflow is calculated in the same way as \( F_{SWin} = M_{SW}/T_{SW} \), where \( 1/T_{DW} \) is the outflow rate (1 per month); \( T_{DW} \) is the theoretical deep water retention time (Table 2); and \( M_{DW} \) is the modelled amount of SPM in the deep water (g). With this, we have defined the inflow and outflow of SPM and the next section will present the sub-models for the internal fluxes.

3.4. Internal sub-models

3.4.1. Overview

1. Sedimentation concerns (1) transport from surface water to deep water (\( F_{SWin} \)), (2) from deep water to A-areas (\( F_{DWin} \), our target variable), and (3) from surface water to ET-areas (\( F_{SWET} \)).

2. Internal loading from the sediments concerns resuspension from ET-areas either back to the surface water or to the deep water. There is no diffusion in this model for SPM. The resuspension (or advection) rate is given by the age of the ET-sediments \( (T_E) \), which is set to 1 month as a default value. This retention time also includes a consideration to the fact that SPM may be entrapped by macrophytes. This approach for internal loading is basically the same as the one for radiocesium in coastal areas (Håkanson, 2000). In that model, \( T_E \) was set to 15 days. SPM entrapment by macrophytes will likely increase the retention time by a factor of 2 (Håkanson and Boullion, 2002), so in this model, we set \( T_E \) to 1 month.

3. Mixing is regulated by the difference in mean monthly temperatures between surface water (SWT) and deep water (DWT). If the difference between SWT and DWT is smaller than 4°C, the coastal water is mixed (or homothermal). The mixing rate \( (R_{mix}) \) is 1 when the coastal waters are homothermal and smaller than 1 during stratified conditions. Monthly data on SWT and DWT are calculated from the temperature sub-model

4. Mineralization is the bacterial degradation of suspended organic particles. This is a temperature dependent process. The model for mineralization used here comes from Håkanson et al. (2000).

5. Burial (including bioturbation), i.e., the transport of matter from bioactive to biopassive A-sediments.

These internal sub-models (see Fig. 9) will be elaborated further below.

3.4.2. Sedimentation

Sedimentation of SPM depends on (see Fig. 10):

1. A default settling velocity, \( v \), which is set to 25 m per month. This is an initial order of magnitude value calculated from two validated models structured in the same way as this model and from empirical data on SPM sedimentation in lakes (Håkanson and Jansson, 1983; Håkanson, 2000). This value is changed into a rate (1 per month) by division with the mean depth for ET-areas (\( D_{ET} \)) for sedimentation on such areas and by the mean depth of the deep-water areas (\( D_{A} \)) for sedimentation on A-areas.

2. The salinity of the coastal water will also influence the settling velocity: the higher the salinity, 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 (\( Y_{sal} \)) operating on the default settling velocity. The salinity is given in %. The norm-value of the moderator is 1% and the amplitude value is set to 1 (see Eq. (23)). This means that if the salinity changes from 5 to 10%, the moderator \( (Y_{sal}) \) changes from 5 to 10 and the sedimentation rate increases by a factor of 2.

3. The modelled concentration of SPM will also influence the settling velocity. This is expressed by
4. The sedimentation of SPM also depends on the amount of resuspended matter. It is assumed that the resuspended matter will settle out faster than the primary materials. The resuspended particles have already been aggregated and they have also often been influenced by benthic activities, which will create a "gluing effect." Here, the resuspended particles settle ten times faster than the primary materials. The fraction of resuspended matter ($\text{DC}_{\text{res}}$; i.e., the resuspension fluxes divided by all inflow fluxes) is calculated from Eq. (24).

Hence, sedimentation on coastal ET-areas ($FS\text{W}_{\text{ET}}$) is given by:

$$FS\text{W}_{\text{ET}} = M_{\text{SW}} \times \kappa_{\text{sedET}} \times ET$$

(19)

Sedimentation from surface to deep water is calculated in the same manner as $FS\text{W}_{\text{SW}} = M_{\text{SW}} \times...
R_{sed}A (1 - ET), and sedimentation on coastal A-areas as:

\[ F_{ETWA} = M_{ET} \times R_{sedA} \]  

(20)

The sedimentation rates for ET- and A-areas are \( R_{sedET} = v/\Delta D_{ET} \) and \( R_{sedA} = v/\Delta D_A \), respectively. The mean depths of the ET- and A-areas, \( \Delta D_{ET} \) and \( \Delta D_A \) are, as mentioned, calculated from the hypsographic curve, the form factor (Vd) and the critical depth (\( D_{TA} \)). The actual monthly settling velocity \( (v) \) is calculated from the default settling velocity of 25 m per year accordingly:

\[ v = \frac{25}{12} Y_{SPM} \times Y_{Sal} (1 - DC_{res}) + 10 \times DC_{res} \]  

(21)

where the dimensionless moderator expressing how changes in SPM influence sedimentation is given by:

\[ Y_{SPM} = 1 + 0.75 \left( \frac{SPM}{50} - 1 \right) \]  

(22)

The dimensionless moderator for salinity \( (Y_{Sal}) \) is:

\[ Y_{Sal} = \left( 1 + \left( \frac{Sal}{T} - 1 \right) \right) \left( \frac{Sal}{T} = Sal \right) \]  

(23)

The fraction of resuspended matter \( (DC_{res}) \) is:

\[ DC_{res} = \frac{F_{ETSW} + F_{ETDW} + F_{ETP} + F_{ETPSW} + F_{ETPSDW}}{F_{LU} + F_{ETSW} + F_{ETPSW}} \]  

(24)

3.4.3. Resuspension

Resuspension back into surface water, \( F_{ETSW} \), is given by:

\[ F_{ETSW} = \frac{M_{ET}(1 - Vd/3)}{T_{ET}} \]  

(25)
Resuspension to deep water, $F_{\text{ETDW}}$, by:

$$F_{\text{ETDW}} = \frac{M_{\text{ET}} \cdot (Vd/3)}{T_{\text{ET}}}$$  \hspace{1cm} (26)

$M_{\text{ET}}$ = the total amount of SPM on ET-areas (g); $Vd$ = the form factor; note that $Vd/3$ is used as a distribution coefficient to regulate how much of the resuspended material from ET-areas will go to the surface water or to the deep water; $T_{\text{ET}}$ = the age of SPM on ET-areas. As already explained in Section 3.4.1, $T_{\text{ET}}$ is set to 1 month.

This completes the set of equations regulating resuspension fluxes of SPM from ET-areas.

3.4.4. Mixing

The mixing between surface water and deep water depends on stratification, which in turn depends on many climatological factors (prevailing winds, season of the year, etc.). The following sub-model for mixing is simple. It gives the monthly mixing rate ($R_{\text{mix}}$: 1 per month) as a function of the absolute difference between surface and deep water temperatures.

If $\text{ABS}(\text{SWT} - \text{DWT}) < 4(\degree\text{C})$ then $R_{\text{mix}} = 1$ else

$$R_{\text{mix}} = \frac{1}{\text{ABS}(\text{SWT} - \text{DWT})}$$  \hspace{1cm} (27)

The mixing rate is never permitted to be higher than 1.

This means that mixing from deep water to surface water will cause an SPM-transport given by:

$$F_{\text{DWT}\text{SW}} = M_{\text{DWT}} \times R_{\text{mix}}$$  \hspace{1cm} (28)

and mixing from surface water to deep water is given by

$$F_{\text{SWT}\text{DWT}} = M_{\text{SWT}} \times R_{\text{mix}}$$

3.4.5. Mineralization

Mineralization means non-deposit net losses of SPM in the water mass related to respiration plus solubilization minus non-photosynthetic formation. The value used for the mineralization rate, $R_{\text{min}}$, regulates the total amount of SPM in the water mass being mineralized each month. The value for $R_{\text{min}}$ used here (0.125 per month) emanates from calibrations with the LEEDS-model (Håkanson, 1999). The mineralization rate operates in this model only on SPM in the surface and deep water, and not in the sediment compartments (for ET-areas and A-areas), which would require different (but largely unknown) mineralization rates. Mineralization is further assumed to be directly proportional to water temperature (Håkanson et al., 2000). This means that the loss of SPM from mineralization in the surface water is:

$$F_{\text{SW}\text{min}} = M_{\text{SW}} \times \frac{R_{\text{min}}}{9}$$  \hspace{1cm} (29)

where 9°C is a reference temperature related to the duration of the growing season (Håkanson and Bouillon, 2002). $R_{\text{min}} = 0.125$ (per month) and the mass (=amount) of SPM in the surface water ($M_{\text{SW}}$) is given by the model. The mineralization loss from the deep water is then:

$$F_{\text{DWT}\text{min}} = M_{\text{DWT}} \times \frac{R_{\text{min}}}{9}$$  \hspace{1cm} (30)

3.4.6. Burial

If the sediments are oxic (i.e., when the bioturbation is high), the age of the A-sediments ($T_A$), and hence also burial ($F_{\text{bur}}$), will be influenced by the biological mixing of zoobenthos. The algorithm for bioturbation (the dimensionless bioturbation factor, BF) is from Håkanson and Karlsson, 2003. We have:

If $\text{O}_2\text{Sat} < 20\%$ then $\text{BF} = 1$ else $\text{BF} = (1 + \text{D}_{\text{AS}})^{0.3}$

(31)

If $\text{O}_2\text{Sat}$ is lower than 20%, zoobenthos are likely to die and bioturbation halted. $D_{\text{AS}}$ is the depth of the bioactive A-sediment layer. The default value for $D_{\text{AS}}$ is set to 10 cm. This means that in oxic sediments $\text{BF} = (1 + 10)^{0.3} = 2.05$ and the sediment likely 2.05 times older than calculated from the ratio between the depth of the active A-sediments ($D_{\text{AS}}$ in cm) and sedimentation (in cm per year).

Burial ($F_{\text{bur}}$) is given by:

$$F_{\text{bur}} = \frac{M_{\text{A}}}{T_A}$$  \hspace{1cm} (32)

where $M_{\text{A}}$ is the total amount of matter in bioactive A-sediments (g) and $T_A$ is the age of the A-sediments. $T_A$ depends on bioturbation and this is given by:

$$T_A = \text{BF} \times D_{\text{AS}} \times \text{Area}(1 - \text{ET}) \times 10000 \left(1 - \frac{W}{100}\right) \frac{d}{P_{\text{FIMA}}}$$  \hspace{1cm} (33)

A general default value for the water content (W) of this sediment layer (0-10 cm) is set to 75%; ET
is calculated from Eq. (4) and the bulk density ($d$ in g/cm$^3$ ww) from a standard formula (Håkanson and Jansson, 1983) given by:

$$d = \frac{100 \times 2.6}{100 + (W + IG (1 - \frac{m}{q})) (2.6 - 1)} \quad (34)$$

where IG is the loss on ignition (=organic content); set to 10% dw as a default value. Values of recent sedimentation (Sed in cm per year), which may be of interest in contexts of sediment dating, may then be calculated from sedimentation ($F_{DNA}$). With dimensional adjustments, we have:

$$Sed = 12 \left( F_{DNA} \times 10^{-4} \right) / \text{Area}(1 - ET) \quad (35)$$

Modelled values for sedimentation will be compared to empirical data from sediment trap measurements. It should be noted that the sediment traps were generally placed in the deepest parts of the coastal areas. It is well known (Håkanson and Jansson, 1983) that net sedimentation increases from zero at the critical depth to maximum values at the deepest part of the basin, a phenomenon often referred to as “sediment focusing”. Thus, the empirical data provides maximum values for sedimentation. To obtain more realistic data for the comparison between modelled values and empirical data, we have used a correction factor for the model-predicted values based on this knowledge. The predicted values for sedimentation are assumed to be correct for U-shaped basins with relative depths approaching 3 ($D_{rel} = (D_{max} \times \sqrt{3}) / (20 \sqrt{\text{Area}})$; $D_{max}$ in m; Area in km$^2$), and too low for V-shaped basins with small $D_{rel}$-values. Thus, the ratio $3/D_{rel}$ is used as a correction factor. This means that the modelled values to be compared to the empirical sediment trap data are given by:

$$Sed_{model} = \frac{3}{D_{rel}} F_{DNA} \quad (36)$$

Note that if $D_{rel}$ is >3, the ratio ($3/D_{rel}$) is set to 1 and that one must multiply by (1/Area A x 30) to get $Sed_{model}$ in g dw/m$^2$ d.

3.5. The panel of driving variables

Table 5 gives the panel of driving variables. These are the coastal-area specific variables needed to run the model. All other parts of the model should not be changed unless there are good reasons to do so.

4. Results

Note that there has been no calibrations of the model. All equations have been motivated by empirical data or results based on empirical data.

The results of the validation are shown in Fig. 11. Here empirical data on sedimentation (sediment trap data, Emg) are directly compared to modelled values (modified from Eq. (36)). Note that the empirical data used here are the mean values of $Sed_{dw}$ and $Sed_{sw}$ for each coastal area given in Table 1; one can assume that the surface sediment traps will give too low values and the deep sediment traps too high values of net sedimentation on the A-areas. In Fig. 11, we also give characteristic empirical uncertainties for sedimentation in sediment traps, and we have used a CV of 0.5 (from Wallin et al., 1992; CV is the coefficient of variation = S.D./MV; where S.D. is the standard deviation and MV the mean value). In the figure, we give the 95% confidence interval (corresponding to a difference of two standard deviations from the mean empirical value). If the modelled values are within ±2 standard deviations from the empirical values, this must be regarded as a good result. The modelled
values are within or very close to those limits in 16 of the 17 cases (94%). There are only poor predictions in one area, Ekön. We will discuss this particular case in the following and also two other cases (Laitsalmi and Langönströmmar).

Also note that the median error is small. This means that the default settling velocity of 25 m per year is probably quite correct. One should also note that this is a blind test in the sense that there have been no changes in the model variables; we have only changed the obligatory coast-specific driving variables listed in Table 5. We will now discuss the results with a focus on the three areas marked in Fig. 11. These are the areas where the differences between modelled and empirical data are relatively high.

5. Discussion

For the coastal area Ekön (SE2 in Table 1), there is empirical data on ET (from Persson et al., 1994a). This is topographically and hydrodynamically a very sheltered coastal area and the empirical ET value is 0.19, which is significantly lower than the model-predicted value (0.75). If we use the empirical ET-value, the results are shown in Fig. 12. We then get very good predictions of:

(A) Sedimentation, the modelled values agree very well with the empirical results.

(B) The operational effect variable, O2Sat (the oxygen saturation of the deep water), the modelled value is between the maximum and minimum empirical values (data from Wallin et al., 1992).

(C) The operational effect variable Secchi depth; the modelled value is close to the empirical value for the summer period.

So, the approach to estimate the critical depth and ET works well for most of the studied coastal areas, but it may fail to predict ET in very sheltered and maybe also in very exposed coastal areas. Evidently, it is always best to base model predictions on reliable empirical data, not just on ET, but on all other variables influencing the modelled values of sedimentation.

Fig. 13 gives results for the coastal area called “Langönströmmar”, or in English “Island Langön rapids”. This is a coastal area known to be dominated by strong currents. The modelled value for the theoretical surface water retention time (\(T_{SW}\)) is 11 days, and the model-predictions of sedimentation are quite good (see Figs. 11 and 13). However, Persson et al. (1994a) gives a \(T_{SW}\)-value of 3 days for this coastal area, and if that \(T_{SW}\)-value is used instead of the value estimated with the formula given in Table 2, the model-predictions are very good (Fig. 13). It has been stressed before (Persson et al., 1994b), the empirical model for \(T_{SW}\) may give poor predictions in estuaries dominated by freshwater input, in coastal areas dominated by current action (as Langönströmmar) and in open coastal areas (if the Exposure is higher than 1.3).

Fig. 14 gives the results in more detail for the coastal area “Langönströmmar”, where the modelled values for sedimentation are close to the empirical data (Fig. 14A).

In this coastal area, we can note the (by far) highest empirical value on sedimentation in deep-water sediment traps (56.4 g dw/m².day). There is a very good correspondence between modelled values for O2Sat and measured data, the modelled values are close to the mean measured O2Sat-value and within plus one standard deviation from the mean (Fig. 14B). There is also a good relationship between modelled Secchi depths and the empirical value (Fig. 14C).
Fig. 12. Simulations in the Eknön area (SE2, see Table 1) if the empirical value (0.19) for the ET-area is being used for (A) sedimentation, (B) the oxygen saturation in the deep water and (C) the Secchi depth. The figure also gives the corresponding empirical data and uncertainties in the empirical data.

Fig. 13. Simulations of sedimentation in the Lagvönströmmar area (SE3, see Table 1) if the value of the theoretical surface water retention time ($T_{SW} = 3$ days) from Persson et al. (1994a) is being used instead of the $T_{SW}$-value predicted by the empirical sub-model.
Fig. 14. Results for the Laitsalmi area (F4, see Table 1) for (A) sedimentation, (B) the oxygen saturation in the deep water and (C) the Secchi depth. The figure also gives the corresponding empirical data and uncertainties in the empirical data.

From these results, we would like to stress the following points:

- It is always preferable to use empirical data to run the model instead of using values estimated from the given sub-models. The sub-models for $T_{SW}$, $T_{DW}$, ET, chlorophyll, etc. have been included here if such reliable empirical data are missing.
- However, empirical data to run and validate models may also be flawed or unreliable. The model predicts mean monthly values for defined coastal areas, and not specific data for certain sample sites and there may be poor time- and area-compatibility between modelled area-typical values and empirical site-typical data.

6. Model tests and simulations

6.1. Calculation of fluxes and model sensitivity

This model may be used to address several interesting issues, e.g., (1) to calculate and compare deposition of matter in different coastal areas, which is essential in studies concerning the age of sediments and sediments as a historical archive, (2) to
test hypothesis about the relative role of various processes in relation to the target variables, and (3) to calculate and rank fluxes. These issues will be briefly discussed in this section. It is very important to identify small and large fluxes of SPM, e.g., in remedial contexts so that realistic expectations can be obtained for various remedial measures intended to reduce SPM and the associated risk of low oxygen concentrations and, hence, the risks to key functional benthic species.

In this scenario, we will compare the fluxes in three coastal areas, one with direct contact with the sea, SE1, one area situated deep into the Finnish archipelago, F4, and one area from the Blekinge archipelago in S. Sweden, SS4. The aim it to see which fluxes dominate in the three cases. The working hypothesis is that there may be major differences in the ranking of the fluxes between the areas, that the fluxes from the sea dominate in area SE1 and not in area F4, where other fluxes, maybe primary production, may dominate.

The results are given in Fig. 15. One can note:

- There are no major differences between the three coastal areas. The surface water fluxes of SPM dominate in all three areas.
- There is a logical difference in the ranking of the fluxes in the three cases, especially concerning: land uplift, which is more important in area SE1, which has a direct contact with the sea. Land uplift is zero in area SS4.
- The working hypothesis concerning the role of the primary production in the coastal areas must be rejected. Primary production is one of the smallest of all the given SPM fluxes in all three areas.
- Most importantly, the main working hypothesis, that there is a major difference in the ranking between the areas must also be rejected. There are no major, only minor differences between the three areas. The surface water fluxes dominate in these cases.

This means that the conditions in the sea play an important role for the transport of SPM, and hence also for all pollutants associated with carrier particles included in this group, in most or maybe all Baltic coastal areas. The entire Baltic Sea is, in fact, made up of several communicating basins (Håkanson et al., 2002). From a hydrodynamical viewpoint, it may be regarded as one system. This is also a logical consequence of the fact that the characteristic theoretical surface water retention times in these coastal areas are short (in the order of days, or in exceptional cases, of weeks).

Fig. 16 gives a compilation of seasonal (monthly) SPM-values in these 17 coastal areas and Fig. 17 shows how sedimentation in cm per year varies on a monthly basis in the areas. It is interesting to note:

![Fig. 15. Simulations giving a ranking of all the SPM-fluxes (transport processes) in the dynamic model for area SE1 (L. Rimm), which has direct contact with the Sea), area SS4 (Guavik, which is also exposed to the Sea) and area F4 (Laitsalmi, Finland), which is deep in the Finnish archipelago.](image-url)
• That area-characteristic SPM-values vary from about 3.5 to 8 mg/l.
• That there are coastal areas without any clear seasonal SPM-patterns, and also areas with higher SPM-concentrations in the summer and fall and also areas with lower values in the summer, depending on the specific characteristics of the coast.
• That the mean net sedimentation varies between 0.1 and 0.65 cm per year and that also for sedimentation there is no clear seasonal pattern prevailing in all coastal areas. One should also note that these are mean values for the entire A-area and that the net sedimentation varies from 0 at sites close to the critical water depth to maximum values at sites in the deepest parts of the coastal areas.
• This means that the age of the bioactive A-sediments (0–10 cm) is between 15 and 100 years in these areas.

6.2. Sensitivity and uncertainty analyses

Sensitivity analysis means that one x-variable in a model is varied in a defined way and the corresponding uncertainty in the y-variable determined, while all else
is constant. Uncertainty analysis means that the uncertainties in many x-variables are accounted for at the same time and the total uncertainty in the y-variable calculated. Here, we will carry out sensitivity and uncertainty analyses according to procedures given by Håkanson (1999).

An initial sensitivity analyses for one of the studied coastal areas, Matvik (SS1) using a coefficient of variation (CV) of 0.5 for sedimentation from surface water to ET-areas (FSWET) is given in Fig. 18 for the target variable, sedimentation on A-areas (FSWA). The idea is to get a quantification of the role of this flux for the value of the target variable, while all else is constant. 100 runs have been simulated and we have used a normal frequency distribution for the uncertainty in the x-variable. Then, one can note that the uncertainty in the target y-variable is considerable. In the following, we will present many tests like this and compare the uncertainty in the y-variable using the data generated for July (month 31), as illustrated in Fig. 18.

Fig. 19 gives the results when we have used a uniform uncertainty (a CV of 0.5 and a normal frequency distribution around each mean value) for all the fluxes in the model. The idea has been to rank the importance of the various uncertainties for the predic-

![Fig. 18. Results from a sensitivity test (100 runs) using data for coastal area SS3 (Matvik). We have defined the uncertainty for one of the fluxes, sedimentation from surface water to ET-areas, by a coefficient of variation (CV) of 0.5 and by a normal frequency distribution around the mean flux, as predicted by the model; and we have kept all else constant. The idea is to study how this uncertainty would influence the uncertainty in the target variable, sedimentation on A-areas. For the following comparative tests, we have selected the data from July (month 31), as indicated in the figure.](image1)

![Fig. 19. Sensitivity analyses using a uniform CV of 0.5 for all fluxes for coastal area Matvik, SS1](image2)
3. The value used for the ET-areas (ET). This is an important distribution coefficient in this model and the ET-value is predicted by a sub-model. Those predictions are, as shown for the coastal area Eknoin, occasionally very uncertain. The characteristic CV is set to 0.5.
4. The theoretical surface water retention time \(T_{SW}\). This value is important because it regulates the fluxes of SPM to and from the sea and/or adjacent coastal areas. \(T_{SW}\) is calculated from an empirical model that has given an \(r^2\)-value of 0.95 (see Table 2), but occasionally (as discussed for the coastal area Lagnöstrommar), the predicted \(T_{SW}\)-value is uncertain and CV is set to 0.25.
5. The theoretical deep water retention time \(T_{DW}\). \(T_{DW}\) is also calculated from an empirical model, which gave an \(r^2\)-value of 0.79. CV is set to 0.35.
6. Land uplift (LU). It is evidently very difficult to set a reliable CV for land uplift. The CV for LU is likely very high and set to 0.5.
7. The Chl-concentration regulating primary production. The CV is set to 0.25 (Wallin et al., 1992).
8. Salinity (Sal). There exists comparatively reliable data on the salinity and the CV is set to 0.15.

![Graph showing uncertainty analyses using characteristic CVs for the driving variables for coastal area Mativik, SS1.](image-url)
9. The feed conversion ratio (FCR) influencing the point source emissions of SPM. We have used a standard value of 1.5, which may not be true for all fish farms. CV is set to 0.1.
10. Surface water temperature (SWT). SWT is predicted from a modified version of a well-tested model and the CV-value is set to 0.1.
11. Finally, coastal area. This value can be determined quite well but there may be uncertainties related to where the boundary line defining the coastal area is drawn. This CV is set to 0.05.

The aim now is (1) to produce a ranking of these uncertainties for the target variable, (2) to see if the model is well balanced, and (3) to control if the predicted CV-values for the target variable correspond to the empirical CV-value, as a check if the assumed CV-values for the driving variables are reasonable.

The following test uses data for coastal area SS1, Marvik (see Table 1). The results are given in Fig. 20. Note:

- The total calculated CV for $F_{DBA}$ according to this testing procedure is 0.83. The empirical CV for sedimentation in sediment traps is 0.5 (Wallin et al., 1992). This means that the assumptions concerning the CV-values for the model variables should be reasonable. The CV's for the model variables should be set according to the precautionary principles so that the calculated CV is not smaller than the empirical CV.
- The most important factor is the uncertainty associated with the value used for the ET-areas. If this uncertainty is omitted, CV for $F_{DBA}$ decreases the most, from 0.83 to 0.36. This means that future model development should concentrate on getting more reliable data and/or sub-models for the ET-areas. This is the best way to reduce the uncertainties in predictions of $F_{DBA}$.
- The model is not so well balanced since the model predictions depend so much on one single uncertainty. In a well-balanced model, no part of the model dominates the calculated uncertainty in the target variables.

![Fig. 21](image-url) A scenario (and a sensitivity test) illustrating the practical use of the model in coastal management. We have varied the annual fish production in the fish farm in this coastal area (Marvik, SS1) from 0 tonnes per year (0 per year), to 10 (the actual value in this area in this study), to 50, 100 and 200 per year and studied how this would likely influence (A) total-N concentrations, (B) sedimentation, (C) Secchi depth and (D) oxygen saturation in the deep water. The figure also shows the corresponding empirical data and uncertainties in the empirical data.
7. Scenario illustrating the practical use of the model

This section has been included to exemplify how this model can be used in practical contexts in coastal water management. The questions asked here are: How large point source emissions of SPM can be accepted in a given coastal area? And why?

We have selected coastal area Jämavik (SSS). In this coastal area there are no other point source emissions of SPM beside those from the fish farm. We have assumed that the fish farm emissions influence the TN-concentration in the water. It would have been best if this influence could have been predicted by a validated mass-balance model for nitrogen, which meet the criteria for a practical useful model discussed in the introduction. Unfortunately, we do not know of any such model, so in this scenario we will do the second best. We will assume that the fish farm emissions influence the TN-concentration in the same manner as they influence the SPM-value in the coastal area. We will also assume (from data given by Wallin et al., 1992) that the regional reference value for the TN-concentration in this coastal area is 260 μg/l (had there been no fish farm in the area). From these presuppositions, we have simulated the changes in TN-concentrations (Fig. 21A), sedimentation (FDWSS; see Fig. 21B), and in our operational effect variables, O₂Sat (Fig. 21D) and Secchi depth (Fig. 21C), if the annual fish production in the farm is set to 0, 10, 50, 100 and 200 tonnes; the actual fish production is 100. From Fig. 16, we can then note:

- If 200 t per year fish were to be produced in this coastal area, the TN-concentrations would likely increase very much, which would reduce the Secchi depth from about 5 to 2.5 m, increase sedimentation and decrease O₂Sat.
- The Secchi depth is the most sensitive operational effect variable in this scenario.
- The changes are likely small if less than 50 t are produced, so this should probably be the maximum production that the regional environmental authorities would permit.

8. Conclusions

We have presented a model for sedimentation in coastal areas. This is a relatively comprehensive dynamic mass-balance model and there are two regression models for operational effect variables incorporated in the model so that the total model may be regarded as an ELS-model (effect-load-sensitivity-model) for coastal water management. The target variable in the dynamic model, sedimentation on accumulation areas, is related to the operational effect variable, oxygen saturation of the deep water, via a regression. The nitrogen concentration is transformed to a primary production sub-model by means of another regression model. All the processes included in the dynamic model are generic and apply for many other substances than SPM, although rate constants and other substance-specific factors may have to be duly adjusted to the different substances, and for other coastal areas than those discussed here. The model has been validated against empirical data from 17 Baltic coastal areas with very good results. The model-predictions are logical also in the only coastal area where the initial, default predictions failed.

The main reason for the high predictive power of the model presented in this paper relates to the model structuring. The same basic principles of model structuring apply to most water pollutants in most aquatic ecosystems. This indicates that in the future, we may see an interesting development in ELS-modelling. This could mean that a better base in the environmental sciences can be established, where validated ELS-models would play an important role in simulations of different strategies for remedial measures, in cost-benefit analyses and in science education.

Finally, it may be said that the only way to derive a generic model yielding perfect predictions for the entire domain of coastal areas on earth, would be to account for all processes. This would be like map making in scale 1:1! Simplifications are always needed, and in this work we have tried to motivate why these simplifications have been done and why this model has its present structure.

References


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