# Chapter 2
# Basic Information on the Baltic Sea

## 2.1 Introduction and Aim

Empirical data ultimately form the basis for most environmental studies. As Goethe once eloquently put it: "Grey, dear friend, is all theory, and green the golden tree of life". The focus of this chapter is on empirical data and empirical models. Extensive databases on the conditions in the Baltic Sea and other aquatic systems have been "data-mined" and in this chapter we will present results showing variations of target variables related to the eutrophication in the Baltic Sea (nutrient concentrations, chlorophyll-a concentrations and Secchi depths) and trend analyses to see if there have been any changes in these variables in the Baltic Sea. To put these results into a wider context, we have also used data from more than 500 aquatic systems throughout the world.

Another aspect of the work presented in this chapter concerns the use of hypsographic curves (i.e., depth/area-curves for defined basins) to calculate the necessary volumes of water of the defined vertical layers. New depth/area curves and volume curves for the Baltic Sea and its five major sub-basins will be presented. These curves have been derived using the, to our knowledge, best available public dataset on the bathymetry of the Baltic Sea (Seifert et al., 2001). This information is essential in the mass-balance modeling for salt discussed in Chap. 3 and the mass-balance modeling for phosphorus discussed in Chaps. 5 and 6. If there are errors in the defined volumes, there will also be errors in the calculated concentrations since, by definition, the concentration is the mass of the substance in the given volume of water.

This chapter also presents an approach to define and differentiate between surface-water and deep-water layers. Traditionally, this is done by water temperature data, which defines the thermocline, or by salinity data, which defines the halocline. Our approach is based on the water depth separating areas where sediment resuspension of fine particles occurs from bottom areas where periods of sedimentation and resuspension of fine cohesive newly deposited material are likely to happen (the erosion and transportation areas, the ET-areas). The depth separating areas with discontinuous sedimentation (the T-areas) from areas with continuous sediment accumulation (the A-areas) of fine materials is called the theoretical wave

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base. This is an important concept in mass-balance modeling of aquatic systems (see Håkanson, 1977, 1999, 2000). The theoretical wave base will also be used to define algorithms (1) to calculate concentrations of matter in these volumes/compartments, (2) to quantify sedimentation by accounting for the mean depths of these compartments, (3) to quantify internal loading via advection/resuspension as well as diffusion (the vertical water transport related to concentration gradients of dissolved substances in the water), (4) to quantify upward and downward mixing between the given compartments, and (5) to calculate outflow of substances from the given compartments.

In this work, the Baltic Sea has first been divided into its five traditional main sub-basins (see Fig. 1.1), the Bothnian Bay (BB), the Bothnian Sea (BS), the Baltic Proper (BP), the Gulf of Finland (GF) and the Gulf of Riga (GR). Note that an important factor in the selection of sub-basins concerns the accessibility of data to run and test the mass-balance model, CoastMab, which gives monthly predictions for entire defined compartments. Empirical monthly values of the salinity have been used to calibrate the CoastMab-model for salt and those calculations provide data of great importance for the mass-balance for phosphorus, namely:

(1) The fluxes of water to and from the defined compartments.
(2) The monthly mixing of water between layers within the given compartments.
(3) The basic algorithm for diffusion of dissolved substances in water in each compartment.

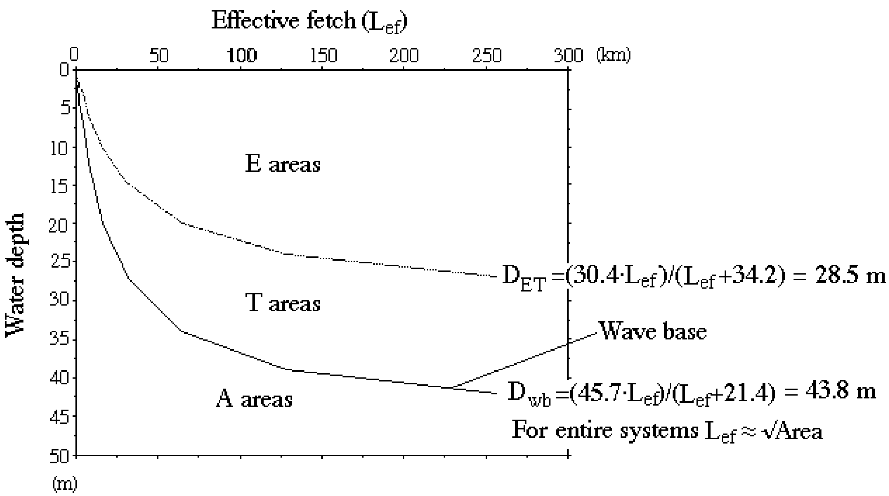


**Fig. 2.1** The ETA-diagram (erosion-transportation-accumulation) illustrating the relationship between effective fetch, water depth and bottom dynamic conditions. The theoretical wave base ($D_{wb}$; 43.8 m in the Baltic Proper on average) may be used as a general criterion in mass-balance modeling to differentiate between surface water with wind/wave induced resuspension and deeper areas without wind-induced resuspension of fine materials following Stokes' law. The depth separating E-areas with predominately coarse sediments from T-areas with mixed sediments is at an average depth of 28.5 m in the Baltic Proper

(4) The water retention rates influencing the turbulence in each compartment, and hence also
(5) The sedimentation of particulate substances in the given compartments.

So, this chapter will provide and discuss the necessary data to run the CoastMab-model for salt in Chap. 3, which in turn provides important data for the calculations of the phosphorus fluxes in Chap. 5. It should be stressed that once we have calibrated the mass-balance model for salt, there will be no further calibrations or tuning of the CoatsMab-model – the same water fluxes will be used also in the mass-balance model for nutrients (phosphorus).

## 2.2 Previous System-Wide Studies in the Baltic Sea

Although this book should be seen as a complement to previous Baltic Sea research, it also contains substantial critique against much of the work that has provided the basis for the current management policy. First, conceptual models have become very popular in this research field. Descriptive, conceptual models consist of informatively drawn figures with arrows which suggest causal paths defining how the ecosystem functions, although these arrows lack quantitative information. Some examples of such models can be found in Rönnberg and Bonsdorff (2004) and Vahtera et al. (2007). This type of models may have some heuristic value, but they may also provide insufficient or even deceptive information about the quantitative ecosystem response from measures against eutrophication (Peters, 1991). In lake eutrophication studies, where considerable ecological improvement has been observed during the last decades (Bryhn and Håkanson, 2007), conceptual approaches have yielded very meagre results with respect to practical usefulness, whereas approaches based on quantitative prediction have been instrumental to the ecological success story in that field (Peters, 1986).

However, other recent work concerning the Baltic Sea has indeed been based on predictive approaches. This brings us to the second main point in our critique. The model that was used to predict the future environmental state and to elaborate abatement goals in the ambitious Baltic Sea Action Plan (HELCOM, 2007) is called the MARE NEST model, and sometimes referred to as the SANBaLTS model. According to its constructors, it "heavily relies on subjective comparison with empirical information in a tuning of basin-specific constants" (Savchuk and Wulff, 2007). This is a very important point that requires a more detailed discussion.

The designers of the MARE NEST model have described several coefficients by means of general values or algorithms (Savchuk, 2006), but have failed to define all of them in this way. Model constants that are still tuned differently for different basins include nutrient mineralization rates in the water and in sediments, the nutrient burial rate in sediments, the denitrification rate, the sediment P sequestration rate and the labile fraction of organic N (Savchuk, 2006). This type of site-specific tuning is a common practice in ecological modeling, although it has been criticized for supporting unreliable, or even untestable, model structures. Careful tuning of several available constants may provide several constant combinations and acceptable validation results every time, making refutation of the model structure very difficult (Mann, 1982; Peters, 1991; Bryhn and Håkanson, 2007).

Furthermore, the MARE NEST model is built on the assumption that sediment erosion and resuspension only occurs in the Baltic Proper and not in the other large Baltic Sea basins (Savchuk, 2006; Savchuk and Wulff, 2007), although it is well known that this flux is substantial in the other basins as well (Jonsson and Carman, 1994; Leivuori and Vallius, 1998; Floderus et al., 1999; Jönsson, 2005). Instead, the total nutrient transport from the sediment to the water in the other basins except in the Baltic Proper is assumed in the MARE NEST model to consist of DIN and DIP leakage only (Savchuk, 2006).

It is possible that the absence of resuspension flux estimates to all basins, and particularly resuspension of glacial material due to land uplift (Jonsson et al., 1990), is a major reason why the MARE NEST modelers have hitherto failed to avoid basin-specific tuning. In this context, it is important to bear in mind that model constructs that require a unique type of tuning for each new site may be very unreliable for predicting how ecological variables will respond to nutrient abatement and other external changes in the future (Mann, 1982; Peters, 1991).

An alternative approach to predict ecological effects in the Baltic Sea from nutrient abatement is the 3D hydrodynamical model used by Neumann (2000), Neumann et al. (2002), Janssen et al. (2004), Thamm et al. (2004), Neumann and Schernewski (2005) and Schernewski and Neumann (2005) and is referred to as ERGOM. This approach does simulate resuspension, although it assumes that the resuspension rate is independent from bottom depth and type (Neumann, 2000). In addition, ERGOM is driven by meteorological data (Neumann, 2000), which cannot be provided for scenarios longer than a few days into the future.

ERGOM lacks basin-specific constants, which could be seen as an advantage in relation to the MARE NEST model, although simulation data from ERGOM using fixed model constants have been successfully validated against empirical data to a rather limited extent in the seven mentioned studies. The validation in Neumann (2000) did not concern any concentrations or Secchi depths but it included changes in the nitrogen budget over one year. Tests in Neumann et al. (2002) included empirical data from three stations in the Baltic Proper. In Janssen et al. (2004), ERGOM was tested against data from one monitoring station with good results, although the model predictions of the spread of cyanobacteria blooms showed little resemblance with satellite pictures over the same blooms. Similarly, Thamm et al. (2004) investigated the spatial distribution of phytoplankton in the Southern Baltic Sea and commented that there was a "limited reliability of the data for spatial analysis". Neumann and Schernewski (2005) included tests against data from one monitoring station. Schernewski and Neumann (2005) produced data that were well in line with average empirical values from the Gulf of Riga and the Baltic Proper, although model results from the other major basins were not validated and should, according to the ERGOM modelers, "be treated with care".

As this book demonstrates, it is both necessary and possible to combine the ambition of the ERGOM modelers to use a fixed set of model constants, with the ambition of the MARE NEST modelers to get good correspondence between modeled and empirical eutrophication data for all of the major basins in the Baltic Sea.

## 2.3 Databases and Methods

Basin-specific data used in this modeling are compiled in Table 2.1 and will be explained in the following section. This table gives data on, e.g., total area, volume, mean depth, maximum depth and the depth of the theoretical wave base ($D_{wb}$ in m), the fraction of bottoms areas dominated by fine sediment erosion and transport (ET-areas) above the theoretical wave base, the water discharge to the given sub-basins (from literature sources; see later), the catchment area, latitude and mean annual precipitation for each basin.

Tables 2.1 and 2.2 show the very comprehensive set of data from the Baltic Proper with more than 40,000 measurements on water temperature, salinity, TN- and TP-concentrations and over 12,000 data on chlorophyll-a concentrations for the period from 1990 to 2005 that has been used in this work. Most water variables in the Baltic Sea and in aquatic systems in general (see Håkanson and Peters, 1995; Håkanson and Bryhn, 2008a) appear with negatively skewed frequency distributions (mean values are higher than medians). This means that one could preferably use median values to represent the characteristic conditions in the given system. From Table 2.2, one can also note that the mean and median values for temperature, salinity and TP-concentrations are generally quite close, but that there are few marked exceptions when a few outliers provide a skewness to the frequency distribution so that the ratio for normality (the mean/median or MV/M50 ratio is clearly different from 1). Note specifically:

- The difference in mean and median values for the salinity in the MW-layer in the Baltic Proper (7.72 and 8.91 psu).
- The relatively high coefficients of variation ($CV = SD/MV$; SD = standard deviation; MV = mean value) for the temperatures in the SW-layers in the Bothnian Bay (1.02) and the Baltic Proper (0.7) and in the DW-layers in the Bothnian Bay (0.64) and the Bothnian Sea (0.59).
- The high CV-values for the TP-concentrations in MWBP (middle-water layer in the Baltic Proper), 0.62, SWBB 0.43, DWBB 0.39 and DWBS 0.38.

These high CVs have been exemplified and stressed here because they will influence the results when empirical data are compared to modeled values using the CoastMab-model for salt and phosphorus, and the uncertainties in the temperature data will influence the calculated fluxes related to mixing, which are based in these empirical temperature data.

The data from the Baltic Proper emanate from samplings all seasons of the year between latitudes 53.9 and 60.2 (°N) and longitudes 12.2 and 23.3 (°W). This means that most parts of the Baltic Proper are covered by these data (see Fig. 2.2). Note that this is the basin with the most reliable data.

**Table 2.1** Basic data (and abbreviations) for the five main sub-basins in the Baltic Sea. These concepts are explained in the text

| | | Gulf of Finland (GF) | Gulf of Riga (GR) | Bothnian Bay (BB) | Bothnian Sea (BS) | Baltic Proper (BP) |
|---|---|---|---|---|---|---|
| Land uplift 1 ($LU_1$) | (mm/yr) | 1.2 | 0.55 | 8.0 | 6.5 | 1.75 |
| Land uplift 2 ($LU_2$) | (mm/yr) | 2.0 | 0.75 | 9.0 | 8.0 | 2.75 |
| Mean land uplift (LU) | (mm/yr) | 1.6 | 0.625 | 8.5 | 7.25 | 2.25 |
| Area (A) | ($km^2$) | 29,600 | 16,700 | 36,300 | 79,300 | 211,100 |
| Wave base (WB) | (m) | 43.8 | 39.2 | 41.1 | 42.5 | 43.8 |
| Area above WB (ET) | ($km^2$) | 18,650 | 13,190 | 23,000 | 32,510 | 87,600 |
| Volume “clay” | ($km^3$/yr) | 0.03 | 0.008 | 0.21 | 0.24 | 0.19 |
| ET-areas (ET) | (%) | 63 | 79 | 63 | 41 | 47 |
| Area below WB ($Area_{WB}$) | ($km^2$) | 10,950 | 3510 | 13,300 | 46,790 | 123,500 |
| Depth, E-areas ($D_E$) | (m) | 25.4 | 24.0 | 25.8 | 27.1 | 28.3 |
| Erosion (E)-areas | ($km^2$) | 12,020 | 7810 | 18,050 | 25,240 | 55,630 |
| Max. depth ($D_{max}$) | (m) | 105 | 56 | 148 | 301 | 459 |
| Volume (V) | ($km^3$) | 1073.3 | 409.4 | 1500.0 | 4889.0 | 13,055 |
| Mean depth ($D_m$) | (m) | 36.3 | 24.5 | 41.3 | 61.7 | 61.8 |
| Relative depth ($D_{rel}$) | (–) | 0.054 | 0.038 | 0.068 | 0.065 | 0.088 |
| Form factor ($V_d$) | (–) | 1.04 | 1.31 | 0.84 | 0.61 | 0.40 |
| Dynamic ratio (DR) | (–) | 4.74 | 5.27 | 4.61 | 4.56 | 7.43 |
| Halocline depth ($D_{hc}$) | (m) | 75 | – | – | – | 75 |
| Water discharge (Q) | ($km^3$/yr) | 29.0 | 33.2 | 100 | 95 | 250 |
| Catchment area (ADA) | ($km^2$) | 421,000 | 167,000 | 269,500 | 229,700 | 568,973 |
| Latitude (Lat) | (°N) | 60 | 57.7 | 64 | 62 | 58 |
| Precipitation (Prec) | (mm/yr) | 593 | 590 | 650 | 700 | 750 |

**Table 2.2** A statistical compilation of water temperatures, salinities and TP-concentrations in surface-water areas, middle-water areas and deep-water areas in the Baltic Proper, the Bothnian Sea and the Bothnian Bay

| | Temp. (°C) | Salinity | TP (μg/l) |
|---|---|---|---|
| Baltic Proper, 1997–2005, Surface water (SW, D < 43.8m) | | | |
| M50 | 5.54 | 7.04 | 18.89 |
| MV | 7.19 | 7.05 | 19.79 |
| SD | 5.06 | 0.90 | 7.85 |
| n | 12,315 | 12374 | 12452 |
| CV | 0.70 | 0.13 | 0.40 |
| Baltic Proper, 1997–2005, Middle water (MW, 43.8m < D < 75m) | | | |
| M50 | 3.91 | 7.72 | 34.07 |
| MV | 4.43 | 8.92 | 43.95 |
| SD | 1.93 | 2.64 | 27.14 |
| n | 3951 | 3989 | 3997 |
| CV | 0.44 | 0.30 | 0.62 |
| Baltic Proper, 1997–2005, Deep water (DW, D > 75m) | | | |
| M50 | 5.16 | 10.28 | 114.61 |
| MV | 5.31 | 10.66 | 115.41 |
| SD | 0.95 | 1.75 | 35.03 |
| n | 6213 | 6289 | 6315 |
| CV | 0.18 | 0.16 | 0.30 |
| Bothnian Sea, 1997–2005, Surface water (D < 42.5 m) | | | |
| M50 | 4.24 | 5.40 | 9.91 |
| MV | 4.65 | 5.41 | 10.05 |
| SD | 2.76 | 0.12 | 2.36 |
| n | 216 | 216 | 216 |
| CV | 0.59 | 0.02 | 0.23 |
| Bothnian Sea, 1997–2005, Deep water (D > 42.5 m) | | | |
| M50 | 3.69 | 6.18 | 0.74 |
| MV | 3.77 | 6.12 | 0.74 |
| SD | 1.11 | 0.38 | 0.28 |
| n | 215 | 215 | 215 |
| CV | 0.30 | 0.06 | 0.38 |
| Bothnian Bay, 1995–1998, Surface water (D < 41.1 m) | | | |
| M50 | 3.11 | 3.33 | 5.11 |
| MV | 3.12 | 3.38 | 5.71 |
| SD | 3.19 | 0.38 | 2.48 |
| n | 350 | 355 | 356 |
| CV | 1.02 | 0.11 | 0.43 |
| Bothnian Bay, 1995–1998, Deep water (D > 41.1 m) | | | |
| M50 | 2.67 | 3.58 | 5.27 |
| MV | 2.42 | 3.61 | 5.70 |
| SD | 1.55 | 0.25 | 2.24 |
| n | 198 | 200 | 202 |
| CV | 0.64 | 0.07 | 0.39 |

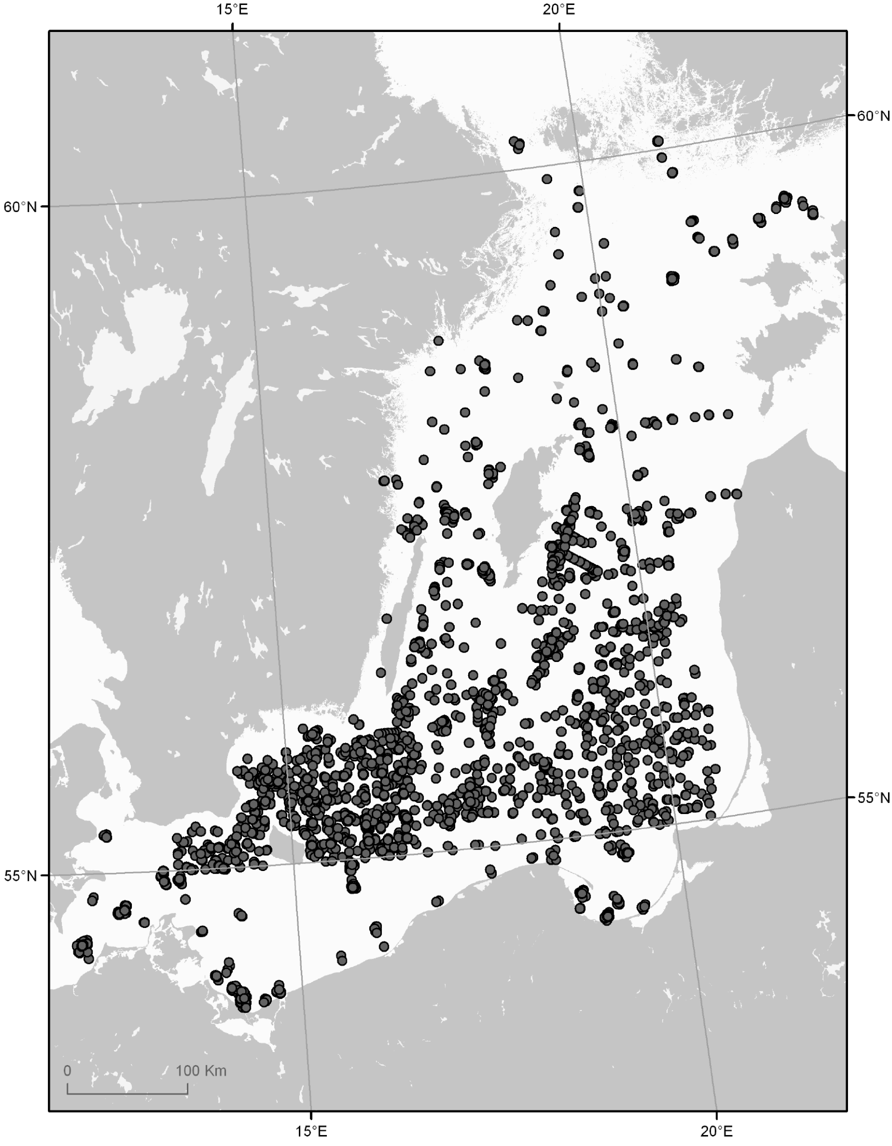


**Fig. 2.2** Sample sites (from HELCOM) in the Baltic Proper

The theoretical wave base is defined from the ETA-diagram (erosion-transport-accumulation; from Håkanson, 1977), which gives the relationship between the effective fetch, as an indicator of the free water surface over which the winds can influence the wave characteristics (speed, height, length and orbital velocity). The theoretical wave base separates the transportation areas (T), with discontinuous sedimentation of fine materials, from the accumulation areas (A), with continuous sedimentation of fine suspended particles. The theoretical wave base ($D_{wb}$ in meter) is, e.g., at a water depth of 43.8 m in the Baltic Proper. This is calculated from Eq. (2.1) (A = area in square kilometer; see also Håkanson and Jansson, 1983):

$$D_{wb} = (45.7 \cdot \sqrt{Area})/(\sqrt{Area} + 21.4) \tag{2.1}$$

It should be stressed that this approach to separate the surface-water layer from the deep-water layer has been used and motivated in many previous contexts for both lakes (Håkanson et al., 2004) and coastal areas (Håkanson and Eklund, 2007). So, this model structure is not new, but it has not been applied before to such large areas as the sub-basins in the Baltic Sea. This approach gives one value for the theoretical wave base related to the area of the system.

Figures 2.3 and 2.4 illustrate empirical data on TP, TN-concentrations, salinities and water temperatures from the Baltic Proper from 100 randomly selected verticals from months 5 to 9 for the period 1997–2005 at stations with water depths larger than 100 m. The idea is to show how these variables vary during the summer time and to illustrate the relevance of the depth intervals used in this modeling. Figure 2.5 exemplifies the variations in chlorophyll data in the Baltic Proper for different depth

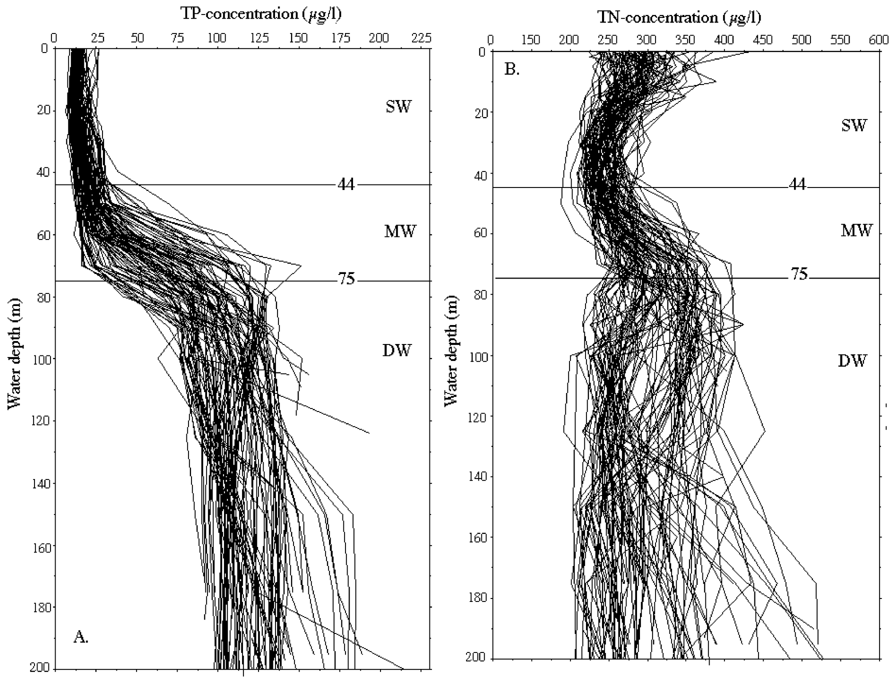


**Fig. 2.3** One hundred daily verticals selected at random from stations deeper than 100 m from the Baltic Proper collected months 5–9 between 1997 and 2005: (**A**) TP-concentrations and (**B**) TN-concentrations; and *lines* indicating surface-water areas (SW), middle-water areas (MW) and deep-water areas (DW)

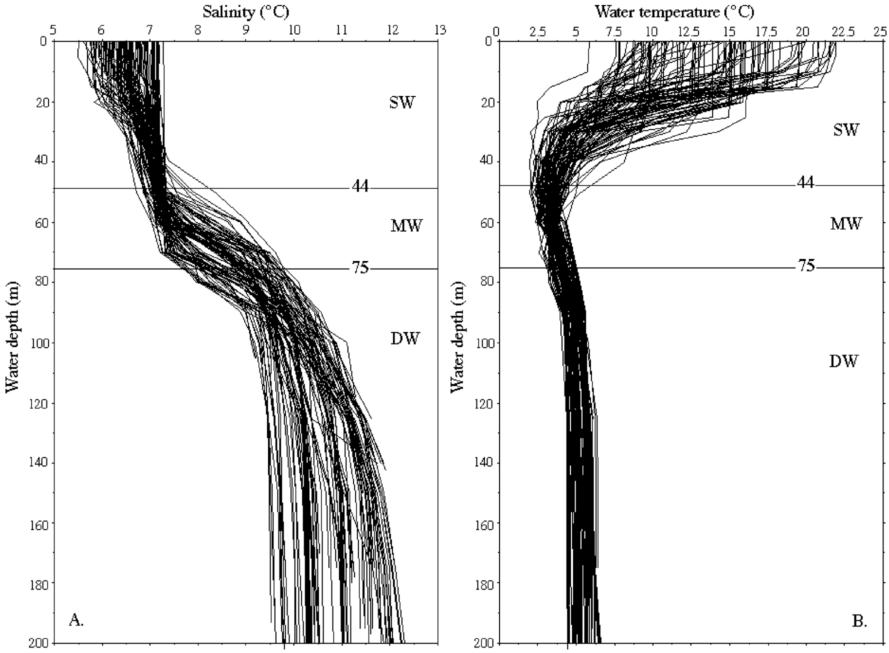


**Fig. 2.4** One hundred daily verticals selected at random from stations deeper than 100 m from the Baltic Proper collected months 5–9 between 1997 and 2005: (**A**) salinities and (**B**) temperatures; and *lines* indicating surface-water areas (SW), middle-water areas (MW) and deep-water areas (DW)

intervals and one can note that the highest values, as expected, are to be found in the upper layer. As a reference to the theoretical wave base, Fig. 2.5 also gives information that the average Secchi depth in the Baltic Proper is about 7 m (the standard deviation is 3.3 based on 14,306 data from the period 1990 to 2005 using data from the HELCOM database). The depth corresponding to two Secchi depths is indicative of the total depth of the photic zone (see Håkanson and Boulion, 2002). Figure 2.6 exemplifies vertical variations in TP-concentrations in the Gulf of Finland (GF) and how these TP-concentrations relate to the mean depth (36 m in GF), the depth of the theoretical wave base (at 41 m in GF) and the mean depth of the halocline (75 m) and the maximum depth of the bay (105 m). Table 2.2 gives a statistical compilation of data on water temperature, salinity and TP-concentrations in the Baltic Proper, the Bothnian Sea and the Bothnian Bay in water layers defined from the theoretical wave base and the average depth of the halocline.

Figures 2.3–2.6 and Table 2.2 have been included here to demonstrate by means of empirical data that the same basic principles related to the relationship between the effective fetch, the water depth and the potential bottom dynamic condition apply to all basins, independent of the salinity of the water. It should be stressed that the average position of the theoretical wave base may not the same as the average position of the thermocline. This is evident from Fig. 2.4B. It is also clear from

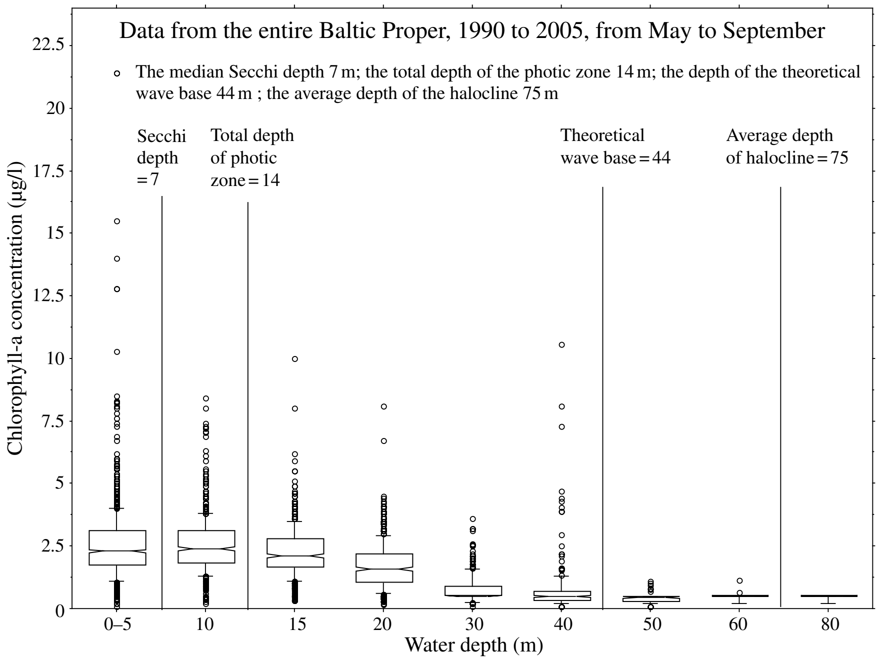


**Fig. 2.5** Chlorophyll-a concentrations at different water depths in the Baltic Proper. The median Secchi depth this period (1990–2005) based on all individual data was 7 m, the theoretical wave base 44 m, and the average depth of the halocline 75 m

Fig. 2.4B that it is often difficult to define the position of the thermocline from measured vertical temperature profiles. Almost any value between 15 and 45 m could be selected based on the data given in Fig. 2.4B for the summer period in the Baltic Proper. This is also true for the other sub-basins in the Baltic Sea, and for most lakes, as exemplified in Fig. 2.7 for Lake Erken, Sweden.

These empirical data support the validity of the theoretical wave base also for large systems. So, in this modeling, the Baltic Proper (BP) and the Gulf of Finland (GF) have been divided into three depth intervals:

(1) The surface-water layer (SW), i.e., the water above the theoretical wave base.
(2) The middle-water layer (MW), as defined by the depth between the theoretical wave base m and the average depth of the halocline.
(3) The deep-water layer (DW) is defined as the volume of water beneath the average halocline.

The Bothnian Bay (BB), the Bothnian Sea (BS) and the Gulf of Finland (GF) have been divided into two layers, the SW and the DW-layers separated by the theoretical wave base. From Table 2.1, one can note that the theoretical wave base is at 43.8 m in GF, 39.2 m in GR, 41.1 m in BB, 42.5 m in BS and 43.8 m in BP. The areas below this depth vary from 3510 $km^2$ in the Gulf of Riga to 123,500 $km^2$ in the Baltic Proper.

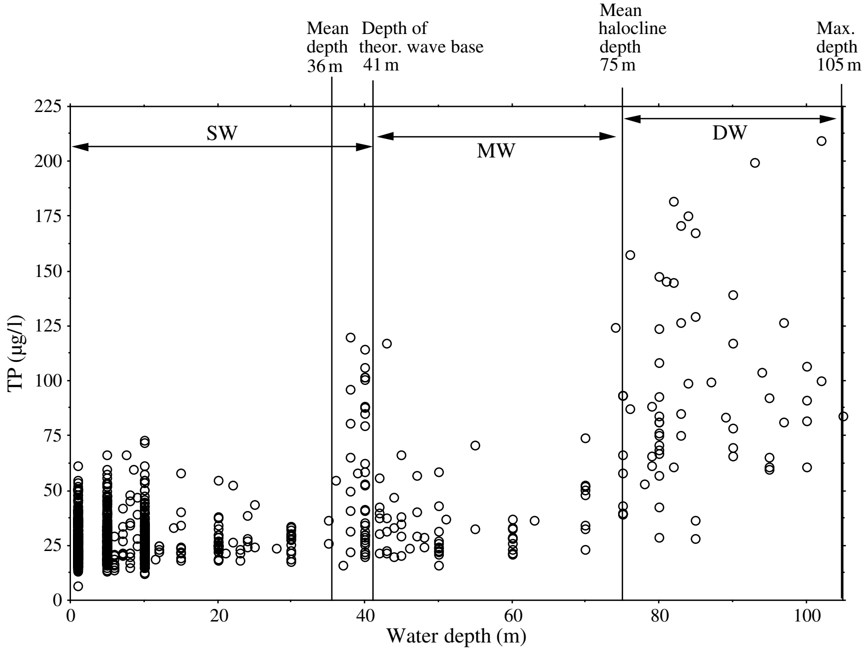


**Fig. 2.6** Total phosphorus concentrations in the Gulf of Finland (1990–1998) collected at different water depths (based on HELCOM data)

It should be stressed that both the theoretical wave base and the depth of the halocline describe average conditions. It is clear from Fig. 2.4A that the halocline varies considerable around 75 m. The actual wave base also varies around 43.8 m in the Baltic Proper; during storm events, the wave base will be at greater water depths (Jönsson, 2005) and during calm periods at shallower depths. The actual wave base also varies spatially within the studied areas. From Figs. 2.4–2.6 and Table 2.2, however, it is evident that the two boundary depths describe the conditions in the Baltic Sea very well.

From Table 2.2, one can also note that:

- The mean salinity is 7.04 psu in the surface-water layer (SW) of the Baltic Proper (BP), 8.92 in the middle-water layer (MW), and 10.66 in the deep-water layer (DW). These values and the given standard deviations (SD) will be used in Chap. 3 (in the mass-balance calculations for salt to determine the fluxes of water to, from and within the system).
- The mean salinity in the surface-water layer in the Bothnian Sea (BS) is 5.41 psu and in the deep-water layer 6.12. The difference in salinity between these two layers is less than 1 psu. So, the Bothnian Sea has not been divided into three layers, just two. The difference between the mean salinities in the two layers is even smaller in the Bothnian Bay (3.38 compared to 3.61) and also the Bothnian Bay (BB) has been divided into two layers.

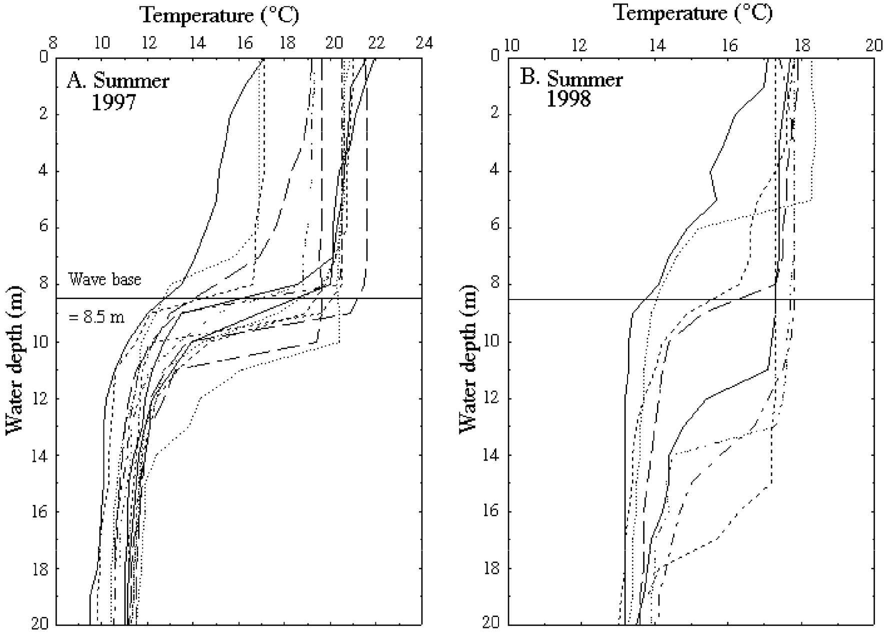


**Fig. 2.7** Temperature data from Lake Erken, Sweden (from the summers of 1997 and 1998) and illustration of the theoretical wave base ($D_{wb}$) in this lake. Each line represents the temperature profile at the monitoring station at a given sampling occasion

The Gulf of Riga (GR) is also divided into two layers. Note that the maximum depth of the Gulf of Riga is just 56 m. There are clear differences in the salinity profiles in the five basins (see Table 2.3) and the aim of the modeling in Chap. 3 is to predict the monthly salinities as close as possible to the empirical data. Note specifically, the coefficients of variation in Table 2.3, which vary from 0.022 in the SW-layer in the Bothnian Sea to 0.34 for the MW-layer in the Baltic Proper. This variability/uncertainty in the empirical data is very important since these data are used in the calibrations of the mass-balance model for salt. This will be explained more thoroughly in the next section.

## *2.3.1 Data Variability/Uncertainty and the Sampling Formula*

How do inherent variations and uncertainties in empirical data constrain approaches to predictions? If the variability within an ecosystem is large, many samples must be analyzed to obtain a given level of certainty in the mean value. There is a general formula, derived from the basic definitions of the mean value, the standard deviation and the Student's t value, which expresses how many samples are required (n) in order to establish a mean value with a specified certainty (Håkanson, 1984):

**Table 2.3** Data on volumes and areas (below the given depths; e.g., 10,900 $km^2$ is the area below the theoretical wave base, which defines the upper limit for the MW-layer in the Gulf of Finland) and salinities (mean values, medians, standard deviations and number of data; data from ICES, 2006)

| Basin | Level | Volume ($km^3$) | Area ($km^2$) | Salinity (Mean) | Salinity (Median) | Salinity (SD) | Salinity (CV) | Number of data (n) |
|---|---|---|---|---|---|---|---|---|
| Gulf of Finland | SW | 851 | 29,600 | 6.18 | 6.11 | 1.09 | 0.17 | 676 |
| | MW | 202 | 10,900 | 7* | 7* | – | – | 0 |
| | DW | 20.0 | 2400 | 10.2* | 10.2* | – | – | 0 |
| Gulf of Riga | SW | 392 | 16,700 | 5.67 | 5.72 | 0.25 | 0.044 | 260 |
| | DW | 17.5 | 3500 | 7.5* | 7.5* | – | – | 0 |
| Bothnian Bay | SW | 1067 | 36,300 | 3.33 | 3.38 | 0.38 | 0.11 | 355 |
| | DW | 433 | 13,327 | 3.58 | 3.61 | 0.25 | 0.069 | 200 |
| Bothnian Sea | SW | 2779 | 79,300 | 5.40 | 5.41 | 0.12 | 0.022 | 216 |
| | DW | 2110 | 46,703 | 6.18 | 6.12 | 0.38 | 0.061 | 215 |
| Baltic Proper | SW | 7315 | 211,100 | 7.04 | 7.05 | 0.90 | 0.13 | 12,374 |
| | MW | 3050 | 123,500 | 7.72 | 8.92 | 2.64 | 0.34 | 3989 |
| | DW | 2690 | 73,000 | 10.28 | 10.66 | 1.75 | 0.17 | 6289 |

*missing data, assumed values

$$n = (t \cdot CV/L)^2 + 1 \quad (2.2)$$

Where t is Student's t, which specifies the probability level of the estimated mean value (usually 95%; strictly, this approach is only valid for variables from normal frequency distributions); CV is the coefficient of variation within a given ecosystem; L is the level of error accepted in the mean value. For example, $L = 0.1$ implies 10% error so that the measured mean value will be expected to lie within 10% of the expected mean value with the probability assumed in determining t. Since one often determines the mean value with 95% certainty ($p = 0.05$), the *t*-value is set to 1.96. For practical purposes, it is reasonable to regard $L \approx 0.2$ (a 20% error in the mean value) as a threshold for practical water management (see Håkanson and Bryhn, 2008a). If the error is greater than that, the mean value may be too uncertain; if the L-value is smaller, the demands on the sampling program may be too high.

In this book, confidence bands are generally given either for individual data or for the mean/median values. The 95% confidence intervals (CI) for the mean/median values are calculated from Eq. (2.3) (Håkanson et al., 2003):

$$CV_{MV} \approx CV_{ind}/\sqrt{n} \text{ or rather } CI = 2 \cdot CV_{MV} \approx 2 \cdot CV_{ind}/\sqrt{n} \quad (2.3)$$

Where $CV_{MV}$ is the CV for the mean value and $CV_{ind}$ is the CV for the individual data; n is the number of data used to determine the mean/median value.

Tables 2.4 and 2.5 give compilations of CV-values for important variables in contexts of eutrophication for brackish open water sites, lakes, rivers and brackish coastal areas. One can note that there are systems and patterns in these CV-values:

- Some variables generally have high CVs, e.g., DIN (dissolved inorganic nitrogen), DIP (dissolved inorganic phosphorus) and the DIN/DIP-ratio (one version of the famous Redfield ratio), other low CVs, e.g., salinity, TN and TP.
- There are seasonal patterns (see Table 2.5) with high CVs for DIN and DIP during the growing season.
- There are differences in CVs related to the length of the sampling period – the longer the sampling period, the higher the CV-value (see Håkanson and Bryhn, 2008a).
- There are also variations among aquatic systems with higher CVs in samples from rivers than from lakes.

Most water variables in coastal areas have CVs between 0.1 and 1. One can then calculate the error in a typical estimate. If $n = 5$ and $CV = 0.33$, L is about 33%. Since few monitoring programs take more samples at a given site during a given sampling event, this calculation has profound implications for the quality of our knowledge of aquatic systems. One reason for the high CV-values in many of these water variables may be linked to the fact that there are large analytical uncertainties in the laboratory determinations of some of these variables (Håkanson et al., 1990). As a rule-of-thumb, one can estimate that for the nutrients (TP and TN), about 50% of the characteristic CV-value for within-system variation during a given month may be related to analytical uncertainties and the rest to actual variations related to biological/ecological processes (Håkanson, 1999).

**Table 2.4** Coefficients of within-system variation (CV) for variables from (A) from Ringkobing Fjord (data from Pedersen et al., 1995; Petersen et al., 2006), (B) CVs at a monitoring station in Chesapeake Bay, months 6–8 (from Bryhn et al., 2007), (C) CVs from lakes and rivers using data from the growing season (May–September; from Stenström-Khalili and Håkanson, 2007) and (D) CVs using data from the growing season from the Baltic Sea and the Danish Sounds from 1987 to 2006 (from Stenström-Khalili and Håkanson, 2007)

| A. Ringkobing Fjord | Daily | Monthly | Yearly | All |
|---|---|---|---|---|
| SPM | 0.20 | 0.38 | 0.70 | 0.81 |
| Secchi depth | 0.11 | 0.20 | 0.42 | 0.68 |
| Chl-a | 0.18 | 0.30 | 0.56 | 1.00 |
| Total-N | 0.07 | 0.12 | 0.24 | 0.51 |
| Total-P | 0.15 | 0.27 | 0.62 | 0.70 |
| Salinity | 0.08 | 0.08 | 0.24 | 0.33 |
| Temperature | 0.03 | 0.10 | 0.53 | 0.56 |

B. Chesapeake Bay; SW-layer

| Temp | Sal | DON | TN | Sec | DN | TP | PN | PP | SPM | DP | Chl | DOP | OrtP | DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.08 | 0.18 | 0.23 | 0.24 | 0.26 | 0.28 | 0.35 | 0.37 | 0.41 | 0.55 | 0.56 | 0.59 | 0.61 | 0.72 | 0.97 |
| *DW-layer* | | | | | | | | | | | | | | |
| Temp | Sal | DN | TN | DON | TP | PN | PP | DIN | DP | OrtP | Chl | SPM | DOP | |
| 0.13 | 0.12 | 0.23 | 0.23 | 0.24 | 0.41 | 0.46 | 0.49 | 0.53 | 0.56 | 0.62 | 0.7 | 0.73 | 0.83 | |

| C. Lakes & rivers | Period | TN | DIN | TP | DIP | DIN/DIP | TN/TP | n |
|---|---|---|---|---|---|---|---|---|
| 28 lakes | 1987–2006 | 0.24 | 0.64 | 0.43 | 0.61 | 0.84 | 0.41 | 4963 |
| 34 river stations | 1987–2006 | 0.36 | 0.7 | 0.48 | 0.64 | 0.87 | 0.49 | 3934 |

| D. Baltic Sea | TN | DIN | TP | DIP | DIN/TN | DIP/TP | DIN/DIP | TN/TP | n |
|---|---|---|---|---|---|---|---|---|---|
| Bothnian Bay | 0.08 | 0.25 | 0.27 | 0.62 | 0.14 | 0.11 | 0.65 | 0.41 | 486 |
| Bothnian Sea | 0.14 | 0.7 | 0.31 | 0.87 | 0.05 | 0.16 | 1.32 | 0.36 | 1022 |
| Baltic Proper | 0.14 | 0.74 | 0.25 | 0.54 | 0.02 | 0.28 | 1.36 | 0.31 | 2663 |
| Kattegat & the Sounds | 0.24 | 1.13 | 0.39 | 0.74 | 0.06 | 0.26 | 1.28 | 0.44 | 4346 |
| Skagerack | 0.23 | 1.16 | 0.37 | 0.72 | 0.04 | 0.18 | 1.58 | 0.4 | 829 |

Background data related to the seasonal variations in TP-concentrations in the three layers in the Baltic Proper for the period from 1990 to 2005 have been compiled in Fig. 2.8. These TP-concentrations and their uncertainty bands are of special importance in the mass-balance modeling for TP, which is many ways constitutes the core part of this book (Chap. 5). Figure 2.8 also illustrates the confidence bands related to $\pm$ one standard deviation of the empirical data. From this figure, it is clear that the median monthly TP-concentrations in the deep-water (DW) layer is generally higher than the TP-concentrations in the MW-layer, which in turn is higher than the TP-concentrations in the SW-layer. There is no overlap in the uncertainty bands in Fig.2.8, which means that the observed differences are statistically and ecologically significant. There are also interesting and important seasonal patterns in these monthly median values. The TP-concentrations in the SW-layer generally attain minimum values in the summer period and highest values in February, March and

**Table 2.5** Monthly CV-values for TN, DIN, TP, DIP, DIN/DIP and TN/TP in the Himmerfjärden Bay (in the Baltic Proper)

| Month | TN | DIN | TP | DIP | DIN/DIP | TN/TP |
|---|---|---|---|---|---|---|
| Jan | 0.13 | 0.30 | 0.10 | 0.10 | 0.57 | 0.12 |
| Feb | 0.11 | 0.26 | 0.09 | 0.12 | 0.54 | 0.13 |
| Mar | 0.14 | 0.47 | 0.15 | 0.47 | 1.05 | 0.16 |
| Apr | 0.16 | 1.49 | 0.24 | 0.92 | 2.01 | 0.27 |
| May | 0.15 | 1.20 | 0.23 | 0.58 | 1.38 | 0.19 |
| Jun | 0.12 | 1.52 | 0.18 | 0.51 | 1.62 | 0.17 |
| Jul | 0.10 | 1.27 | 0.16 | 0.68 | 1.53 | 0.11 |
| Aug | 0.09 | 1.50 | 0.13 | 0.61 | 1.58 | 0.12 |
| Sep | 0.10 | 1.39 | 0.21 | 0.90 | 1.52 | 0.16 |
| Oct | 0.11 | 0.99 | 0.28 | 0.63 | 1.90 | 0.24 |
| Nov | 0.14 | 0.59 | 0.24 | 0.30 | 0.77 | 0.17 |
| Dec | 0.24 | 0.42 | 0.19 | 0.20 | 0.62 | 0.20 |

April. There is generally a maximum difference between the TP-concentrations in the SW and MW-layers in late summer and fall and a minimum difference in March, just before the spring peak in water and nutrient discharge to the Baltic Proper (Voipio, 1981; Stålnacke et al., 1999; Omstedt and Axell, 2003). The seasonal pattern in the DW-layer is not statistically significant but the TP-concentrations in this

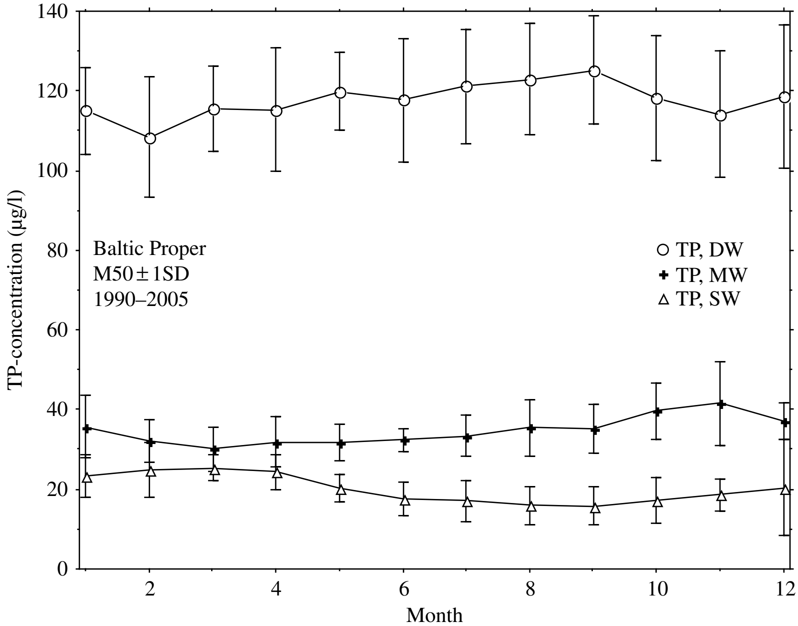


**Fig. 2.8** Compilation of median (M50) monthly TP-concentrations and the corresponding standard deviations (SD) in surface-water (SW), middle-water (MW) and deep-water (DW) in the Baltic Proper (data from 1990 to 2005)

layer (Fig. 2.8) are evidently very variable. The patterns in empirical data such as those illustrated in Fig. 2.8 should form the basis for all analyses concerning TP-variations in the Baltic Sea and the transport processes regulating such variations can be quantitatively analyzed by means of validated mass-balance models (see Håkanson and Eklund, 2007). The data discussed in this chapter are meant to lay an empirical foundation for the process-based mechanistic analyses in Chap. 5.

The databases used for comparative purposes in this work (Table 1.4) is probably one of the most comprehensive ever to address the problems of how TN, TP, salinity and chlorophyll-a concentrations co-vary among and within aquatic systems. The salinity in these systems ranges from zero to 275 psu in hypersaline Crimean lakes; the median salinity is 12.5 psu. The range in the nutrient concentrations spans from oligotrophic systems ($TP < 1\,\mu g/l$) to hypertrophic systems ($TP > 1000\,\mu g/l$). In compiling the databases in Table 2.4, only systems where there are at least 3 samples available for the growing season were accepted. This means that the mean or median values are very uncertain for some of the areas, and quite reliable for many of them.

In summary, many factors (from methods of sampling and analysis to chemical and ecological processes in the water system) influence the empirical values used to characterize entire coastal areas at the time scale of days to years. Since many variables vary greatly, it is often difficult in practice to make reliable, representative, area-typical empirical estimates. Data from specific sites and sampling occasions (the sampling bottle) may represent the prevailing, typical conditions in the ecosystem very poorly.

## 2.4 Size and Form Characteristics of the Sub-basins

Figure 2.9 exemplifies the new hypsographic curve (A) and volume curve (B) for the Bothnian Bay, the theoretical wave base at 41.1 m and how the area above and below the theoretical wave base is defined, and also (in Fig. 2.9B) how the SW-volume and the DW-volume are defined. Figure 2.10 gives a compilation of the hyposographic curves for all five sub-basins, as derived using GIS (Geographical Information System) and bathymetric data from Seifert et al. (2001). Figure 2.11 shows the corresponding volume curves. The areas and volumes calculated from these curves related to the theoretical wave base and the average depth of the halocline will be used in this modeling (in Chaps. 3, 5 and 6). One can note that the area below the theoretical wave base ($D_{wb}$) at 43.8 m in BP is $123.5 \cdot 10^3\,km^2$ and the area below the average depth of the halocline ($D_{hc}$) at 75 m is $73 \cdot 10^3\,km^2$. The volume of the SW, MW and DW-layers in the Baltic Proper (BP) are 7315, 3050 and $2690\,km^3$ and the entire volume is $13{,}055\,km^3$. Limitations in the resolution of the used bathymetric dataset imply that areas and volumes in shallow regions are slightly underestimated and hence the GIS-calculated data have been harmonized with the data provided by HELCOM (1990). For the values of the maximum depths, data from SMHI (2003) have been used.

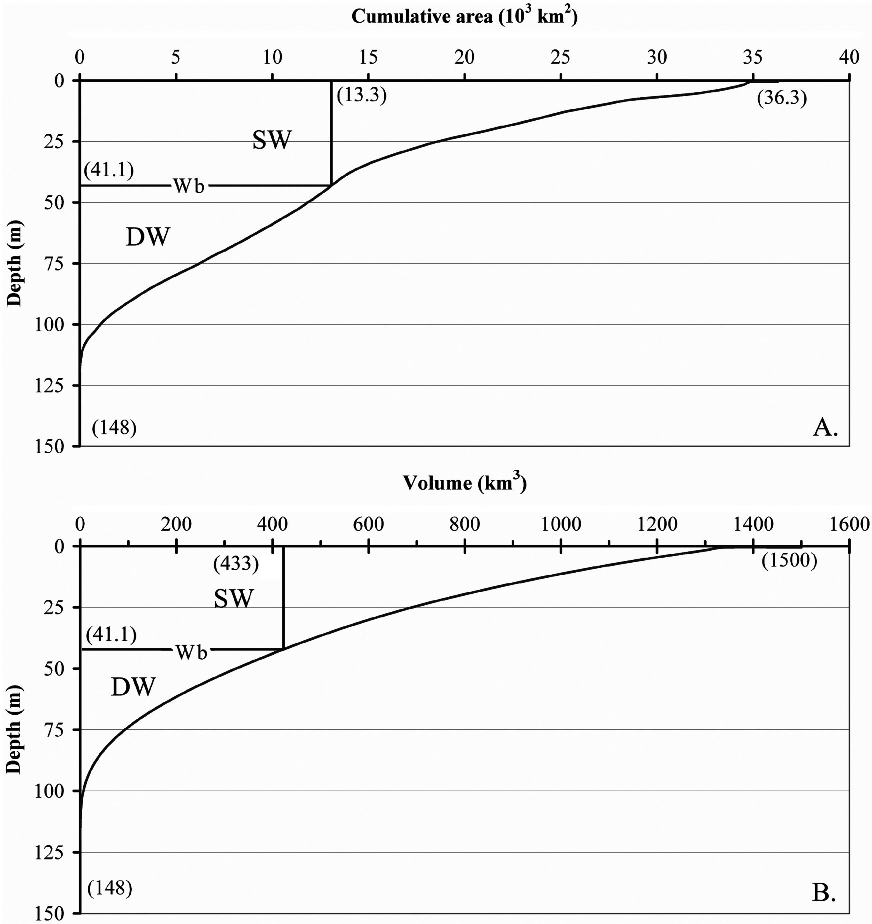


**Fig. 2.9** Hypsographic curve (**A**) and volume curve (**B**) for the Bothnian Bay

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

1. Size parameters: different parameters in length units, such as the maximum depth, parameters expressed in area units, such as water surface area, and parameters expressed in volume units, such as water volume and SW-volume.
2. Form parameters, based on size parameters, such as mean depth and the relative depth.
3. Special parameters, e.g., the dynamic ratio and the effective fetch.

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

Traditionally, the mean depth ($D_m$ in m) is defined as the ratio between the water volume (V in $m^3$) and the area (A in $m^2$), or $D_m = V/A$. In GIS work, the mean

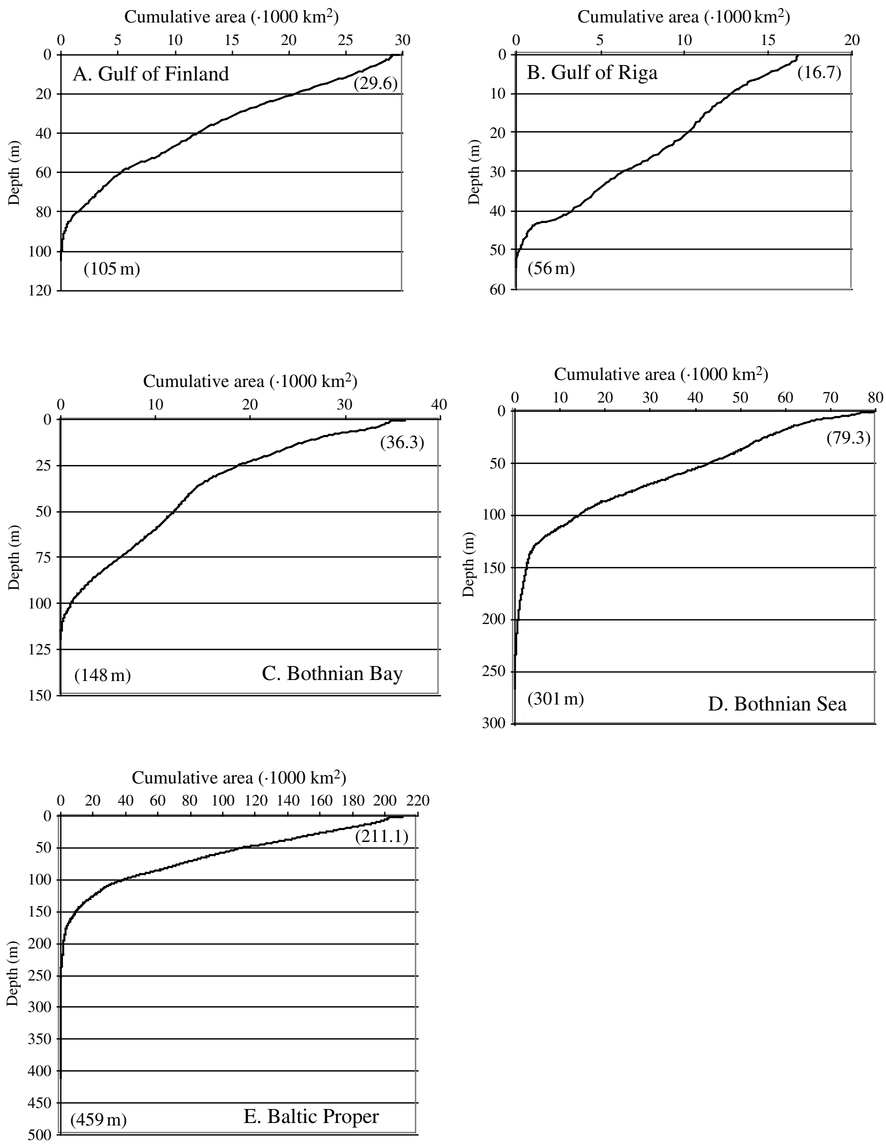


**Fig. 2.10** Hypsographic curves for the five major sub-basins in the Baltic Sea

depth may be estimated from raster data. The depths of all pixels with an elevation value equal to or below zero (water pixels) are summed, and the sum is divided by the number of pixels. To estimate the mean depth below a given depth, only water pixels with a depth equal to or deeper than the given depth are used in the calculations. The mean depth is a most informative and useful parameter in aquatic sciences and it is an integral part of the CoastMab-model.

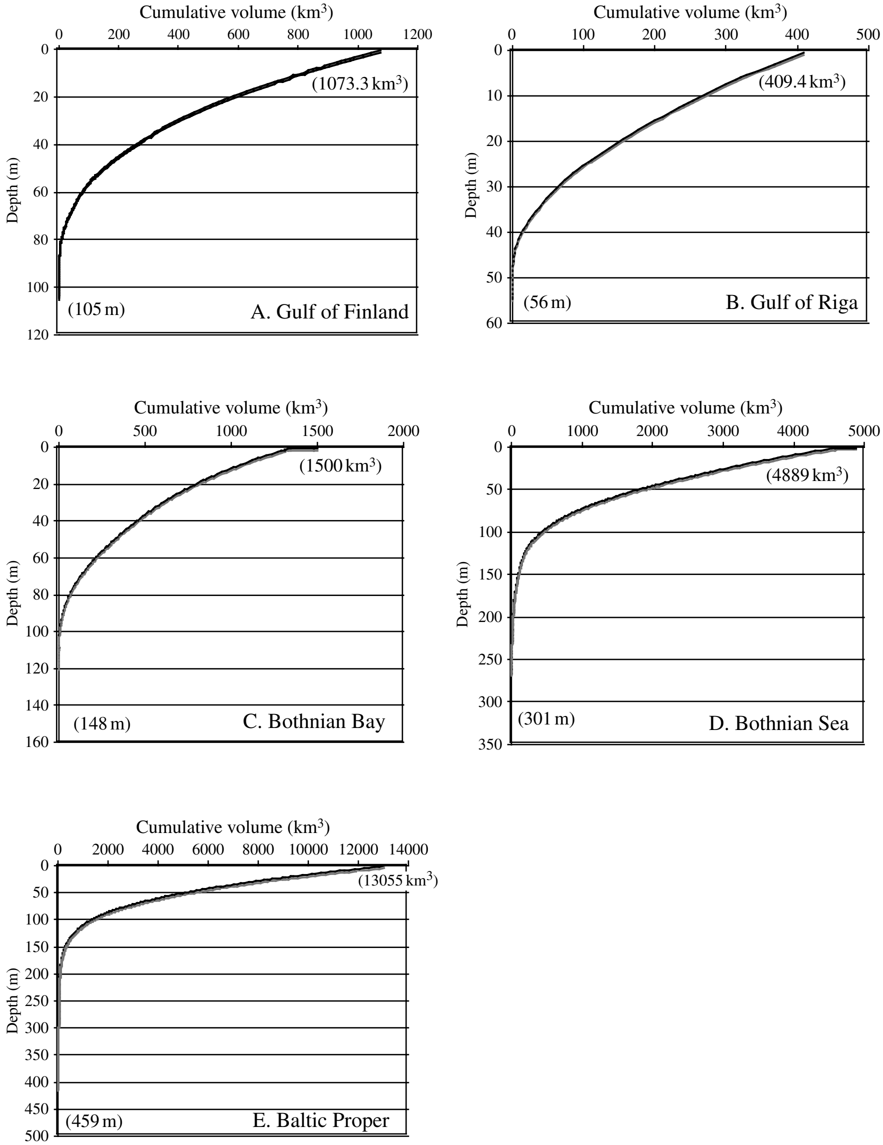


**Fig. 2.11** Volume curves for the five major sub-basins in the Baltic Sea

The relative depth ($D_{rel}$) is defined using the ratio between the maximum depth ($D_{max}$) and the mean diameter of the basin (using the water area, A):

$$D_{rel} = (D_{max} \cdot \sqrt{\pi})/(20.0 \cdot \sqrt{A}) \tag{2.4}$$

The relative depths vary from 0.038 for the Gulf of Riga to 0.088 for the Baltic Proper. Small and deep basins have high $D_{rel}$ values (see Fig. 2.12). The relative

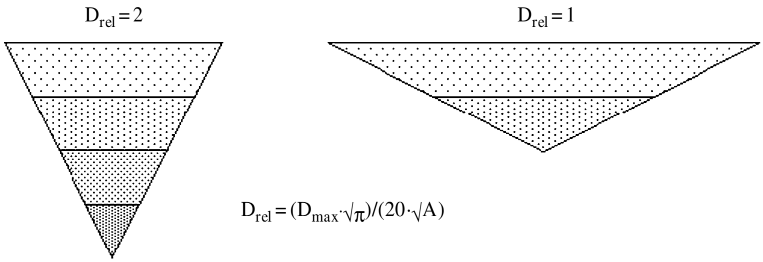


**Fig. 2.12** Illustration of the relative depth ($D_{rel}$) for two different basins

depth is often used as a measurement of the stability and stratification of water masses and to predict oxygen conditions in lakes (Eberly, 1964).

The volume development, also often called the form factor ($V_d$, dimensionless) is defined as the ratio between the water volume and the volume of a cone, with a base equal to the water surface area (A in km$^2$) and with a height equal to the maximum depth ($D_{max}$ in m):

$$V_d = (A \cdot D_m \cdot 0.001)/(A \cdot D_{max} \cdot 0.001 \cdot 1/3) = 3 \cdot D_m/D_{max} \tag{2.5}$$

Where $D_m$ is the mean depth (m). The volume development describes the form of the basin (see Fig. 2.13). The form of the basins is very important, e.g., for internal processes and Fig. 2.13 illustrates relative hypsographic curves for basins with different forms and hence also $V_d$-values. In basins of similar size but with different form factors, one can presuppose that the system with the smallest form factor would have more extensive resuspension, a larger area above the theoretical wave base, and more of the resuspended matter transported to the surface-water compartment than to the deep-water compartment below the theoretical wave base than a system with a higher form factor. This is also the way in which the form factor is used in the CoastMab-model. In this modeling, $V_d$ is also used to influence the predicted Secchi depths (i.e., the water clarity) related to the influence of resuspended matter from land uplift so that more of the resuspended clay particles from land uplift will reduce the water clarity and the Secchi depth in relatively shallow basins than in deeper basins.

The dynamic ratio (DR; see Håkanson, 1982) is defined by the ratio between the square-root of the water surface area (in km$^2$ not in m$^2$) and the mean depth, $D_m$ (in m; $DR = \sqrt{A}/D_m$). DR is a standard morphometric parameter in contexts of resuspension and turbulence in entire basins. Figure 2.14 shows the ET-areas above the theoretical wave base (i.e., areas where fine sediment erosion and transport processes prevail) are likely to dominate the bottom dynamic conditions in basins with dynamic ratios higher than 3.8. Slope processes are known (see Håkanson and Jansson, 1983) to dominate the bottom dynamic conditions on slopes greater than about 4–5%. From Fig. 2.14, one can note that slope-induced ET-areas are likely to dominate basins with DR values lower than 0.052. One should also expect that in all basins there is a shallow shoreline zone where wind-induced waves will create

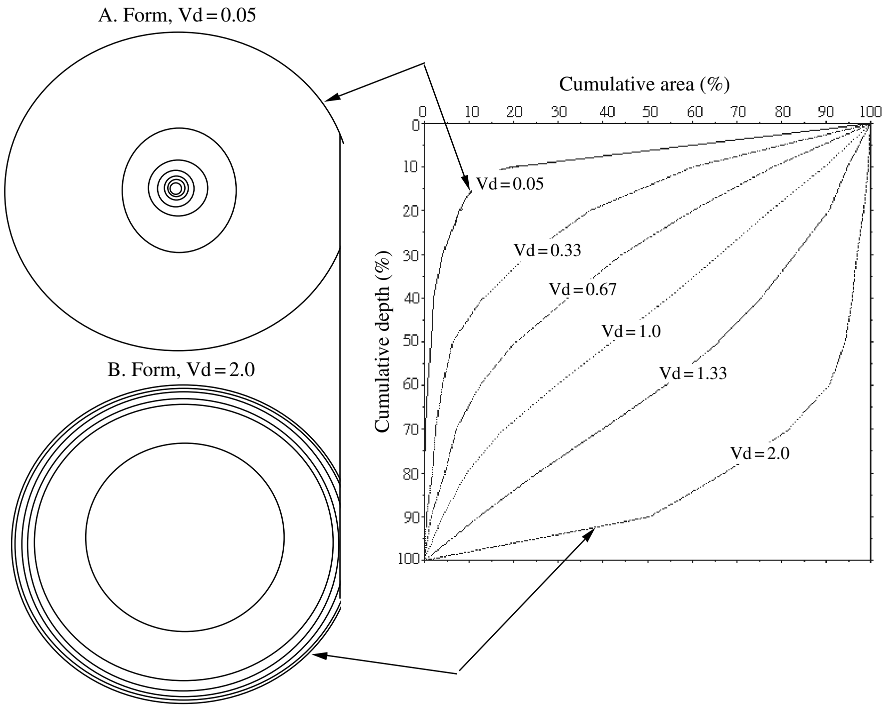


**Fig. 2.13** Schematical illustration of two coastal areas: (**A**) is very convex with a $V_d$-value (form factor, $V_d = 0.05$) and (**B**) the other is very concave ($V_d = 2.0$). From Håkanson and Bryhn (2008a)

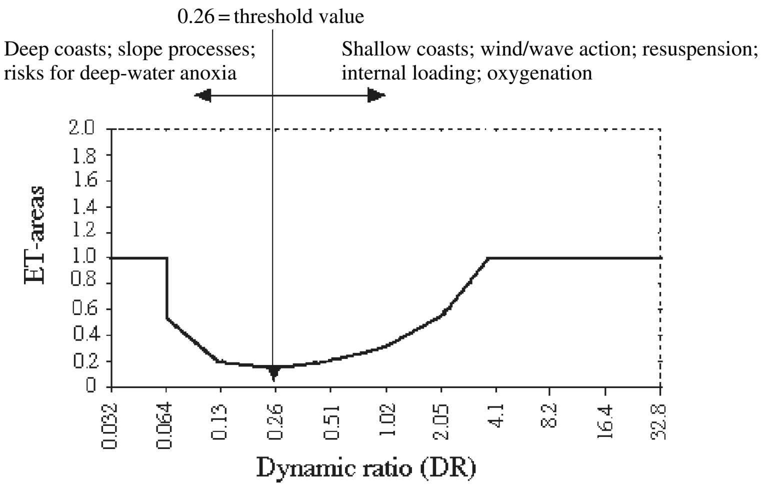


**Fig. 2.14** The relation between the dynamic ratio (DR) and the proportion of bottom areas dominated by erosion and transport processes (ET)

ET-areas, and it is likely that most basins have at least 15% ET-areas. From Fig. 2.14, one can also see that if a basin has a DR of 0.26, one can expect that in this basin the ET-areas would occupy 15% of the area. If DR is higher or lower than 0.26, the percentage of ET-areas is likely to increase. Basins with high DR-values, i.e., large and shallow system are also likely to be more turbulent than small and deep basins. This will influence sedimentation. During windy periods with intensive water turbulence, sedimentation of suspended fine particles in the water will be much lower than under calm conditions. This is accounted for in the CoastMab-model and the dynamic ratio is used as a proxy for the potential turbulence in the monthly calculations of the transport processes.

Among the sub-basins in the Baltic Sea, the Baltic Proper has the highest DR (7.43) and the Bothnian Sea the lowest (4.56).

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

The wave base may also be related to the wave equation (see Smith and Sinclair, 1972):

$$g \cdot H/w^2 = 0.0026 \cdot \left(g \cdot L_{ef}/w^2\right)^{0.47} \tag{2.6}$$

Where g is the acceleration due to gravity $(m/s^2)$; H is the wave height (in m); w the wind speed (m/s); and $L_{ef}$ the effective fetch (in m; see Fig. 2.1). The wave base is often set to one-third of the wave length rather than the wave height. In fact, whatever criteria one would use from the wave theory, it would not give a value that could be used in a simple and rational manner in, for instance, mass-balance models based on the ecosystem scale (models valid for entire basins for longer periods of time, such as weeks and months). Instead, the wave theory gives a whole array of wave heights and wave bases related to different wind situations; and during a period of one week or one month winds can blow from many directions and with many velocities.

The effective fetch ($L_{ef}$ in km in the ETA-diagram in Fig. 2.1) is often defined according to a method introduced by the Beach Erosion Board (1972). The effective fetch gives a more representative measure of how winds govern waves (wave length, wave height, etc.) than the effective length, since several wind directions are taken into account. Using traditional methods, it is relatively easy to estimate the effective fetch by means of a map and a special transparent paper (see Håkanson, 2004b). The central radial of this transparent paper is put in the main wind direction or, if the maximum effective fetch is requested, in the direction which gives the highest $L_{ef}$-value. Then the distance (x in km) from the given station to land (or to islands) is measured for every deviation angle $a_i$, where $a_i$ is ±6, 12, 18, 24, 30, 36 and 42 degrees. $L_{ef}$ may then be calculated from:

$$L_{ef} = \Sigma x_i \cdot \cos(a_i)/(\Sigma \cos(a_i)) \cdot SC' \tag{2.7}$$

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

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

For entire basins, the mean effective fetch may be estimated as $\sqrt{A}$ (see Fig. 2.1). In a round basin, the requested value should be somewhat lower than the diameter ($d = 2 \cdot r$; $r =$ the radius); the area A is $\pi \cdot r^2$ and hence $d = 1.13 \cdot \sqrt{A}$ and the mean fetch approximately $\sqrt{A}$.

## 2.5 Sediments and Bottom Dynamic Conditions

As stressed in Fig. 2.1, the wave base may also be determined from the ETA-diagram (Erosion-Transportation-Accumulation). This approach focuses on the behaviour of the cohesive fine materials settling according to Stokes' law:

- Areas of erosion (E) prevail in shallow areas or on slopes where there is no apparent deposition of fine materials but rather a removal of such materials; E-areas are generally hard and consist of sand, consolidated clays and/or rocks.
- 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. It is sometimes difficult in practice to separate areas of erosion from areas of transportation. The water depth separating transportation areas from accumulation areas, the theoretical wave base, is, as stressed, a fundamental component in these mass-balance calculations.
- Areas of accumulation (A) prevail where the fine materials are deposited continuously (soft bottom areas). It is in these 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 (see Table 2.6). In connection with a storm, the material on the ET-area may be resuspended and transported up and away, generally in the direction towards the accumulation 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 is generally at least 10 times larger, sometimes up to 10,000 times larger, than the vertical component for fine materials or flocs that settle according to Stokes' law (Bloesch and Burns, 1980; Bloesch and Uehlinger, 1986).

An evident boundary condition for this approach to calculate the ET-areas is that if $D_{wb} > D_{max}$, then $D_{wb} = D_{max}$.

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

**Table 2.6** The relationship between bottom dynamic conditions (erosion, transportation and accumulation) and the physical, chemical and biological character of the surficial sediments. The given data represent characteristic values from marine coastal areas based on data from 11 Baltic coastal areas (from Håkanson et al., 1984). ww = wet weight; dw = dry weight

| | Erosion | Transportation | Accumulation |
|---|---|---|---|
| **Physical Parameters** | | | |
| Water content (% ww) | $<50$ | 50–75 | $>75$ |
| Organic content (% dw) | $<4$ | 4–10 | $>10$ |
| **Nutrients (mg/g dw)** | | | |
| Nitrogen | $<2$ | 10–30 | $>5$ |
| Phosphorus | 0.3–1 | 0.3–1.5 | $>1$ |
| Carbon | $<20$ | 20–50 | $>50$ |
| **Metals** | | | |
| Iron (mg/g dw) | $<10$ | 10–30 | $>20$ |
| Manganese (mg/g dw) | $<0.2$ | 0.2–0.7 | 0.1–0.7 |
| Zinc (μg/g dw) | $<50$ | 50–200 | $>200$ |
| Chromium (μg/g dw) | $<25$ | 25–50 | $>50$ |
| Lead (μg/g dw) | $<20$ | 20–30 | $>30$ |
| Copper (μg/g dw) | $<15$ | 15–30 | $>30$ |
| Cadmium (μg/g dw) | $<0.5$ | 0.5–1.5 | $>1.5$ |
| Mercury (ng/g dw) | $<50$ | 50–250 | $>250$ |

$$\text{If ET} > 0.99 \text{ then ET} = 0.99$$
$$\text{If ET} < 0.15 \text{ then ET} = 0.15.$$

From Fig. 2.11, one can conclude that ET-areas are generally larger than 15% (ET = 0.15) of the total area since there is always a shore zone dominated by wind/wave activities. For practical and functional reasons, one can generally also find sheltered areas, macrophyte beds and deep holes with more or less continuous sedimentation, that is, areas which actually function as A-areas, so the upper boundary limit for ET may be set at ET = 0.99 rather than at ET = 1.

The value for the ET-areas is used as a distribution coefficient in the CoastMab-model. It regulates whether sedimentation of the particulate fraction of the substance (here phosphorus) goes to the DW or MW-areas or to ET-areas.

Table 2.6 gives a compilation of physical sediment variables, water content, bulk density and organic content, in areas of erosion, transportation and accumulation for sediments from Baltic Sea coastal areas. The table also gives corresponding data on nutrients (nitrogen and phosphorus). It should be stressed that phosphorus is a very mobile element in sediments, reflecting predominant redox-conditions rather than the depositional patterns. Concentrations of less mobile, contaminating metals and non-contaminating metals in the sediments are also given in Table 2.6 for the three bottom dynamic zones.

Table 2.7 gives a compilation of sediment data from different basins and sites in the Baltic Sea. First, it must be stressed that it is difficult to find good data on phosphorus in Baltic Sea sediments. From the data in Table 2.7, one can note that:

**Table 2.7** Compilation of sediment data from published sources from the Baltic Sea. IG = loss on ignition (organic content)

| BP, 5–13 cm<br>Water depth (m) | IG (%dw) | d $(g/cm^3)$ | N (mg/g dw) | P (mg/g dw) | Source |
|---|---|---|---|---|---|
| 94 | 7.0 | 1.23 | 3.3 | 0.47 | Jonsson et al., 1990 |
| 97 | 6.5 | 1.28 | 3.1 | 0.49 | |
| 107 | 3.4 | 1.51 | 0.3 | 0.29 | |
| 103 | 6.5 | 1.24 | 3.7 | 0.50 | |
| 119 | 6.6 | 1.23 | 1.3 | 0.46 | |
| 92 | 7.1 | 1.22 | 1.9 | 0.49 | |
| 88 | 13.0 | 1.13 | 6.2 | 0.77 | |
| Mean | 7.16 | 1.26 | 2.83 | 0.50 | |
| Median | 6.6 | 1.23 | 3.1 | 0.49 | |
| Number of data | 7 | 7 | 7 | 7 | |
| SD | 2.87 | 0.12 | 1.92 | 0.14 | |
| BS (Husum), 0–1 cm | | | | | |
| | 16.5 | | 3.7 | 1.36 | Håkanson et al., 1984 |
| | 28.6 | | 5.6 | 1.31 | |
| BB (surficial sediments) | | | | 1.5 | Niemistö et al., 1983 |
| GF (0–10 cm) | 14 | | | 1.25 | Virkanen, 1998 |
| BP (0–2 cm) | | | | 0.5–1.5 | FRP, 1978 |
| BB (0–2 cm) | | | | $< 0.5$ to $> 2$ | FRP, 1978 |
| BB (Landsort deep, 91.5 m; data from each centimeter sediments) | | | | | |
| 0–1 | 17 | | | 1.37 | Ahlgren et al., 2006 |
| 1–2 | 14 | | | 1.26 | |
| 2–3 | 11 | | | 1.20 | |
| 3–4 | 11 | | | 1.20 | |
| 4–5 | 12 | | | 1.16 | |
| 5–6 | 10 | | | 1.14 | |
| 6–7 | 10 | | | 1.08 | |
| 7–8 | 9 | | | 1.09 | |
| 8–9 | 10 | | | 1.07 | |
| 9–10 | 10 | | | 0.93 | |
| 14–15 | 9 | | | 1.06 | |
| 19–20 | 8 | | | 0.02 | |
| 29–30 | 9 | | | 0.99 | |
| 39–40 | 6 | | | 0.98 | |
| 49–50 | 7 | | | 0.84 | |

1. Most TP-values from the upper decimeter of Baltic Sea sediments vary in the range from 0.36 to 2 mg TP/g dw. This range will be used in Chaps. 5 and 6 as reference values. If modeled TP-concentrations in accumulation area sediments are higher than 2 or lower than 0.36 mg TP/g dw, this indicates that the TP-fluxes to (i.e., sedimentation of particulate phosphorus) and from (i.e., burial of phosphorus) these sediment compartments may be wrong.

2. The TP-concentration and the organic content (loss on ignition, IG) decrease with sediment depth, as in other aquatic systems (see Håkanson and Jansson, 1983).
3. The TN-concentrations are generally a factor of 3 to 10 higher than the TP-concentrations.
4. The bulk density (d in $g/cm^3$ ww) is between 1.2 and 1.3.

It should also be stressed that one generally finds poor or no correlations between TP-concentrations in water and in sediments (see Fig. 2.15). The main reason for this has already been mentioned: Phosphorus is very reactive in sediments and the phosphorus concentrations in sediments reflect sediment redox-conditions rather than the trophic status of the system. If the oxygen concentration is low, which is often the case in highly productive systems or at sites with high sedimentation of organic matter, phosphorus diffusion from sediment is likely high and phosphorus concentrations in the sediments relatively low. This means that it is rare to find TP-concentrations in sediments higher than 2.5 mg/g dw. All TP in sediments cannot be removed from the sediments by diffusion even if the redox-potential approaches zero (see Cato, 1977; Håkanson and Jansson, 1983). One should expect that glacial clays in the Baltic Sea generally would contain TP-concentration in the range 0.3 to 0.5 mg/g dw (see Table 2.7). We will use 0.36 mg TP/g dw as a minimum reference value for the modeled TP-concentrations in accumulation area sediments (0–10 cm). It is calculated from the mean value minus one standard deviation related to the data given in Table 2.7 (i.e., 0.50–0.14).

Unlike phosphorus, nitrogen concentrations in sediments are known to reflect the trophic status of aquatic systems very well and the C/N-ratio is used to classify lakes into trophic categories (see Fig. 2.16).

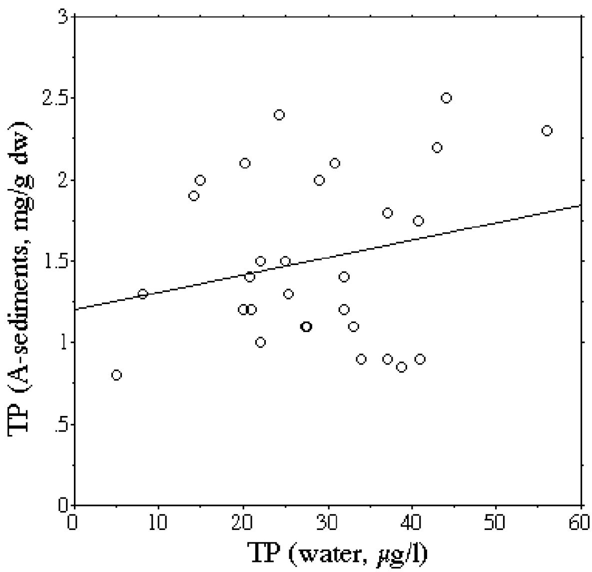


**Fig. 2.15** The relationship between TP-concentrations in water and in surficial accumulation area sediments based on data from 29 lakes (data from Håkanson and Boulion, 2002)

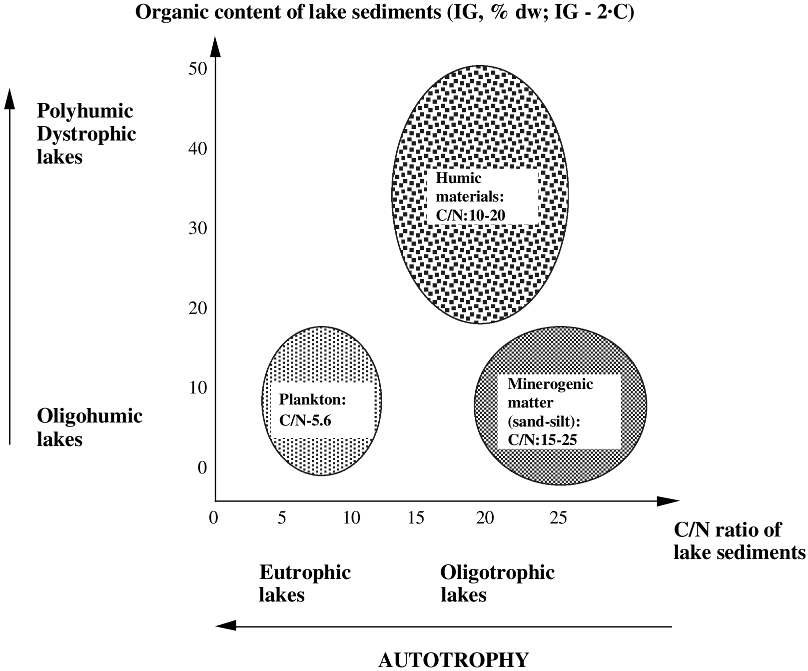


**Fig. 2.16** Lake classification from the relationship between the C/N ratio and the loss on ignition (IG of surficial sediments (modified from Håkanson, 1995)

There is also a well established relationship between the water content (W) and the organic content (loss on ignition, IG) in sediments (see Fig. 2.17). The relationship between W and IG also reflects the potential bottom dynamic conditions, as illustrated in Fig. 2.17. Due to the lack of reliable empirical data on the organic content, the relationship shown in Fig. 2.17 has been used in the following CoastMab-simulations to estimate the organic content from the water content of accumulation area sediments.

The regression in Fig. 2.17 is valid for surficial (0–10 cm) A-sediments and is meant to give a mean value for the entire active A-volume, which has an area of [(1-ET)·Area] and covers 10 cm of sediments. The water content in surface sediments is lower in shallower parts in the ET-areas (see Håkanson and Jansson, 1983). At the theoretical wave base separating A-sediments from T-sediments, the water content is generally about 10% lower than the water content in the deepest part of the basin. In a sediment core, the water content generally decreases vertically due to, e.g., compaction and mineralization.

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

$$d = 260/(100 + 1.6 \cdot (W + IG^* \cdot ((100 - W)/100))) \tag{2.8}$$

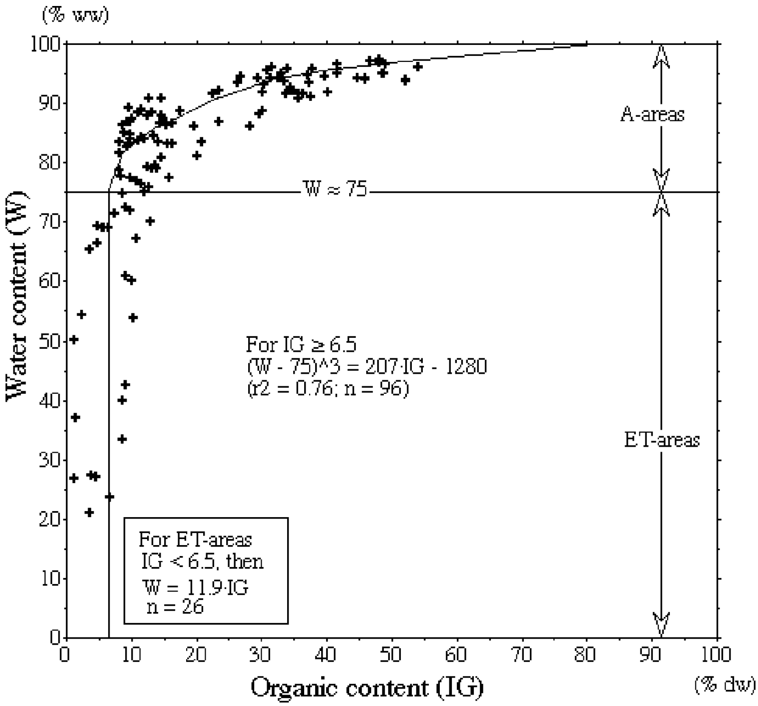


**Fig. 2.17** The relationship between the organic content (loss on ignition, IG) and the water content (W) based on data from 122 sites from 59 lakes covering a very wide range in sediment conditions (from Håkanson and Boulion, 2002)

Based on empirical data mainly from Jonsson (1992), the water content in the top decimeter of accumulation area sediments in the Baltic Sea is set to 75% as a default value for all basins in all following simulations using the CoastMab-model.

## 2.6 The Role of Land Uplift

As stressed in Chap. 1 and shown in Fig. 1.2, land uplift in the Baltic Sea varies from about 9 mm/yr in the Bothnian Bay to about 0 for the southern part of the Baltic Sea. Land uplift contributes with 50–80% of the materials settling below the wave base in the open Baltic Proper (Jonsson et al., 1990; Jonsson, 1992; Blomqvist and Larsson, 1994; Eckhéll et al., 2000). Land uplift influences the entire system in many profound ways, and this will be demonstrated in Chap. 5. When there is land uplift, the new supply of matter eroded from the sediments exposed to wind-generated waves does not emanate just from the newly raised areas but also from increased erosion of previously raised areas. This is schematically illustrated in Fig. 2.18.

It is assumed that the water content of the more compacted sediments from land uplift is 15% lower than the recently deposited sediments close to the theoretical

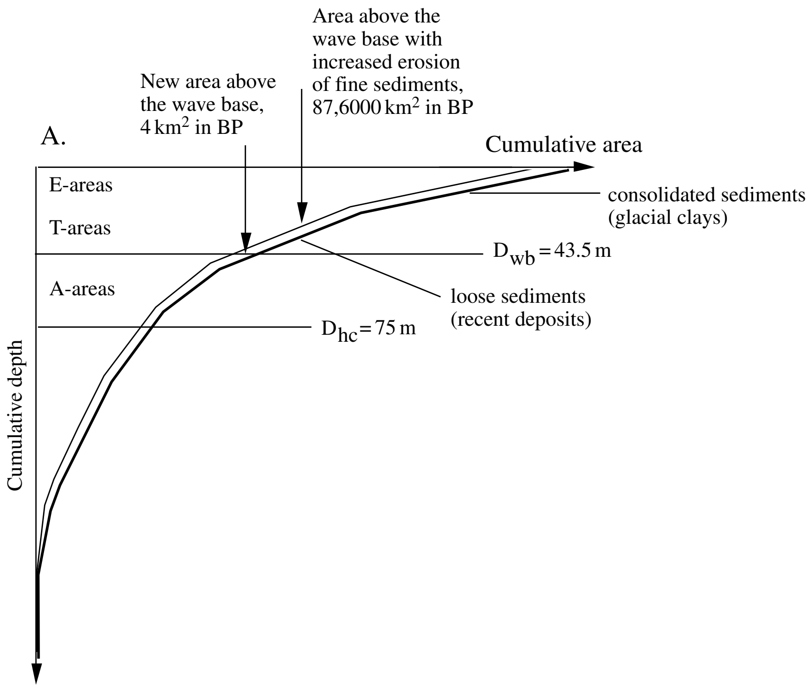


**Fig. 2.18** Illustration of how land uplift influences the area above the theoretical wave base. If there is no land uplift materials deposited above the theoretical wave base, on areas of fine sediment erosion and transport, will only stay on these bottoms until the next resuspension event, often related to increase wind/wave activity. There is by definition no net deposition on the areas of fine sediment erosion and transport (the ET-areas) when there is no land uplift. Land uplift provides a net input of materials to the surface-water compartment. The sediments within the areas of fine sediment erosion (i.e., the older more compacted glacial clays) are relatively consolidated, whereas the more recently deposited sediments close to the theoretical wave base are less consolidated with higher water content, organic content and contents of nutrients and iron

wave base and that the bulk density (d in $g/cm^3$) is 0.2 units higher than in the recently deposited sediments. The bulk density (d) is calculated from the equation just given. The TP-concentration in the material added to the Baltic Sea system from land uplift will be calculated (see Chap. 5) from the reference value for the TP-concentration in glacial clays ($TP_{clay} = 0.36$ mg TP/g dw) and the fraction of the E-areas above the theoretical wave base ($Area_E/Area_{ET}$) and the value calculated by the CoastMab-model for the TP-concentration in the A-sediments beneath the theoretical wave base ($TP_{AMWsed}$ in basins with three layers or $TP_{ADWsed}$ in basins with two vertical layers).

The areas of erosion ($Area_E$) is calculated from the new hyposographic curves (Fig. 2.10) and the corresponding depth given by the ETA-diagram (Fig. 2.1). This means that the depth separating E-areas from T-areas is given by:

$$D_{ET} = (30.4 \cdot \sqrt{Area})/(\sqrt{Area} + 34.2) \qquad (2.9)$$

Note that the area is given in square kilometer in Eq. (2.9) to get the depth in meter.

As stressed, the material added from land uplift does not just contain phosphorus, nitrogen and clay particles but also iron, manganese and many other substances, which may affect the system in different ways (see Table 2.6).

## 2.7 Nutrient Concentrations, Temperatures and Salinities – Data, Trends and Co-variations

The aim of this part is to present trend analyses of how TP-concentrations, TN-concentrations, temperature and salinity in mainly the Baltic Proper have changed from 1990 and until the end of 2005. This is interesting for many reasons, e.g., to understand the trends in the data for chlorophyll given in Fig. 1.7. The basic questions are: Are there any trends? Is there any indication of a critical change in TP-concentrations? If yes, can this be related to changes in temperature, salinity, TN or chlorophyll? Are there different trends in the surface-water layer (SW), the middle-water layer (MW) and the deep-water layer (DW)?

Figure 2.19 gives the first results; Fig. 2.19A shows a trend analysis for TP (regression line, $r^2$ = coefficient of determination, p = statistical probability or uncertainty and n = number of data) using all available data for the SW-layer. Figure 2.19B gives similar information using the median monthly concentrations and the related 95% confidence intervals (CI from Eq. 2.3). Figure 2.20 gives the same type of information as in Fig. 2.19B but for TN-concentrations. From Fig. 2.19, one can note:

- There is a statistically significant trend with slowly decreasing TP-concentrations in the SW-layer in the Baltic Proper in this period. There are no indications of any critical change around 1995.
- Even if the trend with decreasing TP-concentrations in the SW-layer is statistically significant, the decrease is small and the regression line is close to 20 μg/l.
- The seasonal pattern in the median monthly TP-values in Fig. 2.19B is interesting and highly significant in the sense that during a year there are periods with clearly lower and higher TP-concentrations, but this pattern is different for different years so the average seasonal pattern is less pronounced than the pattern for individual years.

One can note that the median monthly values are fairly low in the years between 1996 and 1999. After this, the trend is slightly increasing, which is seen in Fig. 2.19B.

The pattern in TN-concentrations in Fig. 2.20 demonstrates two interesting features. First, that there are no major changes until the very last year (2005). That year, there is a peak value of 410 g TN/l in February of 2005 and there are also very high values from months 5, 8 and 11 in 2005, all higher than 330 μg/l. This should be related to the fact that this year there were massive blooms of cyanobacteria (see,

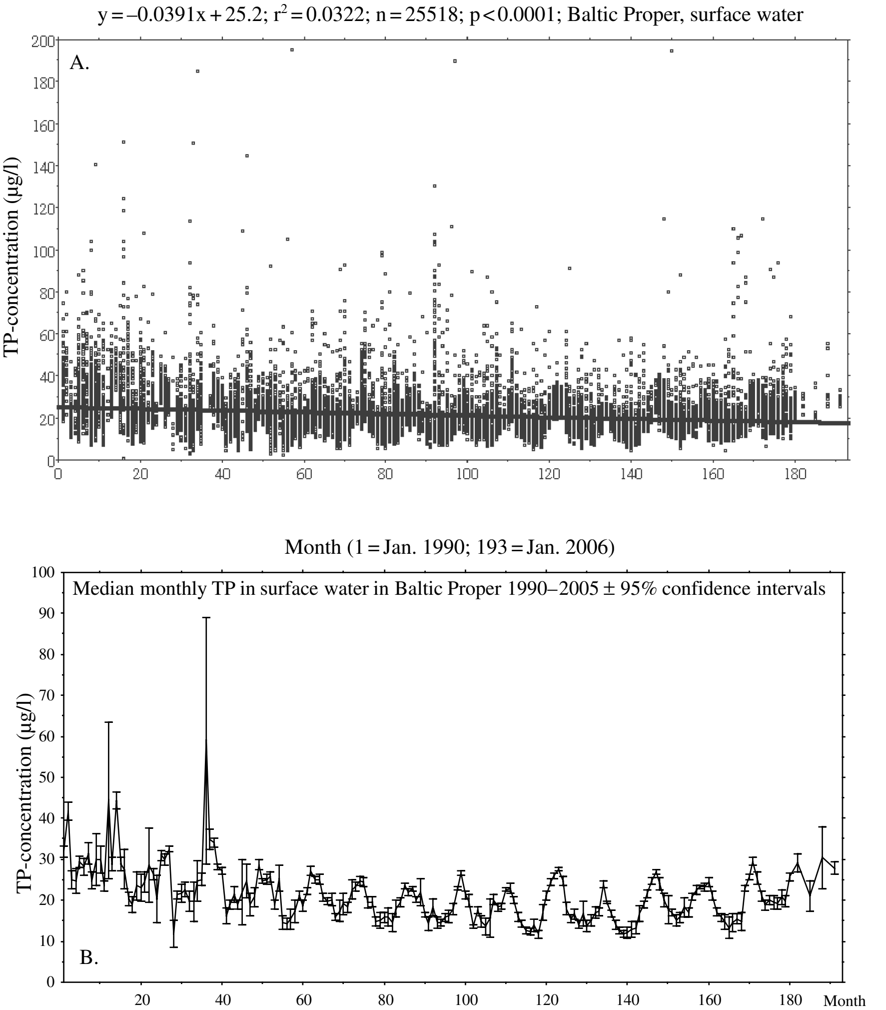


**Fig. 2.19** (**A**) Trends in TP-concentrations in the SW-layer in the Baltic Proper between January 1990 and December 2005. (**B**) Trends in median monthly TP-concentrations and 95% confidence intervals for the median values in the SW-layer in the Baltic Proper between January 1990 and December 2005

e.g., Hansson, 2006). So, N-fixation from cyanobacteria can significantly influence TN-concentrations in the SW-layer in the Baltic Proper.

Figure 2.21 gives results for TP-concentration in the MW and DW-layers. There is an increase in TP in the MW-layer and a more pronounced increase in the DW-layer. One can note that the trends are different in the three layers; slightly decreasing in SW, slightly increasing in MW and more markedly increasing in DW. Can these patterns be related to changes in temperature and salinity?

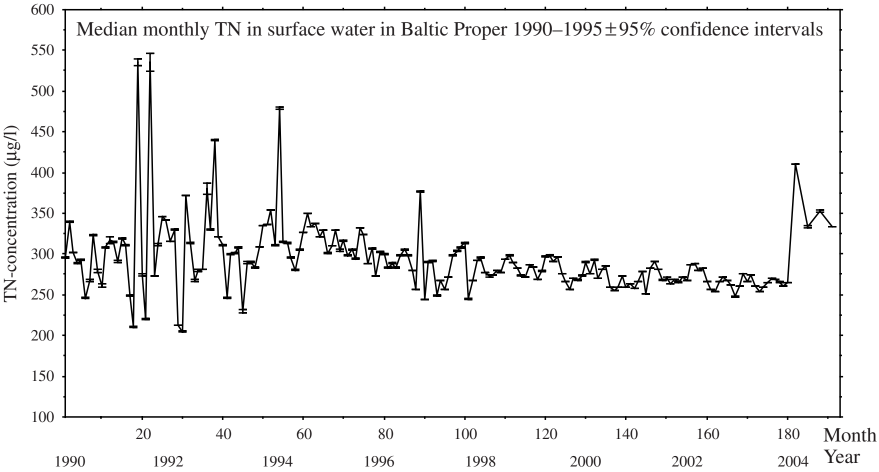


**Fig. 2.20** Trends in median TN-concentrations and 95% confidence intervals for the medians. Note the high concentration in the summer of 2005

Figure 2.22A shows that the SW-temperatures are not increasing during this 15-year period, but slightly decreasing. The changes in water temperatures in the MW-layer are very small. The most marked changes occur in the DW-layer, which has increasing temperatures. It should be stressed that there are many temperature dependent processes that could influence the observed changes in TP-concentrations, especially the increases in the DW-layer. The bacterial decomposition of organic matter in the sediments in the DW-zone is temperature dependent and a higher temperature will increase the diffusion of phosphorus from sediments to water (Håkanson and Eklund, 2007), the upward and downward mixing/transport of water and phosphorus between the different layers depend on the stability of the stratification of the water, which is governed by differences in temperature between the layers – a smaller temperature gradient between two layers will increase the potential mixing and hence also the transport of phosphorus between the layers. If there are major concentration gradients of phosphorus in dissolved forms, this will increase the diffusion of phosphorus and cause, e.g., a diffusive transport from the DW-layer with high concentrations of dissolved phosphorus to the MW-layer with lower concentrations. Only a validated quantitative process-based mass-balance model (such as CoastMab in Chap. 5) can sort out the causal reasons for the pattern observed in the empirical data.

Next, the data were analyzed to see whether variations in salinity co-vary with the observed patterns in TP-concentrations. Figure 2.23 gives trends for salinities in the SW, MW and DW-layers. Again the observed changes are small but most marked for the DW-layer with increasing salinities from less than 10 psu at the beginning of 1990 to 11 psu in 2005. The observed high-salinity water in the DW-layer (the upper part of Fig. 2.23C) coincides with known occurrences of major inflows of high saline water from the Kattegat, e.g., just before month 40, which correlates

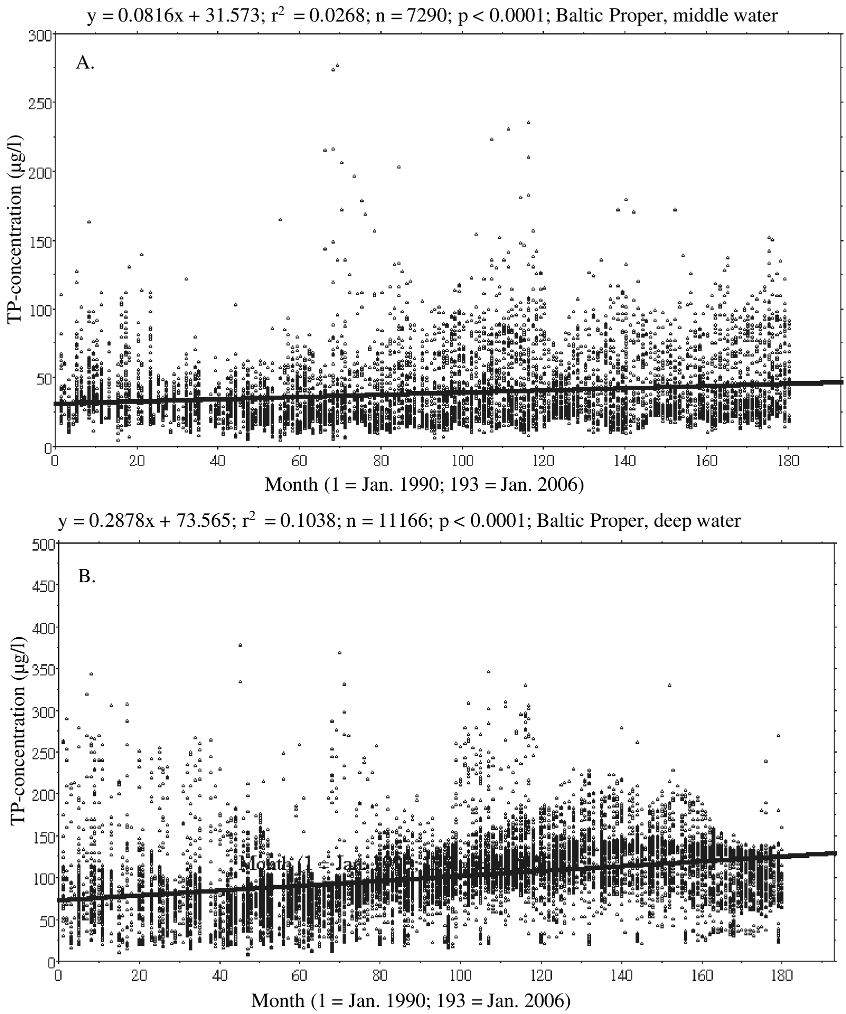


**Fig. 2.21** Trends in TP-concentrations in the Baltic Proper between January 1990 and December 2005 for (**A**) the middle-water layer and (**B**) the deep-water layer

to a major inflow 1993 (see, e.g., BACC, 2008). Differences in salinities between different layers will also influence mixing processes. However, no drastic changes are evident from the salinity data.

Calculating primary phytoplankton production and biomass from chlorophyll (Chl in µg/l) is a focal issue in aquatic sciences. Generally, chlorophyll-a concentrations are predicted from nutrient concentrations, light conditions (the lighter the higher the production and generally also the water temperatures) and water clarity (the clearer the water the deeper the photic zone and the higher the production) (Dillon and Rigler, 1974; Smith, 1979, 2003; Riley and Prepas, 1985; Evans et al.,

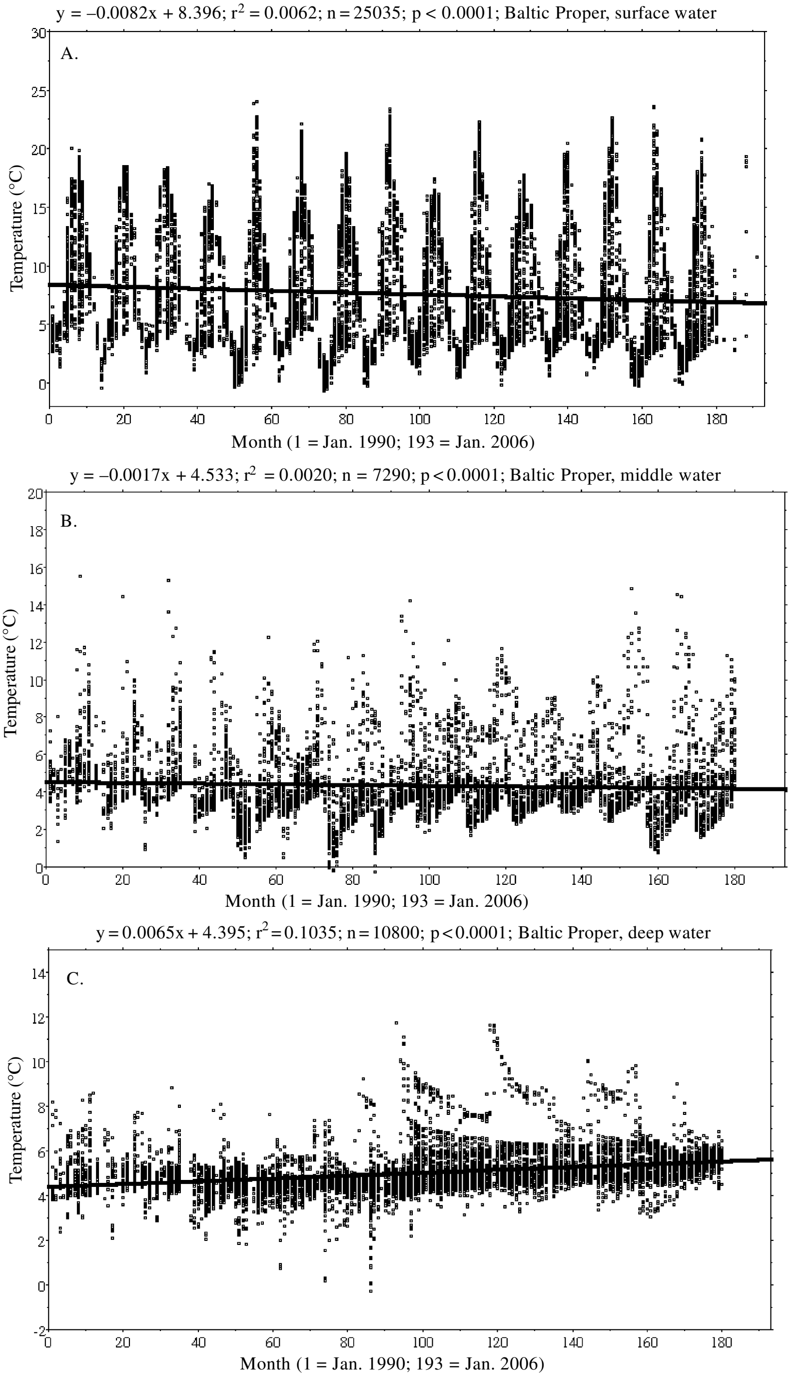


**Fig. 2.22** Trends in water temperatures in the Baltic Proper between January 1990 and December 2005 for (**A**) the surface-water layer, (**B**) the middle-water layer and (**C**) the deep-water layer

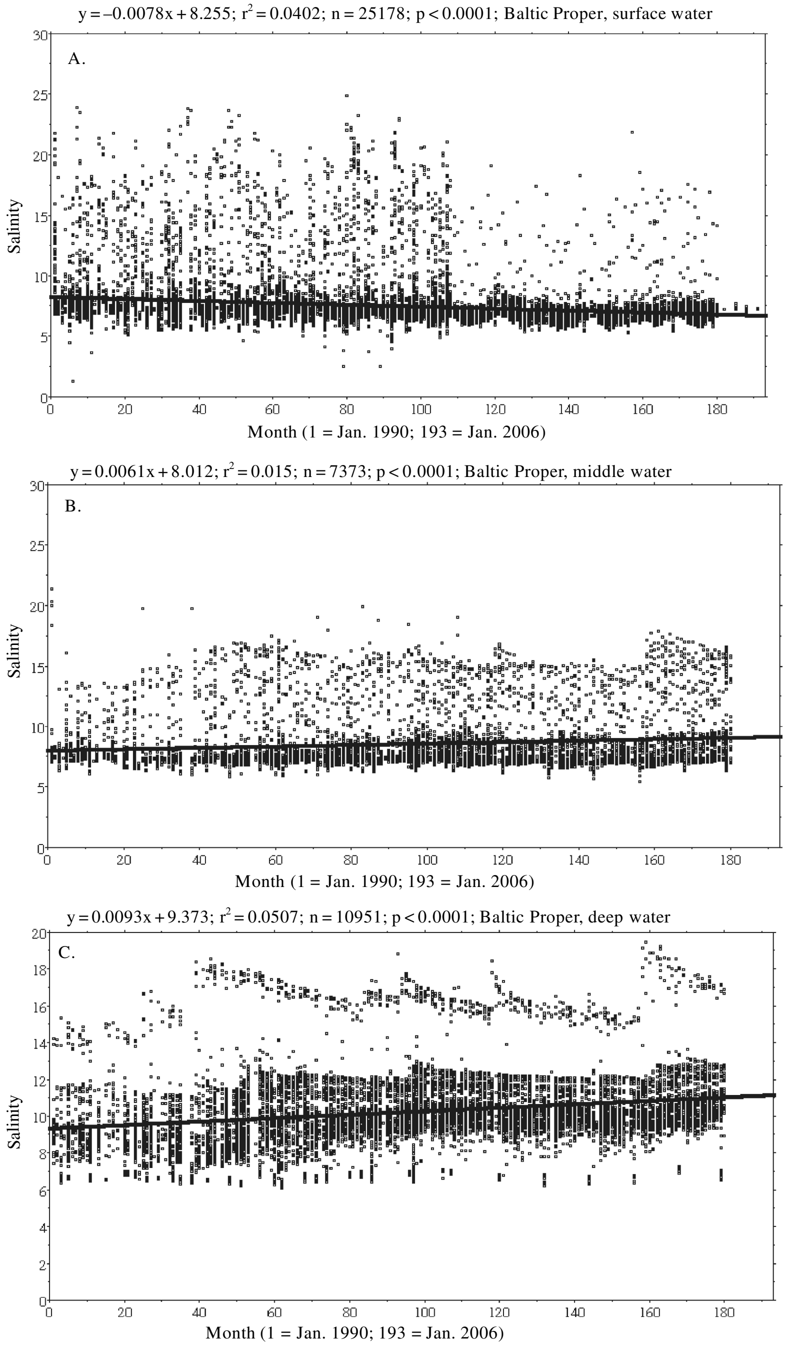


**Fig. 2.23** Variations in salinities in the Baltic Proper between January 1990 and December 2005 for (**A**) the surface-water layer, (**B**) the middle-water layer and (**C**) the deep-water layer

1996; Håkanson and Bryhn, 2008a). Fig. 1.7 gave data on variations in chlorophyll-a concentrations for the period from 1974 to 2005. In this period, there is a small and continuous decline in the chlorophyll values in the Baltic Proper, which demonstrates that eutrophication is not getting worse in the Baltic Proper, but rather the opposite.

Figure 2.24 gives a compilation of median monthly empirical data for TN-concentrations, TP-concentrations and concentrations of chlorophyll-a, as well as standard deviations for the monthly data to show the monthly variability and uncertainty in the median (or mean) monthly values. One can note the wide uncertainty bands, e.g., for chlorophyll in April. This means than when in Chap. 5 empirical data will be compared to modeled values, a certain difference in empirical to modeled values would be expected for chlorophyll in April. Figure 2.24C also shows a typical "twin-peak" pattern in median monthly Chl-values.

The average composition of algae ($C_{106}N_{16}P$) is reflected in the Redfield ratio (7.2 by mass and 16 by atoms; see Redfield, 1958; Redfield et al., 1963). So, by definition, algae need both nitrogen and phosphorus and one focus of coastal eutrophication studies concerns the factors limiting the phytoplankton biomass, as expressed by chlorophyll-a concentrations in the water. If the TN/TP-ratio is lower than 7.2, the conditions would favor phytoplankton species which can take up dissolved nitrogen gas of atmospheric origin. Empirical data show that for the growth of cyanobacteria (generally referred to in contexts of harmful algal blooms) there is a threshold limit for the TN/TP-ratio not at 7.2 but rather at 15 (see Håkanson et al., 2007c and Chap. 4). Figure 2.25A gives a scatter plot of all available data on the TN/TP-ratio ($n = 24,048$) from the surface-water layer in the Baltic Proper from 1990 to 2005 and Fig. 2.25B shows variations in median monthly TN/TP-ratios in relation to the Redfield ratio of 7.2 and the threshold ratio of 15. From these figures, one can note that there are no major changes in the general temporal trend. There is also a very large scatter in the data and seasonal patterns.

Table 2.8 gives a compilation of TN/TP statistics for the Baltic Proper and in this table the data have been divided into four categories: (1) all data from the surface-water layer, (2) all data for situations with temperatures higher than 15 °C (since temperatures higher than 15 °C favour the growth of cyanobacteria; see Chap. 4), (3) all data with Temp $> 15\,^{\circ}$C and from water depths $< 20$ m, and (4) all data with temp $> 15\,^{\circ}$C, water depths $< 20$ m and TP $> 10\,\mu$g/l. This table also gives information on the percentage of the data with TN/TP-ratios smaller than 7.2 and smaller than 15. The main conclusion from this table is that less than 7% of the values are smaller than 7.2 and that between 30 and 50% of the TN/TP-ratios are smaller than 15. Figure 2.26 gives a frequency distribution for the data at sites with temperatures higher than 15 °C.

The key information in Figs. 2.25 and 2.26 and Table 2.8 is that the conditions in the surface-water layer of the Baltic Proper often favor the growth of cyanobacteria. However, in more than 70% of the situations when the water temperature is higher than 15 °C, and the risks of getting blooms of cyanobacteria the highest, the system has TN/TP-ratios higher than 7.2 (see Fig. 2.25). In 30% of the situations,

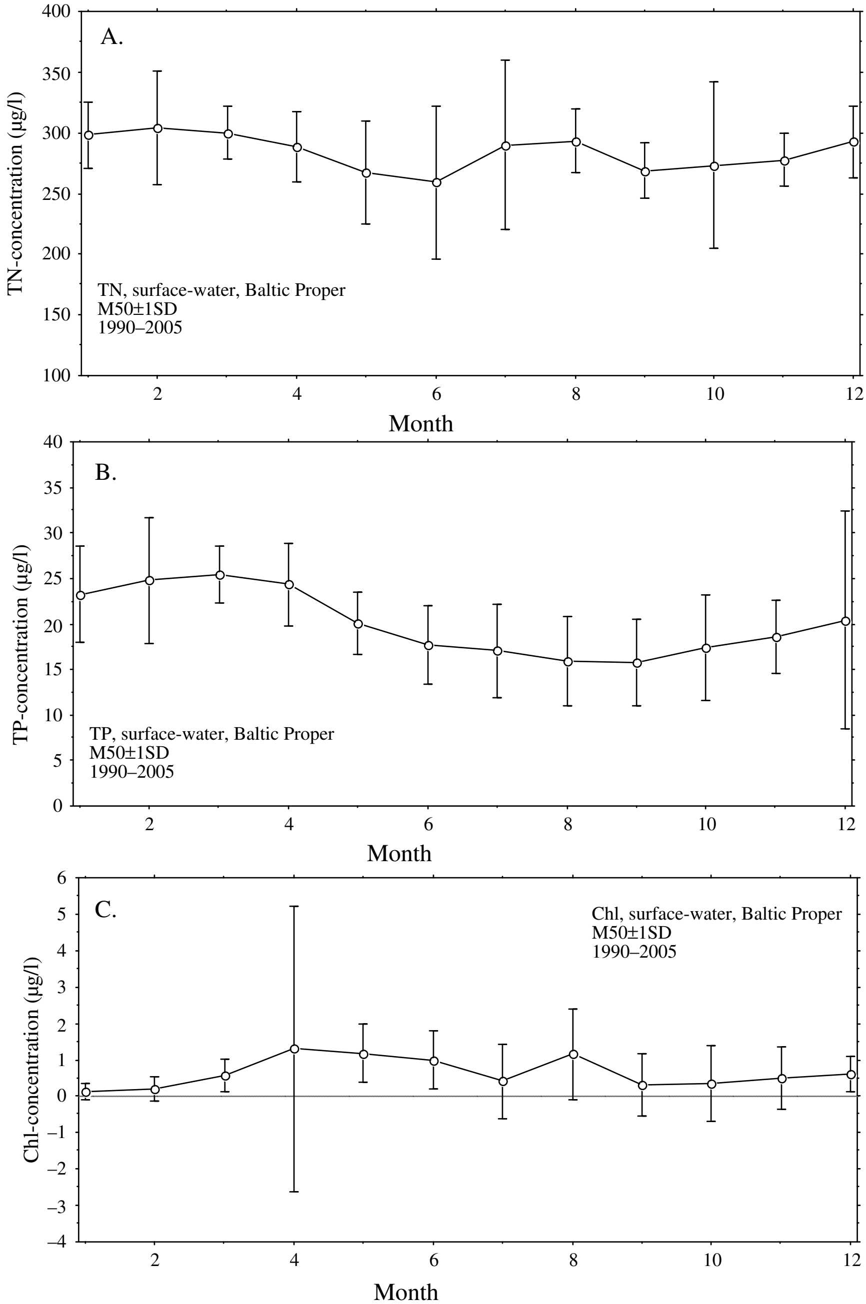


**Fig. 2.24** Monthly median values plus/minus one standard deviation of the empirical data for TN-concentrations (**A**), TP-concentrations (**B**) and concentrations of chlorophyll-a (**C**) based on data from the surface-water layer from the Baltic Proper from the period 1974 to 2005

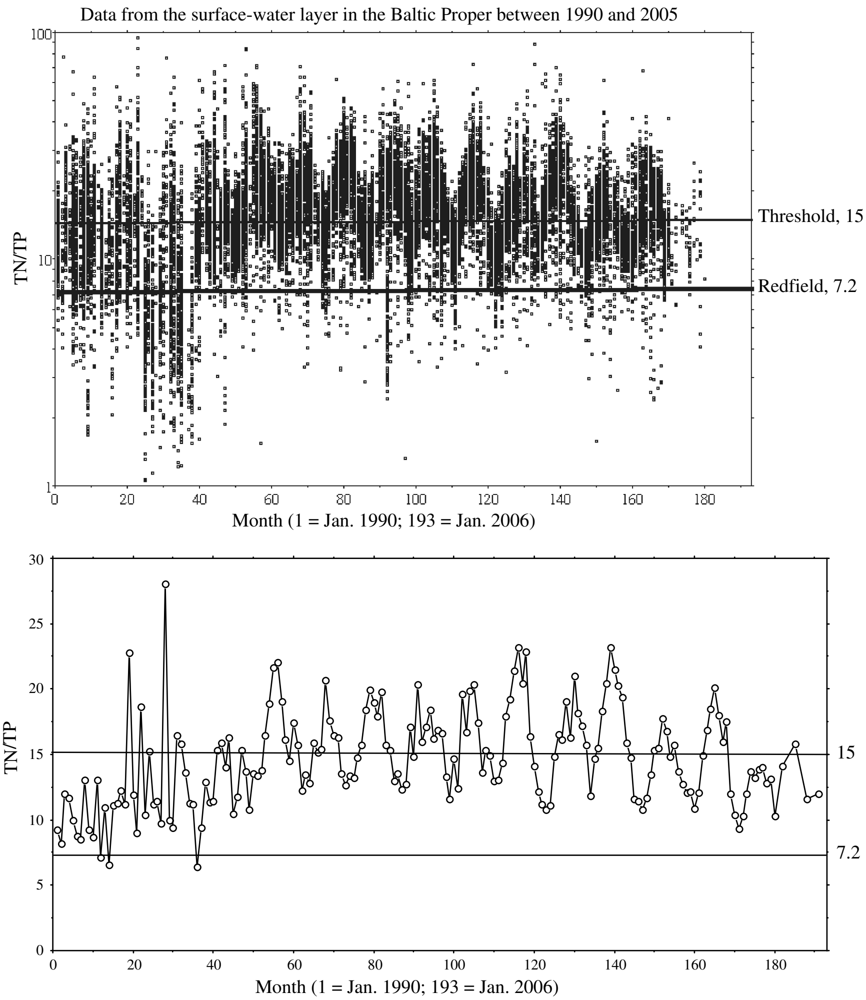


**Fig. 2.25** (**A**) The TN/TP-ratio from all $(n = 24,048)$ surface-water samples in the Baltic Proper using data from 1990 to 2005 in relation to the threshold ratio of 15 and the Redfield ratio of 7.2. (**B**) Variations in mean monthly TN/TP-ratios

and when the TN/TP-ratio is lower than 15, reductions in N would favor nitrogen fixing cyanobacteria, which should be avoided.

## 2.8 Putting the Data from the Baltic Sea into a Wider Context

To get some perspective on the current situation in the Baltic Proper, it is interesting to study the historical development over longer time intervals, but also to compare

**Table 2.8** Compilation of statistical information on TN/TP-ratios in the surface-water layer of the Baltic Proper using data from 1990 to 2005

| | All | Temp. > 15 °C AND | Depth < 20 m AND | TP > 10 μg/l |
|---|---|---|---|---|
| Min. | 1.05 | 1.74 | 1.74 | 1.74 |
| Max. | 171 | 76.9 | 76.9 | 59.4 |
| Mean | 16.5 | 20.1 | 20.4 | 18.7 |
| Median | 15.2 | 19.5 | 19.8 | 18.8 |
| Stand. dev. | 8.1 | 9.2 | 9.2 | 7.4 |
| Coeff. of var. | 0.49 | 0.46 | 0.45 | 0.40 |
| n | 24,048 | 3001 | 2880 | 2577 |
| % < 7.2 | 7.0 | 6.5 | 6.0 | 6.6 |
| % < 15 | 49.1 | 28.8 | 27.5 | 30.7 |

the situation in the Baltic Proper with other aquatic systems (using data from the sources given in Table 1.4).

Figure 2.27 gives a scatter plot between chlorophyll-a concentrations on the y-axis and TP-concentrations on the x-axis. The data in this figure emanate from the surface-water layer for the growing season, and we have added arrows to indicate the median conditions in the Baltic Sea. Note that this figure also gives data from smaller coastal areas in the Baltic Proper. Figure 2.28 provides similar information with TN-concentrations on the x-axis. From these two figures, one can note that there are evidently many systems with a much higher primary production and phytoplankton biomass than the Baltic Proper. Figure 2.27 is based on data from 533 systems. The $r^2$-value for the actual data is 0.73 and for the log-transformed data 0.61. One can see that the spread in the data becomes very wide for higher values of TP and chlorophyll. Figure 2.28 shows that there are data on chlorophyll and TN from 618 areas. The $r^2$-value for the actual data is 0.50 and for the log-transformed data 0.64.

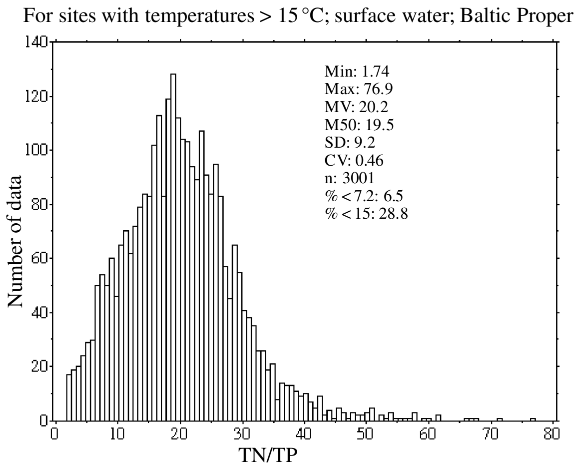


**Fig. 2.26** Frequency distribution for TN/TP-ratios for all samples with temperatures higher than 15 °C during 1990–2005 in the surface-water layer of the Baltic Proper

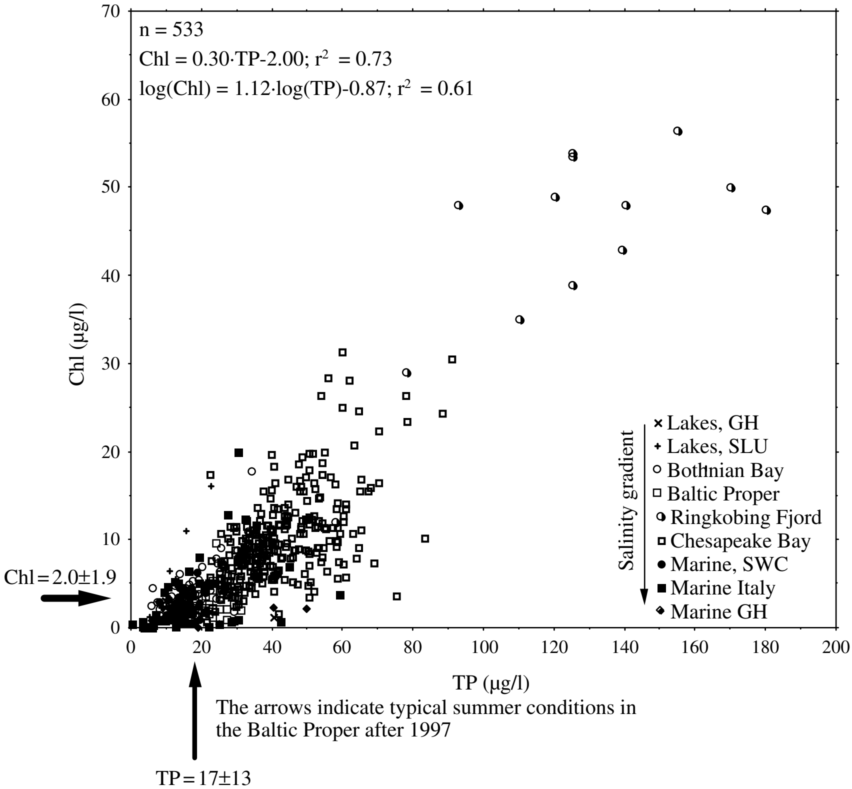


**Fig. 2.27** Scatter plot between median surface-water values of chlorophyll-a and TP-concentrations using data for the growing season from aquatic systems constituting a salinity gradient. The figure also gives regressions for the actual data and log-transformed data for the 533 data points and indicates typical (median) conditions in the open Baltic Proper after 1997. Data from the databases given in Table 1.4; GH represents data from Guildford and Hecky (2000)

Since plankton cells include both nitrogen and phosphorus, since both nutrients are transported to coastal areas by the same rivers, and since there is, in many systems a phosphorus-driven atmospheric nitrogen fixation by cyanobacteria (see Chap. 4), one generally finds a marked co-variation between phosphorus and nitrogen concentrations in aquatic systems, see Fig. 2.29, which is based on data from 495 systems covering very wide ranges in trophic status, size and form, latitudes and salinity. It is interesting to note that only 8 of these 495 systems have TN/TP-ratios lower than 7.2 and that the coefficient of determination is about 0.6 for both the actual and the logarithmic data. When there is a major difference from the general relationship shown by the regression line in Fig. 2.29, there should be specific causal reasons for this, if one first accounts for the scatter related to the inherent uncertainties in the data.

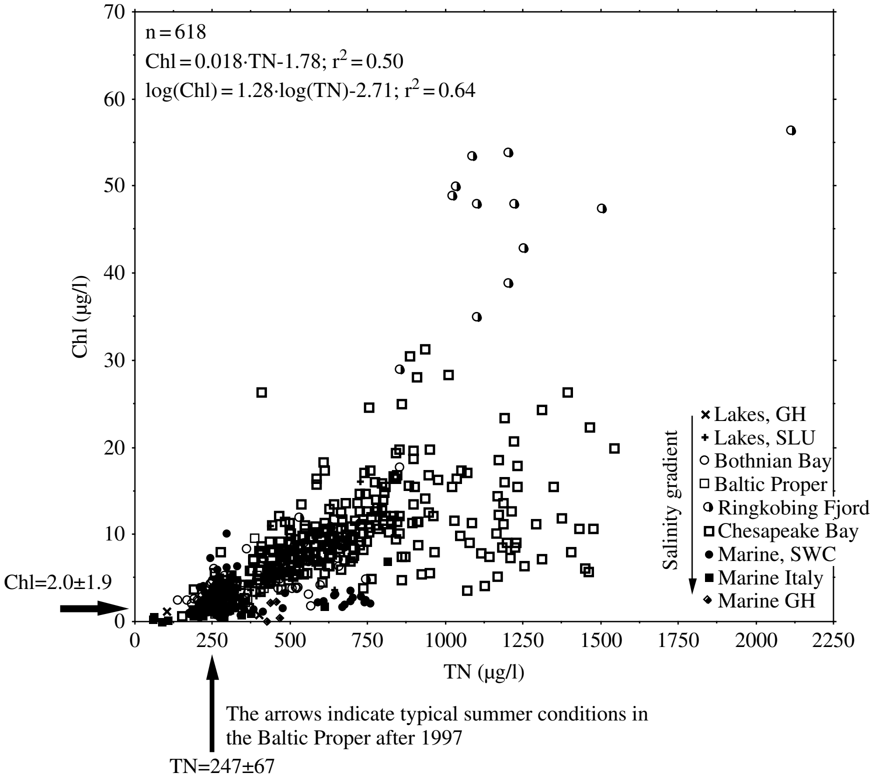


**Fig. 2.28** Scatter plot between median surface-water concentrations of chlorophyll-a and total-N (TN) concentrations for the growing season from aquatic systems constituting a salinity gradient. The figure also gives regressions for the actual data and log-transformed data for the 618 data points and indicates typical (median) conditions in the open Baltic Proper after 1997. Data from the databases given in Table 1.4; GH represents data from Guildford and Hecky (2000)

## 2.9 Conclusions

Traditional hydrodynamic or oceanographic models to calculate water fluxes to, within and out of coastal areas generally use water temperature data (the thermocline) or the salinity (the halocline) to differentiate between different water layers. This chapter has motivated another approach, the theoretical wave base as calculated from process-based sedimentological criteria, to differentiate between the surface-water layer and lower vertical layers and this approach gives one characteristic value for each basin. New morphometric data for the Baltic Sea and the defined sub-basins, and new hypsographic and volume curves based on digitized bathymetric data, have been presented and will be used in the CoastMab-model (in Chaps. 3 and 5). The basic aim of this chapter has been to present empirical data (facts) on the conditions in the Baltic Sea.

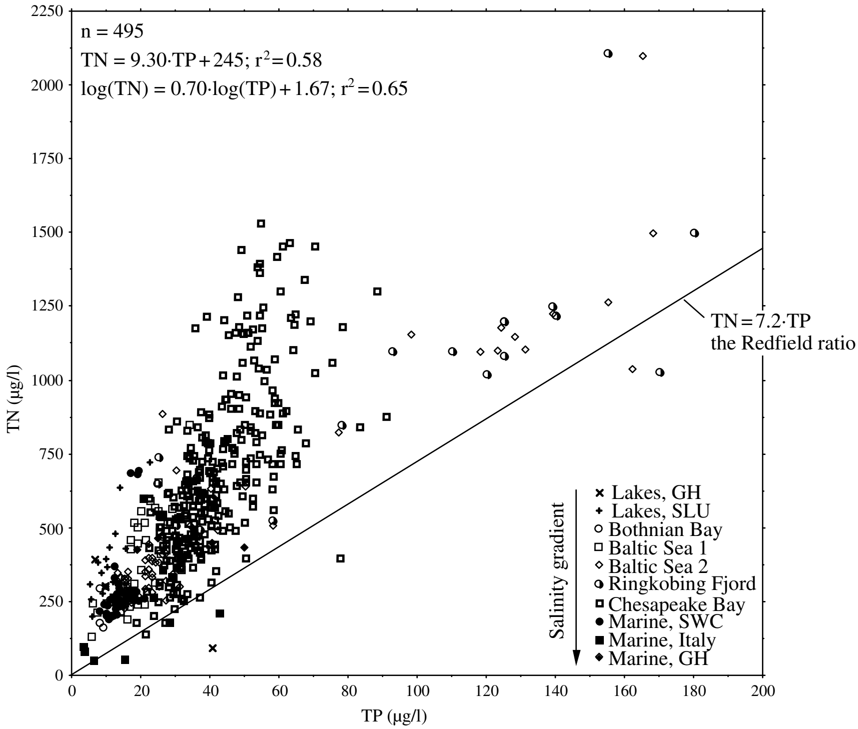


**Fig. 2.29** Scatter plot between SW-concentrations of total-P (TP) and total-N (TN) for the growing season from 9 sub-groups constituting a salinity gradient. The figure also gives regressions for the actual data and log-transformed data for the 495 data points. Data from the databases given in Table 1.4; GH represents data from Guildford and Hecky (2000)

This chapter has used extensive databases from the Baltic Sea on total phosphorus (TP), total nitrogen (TN), chlorophyll, temperature and salinity. We have presented trend analyses to determine whether there have been any changes in these variables between 1990 and 2005 (and between 1974 and 2005 for chlorophyll). To put these results into a wider context, we have also used data from more than 500 systems throughout the world. The TP and TN-values in the Baltic Proper are fairly stable between 1990 and 2005.

The empirical data from the Baltic Sea show:

1. There are no indications of a critical change starting around 1995 in the Baltic Proper. Instead the TP-concentrations in the SW-layer of the Baltic Proper are fairly stable and decreasing rather than increasing in the period between 1990 and 2005.
2. In addition, the TN-concentrations are stable throughout the period from 1990 to 2005, but the values were high in the summer of 2005, which may be related to the very extensive bloom of cyanobacteria that occurred this year.

3. There is no increase in surface-water temperatures in the Baltic Proper (compare global warming), but rather a weak opposite trend. At the same time there is a weak increasing trend in deep-water temperatures.
4. Also the salinities have been fairly stable since 1990.
5. The concentrations of chlorophyll-a show a very slowly decreasing trend in the surface-water layer of the Baltic Proper since 1974.
6. The seasonal pattern in monthly median chlorophyll-a concentrations is relatively stable among the years since 1974 with a peak value of about 3.5 μg/l in April and values around 2 μg/l through the bioproductive season.
7. In the summer time, the average conditions in the surface-water layer of the open Baltic Proper are generally at the boundary between oligotrophic and mesotrophic conditions (with chlorophyll values of about 2 μg/l).
8. Compared to the situation in many other coastal areas, the trophic state in the Baltic Proper is moderate when using both TP and chlorophyll as indicators.
9. To get an overview of the situation in the Baltic Proper, we have divided the water column into three layers, which describe the conditions very well: (1) the surface-water layer, as defined by the depth of the theoretical wave base at 44 m in the Baltic Proper, (2) the middle-water layer between 44 and 75 m, and (5) the deep-water layer given by the average depth of the halocline at 75 m.
10. The median monthly TN/TP-ratio has been higher than 7.2 (the Redfield ratio) during all months since 1994 indicating that the primary production in the system is generally limited by P rather than N. If the TN/TP-ratio is lower than 15, there are increasing risks of blooms of cyanobacteria, especially if the water temperature is above 15 °C.

Finally, it is evident that changes in nutrient concentrations can only be mechanistically explained by means of dynamic mass-balance models based on processes. To carry out such analyses is the focal point in Chap. 5, where the task is to apply the CoastMab-model to the conditions in the entire Baltic Sea, including considerations to land uplift, inflow and outflow, sedimentation, resuspension, burial, mixing, diffusion, mixing and biouptake and retention in biota.

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