Relationship between eutrophication reference conditions and boundary settings considering OSPAR recommendations and the Water Framework Directive—examples from the German Bight

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Originally published in the journal Hydrobiologia, Volume 629, No. 1, 91–106.
DOI: 10.1007/s10750-009-9778-9

Abstract In order to allow for natural variability, the original OSPAR assessment procedure for eutrophication (Comprehensive Procedure) sets the threshold between Non-Problem/Problem Area (elevated levels) at 50% above natural background concentrations, which is equivalent to the boundary setting good/moderate for the EU Water Framework Directive (WFD). The 50% level corresponds to the recent natural variability of nutrient gradients in coastal and estuarine waters in the German Bight. Based on this threshold, a proposal is given for the additional boundary settings required for the WFD assessments. Examples, based on concentrations of total nitrogen and other correlated eutrophication components, are presented. However, for eutrophication effects such as oxygen deficiency, reduced transparency and increased transboundary loads, especially for offshore regions, 50% exceedance of the natural background surpasses 'slight differences' as recommended by the boundary good/moderate for the WFD. For this reason, 15% is proposed as the boundary setting for good/moderate and discussed for different parameters. Overlapping between recent means and their standard deviations and the four boundary settings for the WFD cannot be avoided, thereby causing weak assessments. Since the part of the variability of recent data is caused by hydrodynamics, coupled with salinity variation, the variability could be reduced to some degree by relating the data to mean salinities. By doing this, the significance of classifications could be improved. The application of this procedure is discussed for examples from the German Bight.

Keywords Eutrophication · Assessment · Boundary setting · Reference conditions · Nutrients · Oxygen depletion

Guest editors: J. H. Andersen & D. J. Conley
Eutrophication in Coastal Ecosystems: Selected papers from the Second International Symposium on Research and Management of Eutrophication in Coastal Ecosystems, 20–23 June 2006, Nyborg, Denmark

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Introduction

Eutrophication assessments need boundary settings related to natural background conditions that allow, as far as possible, precise, transparent effect-related results, which are required for focused reduction measures.

Boundary settings should primarily be based on the different stages of eutrophication effects, such as the degree of effects (concentrations, extensions, durations and frequencies) in relation to natural background concentrations. However, the ability to relate the effects quantitatively to causative factors is limited owing to the complexity and variability of interacting processes.

For this reason, a pragmatic first approach was followed by OSPAR for the definition of a general threshold between 'Non-Problem Area' (NPA) and 'Problem Area' (PA) of 50% above the regional specific background concentrations as 'elevated level', "in order to allow for natural variability" (OSPAR, 2005). Variability around 50% is often observed for recent data in transitional and coastal waters. OSPAR and the EUWater Framework Directive (WFD) use similar parameters and basic boundary settings for assessing the eutrophication status. The threshold between Non-Problem Area and Problem Area was suggested by OSPAR as a definition for Quality Objectives and also as the boundary between 'good' and 'moderate' for the WFD (European Communities, 2000; OSPAR, 2004a). This boundary can be seen as a 'key boundary' because by surpassing this value measures are required to improve the environment, controlled by sufficient monitoring (European Communities, 2000; OSPAR, 2005).

Since for the OSPAR assessment only one threshold is used, the significance of the deviation of recent data from this threshold has been discussed extensively (OSPAR, 2004b). However, by introducing the WFD with four boundary settings, overlaps with recent means and their standard deviations are difficult to avoid along observed gradients, causing less significant deviations and assessments. However, focusing on the main (key) boundary setting between good and moderate, the significance requirements for the WFD are similar to OSPAR assessment criteria.In order to keep the variability as low as possible, data may be normalized to specific salinities, thereby reducing hydrodynamic influences.

However, it is evident that the 50% deviation can represent much more than the proposed WFD 'slight differences' from natural background conditions. 'Slight differences' would be something around 20% above natural background values and accordingly 15% or 25% as the boundary setting between good and moderate has been discussed already, but related to high reference values (Andersen et al., 2004).

Fig. 1 Map of recent concentrations of TN (μM) (*top left*) and ▶ associated standard deviations with salinity of 31 indicated (*top right*) in the German Bight, divided into regular squares of 145 km^2, with mixing diagrams for TN concentrations (*middle*) and standard deviations (*bottom*) for surface waters in all the seasons (1998–2002)

Therefore, in addition to the key boundary setting of 50% above natural background conditions, 15% will be discussed as a key boundary for different eutrophication processes, considering effect relationships and data variability.

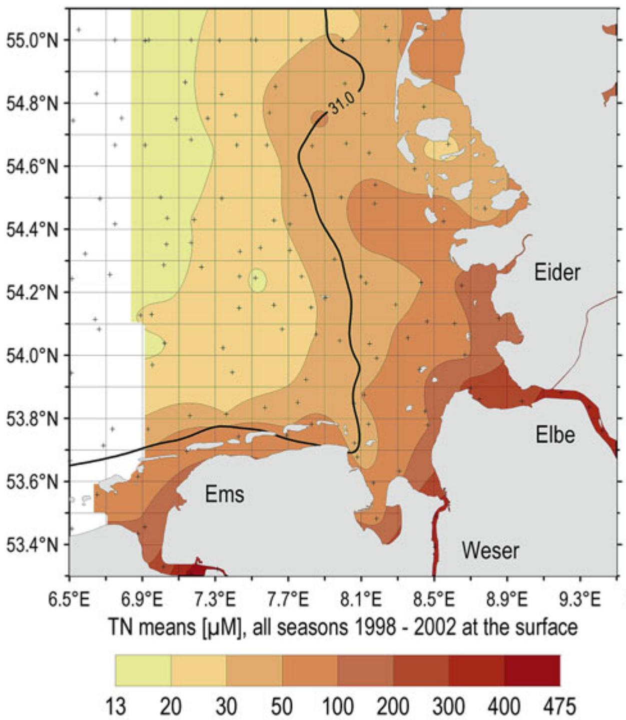
Boundary settings

Natural background concentrations that reflect pristine conditions, not affected by anthropogenic activities (European Communities, 2000), are the basis for boundary settings. The most important boundary setting between good and moderate (transferable to Non-Problem/Problem Area) is defined as 'slight deviation' from reference conditions.

The OSPAR approach, using 50% above background concentrations as the threshold, is still suitable for the assessment of the inner German Bight because recent (1998–2002) mean nutrient and chlorophyll concentrations reflect a regional variability of about 50% as standard deviation. As an example, the surface concentrations of total nitrogen (TN) are shown (Fig. 1, top). For the estimation of the regional variability, the inner German Bight was divided into regular squares of 145 km^2 size. This is in the range of 10% of the maximum extension, allowing a corresponding precision of assessments. For each square, means and standard deviations were calculated.

The recent mean concentrations of TN were less than 20 μM offshore, increasing to more than 200 μM in the estuaries. A salinity of 31 indicates roughly the border between the coastal area to be assessed according to the WFD and the offshore area, both assessed by OSPAR.

The variability surpassed 50% (as standard deviation) mainly along the border of the coastal water, caused by the permanently changing shapes and extensions of river plumes, and was especially high around a salinity of 30 as shown by the mixing diagram with means for the different squares and the standard deviations plotted against the salinity (Fig. 1, bottom). The reasons are the low TN concentrations and the changing gradients along the river plume fronts.


55.0°N
54.8°N
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54.0°N
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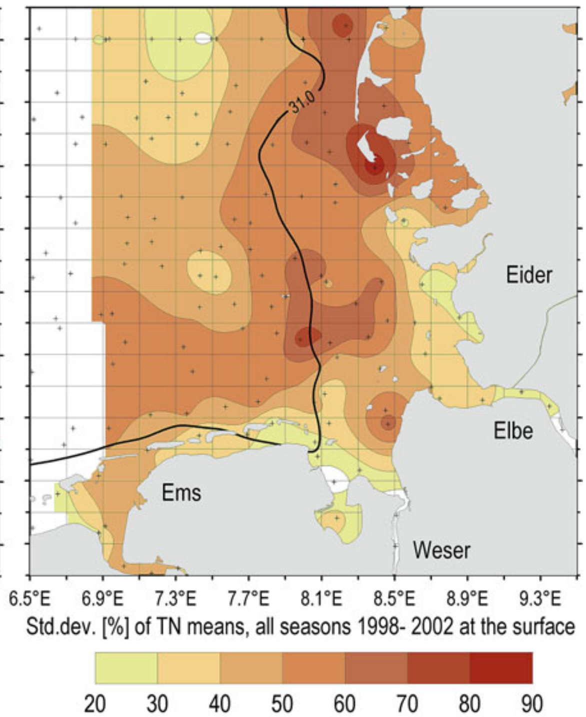
31.0
Eider
Elbe
Ems
Weser
6.5°E 6.9°E 7.3°E 7.7°E 8.1°E 8.5°E 8.9°E 9.3°E
TN means [µM], all seasons 1998 - 2002 at the surface
13 20 30 50 100 200 300 400 475


31.0
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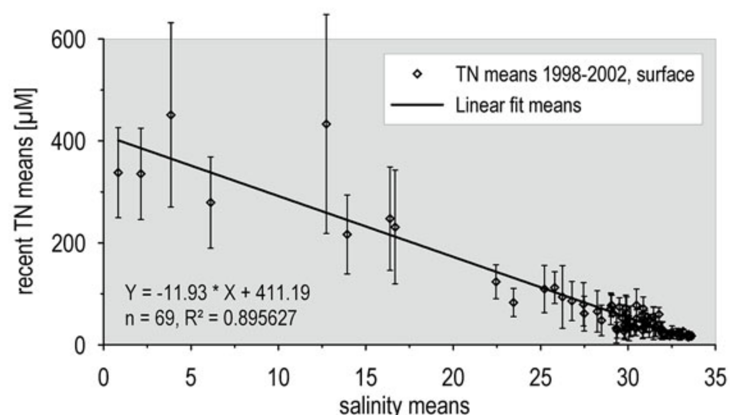
Std.dev. [%] of TN means, all seasons 1998- 2002 at the surface
20 30 40 50 60 70 80 90


TN means 1998-2002, surface
Linear fit means
Y = -11.93 * X + 411.19
n = 69, R² = 0.895627
recent TN means [µM]
salinity means
0 200 400 600
0 5 10 15 20 25 30 35

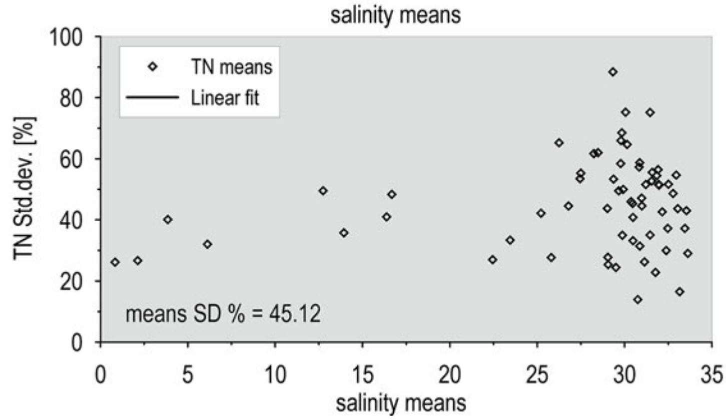

TN means
Linear fit
means SD % = 45.12
TN Std.dev. [%]
salinity means
0 20 40 60 80 100
0 5 10 15 20 25 30 35

Table 1 Scheme of OSPAR/WFD thresholds, based on a 50% key threshold

OSPAR	Further assessment	Non-problem area		Problem area		
WFD class	Reference	High	Good	Moderate	Poor	Bad
% Deviation from background	0	<17	17–**50**	**50**–150	150–450	>450
EQRs [100/(100 + deviation)]	1.0	>0.85	0.85–0.67	0.67–0.40	0.40–0.18	<0.18
TN [μM]	11.1	<13	13–17	17–28	28–61	>61
Oxygen saturation [%]	87	>84	84–80	80–66	66–25	<25
O_2 depletion effects (Table 3)		No effects	80% min. requirement	70% first effects	50% first kills	<40% kills

EQR: Ecological Quality Ratio

The annual changing riverine nutrient discharges to the German Bight vary between 20% and 60% (Pätsch & Lenhart, 2004). Therefore, it is recommended to apply a threshold of 50% above the reference value for increasing eutrophication effects as a first approach in nearshore waters (Table 1) until further refinement, for example by reducing the variability of recent data, is achieved.

The 50% deviation from background concentrations corresponds to the high/good boundary of the WFD (European Communities, 2000). The natural background conditions are indicated as reference conditions for the boundary settings. By OSPAR, these values are defined as ‘high’ status.

Successive boundary settings, which can also be defined as percentage deviations from reference conditions, are proposed according to the WFD requirement of five classes. The differences between these boundary settings were simply defined on a regular basis to keep the procedure as transparent as possible. A factor of 3 for stepwise deviations was chosen, considering the range of current nutrient gradients in the estuaries of the German Bight. Boundary settings between high and good are proposed to be 17% above reference (a third of 50%), those of moderate/poor and poor/bad are taken as 150% (three times 50%) and 450% (nine times 50%) above natural background (Table 1, line 2).

By dividing the reference conditions (= 100%) by the percentages of the thresholds in relation to the reference, the corresponding Ecology Quality Ratios (EQRs) were calculated (0.85–0.18), considering the recommendations that the ‘high’ class is close to 1 and the ‘bad’ class approaches 0 (European Communities, 2002) (Table 1, line 3).

TN concentrations are presented as the master variable, with a reference concentration of 11.1 μM for the offshore area (recent mean surface concentration in the central North Sea at salinities between 34.5 and 35), due to its manifold quantitative relationship to other eutrophication parameters, such as chlorophyll (Nielsen et al., 2002b; Tett et al., 2003; Smith, 2006). The rounded boundary settings are correspondingly 17 μM (50% above reference) for good/moderate, 28 μM for moderate/poor and >61 μM for bad conditions (Table 1, line 4).

Oxygen depletion occurs occasionally during summer in the stratified part of the German Bight (Dethlefsen & von Westernhagen, 1983; Rachor & Albrecht, 1983; Brockmann & Eberlein, 1986). Thermal stratification starts mostly in May (Tomczak & Goedecke, 1964) and initial oxygen depletion is observed in July. Assuming simple stationary conditions, the oxygen demand was calculated for the TN concentrations at the thresholds, equivalent to carbon and nitrogen, by applying the Redfield ratio C:N = 6.75 (Redfield et al., 1963) by which 1 μM N is equivalent to 0.28 mg O_2 l^{-1}, and by using an efficiency factor of 0.4 for the German Bight: mg O_2 l^{-1} = 0.28 μM TN × 0.4.

The factor of 0.4 was introduced based on observed correlations between particulate organic carbon and oxygen depletion in the bottom waters. It is evident that this efficiency of 40% includes influences of residence time, diffusion and exchange processes. The resulting oxygen demand is subtracted from 9.1 mg l^{-1} oxygen concentration which is equivalent to 100% saturation at a mean salinity of 34 and assumed 10°C in the bottom water (Table 2). The resulting potential oxygen consumption, equivalent to

Table 2 TN/Oxygen conversion (example for a 50% key boundary setting = 150% of background)

%	μM TN % in col. 1	mg O_2 l^{-1} (μM TN × 0.28)*	× 0.4 mg O_2 l^{-1} **	Diff from 9.1 mg O_2 l^{-1***}	Sat. %
100	11.1	3.1	1.24	7.86	87
117	13.0	3.64	1.46	7.64	84
150	16.7	4.68	1.87	7.23	80
250	27.8	7.78	3.11	5.99	66
550	61.1	17.1	6.84	2.26	25

* According to the Redfeld ratios, ** corresponding to recent relations (see text), *** 9.1 mg O_2 l^{-1} corresponds to oxygen saturation (at a salinity of 34 and 10°C)

the TN thresholds, was transferred to saturation (%) according to Benson & Krause (1984) (Table 1, line 5).

The natural background concentration of 11.1 μM TN corresponds to 1.2 mg O_2 l^{-1} consumption in the German Bight, resulting in 7.9 mg O_2 l^{-1} residual concentration = 87% saturation, assuming that only 40% of organic matter will be decomposed during these processes. A 50% deviation of TN concentrations from background values would correspond to 80% oxygen saturation in bottom waters.

However, comparing this value with the effect levels of oxygen deficiency, which have been extracted from the literature and compiled in Table 3, the proposed boundary settings are too high. Following the precautionary principle and considering that (i) monitoring of oxygen depletion in stratified bottom waters is usually not performed with a sufficient resolution in space and time and (ii) bottom water is sometimes warmer than 10°C (in the shallow German Bight up to 20°C), it is assumed that 80% oxygen saturation is already worse than good and more than a 'slight deviation' from background because 80% is the minimum requirement for fish cultivation. Therefore, values below 85% should be assessed already as moderate (Table 4).

At 60–70% oxygen saturation significant effects have been observed, considering increased surface/volume reactions of sea-cucumbers as a general indicator. For this reason, 76% is recommended as the boundary between moderate and poor. First kills occur below 50% oxygen saturation, which should be classified at least as poor. Because at around 33% saturation extended mortality of macrofauna was observed in the German Bight (Rachor, 1983; Bauerfeind et al., 1986; Niermann et al., 1990), 35% should be set as the poor/bad boundary. These field observations of severe oxygen depletion effects reflect mainly late stages of longer-lasting eutrophication processes, and are therefore only a rough indicator for setting effect-related boundaries.

For these reasons, 15% deviation from the natural background is proposed as an alternative boundary setting for good/moderate, especially for offshore areas where the occurrence of oxygen depletion indicates significant eutrophication (Table 4). Applying again regular steps, now with an assumed factor of 5, a similar differentiation as for the 50% approach can be achieved for the successive boundaries. However, the boundary for high/good, calculated by this scheme as 3%, has been defined instead as 7%, about half of the boundary for good/moderate, in order to take natural variability at low concentrations into account.

The key boundary setting of 15% results in a TN of 12.8 μM and potential O_2 depletion of 85% saturation. This is significantly above the first effect level of 80% saturation and is therefore proposed as the boundary for good/moderate. Since several different effects have been observed at 60–70% oxygen saturation, the suggested 75% above reference for the border between moderate/poor, corresponding to 19 μM TN or 76% oxygen saturation, is sufficiently above this value (Table 4). A TN concentration of 53 μM, corresponding to 375% above the reference which is proposed as the boundary setting between poor and bad, is equivalent to an oxygen depletion of 35% in the German Bight. This degree of oxygen depletion causes many lethal effects (Table 3).

The Secchi depth is another sensitive assessment parameter, especially in shallow coastal areas with flat-bottom slopes, because it controls the extension of macrophytes which are an important ecosystem

Table 3 Effects of oxygen deficiencies

Oxygen saturation (%)	Organisms	Observed responses	Comments	Literature
1	Oligochaetes, polychaetes, molluscs,	Kills		Gamenick et al. (1996) (G)
1, 6	*Crangon crangon*	Kills		Hagerman & Vismann (1995) (G)
2	Different invertebrates	Kills	Experiments, North & Baltic Sea	Theede et al. (1969) (D)
5–30	*Platichthys flesus*, flatfish	Mortality, reproduction		Tallqvist et al. (1999) (G)
10, 19	Fish & benthic organisms	Kills	German Bight	Dethlefsen & von Westernhagen (1983)
10–30	Macrozoobenthos	Damage of benthos, fish diseases	German Bight, Central North Sea	Rachor (1985)
12	*Crangon crangon*	Changed behavior		Hagerman & Vismann (1995) (G)
<13	Polychaetes	Kills	Limfjorden (Denmark)	Jörgensen (1980) (D)
13	*Amphiura filiformis*, Echinoderm	Emerging	Experiments	Rosenberg et al. (1991) (D)
14	Algae	Reproduction reduced		Peckolt & Rivers (1995) (G)
14, 22	Polychaetes	Emerging	Chesapeake	Pihl et al. (1992) (D)
14, 28	Fish	Migration	Chesapeake	Pihl et al. (1991) (D)
16, 29	*Mytilus edulis*	Delayed development		Wang & Widdows (1991) (G)
18	Bottom fauna	Kills, emerging	German Bight	Niermann (1990)
25	Zooplankton	Kills	Experiments	Roman et al. (1993)
25	*Nephrops norvegicus* (crustacean)	Emerging from tubes or burrows		Baden et al. (1990) (D)
25–43, 50	Macrofauna	Weakening, mortality	German Bight	Rachor (1983)
25–40	Cod, whiting	Migration		Wu (2002)
33	Macrofauna	Decrease	German Bight	Niermann et al. (1990)
31–33	Macrofauna	Mortality, decrease of abundance & richness	German Bight	Bauerfeind et al. (1986)
31	Most benthic organisms	Survival	10°C, salinity 34 assumed	Wu (2002)
33–44	*Monoporeia affinis* (Crustacean)	Activity reduced		Johansson (1997); Wu (2002)
35	*Saduria entomon*	Reduced consumption	of *Bathyporeia pilosa*	Sandberg & Bonsdorff (1996)
36–60	Freshwater fish	Kills	At 20°C	Missouri, 2005
37–48	Crustaceans	Kills	Experiments	Stickle et al. 1989
38	Atlantic sturgeon	Kills	Experiments	Secor & Gunderson (1998)
45–73	*Gadus morhua*	Activity & growth affected		Chabot & Dutil (1999) (G)
48	*Penaeus setiferus* crustacean	Reproduction and metabolism affected		Rosas et al. (1999) (G)
50	Sensitive fish	Avoidance, reduced growth		Breitburg (2002)
50–60	Gobiid fish	Increased respiration Changed metabolism		Petersen & Petersen (1988)
50–80	Different fish species	Blood undersaturation		Davis (1975)
54–63	Fish & bottom fauna	Beginning of negative effects	10°C, salinity 10 & 34	Sedin (2002)

Table 3 continued

Oxygen saturation (%)	Organisms	Observed responses	Comments	Literature
60–70	*Holothuria forskalli* (cucumber)	Increased surf./vol. ratio		Astall & Jones (1991) (D)
62	Cold-water fish	Effects on cold water fishes	10°C, salinity 1	Behar (1997)
74	*Salmo trutta*	Reduced kidney, increased hemoglobin	Experiments	Seager et al. 2000
78	Fish	Minimum requirement	Bioassay	Fishdoc (2005)
85	*Sparus aurata*	Increase of ammonia toxicity		Wajsbrot et al. (1991)
93	Echinoderms	Reproduction affected		Spicer (1995) (G)

Data are partly transferred from reviews by Diaz & Rosenberg (1995) (D), Gray et al. (2002) (G)

Table 4 Scheme of OSPAR/WFD thresholds, based on a 15% key threshold

OSPAR	Further assessment	Non-problem area		Problem area		
WFD class	Reference	High	Good	Moderate	Poor	Bad
% Deviation from background	0	<7	7–**15**	**15**–75	75–375	>375
EQRs [100/(100 + deviation)]	1.0	>0.93	0.93–0.87	0.87–0.57	0.57–0.21	<0.21
TN [μM]	11.1	<11.9	11.9–12.8	12.8–19	19–53	>53
Oxygen saturation [%]	87	>86	86–85	85–76	76–35	<35
O_2 depletion-effects		No effects	80% min. requirement	70% first effects	50% first kills	<40% kills
Secchi depth [%]	100	>92	92–85	85–55	55–18	<18
Secchi depth [m]	7.8	>7.2	7.2–6.6	6.6–4.3	4.3–1.4	<1.4
Flow/content [kt N]	6.7	7.2	7.2–7.7	7.7–11.5	11.5–32	>32

EQR: Ecological Quality Ratio

component (Nielsen et al., 2002a). Similar to the findings of Nielsen et al. (2002a), the Secchi depth was correlated with TN concentrations in the German Bight during summer, resulting in the equation: $\ln [m] = -1.11 \times \ln [TN\ \mu M] + 4.72$. A pristine Secchi depth would be 7.8 m in the open German Bight, deduced from 11.1 μM TN.

The key good/moderate boundary of 12.8 μM TN (15% above background concentration) corresponds with 6.6 m to 85% of the reference depth, whereas 17 μM TN (50% above background concentration, Table 1) would result in 4.8 m which is only 62% of the reference Secchi depth. This is already far beyond good conditions or slight disturbance because this Secchi depth would restrict the possible extension of macrophytes significantly (Nielsen et al., 2002a), by about 30% in the shallow German Bight.

Further aspects for setting boundaries are the acceptable offshore concentrations, affected by long-distance transboundary transports, which are addressed also by OSPAR (2005). A rough budget calculation of N and phosphorus (P) fluxes in the German Bight (24,400 km^2, mean depth 19.5 m, 476 km^3 volume) resulted in a mean content of 74 kt N for natural background concentrations of about 11 μM TN. Reflecting the contradictory results of recent hydrodynamic model exercises (Smith et al., 1996) a very simple dynamic approach was chosen, assuming a constant outflow of 3 cm s^{-1} through the northern border at 55.1° N (Fig. 1) (Mittelstaedt et al., 1983), which is balanced by a constant inflow of 1.8 cm s^{-1} along the larger western border at 6.5° E, in order to receive a closed budget of water masses.

Table 5 Mean annual budget of pristine TN and TP in the German Bight

	Water [km^3 y^{-1}]	TN [$\times$ 10^3 t N y^{-1}]			TP [$\times$ 10^3 t P y^{-1}]		
		Pristine	15% threshold	50% threshold	Pristine	15% threshold	50% threshold
Transboundary import	3198	497.0	572.0	746.0	71.4	82.1	107.0
River discharges	37	11.0	13.0	17.0	0.5	0.6	0.8
Atmospheric input	±0	2.4	2.8	3.6	–	–	–
Transboundary export	3235	503.0	578.0	755.0	72.2	83.0	108.0
Trapping/ remobilization	0 (balanced)	7.4 lost	9.8 Lost	11.6 lost	0.3 net export	0.3 net export	0.2 net export

The natural annual flow of nitrogen nutrients through the German Bight of 497 kt N y^{-1} amounts to seven times the N content, corresponding to the budget of the water masses (Table 5). Allowing a boundary of 15% above background concentrations, the nutrient content of the German Bight will be exchanged nearly eight times per year. At a 50% boundary setting 10 times the N content would be transported through the German Bight. The difference of 249 kt N y^{-1} above the background flow of 497 kt N y^{-1} would correspond to three times the natural background nutrient content (74 kt N). Since the difference between the two boundary settings amounts to 174 kt N y^{-1} which is 10 times the annual historical river discharges (17 kt N y^{-1}, assuming 50% as threshold), a 50% boundary setting for 'good/moderate' cannot be accepted. The reason is that a mean flushing time of about 8 weeks allows the passing nutrients and organic matter an extended participation in the local turnover processes, including the formation of blooms, transient accumulation and significant oxygen depletion within a similar time period.

Owing to the pattern of the residual current system in the southern North Sea (OSPAR, 2000), it can be assumed that a significant load of nutrients and subsequently produced organic matter originate from the southern and western coastal areas.

Differentiating boundary settings along salinity gradients

The relationship of pristine background concentrations to salinity gradients can be established analogous to mixing diagrams by combination and extrapolation of freshwater, coastal and offshore values (Fig. 2). Pristine freshwater endmember concentrations were taken from a model (MONERIS), in which the different soil types were considered (Behrendt et al., 2003). Natural background concentrations for coastal waters are means of published extrapolated historical data (Zevenboom, 1994; Van Raaphorst et al., 2000) and for offshore waters recent means from the central North Sea were used. Natural background concentrations for freshwaters are river-specific. For TP, they are partly below reference conditions in the coastal water.

While linear mixing is the dominant process in the estuaries, nutrient recycling and different nutrient sources become more important in the open water, causing non-linear mixing. In order to approach offshore conditions with their unlimited dilution potential, hyperbolic fits of reference values were calculated and applied for higher salinities. The transition with linear fits is given by crossing points, at a salinity of 31 (Fig. 2). Consequently, for the calculation in the transitional and coastal waters, linear regressions were used up to a salinity of 31, above which the hyperbolic fits were applied, allowing a consistent estimation of background values.

The boundaries can be calculated correspondingly along the salinity gradients, adding 15% to the reference conditions. The final offshore values are fixed at 12.8 μM TN and 0.83 μM TP by the hyperbolic fits.

As an example, the application of the different approaches along the salinity gradients in the German Bight and the German exclusive economic zone is shown by the differences between recent (means 1998–2002) and pristine TN concentrations at the surface as percentages of pristine values (Fig. 3). The main salinities are indicated by isopleths. There is no inconsistency of classification at the salinity of 31, the border between linear and hyperbolic calculations

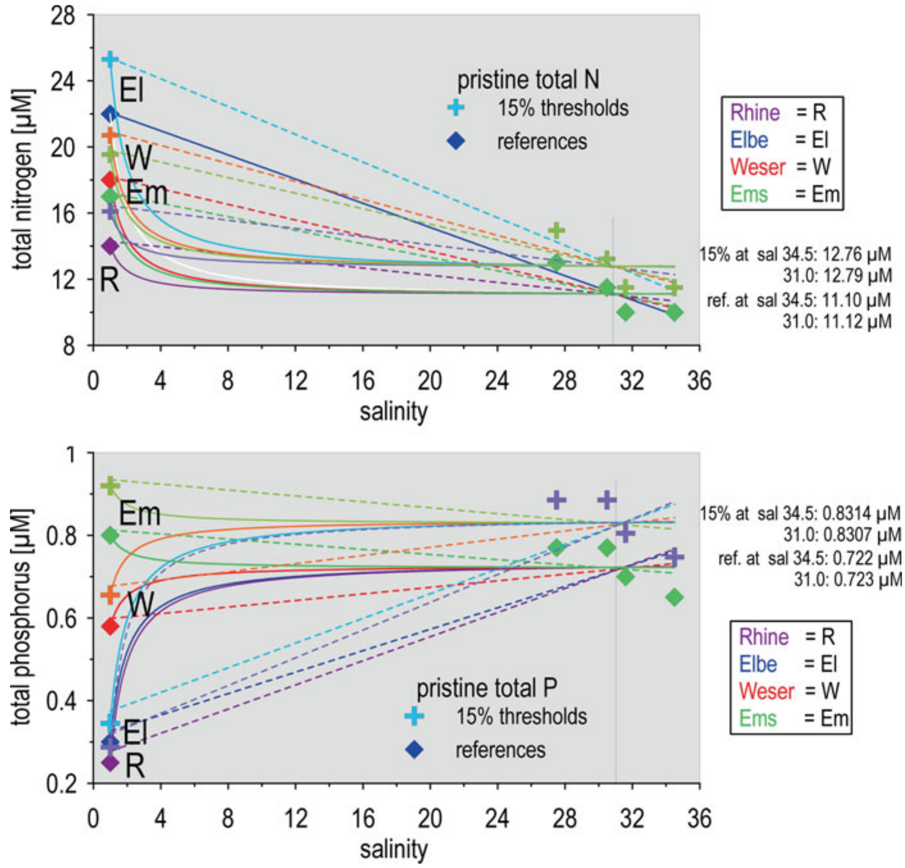


Fig. 2 Pristine mixing diagrams with thresholds for nitrogen (*top*) and phosphorus (*bottom*)

of reference conditions. Using the 50% key boundary approach, the areas assessed as high and good start already west of 7° E, while using the 15% key boundary they start only west of 6.5° E. Accordingly, the areas specified as bad and poor are also more extended by the latter approach. However, the shapes of the differently classified areas are similar.

Boundary settings and data variability

For the assessments, in addition to the representativity of the data, the significance of differences between gradients of recent data and boundary settings is important. As an example, for the variability of recent and pristine data affecting the precision of an assessment, a transect along the Elbe estuary and plume is shown, compiling means of the WFD types crossed and their standard deviations (Fig. 4).

The transect begins in the inner estuary (Elbe 6, type definition transitional water according to the WFD), passing a polyhaline moderately exposed type (Elbe 4), exposed coastal water (Elbe 3, Eider 3), and offshore coastal water of Schleswig-Holstein (SH) affected by the Elbe river plume. Reference conditions, boundary settings and recent data are indicated by means and their standard deviations.

Reference conditions and recent concentrations of TN decrease with increasing salinity in the area influenced by the Elbe. Means of recent data cross the boundary setting between bad and poor (at 375%) within the coastal water. Standard deviations of recent data are in the range of 100 μM (20–70%), while those of boundaries which were calculated in relation to recent salinity gradients are below 10 μM (5–10%).

Recent means in the estuary and the two types further downstream were significantly above the boundary at 375% (above natural background concentrations) between poor and bad. In the type Eider 3, the recent mean and its standard deviations were not significantly above this value and in the offshore

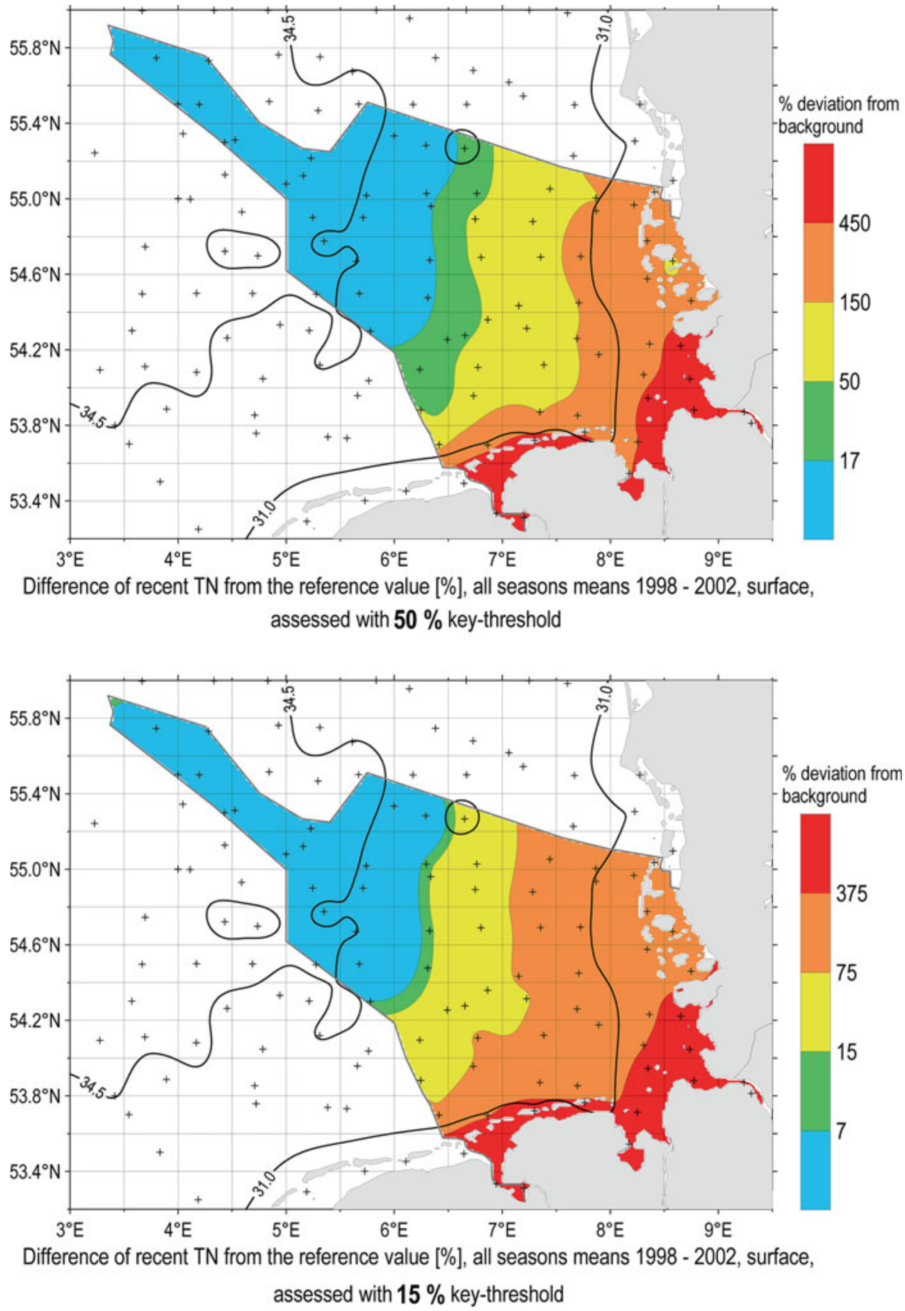


Fig. 3 Differences between recent (means of 1998–2002) and pristine concentrations of TN (μM) as % of pristine values, assessed with the 50% (*top*) and 15% (*bottom*) approaches

coastal water (SH) recent concentrations overlapped between the boundary settings poor/bad and moderate/poor. However, the locations of means in relation to the boundary settings can be used for the assessment, which is bad for the main part of this transect.

A 3-D plot is presented for a related area visualizing the overlapping between boundary settings and recent mean concentrations with their variability. Looking from the coast northwest into the German Bight area, the plot shows the gradients of boundary settings and recent (1998–2002) mean TN concentrations with their standard deviations (Fig. 5). The variability (as μM) was especially high within the estuaries. Offshore, the recent data fell below the boundary setting for poor/bad and later below the moderate/poor boundary. The

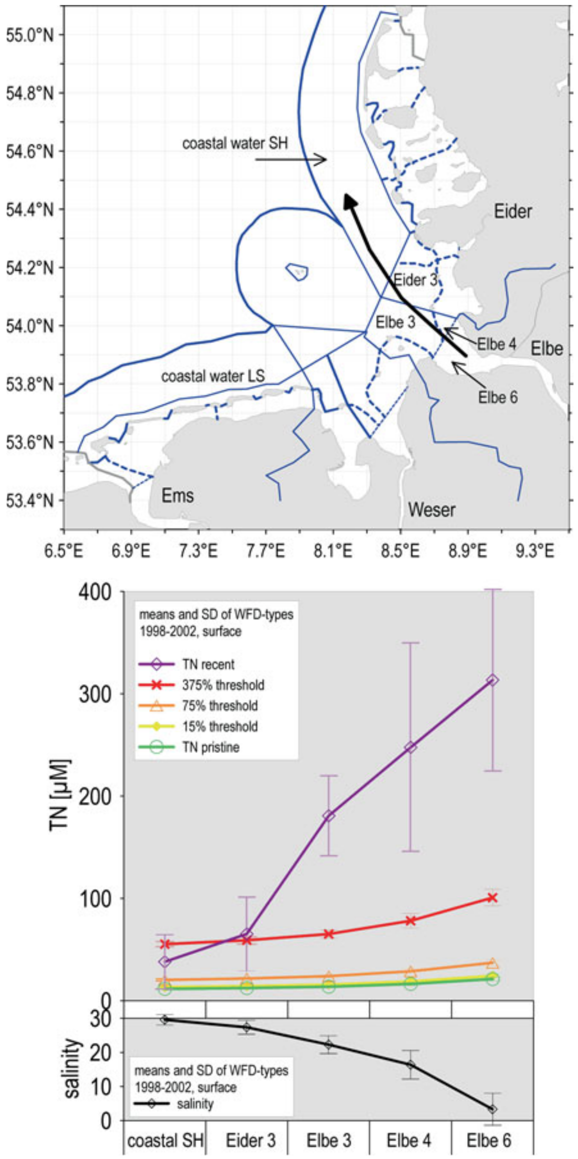


Fig. 4 Transect of recent mean TN concentrations (1998–2002), pristine values and thresholds of the 15% approach along the WFD types (indicated by blue lines in the map above) and water masses of the Elbe estuary and its plume

boundary setting high/good was not presented. In an enlarged section, the extent of overlapping in this area is evident.

Overlapping cannot always be avoided, especially not for four boundary settings, but it may be reduced to some degree by excluding the hydrodynamic variability, which is often coupled with salinity gradients. The reasons for the variability are, in addition to biogeochemical processes, the hydrodynamics that do not need to be assessed. For this reason the variability, for example caused by moving river plumes, can be excluded, thereby reducing the overlapping to some degree. This dynamic approach is compared with a static analysis as presented in Fig. 1.

In order to reduce the influence of hydrodynamic variability, the German Bight was divided into the individual river plume mixing areas and, for each area, mixing diagrams were plotted (Fig. 6). The general mixing diagram of TN for the German Bight showed a significant negative correlation with salinity during the period 1998–2002. As an example, for the Ems estuary and the Ems plume area for each 1-PSU (Practical Salinity Unit) step the mean TN concentration and its standard deviation were calculated. The mean standard deviations were about 15% below those of the squares of 145 km^2 (Fig. 1).

For the salinity-related means and standard deviations, the mean geographic positions were calculated and the data transferred to a map. The resulting gradients were compared with the original TN distribution (Fig. 1) by the calculated differences (Fig. 7). Mainly the differences in concentrations were below 10%. By this procedure, the standard deviations could be reduced especially in the river plume mixing area by more than 20%. However, differences between original data and recalculated values were significant (>20 µM) in parts of the same region as well. Thus, the reduction of salinity-related variability was not generally possible and for some areas the assessments would remain weak with extended overlapping between boundary settings and monitoring data. Using a higher data density, salinity-related variability could be further reduced.

Conclusions and perspectives

Considering causal relationships between different eutrophication parameters, contradictions between reference values can be avoided and decreasing effects (oxygen depletions and Secchi depth limitations) can be coupled to increasing effects (nutrient concentrations) allowing similar deductions of background conditions and related assessment boundaries.

The mainly linear mixing of terrestrial-origin nutrient discharges in transitional and coastal waters with strong salinity gradients allows the calculation of salinity-related natural background concentrations

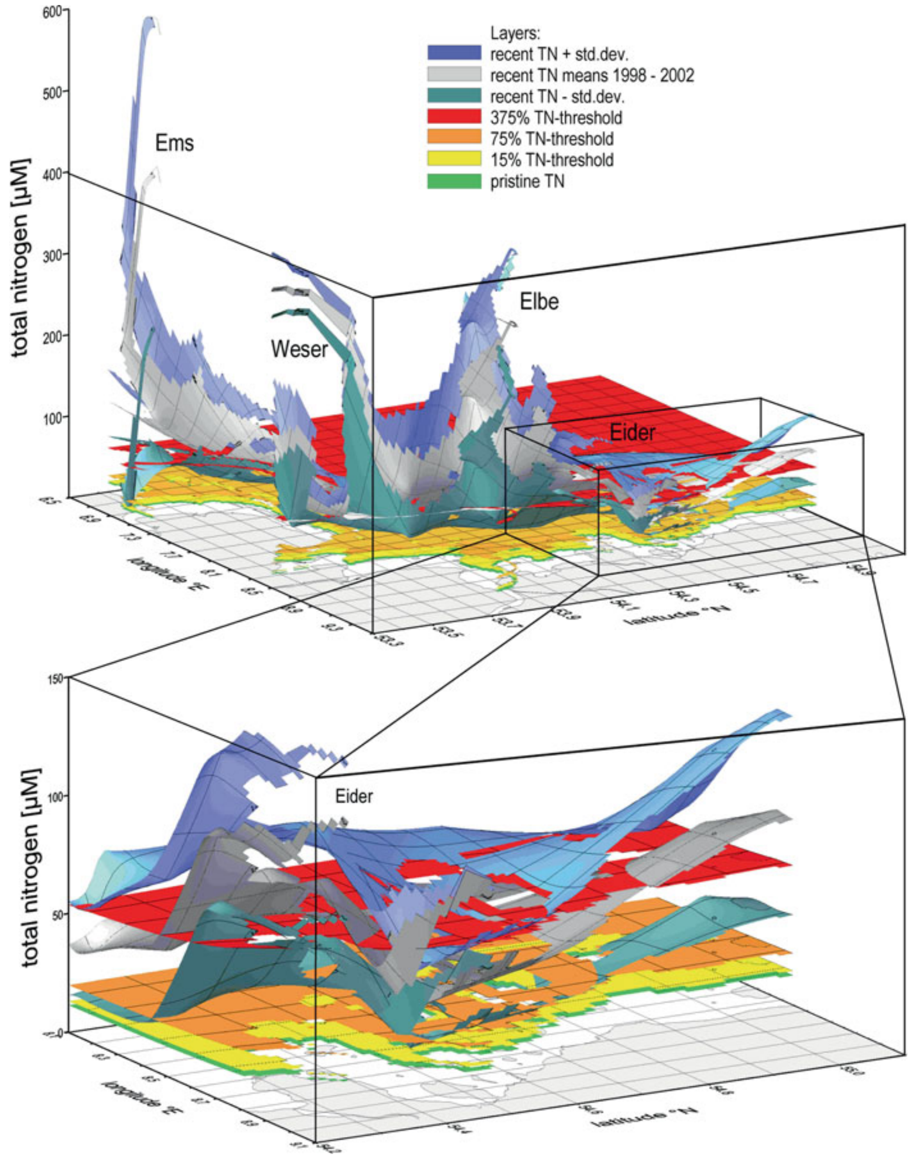


Fig. 5 3-D plot of recent mean TN concentrations and their standard deviations together with thresholds of the 15% approach in the German Bight. View to the northwest towards the sea. The enlarged section represents the North Frisian Coast

and boundary settings. This is also possible for directly coupled effects. However, reflecting the unlimited dilution potential of open waters, fixed offshore values should be defined, for example by approaching offshore values using hyperbolic fittings. In combination with linear fittings, based on the same data, for inshore areas, still consistent assessments can be achieved.

In order to keep the boundary setting as transparent as possible, a percentage relation to natural background concentrations is recommended. Different boundaries, as required by the WFD, may be calculated using constant factors (e.g. 3 and 5 as here proposed) of percentage deviations. Ecological Quality Ratios can be calculated by dividing 100% of the natural background by 100 + x% above the reference value of the boundary setting.

Boundary settings may be related to natural (e.g. hydrodynamic) variability, considering undesirable effects as well. Considering variability, an excess of 50% over natural background values has been introduced by OSPAR as a key boundary. This relation,

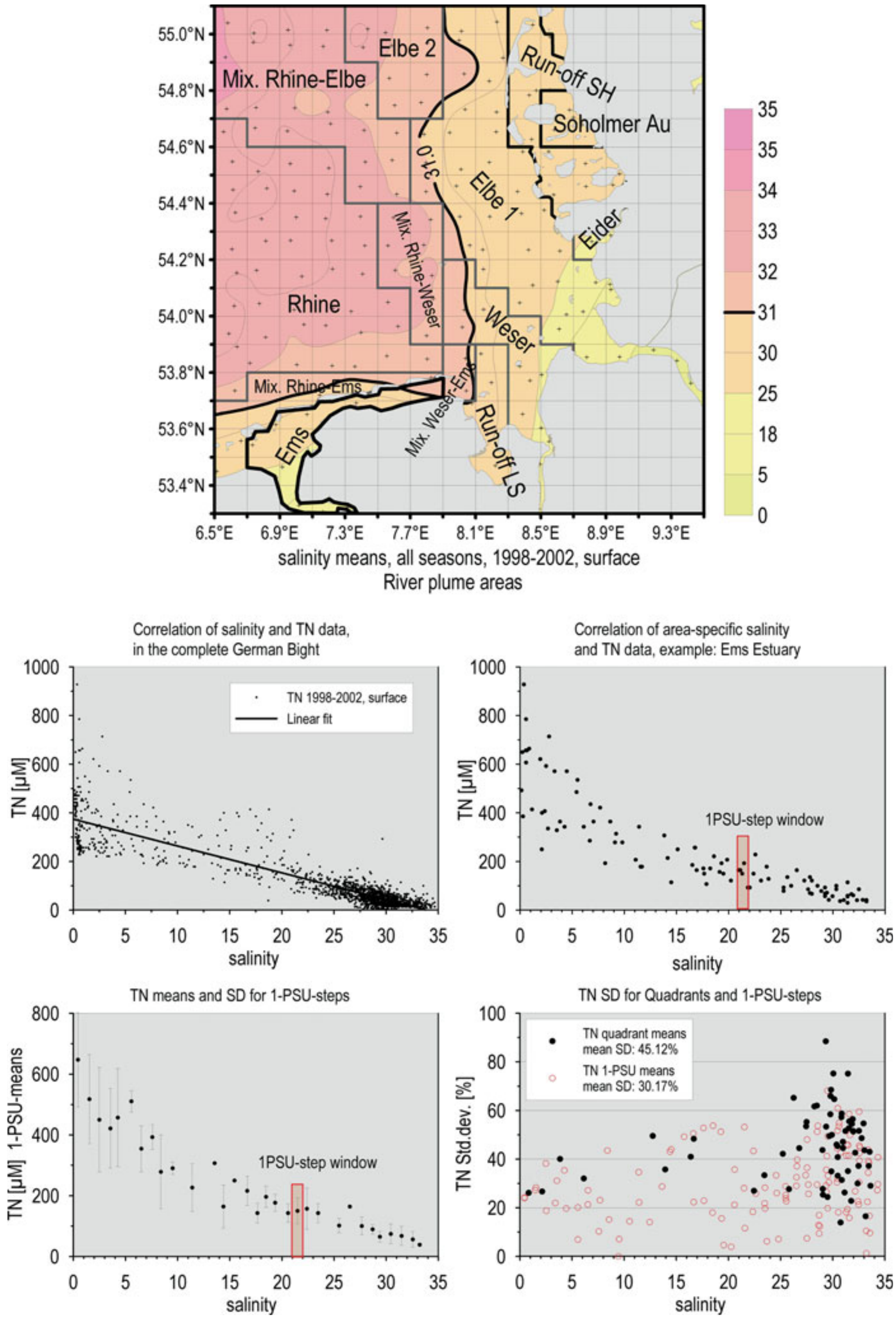


Fig. 6 Map of the German Bight divided into river plume areas (*top*), and mixing diagrams of recent (1998–2002) TN (µM) concentrations for the whole German Bight (*middle plot, left*) and the Ems estuary (*middle plot, right*). Deduced 1-PSU means and their standard deviations for the Ems (*bottom plot, left*) were compared with standard deviations from the squares in Fig. 1 for the Ems estuary (*bottom plot, right*)

however, is too high for some eutrophication effects, and 15% is proposed here as the key boundary especially for offshore waters, based on oxygen depletion, reduction of Secchi depth and extension of transboundary fluxes. At present, the 50% approach appears to be sufficient in near-coastal waters where current nutrient concentrations still exceed natural background concentrations in many areas.

Overlapping of boundary settings with regional gradients including their variability cannot be avoided, especially not for the application of the four boundary settings of WFD.In order to achieve the most significant assessments, the focus should be placed on the key boundaries (good/moderate for WFD or elevated level for OSPAR). Variability can be reduced to some degree by relating the monitoring data to mean local/

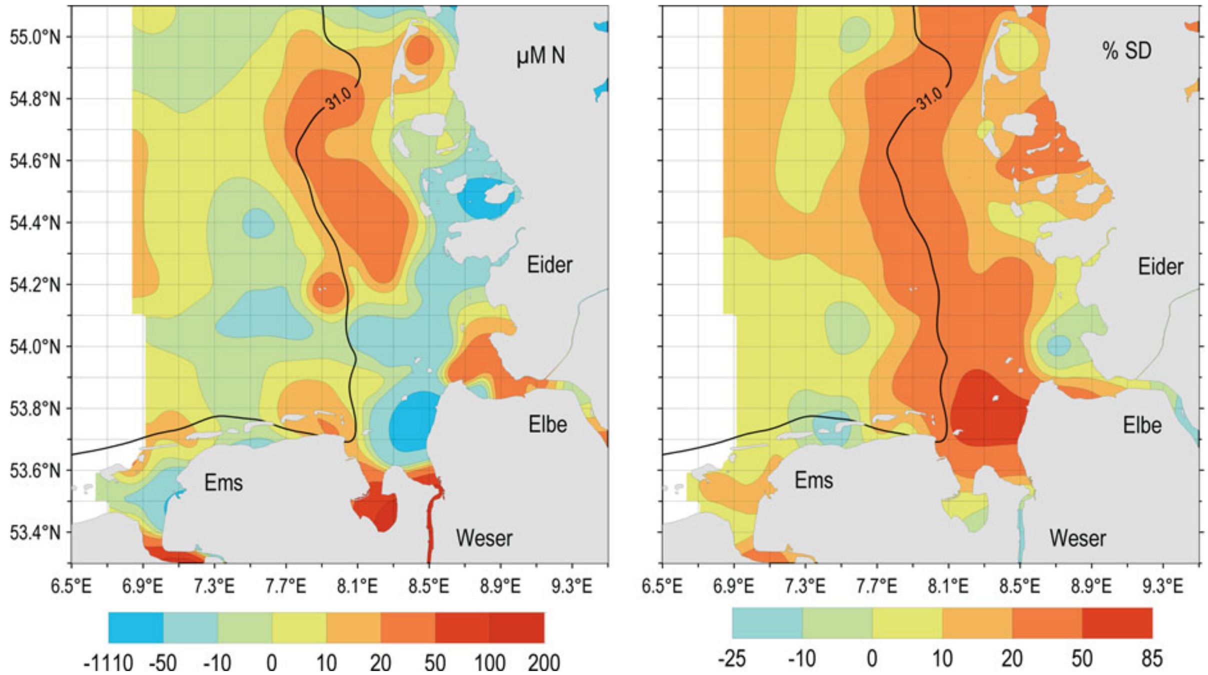


Fig. 7 Differences between TN quadrant means (Fig. 1) and salinity-related (1-PSU step) means (µM) (*left*) and differences in the standard deviations (%) (*right*) in the German Bight in surface waters for all the seasons (1998–2002)

regional salinities. However, ultimately recent means will be assessed in relation to mean boundary settings, and overlapping and variability (specific for areas, time periods and parameters) that affect the precision of classifications should be reported as part of the assessments.

Acknowledgements We thank the several data originators mostly anonymous, and the data centres for the compilation of the nutrient data (ARGE Elbe = Arbeitsgemeinschaft Elbe, Hamburg; MUDAB = Meeresumwelt Datenbank, Hamburg; Wadden Sea Secretariat, Wilhelmshaven). We are grateful to Monika Schütt & Thomas Raabe, Hamburg, for their essential assistance, and the two anonymous experts who reviewed and improved this manuscript.

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