Prepared for:

Royal Haskoning

Sensitivity analysis sand mining scenarios Maasvlakte-2

Report

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1 Introduction

As follow-up of the study "Impact sand mining Maasvlakte 2", additional sand mining scenarios have been defined by the Port of Rotterdam. This report describes the impact of these scenarios on the silt transport, the nutrients and the primary production in the Dutch coastal area, and especially in the Voordelta region. In total, 21 sand mining strategies are defined that differ in mining duration, rate, silt percentage and location, see Tables 1–2 and Figure 1.1. All scenarios take into account the mining of a total of 7.6 Mm^3 of sand during February/March 2008 for dune restoration near Delfland. Of these 21 scenarios, the first 16 have also been discussed in a previous report (Desmit *et al.*, 2007), which was prepared in the framework of the MER.

Next to the 16 sand mining scenarios, 5 scenarios were defined to investigate the model sensitivity for the selected meteorological conditions and for the assumed natural background. In contrast to all other scenarios, scenario 20 ('background') does not simulate an alternative sand mining strategy, but the natural background SPM. The other sensitivity runs include sand mining alternative S1a. The sensitivity runs are summarised in Table 2.

The scenarios were defined progressively, which means that subsequent scenarios were defined based on results of preceding scenarios. This report follows the same progressive order, unless indicated otherwise.

No.	Name	Amount (Mm^3)	MV2 sand mining location	MV2 sand mining rate (Mm^3/yr)	MV2 sand mining duration (year), period	Ratio mining and reclamation area	Percen-tage silt in sediment
0	0-scenario	19	Ter Heide 20m –NAP		feb/march 2008	90:10	2.5
1	Base	312	P2, P4, P5, P6	57	5.5	90:10	2.5
2	Quick-Close	312	P2, P4	150	2	90:10	2.5
3	Slow-Far	312	Far (ver weg)	57	5.5	90:10	2.5
4	Quick	312	P2, P4, P5, P6	150	2	90:10	2.5
5	85-15	312	P2, P4, P5, P6	57	5.5	85:15	2.5
6	Season	312	P2, P4, P5, P6	116	5.5 (mining during aug-feb)	90:10	2.5
7	P5 to p8	312	P2, P4, P8, P6	57	5.5	90:10	2.5
8	Deep pit	312	P2, P4, P5, P6	57	5.5	90:10	2.5
9	S0-autonomous	19	Ter Heide 20m –NAP	3.8/mnd	feb/15 april 2009&2010	90:10	2.5
10	S1a	310	Area 1	150	2	90:10	2.5
11	S1b	310	Area 1	62	5	90:10	2.5
12	S2	310	Area 2	150	2	90:10	1.25
13	S3	310	75% area 1; 25% area 3	150	2	90:10	1.25/2.5
14	S4	310	50% area 1; 50% area 2	62	5 ; area2 Feb-July, area 1 Aug-Jan	90:10	1.25/2.5
15	S1c	290	Area 1	100	2.9	90:10	2.5
16	S1c-restart	85	Area 1	22	4, 2015-2018	90:10	2.5

Table 1: Definition of additional sand mining scenarios

17	S1a 8x 1998	310	Area 1	150	2	90:10	2.5
18	S1a 8x 2001	310	Area 1	150	2	90:10	2.5
19	S1a 8x 2003	310	Area 1	150	2	90:10	2.5
20	background	–	–	–	–	–	–
21	background + S1a	310	Area 1	150	2	90:10	2.5

Table 2: Definition of sensitivity runs

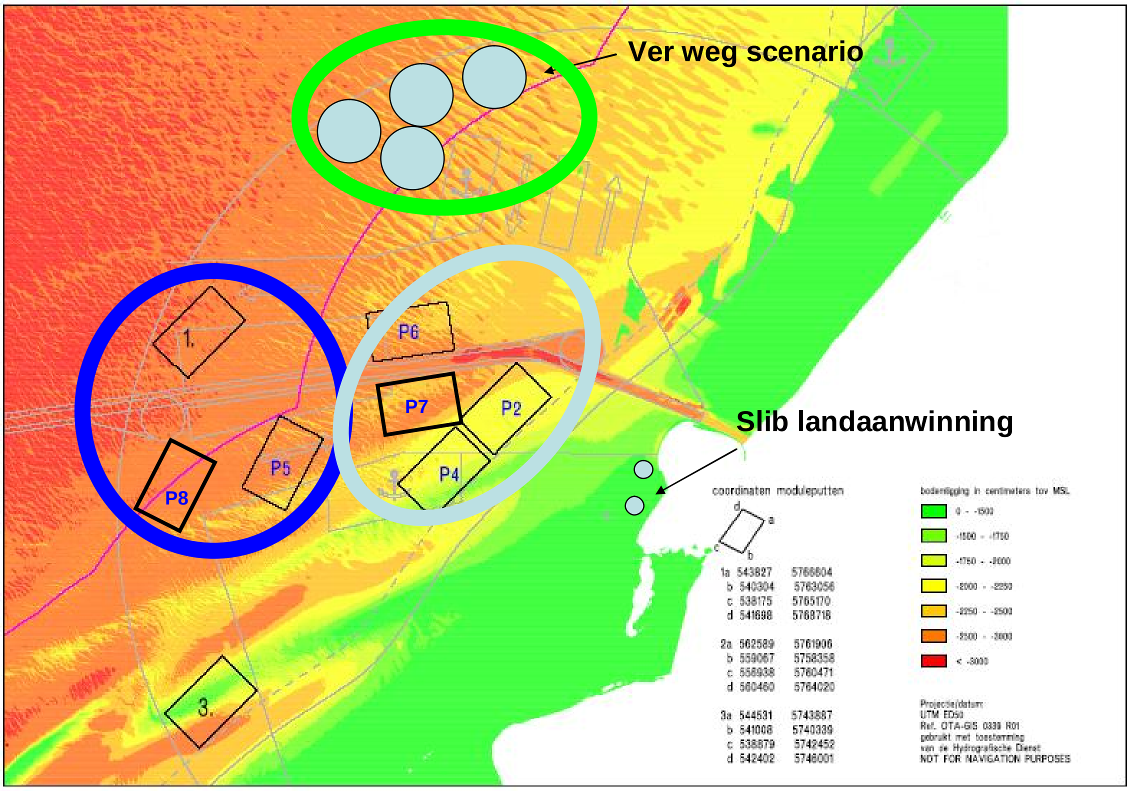


Figure 1.1: Locations of the various sand mining locations and areas (Area 1= grey, Area 2 = green, Area 3 = blue)

All scenarios in Table 1.1 expect scenario 16 'S1c restart' have been simulated for the 8-year period 2008–2015 using the Delft3D-Sed and GEM model describing silt, nutrients and phytoplankton production in the North Sea. S1c restart was simulated for the period 2016-2023, *i.e.* the subsequent 8-year period. Sand mining is assumed to start in 2008; for a later starting year the year label 2008 should be replaced by 'year 1' and 2015 by 'year 8'. The model settings (process parameters, time periods, water-bed exchange, numerical settings etc.) and meteorological forcing are identical to those applied in the base study and described in Royal Haskoning, WL | Delft Hydraulics and Svasek (2006).

The meteorological forcing of the hydrodynamics is based on the period 1996 – 2003, which is available from a hydrodynamic database at WL | Delft Hydraulics. The variable forcing includes space-varying wind speed and direction, waves, river discharges and tide. The hydrodynamics of the period 1996 – 2003 are assumed to be representative for the period

2008 – 2015. In the next chapter, the representativeness of the period 1996 – 2003 with respect to the 30 to 50 year average is discussed.
The inter-annual meteorological variability interacts with the duration of the sand mining activities in a non-straightforward way. It can be imagined that a low rate of sand mining may have less impact than a high rate, but if coincidentally the lower rate is realised during stormy years and the higher rate during calm years, the opposite effect may be realised for SPM. In order to be able to separate completely the effects of inter-annual variability from the impact of sand mining, sensitivity simulations have been made for which a single year of hydrodynamic forcing has been repeated 8 times. This type of simulation has been carried out for 1998 (stormy year), 2001 (average year) and 2003 (calm year) (scenarios 17–19, Table 1.2).

Originally, the background SPM concentration has not been taken into account in the Delft3D-Sed simulations. This is permissible, as the model formulations used behave linearly with respect to the SPM concentration. Superposition of the computed concentration increase due to sand mining and the natural background concentration is therefore allowed. Such a superposition is made in the GEM model to compute phytoplankton production.

In GEM, the background silt (SPM) concentration was taken from a simulation with the Zuno-DD model without silt buffering in the bed, which was carried out in the framework of a previous study (Haskoning *et al.*, 2006). From this simulation, the year-averaged near-surface spatial SPM distribution is used. A seasonal variation as well as a wind-related short-term variation has been applied to derive the year-round background SPM.

The rationale behind this approach was that no model was yet available simulating the seasonal dynamics of the background mud concentration satisfactorily. Recent R&D developments have resulted in an improved SPM modelling approach that takes into account temporary buffering of silt in the seabed. This new model provides the opportunity to simulate the seasonal dynamics of the background SPM in a more consistent way. These new background simulations are further discussed in Chapter 3.

2 Meteorological forcing

This chapter has two main topics:

1. To determine to what extent the years 1996 – 2003 are representative for the long-term wind climate;
2. To determine which years of the period 1996 – 2003 may be considered as calm, average or rough.

Figure 2.1 shows the year-average wind speed and wind direction at Lichteiland Goeree in the period 1951–2004. The long-term average wind speed is 7.3 m/s, the long-term average wind direction is 245 deg. In the period 1996–2003, the average wind speed is slightly higher (7.5 m/s), and the southerly wind component is more important to some extent (236 deg).

Figure 2.2 shows the year-average N-S and E-W wind components at the same location for the same period. In the period 1996–2003, the E-W component is average (1.69 m/s from the West in 1996–2003 versus 1.67 m/s for the complete 54-year period. However, the N-S component is significantly stronger (0.97 versus 0.66 m/s from the South).

It is remarkable that although the average wind speed in 1996 – 2003 is slightly above normal, the average number of storms pro year in the same period is somewhat smaller that the average number of storms pro year in the period 1951 – 2004 (13 versus 17 storms pro year, see Figure 2.3). Also remarkable is the reduction in average wind speed for the period 1964 – 1989. Before 1964 and after 1989 the average wind speed is 7.7 m/s and between 1994 – 1998 6.7 m/s.

Based on the statistics shown in Table 2.1, it is concluded that the wind climate in 1996 – 2003 is sufficiently representative for the long-term average climate, as the deviation of the wind speed and direction from the long-term average remain well within the standard deviation of this long-term average. Only the number of storms is rather low: 104 events occurred in the 8 years considered, whereas the average number of events in an 8 year period is 137.

	Speed (m/s)		**direction (deg)**	
period	*mean*	σ	*mean*	σ
1996-2003	7.51	0.37	236.1	8.3
1951-2004	7.28	0.60	245.4	19.3

Table 2.1 Average wind speed and direction and its standard deviation at Lichteiland Goeree for the periods 1996 – 2003 and 1951 – 2004.

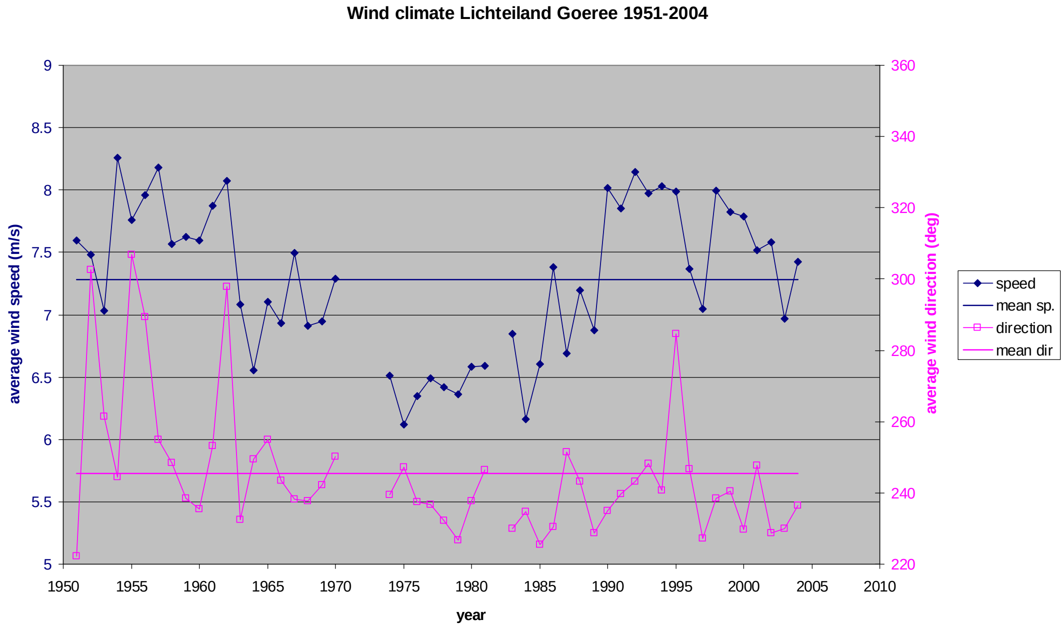


Figure 2.1: Year-average wind speed and direction at Lichteiland Goeree, period 1951-2004.

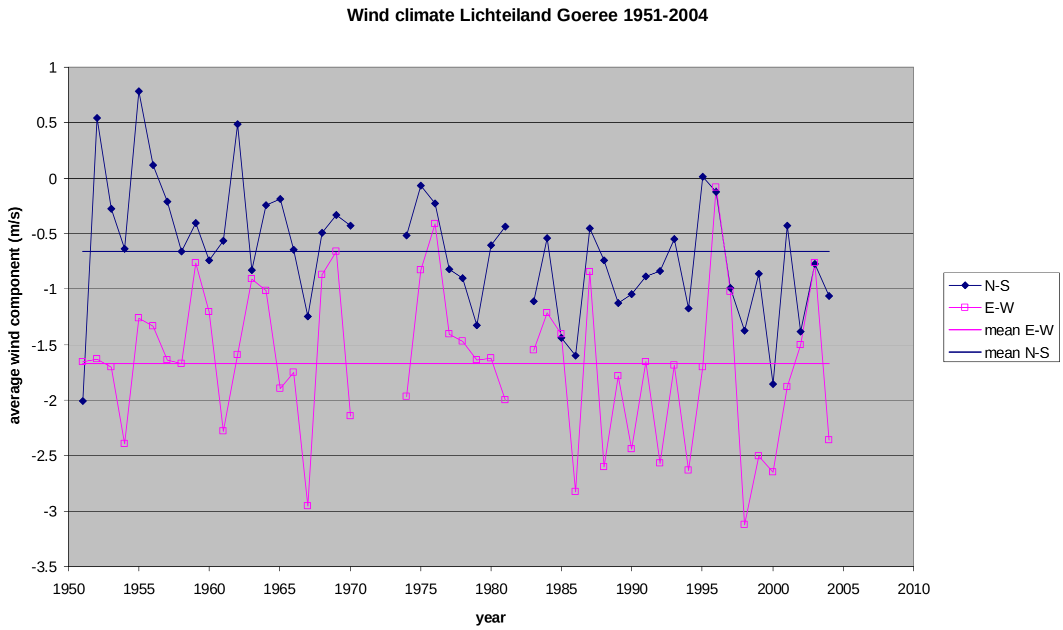


Figure 2.2: Year-average N-S and E-W residual wind component at Lichteiland Goeree, period 1951-2004.

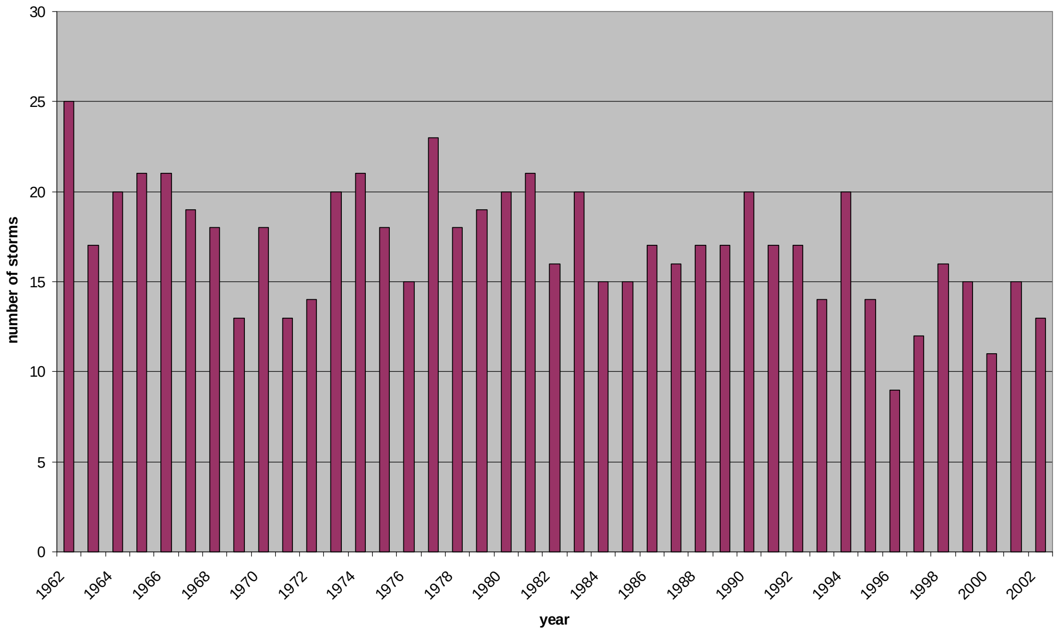


Figure 2.3: Number of storms per year according to KNMI. Period 1962 – 2002. Average number = 17.

The next point of attention is the selection of an average, mild and rough year from the period 1996 – 2003. The repetition of 8× a single year enables an impact assessment of sand mining without the necessity to take account of the effect of inter-annual variability. Of all 8 years considered the average wind speed and direction, river discharge, sediment fluxes through Dover Strait and the Marsdiep according to the background simulations, and the number of storms have been considered. These parameters are shown in Table 2.2.

year	**Speed (m/s)**	**direc-tion (deg)**	**river dis-charge (m^3/s)**	**flux Dover (Mton/y)**	**flux Mars-diep**	**n stoms (–)**
1996	7.37	246.64	1,589	57,616	-2,566	9
1997	7.05	227.26	1,725	85,635	-2,365	12
1998	7.99	238.58	1,743	118,009	-1,839	16
1999	7.82	240.56	2,494	106,826	-1,927	15
2000	7.79	229.83	2,253	127,994	-1,721	11
2001	7.51	247.70	2,599	67,581	-2,087	15
2002	7.58	228.63	2,697	114,898	-1,826	13
2003	6.97	229.86	1,640	71,199	-2,262	≈ 10

Table 2.1 Average wind speed and direction at Lichteiland Goeree for the period 1996 – 2003. Freshwater flow Rhine, residual flow through Dover Strait and the Marsdiep and the number of storms for the same period.

From Table 2.1 it is clear that 1998 is the year with both the highest average wind speed and the highest number of storms. Also, both the observed (based on MWTL data, not shown herein) and computed (see Table 3.1) background SPM concentrations are the highest for the year 1998 within the period 1996 – 2003. The year 1998 is therefore selected as the most stormy year.

The year 2003 is selected as the quietest year. The other candidates, 1996 and 1997 are abandoned because of the higher level of the modelled SPM background concentration (1996) (see Table 3.1) or the number of storms (1997).

The choice of the average year is more ambiguous; notwithstanding the high number (15) of wind events in 2001, this year is selected based on its average wind speed and its observed and modelled average SPM concentration.

A relevant question is how frequent an extreme year like 1998 does occur. To answer this question, the wind climate at Goeree is considered for the period 1951 – 2004. Of the 50 years considered, 1998 ranks 7th in the list of most stormy years. The average wind speed of 8.0 m/s approximately equals the 10-percentile value of the wind speed (*i.e.* the change of a higher year-average wind speed is 0.1). It is concluded that the year 1998 is a quite normal stormy year.

Regarding the number of storms, 1998 is even non-exceptional at all. The number of 16 observed wind evens is even one less than the 41-year average between 1962 and 2002, which is 17 wind events per year. Nevertheless, 1998 is the most stormy year in the period 1996 – 2003.

The average wind speed in the quiet year 2003 ranks 18th in the list of quit years in the period 1951 – 2004. This position about equals the 35-percentile value. The number of wind events in 2003 is about 10. No big storms occurred.

3 Computation of natural background

At the time of the initial sand mining simulations, no SPM transport model of the Dutch coastal zone was available properly taking into account seasonal variability. Therefore, GEM adopted the approach to derive the natural background concentration field from an existing model based on the ZUNO-DD schematisation that reproduces the year-averaged SPM concentration in the Dutch coastal zone reasonably well (see Royal Haskoning *et al.*, 2006). To this constant concentration field seasonal variability and wind response was incorporated using a random cosine function.

In the framework of an R&D project by Delft Hydraulics, to which also Delft Cluster and RIKZ contributed, a new model for SPM transport in the Dutch coastal zone was developed taking into account seasonal variability and sediment buffering in the seabed. The setup and calibration of this model is described in Van Kessel and Brière (2006). It is based on the same schematisation (ZUNO-coarse) and the same process formulations as used for the present sand mining plume dispersion simulations. It is expected that the estimate of the **relative** impact of sand mining with respect to the natural background concentration is more accurate for this approach than for the random cosine approach, as a possible local over- or underestimation of the SPM level will occur in both the impact simulations and the background simulations and will therefore (at least partly) cancel out.

The sensitivity of the ecological simulations with GEM to the applied background concentration fields is evaluated by carrying out identical impact simulations for both background types.

Figure 3.1 shows the daily-average SPM concentration in Area 4 (Voordelta), which is near the sand mining location. The large natural variability is obvious. During summer, a low value of typically 10 mg/l is simulated. During winter, the simulated concentration is typically 40 mg/l, with higher values during storms. As the additional sediment released in the coastal zone by sand mining behaves similar as the natural sediment, the relative concentration increase is quite constant, notwithstanding the strong fluctuation of the absolute concentration level (see right panel). The relative effect increases gradually up to a value of 20% after 2 years (the end of the sand mining activities in scenario s1a). Subsequently, the relative effect decreases exponentially with a time to half value of about 2 years.

Although a SPM concentration increase of 20% in the Voordelta caused by sand mining is substantial, this increase is rather limited compared with the natural variability. For example, the difference between the year-average SPM concentration in the quiet year 2003 and the stormy year 1998 is (22.9–17.1 =) 5.8 mg/l (see Table 3.1). The maximum year-average concentration increase because of sand mining (scenario S1a) is 3.1 mg/l in 1998. On a year-averaged scale, the impact of sand mining on SPM levels in the Voordelta is of the same order as the impact of natural inter-annual fluctuations. The natural intra-annual variability is even substantially larger than the impact of sand mining: the standard deviation of the background is about 9 mg/l, whereas the average impact is only about 3 mg/l.

Nevertheless, sand mining may substantially increase the chance that a certain concentration level is exceeded. Figure 3.3 shows the exceedance percentage of the SPM concentration for the natural background concentration only and including the sand mining scenario s1a. For example, the natural background concentration exceeds the 50 mg/l level 1.4% of the time, but including sand mining this level is exceeded 2.0% of the time.

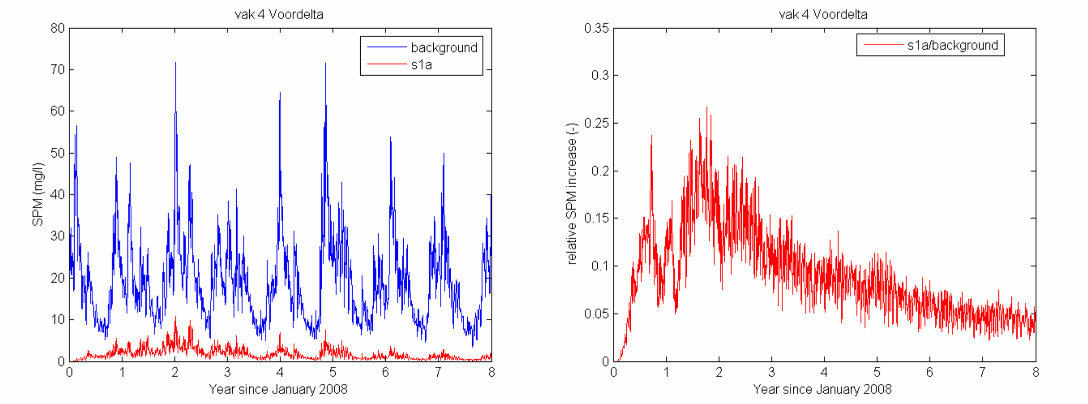


Figure 3.1: Daily-average SPM concentration in Area 4 (Voordelta). Left: concentration in mg/l of background SPM and concentration increase by scenario s1a. Right: relative concentration increase by scenario s1a.

year	**background (mg/l)**	**standard deviation (mg/l)**	**sand mining s1a (mg/l)**	**σ sand mining (mg/l)**
1996	19.8	10.6	1.23	0.93
1997	18.6	7.3	2.76	1.24
1998	22.9	10.9	3.14	1.76
1999	17.8	9.1	1.80	1.11
2000	20.7	12.8	1.73	1.16
2001	18.0	7.5	1.26	0.79
2002	18.9	9.5	0.99	0.60
2003	17.1	9.1	0.78	0.50
mean	19.2	1.9 (inter-annual)	1.71	0.40

Table 3.1: Computed year-average SPM background concentration (column 2), its standard deviation (column 3), computed year-average concentration increase by sand mining scenario s1a (column 4) and its standard deviation (column 5). Area 4 Voordelta.

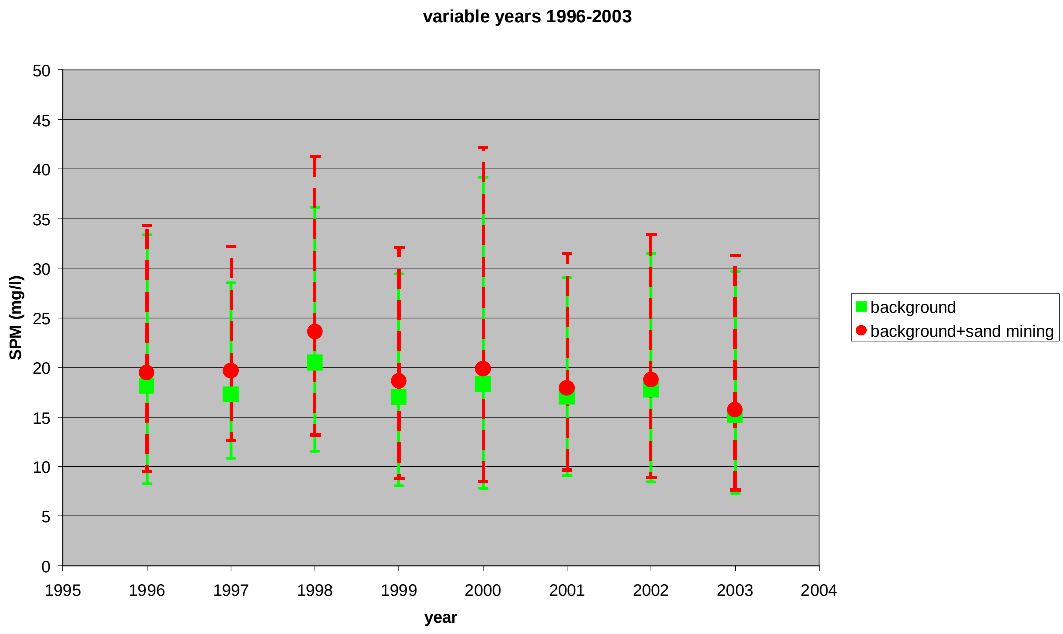


Figure 3.2: 10, 50 and 90-percentile values for the SPM concentration per year in the period 1996 – 2003. Green: natural background only; red: background + sand mining scenario s1a.

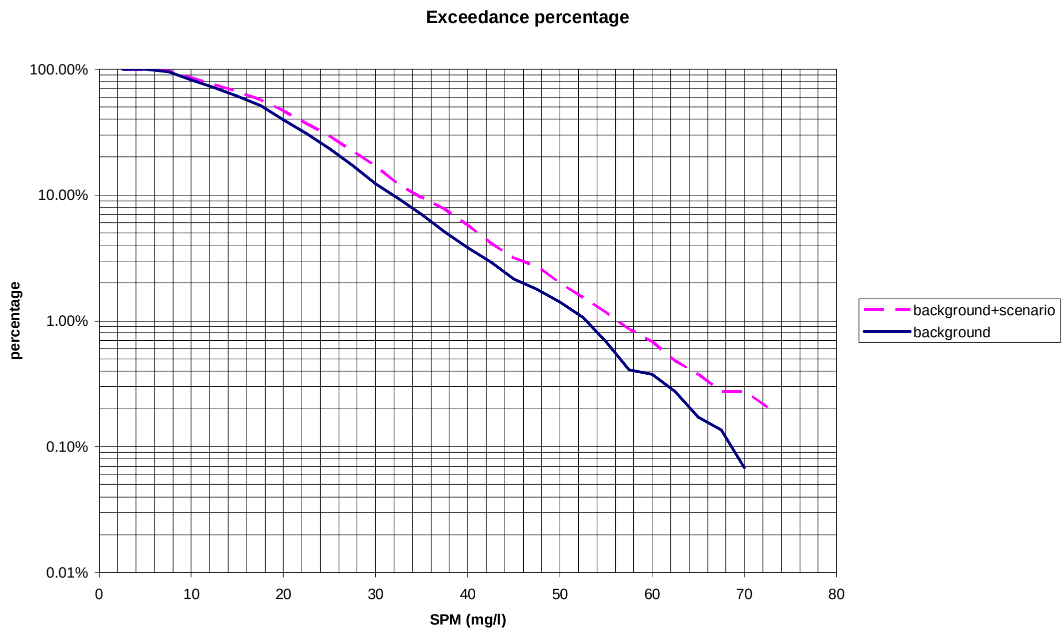


Figure 3.3: Exceedance percentage for SPM concentration in the period 1996 – 2003. Solid line: natural background; dashed line: background + sand mining scenario s1a.

4 Impact on silt

Results are presented for locations and areas. These so-called monitoring areas (in Dutch 'vak') are areas which can be considered as having uniform characteristics. Concentrations are given as spatially averaged concentrations within the monitoring area, and as such filter out purely local effects. Figure 4.1 gives an overview of the monitoring areas used in this report. Note that the colour-shaded monitoring areas encompass one or more numbered areas, except for Wadden Sea west and Wadden Sea west which subdivide monitoring area 30.

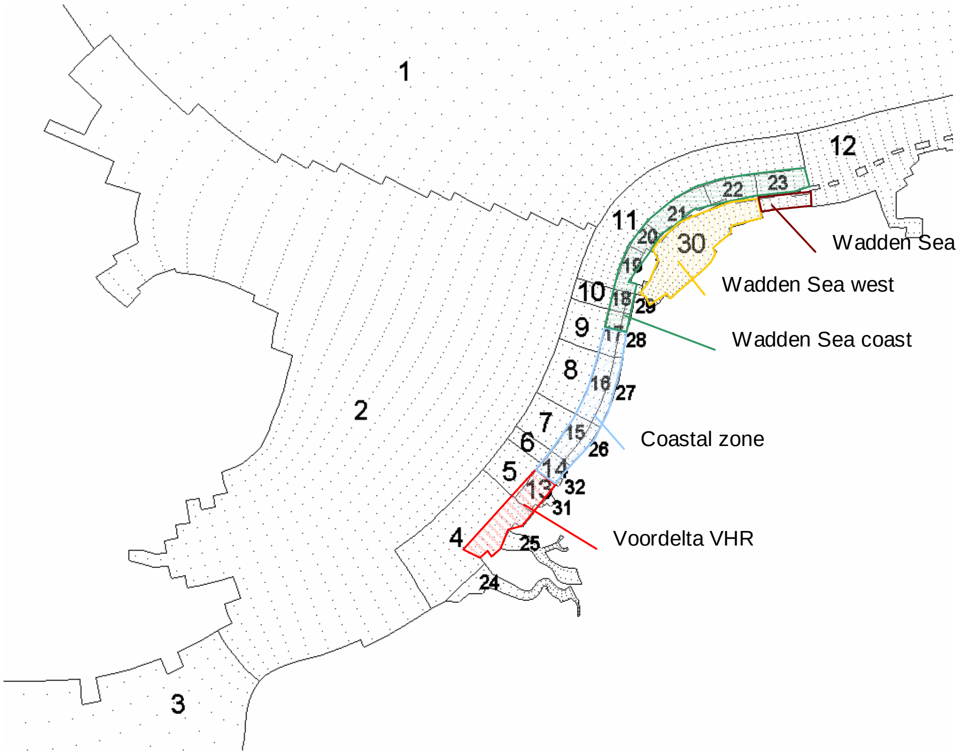


Figure 4.0: Definition of monitoring areas in the numerical model for which spatially-averaged values for SPM, chlorophyll, primary production have been determined. Note that the area 'Voordelta' in the nutrients and primary production simulations is identical to the area to which the bird and habitat directives (VHR) applies. In the SPM simulations, 'Voordelta' refers to monitoring area 4.

4.1 With inter-annual variable climatology

To investigate the impact of the sand mining on the SPM concentration along the Dutch coast, all scenarios shown in Table 1 are computed with Delft3D-SED. Figures 4.1 – 4.7 show the resulting monthly averaged SPM concentration increase in the Voordelta during 8 years after the start of the sand mining activities. Appendix A shows the year-averaged SPM distribution along the Dutch coast for all 8 years and for all scenarios. Figures 4.1 – 4.7 are most suited to evaluate (in a single area) the temporal evolution of the sand mining impact, whereas from Appendix A the spatial evolution of the impact can be assessed.

From these time series and the spatial graphs in Appendix A, the following is observed. The 0-scenario results in a minor SPM concentration increase in the Dutch coastal zone only. This can be well understood from the relatively small volume of sand (26 Mm^3)[1] that is extracted from the seabed, resulting in a small release of fines. Initially, the impact is limited to the direct vicinity of the mining area but gradually, the area of the impact zone increases. However, the impact zone area is inversely related to the impact magnitude: far from the mining area, the computed SPM concentration increase remains very small.

The Base scenario (Table 1) results in a more substantial SPM concentration increase in the Dutch coastal zone. This can be well understood from the large volume of sand (312.5 Mm^3, *i.e.* approx. 16 times more than the total volume for the 0-scenario) that is extracted from the seabed, resulting in a substantial release of fines. The computed concentration increase amounts to up to 4 mg/l in the Voordelta. During the first four years, the impact gradually builds up until a dynamic steady state has been reached. After the end of the sand mining activities, the impact gradually diminishes. Part of the fines that are released due to dredging activities are stored in the bed. During rough weather these fines can be resuspended and therefore the concentration temporarily increases, even after the end of the sand mining. The decrease of fines in the system only proceeds slowly, as the fines that are immobilised in the bed during calm weather are not subject to horizontal dispersion.

[1] *19 Mm^3 maintenance nourishments + 7.6 Mm^3 dune restoration Delfland*

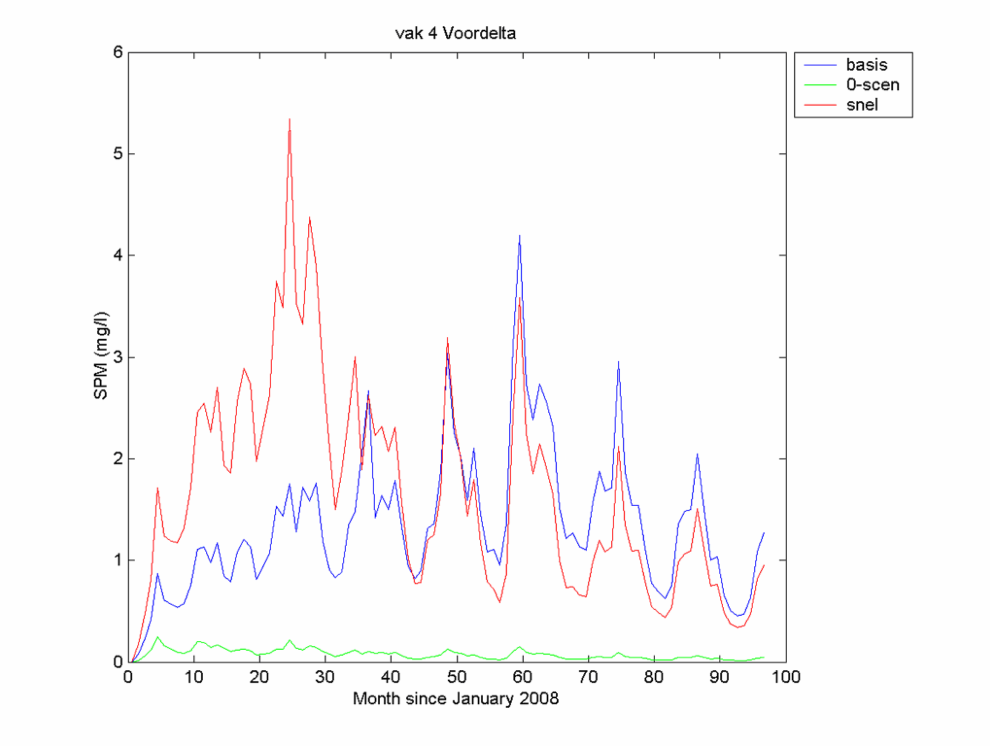


Figure 4.1: Monthly-averaged SPM concentration increase due to sand mining (mg/l). Scenarios Base (blue), 0 (green) and Quick Close (red).

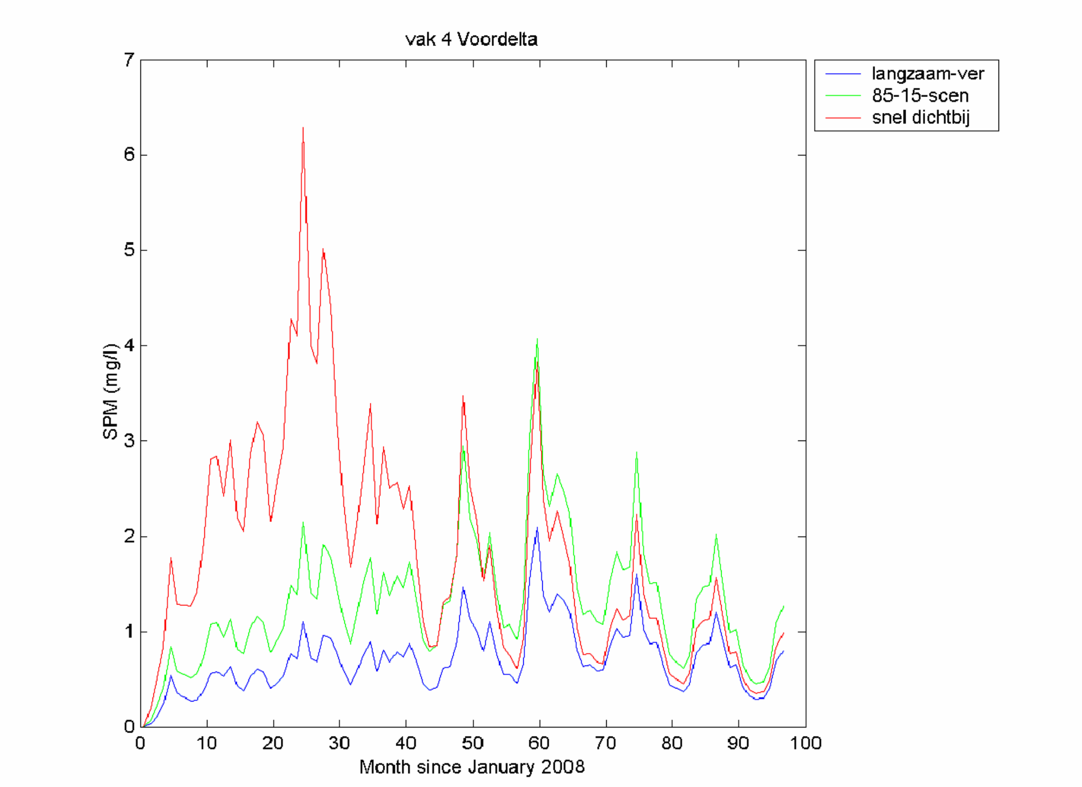


Figure 4.2: Monthly-averaged SPM concentration increase due to sand mining (mg/l). Scenarios Slow-far (blue), 85-15 (green) and Quick-close (red).

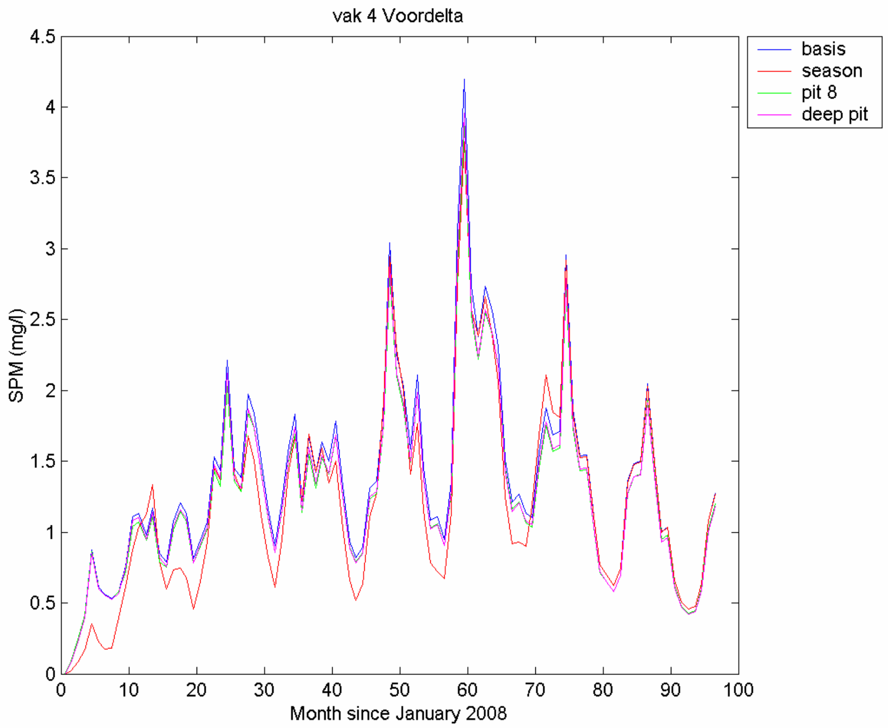


Figure 4.3: Monthly-averaged SPM concentration increase due to sand mining (mg/l). Scenarios *basis* (blue), *Season* (red), *p5 to p8* (green) and *deep pit* (magenta).

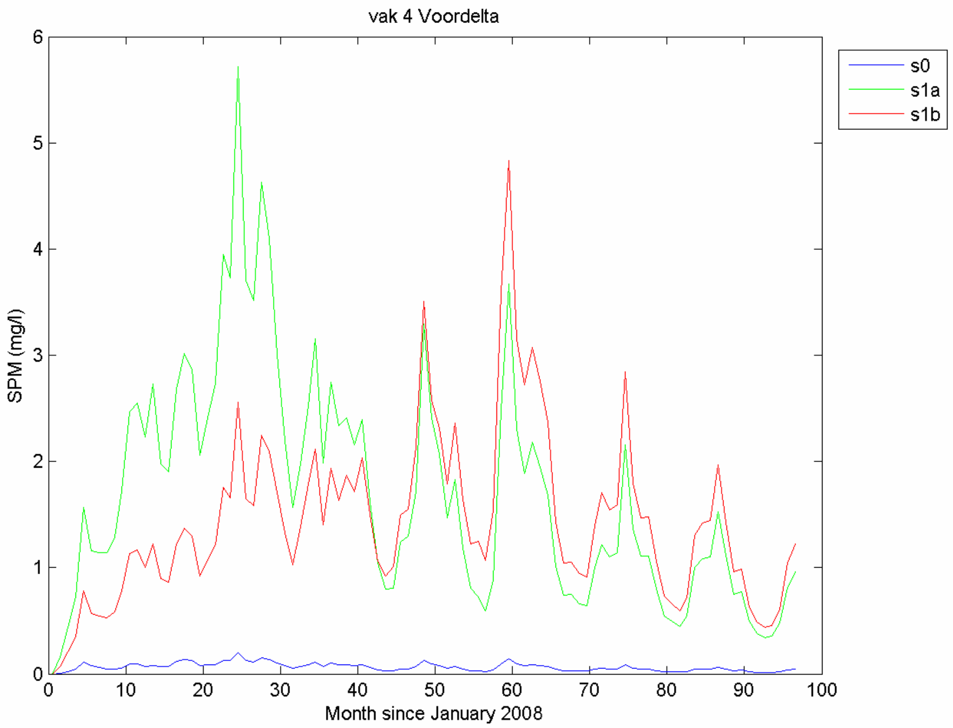


Figure 4.4: Monthly-averaged SPM concentration increase due to sand mining (mg/l). Scenarios *S0* (blue), *S1a* (green) and *S1b* (red).

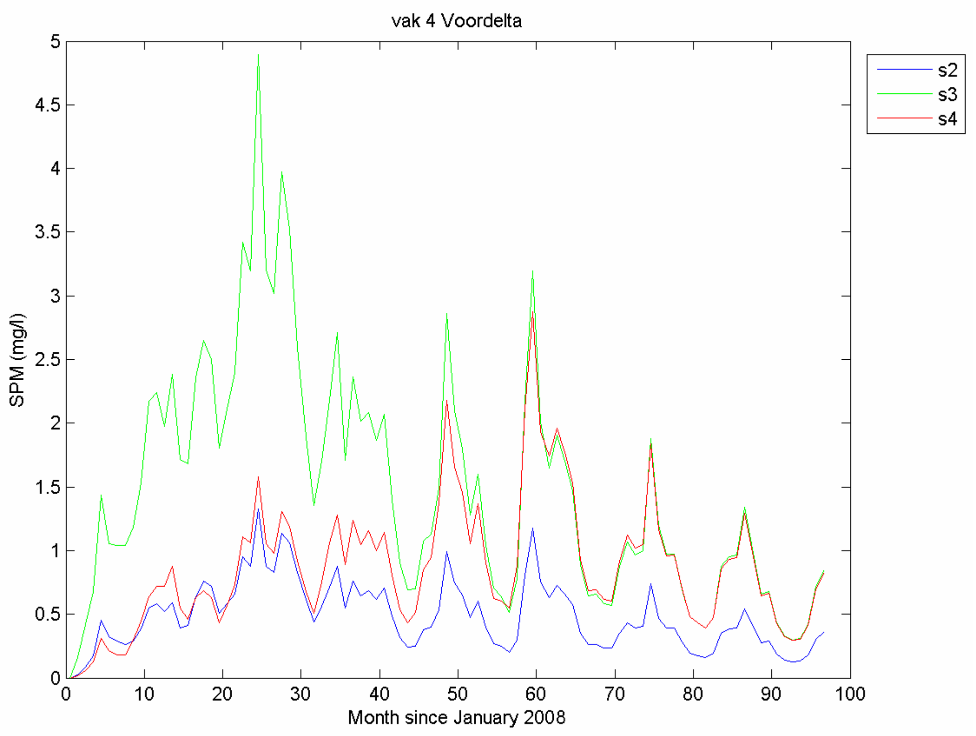


Figure 4.5: Monthly-averaged SPM concentration increase due sand mining (mg/l). Scenarios *S2* (blue), *S3* (green) and *S4* (red).

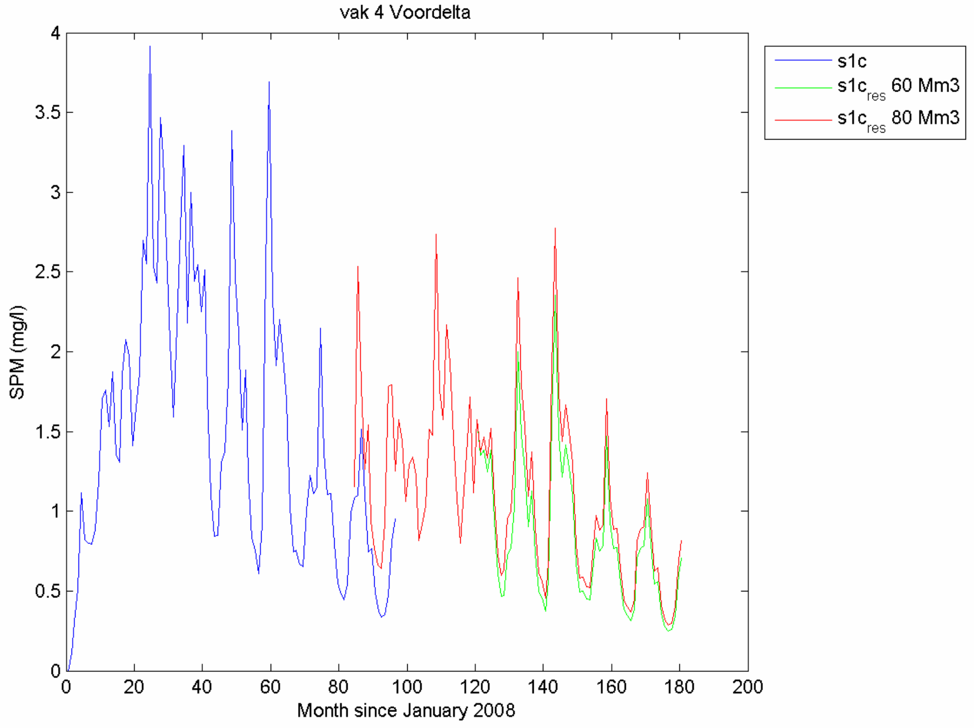


Figure 4.6: Monthly-averaged SPM concentration increase due to sand mining (mg/l). Scenarios *S1c* (blue) and *S1c-restart* (green: 60 Mm^3 variant; red: 80 Mm^3 variant).

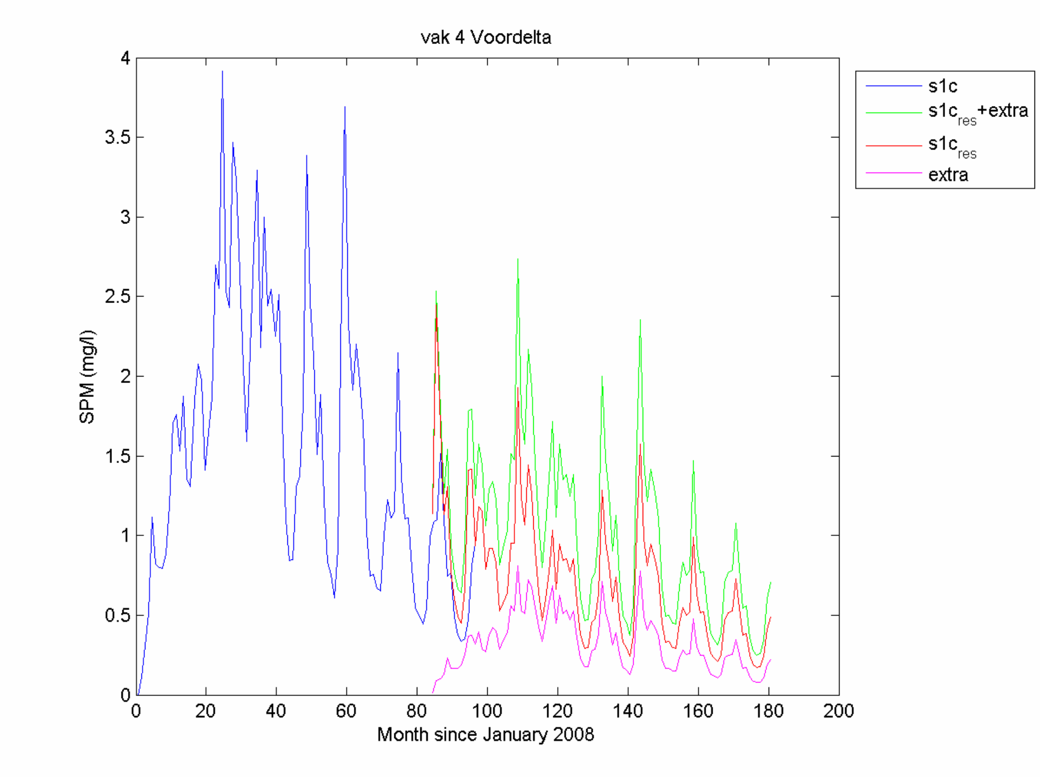


Figure 4.7: Monthly-averaged SPM concentration increase due to sand mining (mg/l). Scenarios *S1c* (blue) and *S1c-restart* (green: 60 Mm^3 variant). As reference, also the effect of a continuation of scenario S1c without additional mining activities is shown (red line). The magenta line is the difference of the green and red lines, *i.e.* the effect of the 60 Mm^3 sand mining only.

As the applied forcing varies between the years (it is remembered that the years 1996 – 2003 have been used for the hydrodynamic forcing of the sediment dispersion model), also the modelled SPM concentration increase varies. Some years may show higher peaks than other years, even if the sediment availability in the Voordelta area is less. The sediment availability tends to be smaller both earlier during the sand mining operation and longer after the completion of these works. It is the interaction of the sand mining scenario with the hydrodynamic forcing that steers the response regarding SPM concentration increase, which makes interpretation of the results less straightforward.

A comparison between the scenarios Base and 85-15 demonstrates that the computed impact is quite insensitive to a reduction of the release rate of 5% at the mining area and a concurrent equal increase of the release rate at the Maasvlakte-2 construction area. The blue line in Figure 4.1 (Base) hardly differs from the green line in Figure 4.2 (85-15).

A comparison between the scenarios Base and Quick (Figure 4.1) demonstrates that the computed impact is sensitive to the rate of sand mining. For the Quick scenario, the maximal effect is reached after two years of sand mining. For the Base scenario the maximal effect is only reached after five years. After four years, the computed SPM concentration increase in the Voordelta for the Quick-scenario drops below the Base scenario. At some distance from the mining area (*e.g.* Appendix B, Fig. 1), a faster rate of sand extraction does not result in a strong increase of the maximal impact, but causes the maximal impact to be reached faster. Close to the mining area, the maximal SPM concentration increase is larger for the quick scenario.

A comparison between the scenarios Base and Slow-Far demonstrates that the latter scenario has a favourable influence on the impact level in the Voordelta: the SPM concentration increase is two times smaller for the Slow-Far scenario compared to the Base scenario. However, this advantage comes at a cost: the impact towards the north is larger for the Slow-Far scenario, notably north of IJmuiden. A comparison between the scenarios Quick and Quick-close shows a slightly higher concentration increase in the Voordelta for the latter scenario during the two years of sand mining. At some distance from the mining area and after two years, the differences between these scenarios are insignificant.

The scenario in which pit 5 is replaced with pit 8 (having a position shifted towards the west, scenario ‘P5 to P8’) does not show a significant difference regarding the concentration increase in the Voordelta compared with the basis scenario (see Figure 4.3). This is also true for the scenario in which the mud accumulation inside the mining pits has been taken into account (scenario ‘deep pit’). Possible net accumulation of fines in the sand pit cannot be modelled explicitly due to the coarseness of the ZUNO GROF grid. Therefore, in order to take account of sediment storage, the critical shear stress has been increased locally. Considering a water depth of 20 m and a deepening of the pit of 5 m, this has been parameterised by a local increase of the critical shear stress for erosion with 50%, which is equivalent with a reduction of the wave- and current-induced bed shear stress with 50% because of the increased depth. The computed small increase of mud storage is due to the fact that the depth averaged advection flux of SPM is much larger than the sedimentation flux in the pit. In case the turbidity increase during sand mining is limited to the first few meters above the bed, the effectiveness of a deep pit acting as net mud deposit will increase.

Figure 4.3 demonstrates that the scenario with periodic seasonal sand mining results in a reduced concentration in the Voordelta between the months February - July. This is also clearly visible in Appendix A, where the spatial distribution of the SPM concentration is shown for the month Apr. – June (no mining) and Oct. – Dec. (double rate of mining). Close to the mining area, the seasonal scenario shows higher concentrations than the basis scenario for the months Oct. – Dec. and lower concentrations for the months Apr. – June. The further from the mining area, the larger the damping of the concentration variations for the periodical mining scenario and the larger the time lag between the start of sand mining and the occurrence of the maximal effect on SPM levels.

Figures 4.4 to 4.7 show the results of the other scenarios. The definition of scenario S1a is comparable with the Quick Close scenario and scenario S1b is comparable with the Base scenario. This is also reflected in the results. Furthermore, it is observed from Figure 4.4 that the increase in SPM is higher for scenario S1b than S1a during the second half of the simulation period. This is a result of the sand mining rate and duration. Scenario S2 has the lowest impact on the sediment concentration increase (in the order of 0.5 mg/l in the Voordelta region). The results of scenario S1c lie in between the results of scenario S1a and S1b. Considering the sand mining rates this was to be expected.

Figures 4.6 and 4.7 demonstrate that the SPM concentration increase for scenario S1c-restart is mainly caused by the released S1c material that remained in the system after end of S1c. Towards the end of the simulation period, the contribution of the additional material (60 to 85 Mm^3 sand mining) becomes more significant. The first year of S1c-restart shows a larger impact than the last year of S1c, although still about the same sediment mass is present in the system. This is explained by the more severe climatology of 1996 (the first year of S1c-restart) compared to 2003 (the last year of S1c).

4.2 With inter-annual constant climatology

The interpretation of the effects of the sand mining scenario's is complicated by the inter-annual variability of the applied meteorology. This variability was included to increase the level of realism of the simulations.

The present section discusses results with constant year climates. The following results are intercompared:

- Scenario s1a with meteorology 1996 – 2003
- Scenario s1a with meteorology 8×1998 (rough year)
- Scenario s1a with meteorology 8×2001 (average year)
- Scenario s1a with meteorology 8×2003 (quiet year)

The selection of the years 1998, 2001 and 2003 is discussed in Chapter 2. Figure 4.8 shows the results on the sensitivity of the impact on the year climate. Both the absolute and the relative impacts are plotted.

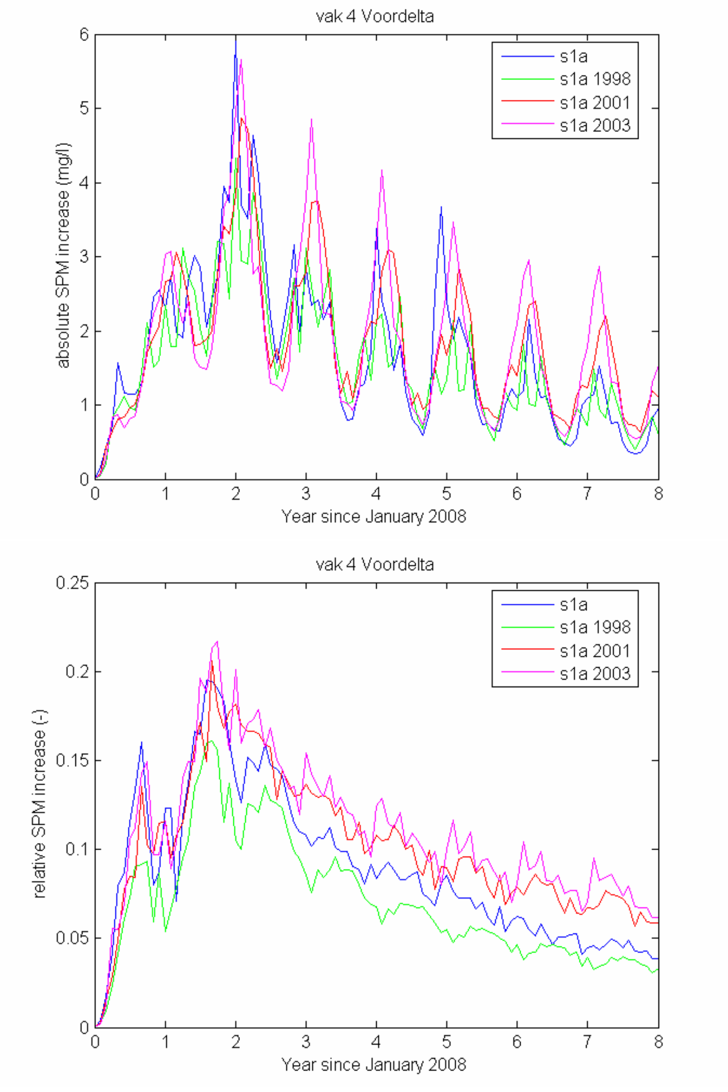


Figure 4.8: Effect of applied year climatology on simulated SPM concentration increase caused by sand mining scenario s1a. Upper panel: absolute increase (mg/l); Lower panel: relative increase (–). Voordelta.

The results for the Voordelta as shown in Figure 4.8 are remarkable. Contra-intuitively, the simulated impact is not very sensitive to the applied year climate. In addition, the moderate sensitivity works in the opposite direction: the milder the climatology, the larger the impact, most notably in the long term. This may be explained as follows. During mild years, the released fines tend to accumulate more in the vicinity of the mining location, whereas during rough years the fines are dispersed faster along the Dutch coast. A single storm within an otherwise mild year therefore has a higher local impact that an identical single storm in a rough year, as more fines released by sand mining are still available for resuspension in the vicinity of the mining area.

However, farther from the sand mining area, rough years are initially less favourable than quiet years, as the released fines affect remote areas at an earlier stage. This is indeed observed in Figure 4.9, where the absolute and relative SPM concentration increase in Area 17 (in the Dutch coastal zone, see Fig. 4.0) is shown. Applying a 1998 climatology (*i.e.* the roughest year), the maximal effect in Area 17 is reached after 3 years, after which a distinct decrease sets in. For the 2001 climatology (*i.e.* the average year), the maximal effect is reached after about 5 to 6 years. For the 2003 climatology (*i.e.* the mild year) the maximal effect has not yet been reached after 8 years. The variable climatology 1996 – 2003 follows the 1998 climatology most closely, which indicates that rough years dominate the dispersion, or the fact that 1998 falls early in the 8 year period. Far away from the mining area, both the absolute and relative effects are smaller for a series of mild years compared to a series of rough years, even taking into account the longer time lag before the maximum effect is reached. This may be explained by the longer time available for dispersion of the sediment pulse, making the peak more diffuse (*i.e.* wider but lower).

Probably the most favourable scenario in the Voordelta is a rough wave climate in winter (when primary production is low anyhow), sweeping away most fines released during sand mining followed by a mild wave climate during spring (when primary production becomes important). Probably the most unfavourable scenario is the reverse situation, *i.e.* a calm winter and a rough spring period, during which the fines accumulated in winter suddenly resuspend. Such a scenario would also be unfavourable for primary production without sand mining, but sand mining may aggravate the ecological consequences of such a natural event.

The probability of such an event is quite small, however. From a wind climate analysis in the most sensitive period, which is the onset of the primary production between March 15 – April 15, it is concluded that one severe storm and three storms occurred in this one month time window in the period 1951 – 2004. Gales (Bft 8) occurred 16 times and near gales (Bft 7) during most years (see Table 4.1 and Figure 4.10). A storm in this period will delay the onset of primary production and may result in a temporary food shortage for fish larvae etc. The likelihood of a storm in the period March 15 – April 15 is in the order of 10%. The likelihood of such a storm following a mild winter period during which the fines released by sand mining accumulate in the vicinity of the mining area (near the Voordelta) is estimated at a few percent only.

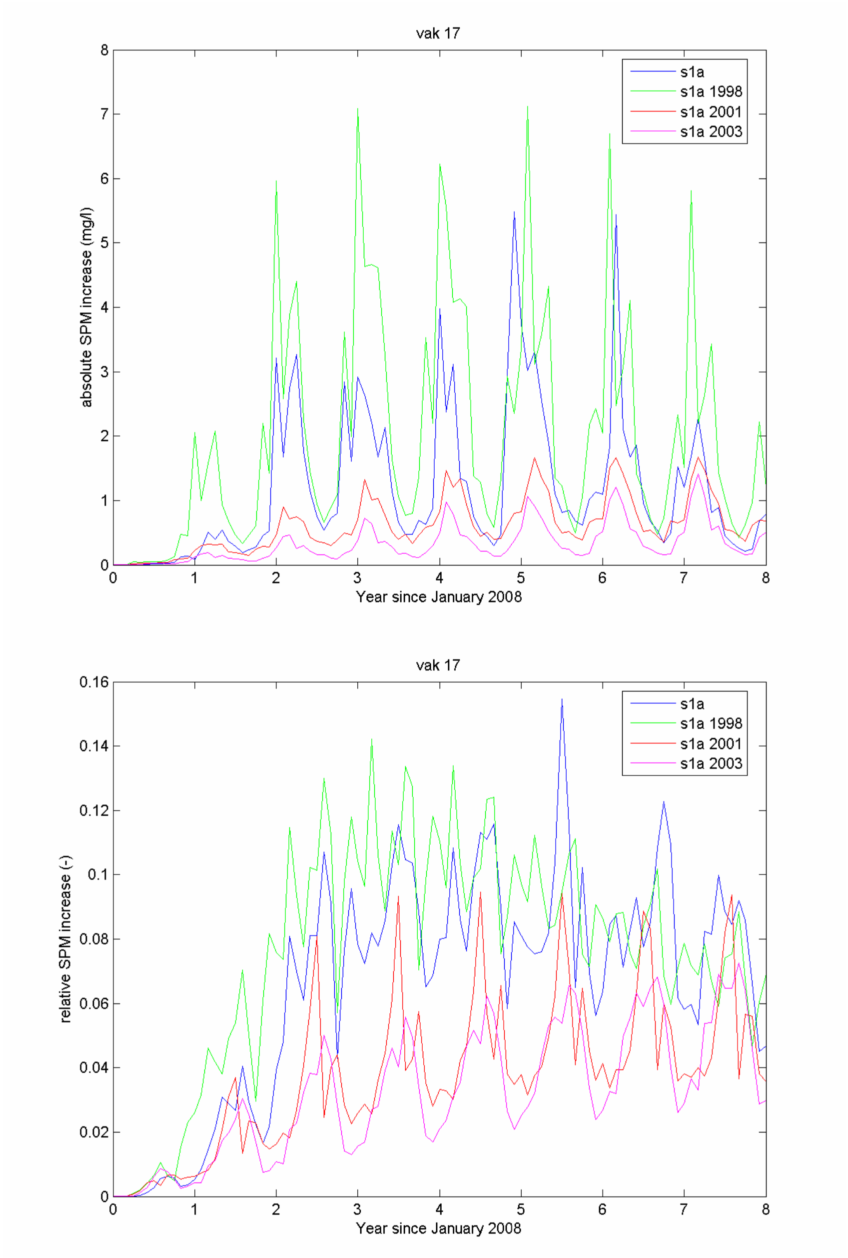


Figure 4.9: Effect of applied year climatology on simulated SPM concentration increase caused by sand mining scenario s1a. Upper panel: absolute increase (mg/l); Lower panel: relative increase (–). Area 17.

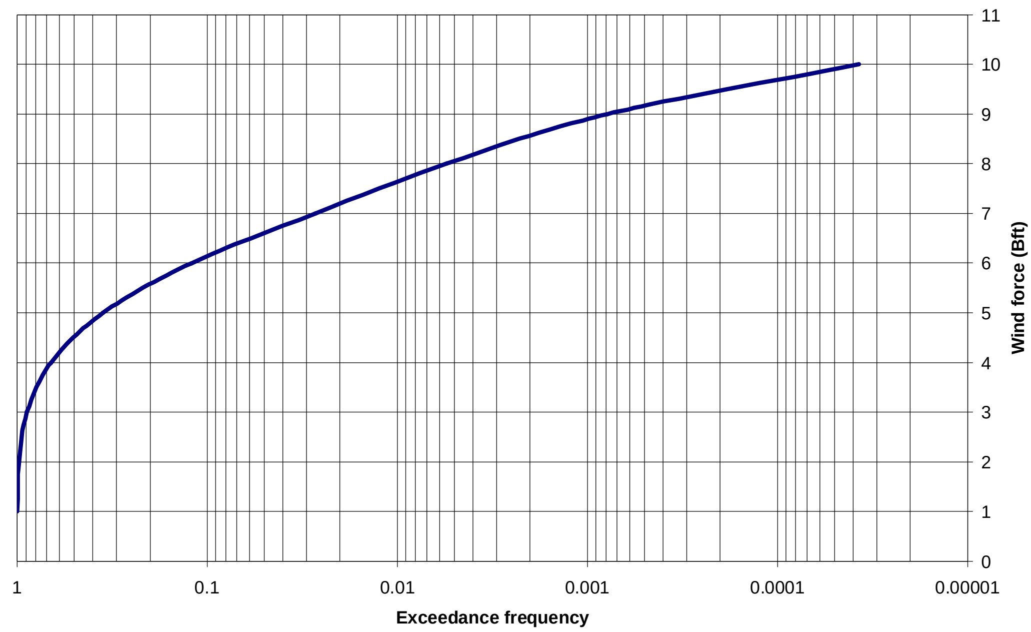


Figure 4.10: Exceedance frequency plot of the hourly wind force at Goeree between 15 March – 15 April, period 1951 – 2004.

Wind force (Bft)	**Number of events**	**Total duration of events (h)**	**Years**
11	0	0	–
10	1	1	1994
9	4	21	66, 94 (2×), 04
8	16	148	51, 52, 61, 62, 66, 67, 68, 78, 85, 87, 94 (2×), 95, 97, 02, 04
7	42	722	almost yearly

Table 4.1: Number of wind events at Goeree in the period 15 March – 15 April between 1951 – 2004.

5 Impact on nutrients and primary production

5.1 Introduction

By reducing the light availability, increased SPM concentrations may have an effect on primary production, which in turn can lead to a shift in nutrient distribution in the North Sea. Previous studies and simulations have shown that the SPM concentration increased by sand mining does indeed lead to a shift in light-limited and nutrient-limited areas. We refer in particular to paragraph 5.5.3 in Royal Haskoning *et al*. (2006), which describes the concept of limiting factors.

The impact of the sand mining activities on the nutrients and primary production in the North Sea are simulated using the Delft3D-ECO (GEM) modelling framework. For a much more detailed description of the model and for all model settings (model grid, vertical aggregation, boundaries, parameter settings), we refer to previous reports (MARE, 2001; Delft Hydraulics, 2005; Haskoning *et al.*, 2006).

Two types of results are produced:
1. annual averaged variations of SPM, primary production and Chlorophyll-*a* relative to the reference scenario (*i.e.* without any sand mining activity), shown in several monitoring areas that are ordered in a way to depict the map of the Dutch coast (Appendix B);
2. eight-year time-series in several locations for the most important substances that determine the phytoplankton distribution (*i.e.* salinity, SPM, Chlorophyll-*a*, NO_3, PO_4, and Si) (Appendix C)

The SPM results discussed in this paragraph are the same as presented in the previous chapter. However, the results are discussed from the viewpoint of effect on nutrients and primary production. Instead of looking at distinct locations, results are discussed for monitoring areas; *i.e.* larger areas which can be considered as having more or less uniform characteristics (Figure 4.0). Instead of looking at high time-frequency variations, results are discussed for annual average conditions. In this way, we focus on the dominant trends.

5.2 Scenarios 0 – 85/15 (run 0-5)

5.2.1 SPM

When inspecting the monitoring-areas averaged results, it appears that the area comprised between the transects “Schouwen” and “Noordwijk” is the zone most affected by the sand mining activities. As expected, the Quick and Quick-close strategies cause an increase in SPM concentrations during the first two years, close to the coast and up to 15 km offshore.

Conversely, the Slow-far scenario shows an increase in importance in the more offshore regions (> 15 km) and its impact is more spread over time. Further north and in the Wadden Sea, on the other hand, all scenarios seem to have a similar impact on SPM concentrations. In those areas, the changes in SPM concentrations are small. However, they are higher than the estimated change in SPM with the 0-scenario. The impact of sand mining is more clearly visible in the south and in the Voordelta VHR region. There, the Quick and Quick-close strategies cause significant increases in SPM concentrations during the first years (20-40% increase). In the Voordelta VHR region, the impact after the sand mining activities in the Quick scenarios steadily decreases in time. After the sand mining activities have been stopped (2010), the impact of the Quick scenarios becomes smaller than the Base scenario.

Everywhere, the Base and the 85-15-scenario show an identical pattern of SPM concentration. Also, the 0-scenario exhibits almost no change in SPM concentration, except during the first year in the coastal regions (vak 13-14-15-16, see Figure 4.0) where the changes remain minor. The close similarity between the 0-scenario and the reference scenario makes it possible to consider the 0-scenario as a quasi-reference scenario.

SPM concentrations are still increased above the background concentration in the more northern areas (*e.g.* vak 17 and 18) after the mining activities have been stopped in 2010 in the Quick scenarios. The silt buffering retains the silt in the sediment as a result of which the travelling time of the released silt from the mining location to the northern areas exceeds by far the actual sand mining period. Away from the sand mining location, silt buffering effectively dampens the effect of different sand mining scenarios. The further away from the sand mining location, the more result from different sand mining scenarios resemble each other.

5.2.2 Chlorophyll-*a* and primary production

The changes in SPM concentration cause changes in the underwater-light availability, and hence in phytoplankton production. This is especially visible in the central and southern areas of the Dutch coast (*e.g.* vak 6-13-14-15-26-27). In those areas, an increase in SPM causes a decrease in primary production and hence, in Chlorophyll-*a*. This indicates that the phytoplankton primary production is mainly light-limited in those locations.

An interesting feature regarding the impact of sand mining on primary production during the first years is the difference between the areas vak 13 and vak 15. In vak 13, the increase in the annual averaged SPM concentration – as compared to the reference – is about 30-45% for the Quick and Quick-close scenarios, while it is about 80% in vak 15. Looking at the subsequent decline in primary production, one can note that it is higher in vak 13 (60-70%) than in vak 15 (30-35%). Also, the Chlorophyll-*a* concentration undergoes a stronger decrease in vak 13 (40%) than in vak 15 (20%). It may seem paradoxical that the location showing the larger SPM increase, shows in the same time the smaller decrease in primary production and in Chlorophyll-*a* concentration. To explain this situation, one may put forward that primary production is mainly limited by light in vak 13, while it is light- and nutrient-limited in vak 15. As a consequence, a change in SPM concentration should affect the primary production <u>on a yearly basis</u> in vak 13 more than in vak 15. In addition, one should realize that there exists a non-linear response between primary production and SPM, even under light limitation, and that there is a difference in limiting factors (see section 5.3.3

and particularly Figure 5.14 of Haskoning *et al.*, 2006 for further explanation – for easy reference, Figures 5.13 and 5.14 are reproduced below as Figures 5.1a and 5.1b).

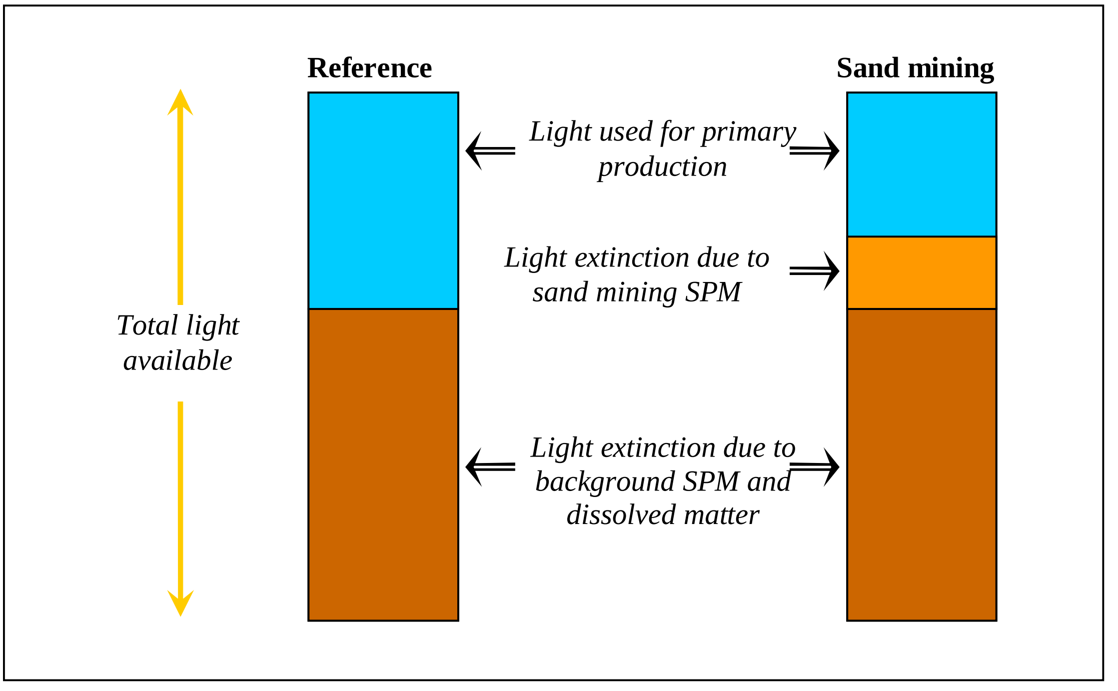


Figure 5.1a: In light limited areas, all available light is used for primary production. Higher SPM values result in lower primary production.

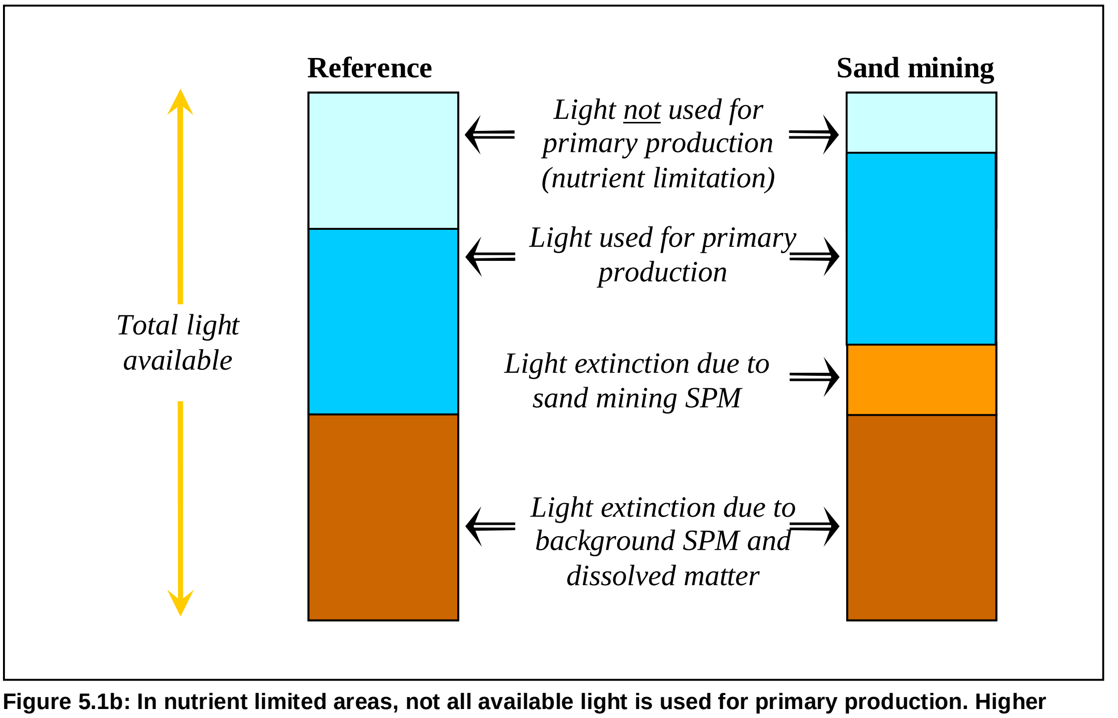


Figure 5.1b: In nutrient limited areas, not all available light is used for primary production. Higher SPM values do not result in lower primary production.

In the Voordelta VHR area, the Quick scenarios show an annual decrease in chlorophyll levels of 30% during the two years of sand mining. Hereafter, the impact rapidly decreases to approximately 10%. The Base scenario has a more or less continuous 20% reduction in chlorophyll levels compared to the reference situation, while the Slow far shows an annual averaged reduction of 10% in concentration.

The light-production relationship can also be observed in the time-series results (Appendix C). The area vak 16, for instance, is to be compared to the location NZR6NW010, which exhibits higher SPM values for the Quick scenarios during the winter 2009-2010 and in spring 2010. The effect on Chlorophyll-*a* is obvious this year, and one can see that the spring bloom of phytoplankton begins later for the Quick scenarios. This delay, in turn, affects slightly the nutrients consumption rate, and hence, the dissolved nutrient concentrations.

Similar effects are observed nearshore along the Noordwijk transect (e.g. location NZR6NW002). In these locations, the phytoplankton production is mainly light-limited all year round, and becomes nutrient-limited only during a short period in late spring and early summer. As a consequence, a variation in SPM concentration affects the Chlorophyll-*a* concentration, especially in the beginning of the bloom when nutrient concentrations are highest. The locations far offshore along this transect (location NZR6NW020, NZR6NW070) exhibit a different case. First, the SPM concentration is not subjected to any change, and secondly, the phytoplankton production is clearly nutrient-limited most of the year. The spring bloom causes the nutrient concentrations to drop rapidly to zero, until September arrives with the regenerated pool of nutrients. For this reason, one may suppose that the nutrient-limited production of NZR6NW070 would vary only slightly in response to a change in SPM concentration, as it is the case of the other nutrient-limited locations.

Another obvious example of nutrient-limited production is the NZR9TS004 station, which is situated close to the Wadden Sea in the north. The same conclusions as for NZR6NW070 may be drawn for this northern station. Also in this case, the SPM concentrations do not vary much as a response to the sand mining activities, though an evolution may be seen between 2008 and 2014. Indeed, slight changes in SPM patterns occur in the time-series from year to year, and the different sand mining scenarios can be seen to have a different impact in the later years. The annual averaged results show also a slight increase in SPM levels in the northern locations. However, the trend is reversed and the SPM values already decrease during the last year of the simulation in all locations. The slight increase in SPM may thus be seen as a reflection of the sand mining activities occurring in the south, but because of the distance from the sand mining the reflection occurs with a delay of a few years.

As pointed out in section 4.6 in Haskoning, WL and Svasek (2006), the salinity as simulated in the Voordelta VHR region is too low compared to the measured salinity. This is especially the case in spring. It leads to an overestimation of the contribution of fresh water to the extinction coefficient and hence to a potential underestimation of the algal biomass in the Voordelta. However, given the availability of hydrodynamic simulations, no sensitivity analysis of the potential underestimation was carried out.

5.3 Scenarios season, p5 to p8, and deep pit (run 6-8)

5.3.1 SPM

The SPM results of the simulation with the parameterised sediment accumulation in the pit (scenario Deep pit) show only very little impact on the turbidity patterns. In order to demonstrate the likely impact of net accumulation of the fines in a deep pit on the chlorophyll, a simulation has been performed with an assumed 25% reduction of the fines due to accumulation in the pit (so-called Deep pit) compared to the Base scenario (run 1). The yearly-averaged results of suspended solids show clearly a difference between the Deep pit scenario and the other ones. Everywhere along the Dutch coast, this option causes a reduction of the SPM in the water phase. The differences may seem negligible in some places, for instance in the Wadden Sea; yet they are significant in the southern areas, for example in area 14, 15, 16 and 18. Differences of even 10% are observed by comparing scenario Deep pit with other scenarios. These differences may play an important role on the primary production by virtue of the non-linear relationship between suspended sediments and light penetration through the water (Desmit *et al.*, 2005). The “p5 to p8” and “season” scenarios exhibit quite similar trends in yearly-averaged suspended solids concentrations. On the time-series graphs, the different scenarios show small differences, and their lines are often superimposed, regardless the parameter.

5.3.2 Chlorophyll-*a* and primary production

As expected from the yearly-averaged sediment concentrations, the yearly-averaged primary production undergoes a lesser decrease with the scenario Deep pit than with the Base scenario. Under light-limited conditions, less sediment in the system will lead to more light available. If light availability increases so much that light-limitation is lifted, less sediment can lead to more primary production. Similarly, a higher yearly-averaged Chlorophyll-*a* level is observed with the Deep pit option than with the Base scenario.

On the other hand, what is more surprising is the yearly-averaged chlorophyll profile for the Season scenario. It obviously exhibits higher values of chlorophyll in the southern areas, especially in vak 13, 14, and in the Voordelta VHR, where it shows less impact of sand mining than the Deep pit option (except in the last years). Still, the suspended solids show the same yearly-averaged profiles in this scenario as in the Basis and the p5 to p8 scenarios.

This may be explained by the fact that the yearly-averaged suspended solid values do not distinguish between summer and winter. As a consequence, the impact of a seasonal dredging is not well reflected in these graphs. In this respect, and only in this special case, the yearly-averaged presentation is somewhat misleading. Seasonal dredging, which occurs outside the period March-July, allows the light availability to be higher during the spring bloom of phytoplankton. During this bloom, phytoplankton growth is often light-limited due to higher nutrients concentrations in the natural system. Hence, even a small increase of the light availability has a significant impact on primary production and on Chlorophyll-*a* concentrations during the spring bloom.

It should be noted that a 10% variation on the yearly-averaged Chlorophyll-*a* corresponds to an average of about 2 μg/l of Chlorophyll-*a*. That is why the decrease in suspended solids and the consecutive increase in Chlorophyll-*a* with the Season option are hardly seen on the time-series figures. The Chlorophyll-*a* variation might presumably be considered as very small. Nevertheless, it plays a non-negligible role in the ecosystem, especially regarding the higher trophic levels which may profit from 10% more energy input.

5.4 Scenarios S0 –S4 S1c and S1c-res (run 9-16)

5.4.1 SPM

Scenario S1a shows the highest yearly averaged increase in SPM concentration (*i.e.* 40% increase in the coastal zone and 30% in the Voordelta VHR region). This is comparable with the Quick scenarios. Sand mining scenario S2 shows the smallest impact, with an exception of vak 6 and 7 which are directly located in the sand mining area 3. The results of S1c scenario show an yearly average maximum increase of 25% in the Voordelta VHR region.

5.4.2 Chlorophyll-*a* and primary production

Scenario S1a (comparable with the Quick scenario) reveals the greatest reduction in Chlorophyll-*a* (up to 30% in the Voordelta VHR region), while sand mining scenario S2 shows the lowest reduction in chlorophyll levels and primary production, except during the first years in the areas vak 6, 7, 13, 14 and the Voordelta VHR. In those areas scenario S4 has a lower impact than scenario S2 during the first years. This can not directly be explained by observing the differences of the annual averaged silt concentration. It can be explained by the fact that in scenario S4, mining is confined to the ecologically active spring/summer period in the far region (area 2, see Figure 1.1) and to the ecologically less active winter period in the near coast region (area 1).

5.5 Natural background without sand mining: random-cosine and dynamic calculation (compared with data)

5.5.1 SPM

To describe the natural background of SPM, a new model was developed taking into account seasonal variability and sediment buffering in the seabed (see Chapter 3, and *in* Van Kessel and Brière, 2006). Both this new model and the random-cosine model for background SPM have been compared to an extensive data set to determine their goodness-of-fit objectively. The DONAR data were collected between 1989 and 2003 at 29 locations in the North Sea. The comparison was made using a ‘cost function’ approach, i.e. a monthly estimate of the goodness of fit by calculating the standard deviation between modelled and measured results. The method is described in Radach and Moll (2006), and the criteria for categorizing the results from ‘very good’ to ‘poor’ fitting are summarized in Table 5.1.

Rating	Conditions	
Very good	0 < cf < 1	Standard deviations
Good	1 < cf < 2	Standard deviations
Reasonable	2 < cf < 3	Standard deviations
Poor	3 < cf	Standard deviations

Table 5.1: Criteria to categorize the results of the cost function (cf) (from Radach and Moll 2006)

Table 5.2 shows the yearly-averaged cost-function values at twenty-nine monitoring stations covering the whole Dutch coast, for the random-cosine model (i.e. rancos) and for the new model (i.e. f2_10). In order to have a significant amount of data to assess the standard deviation, the model results from each year were compared to the data from all available years at a specific location. The results show that both the random-cosine model and the new model exhibit an overall ‘very good’ goodness-of-fit with the data.

Looking at the numbers only, the random-cosine model appears as the most efficient model considering all years and all stations. In the random-cosine model, ‘very good’ scorings predominate while in the new model, ‘very good’ and ‘good’ scorings have the roughly the same frequency of occurrence. However, the differences between the cost functions are small and show that the new model is very promising, though it still has to be improved.

The random-cosine performs better than the new model in particular in the Terschelling transect. It should be noted that model performance at the Terschelling transect is less important, as the sand mining has a small impact on this region.

It should be pointed out that these models are different in the sense that the random-cosine model is based on an empirical approach, while the new model aims at describing in a deterministic way the high-frequency variations of the SPM concentration. Also with respect to the data, care has to be taken. The DONAR data comprise typically of monthly measurements. It has been noted that storm events are notably underrepresented in the data, which may result in an underestimation of the annual average and/or standard deviation. Thus, it is difficult to demonstrate with the cost function the efficiency of the new model regarding the high-frequency variations. Further model developments should make use of the objective cost function comparison, but should also take into account the representativeness of the available monitoring data.

Random Cosine background

Year / *Location*	1996	1997	1998	1999	2000	2001	2002	2003	**Time avg**
NZR2WC002	0.471	0.406	0.376	0.473	0.361	0.361	0.480	0.374	0.413
NZR2WC030	0.636	0.671	0.705	0.582	0.892	0.805	0.765	0.641	0.712
NZR2WC050	0.391	0.354	0.339	0.404	0.369	0.393	0.469	0.381	0.388
NZR2WC070	0.564	0.530	0.501	0.589	0.488	0.455	0.647	0.562	0.542
NZR3SW010	0.680	0.707	0.735	0.608	0.919	0.778	0.587	0.643	0.707
NZR3SW020	0.638	0.494	0.549	0.580	0.810	0.449	0.511	0.587	0.577
NZR4GR006	1.122	1.083	1.044	1.036	1.367	1.225	1.115	1.078	1.134
NZR4GR020	0.597	0.463	0.561	0.495	0.423	0.490	0.510	0.503	0.505
NZR6NW001	0.642	0.436	0.490	0.542	0.615	0.626	0.489	0.345	0.523
NZR6NW002	2.169	2.060	2.177	1.904	2.538	2.368	2.035	2.077	2.166
NZR6NW004	1.125	1.000	1.029	0.977	1.339	1.231	1.078	1.023	1.100
NZR6NW010	0.437	0.475	0.353	0.527	0.663	0.419	0.460	0.491	0.478
NZR6NW020	1.047	0.929	0.988	1.082	0.990	0.888	0.978	0.939	0.980
NZR6NW030	0.590	0.581	0.595	0.610	0.604	0.581	0.528	0.567	0.582
NZR6NW050	0.279	0.380	0.300	0.334	0.398	0.376	0.446	0.345	0.357
NZR6NW070	0.412	0.487	0.396	0.456	0.528	0.539	0.420	0.415	0.457
NZR9TS004	0.252	0.235	0.286	0.173	0.219	0.366	0.277	0.194	0.250
NZR9TS010	0.452	0.411	0.426	0.469	0.525	0.578	0.405	0.391	0.457
NZR9TS050	0.592	0.634	0.612	0.653	0.518	0.662	0.822	0.660	0.644
NZR9TS070	0.503	0.589	0.543	0.564	0.506	0.569	0.636	0.610	0.565
NZR9TS100	0.410	0.355	0.275	0.432	0.414	0.394	0.543	0.276	0.387
NZR9TS135	0.457	0.718	0.466	0.615	0.764	0.663	0.776	0.628	0.636
NZR9TS175	0.688	0.819	0.609	0.759	1.138	0.842	0.959	0.880	0.837
NZR9TS235	0.584	0.436	0.592	0.538	0.798	0.494	0.720	0.686	0.606
WZ190Vliestr	0.621	0.603	0.597	0.627	0.509	0.567	0.597	0.611	0.592
WZ230Blauwe	1.233	1.245	1.149	1.245	1.145	1.206	1.286	1.274	1.223
WZ310Harling	1.965	2.025	1.928	2.067	1.956	1.933	1.922	1.991	1.973
WZ420Dantzig	1.038	0.985	0.975	1.015	0.925	1.040	1.098	1.015	1.011
WZ480Zoutkam	1.012	0.881	0.943	0.947	0.836	0.958	1.079	0.999	0.957
Space avg	0.745	0.724	0.708	0.735	0.812	0.767	0.781	0.731	**0.750**

f2_10 background

Year / *Location*	1996	1997	1998	1999	2000	2001	2002	2003	**Time avg**
NZR2WC002	0.763	0.904	0.833	0.915	0.918	0.781	0.882	0.813	0.851
NZR2WC030	0.781	0.630	0.605	0.352	0.382	0.387	0.581	0.423	0.518
NZR2WC050	0.491	0.539	0.369	0.423	0.387	0.484	0.683	0.582	0.495
NZR2WC070	0.625	0.670	0.583	0.429	0.394	0.488	0.792	0.634	0.577
NZR3SW010	0.424	0.547	0.406	0.510	0.425	0.452	0.621	0.537	0.490
NZR3SW020	0.508	0.555	0.287	0.388	0.526	0.356	0.580	0.481	0.460
NZR4GR006	0.246	0.500	0.622	0.564	0.807	0.474	0.690	0.450	0.544
NZR4GR020	0.563	0.565	0.481	0.569	0.531	0.722	0.729	0.605	0.596
NZR6NW001	0.245	0.508	0.447	0.404	0.694	0.515	0.246	0.292	0.419
NZR6NW002	1.184	1.009	1.169	0.561	1.163	2.009	1.520	0.691	1.163
NZR6NW004	1.347	1.080	2.041	1.005	2.121	1.822	1.309	0.752	1.435
NZR6NW010	1.935	1.127	1.739	0.640	2.385	0.784	1.313	0.782	1.338
NZR6NW020	1.410	1.016	0.659	0.930	1.619	0.990	1.324	1.110	1.132
NZR6NW030	0.624	0.609	0.432	0.535	0.836	0.591	0.656	0.642	0.616
NZR6NW050	0.470	0.485	0.289	0.325	0.404	0.306	0.501	0.494	0.409
NZR6NW070	0.854	0.658	0.406	0.483	0.548	0.576	0.773	0.737	0.629
NZR9TS004	0.375	0.442	0.629	0.377	0.418	0.573	0.788	0.425	0.503
NZR9TS010	1.824	1.095	1.901	0.519	1.668	1.357	1.219	0.642	1.278
NZR9TS050	1.044	1.261	1.083	0.976	1.357	0.981	1.793	1.633	1.266
NZR9TS070	0.963	1.232	0.821	0.826	0.835	0.994	1.311	1.185	1.021
NZR9TS100	0.888	1.064	1.591	1.060	0.974	1.255	1.084	1.388	1.163
NZR9TS135	1.745	1.418	1.483	1.314	1.634	1.741	1.664	2.109	1.639
NZR9TS175	2.550	1.778	1.704	1.652	2.633	2.296	2.029	2.033	2.084
NZR9TS235	2.228	1.655	1.529	1.566	2.083	1.782	1.870	1.892	1.826
WZ190Vliestr	0.483	0.712	0.506	0.568	0.578	0.521	0.598	0.699	0.583
WZ230Blauwe	0.961	1.257	0.801	0.811	0.976	0.899	0.877	1.078	0.958
WZ310Harling	1.890	1.842	1.234	1.367	2.158	2.043	1.715	1.837	1.761
WZ420Dantzig	1.173	1.425	1.226	1.204	1.301	1.261	1.316	1.164	1.259
WZ480Zoutkam	1.300	1.572	1.429	1.351	1.276	1.348	1.455	1.279	1.376
Space avg	1.031	0.971	0.942	0.780	1.105	0.993	1.066	0.944	**0.979**

Table 5.2: Cost-function values for the comparisons between measured SPM data and modelled results in the North Sea. Upper panel: comparison of the random-cosine model with data. Lower panel: comparison of the new model (f2_10) with data. The cost-function values are presented for each year between 1996 and 2003 at 29 monitoring stations. The last column shows the time-average cost-function values for each station, and the last row shows the average values over the 29 stations for each year (see table 5.1 for criteria of fitting). The last number (low-right) is the average of the table.

5.5.2 Chlorophyll-*a* and primary production

An equivalent goodness-of-fit comparison could be generated for Chlorophyll-*a*, but this was not carried out as part of this study. Note that no primary production measurements are available for such an assessment. Alternatively, a visual inspection of the simulated Chlorophyll-*a* against measurements was carried out.

One interesting observation is that, when there are large differences in SPM between the two models, the random-cosine model tends to fit the highest data values, while the f2_10 model tends to fit the lowest data values (except for two stations: NZR6NW010 and NZR5TH002). This shows that, under conditions of high SPM variability, the two models might in some cases exhibit quite different values of SPM despite the fact that they both result in 'very good' cost-function values. In other words, to decide which SPM model is better, no distinction can be made based on the SPM model results. Instead, the GEM model for Chlorophyll-*a* and primary production has to make the distinction. If the GEM model cannot make a distinction either, it has to be concluded that the SPM level is not important at this location and more refined modelling is not necessary.

Comparing Chlorophyll-*a* calculated with the random-cosine and the newly modelled background SPM, it is striking that the difference in Chlorophyll-*a* is generally small even when the SPM concentration is very different. For example, at Schouwen 10 km (NW3SW010) the random-cosine SPM is roughly twice as high as the newly modelled SPM. For Chlorophyll-*a* however, is generally similar although in autumn the Chlorophyll-*a* concentration drops later for the new model than for the random-cosine. At other stations, the other background SPM hardly affects the calculated Chlorophyll-*a* concentration.

The reason for the small difference can again be found in the delicate balance between nutrient-limitation and light-limitation. For example at Noordwijk 10 km (NR6NW010), primary production is phosphate (and silicon) limited in summer. Hence, a higher SPM concentration does not influence Chlorophyll-*a* at this location.

It should be noted that except for the Voordelta, the greater difference between random-cosine SPM and f2_10 SPM occurs in winter when primary production is small. Thus, for Chlorophyll-*a* it does not really matter which background SPM to take as the Chlorophyll-*a* concentration is close to zero anyway.

As a concluding remark, we add that the random-cosine model, which requires much less effort than the new dynamic SPM model, is adequate for studies in which the SPM is not affected, e.g. nutrient reduction studies. The new model is particularly promising within the context of studies in which SPM can be expected to change, e.g. sand mining studies.

5.6 Sensitivity: background SPM on sand mining impact

5.6.1 SPM

The impact of sand mining scenario S1a has been considered for both the random-cosine background SPM and the dynamically modelled SPM (f2_10). On the time series, it is shown that the sand mining does not affect the pattern of SPM but increases the overall value by 5 to 20 mg/l.

The graphs of the annual averages relative to the background show also high differences in some areas between the random-cosine and the f2_10 simulations. The differences observed in monitoring area 16, for instance, show that the sand mining has a greater impact relative to the SPM background in the random-cosine simulation. On the other hand, in monitoring area 13 it is the opposite. Since the sand mining scenarios are the same (S1a), this is simply caused by the fact that the random-cosine background SPM has smaller values than the f2_10 in monitoring area 16 (corresponding to NZR6NW020); and higher values in monitoring area 13 (corresponding to NZR4GR006). The sensitivity runs should therefore be considered on the impact on Chlorophyll-*a* and primary production, not on the somewhat artificial impact on SPM.

5.6.2 Chlorophyll-*a* and primary production

For large parts of the Dutch coastal zone, the different background SPM results in the same change in annual-average Chlorophyll-*a* and primary production. In the Voordelta VHR, at more than 15 km offshore (monitoring areas 5 to 10), the Wadden Sea coast and in the Wadden Sea the impact is not significantly different.

Only in the near coastal zone (0 -15 km) from Hoek van Holland to roughly Callantsoog, different impact predictions are found. Even here, the difference is rarely larger than 10%. The differences are somewhat larger for Chlorophyll-*a* than for primary production, which is an indication that transport plays a role. Primary production is a local ‘process’ only controlled by local conditions. Chlorophyll-*a* (biomass) can be produced locally, but is also transported from elsewhere.

In areas like monitoring area 16, for instance, where significant differences in SPM are observed between the two simulations random-cosine and f2_10, the impact on primary production, though non negligible, remains the same for both models. On the other hand, the monitoring area 27 exhibits lesser differences on SPM but shows in the same time high differences on primary production. This is most probably an example of switch between nutrient-limited growth and light-limited growth. On the time series, the corresponding stations are called NZR6NW020 for monitoring area 16, and NZR6NW002 for monitoring area 27. While the nutrient concentrations are only slightly smaller further from the coast (NZR6NW020), the SPM concentrations, on the other hand, are much lower, and that causes an exponential increase of the light availability in the water column.

The effect of a higher SPM concentration closer to the coast is also observable on the Chlorophyll-*a* concentrations. Though they have quite similar values on the average, the Chlorophyll-*a* concentrations of the random-cosine and the new model exhibit clear seasonal shifts closer to the coast (NZR6NW002), while this is not very much the case further from the coast (NZR6NW020), except in 2010. It appears on the time series of the f2_10 simulation at NZR6NW020 that the SPM in 2010 exhibit a peak in spring, which causes this shift. The nutrient concentrations are in turn affected by the primary production, and the seasonal shifts observed in Chlorophyll-*a* are also observed on the nutrient seasonal profiles. The effect of this 2010-spring shift is otherwise visible in the graph of relative annual averages of Chlorophyll-*a* in the monitoring area 16. In this graph, it is obvious that the spring shift weighs significantly on the annual average of 2010. This points out the evidence that only spring and summer differences in SPM concentrations between the random-cosine and the f2_10 simulations will generate differences in the primary production and the Chlorophyll-*a* concentrations. On the opposite, winter differences in SPM – whatsoever important – will not affect significantly the primary production, and hence will not generate any significant difference in the annual averages of Chlorophyll-*a* concentrations.

Both SPM backgrounds give a good to very good scoring given the cost function. Differences are mostly related to winter conditions which are not relevant for primary production and Chlorophyll-*a*. We observed that both background SPM concentrations lead to very similar impact predictions. Therefore, we conclude that the use of random-cosine background SPM which has been questioned for its more empirical origin, is suitable to predict the impact for all sand mining scenarios.

5.7 Sensitivity: inter-annual variability of SPM (stormy-average-quiet)

5.7.1 Introduction

Climatological conditions influence primary production in multiple ways by changing:

1. Currents
2. SPM (sedimentation and resuspension)
3. River discharge
   a) Extinction (humic substances)
   b) Nutrients
4. Sunlight

All these are taken into account in the GEM model. When defining typical climatological conditions (e.g. stormy), the effects are usually combined. For example, in stormy years more resuspension and thus higher SPM concentrations are expected, but also the river discharge is expected to be higher than average and the sunlight lower than average. In numerical modelling, all the effects can be distinguished in separate scenarios.

The inter-annual variability of SPM arising from differences in wind speed has been presented in chapter 4. Three years are selected: 1998 (stormy), 2001 (average), and 2003 (quiet). The relative impact of sand mining on primary production and Chlorophyll-*a* has to be assessed during those different years. Some preliminary studies have already shown that the driving forcings with regard to primary production and Chlorophyll-*a* in the Dutch coastal system are the suspended solids, which determines the light availability, and the freshwater discharge, which reflects the amount of nutrients and plays a role on the light availability as well, due to the presence of riverine humic substances (dissolved organic matter).

In order to discriminate between those two forcings – SPM and salinity, we have made two types of sensitivity analysis. To remain consistent with all the previous scenarios, we stick to the random cosine function to calculate the background SPM in our water-quality simulations. Also, the random cosine function had the best score in the cost-function comparison. Regarding the sand mining activities, the so-called ‘S1a’ scenario was used.

The first sensitivity analysis focuses on the effect of SPM due to sand mining only. Three synthetic simulations of eight years each have been made by using eight times the same year (i.e. 2001) for the hydrodynamic conditions including river discharges, as well as for the background SPM. Each scenario applies the S1a sand mining strategy. The sunlight is also the same for all scenarios.

Compared to the original S1a scenario that includes real-time hydrodynamic conditions from 1996 to 2003, the synthetic scenarios thus vary in the way climatologic conditions influence the SPM released by the S1a sand mining activities. This is however not the only difference, as repeating the 2001 river discharge eight years in a row will also result in different salinity and nutrient patterns compared to the real-time 1996-2003 series. This can result in different nutrient limitation and through the fresh-water contribution also in different light limitation. These two effects (climatic conditions and river discharge) have not been distinguished in this study.

A second analysis is made the same way, except that the chosen year regarding the hydrodynamic conditions and the background SPM conditions is not 2001, but 2003. Here again, the effect of sand mining activities on primary production can be appreciated for different climatological conditions – the same ones as before: stormy, average, quiet. What is more interesting, however, is to compare the first sentitivity analysis to the second one in order to assess the changes on primary production due to two different seasonal patterns of salinity and related nutrient availability, i.e. the ones of 2001 and 2003.

5.7.2 Chlorophyll-*a* and primary production

The graphs of percentage changes in annual averages for SPM (not shown) are not representative of the complexity of the SPM dynamics in this chapter (see instead the time series). Indeed, especially when trying to compare the relative effect of the sand mining of one year to the natural background of another year, the yearly averages hide too much information and lose significance. This is due to two main reasons: 1) the use of two different years for the background and the sand mining; 2) the complex seasonal pattern of SPM, with higher values and larger differences during the winter than during the summer. However, as previously said, whatsoever important the SPM might be during the winter, it does not affect significantly the primary production in this season. Indeed, only spring, summer and autumn values are important in this respect, and yet as long as the primary production is light-limited.

In the Voordelta VHR, different meteorological conditions result in virtually the same impact on Chlorophyll-*a* and primary production (the latter shown in the figure below), the difference being around 5%. Also, the predicted impact is rather insensitive for different river discharge scenarios, as again the difference is also about 5%.

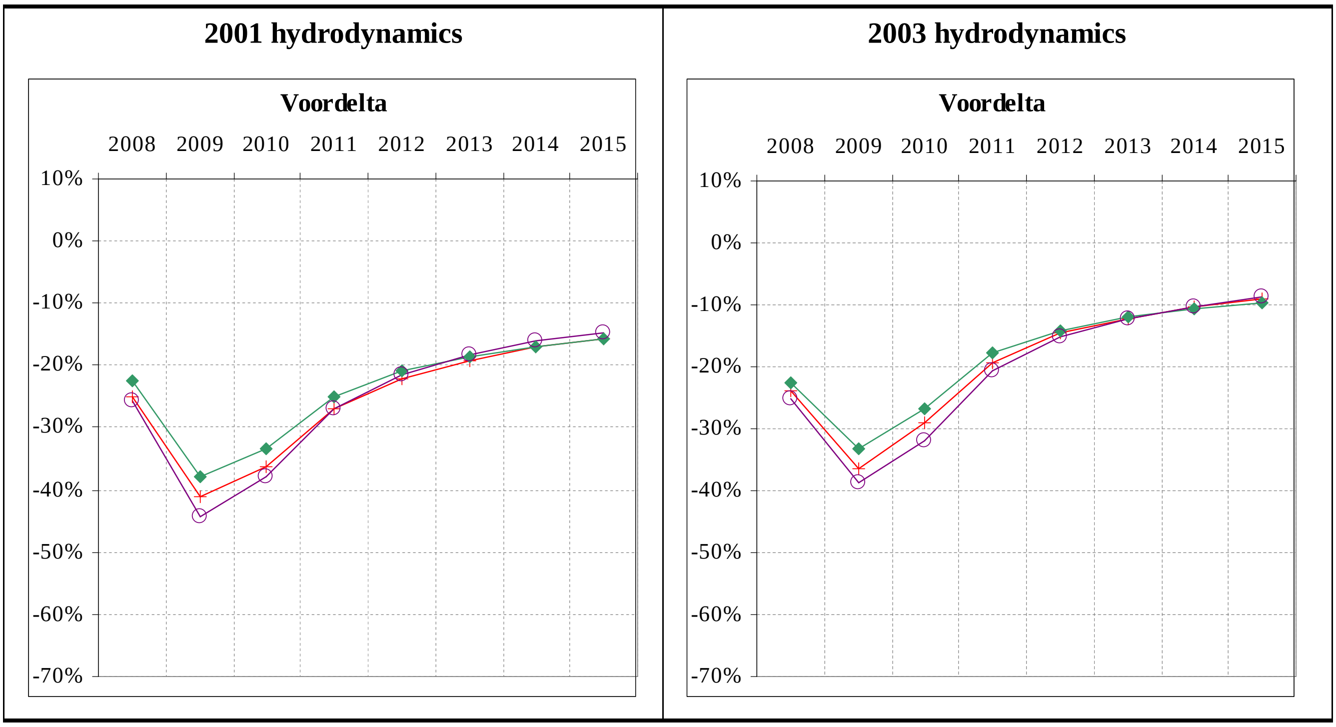


Figure 5.2 Change in primary production in the Voordelta VHR due to sand mining S1a for stormy (purple), average (red) and quiet (green) meteorological years and for the 2001 hydrodynamics (left) and 2003 hydrodynamics (right)

To the north of the current Maasvlakte, the meteorological conditions do result in different impact. The SPM model has shown that in a stormy year, the SPM released during sand mining is stored to a lesser extent in the seabed close to the mining location and is transported to a greater extent to the northern coastal zone. This is reflected in the greater impact of sand mining during stormy years on Chlorophyll-*a* and primary production. For the 2001 hydrodynamics, the impact during persistently stormy years is roughly twice as high as during persistently quiet years. The impact is noticeable up to 15 km offshore and up to the Wadden Sea coast.

On the time series (Appendix C), only small differences are found between the three cases, except in some stations like NZR6NW010 or NZR5TH002. In addition, there are systematic differences between the Reference scenarios and the three meteorological scenarios. These systematic differences are artificially introduced by the chosen approach and the post-processing. For the Reference scenario, the same year (e.g. 2001) is plotted 8 times. When the salinity on December 31 is not equal to the salinity on January 1, the plot shows a jump in Salinity. In other words, the January 1 condition is ‘reset’ at the start of each of the 8 plotted years. For the meteorological scenarios, the Salinity is recomputed for the total 8-year period and thus shows a smooth line without jumps.

Figure 5.3 shows the change in primary production due to sand mining assuming hydrodynamic and background SPM conditions for average years (2001) and quiet years (2003) in monitoring area 17. The change in primary production is 10% lower in quiet years than in average years. It should be noted that part of the change will derive from different in the river discharge. However, the effect of the river discharge was not distinguished separately in this study.

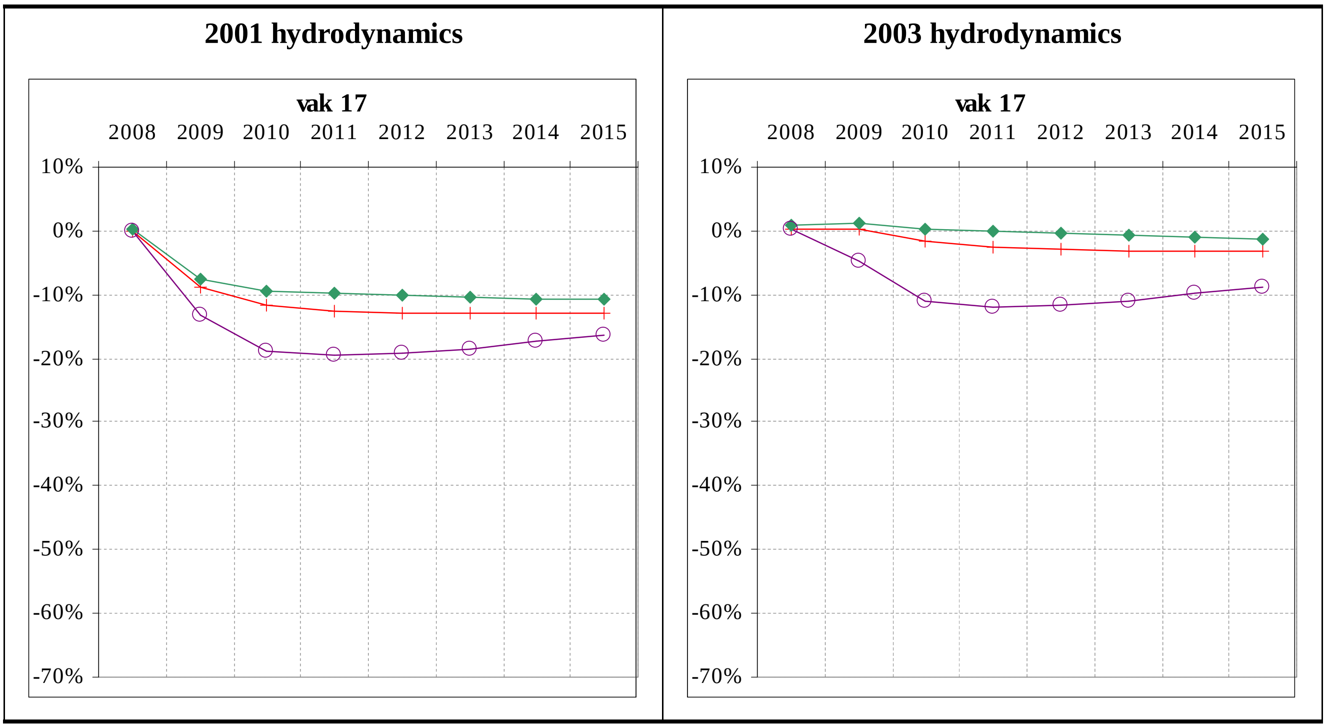


Figure 5.3 Change in primary production in the Voordelta VHR due to sand mining S1a for stormy (purple), average (red) and quiet (green) meteorological years and for the 2001 hydrodynamics (left) and 2003 hydrodynamics (right)

The comparison between two different hydrodynamic conditions (2001 & 2003) for the same meteorological scenarios shows that:

1. There is no large visible change in the SPM concentrations due to sandmining ON THE YEARLY AVERAGE between both years. Yet, there are some differences in the light availability during the spring season, when the bloom starts under light-limiting conditions.
2. Those differences in the spring light-availability are due to the conjugated effects of the background SPM (wind-driven) and of the river discharge. In 2001, the salinity is lower and hence the contribution of humic substances to the extinction is higher than in 2003. In 2001, the background SPM is also somewhat higher than in 2003. Both contributions, which are not related to sand mining, create conditions that are more often light limiting for the spring bloom in 2001 than in 2003.
3. The effect of sand mining on primary production depends on the level of light-limitation created by the ambient conditions. In 2001, the ambient conditions are more critical than in 2003 and hence the added influence of the sand mining SPM to the light extinction creates a larger effect in 2001 than in 2003. In other words, in 2003 the ambient conditions are less critical than in 2001 and thus the system can cope with more additional extinction due to sand mining SPM before having substantial effect on primary production.
4. The resulting effect on primary production is only observable in early spring and late autumn, because during the summer the bloom is phosphorus-limited anyway. If the spring bloom is hindered by a very low light availability, the yearly average of primary production will decrease. In that case, our estimate based on the results is that the relative decrease due to sandmining is between 5 and 10 %. It is clearly the case in vak

17, for instance, where an impact is observed both years under stormy conditions, but where there is no significant impact for the quiet year (2003) under quiet conditions. Indeed, under full quiet conditions, even the sandmining activities will not be sufficient to hinder the spring bloom.

5. This effect, when it happens, is largest north from the sand mining location and along the Dutch coast (5-10%), and it decreases towards the Wadden Sea (2%).

For the Chlorophyll-*a* concentrations, the analysis holds but it is even more complex due to transport. Still, we observe stronger impacts close to the coast and under rough weather conditions.

6 Conclusions

The following conclusions may be drawn regarding the impact of the sand mining scenarios on SPM concentration levels and primary production. Resulting impacts on bird ecology etc. are discussed elsewhere. Of course, the overall evaluation of the scenarios includes many other aspects, which have not been considered herein.

- A faster rate of sand mining results in a larger impact close to the mining area. Further away, the maximum impact is attained earlier, but the maximum level itself does not differ between the fast and slow sand mining scenarios.
- A shift in the location of the mining area towards the north-west is advantageous for the Voordelta, but disadvantageous for the Dutch coastal zone north of IJmuiden.
- Comparing the quick and quick-close sand mining scenario, a shift in the location of the mining area towards the Maasvlakte-2 only results in a change of the local effects for the duration of the sand mining. The SPM concentration increase in the Voordelta becomes slightly larger if the mining area is moved more towards Maasvlakte-2.
- Comparing the quick and quick-close sand mining scenario, we conclude that moving the sand mining location closer to the Maasvlakte-2 reduces the impact on Chlorophyll-*a* slightly in an area more than 4 km offshore up to Egmond to the north of the sand mining. Towards the south (i.e. in the Voordelta), in the nearshore (< 4 km offshore) and to north of Egmond, the quick and quick-close scenario have the same impact on Chlorophyll-*a*, although the quick-close has a greater impact on primary production in the Voordelta than the quick sand mining scenario.
- The impact of the autonomous 0-scenario is very small compared to the reference situation without any sand mining. Only a small impact in the direct southern coastal zone (< 15 km) is simulated during the first year (5 to 10% reduction in Chlorophyll-*a* and primary production).
- A comparison between the scenarios with 90:10 and 85:15 distributions shows only some difference in impact near the Maasvlakte (monitoring area 13). No differences in the impact on chlorophyll on annual scale are observed elsewhere in the North Sea.
- The Quick scenarios show a decline in the annual averaged chlorophyll levels in the Voordelta. During the 2 years of sand mining, the decline is 30%. After the sand mining has stopped, the decline decreases to 10%. The Base scenario shows a reduction of approximately 20% during the 5.5 years of mining activities.
- The Slow-far scenario shows a smaller impact in the Voordelta region (*i.e.* 10% reduction in Chlorophyll-*a*) than the Base scenario.
- In general, the Slow-far scenario can be considered as the scenario with the smallest impact in the coastal zone (<15 km) during the 8 years of simulation. Offshore (> 15 km), this scenario has the highest impact.
- For all scenarios, the simulated impact in the Wadden Sea is insignificant.
- The Base 75% scenario shows a lower sediment concentration in the water column in comparison with the Base scenario, especially in the south and in the Voordelta. This causes the primary production, and hence the Chlorophyll-*a* concentration, to be higher in those areas for the Base 75% scenario.
- The shift from p5 to p8 only exhibits minor effects.

- The Season scenario does not show large differences in annual averaged suspended solids concentrations in comparison with the Base scenario. However, by aiming at the preservation of the spring phytoplankton bloom, the Season strategy gives a 10% decrease in the sand mining impact on Chlorophyll-*a* in comparison with the Base case. This occurs especially in the south and in the Voordelta.
- In general, the sand mining scenario S2 has the lowest impact on Chlorophyll-*a* levels.
- Seasonal differentiating of sand mining over area 1 and 2 (scenario S4) has a positive effect on the impact of sand mining on Chlorophyll-*a* levels in the Voordelta, but a negative effect further offshore.
- The GEM model uses an empirical approach to derive a long-term (seasonal) and short-term (wind-induced) variation from a steady-state concentration pattern in background SPM. It has been questioned if the empirical approach influences the conclusions in this report. During the current study, a new approach has become available to simulate dynamically the background SPM.
- An objective cost-function comparison of the empirical approach (the so-called random-cosine) and the new dynamic modelling approach against SPM measurements has shown that both approaches have a good to very good goodness-of-fit against measurements.
- Both background SPM approaches result in similar impact predictions on primary production and Chlorophyll-*a*. The approaches differ mostly in winter SPM concentrations, which is a period that is not relevant for primary production. In spring and summer, the random-cosine and the new dynamic model predict similar SPM concentrations and hence the impact on primary production is similar as well. We conclude that the use of the random-cosine background SPM, which has been questioned for its more empirical origin, is suitable to predict the impact for all sand mining scenarios.
- In the Voordelta VHR (Bird and Habitat directive), different meteorological conditions result in minor different impacts on primary production and Chlorophyll-*a*. The difference between stormy and quiet years is about 5%.
- In the coastal zone north of the Maasvlakte and in the Wadden Sea coast, meteorological conditions can have a greater effect. The impact during persistently stormy years is roughly twice as high as during persistently quiet years. The impact is noticeable up to 15 km offshore and up to the Wadden Sea coast.
- The sensitivity for changes in ambient (light) conditions (river discharge and background SPM) was tested by repeating the conditions for 2001 and 2003. The effect of sand mining on primary production depends on the level of light-limitation created by the ambient conditions. In 2001, the ambient conditions are more critical than in 2003 and hence the added influence of the sand mining SPM to the light extinction creates a larger effect in 2001 than in 2003.
- Due to differences in ambient conditions, the change in primary production can vary 5% to 10% along the Dutch coast and a few percent towards the Wadden Sea coast.

7 References

Desmit X, Vanderborght J-P, Regnier P and Wollast R. Control of phytoplankton production by physical forcing in a strongly tidal, well-mixed estuary. Biogeosciences (2005), Page(s) 205-218.

Desmit, X., J. Boon, T. van Kessel, A. Nolte (2007). Additional scenarios sand mining Maasvlakte-2. WL | Delft Hydraulics Report Z4103. Delft, The Netherlands.

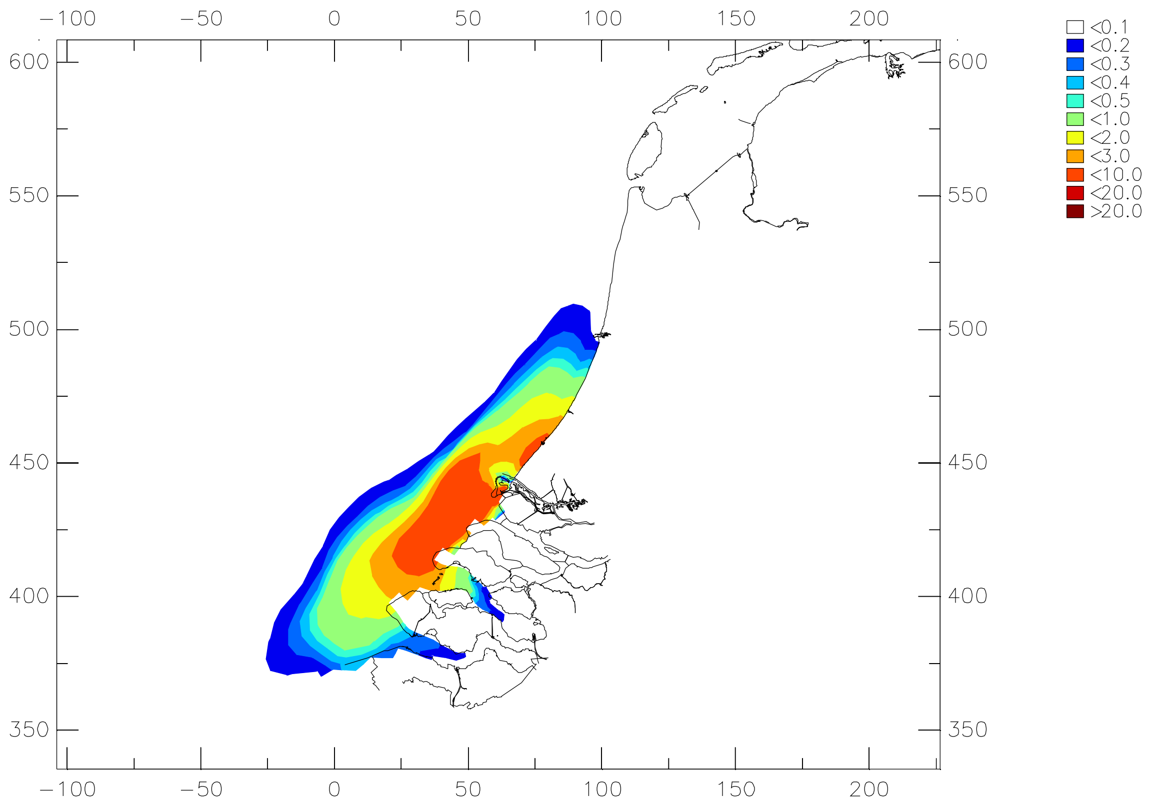
Radach G, Moll A (2006) Review of three-dimensional ecological modelling related to the North Sea shelf system. Part II: Model validation and data needs. Oceanography and Marine Biology: An Annual Review, 44, 1-60.

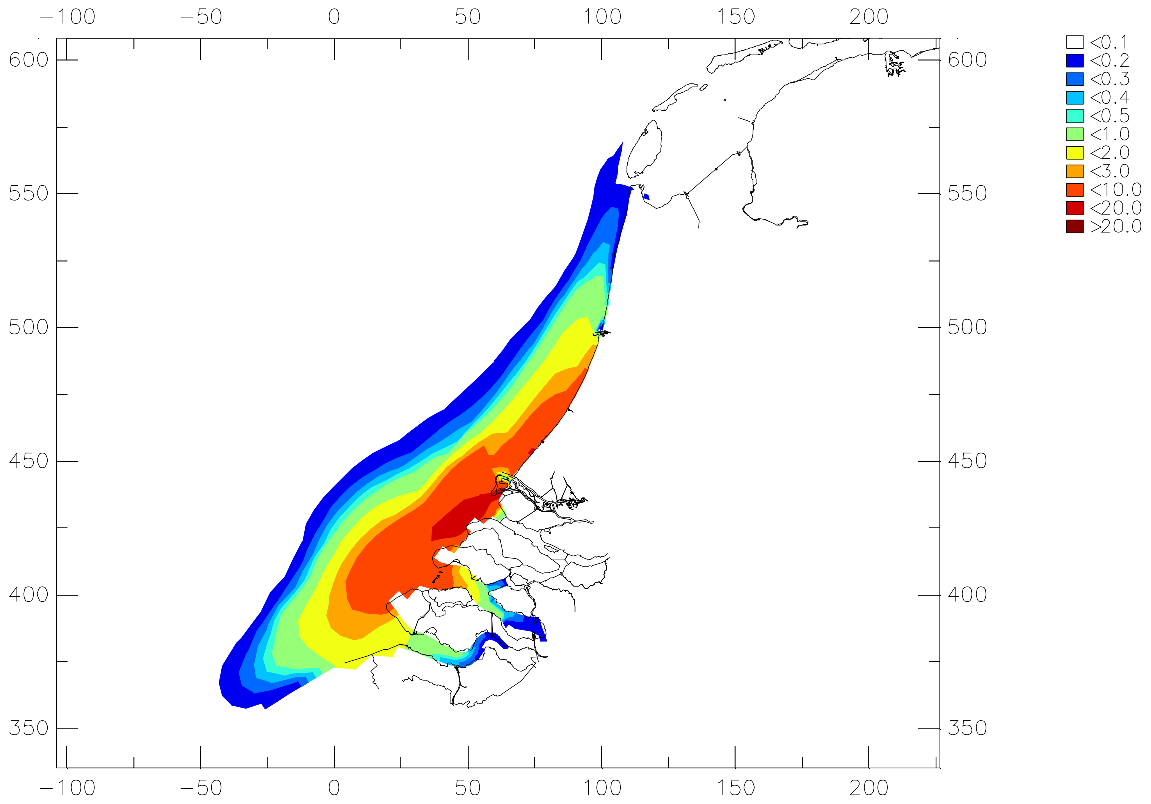
Royal Haskoning, WL| Delft Hydraulics, Svasek, 2006. Impact sand extraction Maasvlakte 2. Mud transport, nutrients and primary production, 2006, 9P7008.O9.

Van Kessel, T. and C. Brière (2006). Modelling of seasonal SPM variations in the Dutch coastal zone. WL | Delft Hydraulics Report Z4150.

A SPM concentration increase in the Dutch coastal zone due to sand mining

N.B. Only scenario s1a is shown as an example. Figures for all other scenarios can be found on the accompanying CD-rom.

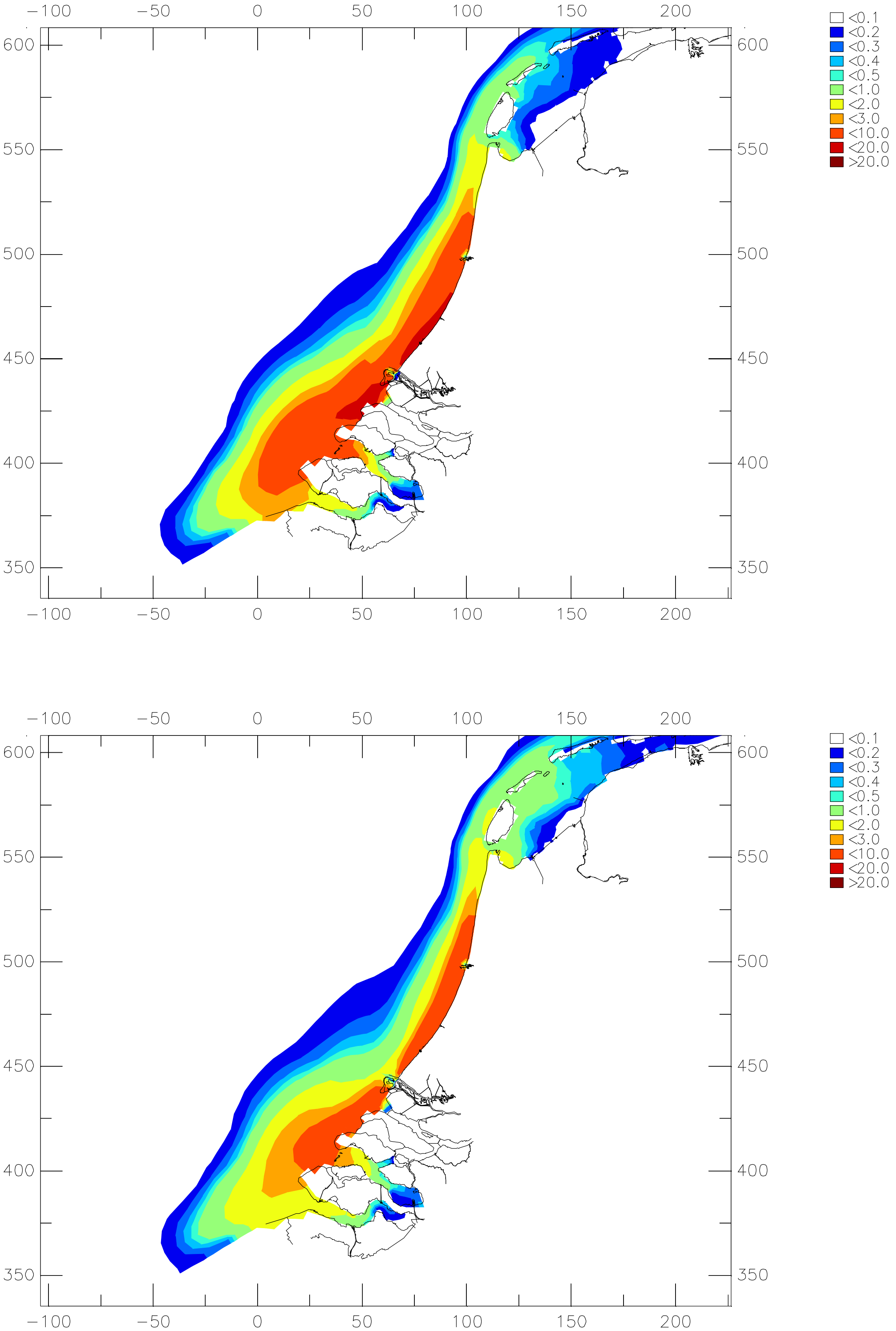




Scenario s1a: year-average concentration (mg/l)
Upper panel: 2008
Lower panel: 2009

WL | Delft Hydraulics

Fig. A1



Scenario s1a: year-average concentration (mg/l)
Upper panel: 2010
Lower panel: 2011

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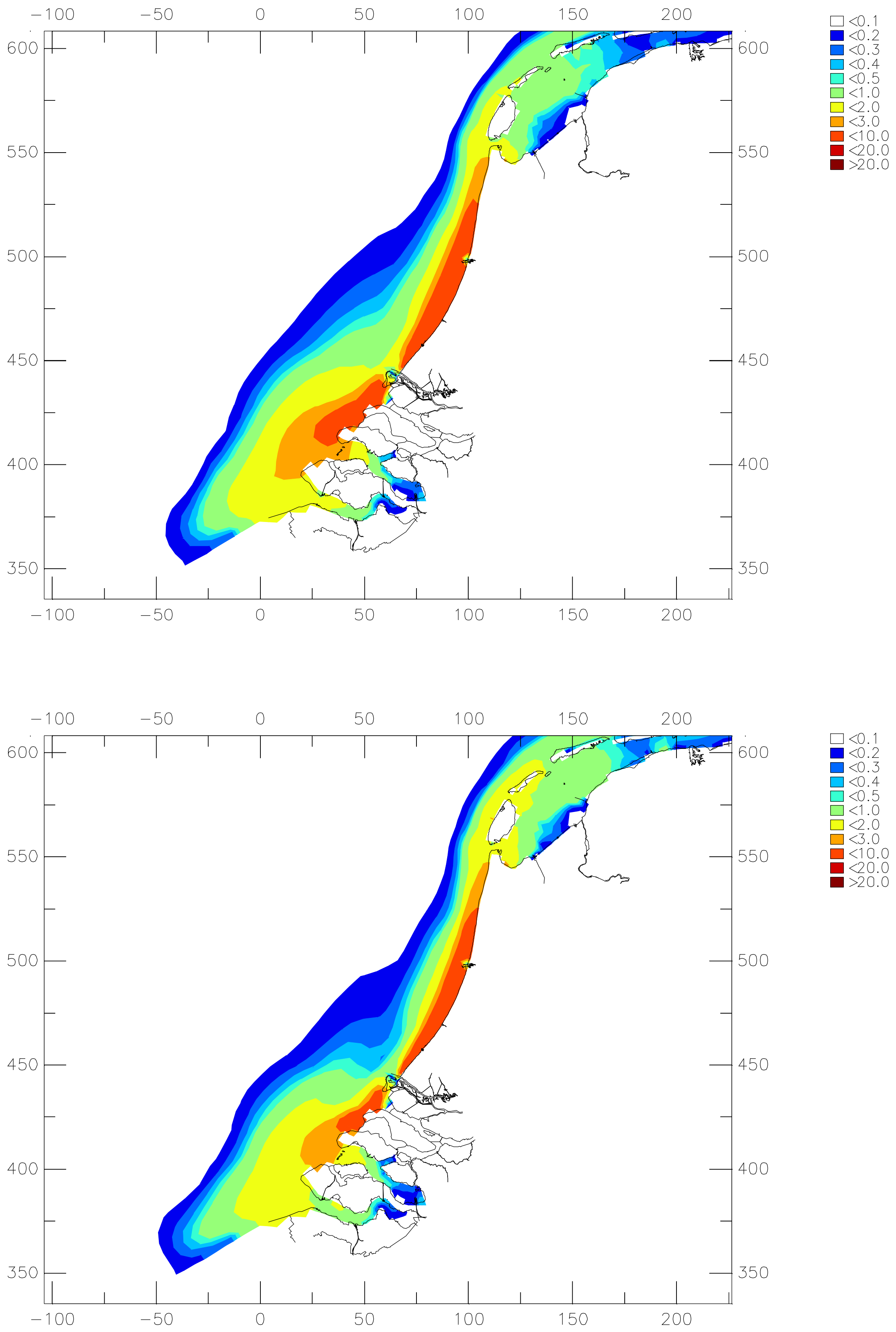
Fig. A2



Scenario s1a: year-average concentration (mg/l)
Upper panel: 2012
Lower panel: 2013

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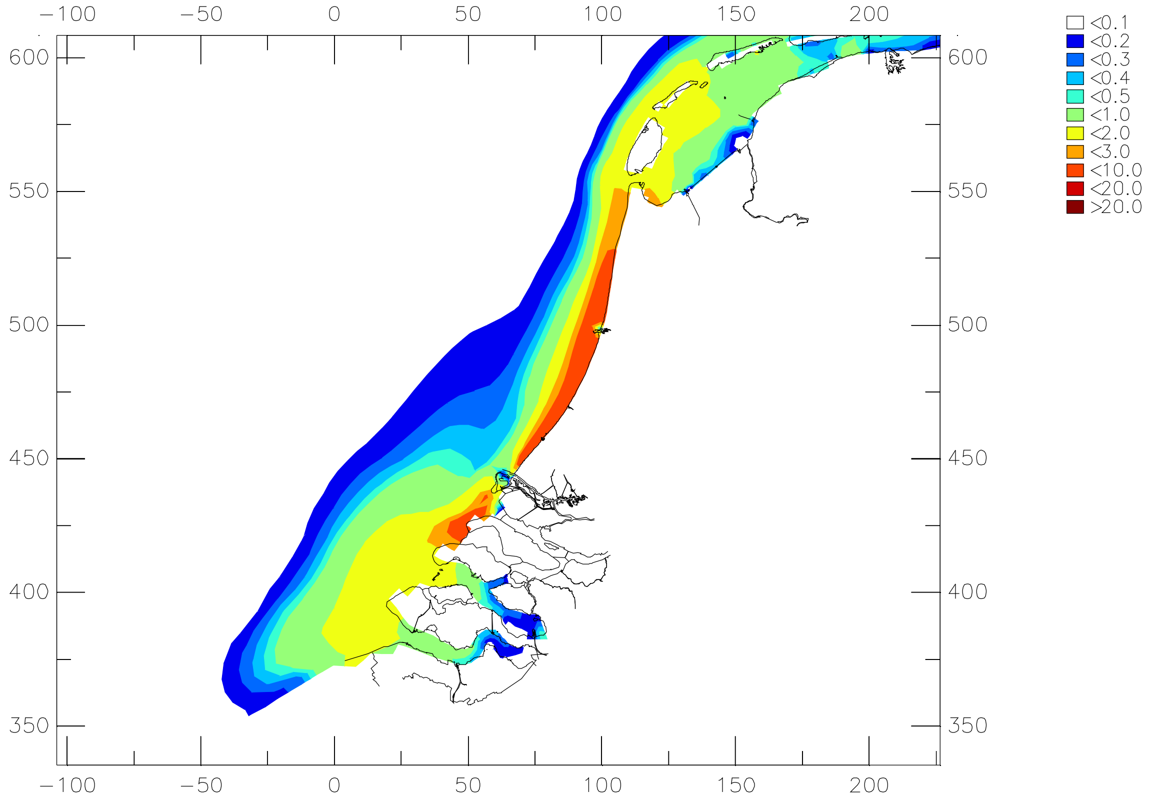
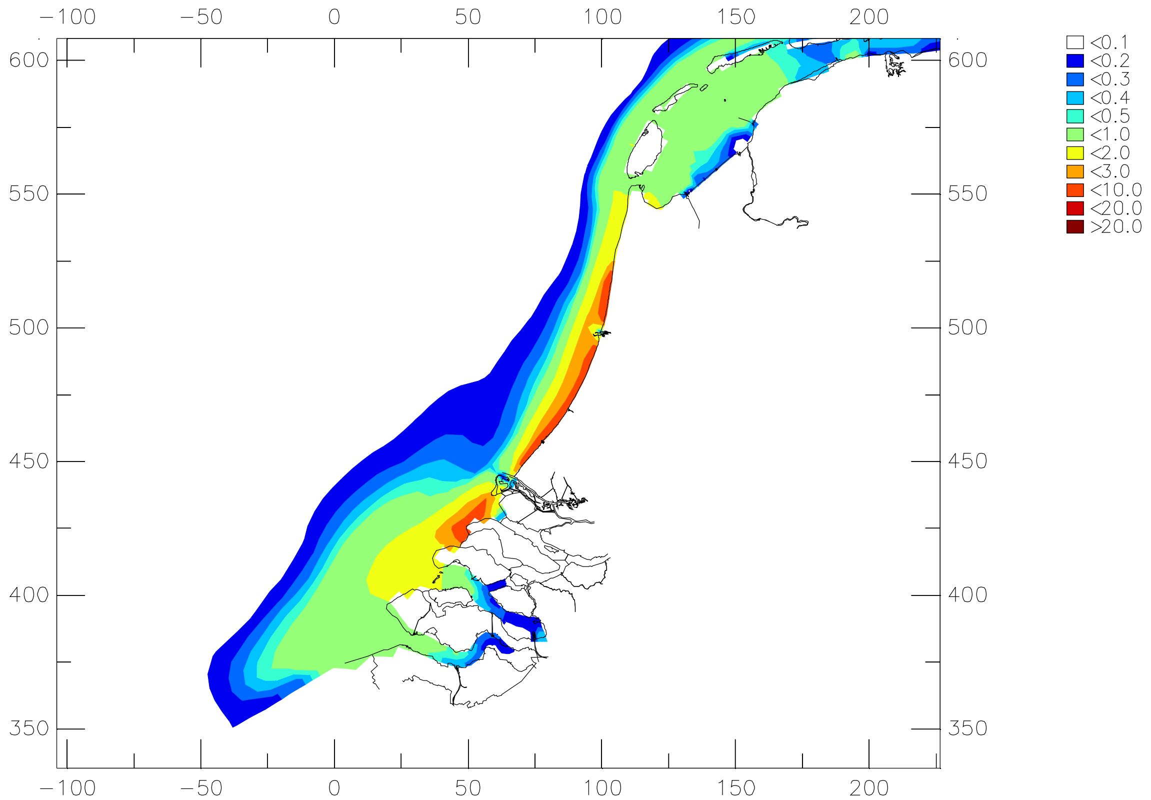
Fig. A3





Scenario s1a: year-average concentration (mg/l)
Upper panel: 2014
Lower panel: 2015

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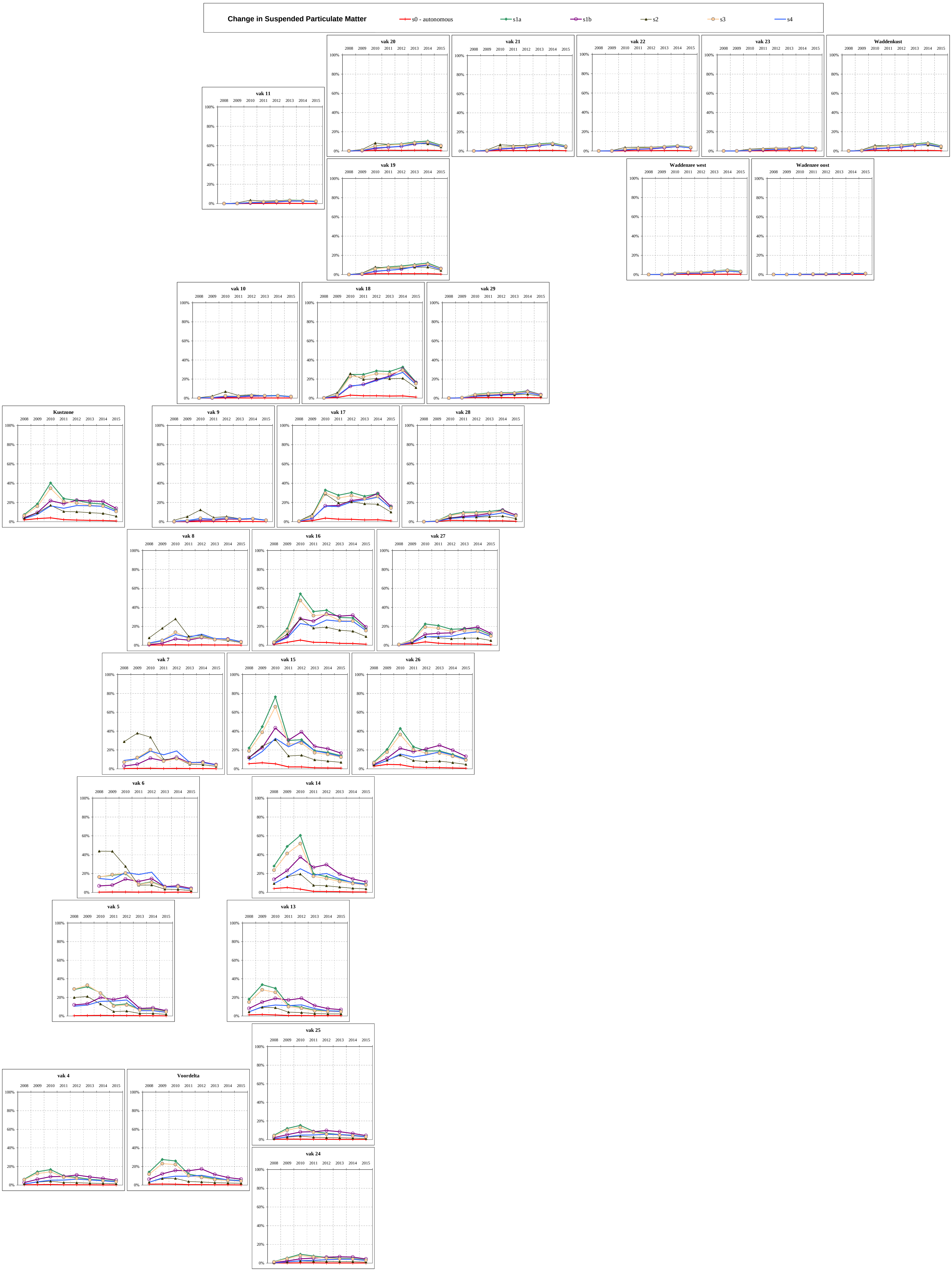
Fig. A4

B Time series of zone and annual averaged SPM, Chlorophyll and primary production.

N.B. Only scenarios s0, s1a, s1b, s2, s3 and s4 are shown as an example. Figures for all other scenarios can be found on the accompanying CD-rom.

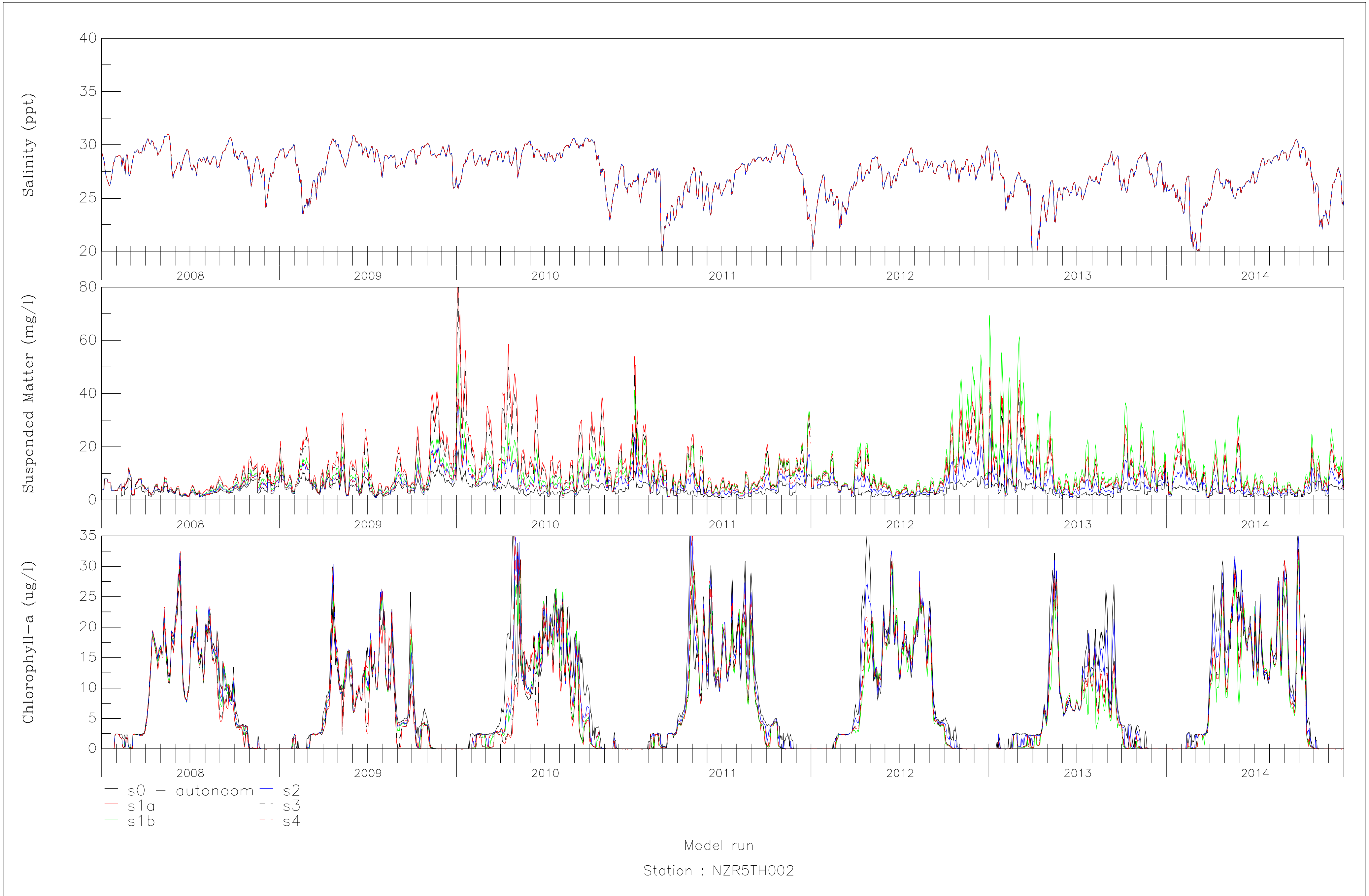

Change in Suspended Particulate Matter
s0 - autonomous
s1a
s1b
s2
s3
s4
vak 20
vak 21
vak 22
vak 23
Waddenkust
vak 11
vak 19
Waddenzee west
Wadenzee oost
vak 10
vak 18
vak 29
Kustzone
vak 9
vak 17
vak 28
vak 8
vak 16
vak 27
vak 7
vak 15
vak 26
vak 6
vak 14
vak 5
vak 13
vak 25
vak 4
Voordelta
vak 24
2008
2009
2010
2011
2012
2013
2014
2015
0%
20%
40%
60%
80%
100%


Change in Primary Production
s0 - autonomous
s1a
s1b
s2
s3
s4
vak 20
vak 21
vak 22
vak 23
Waddenkust
vak 11
vak 19
Waddenzee west
Wadenzee oost
vak 10
vak 18
vak 29
Kustzone
vak 9
vak 17
vak 28
vak 8
vak 16
vak 27
vak 7
vak 15
vak 26
vak 6
vak 14
vak 5
vak 13
vak 25
vak 4
Voordelta
vak 24
2008
2009
2010
2011
2012
2013
2014
2015
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%

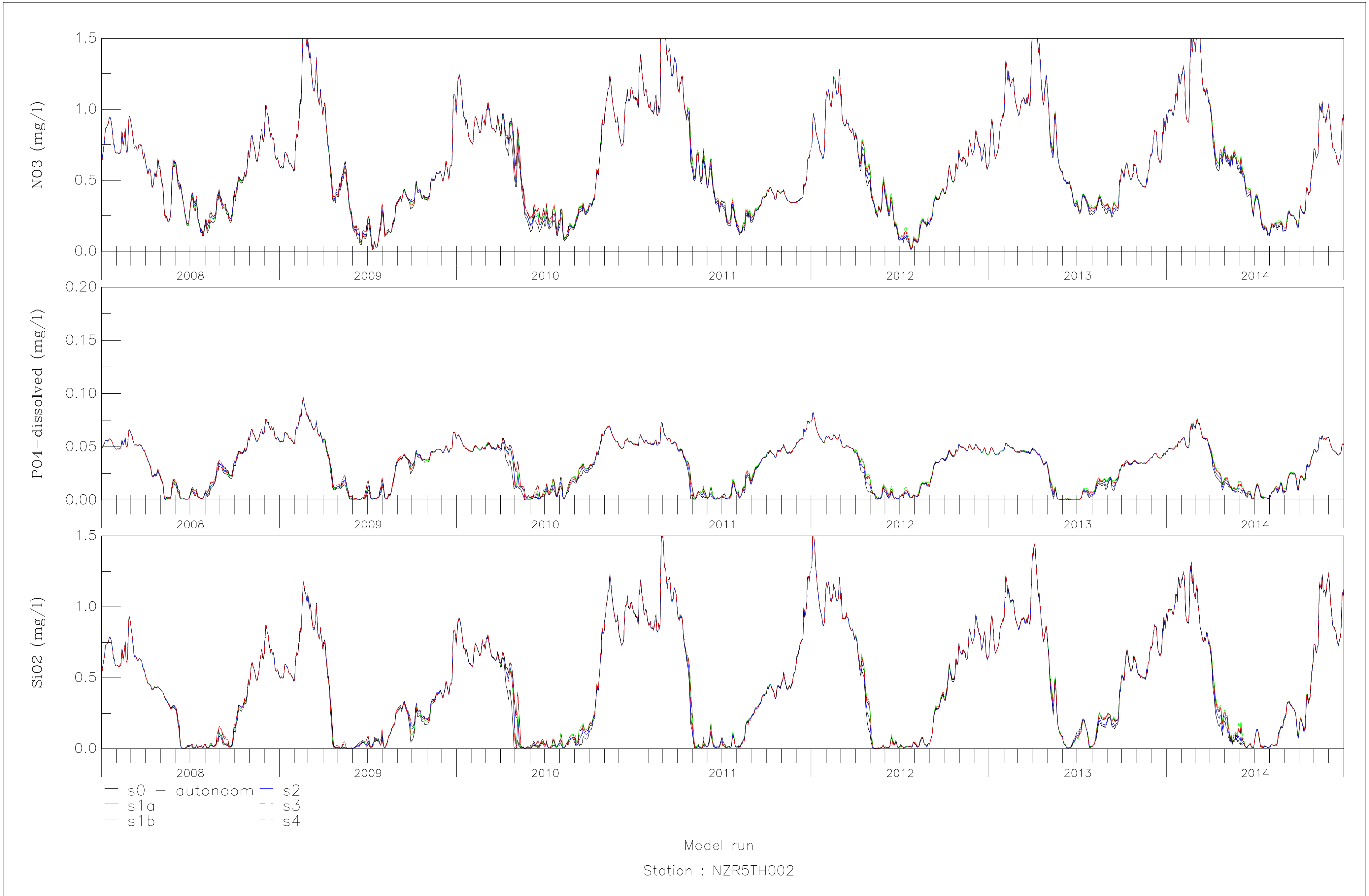

Change in Chlorophyll a Concentration
s0 - autonomous
s1a
s1b
s2
s3
s4
vak 20
vak 21
vak 22
vak 23
Waddenkust
vak 11
vak 19
Waddenzee west
Wadenzee oost
vak 10
vak 18
vak 29
Kustzone
vak 9
vak 17
vak 28
vak 8
vak 16
vak 27
vak 7
vak 15
vak 26
vak 6
vak 14
vak 5
vak 13
vak 25
vak 4
Voordelta
vak 24
2008
2009
2010
2011
2012
2013
2014
2015
10%
0%
-10%
-20%
-30%
-40%
-50%

C Time series of salinity, SPM, Chlorophyll, NO_3, PO_4 and SiO_2 at various monitoring stations.

N.B. Only scenarios s0, s1a, s1b, s2, s3 and s4 at location Terheiden 2 km (TH002) are shown as an example. Figures for all other scenarios and locations can be found on the accompanying CD-rom.



Salinity (ppt)
Suspended Matter (mg/l)
Chlorophyll-a (ug/l)
2008
2009
2010
2011
2012
2013
2014
s0 – autonoom
s1a
s1b
s2
s3
s4
Model run
Station : NZR5TH002


NO3 (mg/l)
1.5
1.0
0.5
0.0
PO4-dissolved (mg/l)
0.20
0.15
0.10
0.05
0.00
SiO2 (mg/l)
2008
2009
2010
2011
2012
2013
2014
s0 – autonoom
s1a
s1b
s2
s3
s4
Model run
Station : NZR5TH002