Validation of the mud buffer model for mud transport in the North Sea coastal zone

on the basis of long-term measurements of Cd

Deltares

Validation of the mud buffer model for mud transport in the North Sea coastal zone

on the basis of long-term measurements of Cd concentrations

Ir. Claire van Oeveren-Theeuwes

1203191-000

Deltares

Title
Validation of the mud buffer model for mud transport in the North Sea coastal zone

Client	Project	Reference	Pages
Rijkswaterstaat Waterdienst	1203191-000	1203191-000-ZKS-0017	35

Keywords
Mud / silt transport, water-bed exchange, buffer model, buffer capacity, residence time, cadmium.

Summary
For large sand extractions in the North Sea, it is still uncertain how large the long-term effect on turbidity is, in comparison with the short term effect caused by the instantaneous dredging plumes. Large uncertainties exist in the time-scale at which the bottom-water exchange of mud takes place. As a result, large safety margins have to be applied, which could lead to unnecessary and costly execution regulations and impediments.

The mud transport model has a water-bed exchange module (the 'buffer module') which could provide insight into the timescales of this exchange. However, this module still needs further validation on the exchange rates between bed and water.

A more reliable estimate on the magnitude of this exchange can be obtained using long-term measurements of (traceable) mud in the bed. Cadmium was regarded as a suitable tracer for this purpose: long-term measurements of the cadmium concentration in the North Sea bed are available and the marked decrease in river load over the 1980's can provide information on the residence time of mud in the system. The overall objective of this project is therefore to further calibrate and validate the water-bed exchange module of the mud transport model, by using cadmium as a proxy for mud.

The objective has been divided over two phases; this document is the final report for the first phase, in which the current best known parameter settings for the buffer module are validated. The study showed that the modelled half-life period for mud in the bottom of the Dutch North Sea coast was in the order of 1.2 years. When compared with measured cadmium concentrations, the model was able to give a relatively good reproduction of the decreasing trend of the cadmium concentration in the bed.

In the proposed additional work (the second phase), two additional sensitivity studies will be executed and the model parameters will be further calibrated on the residence times for mud and the buffer capacity of the bed.

References
RSW/WD-2011/1283, zaaknummer 31040969.0001/Hofman

Version	Date	Author	Initials	Review	Initials	Approval	Initials
1	July 2011	ir. C. van Oeveren	[signature]	dr. ir. T. van Kessel	TvK	ir. T. Schilperoort	i.a. A Nolte

State
final

Contents

1 Introduction

1.1 Background

A momentary but large sand extraction at the North Sea can have long term effects, as a large quantity of silt will be deposited in the sea bottom, which may gradually resuspend for several years. When this silt is released back into the system, the turbidity will increase. Due to its limited grain size, silt has a relatively long residence time in the water column. The increase in turbidity hampers the penetration of sunlight, which can negatively influence the effect chain from algae-growth, fish larvae, shellfish up to birds and large fish.

At this moment, it is still uncertain how large this long-term effect is in comparison with the short term effect caused by the instantaneous turbidity just after the sand extraction. A reliable model with a validated water-bed exchange module can provide an insight into this. The uncertainties in the time-scale at which the bottom-water exchange of silt takes place lead to large uncertainties in the predictions of travel speed and dissipation of a sediment pulse (for instance originating from sand mining activities).

In previous modelling studies on suspended sediments in the southern North Sea (the so-called *VOP-Slib*[1]-projects), the "buffer model" was developed, calibrated and validated for the Dutch coastal zone (Van Kessel et al. 2007, Van Kessel and Brière, 2006, Bruens et al., 2007, Van Maren et al., 2008; Van Kessel et al., 2010). This buffer model simulates the seasonal effects in the mud-exchange between the water and the bed, by means of temporary storage of mud in the sandy North Sea bed. The calibration of this model was mostly based on measurements of the suspended sediment concentrations (CEFAS, DONAR) and on estimates of the residence times. In order to gain more confidence in the long-term model predictions, calibration on the basis of measured silt content in the bed is also needed.

As long as the existing model has not been sufficiently validated on the exchange between the bed and the water, large safety margins are used in the model predictions in the framework of effect studies, like 'MER Zeezandwinning'. This means that the effects are likely overestimated, which could result in unnecessary and costly execution regulations and impediments for large sand extractions, nourishments or maintenance dredging operations. It is expected that the model will also be employed in model studies for the Water and Marine Framework Directives (Kaderrichtlijnen Water en Marien).

A more reliable estimate on the magnitude of the bottom-water exchange could be obtained using long-term measurements of (traceable) mud in the bed. Calibration and validation of the bottom-module for the long term has not been done before. This would therefore be a valuable contribution to the validation of the mud model. Cadmium could be a suitable tracer for this purpose: long-term measurements of the cadmium concentration in the North Sea bed are available and the marked decrease in river load over the 1980's can provide information on the residence time of mud in the system.

1.2 Objective

The overall objective of this project is to further calibrate and validate the water-bed exchange module of the mud transport model, by using measurements of the cadmium concentration in the bed as a proxy for mud.

1. *VOP Slib: Voortschrijdend Onderzoeksprogramma Slib*

The objective has been divided over two phases; in the first phase, presented in this report, the current best known parameter settings for the buffer module are validated, using measurements of cadmium concentrations as a proxy for mud.

The second objective – further calibration of the model parameters – will be performed under the proposed additional work for this project. This phase is expected to start shortly after the finalization of this study.

1.3 Study approach and contents of the report

The study approach for this phase of the study is, straightforward:

- Data analysis, in chapter 2, which focuses on the trends in the cadmium concentrations, the uncertainties in the loads and the half-life of the cadmium in the bed. (In the additional work for this project, the analysis will go into more detail on the physical properties of cadmium as a tracer)
- Model setup, described in chapter 3, which is based on existing hydrodynamic computations and the current best known settings for the mud model.
- Interpretation of the results, chapter 4, which compares temporal trends and estimated half-life periods from literature with the model results.
- Conclusions and recommendations, in chapter 5. The recommendations also directly apply to the additional work for this project.

2 Data analysis

The data analysis presented here focuses on the observed trends and the uncertainties in the data. A more extensive analysis on the behaviour of cadmium and the use of cadmium as a proxy for mud in the Dutch North Sea coast, will be presented in the proposed additional work for this project. This will also include a qualitative comparison of cadmium with other possible tracers.

Data analysis on metals, like cadmium, have been described in detail in Sonneveldt and Laane (2000) and Laane *et al.* (1999). The information in the following paragraphs is cited from these two papers.

2.1 Sources of cadmium for the Dutch coastal zone

Cadmium in the Dutch coastal zone originates from 4 main sources: southern input (via the Channel), rivers, dumping of dredged materials from harbours and atmospheric deposition.

During the 1980's, the annual average particulate load of Cadmium has decreased in the order of 70%. This large reduction is mainly attributed to a decrease in river loads and in the dumping of dredged material. From the 90's and onward, the loads have stabilized.

In the early 1980's, the relative distribution of the various sources of particulate cadmium to the Dutch coastal zone were: 80 – 85% for dredging, 5 – 10% rivers, 5-8% Atlantic Ocean (through The Channel) and 1 – 2% atmospheric deposition.

Because of the decrease in the fluvial and dredged loads, the relative distribution also changed and the southern input from the Atlantic Ocean became relatively more important (30 – 40%). The relative contribution of dredging became 45 – 50%, rivers 5 – 10% and atmospheric deposition 5 – 7%.

2.2 Uncertainties in the load data

As the discharges and contaminant concentrations of the main river outflows are monitored intensely, relatively much data is available for the river and the dumping of dredged material, compared to the southern input and the atmospheric deposition.

Still, the calculated loads from the rivers contain a considerable amount of uncertainty, in the order of at least 30% at the Dutch-German border. More uncertainties are added in the estuaries (e.g. in the filtering capacity of the estuary and in the quantification of loads through sluice systems.

The uncertainties in the atmospheric deposition and the southern input through the channel is considerably larger, and are both estimated at a factor 1.5 – 2.5 for metals.

Finally, the relative error in the total load of compounds through dumping of dredged materials (due to random errors and variability in the measured concentrations) is estimated at about 40%.

All these uncertainties add up, resulting in an estimated range within which the actual annual load can vary, see Fig. 2.1 for the range in the Dutch coastal zone.

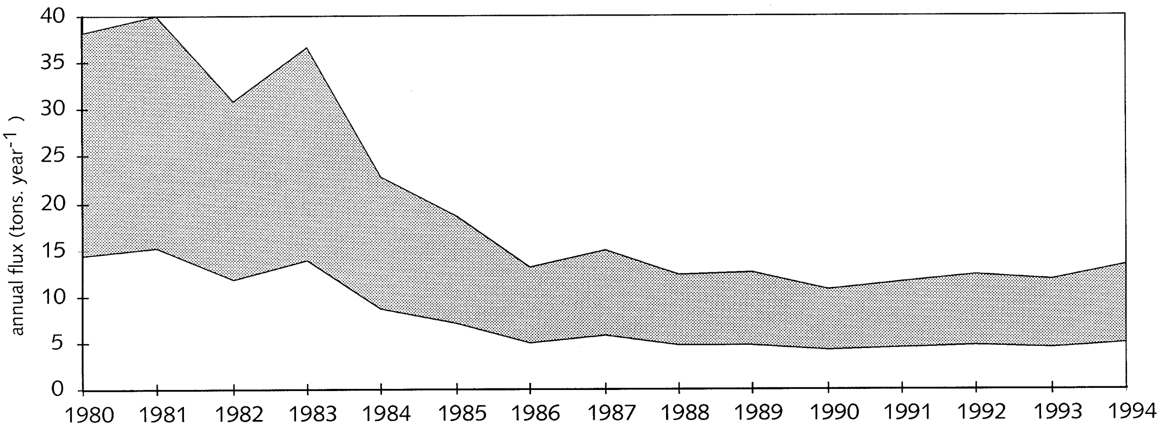


Fig. 2.1. Range in the total mean annual flux of particulate cadmium to the Dutch coastal zone. (from: Laane et al., 1999)

2.3 Observed trends in the cadmium concentration within the mud fraction in the bed

Median cadmium concentrations within the mud fraction (<63 μm) in the bed were derived for 3 zones, see Fig. 2.2. The results for each zone are presented in Fig. 2.3.

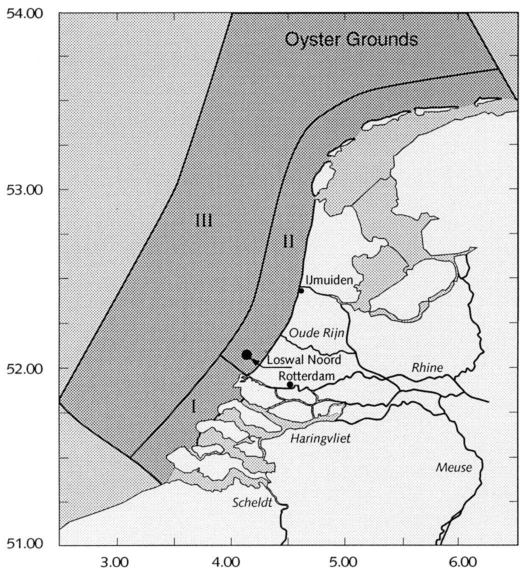


Fig. 2.2: Map of the Dutch coastal zone, showing the subdivision into three areas (I, II, III) and the main freshwater sources. (from: Laane et al., 1999)

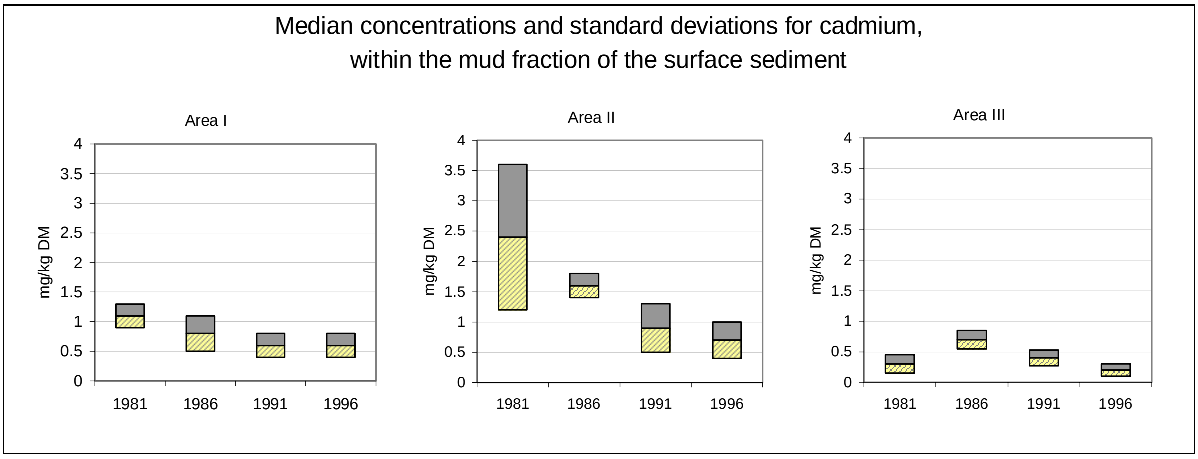


Fig. 2.3: Median concentration of cadmium and standard deviations (half of the difference between the 25 and 75 percentiles) in the fractions of <63 µm in surface sediment for three areas in the Dutch coastal zone (based on data from Laane et al., 1999).

The total reduction of the cadmium concentration in the surface sediments, in the period 1981 – 1996, is about 45% for Area I and 71% for Area II. The reduction for Area III was marked as insignificant.

2.4 Estimates of the half-life for the cadmium concentration in the bed

In Laane *et al.* (1999), rough estimates are made for the half-life period for cadmium in the surface sediment for Area II. They assumed:

- initially, the influence of (bio)chemical reactions can be neglected
- no net sedimentation in the area, $F_{silt,\ in} = F_{silt,\ out}$. The fluxes are approximated to be in the order of 10 Mton/yr.
- initial mass of (active) mud in the area is 28 Mton.

From $t_{½} = \dfrac{\ln 2}{k}$ and $k = \dfrac{F_{silt,out}}{M_{silt}}$, a half-life follows in the order of 1.9 years for the previously deposited cadmium-mud in the active bed layer. This half-life period indicates the residence time for mud in the entire coastal zone (Area II), and thus also includes the time spent in the water phase.

3 Model setup

The transport of mud in the southern part of the North Sea is modelled by combining a series of numerical models: the hydrodynamic model based on the Delft3D-FLOW software, the surface wave model SWAN, and the mud transport model based on Delft3D-WAQ software. The mud transport model relies on information on the water motion and waves from the other two models.

3.1 Hydrodynamic model

The used model is a version of the ZUNO-DD model as used in the VOP-Slib project in 2010. This model makes use of domain decomposition (DD) with 3 computational domains: course, intermediate and fine, (see Figure 3.1). All grids are curvilinear. The refinement between the coarse (blue) and the intermediate (green) grid is by a factor 3, between the intermediate and the fine (red) grid by a factor 2. The finest grid was needed to correctly model the Rhine discharge plume.

This version of the ZUNO-DD model differs slightly from the version that was used in VOP-Slib 2009 and MOS^2 (Deltares, 2010). The intermediate (green) domain has been extended seaward and the finest domain (red) has been extended northward, in order to meet the requirements of other projects in which this model has been used. Furthermore, the mud computations use a non-aggregated grid.

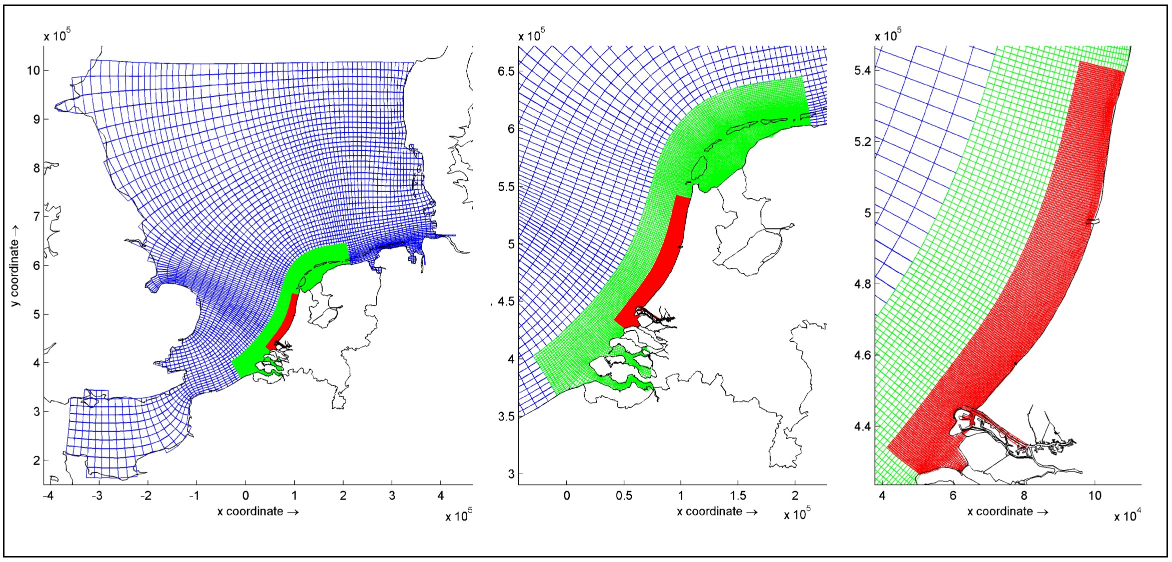


Figure 3.1 Hydrodynamic grids: coarse domain (blue), intermediate domain (green) and fine domain (red).

Corresponding with the previous VOP-Slib project in 2009 and 2008, all three domains consist of 12 vertical σ-layers, with a distribution as indicated in the table below:

layer	(surface) 1	2	3	4	5	6	7	8	9	10	11	(bottom) 12
relative thickness (%)	4.0	5.6	7.8	10.8	10.9	10.9	10.9	10.9	10.8	7.8	5.6	4.0

Table 3.1 Relative distribution of vertical σ–layers, in both the hydrodynamic and the sediment transport model

See Figure 3.2; the bathymetry of the fine grid is based on the most recent version of the Kustrook Fijn model (2009), which consists of a compilation of surveys, the most recent of which was carried out in 2005 (version 6.3). The bathymetry of the intermediate and coarse grid originates from a compilation by the Northwest European Shelf Operational Oceanographic System (NOOS).

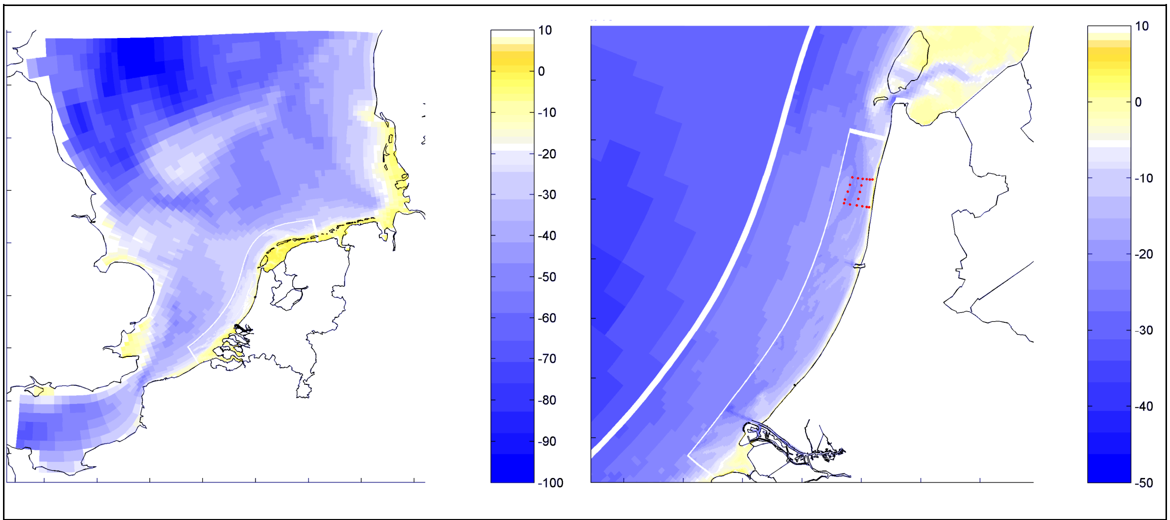


Figure 3.2 Model bathymetry: coarse, intermediate and fine domain. The white lines represent the boundaries of the domains. As a domain-decomposition requirement, the depth is held constant between both sides of the boundaries. The red dots in the right-hand plot represent the measurement locations.

The model has an open boundary in the Channel and an open boundary with the Atlantic Ocean in the north. The hydrodynamic simulations include a tide based on astronomic components, and the actual forcing of rivers discharges, wind and atmospheric pressure. Space varying wind velocities and atmospheric pressure are obtained from the KMNI HIRLAM model (http://hirlam.org, www.knmi.nl/ 22 km grid resolution version). The phase and amplitude of the main tidal constituents have been obtained from the Dutch DCSM-v5 (K.B. Robaczewska *et al*, 1997; *in C. Cronin et al, 2009*). More information on the general setup, calibration and validation of the used hydrodynamic model can be found in the report for the MoS^2 project (Deltares, 2010).

3.1.1 Hydrodynamic simulation period

Due to the relatively high accuracy of this model (compared to ZUNO-Coarse), computing one hydrodynamic year will already require a relatively long computation time (in the order of one week) and will produce large files for the coupling with the mud transport model. For practical reasons, it is therefore not feasible to model the full hydrodynamic period of 20 years with this model. Additionally, in order to provide an improved set of parameters before the start of the new MER, a relatively short time span was desired for the project. For this reason, the results of an existing hydrodynamic computation of the year 2007 were used, which had also been used in the VOP-Slib project of 2010 (Deltares, 2010). The hydrodynamic data set of 2007 can be repeated multiple times to arrive at the desired simulation period for mud transport.

In the proposed additional work for this project, we will perform a further sensitivity analysis for this approach. In this analysis, two simulations will be done with the ZUNO-Coarse model (both comprising a hydrodynamic and a mud computation). For one simulation the entire period of 20 hydrodynamic years will be computed; the other simulation will use the same approach as done for the present computations (but then using the coarse model). The analysis will give a more detailed comparison of the meteorological conditions (wind, waves, river discharge) of 2007 versus the conditions in the simulation period (1981- 2000).

3.2 Wave modelling

The influence of waves is an important mechanism for the resuspension of silt. To account for the temporal dynamics of the waves, we made use of a data-model integration technique. This method has also been applied successfully in previous studies (M. Blaas *et al*, 2008; C. Cronin *et al*, 2009). The method uses an annual mean spatial pattern of the significant wave height H_s and the mean period T_{m02}, which were generated by a SWAN model run on a coarse grid (ZUNO-Coarse). This spatial pattern is then integrated with time series of wave buoy data (for 2007), to obtain time series of H_s and T_{m02} at each cell of the grid. Subsequently, these parameters are interpolated onto the finer grids.

3.3 Mud transport model

The output of the hydrodynamic computation will be coupled to the mud transport model (Delft3D-WAQ), which is based on the same three grids.

The mud model includes a three-fraction description of sediment characteristics, with three spatial- and temporal-constant settling velocities, of $1.25\ 10^{-4}$ m/s (10.8 m/d), 10^{-3} m/s (86.4 m/d), $1.16\ 10^{-6}$ m/s (0.1 m/d), respectively for each fraction. A concentration for each of the three sediment fractions was prescribed at the channel and northern boundaries. Concentrations for the three fractions were also included in the river discharges, as well as specific point- or line sources representing erosion of cliffs (e.g. off East Anglia) and the Flemish Banks. These values were derived from estimates of SPM transport in literature, see Van Kessel and Brière, 2006.

3.3.1 The buffer model

Part of the fine sediment particles that settle onto the bed will be entrained within the pores of the sand grains. The remainder will form a thin mud layer on top of the bed. Processes like consolidation, bioturbation and migration of bed forms will also cause mixing of mud particles into the sand. (van Kessel *et al.*, 2010)

In the buffer model, this is schematized by two bed layers, a sand and a mud (fluff) layer, and overlying water layer with prescribed interactions between these layers. The top layer in the bed solely consists of mud, while the sandy ‘buffer’ layer underneath represents the entrainment of mud particles in the sand skeleton. Because the muddy top layer can occur in patches, also direct exchange between the buffer layer and the water column can take place.

The mud in the top layer is highly erodible and the exchange between this layer and the water column will take place on short timescales. The exchange between the buffer layer and the water column is assumed to be much slower. Therefore, in the framework of investigating long-term effects, the amount of buffering in the second layer becomes of main interest.

The buffer model is schematized as follows: if the mass of mud per unit area in the top layer is below some critical value, the erosion rate in the top layer (E_1) is assumed proportional to the sediment mass per m^2. This behaviour is addressed as first-order resuspension. If the patches grow in size, the erosion rate will increase proportionally until the critical mass is attained. From that moment, the erosion rate is zero-order, which implies that it is independent of the sediment mass in the top layer.

In the second layer, the erosion of the sand, as given by a pick-up function for sand only, governs the erosion flux of mud from this layer (E2). The erosion flux is computed in proportion to the mud content (per m^2) in the layer.

Settling of mud takes place in the water column. A fraction α of the settling flux contributes to the mud mass in the second layer, while the remaining portion (1- α) contributes to the top layer. Usually, α is much smaller than 1. Storage (buffering) of mud in the sand layer stops if the mud fraction in the layer exceeds a threshold. A settling flux towards the second layer may also occur if the layer is completely covered by the top layer. The physical processes behind this are consolidation, bioturbation and reworking of the bed due to the propagation of bed forms.

Figure 3.3 below gives a schematic representation of the buffer model and the main processes for the bottom-water exchange. Fluxes D1 and D2 represent the settling fluxes towards layers S1 and S2, respectively. Fluxes E1 and E2 are the erosion fluxes from both layers.

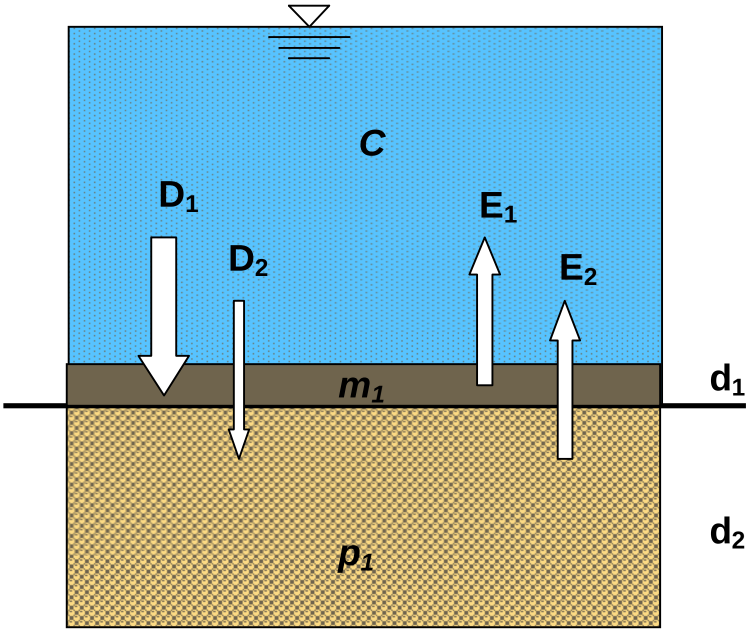


Figure 3.3 Schematic representation of the buffer model and the exchange of mud between bottom and water.

The most relevant parameter settings for the mud model are summarized in the table below. These settings are noted as the best known settings of this moment and were optimized for the reproduction of observed suspended sediment concentrations.

parameter	value	units	description
ρ_{solids}	2600	kg DM/m^3	particle density of solids
d_2	0.1	m	thickness of buffer layer (layer S2)
$Fr_{TIM, S2, max}$	1	[-]	maximum fraction of total inorganic matter in layer S2
$v_{sed, iM1}$	10.8	m/d	sedimentation velocity of fraction IM1
$v_{sed,iM2}$	86.4	m/d	sedimentation velocity of fraction IM2
$v_{sed,iM3}$	0.1	m/d	sedimentation velocity of fraction IM3
$\tau_{crit, Sed, S1}$	1000	N/m^2	critical shear stress for sedimentation (same for IM1, IM2 and IM3)
$Fr_{IM1, Sed, S2}$	0.05	[-]	fraction of sedimentation towards S2, for IM1
$Fr_{IM2, Sed, S2}$	0.0125	[-]	fraction of sedimentation towards S2, for IM2
$Fr_{IM3, Sed, S2}$	0.005	[-]	fraction of sedimentation towards S2, for IM3
$\tau_{shields}$	1.5	N/m^2	Shields shear stress for resuspension
$\tau_{crit, Res, S1, IM1}$	0.2	N/m^2	critical shear stress for resuspension from top layer, IM1 (same for IM2)
$\tau_{crit, Res, S1, IM3}$	0.1	N/m^2	critical shear stress for resuspension from top layer, IM3
$\tau_{crit, Res, S2, IM1}$	1000	N/m^2	critical shear stress for resuspension from buffer layer, IM1 (same for IM2 and IM3)
Z_{res}	8640	gDM/m^2/d	first-order resuspension flux (same for IM1, IM2 and IM3)

All other parameter settings are the same as used for the VOP-Slib project in 2010. For detailed information, reference is made to the report (Deltares, 2010).

The version of the delwaq executable that was used for the simulations is version 4.5208, which is a specialized version, dated from 16-08-2010.

3.3.2 Modelling cadmium as a tracer for mud

To model cadmium as a mud fraction, some assumptions and schematizations were made:

- The cadmium in the North Sea behaves conservatively: decay by (bio-)chemical processes are not taken into account.
- The cadmium in the North Sea forms a stable binding with the mud particles, desorption of the cadmium is not taken into account.
- The discharge of cadmium in the model is schematized and only takes place via the river loads. A 'bulk' correction factor is applied to the load, so that the total flux of cadmium from the rivers into the model is representative for the combined flux of all processes. Since the estimates from literature indicate a wide range of uncertainties for this flux (see chapter 2), two different correction factors have been determined, to match the upper and the lower limit of the range of uncertainties.
- The cadmium in the model is distributed over the 2 main fractions, IM1 and IM2. (The third 'background' fraction IM3 is ignored, since this fraction is not a major contributor to

the buffering of the second bottom layer.) The mass can be obtained by multiplying the measured concentration with the initial mass of IM1 and IM2. This is done by interpolating the measured concentrations onto the model grid and multiplying the result with the initial masses of IM1 and IM2 (separately). This gives the initial masses for IM4 and IM5, the two cadmium fractions. IM4 and IM5 have the same sediment characteristics as IM1 and IM2 respectively.

4 Results

4.1 Introduction

As explained in chapter 2, large uncertainties in the estimated cadmium loads still exist. This means that there are two types of uncertainties for Cadmium dispersion:

1 How large is the Cadmium load to the coastal zone (source strength, e.g. fluvial load, load from the south, atmospheric deposition)?

2 How fast does Cadmium spread in the coastal zone (depends on residence time and buffer capacity, amongst others)

As the residence time is larger, more Cadmium accumulates in the coastal zone and, as a result, the actual influence of the fluvial load becomes less. For example, a Cadmium load of 10 t/year from the Rhine has a much larger impact if only 50 t Cadmium resides in the coastal zone than if 500 t resides herein.

Both uncertainties can still be evaluated independently, because the effect of source strength in the model is linearly scalable and the effect of buffer capacity is not. In other words, for a specific buffer capacity, the effect of the source strength can be scaled in the postprocessing of the computation. A larger load will influence the absolute values of the cadmium concentrations, but will not lead to a different distribution or residence times.

A different buffer capacity, on the other hand, leads to a different distribution of the cadmium and can therefore not be scaled. The "best match" for the buffer capacity can thus only be investigated by calibration of the parameters.

In the study, the contribution of the cadmium loads from the rivers were scaled to match the upper and lower estimate of the actual load. To match the total cadmium flux in the coastal zone over the period 1981 – 1994, the modelled load had to be corrected by a factor 0.9 for the upper limit or a factor 0.35 for the lower limit. In order to evaluate the model performance within the range of the uncertainties in the actual load, this chapter discusses the results for both ends of the range. (In the proposed additional work, the effect of differences in the buffer capacity is further investigated.)

4.2 Time series of the cadmium concentration in the bed

Not all monitoring stations had measurements that covered the entire period. The results are presented for the near-shore stations "Ter Heijde 1", "Ter Heijde 10", "Noordwijk 2", "Egmond aan Zee 1", "Callantsoog 1" and "Callantsoog 10"; and for the off-shore stations "Rottumerplaat 70" and "Callantsoog 70".

Only those measurement stations were considered, that had 3 or more measurements within the considered period. Additionally, stations that were directly in front of a river mouth, like Appelzak and Goeree, were not considered representative, because of the large sensitivity to the application of the load in the model. (In the model, all import of cadmium is attributed to the river discharge, while in reality, part of this annual load comes from other sources, viz. dredging and dumping, southern import and atmospheric deposition. This leads to a different spatial distribution of cadmium, spreading it out over a wider area.)

Figure 4.1 shows the locations of the considered output stations. The time series graphs can be found in Appendix A.

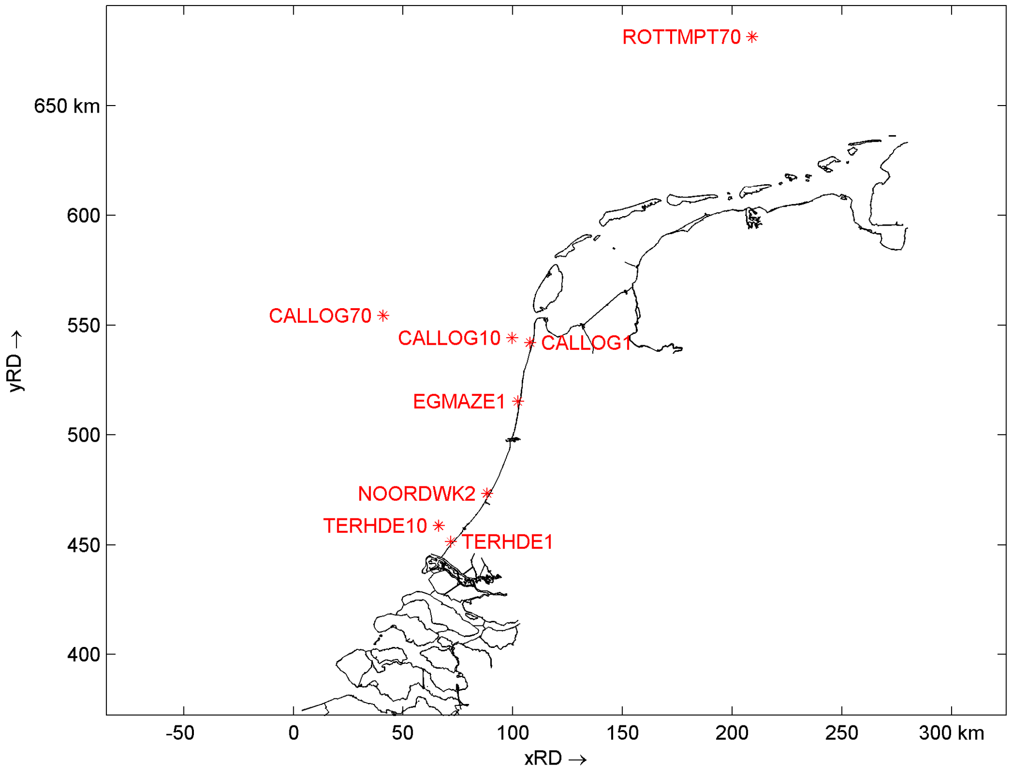


Figure 4.1 Measurement and output stations for the model. Only those measurement stations were selected, that had 3 or more measurements within the considered period.

The cadmium concentration is shown for the entire active layer of the bed (top layer and buffer layer). The results show that:

a) The measured trends are reproduced fairly well by the model, as most measurements fall within the range of the uncertainties in the load. This confirms that the magnitude of the load can be expected to lie inside this range.

b) In general, the decreasing trend between 1981 and 1991 of the model is slightly steeper than the decreasing trend in the measurements. This could indicate that the residence time is still slightly underestimated in the model.

c) When looking at the result for the computation without loads, the concentration typically drops below 50% of the initial load after 1 year.

d) At some stations, an increase of the cadmium concentration can be seen in the first year. This effect is mainly visible for the upper estimate of the load and is a spinup effect of the bottom to the river load. For the determination of the residence time, the first year is therefore ignored. (In future computations, this could be solved by allowing the simulation to spinup for an extra 2-3 years.)

e) The concentration in the stations further offshore (Callantsoog-70 and Rottumerplaat-70), is underestimated by the model. This can be caused by the fact that loads only enter the model through the rivers, leading to a more concentrated transport of mud along the coast. However, it can also be the result of a too small buffer capacity (leading to underestimation of the initial sediment mass). The results clearly show that the cadmium concentration in the offshore stations is hardly influenced by the river discharge (green line is almost on top of blue lines), as expected.

4.3 Spatial patterns

Appendix B shows the map output for the cadmium concentrations in the active surface layer of the bed (top layer and buffer layer combined). Again, both the lower and the upper estimate for the load is shown. Measurement data were mostly available for 1981, 1986, 1991, 1996 and 2000. Measurements were also available for some intermediate years, but on very few locations, which made the spatial interpolation less reliable.

In compliance to the abovementioned observations in the time series, the map-results confirm that:

f) The lower limit for the cadmium load gives a slight underestimation and the upper limit leads to a general overestimation of the measured cadmium concentration in the bed. The actual load can be expected to lie somewhere in between.

g) The modelled Cadmium is transported in a narrower plume along the coast than what is suggested by the data. This was already (partially) explained by the fact that in the model, cadmium only enters the model as a river load. The locations of the dump sites have not been taken into account, nor the southern input, which is expected to play a larger role further offshore. Another explanation could be an underestimation of the buffer capacity, leading to an underestimation of the initial mass in the bed.

4.4 Residence times

As mentioned in chapter 2, in literature (Laane et al., 1999), a rough estimate was given for the half-life period of previously deposited mud in the Dutch coastal zone of 1.9 years. This half-life period indicates the residence time of mud in the entire coastal zone, from Hoek van Holland to Schiermonnikoog; it therefore also includes the time spent in the water phase.

Based on the trends in the time series, we can estimate the modelled half-life of cadmium in the bottom, by determining the period when the initial concentration has reduced by a factor 2. This is determined for the situation when the load is zero, in order not to include the addition of new material into the model. For the presented output stations, the concentrations reached 50% of their initial value after a period of about 1.2 years. The found value of 1.2 years for the half-life still includes the effect of the influx of material originating from neighbouring cells. This could lead to an overestimation of the actual half-life period.

It must be noted, that this half-life period indicates the residence time in the bottom for a single location. It therefore differs from the estimated 2 years in literature, which denotes the residence time in the entire coastal zone (including water phase) and is therefore longer.

Looking at the time series plots shows that the trends in the decline are reproduced fairly well by the model. In the proposed additional work for this project, the model will be further calibrated for the residence time and buffer capacity of the bed. Additionally, the residence time of a mud particle in a balance area along the Dutch coast will be investigated.

5 Conclusions and recommendations

5.1 General conclusions on the model performance

a) For the coastal zone, the model predicted half-life periods for particles in the bottom in the order of 1.2 years.

b) Overall, the observed decline of the cadmium concentration in the bed agreed reasonably well with the measurements.

c) The schematized discharge of cadmium in the model only takes place via the river loads. Other sources, like dumping of dredged material, atmospheric deposition and southern input from the Channel have not been separately accounted for. Instead, a 'bulk' correction factor is applied to the river load, so that the total flux of cadmium from the rivers into the model is representative for the combined (estimated) flux of all processes. By scaling this flux for both the upper and the lower side of the range, we were able to investigate the sensitivity for the uncertainty in this parameter. It was shown that the uncertainties in the annual flux also influenced the magnitude of the concentrations in the bed, as was expected. However, the half-life remained of the same order for both loads, as these strongly depend on the (defined) buffer capacity in the model. This indicates that the determination of the residence time is not very sensitive for the uncertainties in the river loads.

d) Excluding other sources has resulted in a different spatial distribution. Concentrations are generally overestimated near the estuary mouth, while the concentrations further offshore are generally underestimated by the model. In reality, part of the total load will enter the North Sea from the south (through the Channel) and will thus be distributed further offshore than when entering the coast from the river. In the model, transport of cadmium mainly took place near the coast.

5.2 Further recommendations for the additional work or for future research

e) In the model, the cadmium load was specified by monthly values of the concentration in the rivers. But these values are not necessarily representative for the average concentration in that month, because of the low temporal resolution of these measurements (1 per month). This results in peaky variations of the load, which may or may not be physically accurate and makes the interpretation of the results more difficult. For future research, it is therefore recommended to use annual averages for the concentration.

f) By accounting for the different sources of cadmium, the model may be able to give a better reproduction of the spatial distribution of the cadmium concentration in the bed. But it should be considered if it is necessary for the calibration of the buffer model. Possibly only a background concentration could be implemented, to better match the cadmium concentrations further offshore.

g) By determining the bandwidth of the uncertainties of the loads in more detail (and possibly also other uncertainties), it could be possible to define a reliability range for the parameter settings ("optimistic" and "pessimistic" set of parameters).

h) An extra spinup time of at least 2-3 years should be added to minimize the initial response of the bottom to the cadmium load.

i) By predefining a balance area along the Dutch coastal zone in the model computations, it is possible to investigate the residence time of mud in the entire coastal zone, instead of for a single location only. This value can then be compared with the rough estimate from literature.

References

Kessel, T, van; J.C. Winterwerp; B. van Prooijen; M. van Ledden; W. Borst. (2010). Modelling the seasonal dynamics of SPM with a simple algorithm for the buffering of fines in a sandy seabed. Continental Shelf Research. DOI:10.1016/j.csr.2010.04.008.

Laane, R.W.P.M.; H.L.A. Sonneveldt; A.J. Van der Weyden; J.P.G. Loch; G. Groeneveld (1999). Trends in the spatial and temporal distribution of metals (Cd, Cu, Zn and Pb) and organic compounds (PCBs and PAH's in Dutch coastal zone sediments from 1981 to 1996: a model case study for Cd and PCBs. Journal of Sea Research 41 (1999) 1-17.

Sonneveldt, H.L.A., Laane, R.W.P.M., 1999. Prediction of sediment quality in the Dutch coastal zone: model validation and uncertainty analysis for Cd, Cu, Pb, Zn, PCBs and PAHs. In: Rainbow, P., et al. (Eds.), Forecasting the environmental fate and effects of toxic chemicals. SETAC-Europe

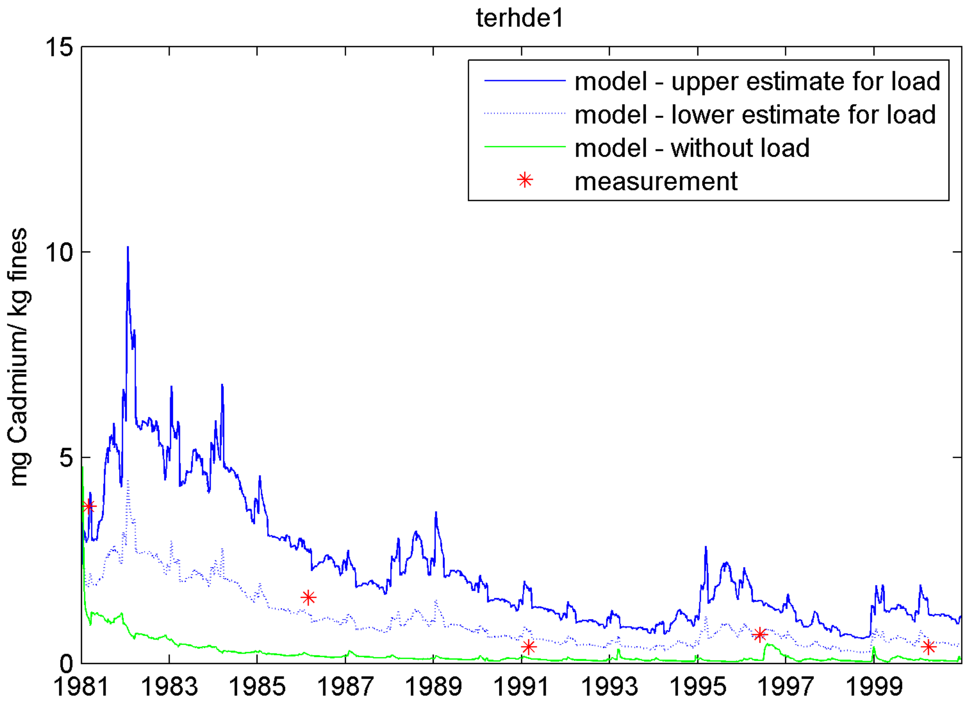
Deltares, 2010. L. Sittoni. Report VOP-Slib 2010, Loswallen

Deltares, 2010. C. Cronin; M. Blaas. Report for the MOS^2 project (Model-Supported Monitoring of SPM). WP3

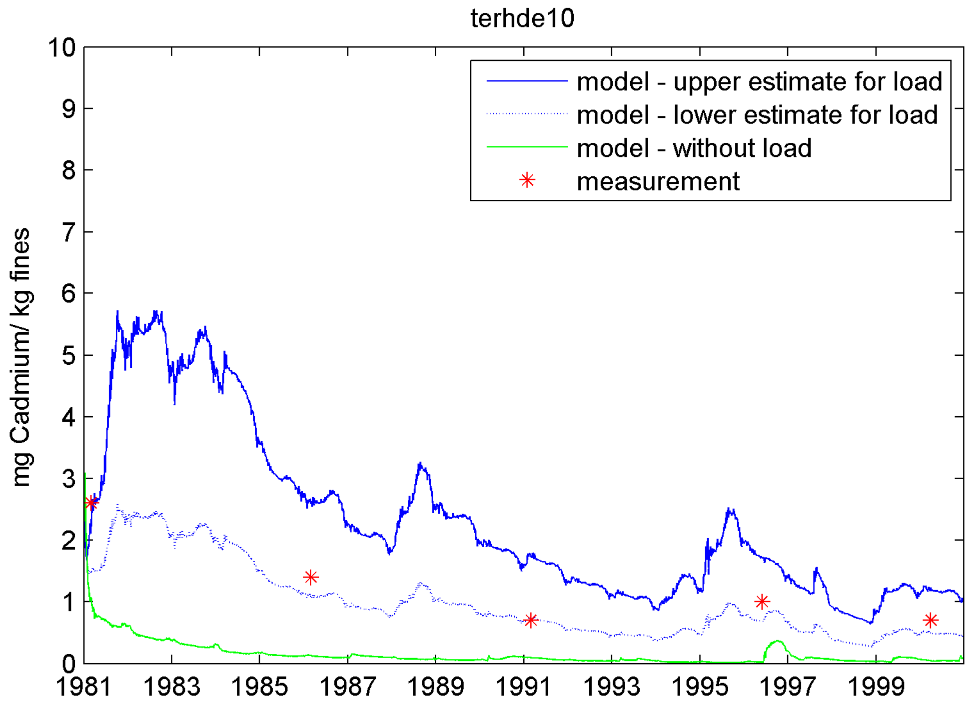
A Time series of the cadmium concentration in the bed

Measured (red stars) and modelled (blue and green lines) cadmium concentration within the fraction <63 μm in the bed [mg/kg fines], at monitoring stations “Ter Heijde 1”, “Ter Heijde 10”, “Noordwijk 2”, “Egmond aan Zee 1”, “Callantsoog 1” and “Callantsoog 10”; and for the off-shore stations “Rottumerplaat 70” and “Callantsoog 70”. The blue lines show the result for the upper estimate (solid) and the lower estimate (dashed) of the annual load. The green lines show the result for the case when the load is zero.

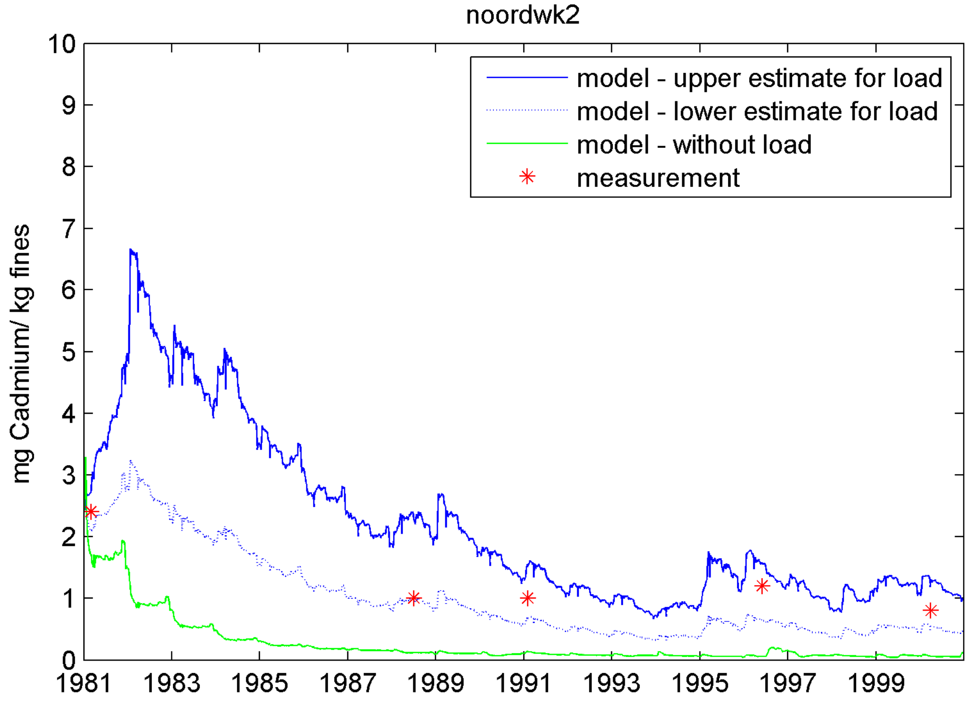
Ter Heijde 1



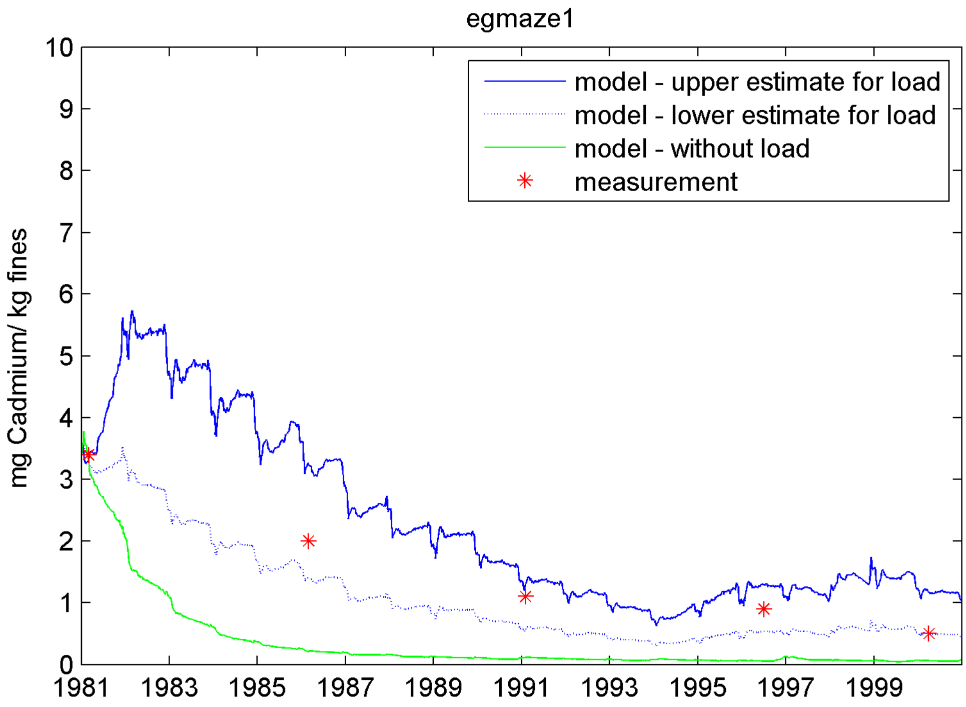
Ter Heijde 10



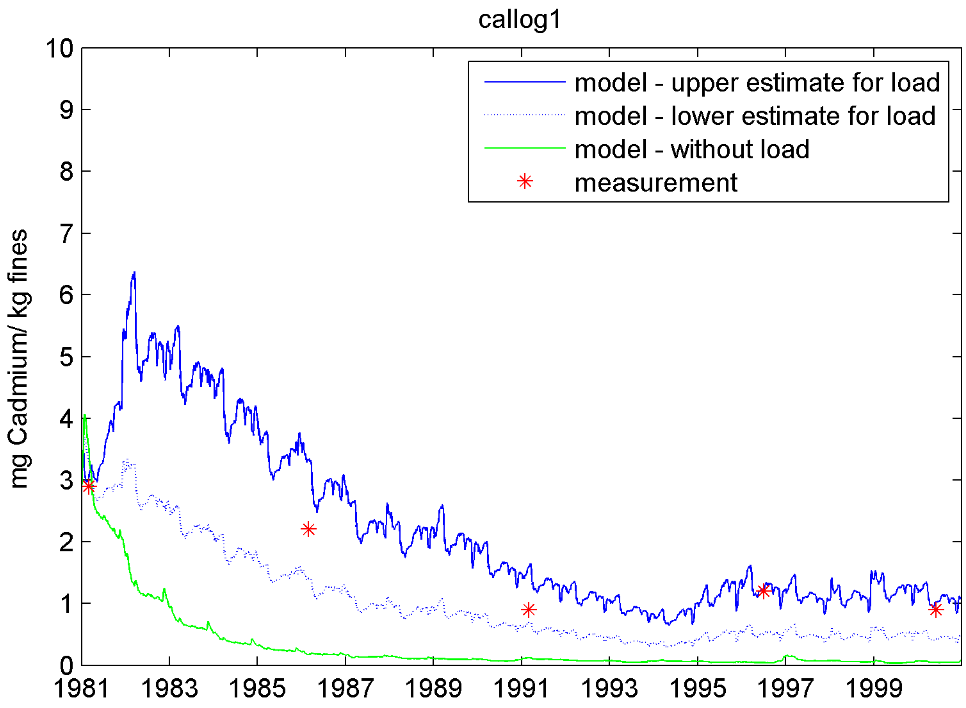
Noordwijk 2



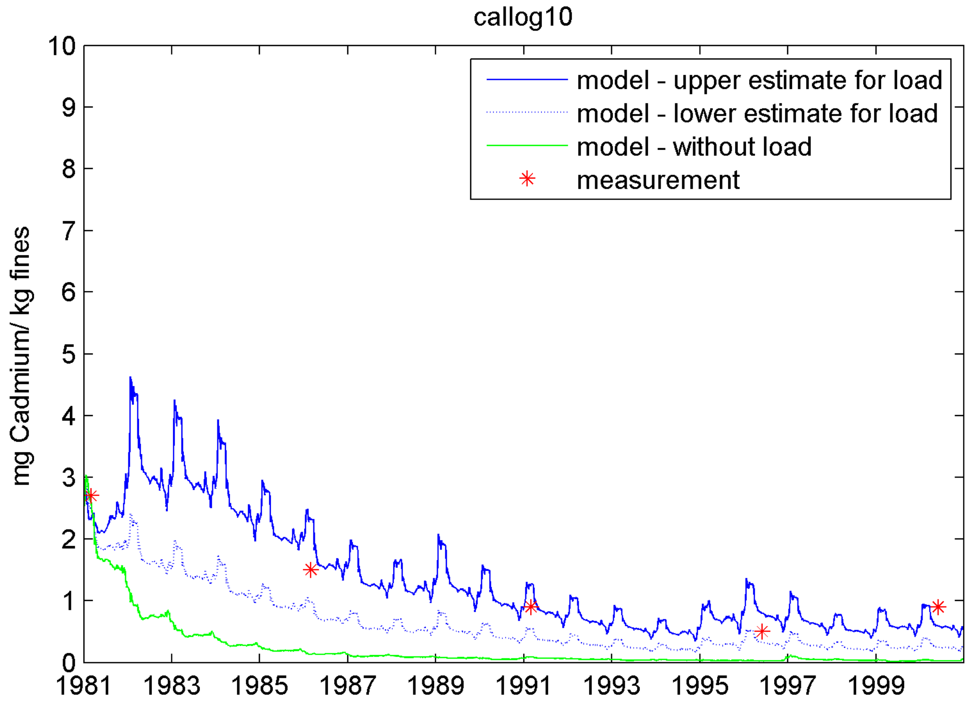
Egmond aan Zee 1



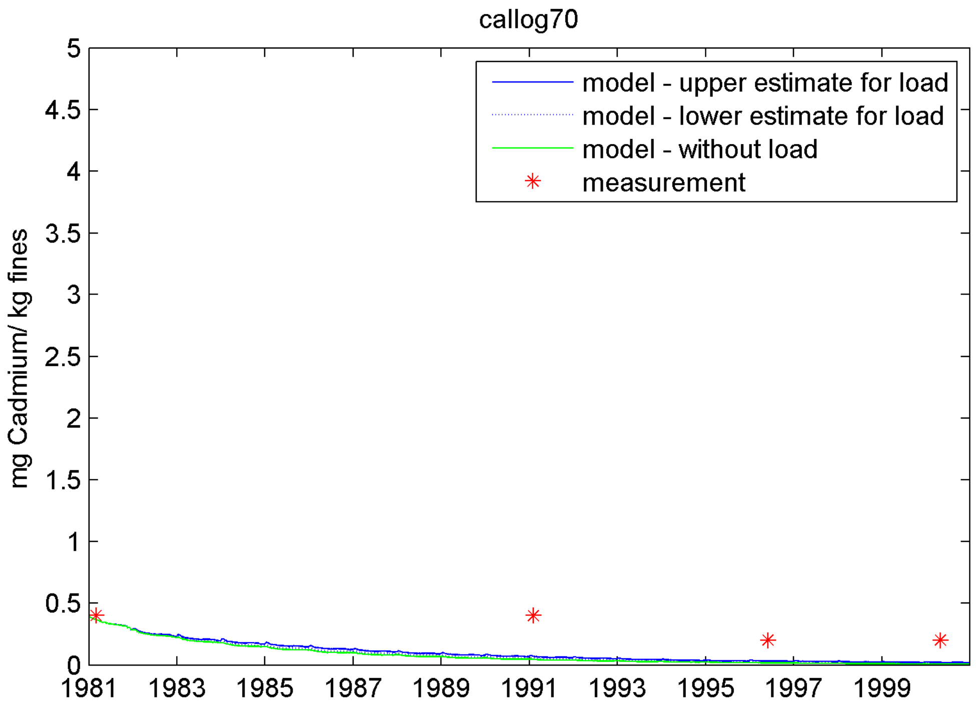
Callantsoog 1



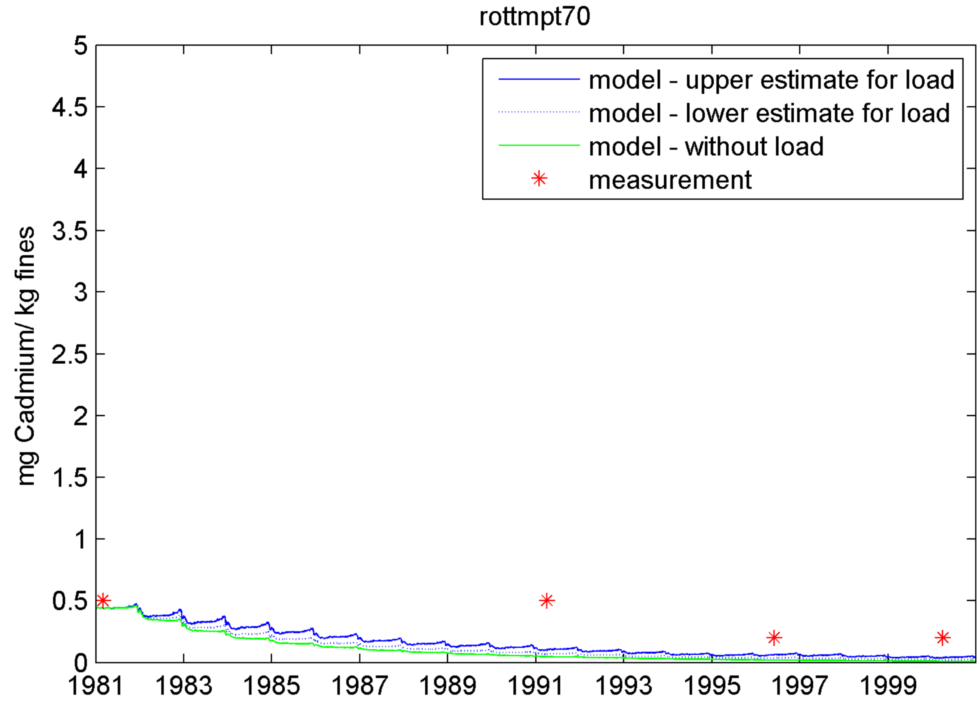
Callantsoog 10



Callantsoog 70



Rottumerplaat 70

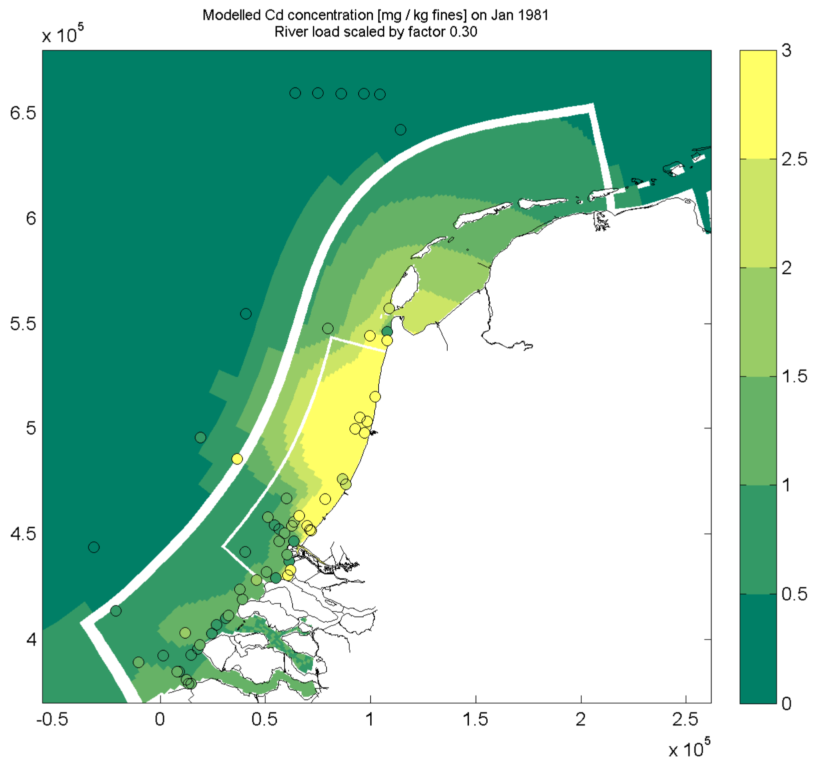


B Map plots of the cadmium concentration in the bed

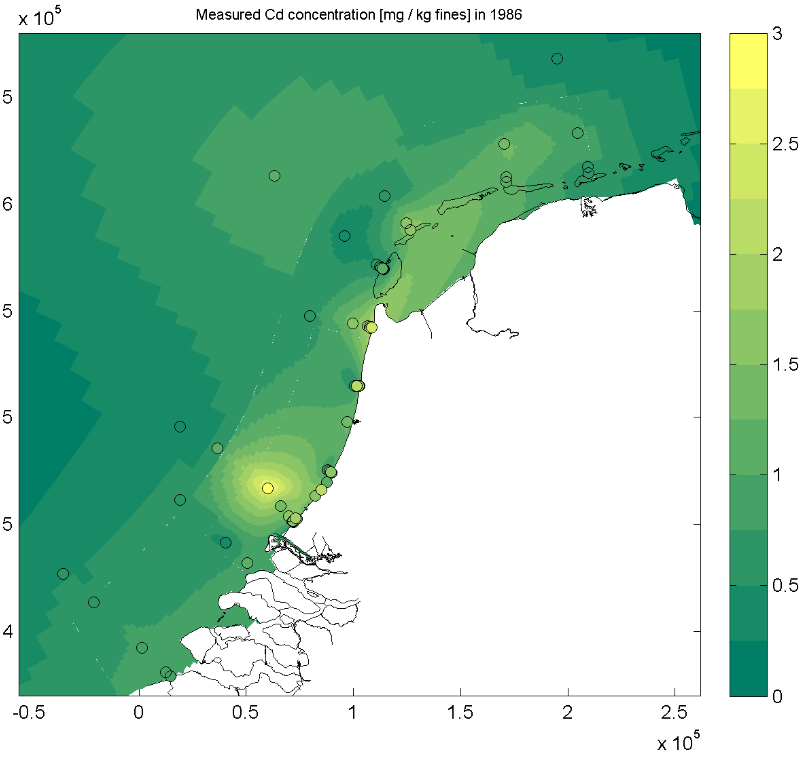
Interpolated data (left) and model results (right) of the cadmium concentration within the fraction <63 μm in the bed [mg/kg fines]. The upper right-hand plot shows the result for the upper estimate of the actual annual load, the lower plot shows the lower estimate. The dots represent the actual measured values.

1981 (initials)

Initial conditions were derived from the interpolated data and therefore show the same distribution as the graph on the left. The white bands represent the boundaries between the different computational domains.

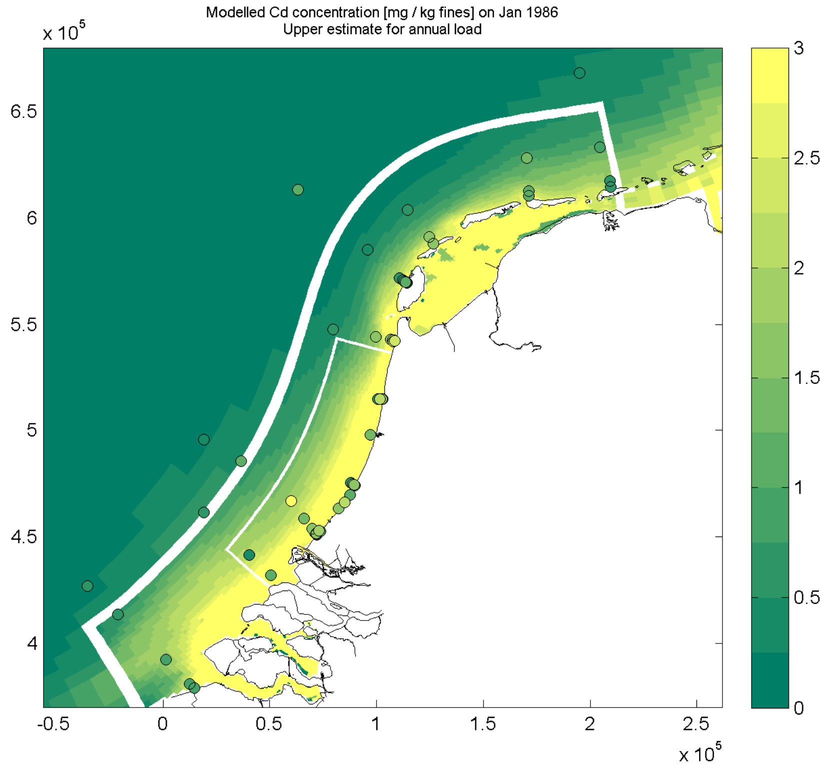


1986 - data

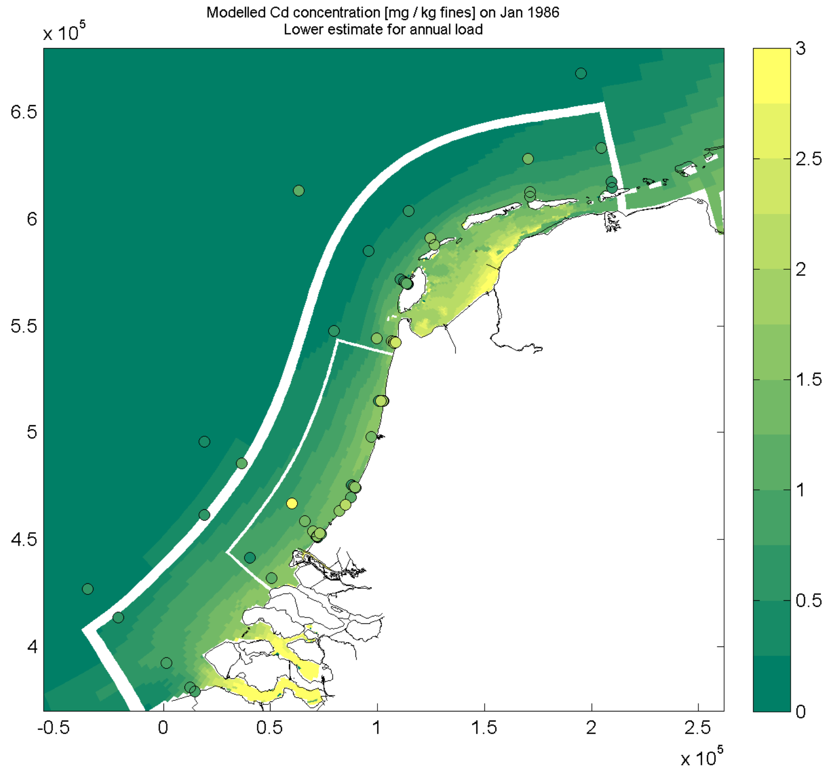

Measured Cd concentration [mg / kg fines] in 1986
x 10^5
6.5
6
5.5
5
4.5
4
-0.5
0
0.5
1
1.5
2
2.5
x 10^5
3
2.5
2
1.5
1
0.5
0

1986 – model

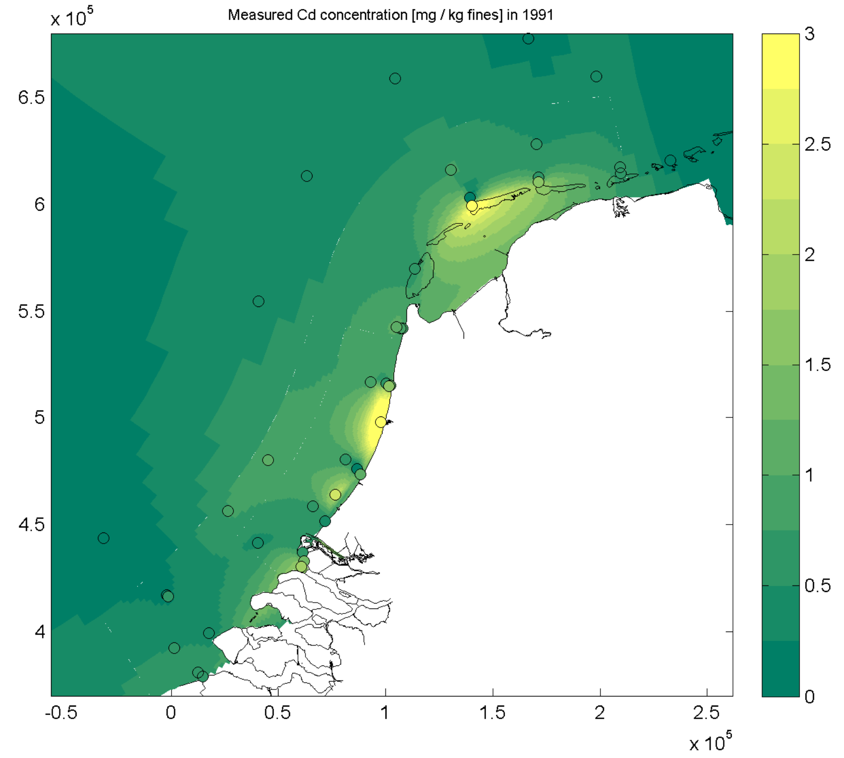
upper estimate for load:



lower estimate for load:

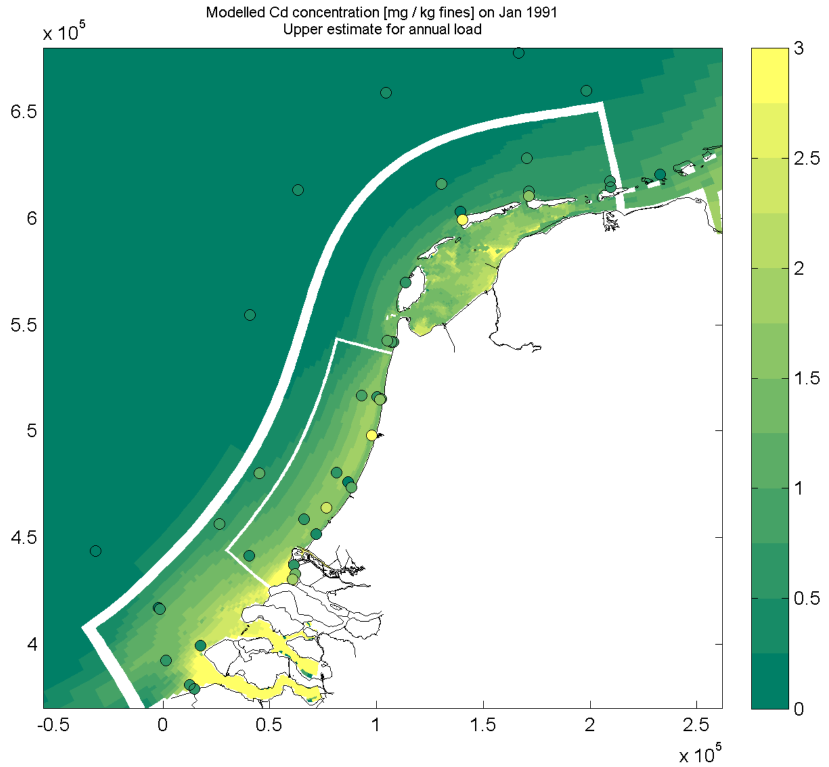


1991 – data

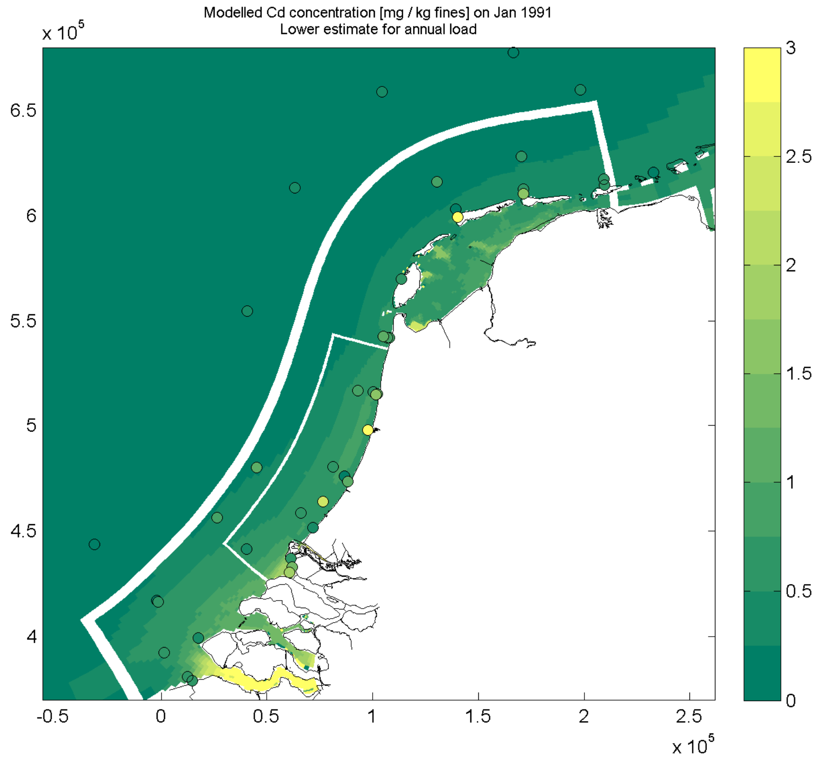

Measured Cd concentration [mg / kg fines] in 1991
x 10^5
6.5
6
5.5
5
4.5
4
-0.5
0
0.5
1
1.5
2
2.5
x 10^5
3
2.5
2
1.5
1
0.5
0

1991 – model

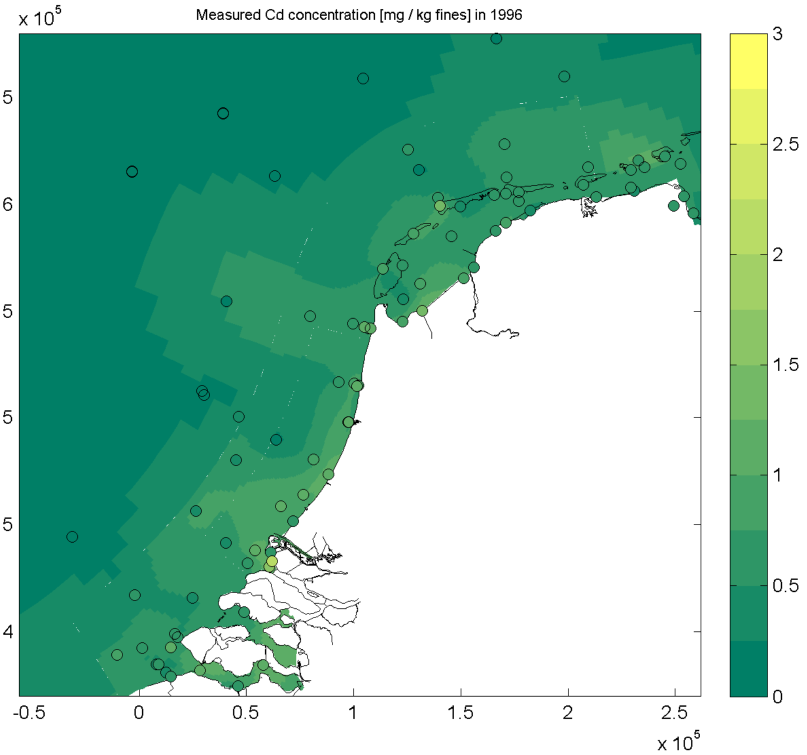
upper estimate for load:



lower estimate for load:



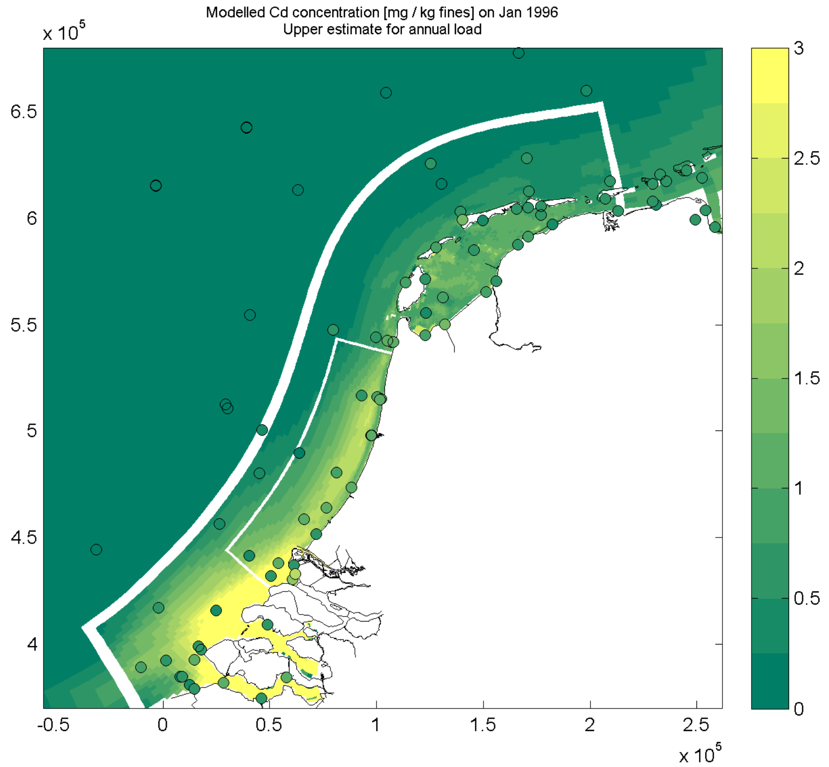
1996 – data


Measured Cd concentration [mg / kg fines] in 1996
x 10^5
6.5
6
5.5
5
4.5
4
-0.5
0
0.5
1
1.5
2
2.5
x 10^5
3
2.5
2
1.5
1
0.5
0

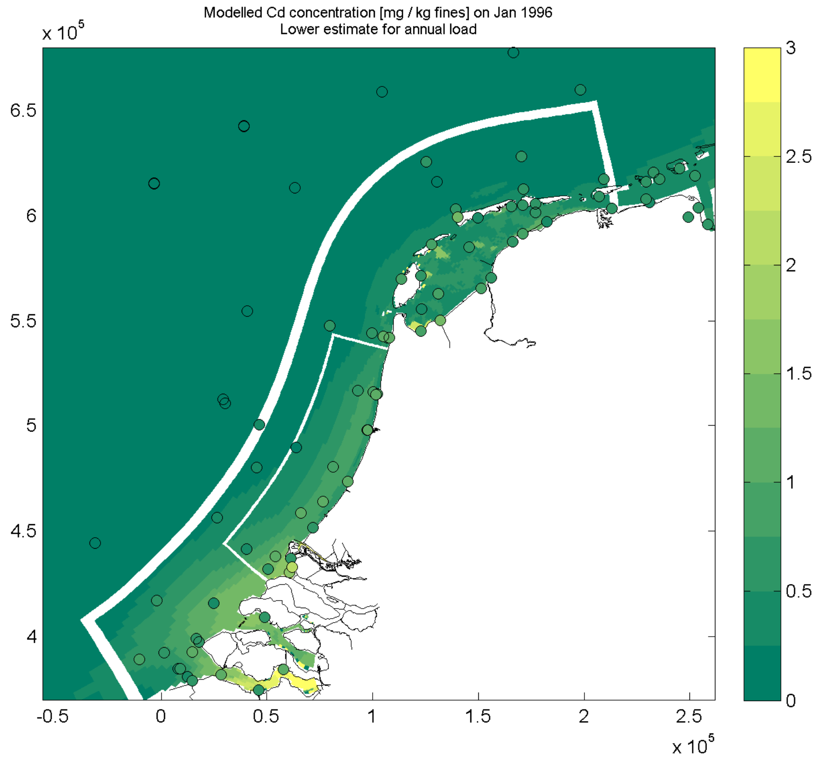
Deltares

1996 – model

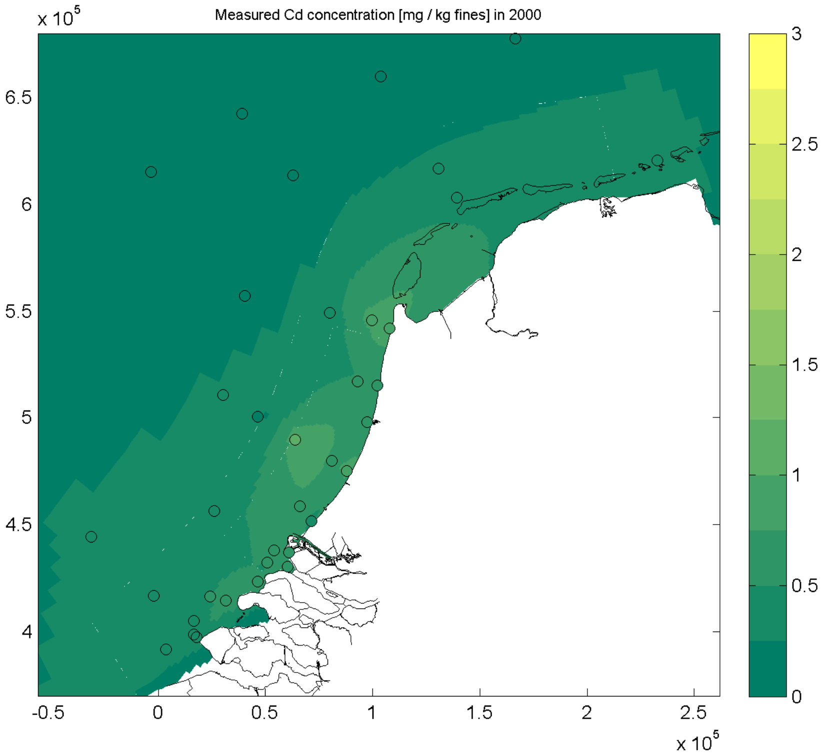
upper estimate for load:



lower estimate for load:

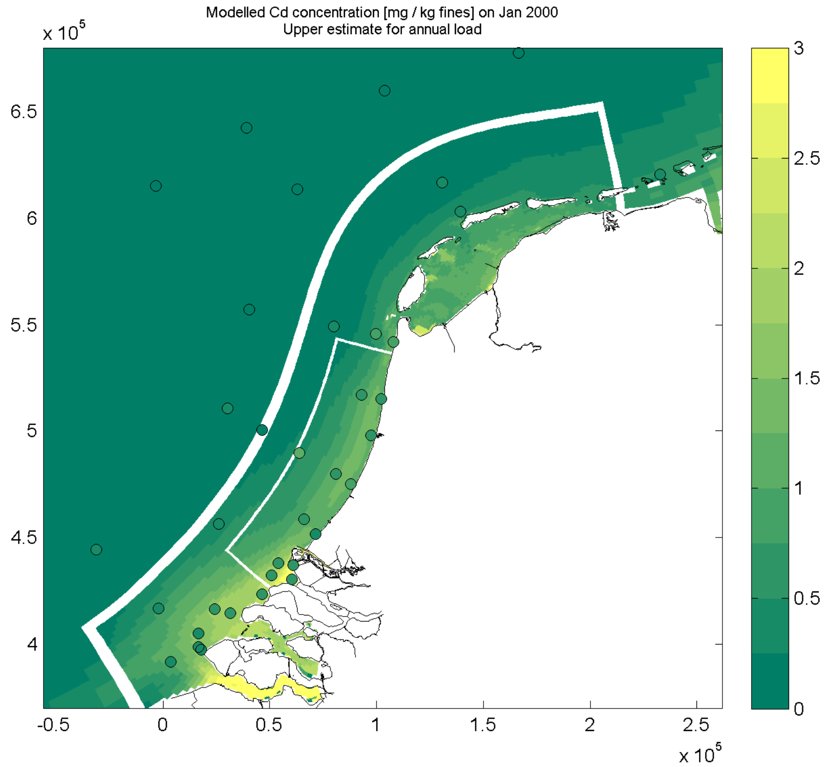


2000 – data


Measured Cd concentration [mg / kg fines] in 2000
x 10^5
6.5
6
5.5
5
4.5
4
-0.5
0
0.5
1
1.5
2
2.5
x 10^5
3
2.5
2
1.5
1
0.5
0

2000 – model

upper estimate for load:



lower estimate for load: