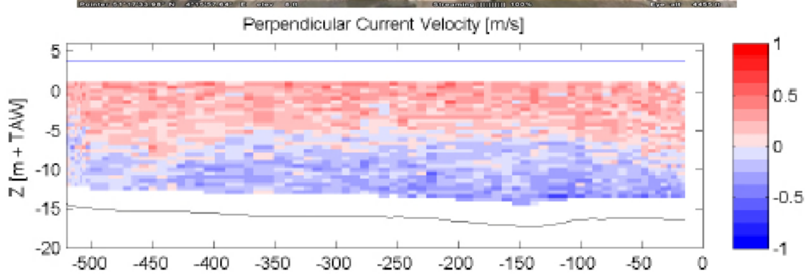
VLAAMSE OVERHEID

DEPARTEMENT MOBILITEIT EN OPENBARE WERKEN
WATERBOUWKUNDIG LABORATORIUM

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Bestek 16EB/05/04

Deurganckdok



Deelrapport 4.1: Analyse van aanslibbingsprocessen en -invloeden

Report 4.1: Analysis of siltation processes and factors

20 mei 2008

I/RA/11283/06.129/MSA

i.s.m. WL | delft hydraulics en GEMS International

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GLOSSARY

$\alpha_{set,dens}$	Coefficient for settled fraction during density currents [-]
$\alpha_{set,eddy}$	Coefficient for settled fraction during eddy formation [-]
BIS	Dredging Information System used in the Lower Sea Scheldt
B	Buoys (for buoys 84 and/or 97)
c	Suspended sediment concentration [mg/l]
c_1	calibration constant used in formula for F_t [-]
c_2	calibration constant used in formula for F_d [-]
c_s	Coefficient used in suspended sediment concentration predictor [-]
c_{ss}	Coefficient used in salinity amplitude predictor [-]
c_t	Coefficient used in suspended sediment concentration predictor [-]
d	Density of dredged sediment [kg/dm³]
DGD	Deurganckdok
ΔS	Salinity amplitude (variation per tide) [ppt]
F_t	Tidal prism induced sediment influx [g/tidal cycle]
F_d	Sediment influx due to density currents [g/tidal cycle]
F_e	Sediment influx due to eddies (horizontal entrainment) [g/tidal cycle]
HCBS	High Concentration Benthic Suspensions
M	mass of dry solids [ton]
Q	Upstream river discharge [m³/s]
$Q_{s,d}$	Net solid discharge due to density current [g/s]
$Q_{s,e}$	Net solid discharge due to turbulent exchange in eddy's [g/s]
ρ_s	density of the solid minerals [kg/dm³]
ρ_w	density of clear water [kg/dm³]
S	Salinity [ppt]
t_{0d}	Reference situation for densimetric analysis (empty dock)
t_{0e}	Reference situation for volumetric analysis (24 March 2006)
T	Temperature [°C]
TA	Tidal amplitude [m]

TDS	Tons of dry solids
V	Dredged sludge volume [m^3]

1. INTRODUCTION

1.1. The assignment

This report is part of the set of reports describing the results of the long-term measurements conducted in Deurganckdok aiming at the monitoring and analysis of silt accretion. This measurement campaign is an extension of the study "Extension of the study about density currents in the Beneden Zeeschelde" as part of the Long Term Vision for the Scheldt estuary. It is complementary to the study 'Field measurements high-concentration benthic suspensions (HCBS 2)'.

The terms of reference for this study were prepared by the 'Departement Mobiliteit en Openbare Werken van de Vlaamse Overheid, Afdeling Waterbouwkundig Laboratorium' (16EB/05/04). The repetition of this study was awarded to International Marine and Dredging Consultants NV in association with WL|Delft Hydraulics and Gems International on 10/01/2006. The project term was prolonged with an extra year from April 2007 till March 2008, 'Opvolging aanslibbing Deurganckdok'.

Waterbouwkundig Laboratorium– Cel Hydrometrie Schelde provided data on discharge, tide, salinity and turbidity along the river Scheldt and provided survey vessels for the long term and through tide measurements. Afdeling Maritieme Toegang provided maintenance-dredging data. Agentschap voor Maritieme Dienstverlening en Kust – Afdeling Kust and Port of Antwerp provided depth sounding measurements.

The execution of the study involves a twofold assignment:

- Part 1: Setting up a sediment balance of Deurganckdok covering a period of one year, i.e. 04/2007 – 03/2008
- Part 2: An analysis of the parameters contributing to siltation in Deurganckdok

1.2. Purpose of the study

The Lower Sea Scheldt (Beneden Zeeschelde) is the stretch of the Scheldt estuary between the Belgium-Dutch border and Rupelmonde, where the entrance channels to the Antwerp sea locks are located. The navigation channel has a sandy bed, whereas the shallower areas (intertidal areas, mud flats, salt marshes) consist of sandy clay or even pure mud sometimes. This part of the Scheldt is characterized by large horizontal salinity gradients and the presence of a turbidity maximum with depth-averaged concentrations ranging from 50 to 500 mg/l at grain sizes of 60 - 100 µm. The salinity gradients generate significant density currents between the river and the entrance channels to the locks, causing large siltation rates. It is to be expected that in the near future also the Deurganckdok will suffer from such large siltation rates, which may double the amount of dredging material to be dumped in the Lower Sea Scheldt.

Results from the study may be interpreted by comparison with results from the HCBS and HCBS2 studies covering the whole Lower Sea Scheldt. These studies included through-tide measurement campaigns in the vicinity of Deurganckdok and long-term measurements of turbidity and salinity in and near Deurganckdok.

The first part of the study focuses on obtaining a sediment balance of Deurganckdok. Aside from natural sedimentation, the sediment balance is influenced by the maintenance and capital dredging works. This involves sediment influx from capital dredging works in the Deurganckdok, and internal relocation and removal of sediment by maintenance dredging works. To compute a sediment balance an inventory of bathymetric data (depth soundings), density measurements of the deposited material and detailed information of capital and maintenance dredging works will be established.

The second part of the study is to gain insight in the mechanisms causing siltation in Deurganckdok, it is important to follow the evolution of the parameters involved, and this on a long and short term basis (long term & through-tide measurements). Previous research has shown the importance of water exchange at the entrance of Deurganckdok is essential for understanding sediment transport between the dock and the Scheldt river.

1.3. Overview of the reports

1.3.1. Reports

This document is to be seen as an integration report of all measurements performed in one year. Therefore, the reports of the project 'Opvolging aanslibbing Deurganckdok' as summarized in Table 1-1 are used as basic input for the analysis of siltation processes and their influences in Deurganckdok. In addition, two reports are listed from the HCBS (High Density Benthic Suspensions in the Lower Sea-Scheldt) project of which long term measurements at buoys 84 and 97 are used in this analysis.

Table 1-1: Overview of Deurganckdok and HCBS Reports

Report	Description
DEURGANCKDOK: Sediment Balance: Bathymetry surveys, Density measurements, Maintenance and construction dredging activities	
1.1	Sediment Balance: Three monthly report 1/4/2006 – 30/06/2006 (I/RA/11283/06.113/MSA)
1.2	Sediment Balance: Three monthly report 1/7/2006 – 30/09/2006 (I/RA/11283/06.114/MSA)
1.3	Sediment Balance: Three monthly report 1/10/2006 – 31/12/2006 (I/RA/11283/06.115/MSA)
1.4	Sediment Balance: Three monthly report 1/1/2007 – 31/03/2007 (I/RA/11283/06.116/MSA)
1.5	Annual Sediment Balance (I/RA/11283/06.117/MSA)
1.6	Sediment balance Bathymetry: 2005 – 3/2006 (I/RA/11283/06.118/MSA)
Factors contributing to salinity and sediment distribution in Deurganckdok: Salinity-Silt (OBS3A) & Frame measurements, Through tide measurements (SiltProfiling & ADCP)	
2.1	Through tide measurement Siltprofiler 21/03/2006 Laure Marie (I/RA/11283/06.087/WGO)
2.2	Through tide measurement Siltprofiler 26/09/2006 Stream (I/RA/11283/06.068/MSA)
2.3	Through tide measurement Sediview spring tide 22/03/2006 Veremans (I/RA/11283/06.110/BDC)
2.4	Through tide measurement Sediview spring tide 27/09/2006 Parel 2 (I/RA/11283/06.119/MSA)

Report	Description
2.5	Through tide measurement Sediview neap tide (to be scheduled) (I/RA/11283/06.120/MSA)
2.6	Salinity-Silt distribution & Frame Measurements Deurganckdok 13/3/2006 – 31/05/2006 (I/RA/11283/06.121/MSA)
2.7	Salinity-Silt distribution & Frame Measurements Deurganckdok 15/07/2006 – 31/10/2006 (I/RA/11283/06.122/MSA)
2.8	Salinity-Silt distribution & Frame Measurements Deurganckdok 15/01/2007 – 15/03/2007 (I/RA/11283/06.123/MSA)
Boundary Conditions: Upriver Discharge, Salinity Scheldt, Bathymetric evolution in access channels, dredging activities in Lower Sea Scheldt and access channels	
3.1	Boundary conditions: Three monthly report 1/1/2007 – 31/03/2007 (I/RA/11283/06.127/MSA)
Analysis	
4.1	Analysis of Siltation Processes and Factors (I/RA/11283/06.129/MSA)
HCBS: Ambient conditions in theriver Scheldt	
5.3	Overview of ambient conditions in the river Scheldt: Januari – June 2006
5.4	Overview of ambient conditions in the river Scheldt: July – December 2006

1.3.2. Measurement actions

Following measurements have been carried out during the course of the project:

1. Monitoring upstream discharge in the Scheldt river
2. Monitoring salinity and sediment concentration in the Lower Sea Scheldt taken from permanent data acquisition sites at Lillo, Oosterweel and up- and downstream of the Deurganckdok.
3. Long term measurement of salinity distribution in Deurganckdok.
4. Long term measurement of sediment concentration in Deurganckdok
5. Monitoring near-bed processes in the central trench in the dock, near the entrance as well as near the landward end: near-bed turbidity, near-bed current velocity and bed elevation variations are measured from a fixed frame placed on the dock's bed.
6. Measurement of current, salinity and sediment transport at the entrance of Deurganckdok for which ADCP backscatter intensity over a full cross section are calibrated with the Sediview procedure and vertical sediment and salinity profiles are recorded with the SiltProfiler equipment
7. Through tide measurements of vertical sediment concentration profiles -including near bed highly concentrated suspensions- with the SiltProfiler equipment. Executed over a grid of points near the entrance of Deurganckdok.
8. Monitoring dredging activities at entrance channels towards the Kallo, Zandvliet and Berendrecht locks
9. Monitoring dredging and dumping activities in the Lower Sea Scheldt

In situ calibrations were conducted on 15 March 2006, 14 April 2006, 23 June 2006 and 18 September 2006 to calibrate all turbidity and conductivity sensors (IMDC, 2006f & IMDC, 2007l).

1.4. Structure of the report

This report presents a global analysis of the collected data in order to illuminate the siltation process and its influences in the Deurganckdok. In this respect, Chapter 2 will introduce the site of investigation. It further describes the different possible driving processes (both natural and human) leading to the siltation of the dock. Chapter 3 deals with the collected data over the one-year measurement period and the performed analyses. These results will support the discussion on the siltation process and its influencing factors in Chapter 5. Finally, Chapter 6 will discuss some limitations of the actual data set and recommendations for a better investigation of the siltation process in the dock.

2. BASICS OF SEDIMENTATION IN DEURGANCKDOK

2.1. Project Area: Deurganckdok

Deurganckdok is a tidal dock situated at the left bank in the Lower Sea Scheldt, between Liefkenshoek and Doel. Deurganckdok has the following characteristics:

1. The dock has a total length of 2750 m and is 450 m wide at the Scheldt end and 400 m wide at the inward end of the dock
2. The bottom of Deurganckdok is provided at a depth of –17m TAW in the transition zones between the quay walls and the central trench. The bottom in the central trench is designed at –19 m TAW.
3. The quay walls reach up to +9m TAW

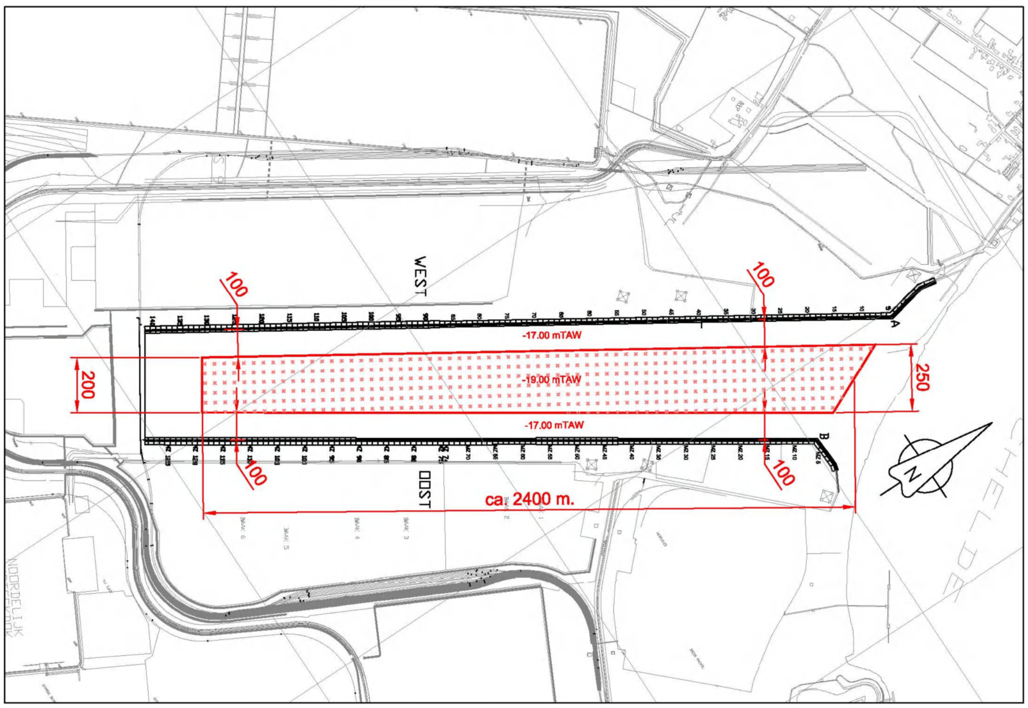

Figure 2-1: Overview of Deurganckdok

The dredging of the dock is performed in 3 phases. On 18 February 2005 the dike between the Scheldt and the Deurganckdok was breached. On 6 July 2005 Deurganckdok was officially opened. The second dredging phase was finalized a few weeks later. The first terminal operations have started since. In February 2007, the third dredging phase started and is planned to be finalized in 12 months time (by February 2008).

2.2. Siltation processes and influences

The first part of the study aims at determining a sediment balance of Deurganckdok and the net influx of sediment. The sediment balance comprises a number of sediment transport modes: deposition, influx from capital dredging works, internal replacement and removal of sediments due to maintenance dredging (Figure 2-2).

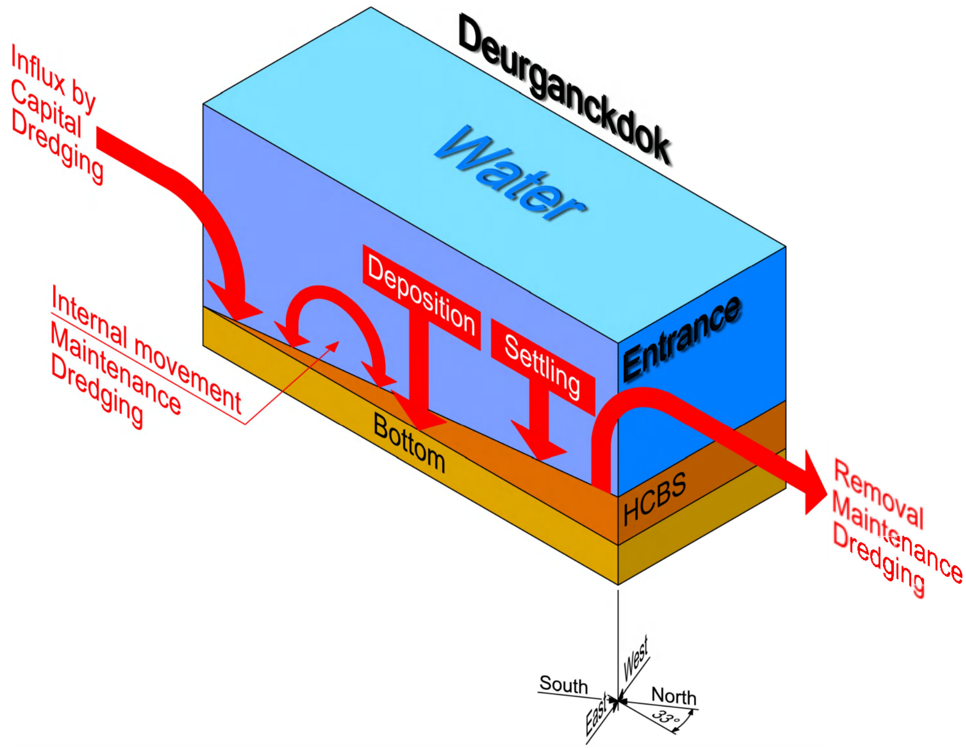

Figure 2-2: Elements of the sediment balance

A net deposition can be calculated from a comparison with a chosen initial condition t_0 (Figure 2-3). The mass of deposited sediment is determined from the integration of bed density profiles recorded at grid points covering the dock. Subtracting bed sediment mass at t_0 leads to the change in mass of sediments present in the dock (mass growth). Adding cumulated dry matter mass of dredged material removed since t_0 and subtracting any sediment influx due to capital dredging works leads to the total cumulated mass entered from the Scheldt river since t_0.

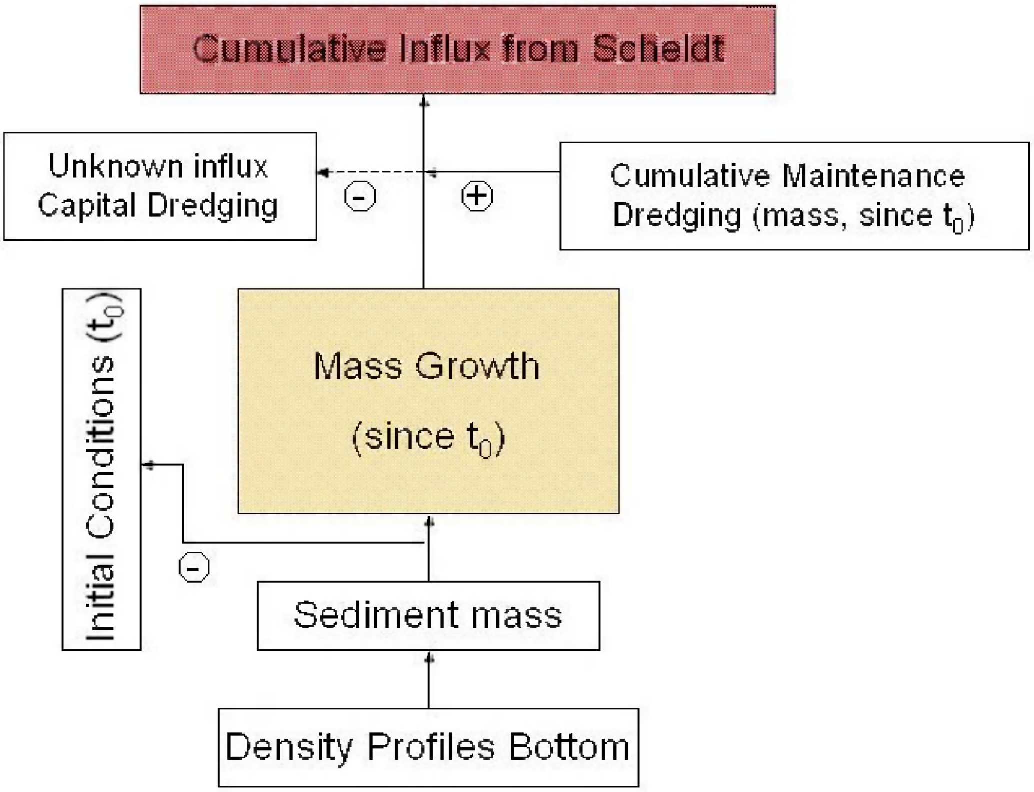

Figure 2-3: Determining a sediment balance with bed density profile data

The main purpose of the second part of the study is to gain insight in the mechanisms causing siltation in Deurganckdok. The following mechanisms will be aimed at in this part of the study:

- Tidal prism, i.e. the extra volume in a water body due to high tide
- Eddy circulation due to passing tidal current
- Density currents due to salinity gradient between the Scheldt river and the dock
- Density currents due to highly concentrated benthic suspensions

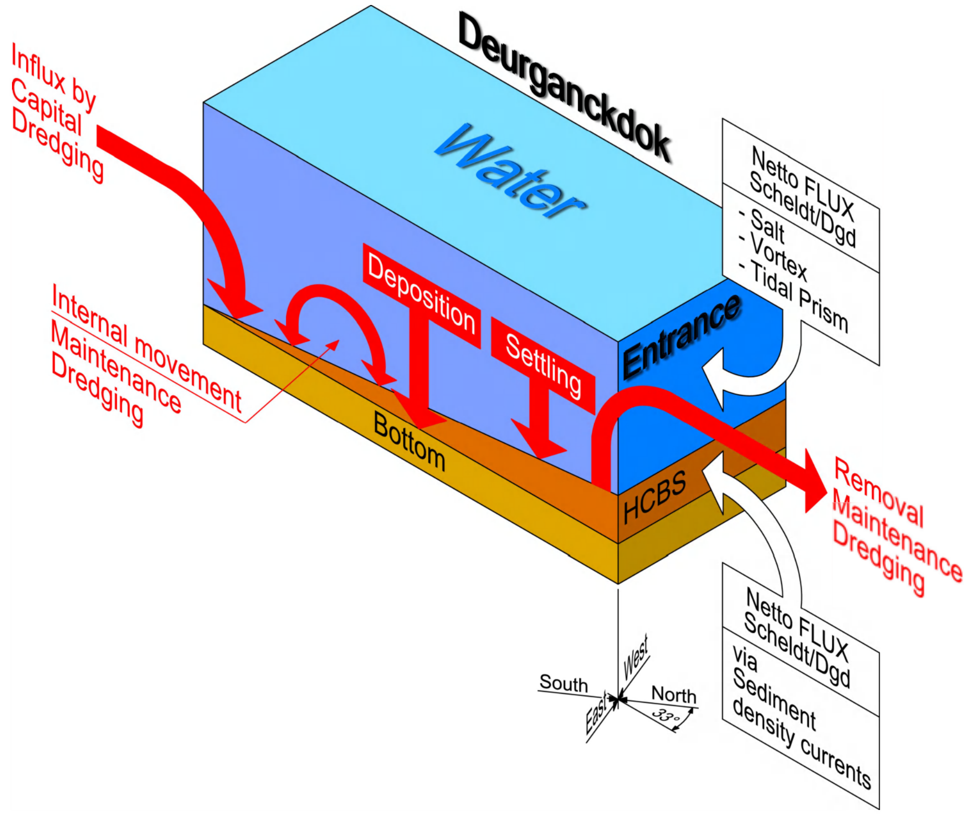

Figure 2-4: Transport mechanisms

These aspects of hydrodynamics and sediment transport determine the parameters to be measured during the project. Measurements will be focused on three types of timescales: one tidal cycle, one neap-spring cycle and seasonal variation within one year.

Following data are being collected to understand these mechanisms:

- Monitoring upstream discharge in the Scheldt river.
- Monitoring salinity and sediment concentration in the Lower Sea Scheldt at permanent measurement locations at Oosterweel, up- and downstream of the Deurganckdok.
- Long term measurement of salinity and suspended sediment distribution in Deurganckdok.
- Monitoring near-bed processes (current velocity, turbidity, and bed elevation variations) in the central trench in the dock, near the entrance as well as near the current deflecting wall location.
- Dynamic measurements of current, salinity and sediment transport at the entrance of Deurganckdok.
- Through tide measurements of vertical sediment concentration profiles -including near bed high concentrated benthic suspensions.
- Monitoring dredging activities at entrance channels towards the Kallo, Zandvliet and Berendrecht locks as well as dredging and dumping activities in the Lower Sea Scheldt.
- In situ calibrations were conducted on several dates to calibrate all turbidity and conductivity sensors.

3. COLLECTED AND PROCESSED DATA

3.1. Collected data

Table 3-1: Overview of measurements and dredging activities in Deurganckdok

	March 06	April 06		May 06		June 06		July 06		August 06		September 06	
ACTIVITY	16 - 31	1 - 15	16 - 30	1 - 15	16 - 31	1 - 15	16 - 30	1 - 15	16 - 31	1 - 15	16 - 31	1 - 15	16 - 30
bed measurements													
depth sounding													
density measurements													
maintenance dredging													
sweep beam dredging - sill													
sweep beam dredging - commercial quays													
capital dredging													
near-bed continuous monitoring													
suspended sediment concentration: profile													
suspended sediment concentration: local													
local velocity													
bottom elevation tracking / solidity													
water level													
quay wall continuous monitoring													
suspended sediment concentration													
salinity													
water level													
temperature													
dock entrance: 13-hours Siltprofiler													
suspended sediment concentration: profile													
salinity													
temperature													
water level													
dock entrance: 13-hours Sediview													
suspended sediment concentration													
velocity profile													
temperature													
salinity													
Buoy 84 and 97													
suspended sediment concentration													
local velocity													
temperature													
water level													
Liefkenshoek: transect Scheldt													
suspended solids concentration: profile													
velocity profile													
curr. deflect. wall Deurganckdock: transect Scheldt													
suspended solids concentration: profile													
velocity profile													
bed Deurganckdok: inside and entrance area													
particle size distribution													
composition													
zeta potential													
consolidation													
shear strength													
cappilary suction time													
free water Deurganckdok: inside and entrance area													
particle size distribution													
settling velocity													
velocity: profile and local													
suspended sediment concentration: local													

	October 06		November 06		December 06		January 07		February 07		March 07	
ACTIVITY	1 - 15	16 - 31	1 - 15	16 - 30	1 - 15	16 - 31	1 - 15	16 - 31	1 - 15	16 - 28	1 - 15	16 - 31
bed measurements												
depth sounding		■			■				■		■	
density measurements												
maintenance dredging	■	■								■		■
sweep beam dredging – sill	■		■	■	■			■	■	■	■	■
sweep beam dredging – commercial quays	■									■		
capital dredging							■	■	■	■	■	■
near-bed continuous monitoring												
suspended sediment concentration: profile	■								■	■	■	■
suspended sediment concentration: local	■								■	■	■	■
local velocity	■								■	■	■	■
bottom elevation tracking / solidity	■								■	■	■	■
water level	■								■	■	■	■
quay wall continuous monitoring												
suspended sediment concentration	■								■	■	■	■
salinity	■								■	■	■	■
water level	■								■	■	■	■
temperature	■								■	■	■	■
dock entrance: 13-hours Siltprofiler												
suspended sediment concentration: profile												
salinity												
temperature												
water level												
dock entrance: 13-hours Sediview												
suspended sediment concentration												
velocity profile												
temperature												
salinity												
Buoy 84 and 97												
suspended sediment concentration	■	■	■	■	■	■	■	■	■	■	■	■
local velocity	■	■	■	■	■	■	■	■	■	■	■	■
temperature	■	■	■	■	■	■	■	■	■	■	■	■
water level	■	■	■	■	■	■	■	■	■	■	■	■
Liefkenshoek: transect Scheldt												
suspended solids concentration: profile												
velocity profile												
curr. deflect. wall Deurganckdock: transect Scheldt												
suspended solids concentration: profile												
velocity profile												
bed Deurganckdok: inside and entrance area												
particle size distribution	■											
composition	■											
zeta potential	■											
consolidation	■											
shear strength	■											
cappilary suction time	■											
free water Deurganckdok: inside and entrance area												
particle size distribution												
settling velocity												
velocity: profile and local												
suspended sediment concentration: local												

3.2. Performed analyses

In the framework of HCBS and DGD many data has been collected along the Scheldt estuary with respect to a variety of environmental variables, such as flow velocity, settling velocity, bathymetry, suspended sediment concentrations, salinity, temperature, water level, etc. This study focuses on the siltation process in and close to Deurganckdok. As a result, only data in the area around Deurganckdok is selected.

3.2.1. Previously reported analyses

- Sediment balance: Bed measurements in Deurganckdok
  - difference maps of bed elevation
  - temporal evolution of bed elevation at specified sections and zones
  - volumetric siltation rates in specified zones
    - gross yearly averaged siltation rate
    - natural siltation rate
  - depth of equal density layers (from density measurements)
  - computed total sediment mass (from density measurements)
  - dredged sediment amounts from maintenance and capital dredging
  - temporal evolution of tide prism by capital dredging operations
- Quay-wall continuous monitoring (locations at entrance and back of dock)
  - weekseries of salinity, suspended sediment concentration, temperature and water level
  - average tidal cycles of salinity, suspended sediment concentration and temperature, and their (cross-dock, along-dock and diagonal) gradients
- Near-bed continuous monitoring (south of sill and the current deflection wall)
  - time series of suspended sediment concentration near bottom
  - time series of bottom elevation and water level
  - tidal evolution (ebb – flood) of suspended sediment concentration in 10 equidistant layers in 1 m above the bottom
  - time series of velocity, suspended sediment concentration and sediment mass flux 0.5 and 1 m above bottom
  - tidal evolution (ebb – flood) of suspended sediment concentration, velocity and sediment mass flux 0.5 and 1 m above bottom
- Dock entrance (measurement grid)
  - vertical profiles of suspended sediment concentration, salinity and temperature
  - time evolution of the above-mentioned vertical profiles
  - transects of suspended sediment concentration, salinity and temperature
  - bottom elevation
  - averaged values of suspended sediment concentration, salinity and temperature for the entire water column, and the top and bottom 50% of the water column
- Dock entrance (transect along sill)
  - transects of suspended sediment concentration, velocity and sediment mass flux
  - time series of discharge and sediment mass flux
- Buoy 84 and 97

  - time series of suspended sediment concentration, local velocity, temperature and water level: measured near bottom and at half of the water column
  - monthly and three-monthly averages, minima and maxima in relation of the tide
- Scheldt area around Deurganckdok
  - transects of suspended sediment concentration, velocity and sediment mass flux
- Deurganckdock: inside and entrance area
  - particle size distribution of both bed and suspended sediment
  - bed: sediment composition, zeta potential, consolidation, shear strength, capillary suction time
  - water column: settling velocity
  - velocity: local and profile

3.2.2. Supplementary analyses

- Quay-wall continuous monitoring
  - hysteresis loop of salinity and suspended sediment concentration gradients in relation to the upstream discharge rate

4. CONCEPT OF A SEDIMENTATION MODEL WITH DATA-ASSIMILATION

4.1. Introduction

To investigate the sediment accumulation in Deurganckdok, it is essential to gain knowledge on the sediment transport phenomena and their influencing processes and/or parameters. A large number of measurements have been obtained and analysed. This knowledge gives now the opportunity to set up an emprical model of the sedimentation of a tidal dock based on physical processes and data assimilation.

On a yearly basis, the settled sediment mass M_{year} is calculated as:

$$M_{year} = \int_{year} F_{in}\,dt - \int_{year} F_{out}\,dt$$

Whereas the incoming flux F_{in} at the dock entrance depends on both the flow rates and the suspended sediment concentration, contributions to the outgoing flux F_{out} are related to local dredging operations (sweepbeam) and erosion. Erosive fluxes are considered as of minor importance because the general layout of the dock acts as a sediment trap (cf. depth in relation to the entrance sill). As will be discussed later, eddy flows at the dock entrance may result in an outgoing sediment mass flux but this will be intrinsically considered in the ingoing flux definition. Hence, the settled sediment mass is rewritten as:

$$M_{year} = \int_{year} F_{net}\,dt$$

As a result, the sediment mass accumulation in the dock can be determined in two ways, i.e:

- The increase of bed sediment mass measured by density profiles, and
- The time integration of the sediment mass flux at the entrance of the dock.

However, it is clear that the first method requires in situ density profiles that have only been measured once in the considered period of March 2006 - March 2007. Uncertainties on the dredged sediment masses only make this method more complicated. It is therefore suggested to develop for the time being only the second method in order to make a best estimate of the sediment accumulation in the dock.

Hence, the aim is to develop a relation between the incoming sediment mass flux and the different contributing processes occurring outside the dock, i.e. in the Scheldt river. It should be stated from the beginning that the mass flux concerns an estimate and that its accuracy strongly depends on the availability and quality of the collected data. The sediment mass flux can indeed be determined at different levels of detail and complexity, i.e. considering more influencing parameters or processes. Obviously, the less influences are considered, the larger the error will be on the yearly-accumulated mass in Deurganckdok. However, the consideration of these influences in defining the mass flux is only possible when collected data allows it.

Hence, the accumulated sediment mass in the dock can be estimated as:

$$M_{year} = \int_{year} \int_{A} v(x,z,t).c(x,z,t)\, dA\, dt$$

where dA is an elementary part of the cross-sectional area at the entrance. Hence, the local flow velocity and suspended sediment concentration need to be estimated to compute M_{year}. These two variables depend on different environmental conditions, and are discussed below.

4.2. Local velocity

The local velocity at the dock entrance depends on the vertical and horizontal velocity profiles. Its spatial distribution is tide-driven and results from differences in water level between the Scheldt and the inner-dock area. Additionally, salinity driven density currents and eddy currents at the entrance may complicate the velocity profiles. Thus:

Flow velocity ~ Tidal amplitude h

~ Salinity amplitude

4.3. Local suspended sediment concentration

The influx of suspended sediment concentration obviously depends on the concentration in the Scheldt river and local bottom shear conditions. Therefore:

c, DGD ~ c, Scheldt

~ salinity ~ tidal amplitude / upstream river discharge

~ temperature (seasonal effects)

~ shear stress ~ tidal amplitude (neap, mean and spring tide)

4.4. Practical approach

The above indicates that different relationships need to be determined in order to allow the consideration of sediment transport influencing factors in the flux calculation. The success of this exercise largely depends on the quality and availability of measurement data. During the period March 2006 – March 2007 many data have been collected, as summarized in §3.

For developing the relations, some data collection locations are essential, i.e.

- buoys 84 and 97, located in the Scheldt river (locations shown in Appendix A): measurements near the bottom and half of the water column (IMDC 2006e, IMDC 2007h, IMDC 2007i);
- both sides of dock entrance: measurements near the bottom and half of the water column (IMDC 2006e, IMDC 2007h; IMDC 2007i);
- 13-hours intensive measurement campaigns at dock entrance returning the local and total sediment mass flux (IMDC 2006 b, c, d; IMDC 2007g).

Whereas the 13-hours measurement campaigns reveal detailed information on the spatial and temporal (during spring and mean tide) evolution of the local flow velocity v, the suspended sediment concentration c and on the related sediment flux in the vicinity of the entrance of DGD, the other measurements give long-term evolutions of some local variables.

Hence, from the short-term measurements a spatial relationship can be established between the tidal evolution and the sediment mass flux. Moreover, temporal evolutions of salinity, suspended sediment concentration and velocity (incl. density currents and recirculation flows) are determined.

The aim subsequently consists of developing a relationship between the local mid-term (near-bottom and near-surface) measurements at the quay walls of the dock entrance and the cross-sectional measurements. However, these mid-term measurements do not cover a complete year. For that reason, a relationship needs to be established between the mid-term measurements at the dock entrance (covering appr. 3 months) and the long-term measurements performed at buoys 84 and 97 in the Scheldt (covering an entire year). This is further specified below and in Figure 4-1.

Assume the following measurement periods:

- short-term at dock's entrance cross-section (13 h): $[t_{ST,s}, t_{ST,e}]$
- mid-term at dock's quay walls (~3 months): $[t_{MT,DGD,s}, t_{MT,DGD,e}]$
- long-term at buoys 84 and 97 (~1 year): $[t_{LT,B,s}, t_{LT,B,e}]$

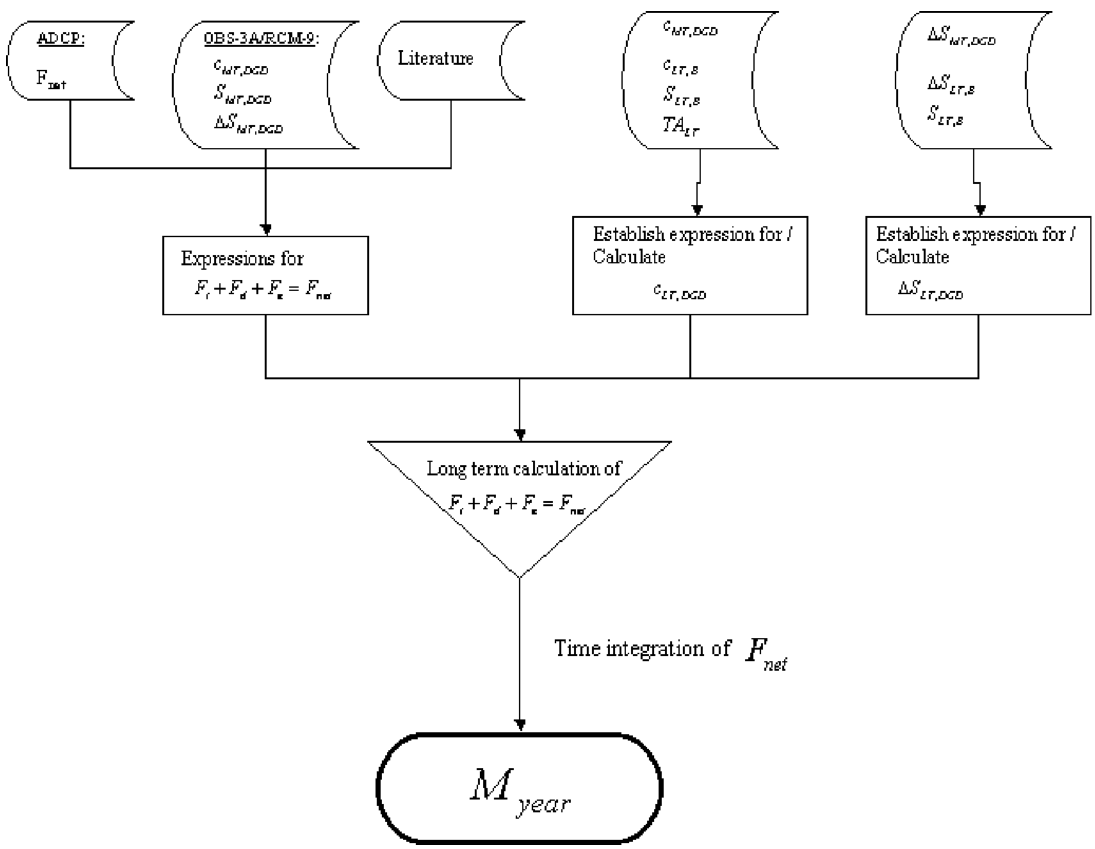

Figure 4-1: Overall method for empirical model of sedimentation in Deurganckdok with data-assimilation.

<u>Step 1: determination of relationship between mass flux and locations at sides of dock entrance</u>

The sediment mass flux per tide is only available during the cross-sectional measurements and is a function of a string of parameters:

$$F_{net} = f_{ST}\left(c_{MT,DGD}, S_{MT,DGD}, \Delta S_{MT,DGD}, Q_{LT}, T_{LT}, h\right)$$

Not only the suspended sediment influx as well as the distribution of suspended sediment along the dock's entrance are observed during in situ measurements, the flow pattern is observed as well from which important insights in the active mechanisms can be deduced.

Variables T, h and Q are long term variables and are available the entire year. To the contrary, c and S are only available for mid term periods and need to be further specified. Therefore, in order to calculate F_{net} for every tide in a year, c and S need to be available throughout the year. For this purpose relationships in step 2 are established.

<u>Step 2: determination of relationship between locations at sides of dock entrance and Scheldt</u>

Since during three mid term periods measurements exist both at the buoys in the Scheldt (non-stop) and at the dock's quay walls (about 6 weeks), relationships can be established and calibrated for a number of required parameters between the locations at the buoys and the dock's entrance:

- Sediment concentration:

The relationship can be established based on:

$$c_{MT,DGD} = f_{LT,c}(c_{LT,B}, S_{LT,B}, h_{LT})$$

Of which all parameters are known. Once $f_{LT,c}$ is known the long term sediment concentration near the dock's entrance $c_{LT,DGD}$ can be estimated for the complete year by:

$$c_{LT,DGD} = f_{LT,c}(c_{LT,B}, S_{LT,B}, h_{LT})$$

Here, it is assumed that the sediment concentration at the buoys in the Scheldt and the sediment concentration at the dock's entrance are linked by salinity and tidal amplitude at the buoys in the Scheldt as these two parameters determine to a large extend the flow velocity. Note that sediment concentration measurements in the Scheldt show a distinct behaviour for spring tides at which a sudden increase of sediment concentration can be observed. This observation is assumed to be the result of an increased bed shear stress exceeding the critical shear stress for erosion or resuspension. Furthermore, the tidal mean salinity level is a measure for the position of the turbidity maximum, which is an important influence on sediment concentrations.

- Salinity (and salinity amplitude):

In the same way, a relationship is assumed to exist between the salinity amplitude $\Delta S_{LT,DGD}$ at the dock's entrance at one hand and the salinity $S_{LT,B}$ and the salinity amplitude $\Delta S_{LT,B}$ at the buoys in the Scheldt. The relationship can be established from:

$$\Delta S_{MT,DGD} = f_{LT,\Delta S}\left(\Delta S_{LT,B}, S_{LT,B}\right)$$

Again, all these are known since measurements in the dock are mid term and the measurements at the buoys are long term. Once $f_{LT,\Delta S}$ has been found, the salinity amplitude on the long term can be estimated by:

$$\Delta S_{LT,DGD} = f_{LT,\Delta S}\left(\Delta S_{LT,B}, S_{LT,B}\right).$$

Step 3: Sediment mass flux

Using the parameters calculated in step 2 for the complete year, the net sediment flux per tide F_{net} can be calculated for each tide during this year. Time integration of F_{net} over the year leads to the cumulative influx of sediment into the dock due to natural mechanisms.

$$M_{year} = \int_{t_s}^{t_e} f_{ST}\left(S_{LT,DGD}, \Delta S_{LT,DGD}, c_{LT,DGD}, Q_t, T_t\right) dt$$

5. IMPLEMENTATION OF A SEDIMENTATION MODEL WITH DATA-ASSIMILATION

5.1. Introduction

In order to estimate the annual sediment accretion due to natural phenomena, the relationships mentioned above need to be established. The main objective is to determine the trends in sediment influx within neap-spring cycles, high and low river runoff periods and different seasons. Combining the different effects into an estimate of sediment influx per tide leads to a continuous series.

First, in order to determine which driving parameters are needed for the long-term estimate of the sediment influx per tide, mid term measurements of these parameters have to be available.

Secondly, the year-round measurements at buoy 84 and buoy 97 can be used as a basis for the determination of the first level of estimations: from three mid-term measurement campaigns at the entrance of Deurganckdok (salinity and suspended sediment concentration) and the measurements of salinity at the buoys in both directions at about 2 km from the dock an empirical relation can be established to estimate the measured parameters near the dock in between the measured periods. Estimated parameters need to be selected in advance.

Thirdly, a semi-analytical solution can be determined for the sediment accumulation in the dock based on the continuous series obtained in the second step. The solution can be partially checked by comparison with short-term measurements (through-tide).

5.2. Parameters needed for influx estimate

Three main forces near the entrance drive the mixing of estuarine sediments into the dock: density currents, large eddy circulation and tidal filling. As a consequence the sediment inflow will be determined based on mean salinity, salinity amplitude and mean sediment concentration in the estuarine waters near the dock and the tidal amplitude.

5.3. Determination of relationships between physical parameters

Of the three main parameters chosen to be variables in the influx estimating model, two have to be determined from an empirical relationship between measurements at two buoys (buoy 84 and buoy 97) on one end and at the entrance of the dock at the other end: salinity amplitude and mean sediment concentration.

Since the long-term character of the estimate, all instantaneous measurements have been low pass filtered with a window of 7 days. In this way the trends on weekly timescales can be determined, and shorter-term variations will be introduced through the tidal amplitude of each tide.

Different relationships have been tested for their ability to predict the values at the dock's entrance: salinity amplitude and sediment concentration.

5.3.1. Salinity amplitude

In this section the function mentioned higher is established:

$$\Delta S_{LT,DGD} = f_{LT,\Delta S}\left(\Delta S_{LT,B}, S_{LT,B}\right)$$

The following functions have been tested for their proportionality with salinity amplitude at Deurganckdok (in blue in Figure 5-1):

- Salinity difference between buoy 84 and buoy 97 ($= S_{B84} - S_{B97}$, Figure 5-1 a);
- Difference in tidal average salinity at B84 and B97 ($= \overline{S_{B84}} - \overline{S_{B97}}$);
- Difference in salinity amplitude B84 and B97 ($= \Delta S_{B84} - \Delta S_{B97}$);
- Amplitude of salinity gradient between B84 and B97 ($= \Delta(S_{B84} - S_{B97})$, Figure 5-1 b);
- Average of salinity amplitudes B48 and B97 ($= 0.5(\Delta S_{B84} + \Delta S_{B97})$, Figure 5-1 c)

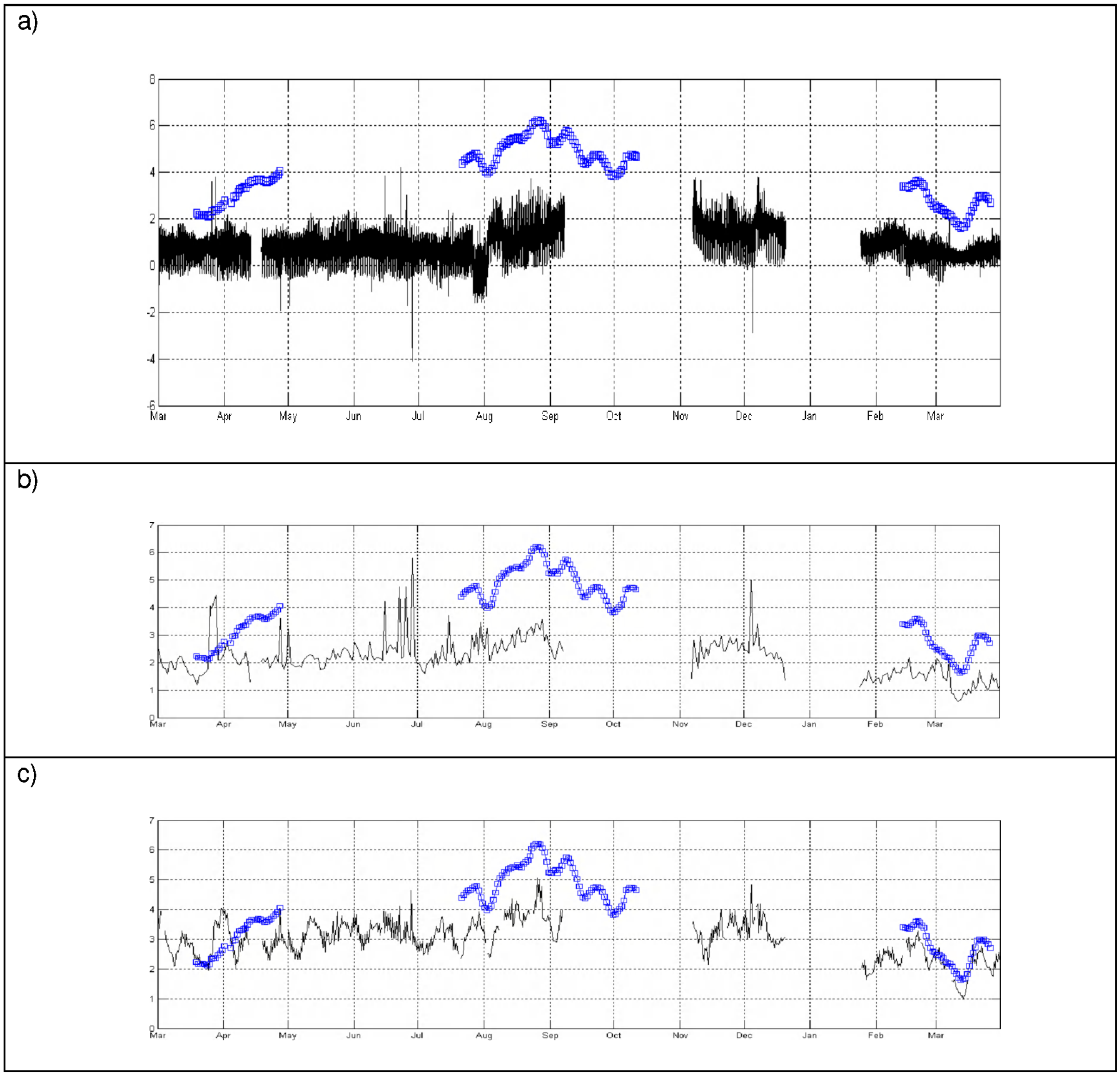

Figure 5-1: a) Salinity difference (unfiltered, buoy 84 – buoy97) in black and salinity amplitude at DGD in blue with markers; b) Range per tide in salinity difference between buoy 84 and buoy 97 in black and salinity amplitude at DGD in blue with markers; c) Average salinity amplitude (buoy 84 and buoy 97) in black and salinity amplitude at DGD in blue with markers.

The first parameter in the list, a salinity difference (0 – 3 ppt), or salinity gradient (0 – 0.75 ppt/km), shows some correlation with salinity amplitude at DGD but not a very strong one.

The second parameter, the difference in tidal average salinity of buoys 84 and 97 shows no useful correlation with the salinity amplitude at DGD, neither does the difference in salinity amplitude of the buoys show such a correlation.

Since Figure 5-1a shows some relationship between the salinity amplitude at DGD and the variation in salinity difference between buoy 84 and 97, a fourth parameter has been investigated to find a possible correlation with DGD observations: the tidal amplitude of the salinity gradient between buoys 84 and 97. Shown in Figure 5-1 b and clearly related to DGD salinity amplitude, obviously due to the process of tidal excursion of the salt wedge. Nevertheless, the relationship seems to leave a large part of the variation unexplained.

The last parameter (Figure 5-1 c) shows the best correlation with the salinity amplitude at the dock's entrance: simply the average of the salinity amplitudes at buoys 84 and 97. Still a clear variation of the proportionality with the season is observed, which is probably related to the upstream discharge and the mean salinity, which are related through the position of the end of the salinity wedge. The salinity amplitude at the dock's entrance seems to be amplified at times of low river runoff since the salinity amplitude is in that case higher than the average of the buoys, which are located at two different sides of the dock.

Therefore an amplification factor varying with upstream discharge and/or mean salinity can be adopted. The upstream discharge could be used here, although the disadvantage is the time lag between discharge change and salinity change further downstream. An increase in upstream discharge initially does not affect the salinity level at DGD much, after 5-7 days the salinity begins to drop under the persisting high upstream discharge. When the fresh water discharge decreases the salinity initially remains low and increases after 5-7 days of low discharge (Figure 5-2). It could be stated that the mean salinity level is the 'memory' of the upstream discharge of the past couple of weeks, or the change in average salinity over time is inversely proportional with discharge. Indeed, advection makes salt travel upstream in times of low river runoff.

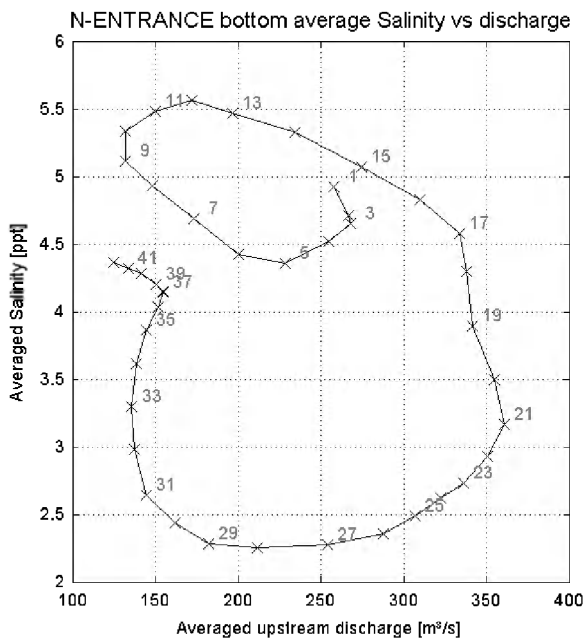

Figure 5-2: Hysteresis loop of salinity at the entrance of Deurganckdok under influence of river runoff. Data is filtered with a window of 7 days, numbers represent days after start of the measurements.

Therefore, an amplification coefficient c_{ss} dependent on average salinity of buoy 84 and buoy 97 is used (Figure 5-3):

Equation 5-1:

$$c_{ss} = 1 + e^{-S'/\bar{S}}$$

Where: $\bar{s}$ is the average salinity and s' is a reference salinity (a parameter to be calibrated).

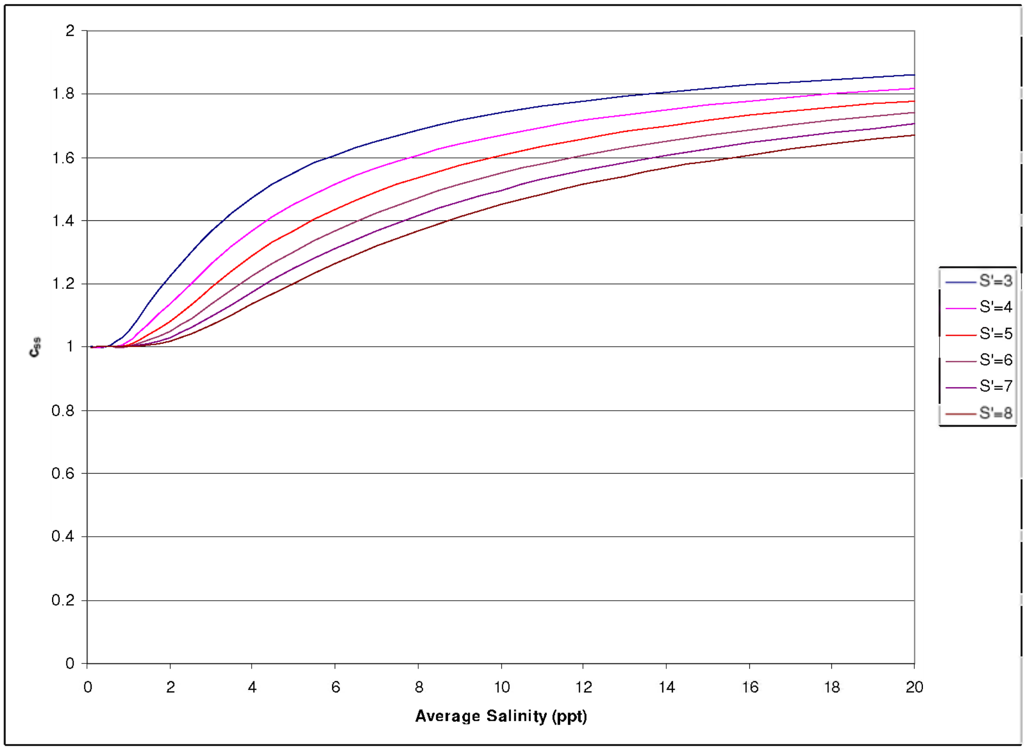

Figure 5-3: Amplification coefficient for estimation of salinity amplitude at DGD.

Experimentally, the best value for the reference salinity has been found at 6.5 ppt, resulting in the evolution over time of salinity amplitude measured at the dock (mid term) and the predicted salinity amplitude (long term) shown in Figure 5-4. The relationship with river runoff is obvious since the summer delivers low fresh water discharge and winter (feb-march) higher fresh water discharge.

As a result, the following relationship will be adopted for further use in the empirical model for sedimentation:

Equation 5-2:

$$\Delta S_{LT,DGD} = f_{LT,\Delta S}\left(\Delta S_{LT,B}, S_{LT,B}\right) = \frac{1}{2} c_{ss}\left[\Delta S_{LT,B84} + \Delta S_{LT,B97}\right]$$

where: $c_{ss} = 1 + e^{6.5/\bar{S}}$ and $\bar{S} = 0.5\left[\overline{S_{LT,B84}} + \overline{S_{LT,B97}}\right]$

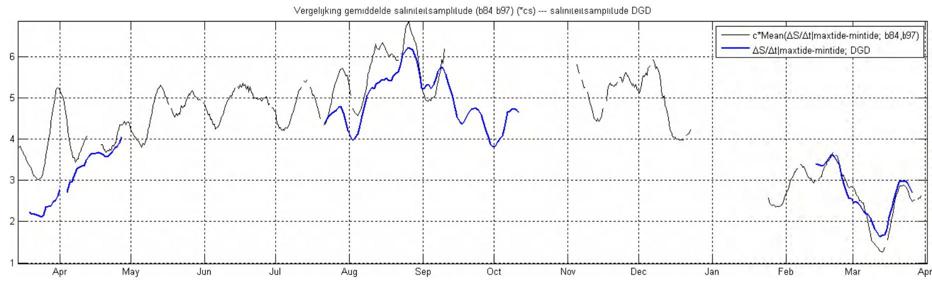

Figure 5-4: Measured salinity amplitude at DGD in blue and estimated salinity amplitude (yearround) in black using the amplification coefficient c_{ss}.

The normalised root-mean-square error (NRMSE) has been calculated to be 0.17 for this relationship and the error distribution is shown below.

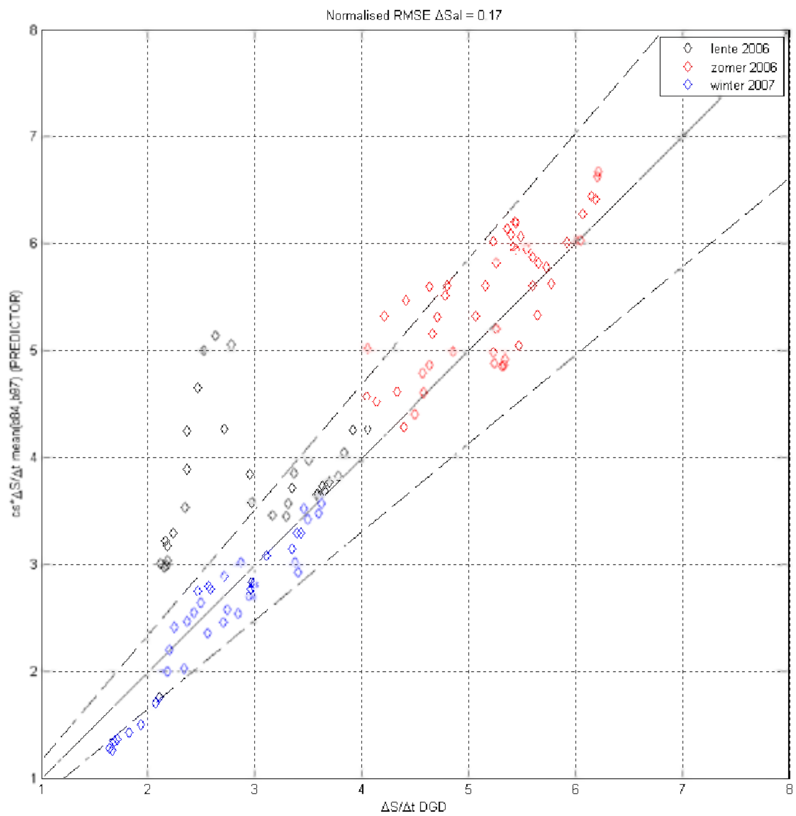

Figure 5-5: Calibrated model results for estimation of salinity amplitude at DGD from long-term measurements at buoys 84 and 97.

Since an estimate of the errors made in each step, and the accumulation of errors throughout the procedure we will work not only with a model for the estimated parameter (full black line), but also with a low and high estimate of the parameter. Therefore the estimated parameters are multiplied with (1-NRMSE) for the low estimate and with (1+NRMSE) for the high estimate, which are shown by the interrupted lines in Figure 5-5.

5.3.2. Suspended Sediment Concentration

In this paragraph following function will be established:

$$c_{LT,DGD} = f_{LT,c}(c_{LT,B}, S_{LT,B}, h_{LT})$$

Since the spatial variability of the suspended sediment concentration is very high in a dynamic environment like the Scheldt's estuary it is very difficult to adopt the same principle as for salinity amplitude, i.e. that the values near Deurganckdok can be estimated from measurements at buoy 84 and buoy 97. The estimated suspended sediment concentration near the entrance of the dock will not always be directly related to the measured suspended sediment concentration at the buoys. The equation above reduces to:

$$c_{LT,DGD} = f_{LT,c}(S_{LT,B}, h_{LT})$$

Based on the fact that suspended sediment can only be kept in suspension against gravity through turbulence induced vertical mixing, the suspended sediment concentration will be dependent on maximal flood and ebb velocity, which in turn is dependent on the tidal amplitude of surface elevation. A first factor in the estimate of tidal average suspended sediment concentration will be dependent on the tidal amplitude.

Based on the long term measurements it was found that variations in average suspended sediment concentration between neap and spring tide with other conditions relatively constant were 30% more (spring tide) and about 30% less (neap tide) compared to average tides. Therefore the first (dimensionless) factor for SSC estimation is taken to be:

Equation 5-3:

$$c_t = h / \overline{h}$$

Since tidal elevation is around 3 m for neap tides, 5 m for an average tide ($\overline{h}$) and 6.5 m for spring tides, c_t varies from 0.7 to 1.3 during a regular neap-spring cycle.

The second important feature in the long-term variation of average suspended sediment concentration is the position of the turbidity maximum, which is a zone occurring in meso and macro tidal estuaries at which sediment concentrations are higher than elsewhere (Dyer, 1973). Furthermore the position of the turbidity maximum is influenced by the upstream river discharge. The combined effects of tidal pumping and river discharge determine its position and formation. Tidal pumping occurs due to the flood-dominated tidal asymmetry causing higher flood velocities to resuspend and transport more sediment inland than ebb velocities transport seaward. At one point along the estuary the influence of river discharge on amplification of the ebb current velocity becomes important enough to counter tidal pumping and to form a sediment trap. Hence, a higher river runoff causes a more seaward position of the turbidity maximum, and causes a more seaward position of the tip of the salt intrusion. Usually the turbidity maximum is located near the tip of the salt wedge, or at average salinity of 1 to 5 mg/l. Since average salinity is known for the two buoys and the average salinity decreases gradually towards the tip of the salt wedge, the second factor for the estimation of average sediment concentration can be taken to be a function of the mean of the average salinity of buoys 84 and 97.

Physically the following statement should be implemented in this factor: the distance to the turbidity maximum is related to the average suspended sediment concentration and the average salinity is proportional with the distance to the turbidity maximum upstream. Since the most downstream location of the turbidity maximum is near Prosperpolder (Wollast en Marijns, 1981), the turbidity maximum cannot be far away downstream from DGD.

It is assumed that the turbidity maximum is around the position where the average salinity is about 3 ppt, any value less than 3 ppt indicates the turbidity maximum is slightly downstream, but not far. Any value higher means that the turb max is upstream, the higher the salinity the more upstream.

Based on these facts the following function has been set up:

Equation 5-4:

$$c_s = a\cos^2\left(\frac{\overline{S}-3}{b}\right)$$

Where $\overline{S}$ is the mean of the tidally averaged salinities at buoys 84 and 97 ($\overline{S} = 0.5\left[\overline{S_{LT,B84}} + \overline{S_{LT,B97}}\right]$). This function has been chosen from four candidates for the best correlation with measurements (Figure 5-6).

Graphically the function looks as follows (green line) for a=1 and b=10:

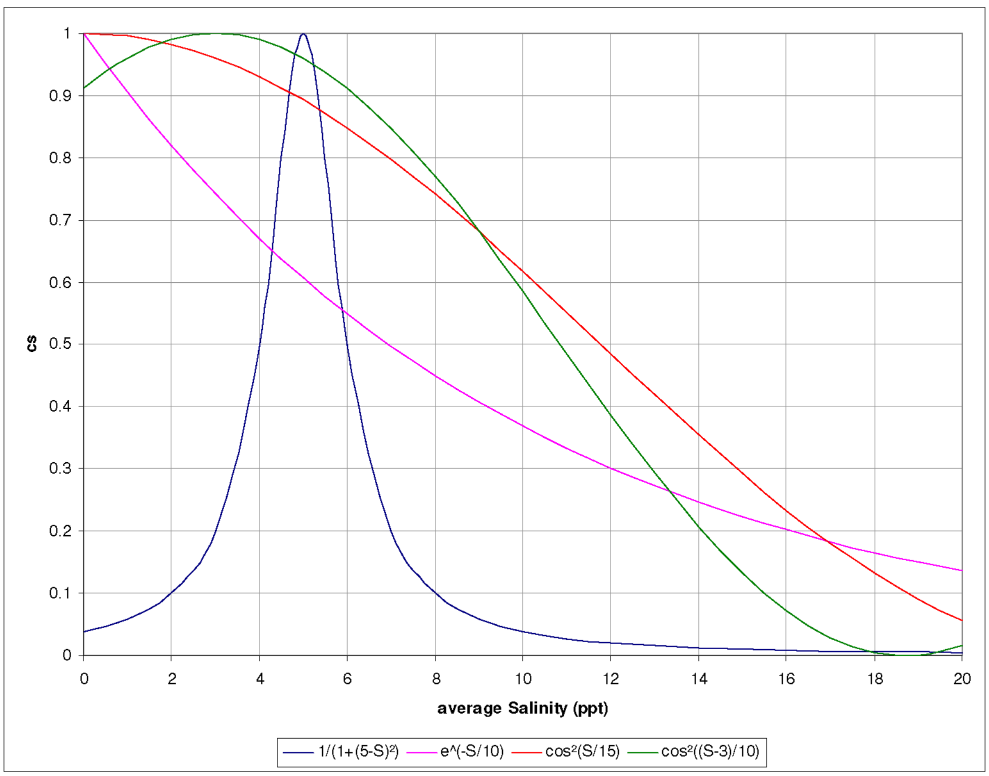

Figure 5-6: Possible functions for coefficient representing the proximity of the turbidity maximum.

The multiplication of these two factors and the tuning of coefficients have lead to the relatively good prediction of the average suspended sediment concentration $\overline{c}$ near the entrance of Deurganckdok (Figure 5-7):

Equation 5-5:

$$\bar{c} = c_t c_s$$

Measured series are more limited in time-span since the average is used of four equipments at both sides at the dock's entrance at bottom and top of the water column. Remaining gaps in the estimated series are due to gaps in salinity data from buoys 84 and 97 and are filled by either measured values at DGD or linear interpolation.

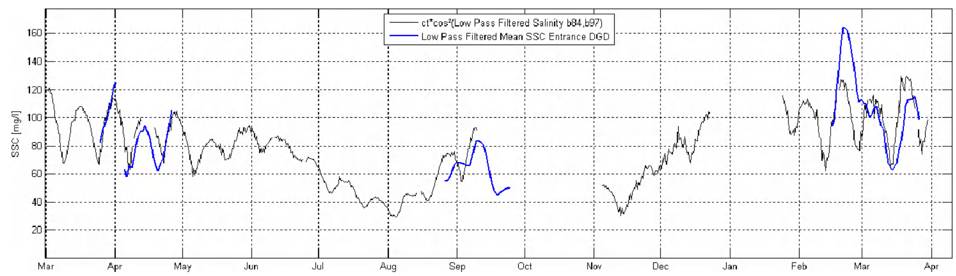

Figure 5-7: Low pass filtered suspended sediment concentration measured at DGD (blue) versus the estimated mean suspended sediment concentration year-round.

Here the model has an NRMSE of 0.16. Again, the higher and lower estimate will be the middle estimate multiplied by 1+NRMSE and 1-NRMSE respectively (Figure 5-8).

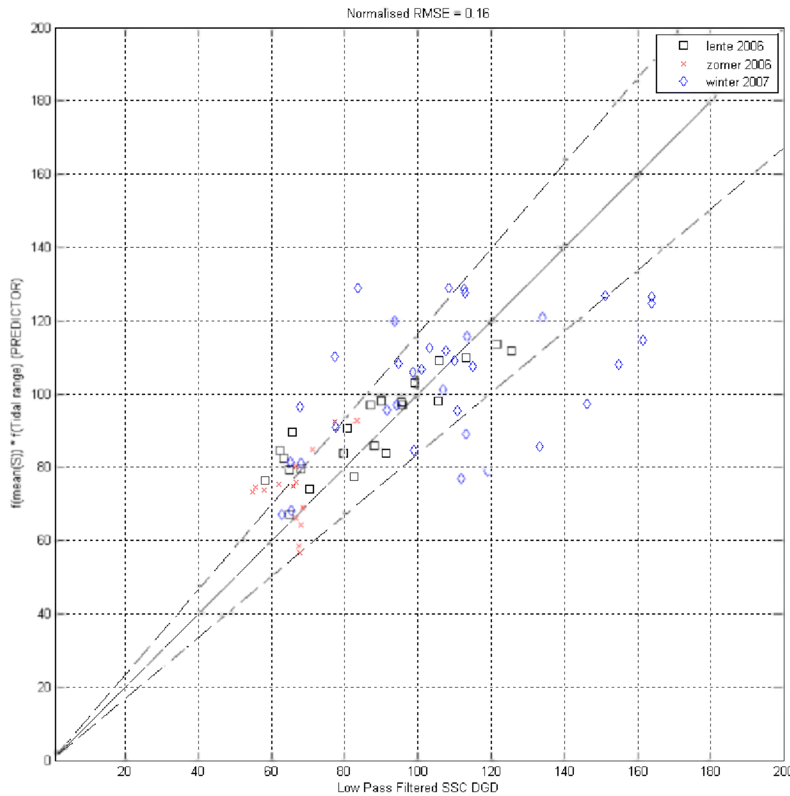

Figure 5-8: Performance of suspended sediment concentration predictor.

5.4. Estimation of long term sedimentation

Since the momentum of currents in the dock is very limited the amount of sediment deposited in the dock will always be dependent on the amount entering the dock, i.e. the fraction of suspended sediment entering which is not advected out. This fraction is dependent on the settling velocity. In a first stage, the settling velocity over a tidal cycle will be assumed constant. It will be assumed that hydrodynamic conditions within the dock will never result in bed shear stress high enough to erode and resuspend sediments.

The net flux of sediments can be described by the integral in Equation 5-6, the convention for velocity v being positive downstream or outbound the dock. The total flux can be decomposed into three components. (i) the flux due to the average velocity over the entrance section of the dock, meaning the tidal filling and emptying of the dock with a volume equal to its tidal prism (first term in Equation 5-7); (ii) the flux due to mixing effects induced by density currents, typically characterised by velocity stratification; (iii) flux generated by eddies along the entrance of the dock (horizontal entrainment).

Equation 5-6:

$$F = -\int_A \int_T v(t,x,z)c(t,x,z)dtdA$$

Equation 5-7:

$$F \approx -A\int_T \bar{v}(t)\bar{c}(t)dt - T_{dens}\int_A \overline{v_{dens}}(x,z)\bar{c}(x,z)dA - T_{eddy}\int_A \overline{v_{eddy}}(x,z)\bar{c}(x,z)dA$$

$$= F_t + F_d + F_e$$

where: A is the cross sectional area of the entrance of DGD

v is the flow velocity perpendicular to the entrance (convention positive downtream).

c is the suspended sediment concentration

T is the tidal cycle period

T_{dens} is the duration of density currents

T_{eddy} is the duration of eddy circulation

v_{dens} is the velocity perpendicular to the entrance due to density currents

v_{eddy} is the velocity perpendicular to the entrance due to large eddies

F is the net sediment flux during 1 tidal cycle (convention positive downstream)..

F_t is the tide induced sediment influx

F_d is the sediment influx due to density currents

F_e the sediment influx due to eddies (horizontal entrainment).

5.4.1. Tidal Filling

The first term in the RHS of Equation 5-7 can be seen as the fraction of sediment influx due to the tidal filling and emptying of the dock. The velocity and sediment concentration in this term are averaged over the cross section. A function for an estimate of this term should therefore be a function of tidal amplitude, average sediment concentration and dock's surface area, which are all known or estimated in previous steps.

This function is thus of the following shape, being an estimate for the sediment influx in g per tidal cycle:

Equation 5-8:

$$F_t = c_1.h.A_h.\bar{c}$$

in which: c_1 is a dimensionless constant (=0.9), h is tidal amplitude (m/tide), A_h is the surface area of the dock (m²) and $\bar{c}$ is the average sediment concentration over the entrance's cross section area (g/m³).

The constant c_1 in Equation 5-8 is a measure of the fraction of the sediment entering due to tidal filling remaining in the dock after settling. Since an extensive measurement campaign on sediment properties and settling has been carried out in the dock from 5 to 7th of September 2006 a good amount of information is present about the settling velocity, floc size and settling fluxes near the bottom (IMDC, 2006g). Floc size and floc settling velocity spectra were measured using the INSSEV equipment. Floc settling velocity has been found in the range of 0.5 to 1.5 mm/s for microflocs and of 2 to over 5 mm/s for macroflocs. Concerning residence time of a floc in the dock –only taking into acount tidal prism exchange- the exchange rate is compared to the volume of the dock. This short exercise learns that the residence time is at least 40 hours in absence of eddy's and density currents and taking into acount a nominal depth of the dock at half its length (construction in progress). When this number is compared to a settling velocity in the range 0.5 – 5 mm/s, one can only conclude that sediments suspended in water entering the dock due to tidal filling must be settled out almost completely. The fraction c_1 has been taken at 0.9.

5.4.2. Density Currents

The second and third term in the RHS of Equation 5-7 are a measure of the mass of sediment accumulating in the dock due to phenomena with important spatial gradients over the dock's entrance, i.e. density currents and horizontal eddy circulations respectively. In this case the velocity and sediment concentration are the average over one tidal cycle since concentration gradients are very difficult to be calculated in between the measurement periods. For the velocity of density currents and eddies one value is used per tide based on a parameter with the capacity to predict the intensity of the current: salinity amplitude for density currents, tidal amplitude (tidal coefficient) for large eddies.

The integral could be approximated by a function of average sediment concentration (available by estimate) and the intensity of the density currents / eddies, the latter being unavailable throughout the whole year. Therefore it will be assumed that the salinity amplitude at the dock's entrance is a measure for the intensity of the density current, as it is the driving force for exchange between high and low density volumes resulting in stratified current profiles. The tidal amplitude is a measure for flood and ebb velocities in the Scheldt River; in turn inducing shear along the open entrance to the dock, resulting in large eddies at the entrance. The vorticity of the eddy has an opposite sign during flood compared to during ebb (vorticity is calculated as the rotor of the velocity field, its sign determined with the righ-hand rule, negative for clock-wise rotation and vice versa).

If now the density current is schematised in two layers of equal thickness with flow velocities in opposing direction and equal velocity magnitude, the sediment mass deposited in the dock due to density currents can be estimated as follows. The schematisation implies that due to the density current an amount of water is exchanged without changing the volume in the dock, discharge out equals discharge in (Figure 5-9). The fraction of the sediment in the inflowing water that is settled out and deposited in the dock multiplied by the exchanged liquid discharge times the average sediment concentration is a measure for the net sediment influx due to density currents. The average sediment concentration is available through estimate, the average exchanged liquid discharge is proportional to the salinity amplitude, but the fraction of sediment settled out is unknown.

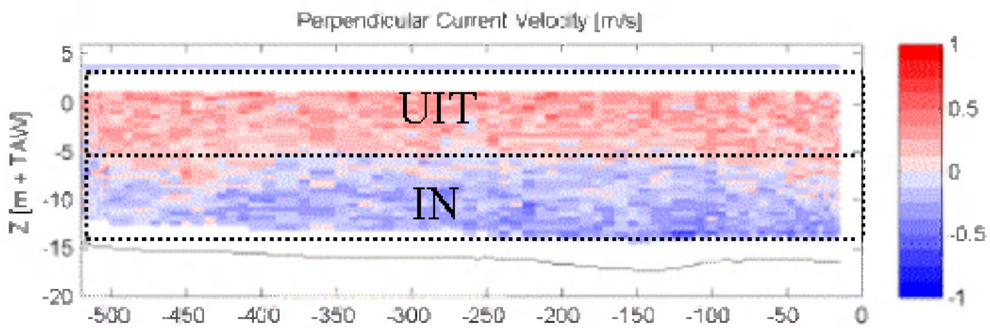

Figure 5-9: Example of density current at high water, denser, more saline water flows in the dock (v<0) in the lower half of the water column and fresher water flows out in the upper half. Schematisation in black.

However, the measurements of sediment concentration near the bottom and near the surface can give some information through a concentration gradient. From through-tide measurements it can be concluded that from high water to 3 hours after high water density currents are roughly inbound near the bottom and outbound near the surface (situation as in Figure 5-9), from low water to 3 hours before high water is it the opposite. This behaviour is in line with schematisations presented in PIANC (2008).

When the vertical gradient of sediment concentration (positive for increasing concentration with depth) is calculated between high water and three hours after high water (bottom: inflow/high concentration, surface: outflow/low concentration) it can be applied as a measure of the amount of suspended sediment that flows in but does not flow out again, the net influx due to density currents during this high water density current. In the same way the vertical gradient during and after low water can be a measure of the fraction of sediment that flows out but does not come in again during the low water density current, which has opposite flow directions. The relative difference of vertical gradient between the high tide case (Figure 5-9) and the low water case can be taken as a measure for the unknown settled fraction during a tidal cycle (Equation 5-9). In the case of Deurganckdok density currents have been found to have a higher vertical sediment concentration gradient during the high water case -when estuarine water flows in the dock near the bottom-compared to the low water situation –when water from the doch flows out near the bed. In both situations the concentration is higher in the lower part of the water column. The conclusion is that during the high water situation an amount of sediments is imported in the dock, during the low water situation a slightly smaller amount is exported again. The net imported fraction of all exchanged sediments over a tidal cycle is then equal to $\alpha_{set,dens}$.

Equation 5-9:

$$\alpha_{set,dens} = \frac{\left(\left.\frac{dc}{dz}\right|_{HW} - \left.\frac{dc}{dz}\right|_{LW} \right)}{\left.\frac{dc}{dz}\right|_{tidalcycle}}$$

The velocity related to the density difference can be found in Kranenburg (1996), and is expressed as follows assuming no friction with the bed and equal layer thickness:

Equation 5-10:

$$u_d = 0.5(\varepsilon g h)^{1/2}$$

in which: $\varepsilon = \frac{\rho_2 - \rho_1}{\rho_2}$; ($\rho_2 > \rho_1$ and $\varepsilon << 1$)

Now it follows that the net solid discharge due to density currents can be calculated from a number of estimated parameters (each with low, normal and high estimate):

Equation 5-11:

$$Q_{s,d} = \alpha_{set,dens}\left(\frac{A_{cs}}{2}\right)c_2(\varepsilon g h)^{1/2}\bar{c}$$

where: A_{cs} is the cross sectional area of the entrance, c_2 is a constant, ε is the relative density difference per tide (equivalent to the salinity amplitude), $\alpha_{set,dens}$ is a coefficient representing the settled fraction of sediment inflow due to density currents and $\bar{c}$ is the tidal average sediment concentration.

In this relation $\Delta\rho$ is a measure for the pressure gradient providing momentum for density currents, in turn being an indicator for the intensity of the density current.

Coefficient c_2 is dimensionless and has been used to calibrate the suspended sediment flux against available observations from through-tide measurements. From Equation 5-10 its values should be close to 0.5, here it has been set to 0.55 after comparison of estimated density current in Equation 5-11 and observed density current magnitude during through-tide measurements with ADCP equipment.

Additionally, the effect of tidal filling and emtying on the density current should be taken into account. In Figure 5-10 an overview is given of schematisations of different possible situations. When the dock is being emptied by falling water levels all the net outflow has pass through half of the cross section (again for schematised density current with equal flow area in and outgoing currents). In case of DGD the dock is relatively fresh (lower salinity) during tidal emptying, and thus the top right plot applies. For tidal filling of DGD the middle lower plot applies.

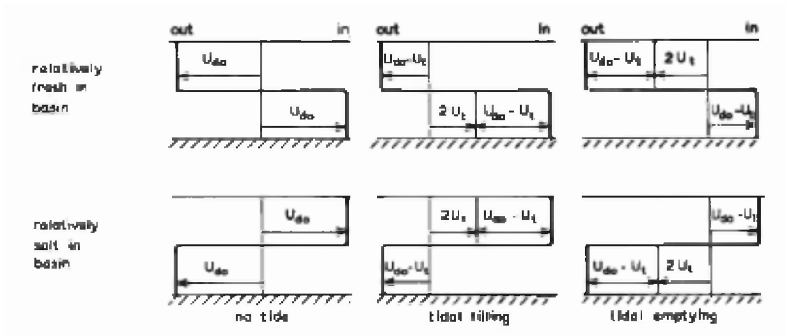

Figure 5-10: Influence of tidal filling and emptying on a density current (Eysink, 1983). Where U_{do} is the exchange velocity without influence of tidal in- and outflow, U_t is the flow velocity related with tidal prism.

An estimate of Udo and Ut learns that Udo is about 10 times higher than Ut, therefore it has been assumed that the effect of tidal filling and emptying can be neglected.

Some modelling studies indicate a possible reflection of an internal saline water wave from the back of the dock. The effect of this reflection can be damping or limitation in time period of the density current (Van Maren, personal communication).

5.4.3. Large Horizontal Eddy

A similar approach could be adopted for schematisation and estimation of the effect of large horizontal eddy formation and related turbulent exchange along the entrance on sediment influx. During flood current in the Scheldt River shear induces clockwise eddy circulation (Figure 5-11), during ebb current anti-clockwise. A consideration should be made about the difference in flood velocity and ebb velocity.

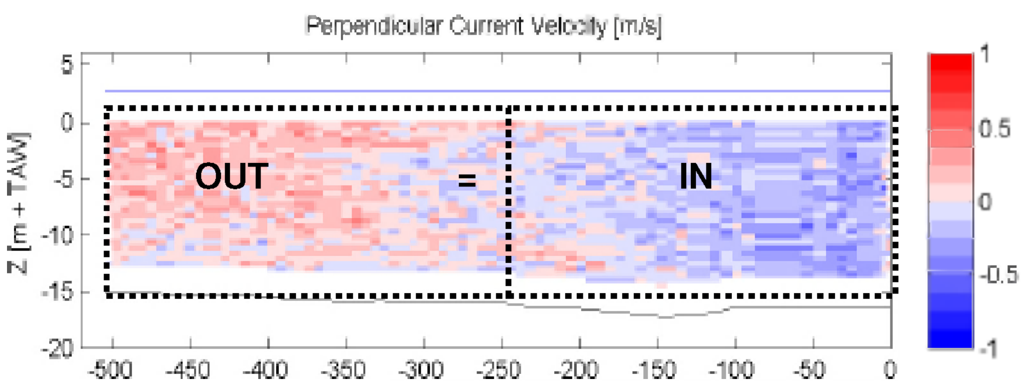

Figure 5-11: Example of eddy circulation flow at the entrance of the dock during flood: at the inland end water flows in (v<0) at the seaward end water flows out, view towards the Scheldt. Schematisation in black.

Similar to the density current approach the exchanged waters are calculated from mean velocity magnitude in the eddy and the tidal coefficient to account for the neap-spring cycle variations in current velocity in the Scheldt estuary. Half of the cross section area times the mean current velocity in the eddy times the period during which this situation occurs per tidal cycle equals the exchanged volume of water due to turbulent exchange. Multiplication by the mean sediment concentration (only tidal mean of concentration is available year-round from estimates) gives the exchanged sediment volume. A fraction of this volume will remain in the dock due to settling and deposition at decelerating current.

Information from measurements useful for an approximation of this fraction is the suspended sediment concentration gradient along the entrance measured during three campaigns, again, it is impossible to calculate for periods in between measurement campaign at DGD based on long term measurements at buoys 84 and 97. Therefore an approximation is based on the difference between the gradient during ebb and during flood. Considering the gradient is calculated as the concentration at the left quay (North-Entrance), minus the concentration at the right quay (South-Entrance) divided by the distance and the rotational direction of the eddy (flood: clockwise, ebb: anti-clockwise) the following is true, temporally provided ebb and flood velocities are equal (Table 5-1):

Table 5-1: Relation between influx due to eddy circulation and tidal phase

Tidal phase	**Duration**
$\left.\frac{dc}{dB}\right\|_{flood} \sim -Q_{s,e}$	HW-3 to HW = 3 hours
$\left.\frac{dc}{dB}\right\|_{ebb} \sim Q_{s,e}$	HW+2.5h to HW+4h = 1.5 hours

When the eddy is clockwise during flood and the gradient is negative (concentration lower on the North side) it can be assumed that less sediment is advected out than is advected in. For the counter-clockwise eddy during ebb a positive gradient also means that less sediment is advected out than is advected in.

From the average duration of the eddy velocity pattern during the different tidal phases it is observed that the duration of the ebb eddy is smaller than of the flood eddy, the flood eddy being substantially stronger because during falling tide the mixing layer is advected out of the entrance area (see also Eysink, 1989). In literature it is often assumed no eddy can be formed in case of strong tidal outflows, however, a weak eddy has been observed at DGD's entrance during ADCP measurements. Also it is known that the Scheldt estuary is flood dominated near DGD according to the classification of Dyer (1995) and from observations (IMDC, 2006). This means that flood velocity is higher than ebb velocity, another the reason for the stronger eddy during rising tide. Therefore the horizontal sediment concentration gradient during rising tide is multiplied by a factor 2. The coefficient representing the fraction of circulated sediment remaining in the dock is calculated as follows:

Equation 5-12:

$$\alpha_{set,eddy} = \frac{\left(\left.\frac{dc}{dB}\right|_{ebb} - 2\left.\frac{dc}{dB}\right|_{flood} \right)}{\left.\frac{dc}{dB}\right|_{tidalcycle}}$$

The approximated net solid discharge due to eddy circulation is calculated as a function of the settled fraction, the mean concentration, the mean eddy velocity and the tidal coefficient:

Equation 5-13:

$$Q_{s,e} = \alpha_{set,eddy} \bar{v}_{eddy} \left(\frac{A_{cs}}{2} \right) \left(\frac{h}{\bar{\bar{h}}} \right) \bar{c}$$

where: A_{cs} is the cross sectional area of the entrance, $\alpha_{set,eddy}$ is the coefficient representing the settled fraction of sediment inflow due to eddy currents, $\bar{c}$ is the tidal average sediment concentration $\bar{v}_{eddy}$ is the average eddy current velocity and $\left(\frac{h}{\bar{\bar{h}}} \right)$ is the tidal coefficient.

For $\bar{v}_{eddy}$ a value of 0.05 m/s has been used for the minimum estimate, a value of 0.10 m/s for the mid estimate and a value of 0.15 m/s for the maximum estimate. Note that these values are average velocity magnitudes over half of the entrance area and over the period during which the eddy is present. Maximum eddy velocities may amount to a factor three higher.

As mentioned above the mixing layer at the entrance of the dock is advected out of the dock due tidal emptying and advected in the dock during tidal filling. Obviously this effect is stronger when tidal filling and emtying flow is stronger, i.e. during spring tide. To acount for this effect an extra correction is applied based on Eysink (1989): the exchanged liquid discharge rate is reduced with $\beta Q_t = \beta A_{cs} u_t$ with u_t the average tidal filling/emptying velocity, which is about a factor 2 higher during spring tide compared to neap tide.

The expression for net solid discharge due to turbulent exchange Equation 5-13 becomes:

Equation 5-14:

$$Q_{s,e} = A_{cs} \left[\frac{1}{2} \alpha_{set,eddy} \bar{v}_{eddy} \left(\frac{h}{\bar{\bar{h}}} \right) - \beta \frac{2 A_h h}{A_{cs} T} \right] \bar{c}$$

Where β is dimensionless and equal to 0.11.

5.4.4. Overall net sediment inflow per tidal cycle

Since suspended sediment concentration gradients (vertical and horizontal) are only measured during limited periods, the average $\alpha_{set,dens}$ and $\alpha_{set,eddy}$ have been determined:

Table 5-2: Value of coefficient representing settled fraction

parameter	Value [-]
$\alpha_{set,dens}$	0.36
$\alpha_{set,eddy}$	0.6

Next the estimated net solid discharge components due to density currents and large eddies have been multiplied with the duration of existence during a tidal cycle, from where the amount of sediment influx per tide is obtained: F_d due to density currents and F_e due to the turbulent exchange processes in eddy's in the boundary layer.

The total net influx of suspended sediment into DGD is calculated as the sum of influx due to tidal prism (F_t), the influx due to density currents (F_d) and the flux due to eddy circulation currents (F_e). Density currents account for the largest part of the siltation with an average contribution to siltation of about 800 Tons Dry Matter (TDS) per tide followed by tidal prism exchange (250 TDS per tide) and horizontal eddy circulation (250 TDS per tide).

After executing all required calculations sediment fluxes are in the range of 500 to 3000 TDS per tide have been obtained (Figure 5-13). Since large uncertainties remain in the estimates a low and high estimate have been calculated leading to an uncertainty interval around the calculated flux values.

The variation in net sediment inflow is relatively limited throughout the year, with a slight decrease during the summer. The reason is that for example during winter the sediment concentration is higher (Figure 5-7) while the salinity amplitude is lower (Figure 5-4) due to the higher river runoff. Both effects partially single out each other. The cumulative natural siltation is shown in Figure 5-14.

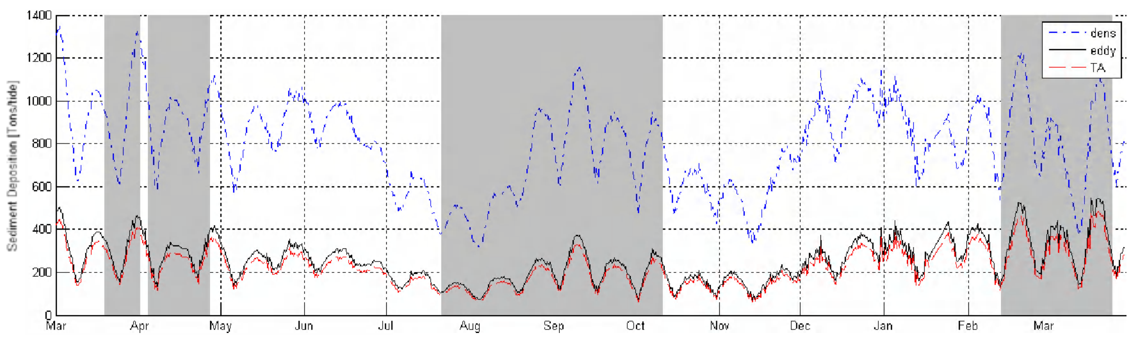

Figure 5-12: Sediment influx due to density currents, eddy circulation and tidal amplitude (tidal prism).

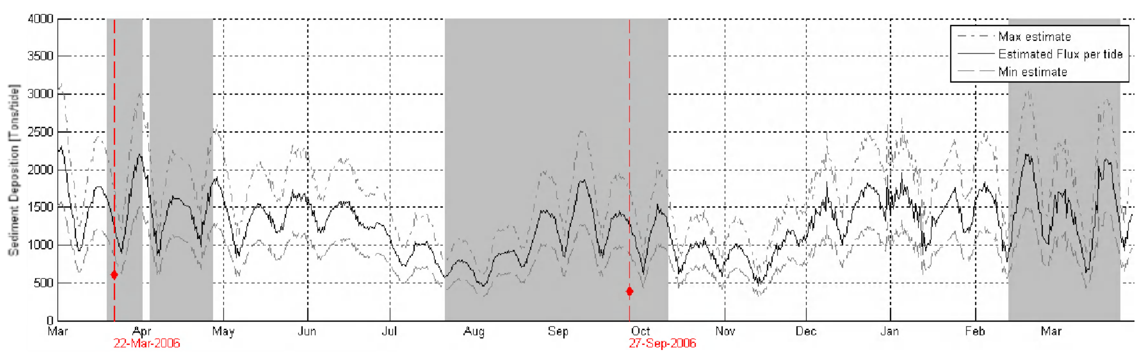

Figure 5-13: Time series of estimated sediment influx (with uncertainty interval), grey zones indicate periods of measurement in DGD, red dots indicate through-tide measurements of which the observed suspended sediment influx is available.

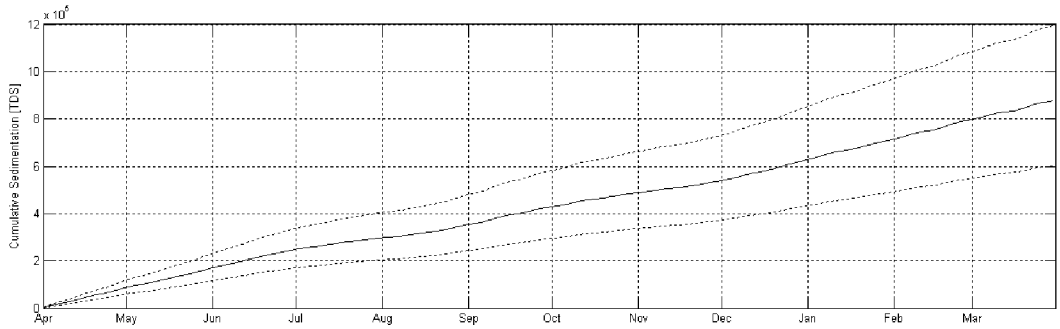

Figure 5-14: Cumulative natural sedimentation in black (x100,000 TDS) with zero at April 1st 2006, uncertainty band in grey. Average sedimentation rate varies with seasons, lowest rates in July and August.

After calculation of an estimate for each tide from 1st of March 2006 to 1st of March 2007 the time integral has been calculated (Table 5-3). The main estimate shows a value of 861,000 tons dry matter net inflow of suspended sediments in 12 months. The uncertainty on these values should be taken as high as 30-40% according to the low and high estimates.

In the table influx values for the three main contributing components of sedimentation have been listed separately. However, these phenomena do not exist individually and interact during tidal phases. By consequence these values are not to be evaluated individually either. When by a future change in dock geometry the flow patterns of one component are changed, certainly the others will change in the process and expected sedimentation reductions based on the table below might be different from reality.

Table 5-3: Yearly suspended sediment influx estimate Deurganckdok (x1000 TDS)

	Low estimate	Mid estimate	High estimate
Tidal prism influx	129	**153**	176
Density current influx	396	**536**	689
Eddy circulation influx	66	**172**	308
Total sediment influx	591	**861**	1172

Sediment movements within the dock from capital dredging works have not been included in this calculation; these values give an indication of the natural inflow of suspended matter due to advection, settling and deposition. Other influences like nearby dredging activities, erosion and resuspension within the dock due to eg. vessel propeller jets have not been included.

A method exists to estimate sediment entrainment into a tidal dock by ships moving past the dock along the Main River or channel. The ship moving past an entrance initially induces an acceleration of the flow in the channel, leading relatively clear water to flow out of the dock. Later, the ship's rear end passes and induces water to flow back in the dock, this time more turbid waters laden with sediments stirred up by the ship's propeller (PIANC, 2008). However, this has not been specifically observed from observations near DGD, possibly because of the large width of the Scheldt relative to the width of the passing ships. Therefore this effect is neglected.

The effect of individual ships moving into the dock may have a more significant effect, especially during highly dynamic tidal phases. This requires separate studies where the wake of a passing container vessel has to be observed, which did not occur during presently executed studies.

An additional source of sediment not represented by the above method is the near bed movement of highly concentrated layers or even fluid mud. Frame measurements on the sill at 0.1m and 1m above the bed show rare concentration peaks of over 3 g/l and no indication has been found of fluid mud layers with concentration over 25 g/l. Therefore it can be assumed that inflow of gravity driven fluid mud flows over the sill at the entrance of Deurganckdok during slack water is of limited or no influence on the sediment balance of the dock.

5.5. Comparison with dregding

Additionnally, the results have been compared to dredged sediment mass in the same period. From BIS data obtained from Afdeling Maritieme Toegang the sediment mass in TDS has been calculated for every week between April 1st 2006 and March 31st 2007. When the sediment mass present in the dock at April 1st is set to zero the evolution of the cumulative natural inflow of sediments per tide has been has been deduced with the mass of sediments removed by dredging (Figure 5-15).

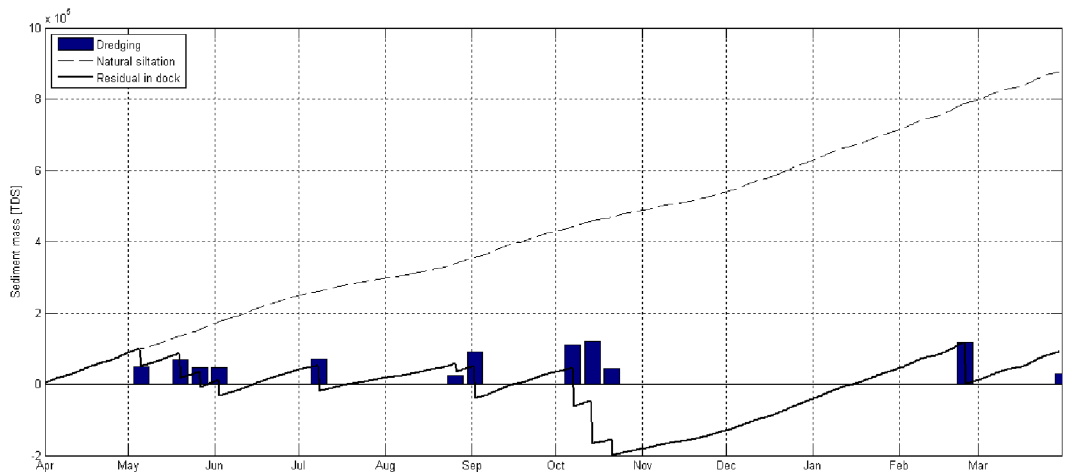

Figure 5-15: Dredged mass (TDS) per week, cumulative natural inflow of sediments and residual sediments in the dock. Sediment mass present in the dock at April 1st is set to zero.

In spring and summer the dredging activities balanced siltation rates, in the month of October a major dredging effort sets back the sediment mass in the dock to 200,000 TDS below the level at April 1st 2006. By the end of February 2007 the dock trapped another 300,000 TDS going up to over 100,000 TDS relative to April 1st 2006. After another campaign in the last week of February the dock was levelled again and with extra siltation in the month of March the final balance on March 31st 2007 is 100,000 TDS above the level of April 1st 2006.

5.6. Water balance through-tide measurements

Since several through-tide discharge and sediment flux measurements have been carried out simultaneously along transects K and I as well as across the entrance of DGD a balance could be calculated of the water body enclosed by those three transects. As a check for the applicability of future data of transects K and I the water balance during through-tide measurements can be calculated. A simple mass balance learns that the sum of the time-integrated discharge through the sides of a water body equals the difference in volume of the body before and after that period of time.

$$\Delta V_T = \int_T Q_{DGD}\,dt + \int_T Q_I\,dt - \int_T Q_K\,dt$$

Where all discharges Q are positive downstream.

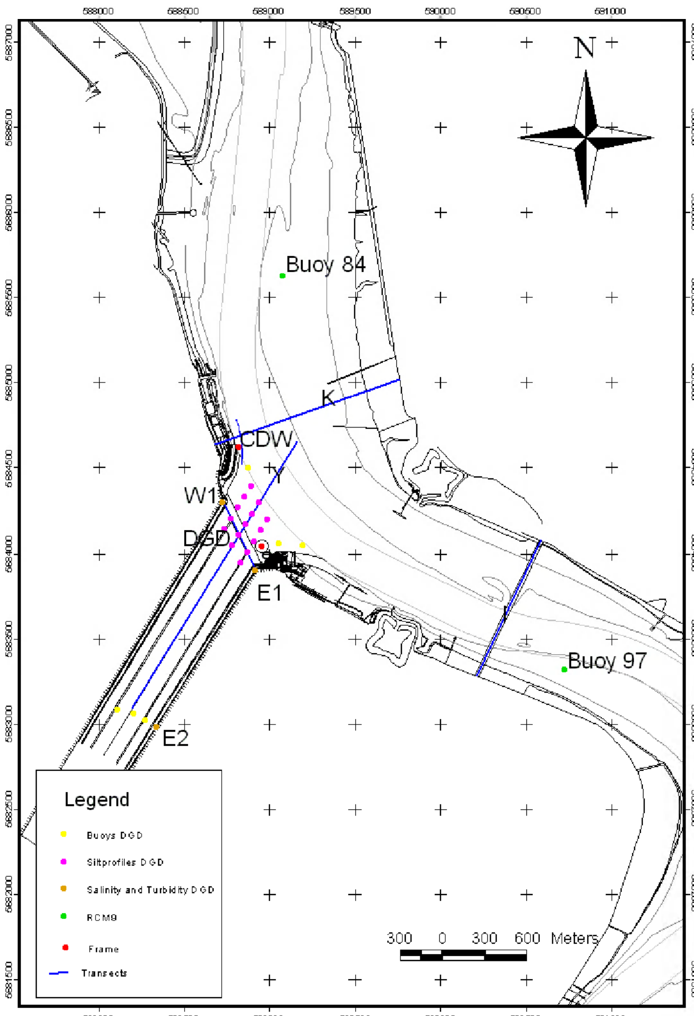

Figure 5-16: Transects K, I and DGD enclose a water body along the Scheldt River

In case this balance is well closed the measurements allow to draw conclusions on the suspended sediment balance in this region: the difference in net flux through transects K and I should then be equivalent to the suspended sediment flux in DGD.

The check has been carried out for two measurement campaigns, on 22th of March 2006 and 27th of September 2006. For both campaigns the net water discharge –or the volume passed during one tidal cycle- was positive for both transects across the Scheldt river (K and I). However, when the balance is made of the stretch of river between them by adding the net discharge from DGD the check does not match, in one campaign (March 2006) the net volume of water accumulated in the enclosed stretch was –2.3 million m^3, for the other campaign (Sept 2006) 3.1 million m^3 (Table 5-4).

The surface area of the river stretch is of the order of magnitude of 3 million m^2, this means that a net volume of water in this area of several million m^3 accounts for about 0.5 m to 1 m difference in water surface elevation. The difference between two successive high water levels between which the campaigns have been carried out was in the range 0.05 m to 0.3 m.

The conclusion is that calculating a numerically integrated volume balance over a tidal cycle induces large errors. The time between two transects is too large to catch the varying flow conditions sufficiently and extrapolation towards the intertidal areas adds to the uncertainty. Therefore it is very hard to calculate a sediment balance of DGD based on measurements along transects up- and downstream of the dock.

Table 5-4: Net water flux per transect and for the control volume (x1000 m^3)

Transect	**22nd of March 2006**	**27th of September 2006**
DGD	3600	690
I	13470	7140
K	19360	4780
ΔV_T	**-2300**	**3100**

6. CONCLUSIONS AND RECOMMENDATIONS

The annual sediment influx in Deurganckdok has been estimated after synthesis of extensive measurement campaigns at short, mid and long term durations. Extensive use of the available data has led to an estimated inflow of sediments due to natural phenomena of 860,000 TDS in twelve months between 1st of April 2006 and 31st of March 2007. An uncertainty of 30 to 40% should be taken into account due to a range of spatial and temporal gaps in the data hailing from the limited possibility of measurement coverage. Sedimentation rates per tide range 500-1000 TDS for neap tides and 1000-2500 TDS for spring tides.

Numerical modelling efforts in the past have shown results of similar magnitude with sedimentation rates at 1200 TDS per neap tide and 1700 TDS per spring tide (IMDC, 1998; Fettweiss et al., 1999). New modelling efforts with highly detailed 3D models being carried out by Van Maren (2006) show results of 700 to 1500 TDS per tide. The report points out the significant effect of constructing a current deflecting wall at the dock's entrance.

Density profiling campaigns of the dock's bed in 2005 (IMDC, 2006f) where removed material by dredging has been taken into account have shown sedimentation rates in the central trench only (with half the dock's length at that time) of 300 to 750 TDS per tide. Through-tide measurement campaigns using ADCP backscatter have shown net sediment import figures of 400 to 700 TDS per tide.

When the obtained estimate is compared to the dredged mass of about 800,000 TDS in the same period we can say the estimated influx is relatively close, since the sediment mass present in the dock increased with 100,000 TDS over one year.

Towards the future analyses of siltation in Deurganckdok, the empirical model presented in this report is a promising tool for determination of the dock's siltation rate with relatively limited effort. Moreover, after repeating the exercise over the planned next two years (April 2007 – April 2008 and April 2008 – April 2009) the model can be calibrated and validated for the dock with full lengh. The parameters determined as such can then be applied as long as the dock's geometry remains unchanged. In that case the only input data required is salinity in the Scheldt River up- and downstream of the dock.

Therefore, it is important data acquisitions at both buoy 83 and buoy 95 are continued. These data sets -combined with simultaneous measurements in the dock– will then allow further tuning and uncertainty reduction of the present model.

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IMDC (2006d) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.4 Through tide measurement Sediview spring tide 27/09/2006 Parel 2 (I/RA/11283/06.119/MSA).

IMDC (2006e) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.6 Salt-Silt distribution & Frame Measurements Deurganckdok 13/3/2006 – 31/05/2006 (I/RA/11283/06.121/MSA).

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IMDC (2007c) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 1.3 Sediment Balance: Three monthly report 1/10/2006 – 31/12/2006 (I/RA/11283/06.115/MSA)

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IMDC (2007f) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.2 Through tide measurement SiltProfiler 26/09/2006 Stream (I/RA/11283/06.068/MSA)

IMDC (2007g) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.5 Through tide measurement Sediview neap tide (to be scheduled) (I/RA/11283/06.120/MSA)

IMDC (2007h) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.7 Salt-Silt distribution & Frame Measurements Deurganckdok 15/07/2006 – 31/10/2006 (I/RA/11283/06.122/MSA)

IMDC (2007i) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.8 Salt-Silt distribution & Frame Measurements Deurganckdok 15/01/2007 – 15/03/2007 (I/RA/11283/06.123/MSA)

IMDC (2007j) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 3.1 Boundary conditions: Three monthly report 1/1/2007 – 31/03/2007 (I/RA/11283/06.127/MSA)

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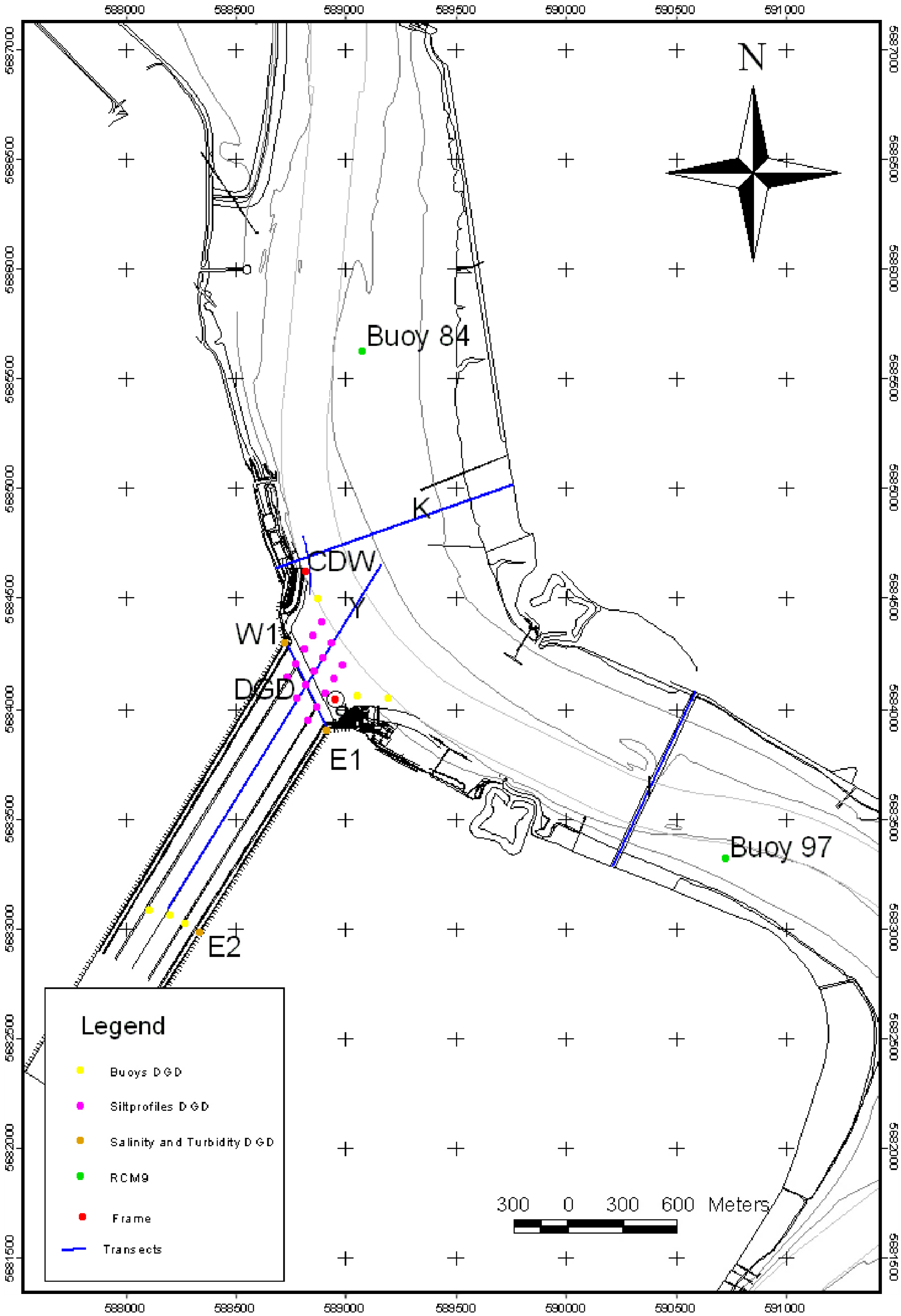
APPENDIX A. LOCATION IN SITU MEASUREMENT SITES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Buoy 97
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Salinity and Turbidity DGD
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Frame
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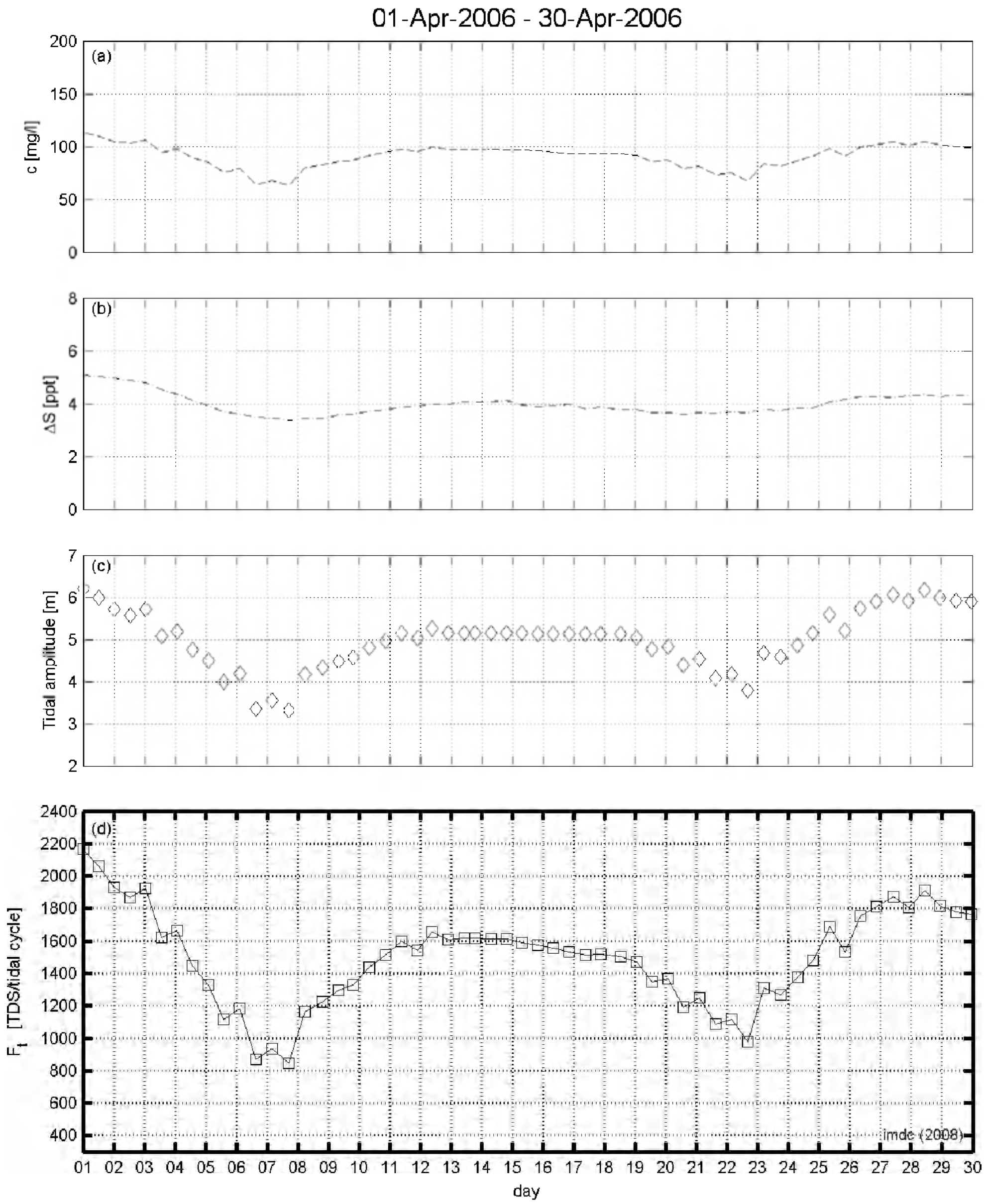
APPENDIX B. SILTATION RATES PER MONTH

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing	
Analysis Siltation Processes	
	Location: Deurganckdok



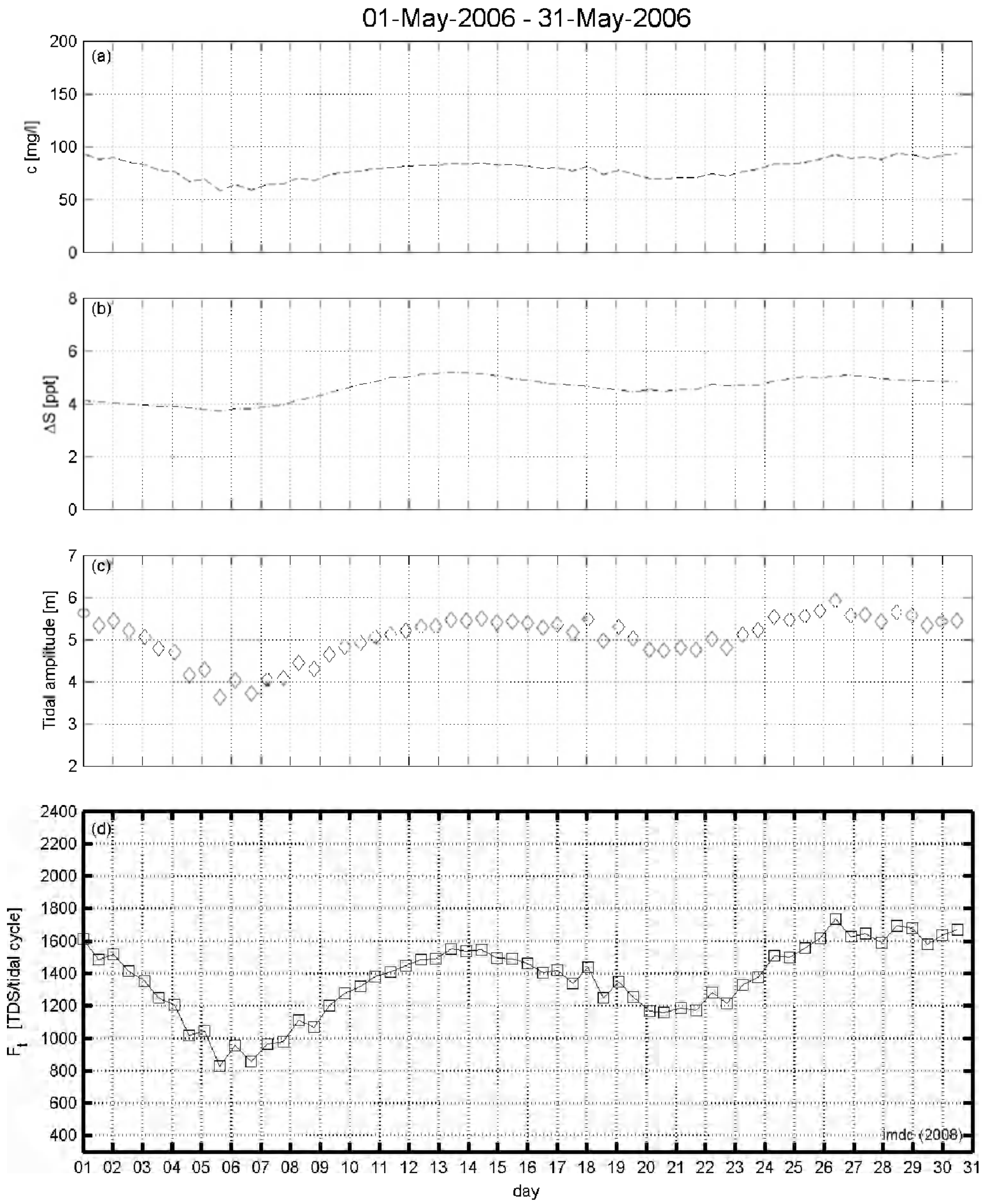
Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).	Data Processed by: IMDC I/RA/11283/06.129/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Data Processed by:

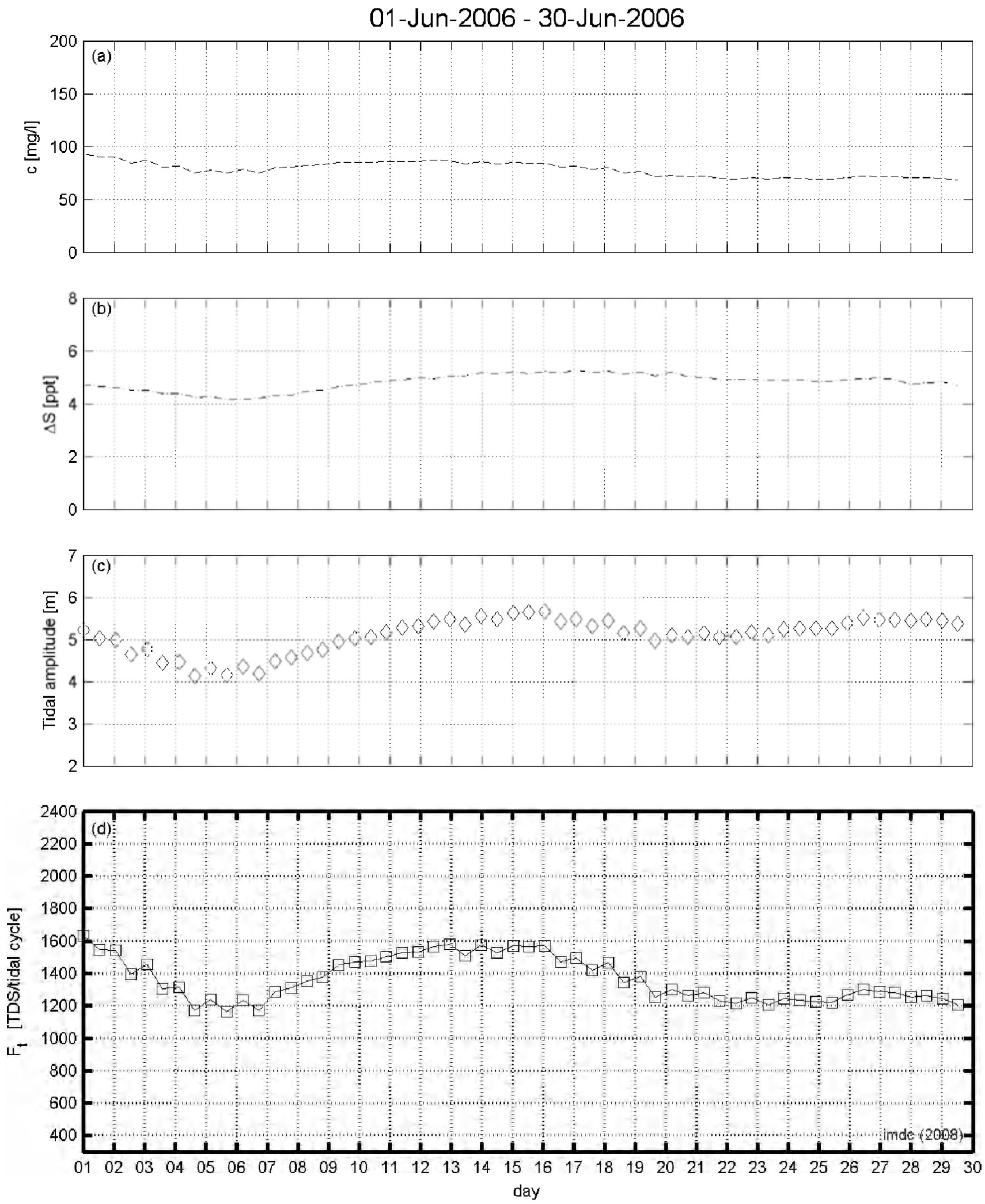
I/RA/11283/06.129/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Data Processed by:

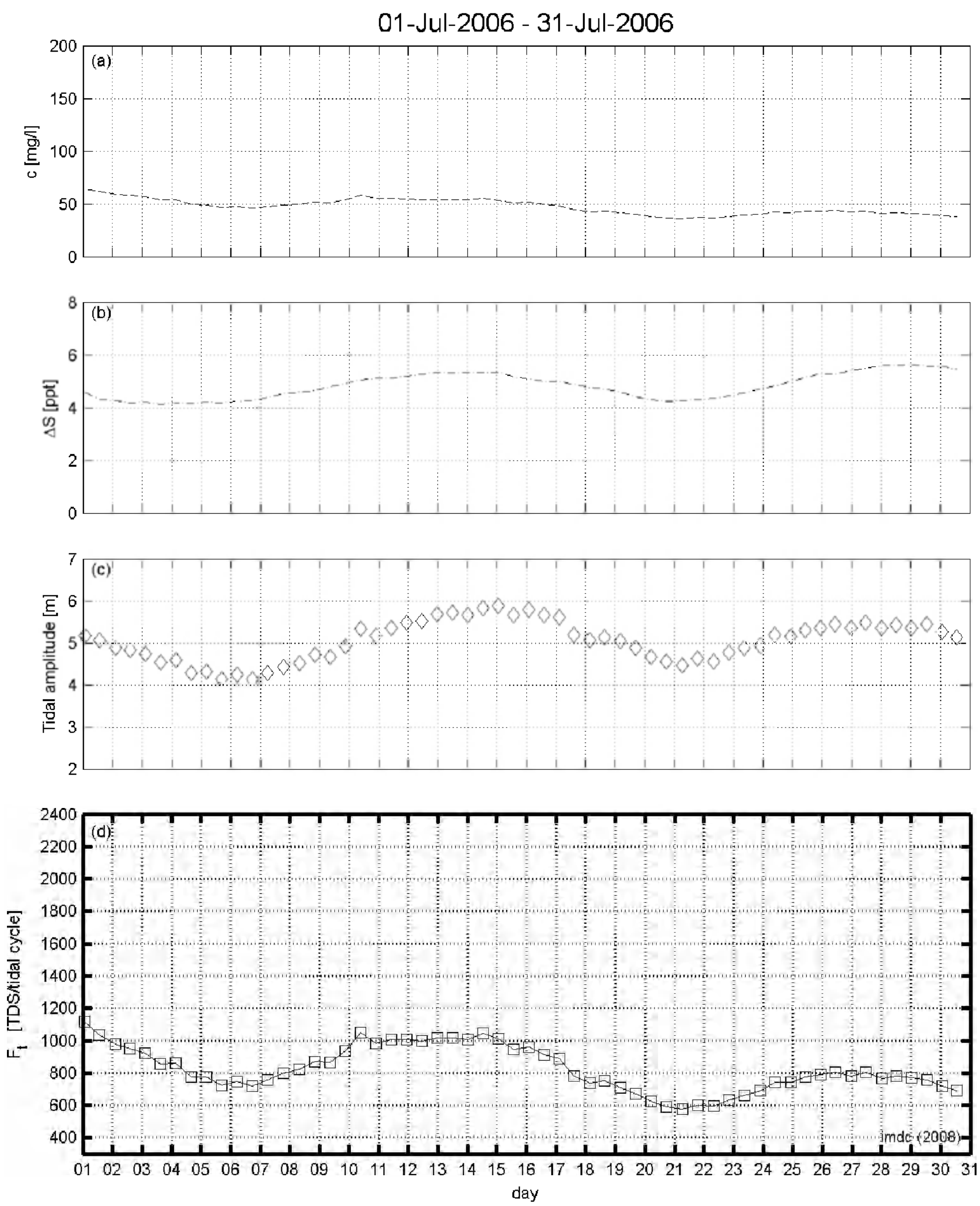
I/RA/11283/06.129/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



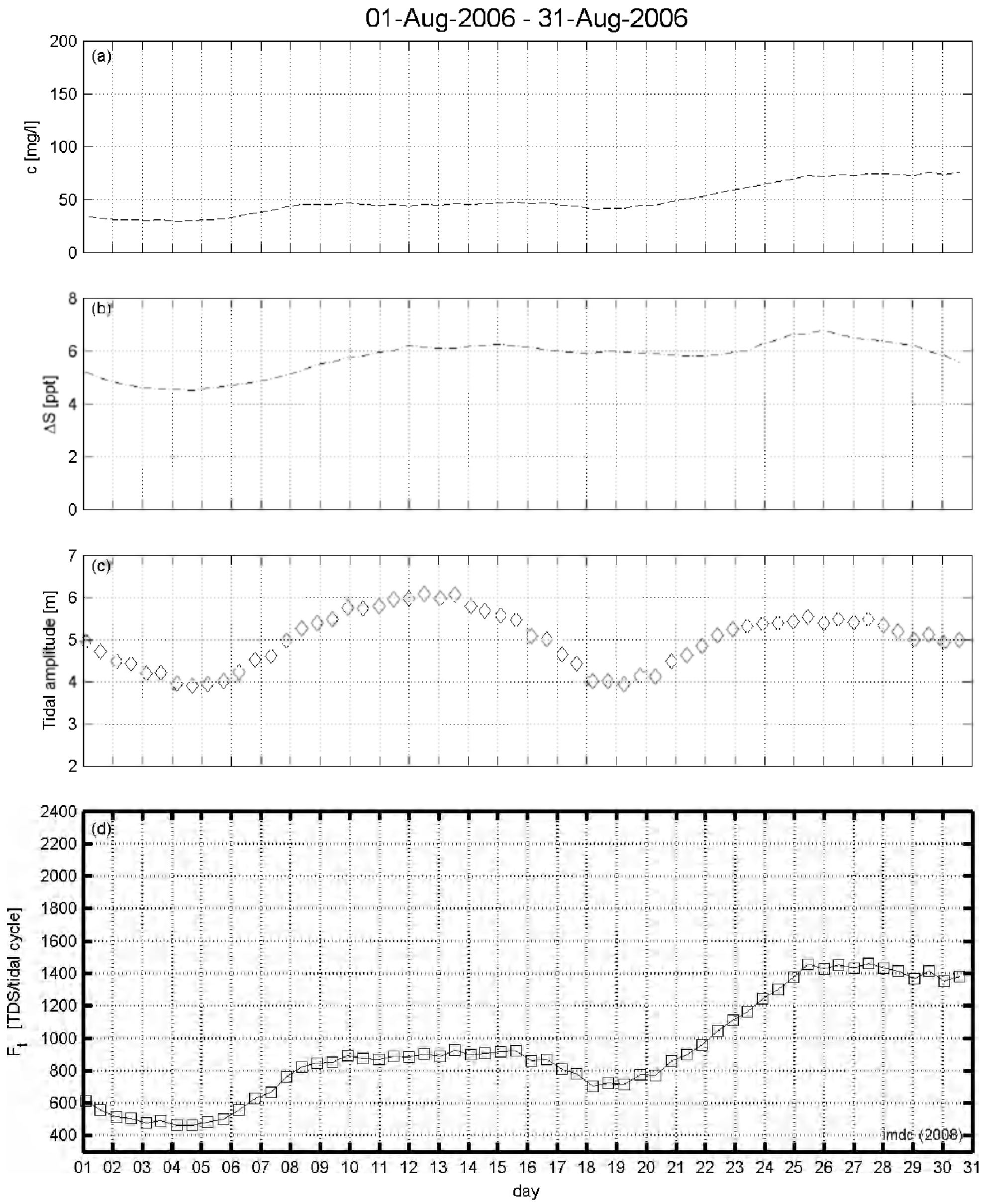
Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Data Processed by: IMDC

I/RA/11283/06.129/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes	
	Location: Deurganckdok



Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Data Processed by: IMDC

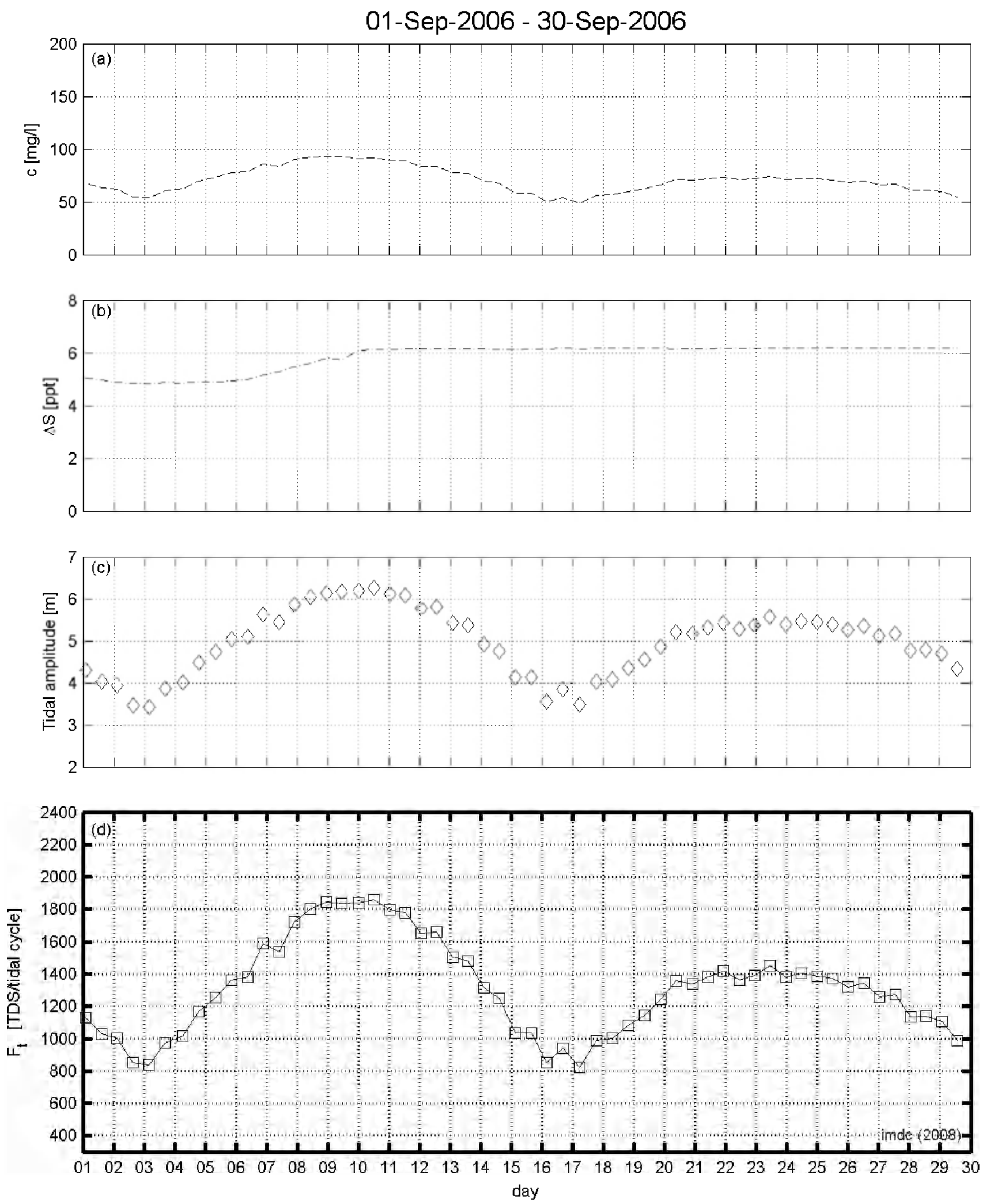
I/RA/11283/06.129/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Data Processed by:

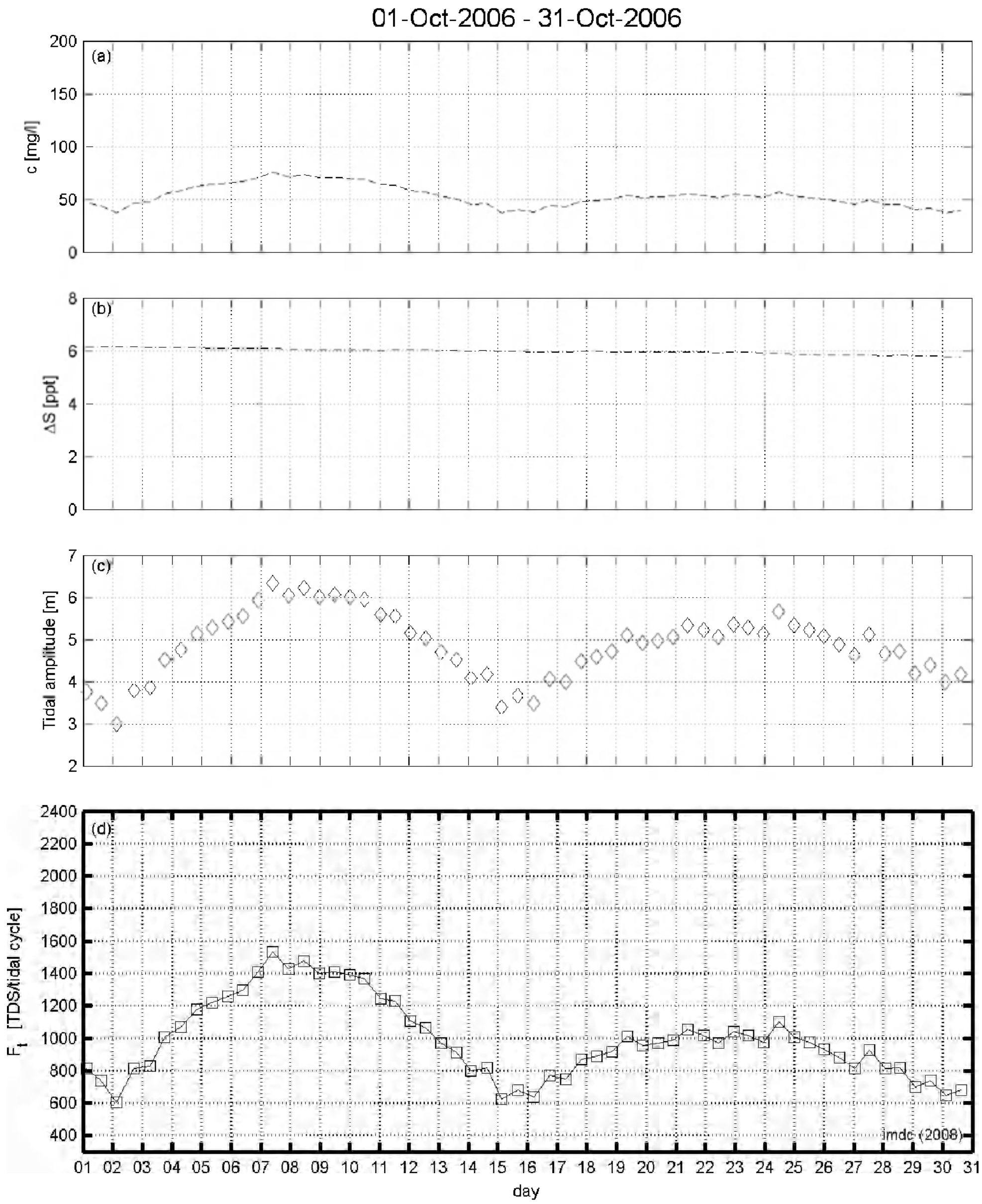
I/RA/11283/06.129/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

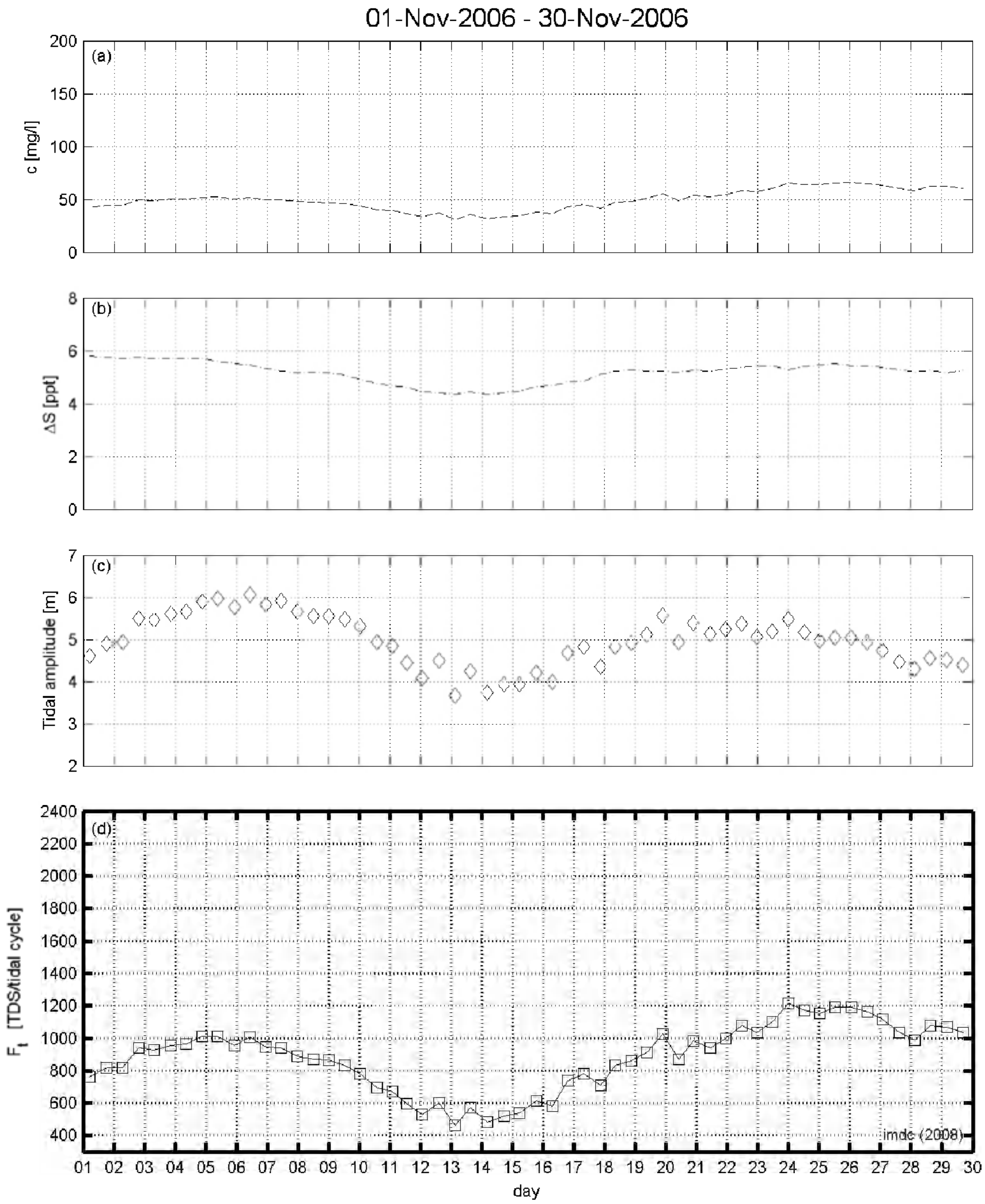
Deurganckdok



Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Data Processed by:

I/RA/11283/06.129/MSA



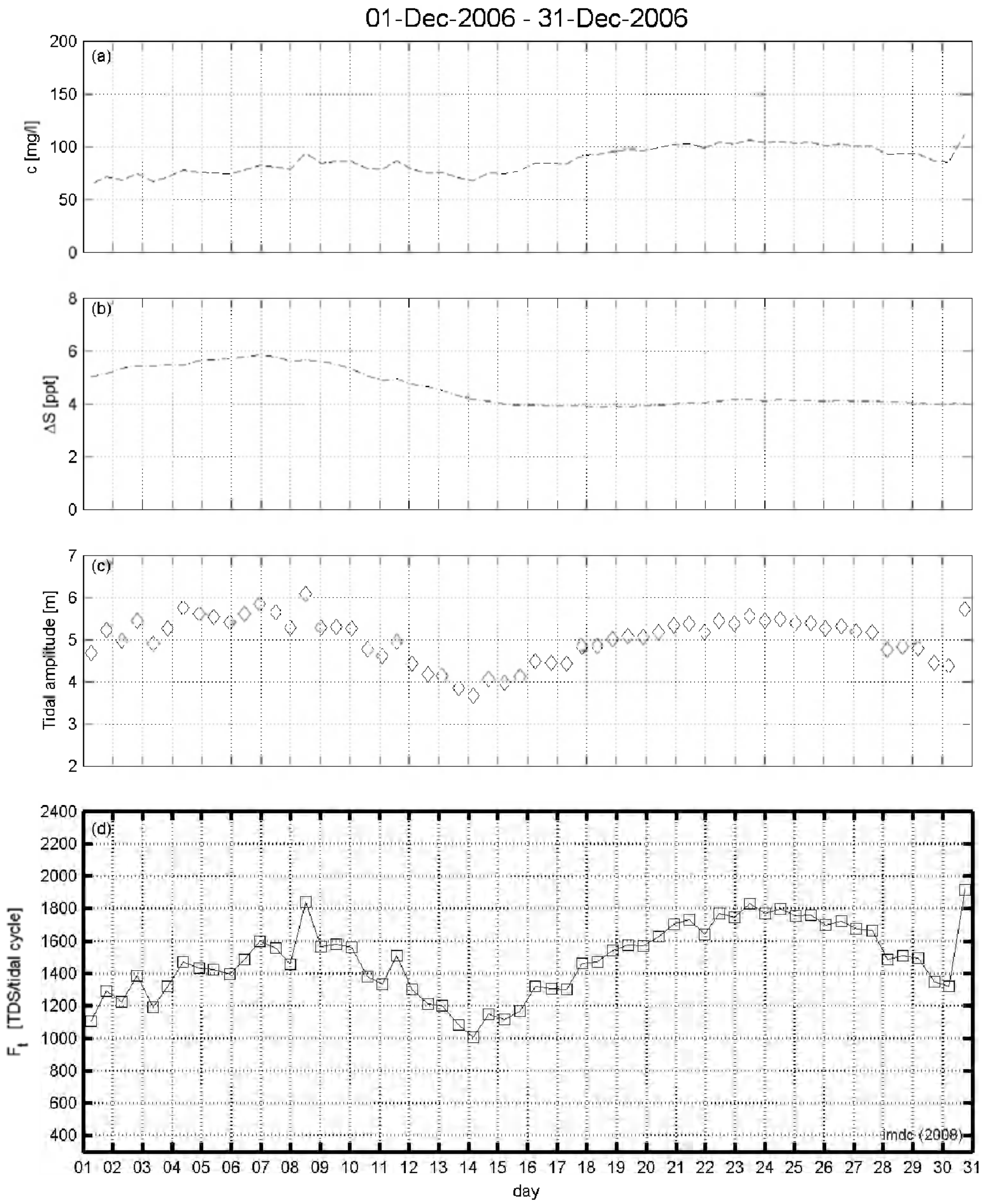
Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Data Processed by:

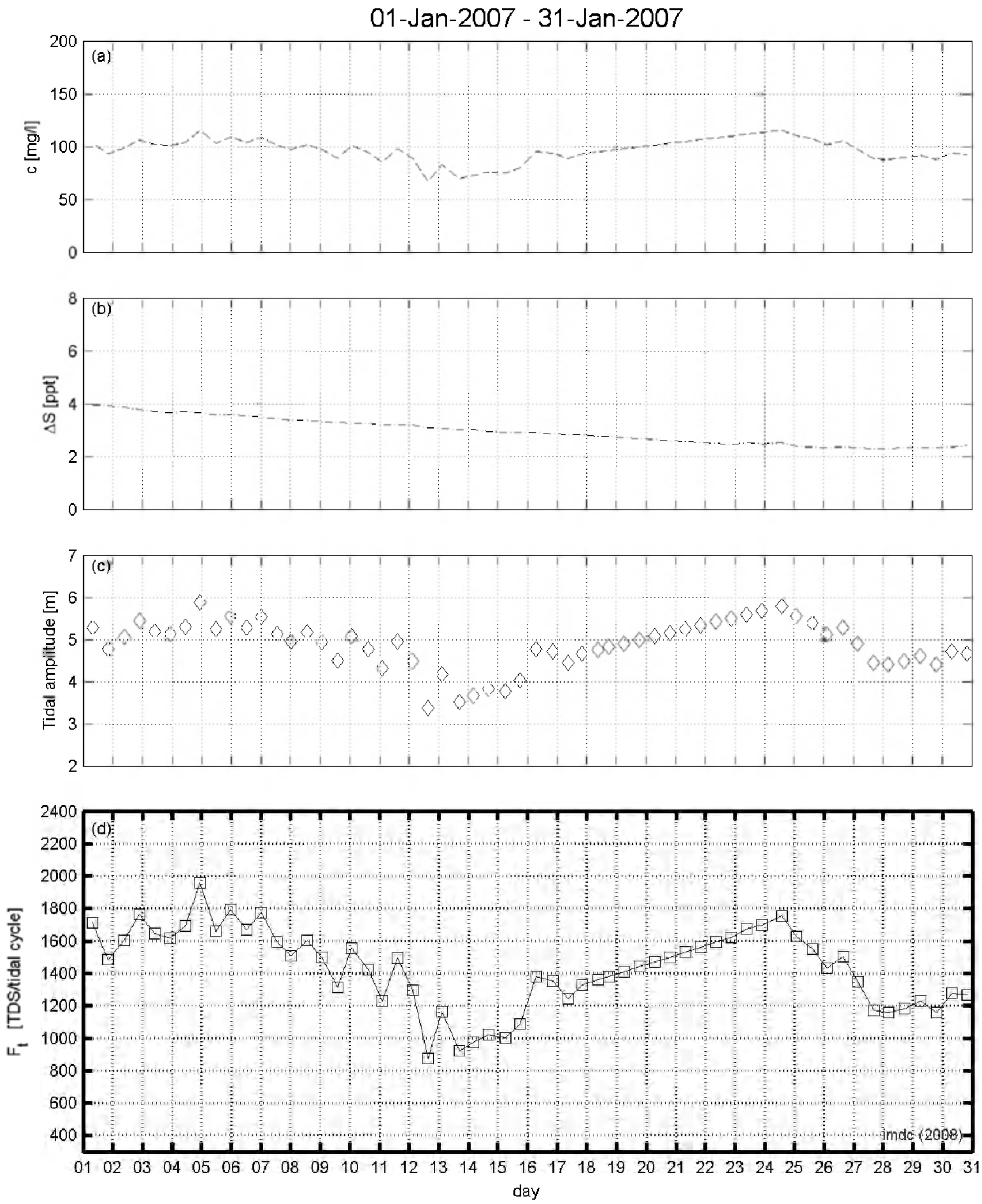
I/RA/11283/06.129/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Data Processed by:

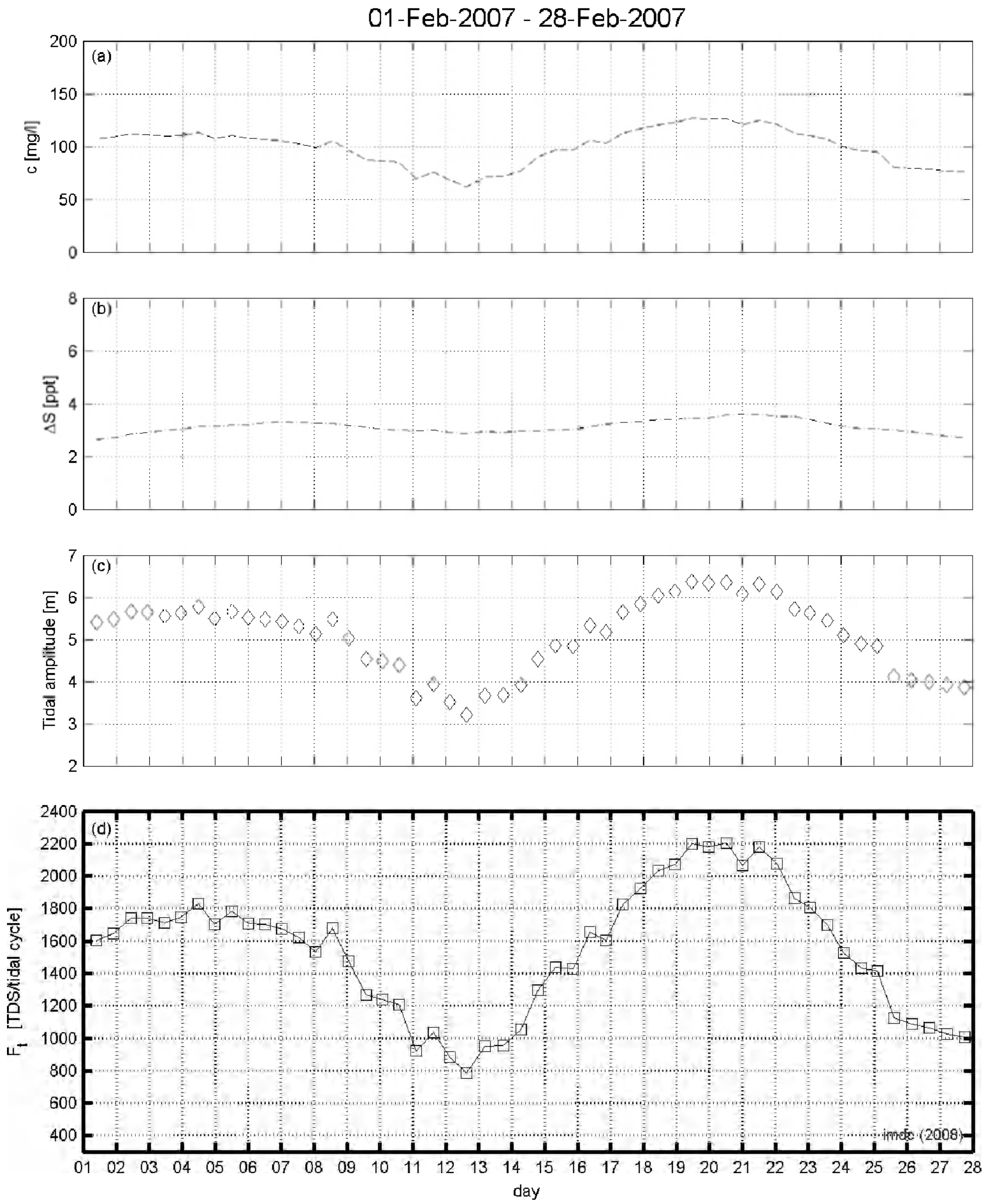
I/RA/11283/06.129/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Data Processed by:

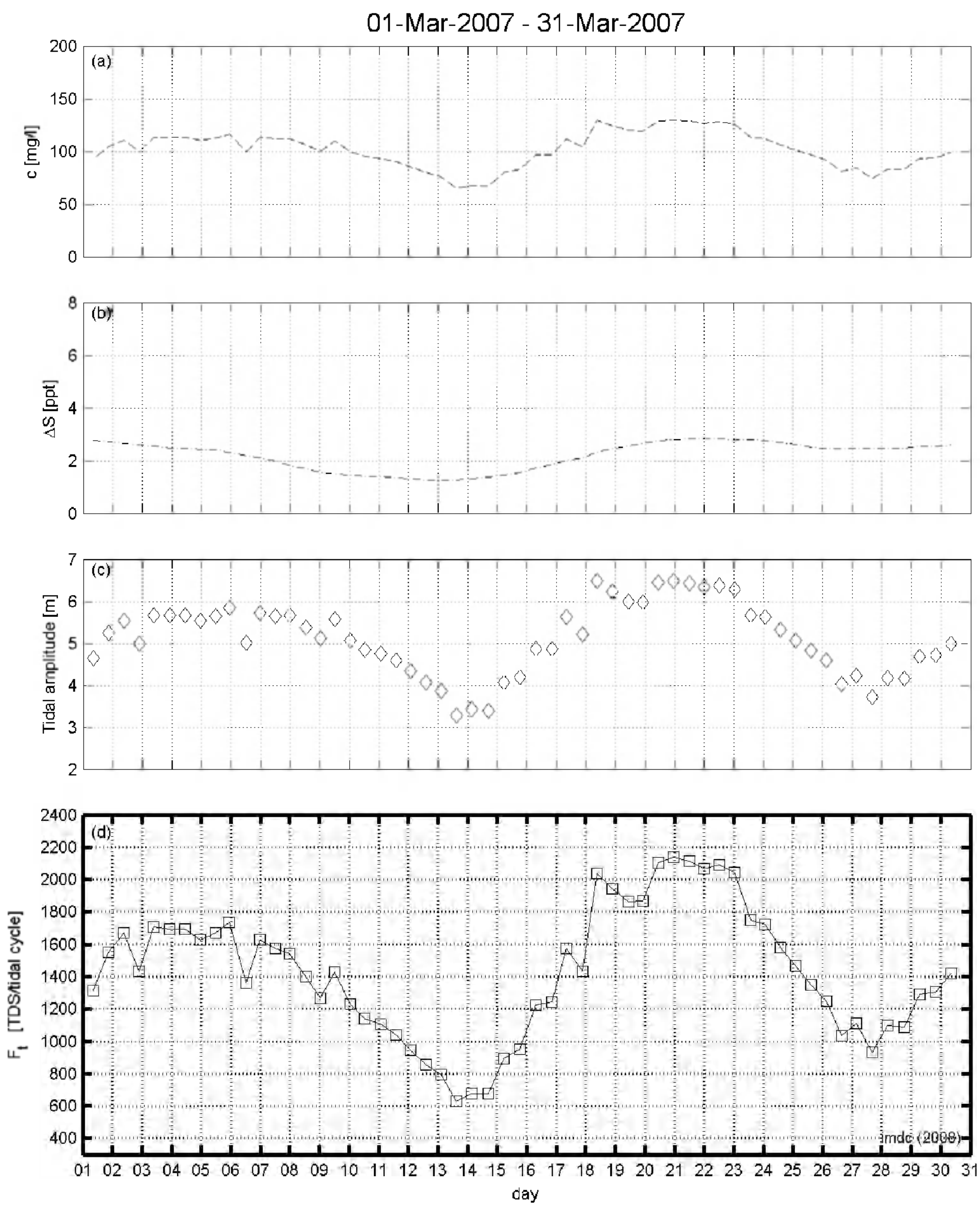
I/RA/11283/06.129/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

Data Processed by:

I/RA/11283/06.129/MSA

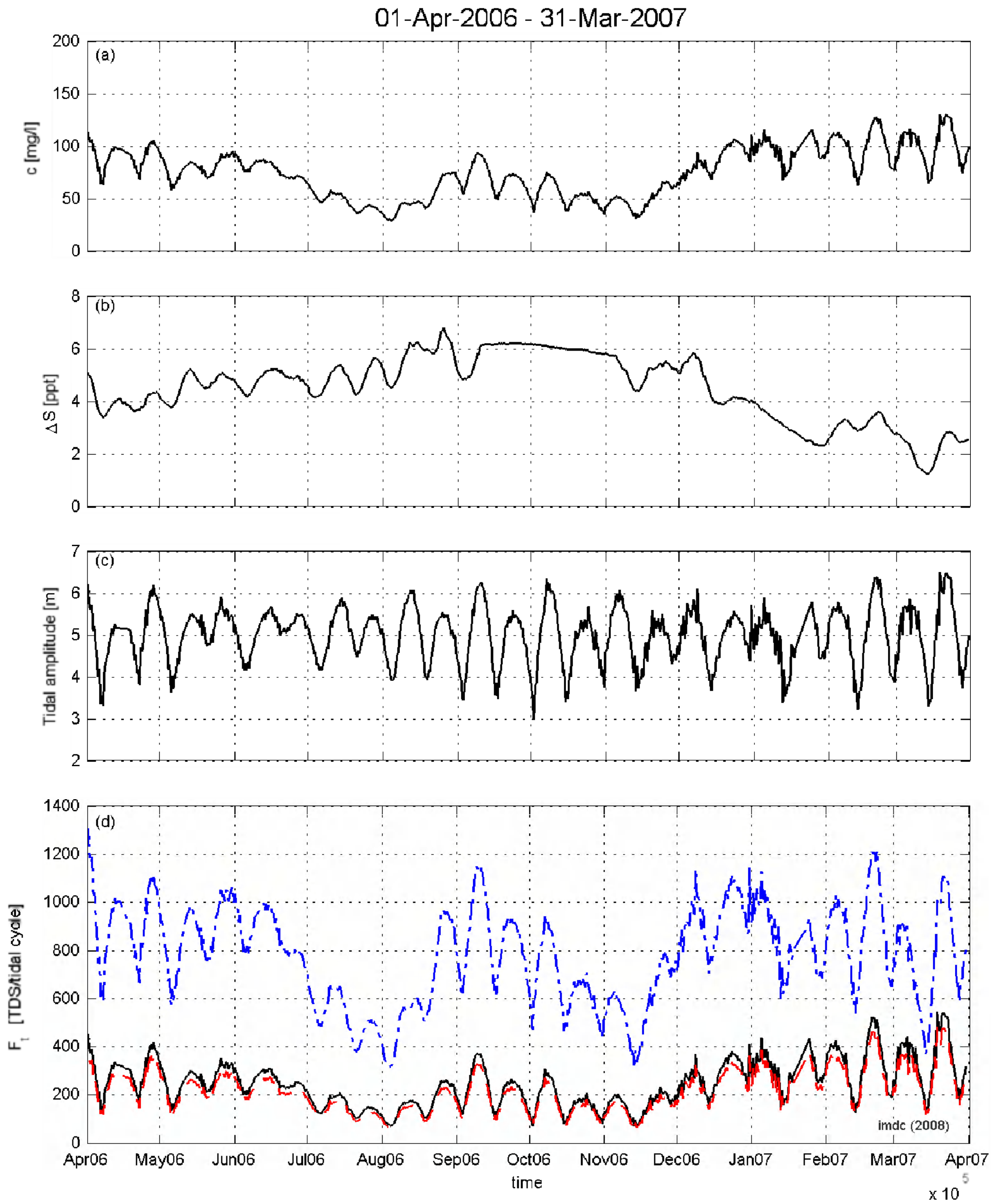
APPENDIX C. MAIN AMBIENT CONDITIONS VERSUS 3 COMPONENTS

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d), due to density currents (blue), tidal amplitude (black) and eddy's (red).

Data Processed by: IMDC

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