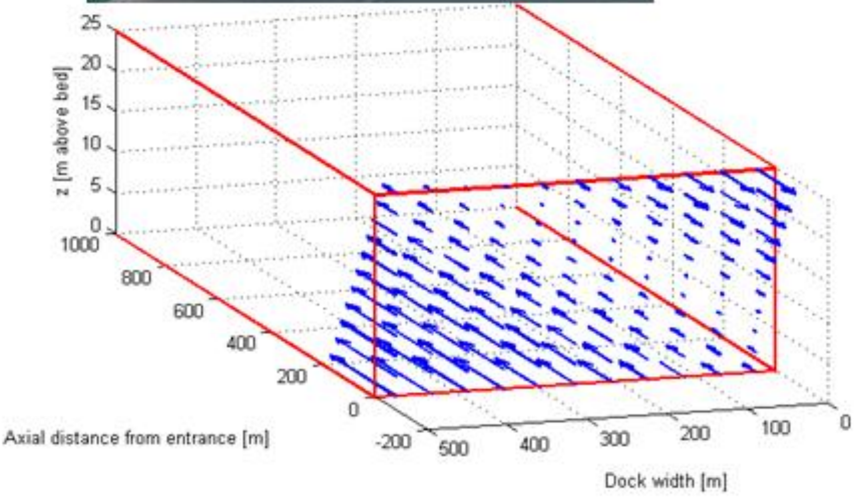
VLAAMSE OVERHEID

DEPARTEMENT MOBILITEIT EN OPENBARE WERKEN
WATERBOUWKUNDIG LABORATORIUM

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Bestek 16EB/05/04



Deelrapport 4.20 : Analyse van aanslibbingsprocessen en -invloeden

Report 4.20 : Analysis of siltation processes and factors:

April 2006 – March 2009

November 4th, 2010

I/RA/11283/08.098/MSA

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Approval

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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 [-]
ΔS	Salinity amplitude (variation per tide) [ppt]
Δc_B	Horizontal sediment concentration difference (North – south quay) [mg/l]
Δc_z	Vertical sediment concentration difference (bottom – top) [mg/l]
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
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]
h	Tidal amplitude [m]
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 eddies [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]
Tp	Tidal period (~12.4h)
TDS	Tons of dry solids
u_d	Flow velocity related to density currents [m/s]
V	Dredged sludge volume [m³]

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

Monitoring Deurganckdok:

Report	Description
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)
1.10	Sediment Balance: Three monthly report 1/4/2007 - 30/06/2007(I/RA/11283/07.081/MSA)
1.11	Sediment Balance: Two monthly report 1/7/2007 – 31/08/2007 (I/RA/11283/07.082/MSA)
1.12	Sediment Balance: Four monthly report 1/09/2007 – 31/12/2007 (I/RA/11283/07.083/MSA)
1.13	Sediment Balance: Three monthly report 1/1/2008 – 31/03/2008 (I/RA/11283/07.084/MSA)
1.14	Annual Sediment Balance (I/RA/11283/07.085/MSA)

Report	Description
1.20	Sediment Balance: Three monthly report 1/4/2008 - 30/6/2008 (I/RA/11283/08.076/MSA)
1.21	Sediment Balance: Three monthly report 1/7/2008 – 30/9/2008 (I/RA/11283/08.077/MSA)
1.22	Sediment Balance: Three monthly report 1/10/2008 – 31/12/2008 (I/RA/11283/08.078/MSA)
1.23	Sediment Balance: Three monthly report 1/1/2009 – 31/03/2009 (I/RA/11283/08.079/MSA)
1.24	Annual Sediment Balance (I/RA/11283/08,080/MSA)
Factors contributing to salt and sediment distribution in Deurganckdok: Salt-Silt (OBS3A) & Frame measurements, Through tide measurements (SiltProfiling & ADCP) & Calibrations	
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 average tide 27/09/2006 Parel 2 (I/RA/11283/06.119/MSA)
2.5	Through tide measurement Sediview average tide 24/10/2007 Parel 2 (I/RA/11283/06.120/MSA)
2.6	Salinity-Silt distribution & Frame Measurements Deurganckdok 17/3/2006 – 23/05/2006 (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)
2.9	Calibration stationary equipment autumn (I/RA/11283/07.095/MSA)
2.10	Through tide measurement SiltProfiler 23 October 2007 (I/RA/11283/07.086/MSA)
2.11	Through tide measurement Longitudinal Salinity distribution 12/3/2008 during springtide - Deurganckdo (I/RA/11283/07.087/MSA)
2.12	Through tide measurement Sediview winter 11 March 2008 during spring tide Transect I (I/RA/11283/07.088/MSA)
2.13	Through tide measurement Sediview winter 11 March 2008 during spring tide Transect K (I/RA/11283/07.089/MSA)
2.14	Through tide measurement Sediview winter 11 March 2008 during spring tide Transect DGD (I/RA/11283/07.090/MSA)
2.15	Through tide measurement SiltProfiler 12 March 2008 during spring tide

Report	Description
	(I/RA/11283/07.091/MSA)
2.16	Salinity-Silt distribution Deurganckdok summer (21/6/2007 – 30/07/2007) (I/RA/11283/07.092/MSA)
2.17	Salinity-Silt distribution & Frame Measurements Deurganckdok autumn (17/09/2007 - 10/12/2007) (I/RA/11283/07.093/MSA)
2.18	Salinity-Silt distribution & Frame Measurements Deurganckdok winter (18/02/2008 - 31/3/2008) (I/RA/11283/07.094/MSA)
2.19	Calibration stationary & mobile equipment winter (I/RA/11283/07.096/MSA)
2.20	Through tide measurement Sediview DGD during average tide Spring 2008 – 19 June 2008 (I/RA/11283/08.081/MSA)
2.21	Through tide measurement Sediview DGD during average tide Spring 2008 –26 June 2008 (I/RA/11283/08.082/MSA)
2.22	Through tide measurement Sediview DGD during neap tide Summer 2008 – 24 September 2008 (I/RA/11283/08.083/MSA)
2.23	Through tide measurement Sediview DGD during spring tide Summer 2008 – 30 September 2008 (I/RA/11283/08.084/MSA)
2.24	Through tide Measurement Sediview on 10/12/2008 during neap tide - Deurganckdok (transect DGD) (I/RA/11283/08.085/MSA)
2.25	Through tide Measurement Sediview on 02/12/2008 during spring tide - Deurganckdok (transect DGD) (I/RA/11283/08.086/MSA)
2.26	Through tide Measurement Sediview on 06/03/2009 during neap tide - Deurganckdok (transect DGD) (I/RA/11283/08.087/MSA)
2.27	Through tide Measurement Sediview on 12/03/2009 during neap tide - Deurganckdok (transect DGD) (I/RA/11283/08.088/MSA)
2.28	Through tide measurement ADCP eddy DGD Summer 2008 – 1 October 2008 (I/RA/11283/08.089/MSA)
2.29	Through tide measurement Siltprofiler DGD Summer 2008 – 29 September 2008 (I/RA/11283/08.090/MSA)
2.30	Through tide Measurement SiltProfiler 13 March 2009 at the entrance of Deurganckdok (I/RA/11283/08.091/MSA)
2.31	Through tide Measurement Longitudinal Salinity Distribution on 11/03/2009 during spring tide - Deurganckdok (I/RA/11283/08.092/MSA)
2.32	Salinity-Silt distribution Deurganckdok: Six monthly report 1/4/2008 - 30/9/2008 (I/RA/11283/08.093/MSA)
2.33	Salinity-Silt distribution Deurganckdok: Six monthly report 1/10/2008 – 31/3/2009 (I/RA/11283/08.094/MSA)
2.34	Calibration stationary & mobile equipment Autumn 2008 (I/RA/11283/08.095/MSA)

Report	Description
Boundary Conditions: Upriver Discharge, Salt concentration 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)
3.10	Boundary conditions: Three monthly report 1/4/2007 – 30/06/2007 (I/RA/11283/07.097/MSA)
3.11	Boundary conditions: Three monthly report 1/7/2007 – 30/09/2007 (I/RA/11283/07.098/MSA)
3.12	Boundary conditions: Three monthly report 1/10/2007 – 31/12/2007 (I/RA/11283/07.099/MSA)
3.13	Boundary conditions: Three monthly report 1/1/2008 – 31/03/2008 (I/RA/11283/07.100/MSA)
3.14	Boundary conditions: Annual report (I/RA/11283/07.101/MSA)
3.20	Boundary conditions: Six monthly report 1/4/2008 – 30/09/2008 (I/RA/11283/08.096/MSA)
3.21	Boundary conditions: Six monthly report 1/10/2008 – 31/03/2009 (I/RA/11283/08.097/MSA)
Analysis	
4.1	Analysis of Siltation Processes and Factors April 2006 – March 2007 (I/RA/11283/06.129/MSA)
4.10	Analysis of Siltation Processes and Factors April 2007 – March 2008 (I/RA/11283/07.102/MSA)
4.20	Analysis of Siltation Processes and Factors April 2006 – March 2009 (I/RA/11283/08.098/MSA)

HCBS2:

Report	Description
Ambient Conditions Lower Sea Scheldt	
5.3	Overview of ambient conditions in the river Scheldt – January-June 2006 (I/RA/11291/06.088/MSA)
5.4	Overview of ambient conditions in the river Scheldt – July-December 2006 (I/RA/11291/06.089/MSA)
5.5	Overview of ambient conditions in the river Scheldt : RCM-9 buoy 84 & 97 (1/1/2007 - 31/3/2007) (I/RA/11291/06.090/MSA)
5.6	Analysis of ambient conditions in the river Scheldt, September 2005 – March 2007 (I/RA/11291/06.091/MSA)
Calibration	
6.1	Winter Calibration (I/RA/11291/06.092/MSA)
6.2	Summer Calibration and Final Report (I/RA/11291/06.093/MSA)

Through tide Measurements Winter 2006	
7.1	21/3 Scheldewacht – Deurganckdok – Salinity Distribution (I/RA/11291/06.094/MSA)
7.2	22/3 Parel 2 – Deurganckdok (I/RA/11291/06.095/MSA)
7.3	22/3 Laure Marie – Liefkenshoek (I/RA/11291/06.096/MSA)
7.4	23/3 Parel 2 – Schelle (I/RA/11291/06.097/MSA)
7.5	23/3 Laure Marie – Deurganckdok (I/RA/11291/06.098/MSA)
7.6	23/3 Veremans Waarde (I/RA/11291/06.099/MSA)
HCBS Near bed continuous monitoring (Frames)	
8.1	Near bed continuous monitoring winter 2006 (I/RA/11291/06.100/MSA)
INSSEV	
9	Settling Velocity - INSSEV summer 2006 (I/RA/11291/06.102/MSA)
Cohesive Sediment	
10	Cohesive sediment properties summer 2006 (I/RA/11291/06.103/MSA)
Through tide Measurements Summer 2006	
11.1	Through Tide Measurement Sediview and SiltProfiler 27/9 Stream - Liefkenshoek (I/RA/11291/06.104/MSA)
11.2	Through Tide Measurement Sediview 27/9 Veremans - Raai K (I/RA/11291/06.105/MSA)
11.3	Through Tide Measurement Sediview and SiltProfiler 28/9 Stream - Raai K (I/RA/11291/06.106/MSA)
11.4	Through Tide Measurement Sediview 28/9 Veremans – Waarde (I/RA/11291/06.107/MSA)
11.5	Through Tide Measurements Sediview 28/9 Parel 2 - Schelle (I/RA/11291/06.108/MSA)
11.6	Through Tide measurement Longitudinal Salinity Distribution 26/9 Scheldewacht – Deurganckdok (I/RA/11291/06.161/MSA)
Analysis	
12	Report concerning the presence of HCBS layers in the Scheldt river (I/RA/11291/06.109/MSA)

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 September 10th 2007, February 4-5 2008 and October 27-28 2008 to calibrate all turbidity and conductivity sensors (IMDC, 2008f,o & IMDC, 2009c).

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 three years measurement period and the performed analyses. These results will support the discussion on the siltation process and its influencing factors in Chapter 5. Chapter 6 describes the analysis of the full project covering three years of measurements. In chapter 7 conclusions and recommendations are formulated.

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:

- The dock has a total length of 2500 m and is 450 m wide at the Scheldt end and 400 m wide at the inward end of the dock
- 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.
- The quay walls reach up to +9m TAW

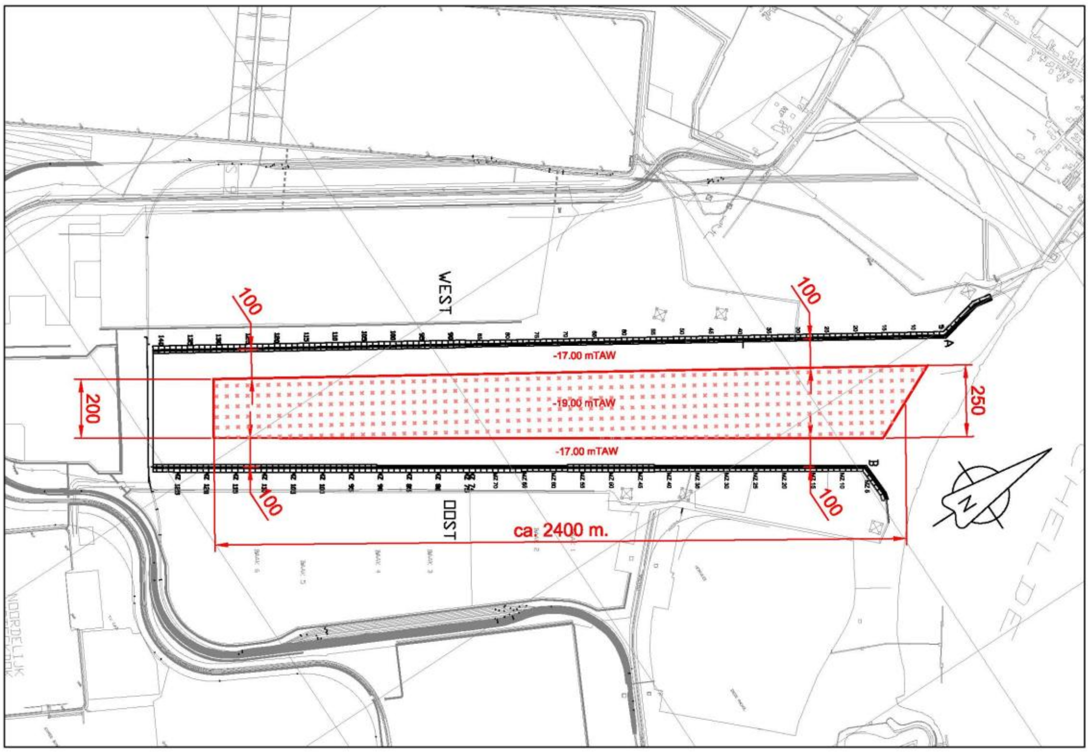


Figure 2-1: Overview of Deurganckdok

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 has been finalized in 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).

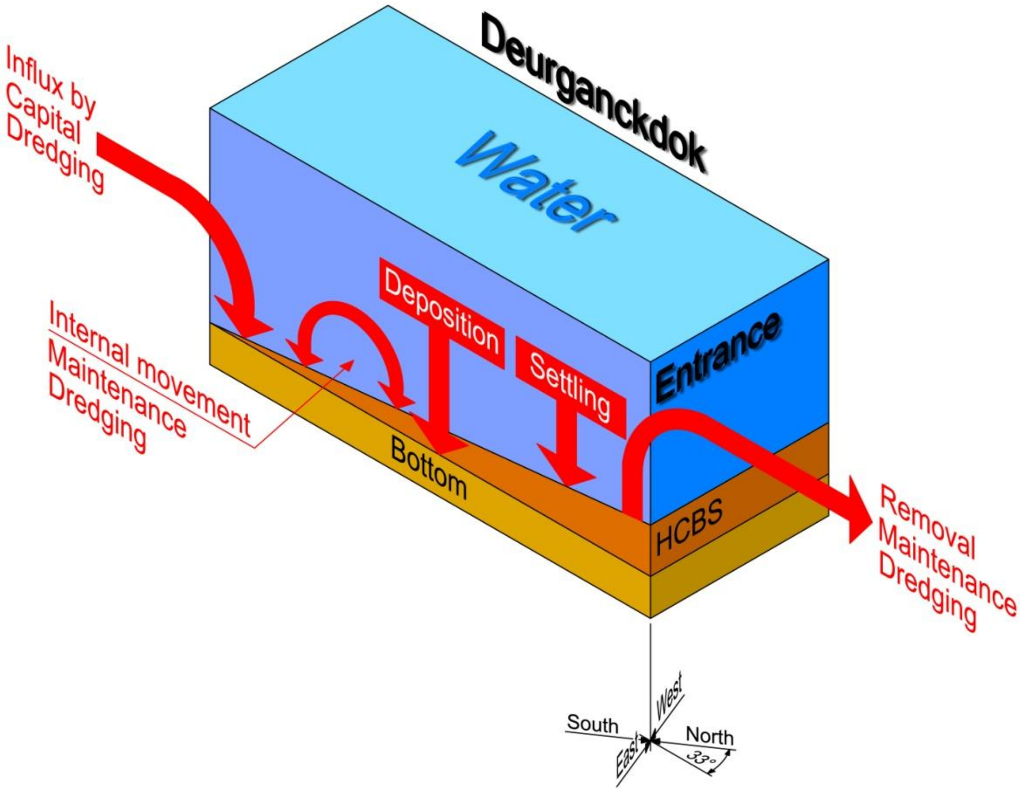


Figure 2-2: Elements of the sediment balance

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.

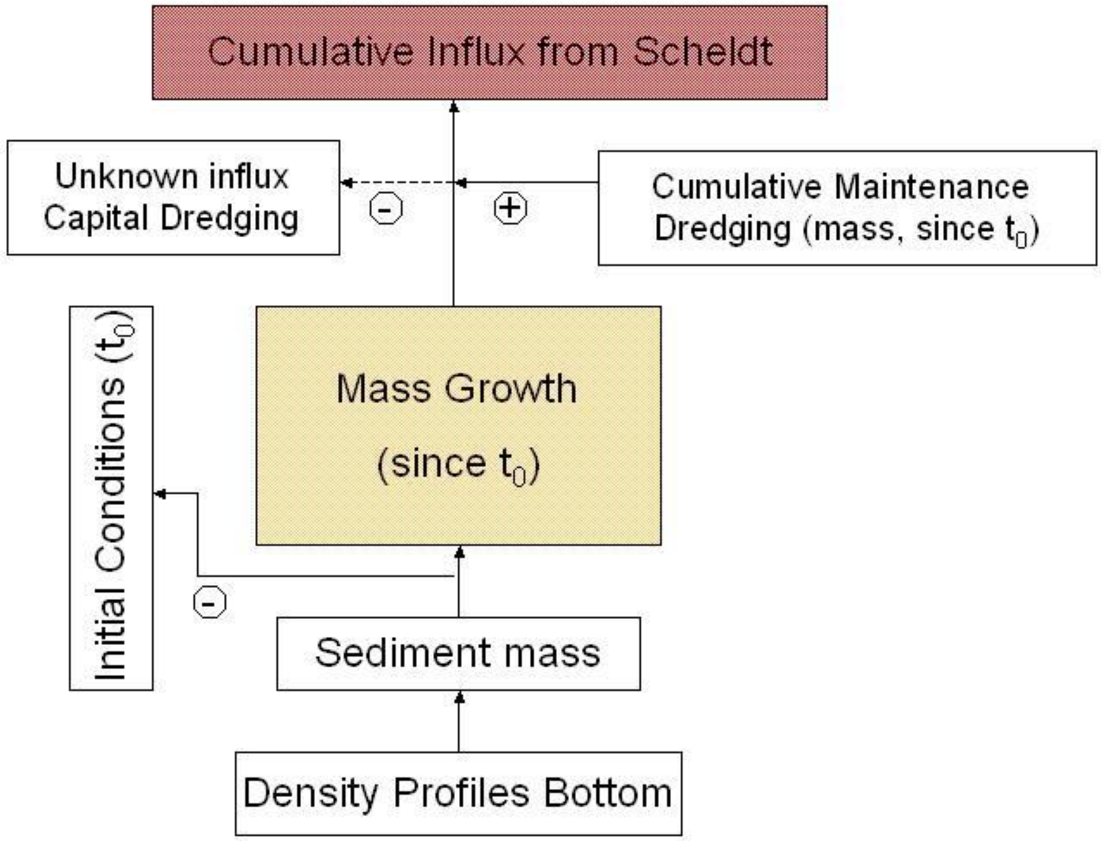


Figure 2-3: Determining a sediment balance with bed density profile data

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

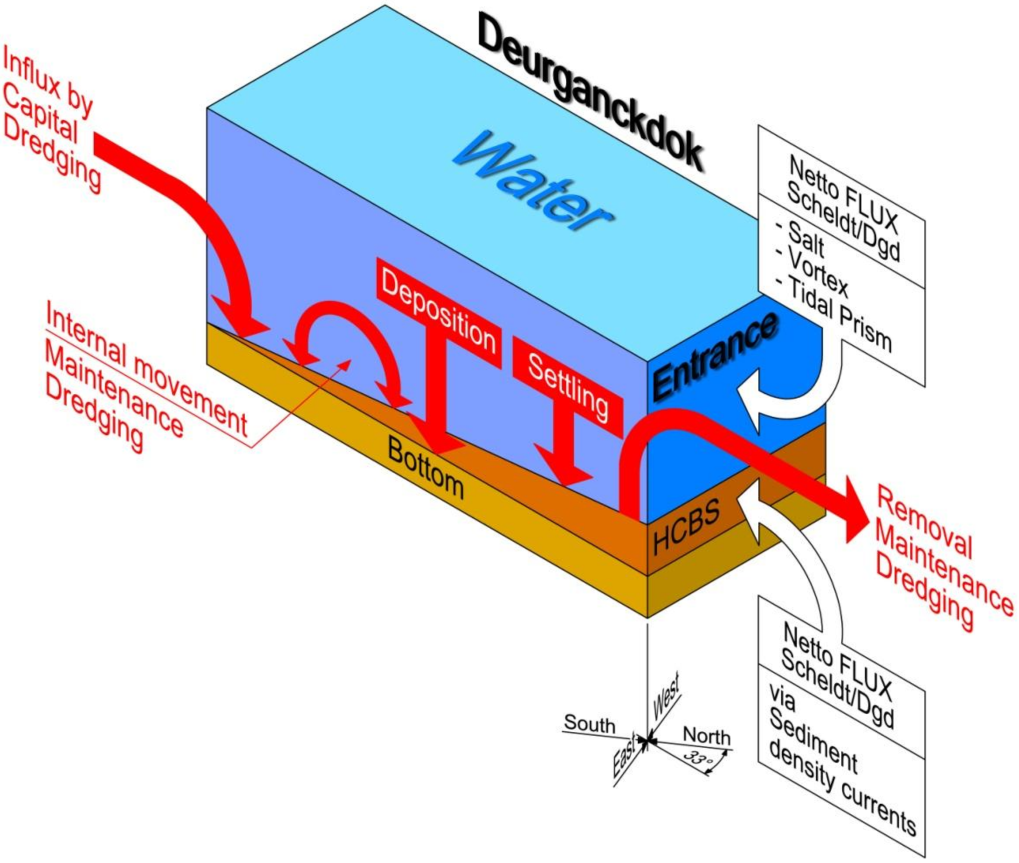


Figure 2-4: Transport mechanisms

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

In this section an overview is given of all measurements executed in and near Deurganckdok during the three years of measurements. For a map of equipment locations outside Deurganckdok of which data has been used please refer to APPENDIX A.

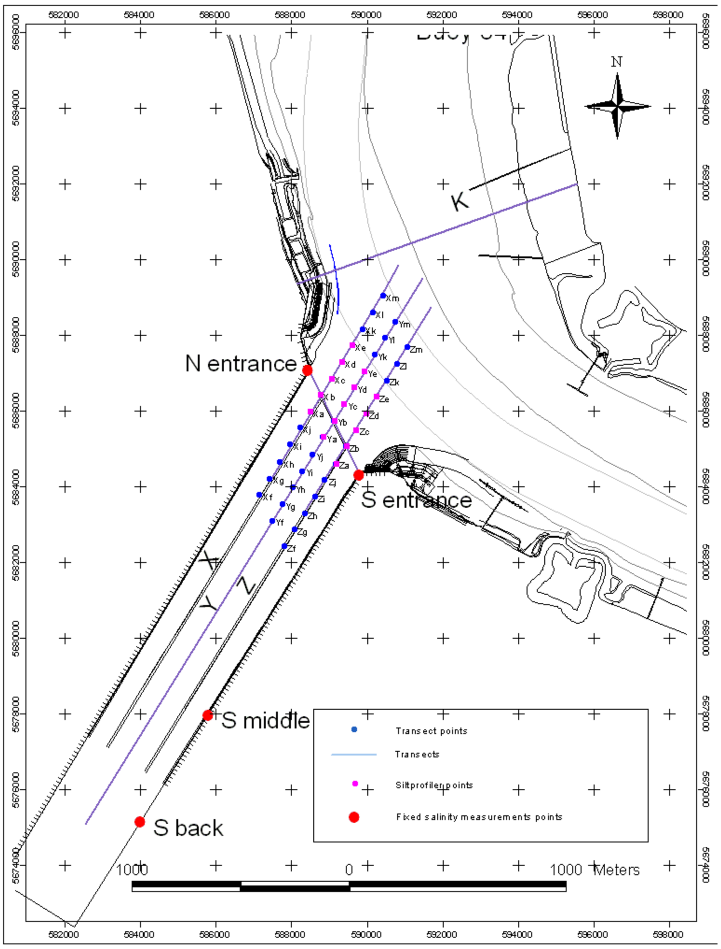


Figure 3-1: Location of measurement equipment and sailed tracks at Deurganckdock

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

	April 06		May 06		June 06		July 06		August 06		September 06	
ACTIVITY	**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												
Through-tide DGD												▓
Near bed monitoring	▓	▓	▓	▓				▓	▓	▓	▓	▓
Salt Silt long term DGD	▓	▓						▓	▓	▓	▓	▓
Density profiling												

	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							▒	▒	▒	▒	▒	▒
Through-tide DGD												
Near bed monitoring	▓								▓	▓	▓	▓
Salt Silt long term DGD	▓								▓	▓	▓	▓
Density profiling												

	April 07		May 07		June 07		July 07		August 07		September 07	
activity	**1 - 15**	**16 - 30**	**1 - 15**	**16 - 31**	**1 - 15**	**16 - 30**	**1 - 15**	**16 - 31**	**1 - 15**	**16 - 31**	**1 - 15**	**16 - 30**
depth sounding		▒		▒		▒		▒		▒	▒	▒
density measurements											▒	
maintenance dredging	▒	▒								▒		
sweep beam dredging - sill	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
sweep beam dredging - commercial quays	▒	▒	▒	▒						▒		▒
capital dredging	▒		▒	▒	▒	▒		▒	▒	▒	▒	▒
Through-tide DGD												
Near bed monitoring	▓	▓										▓
Salt Silt long term DGD						▓	▓	▓				▓
Density profiling											▓	

	October 07		**November 07**		**December 07**		**January 08**		**February 08**		**March 08**	
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**
depth sounding		▨	▨	▨	▨	▨	▨	▨	▨		▨	
density measurements		▨		▨	▨			▨		▨		
maintenance dredging				▨				▨	▨	▨	▨	
sweep beam dredging - sill		▨	▨	▨	▨	▨	▨	▨	▨		▨	
sweep beam dredging - commercial quays			▨	▨			▨	▨	▨			
capital dredging	▨	▨		▨	▨				▨			
Through-tide DGD		■									■	
Near bed monitoring	■	■	■	■	■					■	■	■
Salt Silt long term DGD	■	■	■	■	■					■	■	■
Density profiling		■		■	■			■		■		

	April 08		**May 08**		**Jun-08**		**Jul-08**		**Aug-08**		**Sep-08**	
ACTIVITY	**1 - 15**	**16 - 30**	**1 - 15**	**16 - 31**	**1 - 15**	**16 - 30**	**1 - 15**	**16 - 31**	**1 - 15**	**16 - 31**	**1 - 15**	**16 - 30**
depth sounding	▨		▨		▨		▨		▨	▨	▨	▨
density measurements		▨			▨				▨	▨	▨	
maintenance dredging				▨						▨		
sweep beam dredging - sill	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
sweep beam dredging - commercial quays	▨						▨	▨				
capital dredging												
Through-tide DGD						■						■
Near bed monitoring	■											
Salt Silt long term DGD	■	■	■	■	■	■	■	■	■	■	■	■
Density profiling			■		■				■	■	■	

	Oct-08		**Nov-08**		**Dec-08**		**Jan-09**		**Feb-09**		**Mar-09**	
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**
depth sounding	▨	▨	▨	▨			▨		▨		▨	▨
density measurements		▨	▨					▨			▨	
maintenance dredging		▨							▨	▨	▨	
sweep beam dredging - sill	▨	▨	▨	▨			▨	▨	▨	▨	▨	
sweep beam dredging - commercial quays		▨	▨									
capital dredging												
Through-tide DGD					■						■	
Near bed monitoring												
Salt Silt long term DGD	■	■	■	■	■	■	■	■	■	■	■	■
Density profiling		■	■					■			■	

Through tide measurements: Siltprofiler gauging points			
Location	***Easting (UTM ED 50)***	***Northing (UTM ED 50)***	***Period***
Location 1: Xa	588549	5684335	21/03/2006, 26/09/2006, 23/10/2007, 12/03/2008 29/09/2008 13/03/2008
Location 2: Xb	588596	5684411	
Location 3: Xc	588643	5684486	
Location 4: Xd	588690	5684562	
Location 5: Xe	588737	5684638	
Location 6: Ya	588606	5684217	
Location 7: Yb	588653	5684293	
Location 8: Yc	588700	5684368	
Location 9: Yd	588747	5684444	
Location 10: Ye	588793	5684520	
Location 11: Za	588662	5684099	
Location 12: Zb	588709	5684174	
Location 13: Zc	588756	5684250	
Location 14: Zd	588803	5684326	
Location 15: Ze	588850	5684402	

Through tide measurements: Transects

Location	***Easting (UTM ED 50)***		***Northing (UTM ED 50)***		***Period***
Deurganckdok (in dock) (transect Y)	Left Bank	Right Bank	Left Bank	Right Bank	21/03/2006, 26/09/2006 & 12/03/2008
	589059	591298	5684948	5683077	
Liefkenshoek (transect I)	Left Bank	Right Bank	Left Bank	Right Bank	22/03/2006, 27/09/2006 & 11/03/2008
	590318	590771	5684257	5683302	
Deurganckdok (downstream) (transect K)	Left Bank	Right Bank	Left Bank	Right Bank	22 - 23/03/2006, 27 - 28/09/2006 & 11/03/2008
	588484	589775	5684924	5685384	
Deurganckdok (entrance) (transect DGD)	Left Bank	Right Bank	Left Bank	Right Bank	22/03/2006, 27/09/2006, 24/10/2007, 11/03/2008, 19-26/06/2008 24-30/09/2008 2-10/12/2008 6-12/03/2009
	588765	588541	5684056	5684527	
Schelle (transect S)	Left Bank	Right Bank	Left Bank	Right Bank	23/03/2006 & 28/09/2006
	592645	592953	5665794	5665682	
Waarde (transect W)	Left Bank	Right Bank	Left Bank	Right Bank	23/03/2006 & 28/09/2006
	573541	571318	5696848	5694933	
Deurganckdok (in dock) (Transect X, transect Y, transect Z)	North Side	North Side	South Side	South Side	01/10/2008
	588737 588793 588850	5684638 5684520 5684402	588408 588465 588521	5684107 5683989 5683871	

Near bed continuous monitoring			
Location	***Easting (UTM ED 50)***	***Northing (UTM ED 50)***	***Period***
Deurganckdok CDW	588653	5684906	14/03/2006 – 05/04/2006
Deurganckdok CDW	588685	5684880	19/04/2006 – 23/05/2006
Deurganckdok Sill	588805	5684170	19/04/2006 – 23/05/2006
Deurganckdok CDW	588685	5684880	18/07/2006 – 11/10/2006
Deurganckdok Sill	588805	5684170	19/07/2006 – 11/10/2006
Deurganckdok CDW	588685	5684880	15/03/2007 – 12/04/2007
Deurganckdok Sill	588805	5684170	09/02/2007 – 18/04/2007
Deurganckdok CDW	588685	5684880	26/09/2007 – 05/12/2007
Deurganckdok Sill	588805	5684170	10/10/2007 – 28/11/2007
Deurganckdok CDW	588685	5684880	20/02/2008 – 02/04/2008
Deurganckdok Sill	588805	5684170	27/02/2008 – 09/04/2008
Salt Silt measurements Deurganckdok			
Location	***Easting (UTM ED 50)***	***Northing (UTM ED 50)***	***Period***
P&O 1	588074	5682942	17/03/2006 – 28/04/2006
P&O 2	588767	5684045	17/03/2006 – 28/04/2006
PSA	588536	5684523	17/03/2006 – 28/04/2006
P&O 1	588074	5682942	20/07/2006 – 12/10/2006
P&O 2	588767	5684045	20/07/2006 – 12/10/2006
PSA	588536	5684523	20/07/2006 – 12/10/2006
P&O 1	588074	5682942	12/02/2007 – 27/03/2007
P&O 2	588767	5684045	12/02/2007 – 27/03/2007
PSA	588536	5684523	12/02/2007 – 27/03/2007
P&O 1	588074	5682942	20/06/2007 – 31/07/2007
P&O 2	588767	5684045	20/06/2007 – 31/07/2007
PSA	588536	5684523	20/06/2007 – 31/07/2007
P&O 1	588074	5682942	17/09/2007 – 10/12/2007
P&O 2	588767	5684045	17/09/2007 – 10/12/2007
PSA	588536	5684523	17/09/2007 – 10/12/2007
N entrance (PSA HNN)	588536	5684523	20/02/2008 – 28/04/2008
S entrance (DB Ports)	588767	5684045	20/02/2008 – 28/04/2008
S middle (DB Ports)	588074	5682942	20/02/2008 – 28/04/2008
S back (DB Ports)	587760	5682449	20/02/2008 – 28/04/2008
N entrance (PSA HNN)	588536	5684523	14/05/2008 – 26/09/2008
S entrance (DB Ports)	588767	5684045	14/05/2008 – 26/09/2008
S middle (DB Ports)	588074	5682942	14/05/2008 – 26/09/2008
S back (DB Ports)	587760	5682449	14/05/2008 – 26/09/2008
N entrance (PSA HNN)	588536	5684523	28/04/2008 – 31/03/2009
S entrance (DB Ports)	588767	5684045	28/04/2008 – 31/03/2009
S middle (DB Ports)	588074	5682942	28/04/2008 – 31/03/2009
S back (DB Ports)	587760	5682449	28/04/2008 – 31/03/2009
Settling velocity – INSSEV			
Location	***Easting (UTM ED 50)***	***Northing (UTM ED 50)***	***Period***
Deurganckdok CDW	588717	5684898	05/09/2006
Deurganckdok SILL	588800	5684250	06/09/2006
Deurganckdok Western quay wall	588452	5684355	07/09/2006

Density profile campaigns
5th September 2007
16th October 2007
16th November 2007
5th December
24th January 2008
22nd February 2008
1st May 2008
5th June 2008
11th August 2008
26th August 2008
11th September 2008
20th October 2008
6th November 2008
30th January 2009
12th March 2009

	Easting [UTM ED50]	***Northing [UTM ED50]***	***Period***	***[m] above botttom***	***Elevation [m TAW]***
Buoy 84	588971	5686097	Jan2006 – Sep2009	3.3	-5.8
				0.8	-8.1
Buoy 97	590932	5683350	Jan2006 – Jul2008	3.3	-5.1
				0.8	-7.5

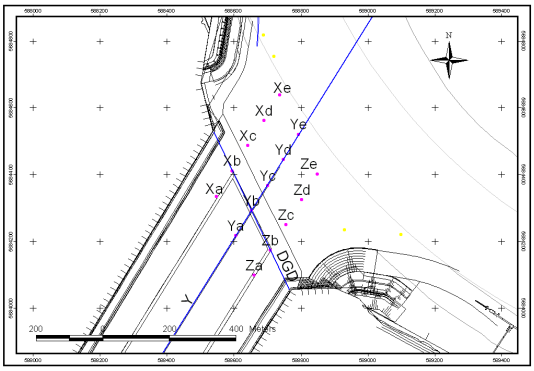


Figure 3-2: Through tide SiltProfiler measurements – Entrance Deurganckdok

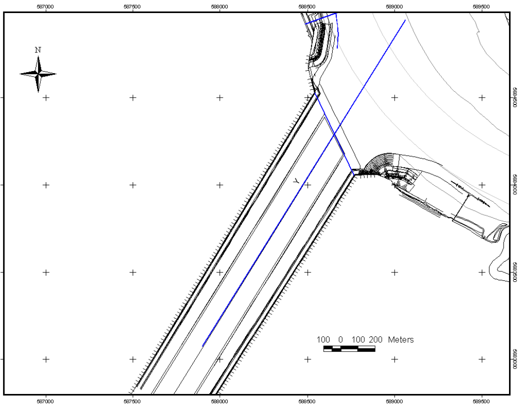


Figure 3-3: Through tide Salinity measurements – Deurganckdok (transect Y)

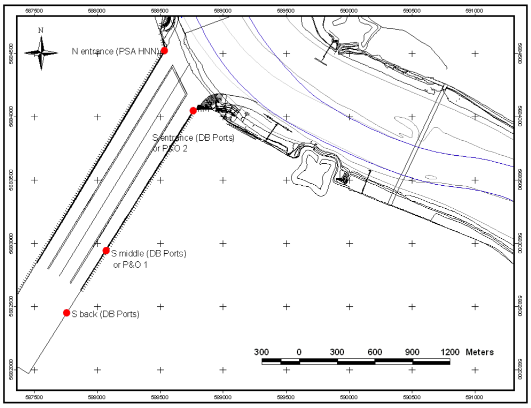


Figure 3-4: Long term salinity measurements Deurganckdok

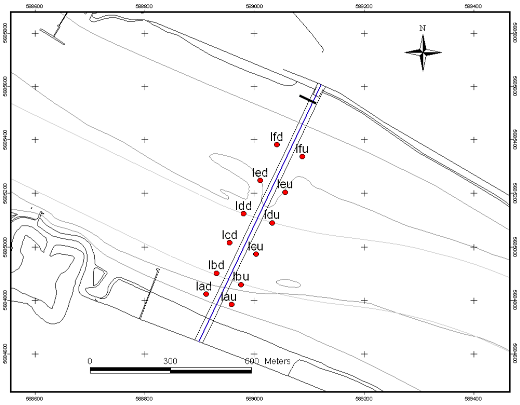


Figure 3-5: Through tide ADCP & SiltProfiler measurements – Upstream Deurganckdok (transect I)

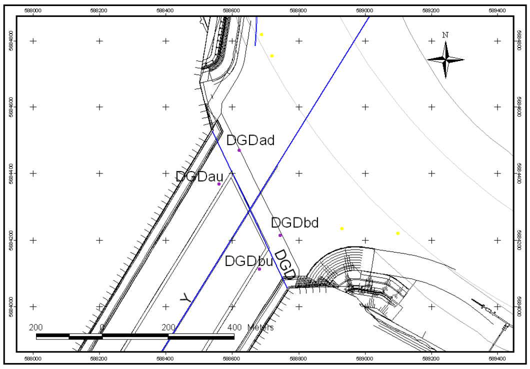


Figure 3-6: Through tide ADCP measurements – Entrance Deurganckdok (transect DGD)

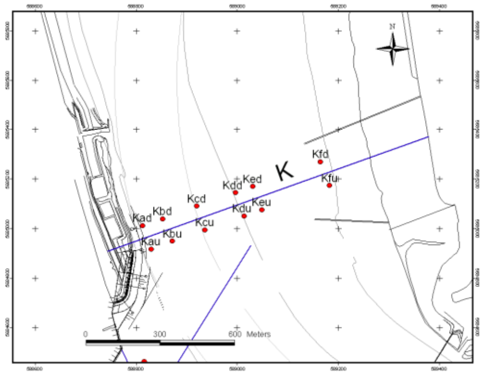


Figure 3-7: Through tide ADCP & SiltProfiler measurements – Downstream Deurganckdok (Transect K)

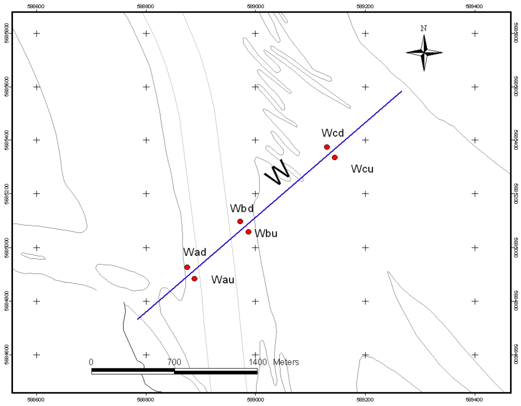


Figure 3-8: Through tide ADCP measurements - Waarde (transect W)

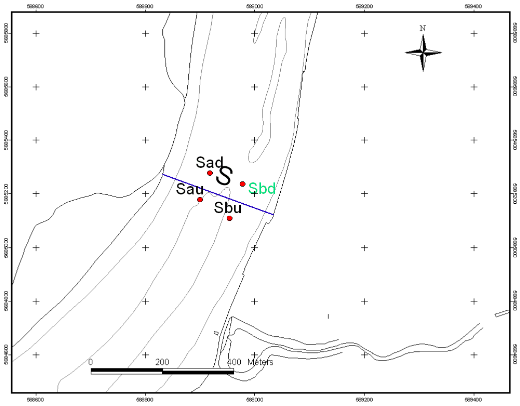


Figure 3-9: Through tide ADCP measurements - Schelle (transect S)

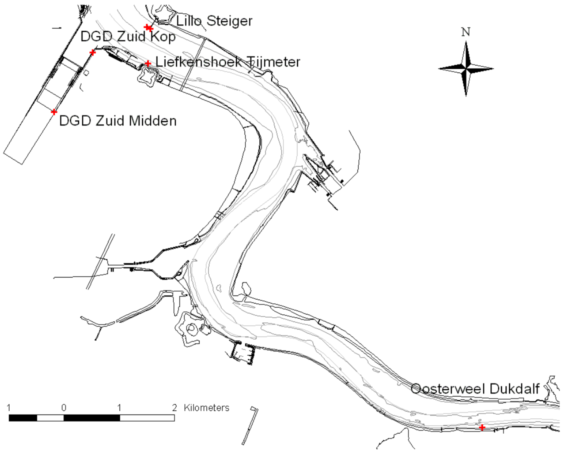


Figure 3-10: Calibration measurements - 15/03/2006 & 14/04/2006

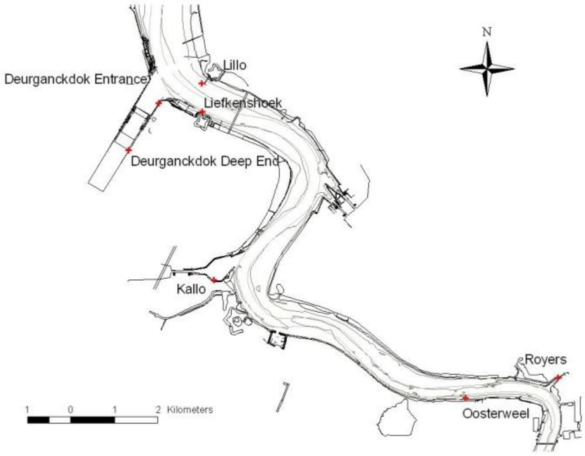


Figure 3-11: Calibration measurements – 23/06/2006 & 18/09/2006

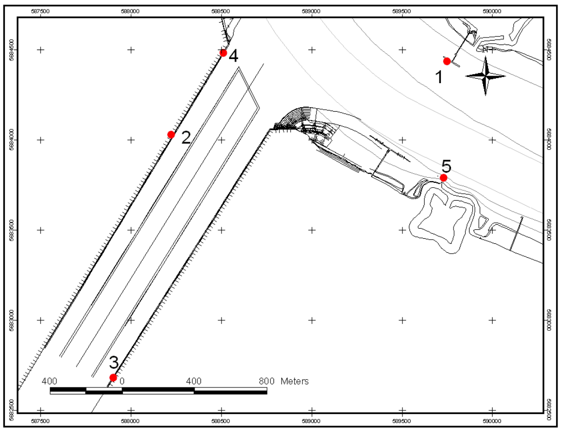


Figure 3-12:Calibration measurements – 10/09/2008

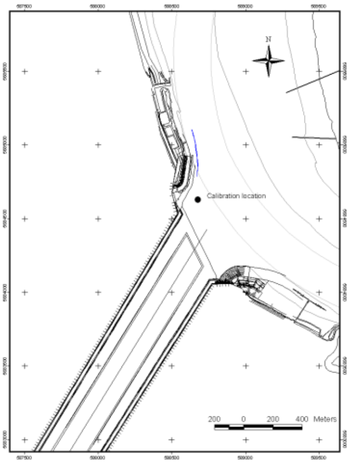


Figure 3-13:Calibration measurements – 04/02/2008 & 05/02/2008

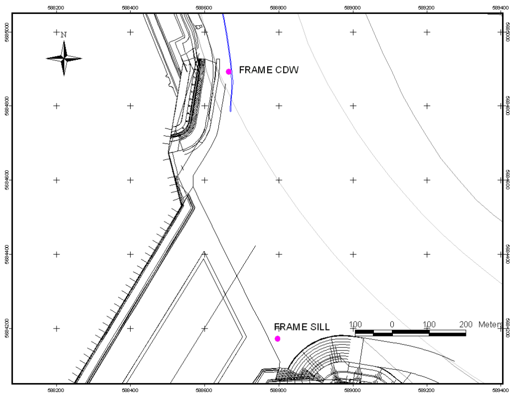


Figure 3-14:Near bed continuous monitoring

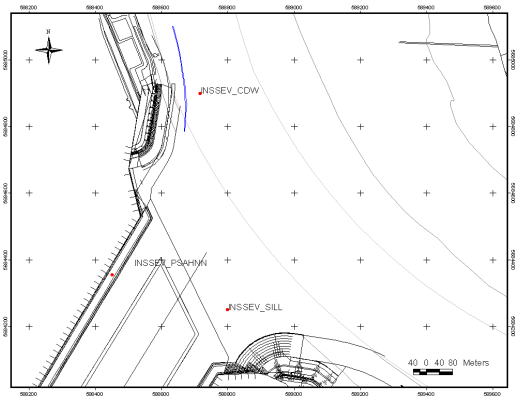


Figure 3-15: Settling velocity (INSSEV) 05/09/2006 – 07/09/2006

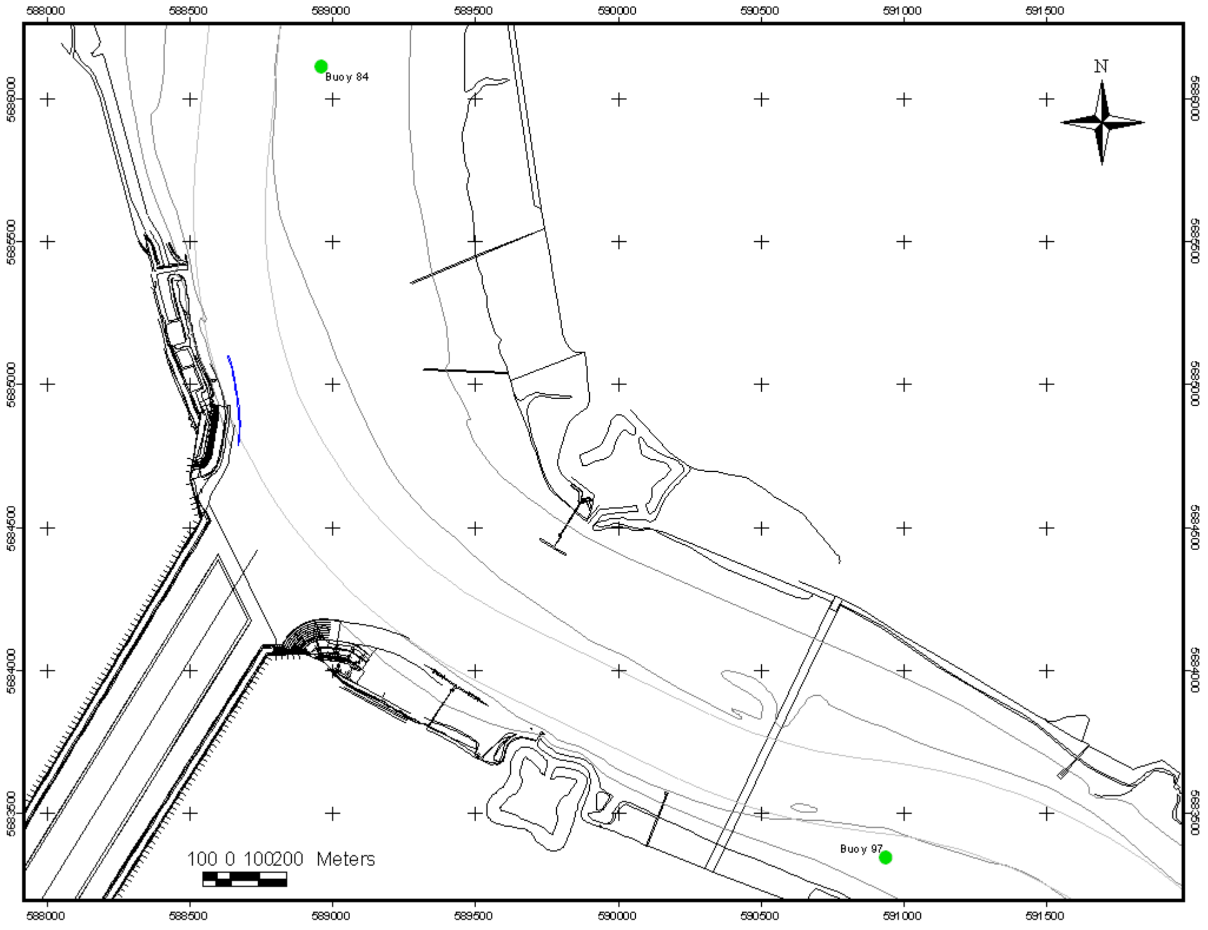


Figure 3-16: Long term measurements in the Lower Sea Scheldt

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

In this section an overview is given of analyses executed on DGD data in the past. Report numbers refer to the project specific numbering defined in Table 1-1.

- Sediment balance: Bed measurements in Deurganckdok (Reports 1.1 - 1.24)
    - 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 at entrance, center and back of dock (Reports 2.6 – 2.8, 2.16 – 2.18, 2.32, 2.33)
    - 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 (Reports 2.6 – 2.8, 2.16 – 2.18)
    - 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 and along-dock transect: profiling (Reports 2.1, 2.2, 2.10, 2.11, 2.15, 2.29 – 2.31)
    - 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 (3 depths)
  - 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 (Reports 2.3 – 2.5, 2.14, 2.20 – 2.27)
  - transects of suspended sediment concentration, velocity and sediment mass flux
  - time series of discharge and sediment mass flux
- Dock entrance: transects X, Y and Z perpendicular to dock's axis (Report 2.28)
  - Transects of vertical flow velocity profiles
  - Depth averaged flow velocity in top 12m: vector fields
  - Eddy development and intensity
- Buoy 84 and 97 (Reports 3.1, 3.10 – 3.14, 3.20, 3.21)
  - 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 (Reports 2.12, 2.13)
  - transects of suspended sediment concentration, velocity and sediment mass flux
- Deurganckdock: inside and entrance area (Report 9)
  - 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

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 empirical 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:

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

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:

$$M_{year} = \int\limits_{year} F_{net}\, dt$$

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.

The first method requires in situ density profiles measured at a sufficiently fine grid covering the dock at two points in time. The second method consists of a time integration which means that information is needed with a very high frequency in time. It is not possible to measure sediment profiles at a continuous basis: an empirical conceptual model of the sediment exchange at the dock's entrance can provide a solution. This report deals with that method.

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 2009 data has been collected, as summarized in Chapter 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);
- both sides of dock entrance;
- 13-hours intensive measurement campaigns at dock entrance returning the local and total sediment mass flux (e.g. IMDC 2008g,l; IMDC 2009a,b,e,n).

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, the suspended sediment concentration 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 phase 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. Note that in the third year of the project continuous measurements were executed making this step redundant.

Assume the following measurement periods:

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

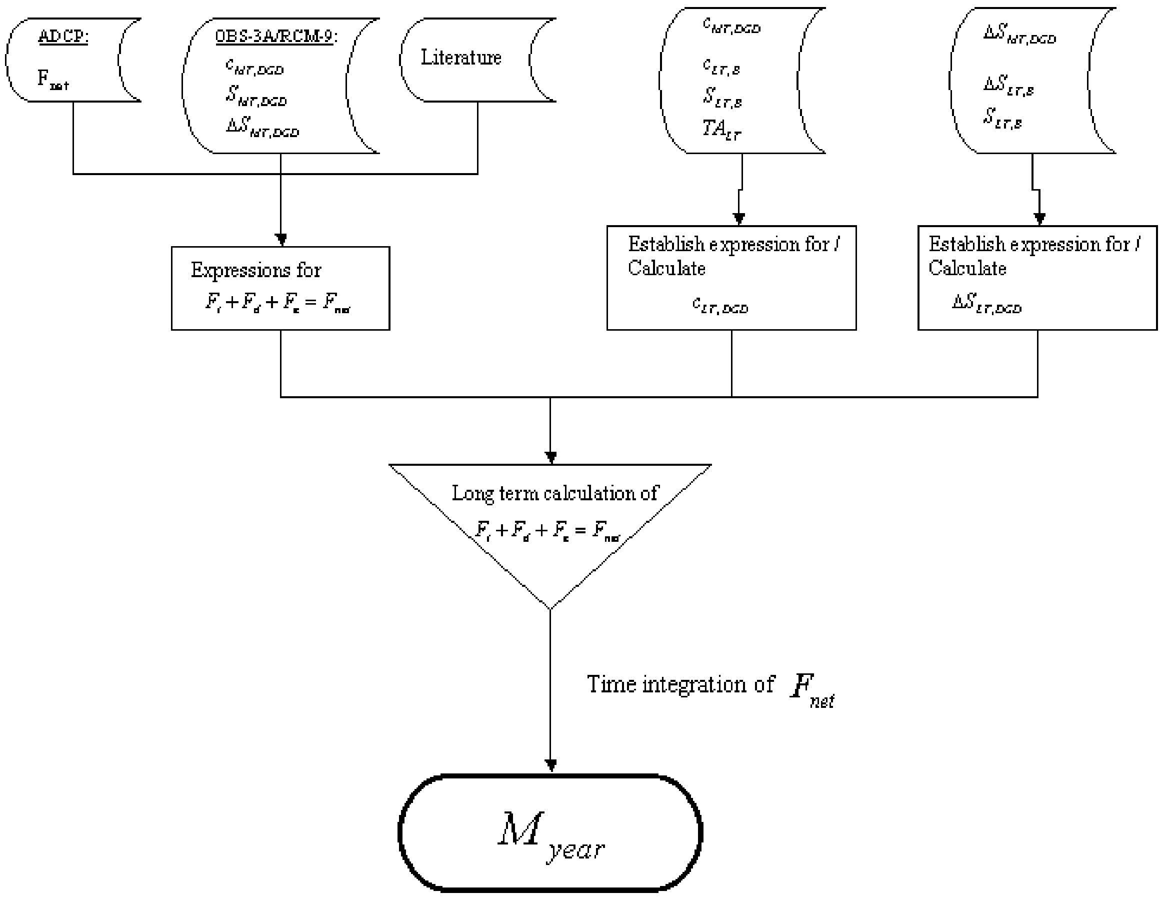


Figure 4-1: Overall method for empirical model of sedimentation in Deurganckdok with data-assimilation.

Step 1: determination of relationship between mass flux and locations at sides of dock entrance

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 midterm 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.

Step 2: determination of relationship between locations at sides of dock entrance and Scheldt

Since during three midterm periods measurements are available 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:

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

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 assuming that $f_{LT,c}$ is valid for long term data:

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

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 and sediment concentration. 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:

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

Again, all these are known since measurements in the dock are midterm 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 assuming again that the function $f_{LT,\Delta S}$ is also valid for long term data:

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

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.

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

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.

During the first two years of the measurements –DGD1 and DGD2- measurements at the dock entrance quay walls were available during limited periods only, e.g. three times four weeks in a year. For the last year of measurements analysed in this report nearly continuous measurements have been conducted with OBS equipments at either side of the entrance and on two locations further landward, on each location OBS's have been deployed on two depts. The availability of year-round data has rendered the uncertainty-introducing estimates of suspended sediment concentration and salinity amplitude redundant.

The long time series are direct input for the semi-analytical solution of the sediment accumulation in the dock. For DGD1 the solution could only be partially checked by comparison with short-term measurements (through-tide). In DGD2 a new dataset is available from regularly executed density profiling in the dock bed. Combined with records of dredged mass a fairly exact balance can be determined of the sediment movements across the entrance. Even more frequent trough-tide measurements during DGD3 made the validation of the model more extensive.

In the analysis of the second year into the project (DGD2) some improvements have been implemented compared with the first year in the project (DGD1). The main difference is the way the fraction of exchanged sediment due to density currents and eddy circulation is determined. The obtained values are the result of a more thorough analysis of the sediment exchange. The result for density currents was in the same order of magnitude of the DGD1 analysis. More insights into the turbulent exchange through eddy's are gained because of the ADCP measurements along the axis of the dock near the entrance on 1st of October 2008. The parameters obtained with this method are calculated again with the DGD3 data and shows comparable values.

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 tidal range, mean salinity, salinity amplitude and mean sediment concentration in the estuarine waters near the dock and the tidal amplitude.

During the first two years into the project salinity and sediment concentration have been measured only during three limited periods throughout the year. A method had to be found to estimate these quantities for a complete year based on measurements a few kilometres further up and down the Scheldt Estuary. The method is described by IMDC (2008b and 2009o) and used in the analysis of the DGD1 and DGD2 subprojects.

Since this method introduced a significant amount of uncertainty it was decided to invest an extra effort in the continuous measurement of salinity and suspended sediment concentration on both ends of the dock entrance at two depths. Therefore the tidal mean sediment concentration and the salinity amplitude have been calculated directly from the measurements for a full year (Figure 5-1).

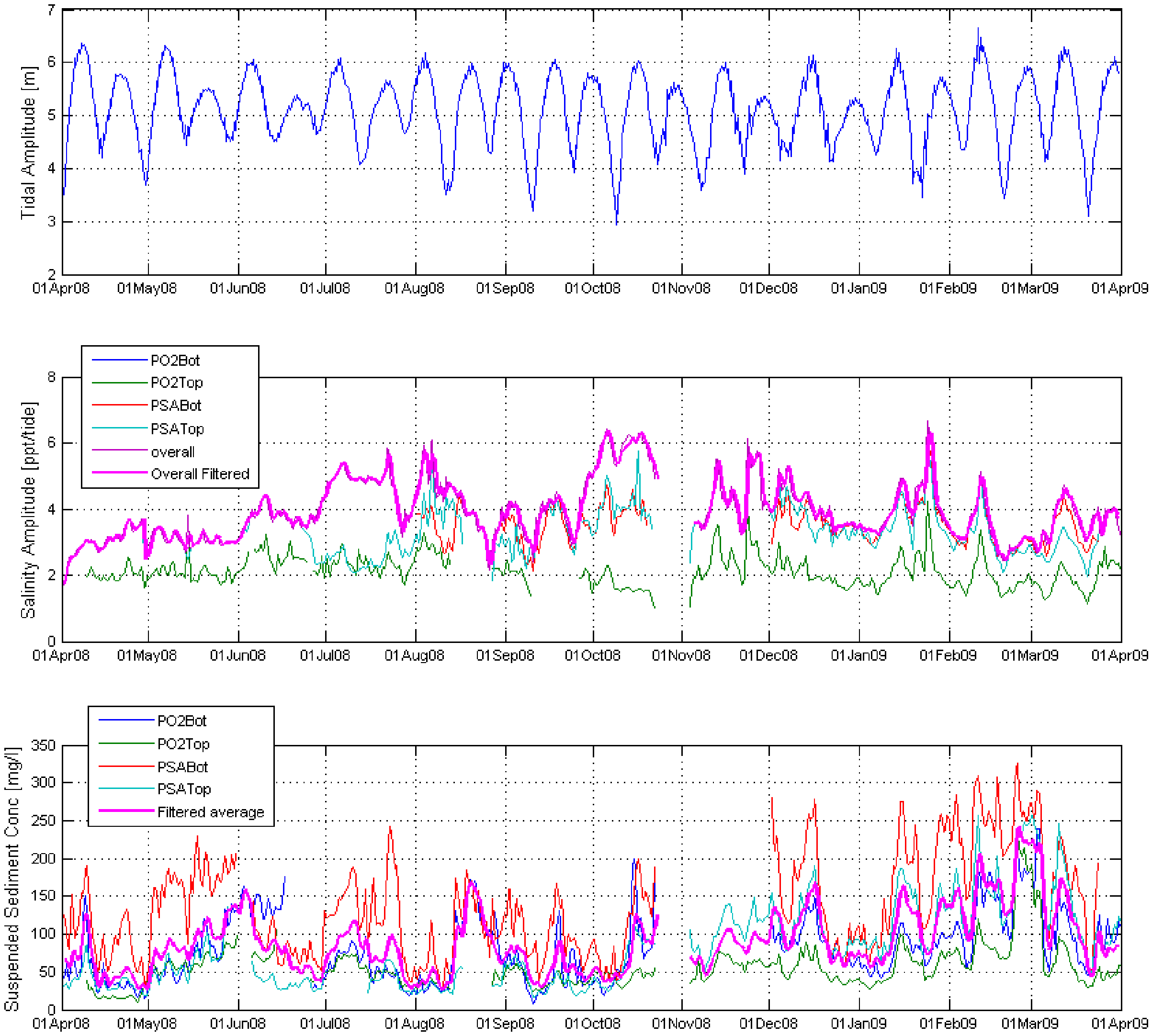


Figure 5-1: Tidal amplitude, salinity amplitude and sediment concentration data from year-round measurements at Deurganckdok. Tidal mean values are given, except for the pink lines showing filtered overall salinity amplitude (middle panel) and filtered average sediment concentration.

5.3. Estimation of long term sedimentation

The method presented below has been used for the calculation of the siltation during the second year of measurements, and has been applied -with only minor adaptations- to the third year of measurements as well since the assumptions made during the second year of analysis proved to hold for the third year. The coefficients used for the ratio of exchanged sediments remaining in the dock have been changed according to new calculations based on a full year of measurements. An overview of the evolution of the coefficients in the model in the preliminary reports of the first two project years in comparison with the final computations given in this report is shown in §6.2.2

The suspended sediment concentrations and salinity amplitude data used as input for the third year of model calculations has been taken directly from filtered measurements, executed throughout the best part of the year (end of April 2008 until end of March 2009). Since the measurements used for DGD3 are measured directly at the entrance a Godin-type filter has been applied compared to the 7 day filter applied for measurements taken several kilometres away from the dock as was the case during the DGD1 and DGD2 project years.

Since the momentum of currents in the dock is very limited the amount of sediment deposited in the dock will always be strongly dependent on the amount entering the dock, i.e. the fraction of intruded suspended sediments which is not advected out is expected to be relatively high. This fraction is dependent on the settling velocity. 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 5-1, 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 5-2); (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). Overbars denote averaging over all variables not integrated over, considering resp. x, z and t for along dock entrance, vertical and temporal dimensions.

Equation 5-1:

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

Equation 5-2:

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

$$= F_t + F_d + F_e$$

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

$\bar{v}$ is the flow velocity perpendicular to the entrance (convention positive seawards), averaged over the dock entrance cross section area.

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

$\overline{v_{dens}}$ is the velocity perpendicular to the entrance due to density currents, averaged over a tidal cycle

$\overline{v_{eddy}}$ is the velocity perpendicular to the entrance due to large eddies, averaged over a tidal cycle

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).

5.3.1. Tidal Filling

The first term in the RHS of Equation 5-2 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 from the quasi continuous measurements. For the third year the full dock dimensions after completion of the construction works have been applied, which are most important for the component of the tidal filling (2500 m in length and 425 m as the average width).

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

Equation 5-3:

$$F_t(t) = c_1.h(t).A_h.\overline{c(t)}$$

in which: c_1 is a dimensionless constant, h is tidal amplitude (m), 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 5-3 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 account 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 account 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 flocs entering the dock due to tidal filling will have settled with high probability. However, other fractions with lower settling velocity might reside in the water column and the relatively low turbulence intensity might still keep part of the microflocs and finer fractions in suspension. An alternative analysis has been made of the settling ratio due exchange by tidal filling. The subdivision of the sediment exchange in three components is artificial, and thus an exact calculation of the settling ratio of this virtual part of the exchanged sediments is not possible. Since the long list of through-tide measurements have revealed a mean trapping efficiency of the dock of 0.39 with a relatively small variance and the calculation of the partial trapping efficiency (settling ratio) for sediments exchanged by density currents and horizontal entrainment (eddies) the value for tidal exchange can be deduced as follows:

$$e_s = w_d \alpha_{set,dens} + w_e \alpha_{set,eddy} + w_t \alpha_{set,tide} = 0.39$$

The values of $\alpha_{set,dens}$ (0.35) and $\alpha_{set,eddy}$ are calculated based on measurements (see below), and w_d, w_e and w_t are the relative weights of the contribution of the density currents, horizontal eddies and tidal exchange components and are known from previous calculations ($w_d = 0.66$, $w_e = 0.10$) and measurements (tidal exchange volume is about 24% of the totally exchanged volume, w_t=0.24). From this information the parameter $\alpha_{set,tide}$ can be deduced to be equal to 0.67, which is called c_1 in the present study in order to distinguish from the parameters calculated directly from measurements.

5.3.2. Density Currents

The second and third term in the RHS of Equation 5-2 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. 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 (measured) 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 right-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 5-2). 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 from measurements, the average exchanged liquid discharge is proportional to the salinity amplitude, the fraction of sediment settled out is unknown.

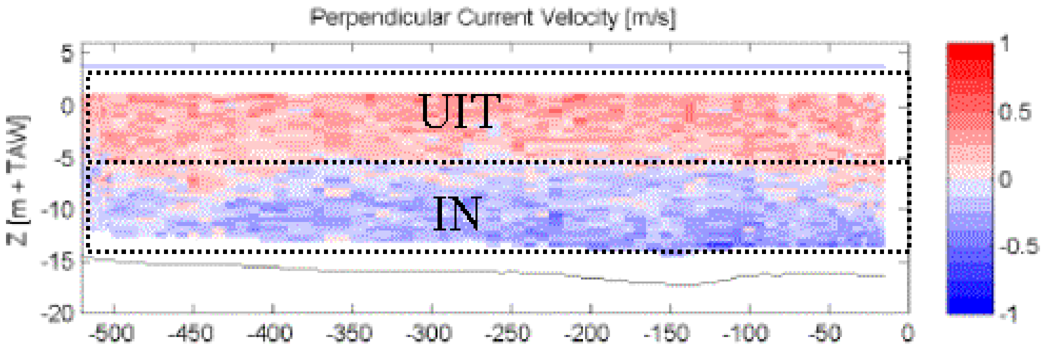


Figure 5-2: Example of density current at high water, denser, more saline water flows in the dock (v<0) in the lower half of the water column and fresher water flows out in the upper half. Schematisation in black.

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 5-2), 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 one hour 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.

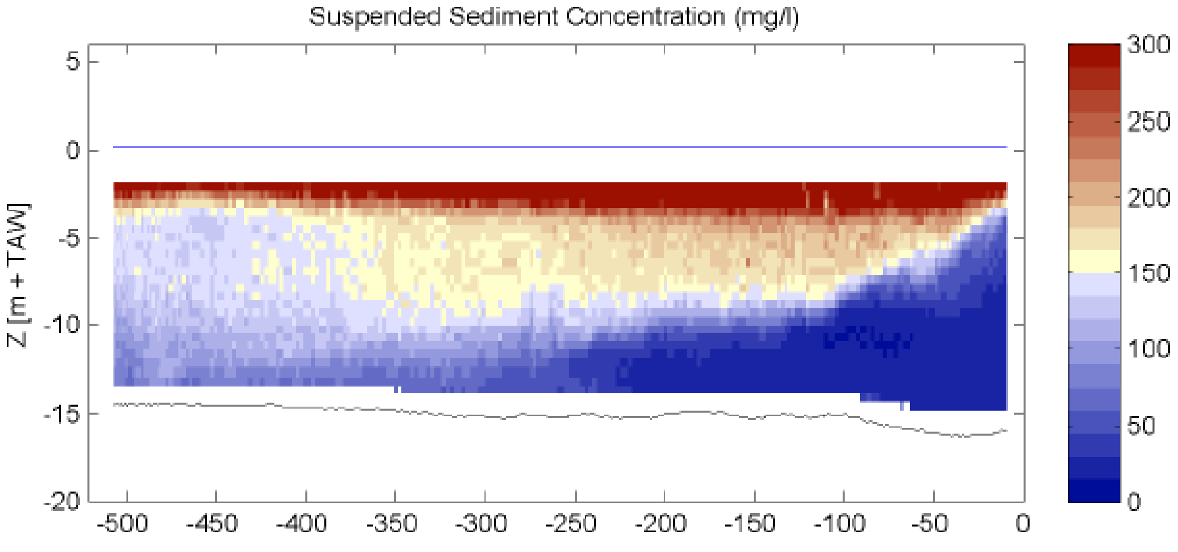


Figure 5-3: inverse sediment concentration profile during low water density current.

The relative difference of vertical gradient between the high tide case (Figure 5-2) and the low water case can be taken as a measure for the unknown settled fraction during a tidal cycle (Equation 5-4). 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 dock flows out near the bed. In many cases though the gradient in the latter phase of the tidal cycle is negative: the sediment concentration is higher near the surface than near the bottom due to the sediment laden fresher waters flowing in the top zone and the more brackish settled waters from the dock flowing out below. A rather extreme case of this phenomenon has been observed during the measurements on March 12th 2008, which were done during a northwest storm (Figure 5-3). In other cases 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 two cases are possible: (i) A slightly smaller amount is exported again and (ii) when the concentration gradient is negative an extra amount is imported.

The net imported fraction of all exchanged sediments over a tidal cycle should take into account these observations and is represented by $\alpha_{set,dens}$. Since no detailed information about vertical sediment gradients is available throughout the year, two option are possible: either a constant fraction is used or the fraction is a function of certain ambient conditions. In order to make an appropriate choice and to find a good value for the retained fraction of sediments exchanged by density currents in the dock a thorough analysis has been done on the matter.

When it is assumed that density currents at low water and at high water exist during the same amount of time (3 hours after high and low water respectively), the fraction of sediments exchanged by density currents that are retained in the dock can be expressed as follows:

Equation 5-4:

$$\alpha_{set,dens} = \left(\frac{c_{bot} - c_{top}}{c_{max,v}}\right)_{HW} + \left(\frac{c_{top} - c_{bot}}{c_{max,v}}\right)_{LW}$$

When $\Delta c_z = c_{bot} - c_{top}$ this becomes:

Equation 5-5:

$$\alpha_{set,dens} = \frac{\Delta c_{z,HW}}{c_{max,v,HW}} - \frac{\Delta c_{z,LW}}{c_{max,v,LW}}$$

And

$$c_{max,v} = \max\,(c_{bot}\;, c_{top})$$

Where the ‘max’ subscript denotes the maximum of top and bottom concentrations, and the HW and LW subscripts indicate that an average is taken from HW to HW+1h and LW to LW+1h respectively since at these times the density currents are existing independently from the other exchange mechanisms.

This method avoids the influence of instances at which the denominator becomes close to zero and by result some calculated values are very high and distort the average.

When applied to the measurements at the entrance of the dock we see that the net retained fraction at high water (blue) is always higher than the net exported fraction during low water (green line in Figure 5-4), the same result as for the DGD2 measurements The difference between both is than the equivalent of the overall net fraction of sediments exchanged by density currents retained in the dock over a full tidal cycle (red circles). This value varies between 0 and 0.8 and will be used in the calculations with a constant value (average) of 0.35. This figure is in close agreement of the value 0.30 obtained in the previous (DGD2) project year.

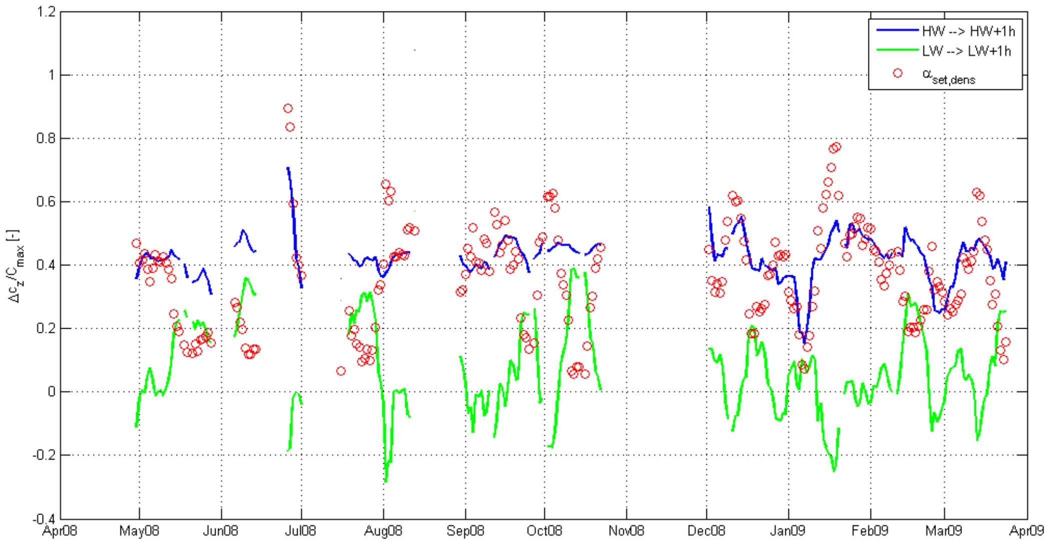


Figure 5-4: Net imported fraction at high water density current and net exported fraction during low water density current. The overall imported fraction over one tide is the difference between both.

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 5-6:

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

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

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

Equation 5-7:

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

Where $Q_{s,d}(t)$ is the solids exchange rate due to density currents 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 $\overline{c(t)}$ is the tidal average sediment concentration.

In this relation ε is a measure for the pressure gradient providing momentum for density currents, in turn being an indicator for the intensity of the density current. Its value is largely dependent on the salinity amplitude at the surface. Comparison with measurements learned that it can be assumed that both are equivalent in the case of DGD.

Coefficient c_2 is dimensionless and has been used before to calibrate the suspended sediment flux against available observations from through-tide measurements, but from Equation 5-6 its value should be close to 0.5, which has been used since the exact calculation of $\alpha_{set,dens}$ no calibration should be done.

Additionally, the effect of tidal filling and emptying on the density current should be taken into account. In Figure 5-5 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.

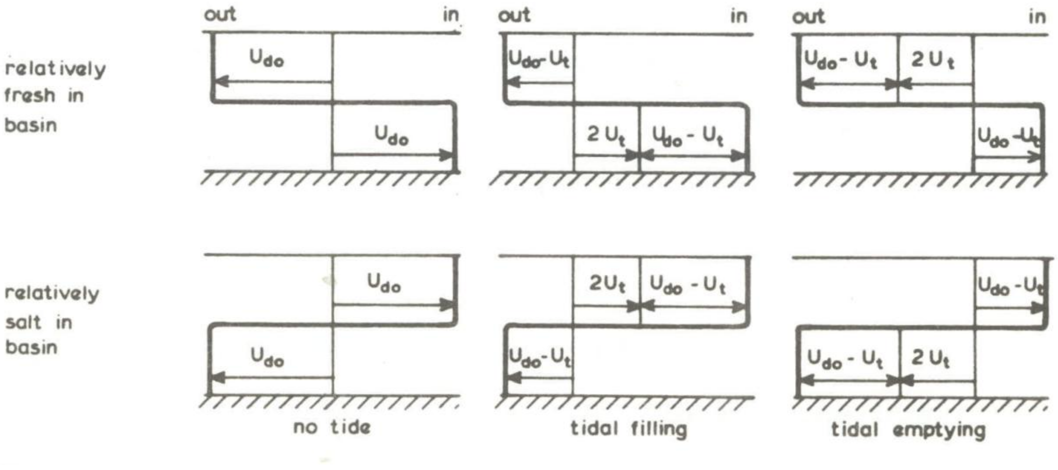


Figure 5-5: Influence of tidal filling and emptying on a density current (Eysink, 1983). Where U_{do} is the exchange velocity without influence of tidal in- and outflow (ν_{dens} in the nomenclature of this report), U_t is the flow velocity related with tidal prism.

An estimate of u_{d0} and u_t learns that u_{d0} is about 10 times higher than the latter, therefore it has been assumed that the effect of tidal filling and emptying can be neglected and that both exist independently.

Some modelling studies indicate a possible reflection of an internal fresh water patch off the back face of the dock. The effect of this reflection can be damping or limitation in time period of the density current (Van Maren et al, 2009) and is expected to be reduced with a longer dock such as during DGD2 and DGD3 campaigns.

The calculated velocity related to density currents as a function of salinity amplitude shows for the middle estimate a variation between 0.3 m/s (end of winter) and 0.45 m/s at the end of the summer dry season (Figure 5-6).

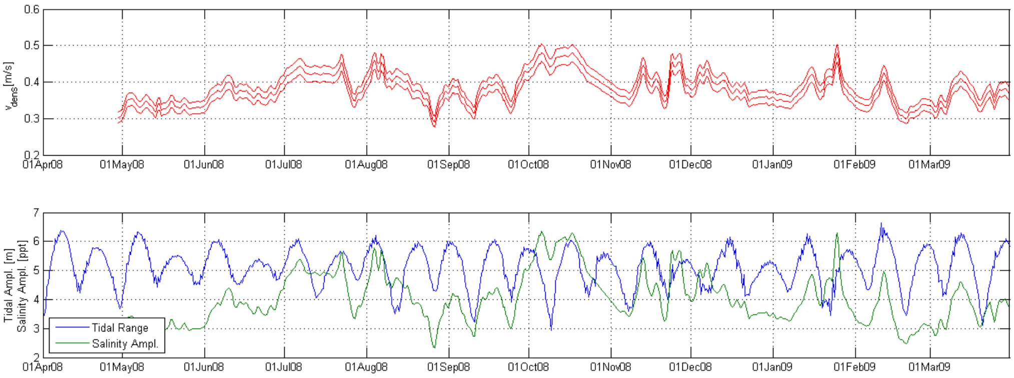


Figure 5-6: Calculated velocity related to density differences, with low, mid and high estimate, where low and high estimates incorporate a 10% error on the measured salinity amplitude (top) and the influence factors: salinity amplitude and tidal range (bottom).

5.3.3. Large Horizontal Eddy

A similar approach can 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 5-7), during ebb current anti-clockwise. A consideration should be made about the difference in flood velocity and ebb velocity.

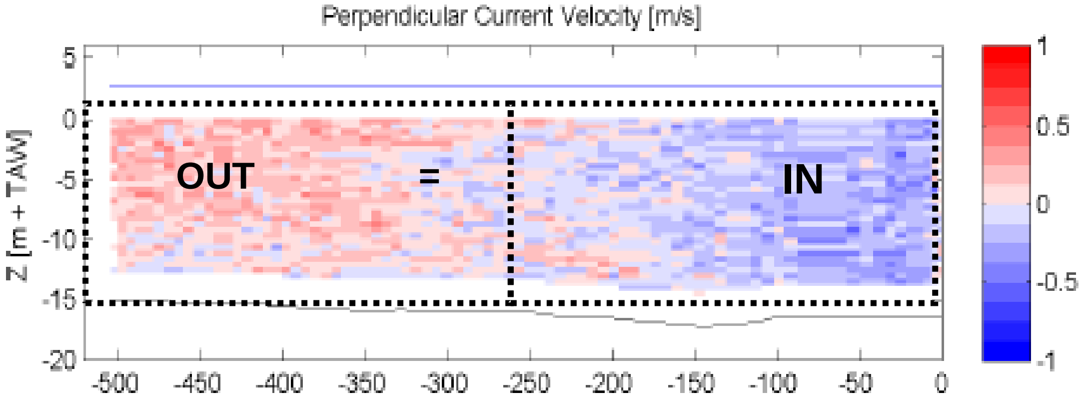


Figure 5-7: Example of eddy circulation flow at the entrance of the dock during flood: at the inland end water flows in (v<0) at the seaward end water flows out, view towards the Scheldt. Schematisation in black.

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 used) 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 the complete year of the DGD3 campaign. An approximation of the ratio $\alpha_{set,eddy}$ is based on the relative gradients during ebb and during flood. Considering that (i) 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 (ii) 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	**Eddy direction**	**gradient**	**Duration**	**Residual transport**
Flood	clockwise	positive	HW-3 to HW = 3 hours	Outwards (-)
Ebb	Anti-clockwise	positive	LW-1h to LW = 1 hour	Inwards (+)
Flood	clockwise	negative	HW-3 to HW = 3 hours	Inwards (+)
Ebb	Anti-clockwise	negative	LW-1h to LW = 1 hour	Outwards (-)

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

It is observed that the flood eddy is 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 of DGD1. During the course of the DGD3 measurements campaigns the ebb eddy disappeared almost completely, probably due to the lengthening of the dock leading to a 70% increased tidal prism and stronger outflow during ebb. This in turn advects the eddy out of the dock and is therefore unable to develop (see also 6.1.3.2). Also it is known that the Scheldt estuary is flood dominated near DGD according to the classification of Dyer (1995) and from observations. 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 falling tide is multiplied by a factor 0.5 (Equation 5-8).

The coefficient representing the fraction of entering sediments remaining in the dock is calculated as follows:

Equation 5-8:

$$\alpha_{set,eddy} = \left(\frac{c_{SE} - c_{NE}}{c_{max,h}}\right)_{Flood} + \frac{1}{2}\left(\frac{c_{NE} - c_{SE}}{c_{max,h}}\right)_{Ebb}$$

And

$$c_{max,h} = \max\left(c_{SE}\ , c_{NE}\right)$$

Where SE is 'South Entrance' and NE is 'North Entrance'. Again the assumption is made, in contrast to the DGD1 analysis, that the duration is equal during the ebb and flood eddy: 3 hours each. However, the weaker eddy during ebb is incorporated by the factor 0.5 multiplied with the ebb fraction (the second term on the RHS).

When $\Delta c_B = c_{NE} - c_{SE}$ the fraction alpha becomes:

Equation 5-9:

$$\alpha_{set,eddy} = \frac{1}{2}\frac{\Delta c_{B,Ebb}}{c_{max,h,Ebb}} - \frac{\Delta c_{B,Flood}}{c_{max,h,Flood}}$$

In which the subscript ‘Ebb’ means averaged over three to two hours before low water, and ‘Flood’ means averaged over three to two hours before high water. Note that the fraction alpha is calculated based on one hour in the tidal cycle to avoid influence of interaction with density currents near high and low water. The effect of the eddy on the sediment flux is accounted during 2 times three hours per tidal cycle.

Both terms are calculated (without factor 0.5 for ebb) and plotted in (Figure 5-8). It is clear that the horizontal gradient is predominantly positive, and higher (more than a factor two) during ebb than during flood. Since a positive gradient during an ebb (flood-)-eddy implies net import (export), the tidal average imported fraction is mostly positive, although during some periods it is shown to be negative (i.e., net output). The computed $\alpha_{set,eddy}$ shows high variability throughout the neap-spring cycles and the seasonal variation. But, a yearly average has been used (0.14) for the further analysis for the following two reasons: (i) no clear correlation has been found with any of the mentioned time scales and (ii) the use of data from four different equipments leads to some gaps in the data. Therefore, the computed net influx due to eddy exchange (F_e) is always positive.

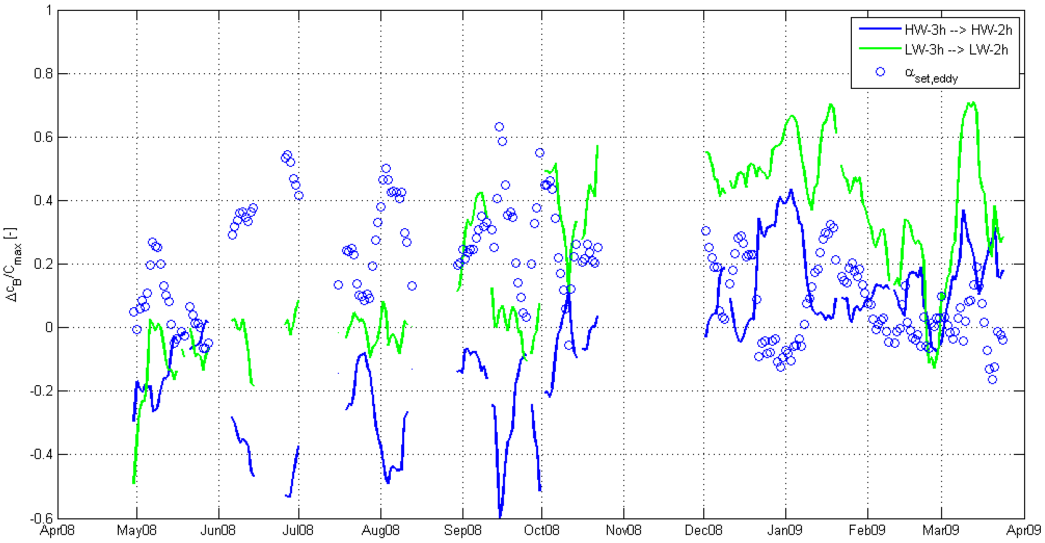


Figure 5-8: Relative sediment gradients along the entrance of the dock.

Since the ebb gradient counts only half and the fact that a positive gradient during flood corresponds to net sediment export, the overall fraction of exchanged sediment due to eddies that remains in the dock after a full tidal cycle is very limited and in some tidal cycles even negative.

This seems a surprising result, but considering the flow field and the phasing of the sediment concentration during the tidal cycle this might well be possible. It is also observed that before October 1st 2008 the along-entrance ssc gradient is mainly negative and after December 1st 2008 mainly positive. There is no explanation for this behaviour and might be an equipment offset issue. However, the difference between ebb and flood gradient is used for this purpose, so any difference in offset is singled out.

The approximated net solid discharge and total solids flux per tide due to a horizontal eddy $F_e(t)$ is calculated as a function of the settled fraction, the mean concentration, the mean eddy velocity and the tidal coefficient:

Equation 5-10:

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

where: $Q_{s,e}(t)$ is the net solid discharge due to eddy exchange, 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, $\overline{c(t)}$ is the tidal average sediment concentration $\bar{v}_{eddy}$ is the average eddy current velocity and $\left(\frac{h(t)}{\bar{h}}\right)$ 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. The fact that the ebb eddy is weaker is already integrated in the alpha coefficient.

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 emptying flow is stronger, i.e. during spring tide. To account 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 solids flux per tidal cycle due to eddy exchange Equation 5-10 becomes:

Equation 5-11:

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

Where β is dimensionless and equal to 0.05.

5.3.4. Overall net sediment inflow per tidal cycle (3rd year)

Since suspended sediment concentration gradients (vertical and horizontal) are based on measurements of different instruments, some periods with no data remain. Therefore, the yearly average $\alpha_{set,dens}$ and $\alpha_{set,eddy}$ have been determined:

Table 5-2: Value of coefficient representing settled fraction

parameter	Value [-]
$\alpha_{set,dens}$	0.35
$\alpha_{set,eddy}$	0.14

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 eddy 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. A summary of equations used throughout this study is included below.

Density currents account for the largest part of the siltation with an average contribution to siltation of about 300 to 2000 Tons Dry Matter (TDS) per tide followed by tidal prism exchange (200-1000 TDS per tide) and horizontal eddy circulation (20-300 TDS per tide).

After executing all required calculations, sediment fluxes are in the range of 250 to 3000 TDS per tide (Figure 5-10). A low and high estimate have been calculated leading to an uncertainty interval around the calculated flux values. This interval has been reduced due to the year-round measurements at the dock measurements instead of estimates based on an empirical relationship. The error on measurements used as input for the model has been set at 10%, which has been implemented throughout the calculations resulting in the error margins shown in the influx rates.

The variation in net sediment inflow is relatively limited throughout the year, with a slight decrease during late summer and an increase in late winter, that is when turbidity levels are high due to the proximity of the turbidity maximum and the strong spring tides in February and March. The reason for the relatively low summer-winter variation is that for example during winter the sediment concentration is higher while the salinity amplitude is lower (Figure 5-1) due to the higher river runoff. Both effects partially single out each other. The highest sedimentation rates are found in February 2009. The cumulative natural siltation is shown in Figure 5-11. An overview of the monthly siltation with influence factors is given in APPENDIX B, one year variation in siltation rate and influence factors is shown in APPENDIX C.

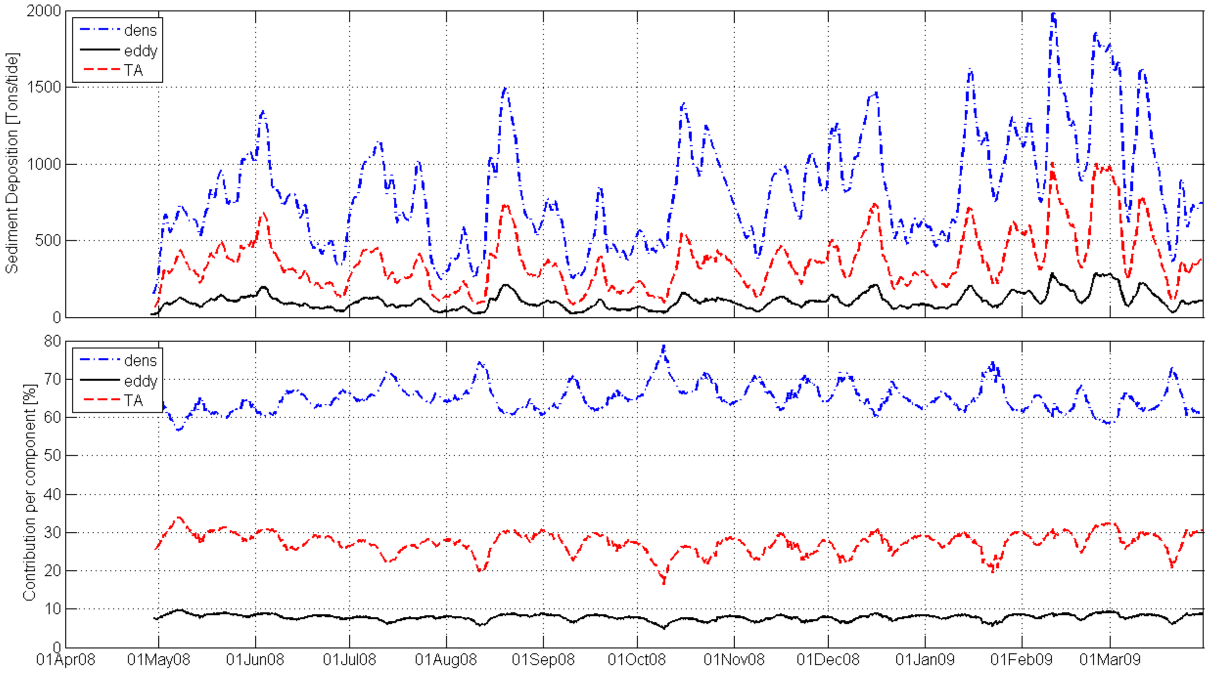


Figure 5-9: Sediment influx due to density currents, eddy circulation and tidal amplitude (top panel), relative contribution of the siltation rate per component (lower panel).

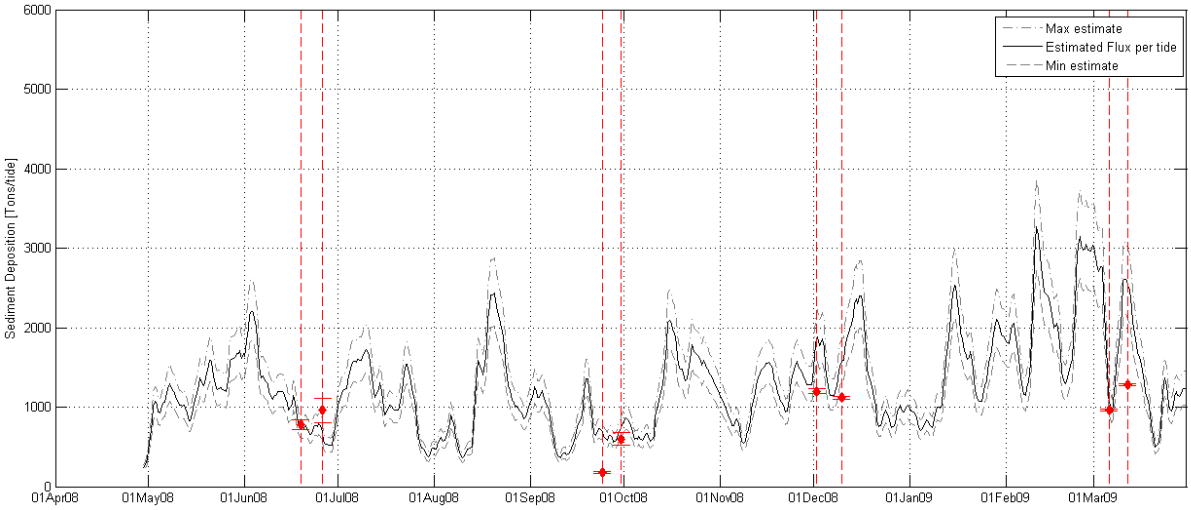


Figure 5-10: Time series of estimated sediment influx (with uncertainty interval), grey zones indicate periods of measurement in DGD, red dots indicate through-tide measurements of which the observed suspended sediment influx is available.

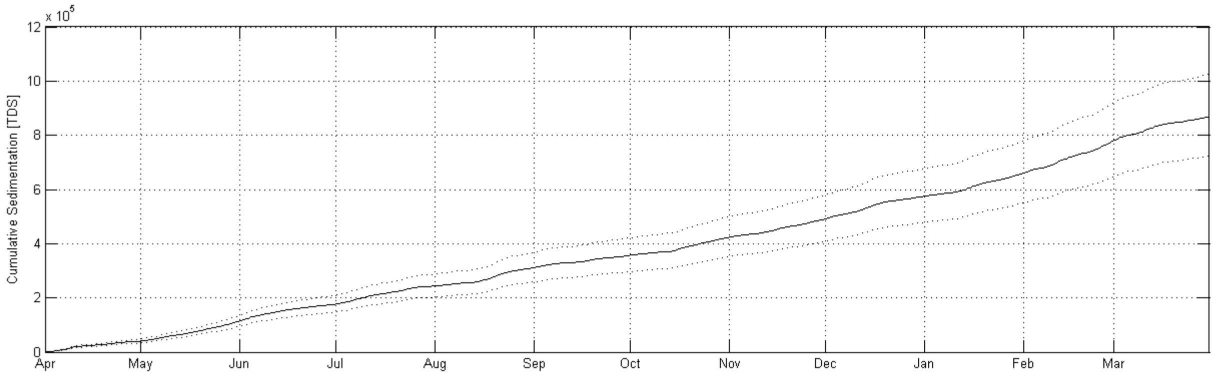


Figure 5-11: Cumulative natural sedimentation in black (x100,000 TDS) with zero at May 1st 2008, uncertainty band in grey. Average sedimentation rate varies with seasons, lowest rates in September and October.

After calculation of an estimate for each tide from 1st of May 2008 to 31st of March 2009 the time integral has been calculated for the 11 months of measurements and has been recalculated to full year figures(Table 5-3). The main estimate shows a value of 880,000 tons dry matter net inflow of suspended sediments in 12 months. The uncertainty on these values should be taken at 20% 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 always exist independently and interact during many tidal phases. By consequence these values are not to be evaluated individually either.

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

	Low estimate	Mid estimate	High estimate
Tidal prism influx	221	**246 (≈28%)**	271
Density current influx	482	**566 (≈64%)**	654
Eddy circulation influx	30	**71 (≈8%)**	120
Total sediment influx	733	**883**	1045

The lower sediment influx due to the large eddy at the entrance is the main difference with previous (DGD1) results. The analysis performed on the sediment concentration measurements on both sides of the dock's entrance leads to a small average ratio of the eddy-exchanged sediments retained in the dock. Since the interaction of the eddy with tidal filling is rather important in Deurganckdok the flood eddy is advected into the dock during rising tide and is located away from the entrance, preventing it to take part in the exchange between dock and river. This effect was probably less pronounced during the first year in the project since the dock was shorter at that time, reducing the tidal prism. This topic is covered in §6.1.3.2. The waters contributing to the filling of the dock enter on the eastern side of the entrance and the eddy is located slightly South of the western part of the entrance, which is the main reason why we see high sedimentation rates there during periods undisturbed by dredging (Figure 5-12). This hypothesis has been confirmed after analysis of the DGD3 data.

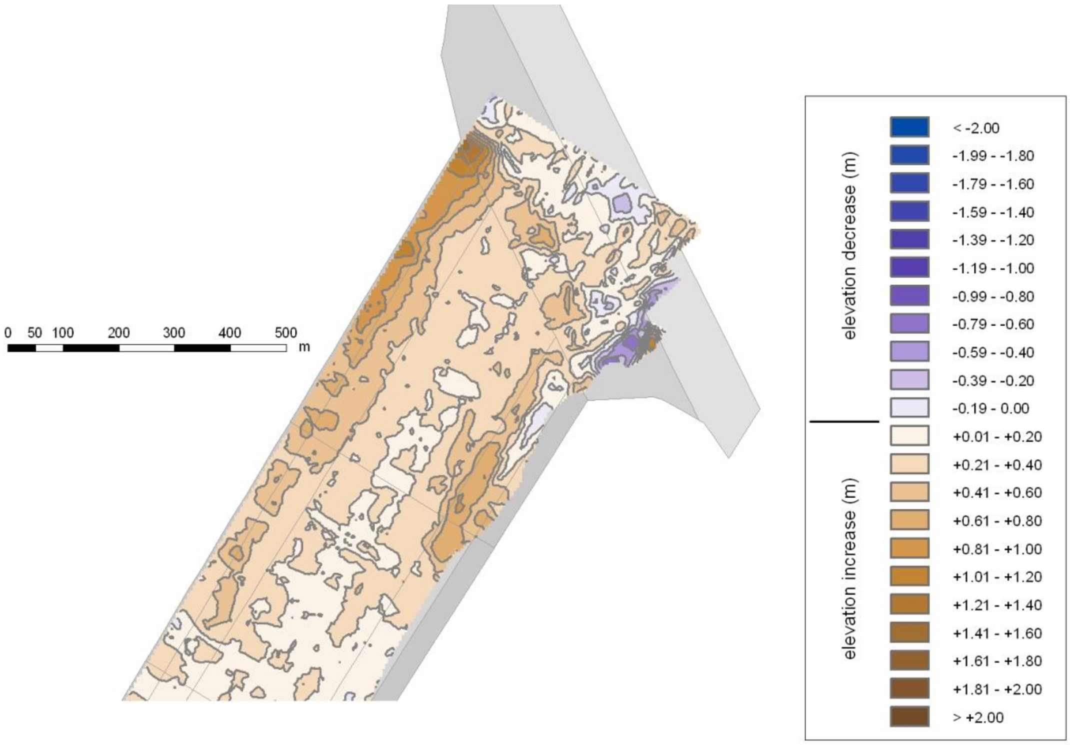


Figure 5-12: Example of siltation near north part of the entrance of the dock, in the First year of the project with the dock not yet at full length.

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.

Below is given a summary of the equations used for the sedimentation model:

$$F(t) = F_t(t) + F_d(t) + F_e(t)$$

$$F_t(t) = c_1.h(t).A_h.\overline{c(t)}$$

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

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

$$\varepsilon(t) = \Delta S(t)/\rho$$

$$\alpha_{set,eddy} = \frac{1}{2}\frac{\Delta c_{B,Ebb}}{c_{max,Ebb}} - \frac{\Delta c_{B,Flood}}{c_{max,Flood}}$$

$$\alpha_{set,dens} = \frac{\Delta c_{z,HW}}{c_{max,HW}} - \frac{\Delta c_{z,LW}}{c_{max,LW}}$$

With:

$c_1 = 0.66$

$c_2 = 0.5$

$A_h = 2500x425m^2 = 1.0625e6m^2$

$A_{cs} = 15x500m^2 = 7500m^2$

$T_{dens} = 5.3600s = 1.8e4s$

$T_{eddy} = 4.3600s = 1.44e4s$

$\alpha_{set,dens} = 0.35$ (yearly average)

$\alpha_{set,eddy} = 0.14$ (yearly average)

$v_{eddy} = 0.05 - 0.10 - \ 0.15\ m/s$ (Low-mid-high estimate)

$\beta = 0.05$

$\rho = 1010 kg/m^3$

Time indication t is an index and not a continuous time since t indicates the discrete times of each tidal cycle.

5.4. Water volume exchange rate

The formulations given above for the sediment influx rate also contain the formulas for the gross water exchange rates for each component. These are obtained by dividing by the settling ratios and the sediment concentration. The exchanged volume of water per tidal cycle is given in Figure 5-13.

The components due to tidal prism and the large horizontal eddy are closely related and show a similar pattern where the eddy component is slightly larger. The tidal prism induces an exchange of about 5 to 7 Mm³ water per tidal cycle, horizontal entrainment (eddy) accounts for 6 to 9 Mm³ (Table 5-4). Density currents cause a liquid exchange of a manifold of the other components: 20 to 30 Mm³ per tidal cycle.

Table 5-4: Three mechanisms' exchange share

	Liquid exchange (Mm³)	Percent of total (%)
Tidal prism	**5 - 7**	**15**
Density current	**20 – 30**	**65**
Eddy circulation	**6 – 9**	**20**
Total	**30 - 45**	**100**

The total liquid exchange is therefore estimated at about 40 Mm³ per tidal cycle, with a typical neap-spring variation of 10 Mm³, seasonal variations due to differences in salinity amplitude account for a variation of 5 Mm³.

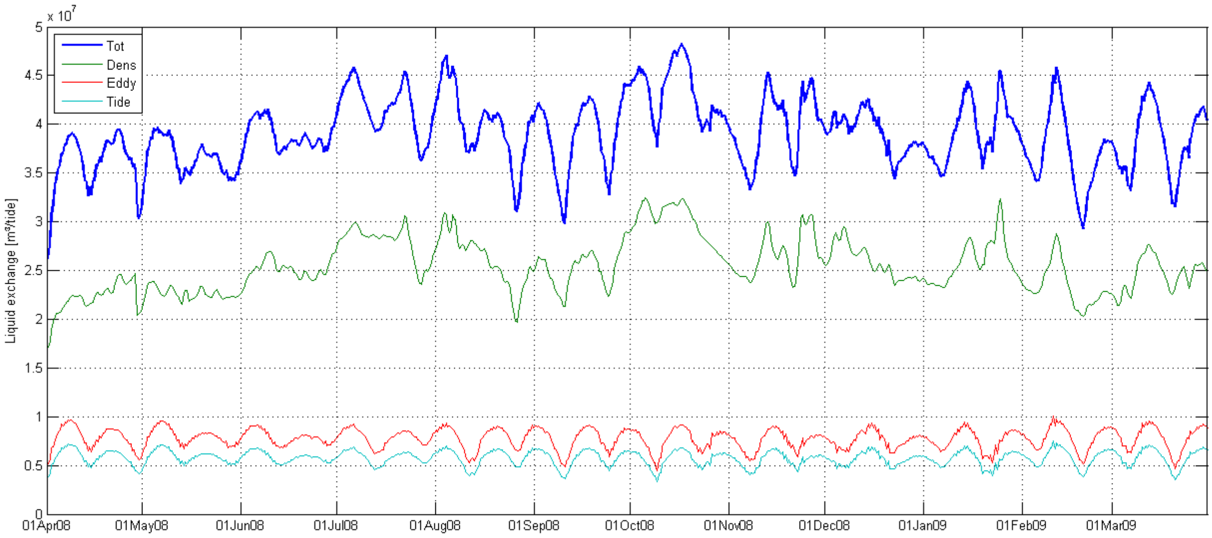


Figure 5-13: Liquid volume exchange per tidal cycle due to the three main components and the total.

5.5. Conclusions on third year of siltation calculations

The data from the third year of measurements was used to calculate the input parameters following the methods used for the DGD2 period. The values for sediment retention ratio's due to eddy and density current circulations obtained with the DGD3 data show comparable values. The only settling ratio for which no calculation method is used (tidal prism exchange) was based on a rudimentary calculation of the fraction of sediments that would reach the bed after settling over half a tidal cycle. This method ignores the turbulent mixing that the (rather low) flow velocities inside the dock induce. In the third year calculations the settling ratio due to sediments exchanged by tidal filling and emptying have been determined based on the trapping efficiency of the dock. The weighted average of the settling ratios of the three main components should be equal to the measured trapping efficiency of the dock (0.39). The only unknown in this equation is the settling ratio of the tidal prism exchange and can therefore directly be determined. This is the only difference in calculation of the influx rate during the third year compared to the previous years.

The different approach used to gather input for the semi-analytical model did no longer imply filtering over a period of multiple days. The higher variability in the input data as a result of this resulted in a higher variability in output influx rates, with lower neap tide values and higher spring tide values. Obviously, because the input data was produced with dependency on the tidal amplitude for DGD1 and 2 the calculated sediment influx was less dependent on the tidal amplitude in the DGD3 calculation results. A higher part of the variation was due to the other ambient conditions.

When the obtained estimate (883,000 TDS) is compared to the balance of the dredged mass of about 990,000 TDS in the same period the amount of sediment in the dock has been reduced. The trend shown by the Navitracker density profiling measurements between March 2008 and August 2008 shows a decrease but unfortunatley the change in measurement technique from there on makes that the most recent sediment mass measurements with the Densitune equipment are incomparable with previous ones. The Densitune data has not been used in this analysis.

The mean calculated sediment influx rate amounts to 1291 TDS/tide, a 25% increase compared to DGD2 calculations, mainly due to the dock length increase and very high suspended sediment concentrations during February-March 2009.

The standard deviation on influx rates increased from 311 and 302 TDS/tide for DGD1 and DGD2 data respectively to 592 TDS/tide in DGD3 calculations.

Measured influx rates by ADCP backscatter calibration with Sediview shows influx rate values that are in the same range but are on average lower than the calculated values, especially during spring tides. However, the long term evolution of mass present in the dock (measured by bed density profiling with Navitracker) corresponds quite well with the cumulative influx calculated with the model, see § 6.2.4.

When influx rate calculations will be resumed after the construction of the current deflecting wall near the north end of the entrance the established parameters of the model will no longer be valid, e.g. duration of eddy and density current circulation, settling ratios, vertical concentration gradients. Therefore new measurements will be necessary to observe the change in behaviour of flow, salinity and sediment concentration structure after the current deflecting wall has been completed.

6. THREE YEARS INTEGRATED ANALYSIS

6.1. Observed features

6.1.1. 3D flow pattern

6.1.1.1. Structure

At some tidal phases either density currents or a horizontal eddy dominate the flow pattern, at other phases a combination of both existed, usually further combined with tidal filling/emptying (Figure 6-1). An example of individually occurring density currents has been shown in Figure 5-2 and of a horizontal eddy in Figure 5-7. Observations of combinations of 2 components are shown in Figure 6-2.

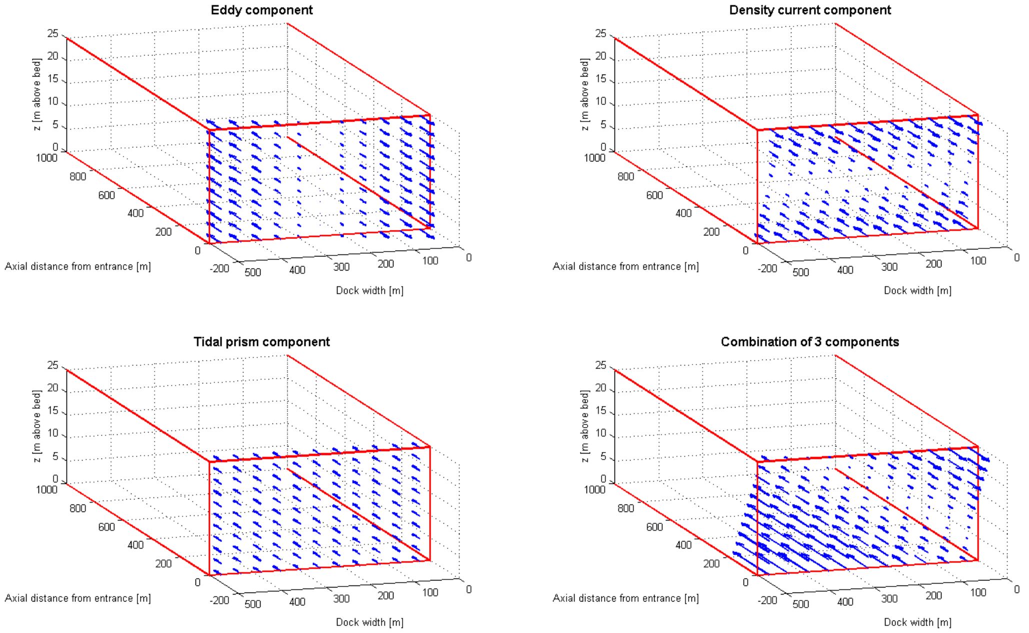


Figure 6-1: Visualisation of the three main components of the flow at the dock's entrance and their interaction: Top left: horizontal eddy; top right: density current; lower left: tidal filling; lower right: superimposed three components. Views from outside the dock, x=0 plane corresponds to the north quay wall.

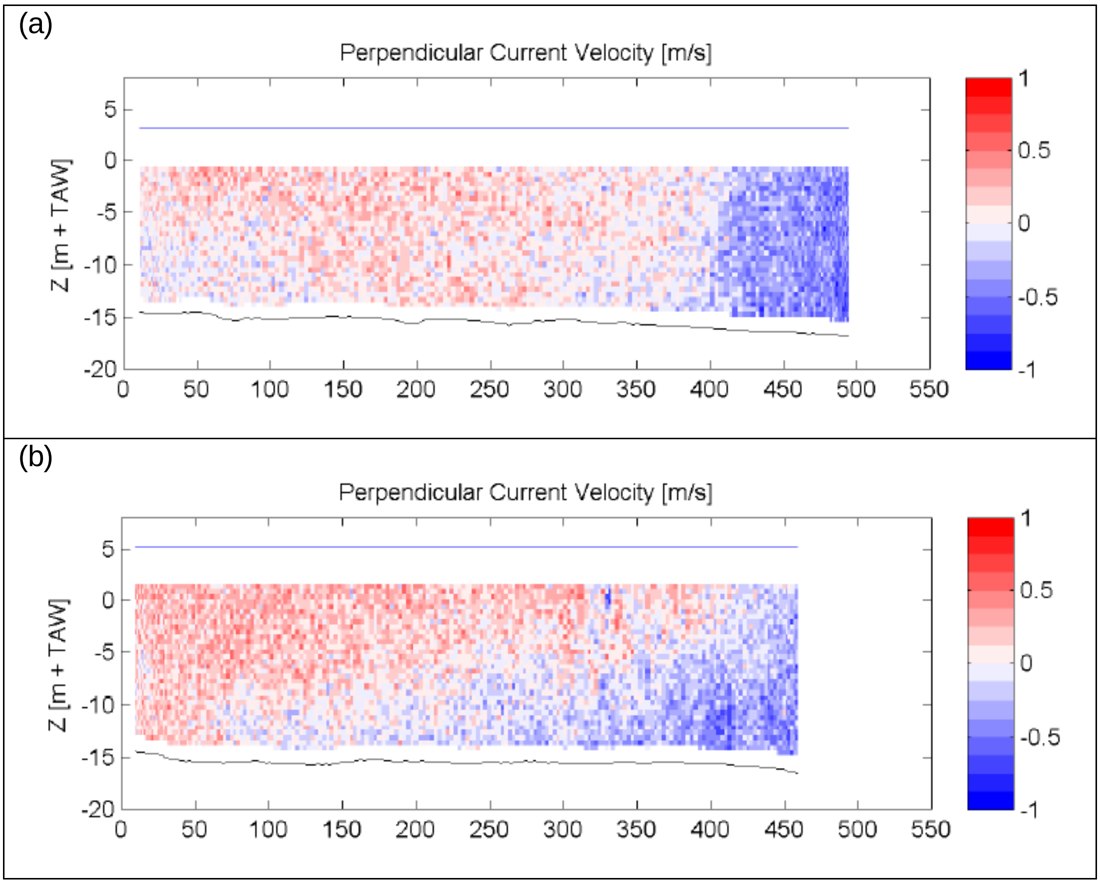


Figure 6-2: Top panel: combination of horizontal eddy and tidal inflow during rising tide; lower panel: combination of a horizontal eddy and density currents around high water. View from WITHIN the dock (x=0 corresponds to north quay wall), positive flow velocity is outflow.

6.1.1.2. Phasing

An analysis has been made of the tidal phase of start and end of density currents and horizontal eddy formation, both during rising and falling tide. During the course of three years of through-tide current measurements across the entrance of the dock flow profiles have been visualised systematically. From the graphical representation of the flow field of each measured tidal cycle the phase during which density currents and/or a horizontal eddy where present have been listed.

The rising tide phase is characterised by a relatively constant pattern of density currents from shortly before or after low water until about 4 hours to 3 hours before high water and a clockwise horizontal eddy afterwards until high water. The same phasing has been observed during three years of observations.

The phasing during falling tide has however changed significantly over the years (Figure 6-3):

- In the first year (DGD1), density currents have been observed from around high water until 2.5 hours to 3.5 hours after high water, with the longest duration in high salinity amplitude conditions. An anti-clockwise horizontal eddy during ebb has been observed from 2.5 hours until 4.5 hours after high water. Density currents with the relatively saline dock started already 2 hours before low water.

- During the second year (DGD2) the phase of the change from density currents to the horizontal eddy shifts from 3 to 5 hours after high water. In other words the density currents lasted longer and the ebb tide eddy started later. Low water density currents did no longer start before low water, but rather at low water.
- The third year (DGD3) saw the disappearance of an eddy during ebb.

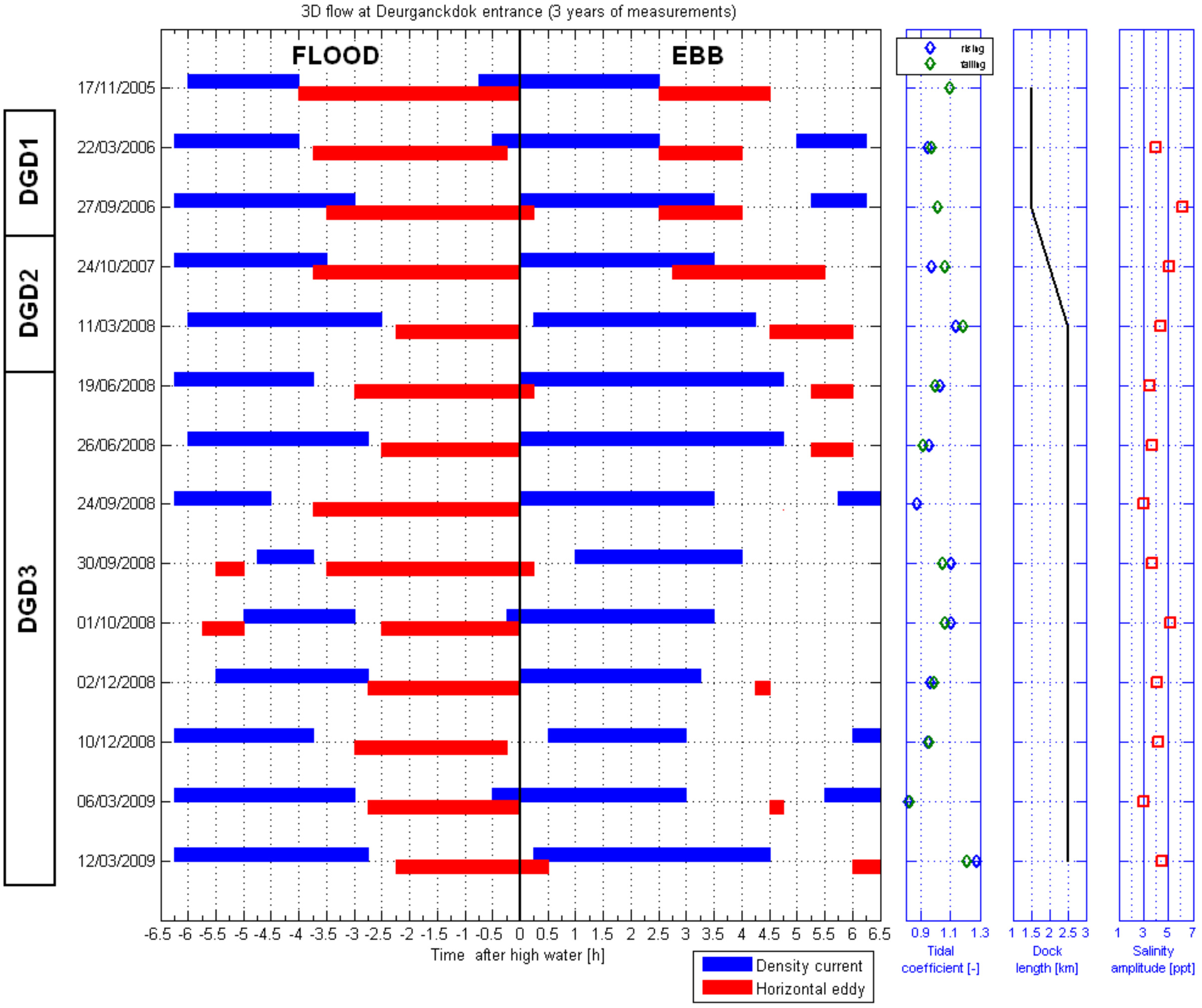


Figure 6-3: Phasing of the 3D flow pattern at DGD entrance during 3 years of changing dock length. Tidal coefficient, dock length and salinity amplitude are influence factors shown at the right panels.

During rising tide a horizontal eddy is formed at the entrance, but it is deformed by tidal filling of the dock. The combined flow fields due to a flood eddy and tidal filling is observed during the measurements with ADCP along three transects near the entrance, parallel to the dock's axis (IMDC, 2009p). It can be schematised as a high flow velocity inward at the south end of the entrance and a small eddy at the northern quay wall just inside of the entrance. An eddy is formed but does not contribute directly to the exchange of sediments across the entrance. This situation occurs during the phase of strongly rising water levels.

Shortly before high water the tidal filling component drops and the eddy can grow to its undisturbed shape across the entrance of the dock, fully contributing to the exchange process. Depending on the ambient river conditions the eddy is combined with density currents during a short while and is further dissipated due to the density difference and the deceleration of tidal flow after high water.

6.1.2. Flow pattern and sediment transport

An individual eddy symmetrically positioned over the dock's entrance occurs when tidal filling or emptying is not active (e.g. at high water). The tidal flow along the entrance will generate an eddy due to turbulent entrainment and as such sediments will be entering the dock at the part of the eddy down the flow in the estuary (Southwest during flood, Northeast during ebb). The structure of the eddy will lead to settling of sediments in the centre (at the sill), a part of the entrained sediments will be transported to a secondary gyre circulating further in the dock which will deposit sediments at its centre. But overall the eddy will keep a large part of the sediments in suspension and guide it back towards the river.

In the case of density currents dominating the flow the situation depends on the direction of the currents. With a saline dock the outflow will be near the bed and the inflow near the surface. Since the (in many cases more turbid) river waters flow in near the surface, descend by entrainment with the saline-fresh water interface, and flow out near the bed the ratio of sediments depositing will be relatively low, or even negative. In the opposite case, during the first 2-3 hours after high water, the turbid river water flows in near the bed and dock waters flow out near the surface. In this case sediment mixing from the inflowing waters towards the out flowing waters at the density interface has to occur upwards, against the settling velocity. This leads to a very efficient trapping of sediments.

An eddy during flood combined with tidal filling causes a small eddy just south of the northwest corner near the quay wall. This eddy traps sediments due to decelerations and part of it is settled during rising tide. Shortly after the opening of the dock the fastest deposition rates were observed in this zone. When near high water this eddy moves more towards the river and grows, a cloud of sediments comes with it. And exactly at this stage density currents start a movement inside the dock near the bed causing large sediment import. So, in case of the combination of a horizontal eddy and tidal inflow the inward flux occurs with a higher velocity than the outward flowing part of the eddy (see also Figure 6-2 a). This means that in any case the flow has to decelerate between in- and outflow. Decelerating flow laden with sediments will see a reduction in sediment transport capacity and settling of sediments towards the bed. This is a case of non-linear interaction between components of the flow during which the sediment import will be higher than the sum of both individual components if they would occur separately. This effect is very difficult to quantify and is not directly incorporated in the analytical model described above, although it is indirectly incorporated by the use of settling ratios based on sediment concentration gradients.

6.1.3. Effect of change in dock length

6.1.3.1. On density currents

With the full length of the dock the low water density currents starts later, which has also been reported by Van Maren (2009) based on numerical simulations. He points out that at low water a fresh water patch enters the dock at the surface which travels towards the back of the dock and is reflected off the back end. When the reflected patch reaches the entrance again after roughly half a tidal period it disturbs the start of the high water density current postponing it about two hours and leading to less sediment intrusion by density currents. This situation occurs with a full length dock and is especially observed during periods of high salinity amplitudes when the travel time of the low-salinity patch is shorter. This behaviour has been studied in this study by comparing through tide measurement campaigns with high salinity amplitude conditions both with short and longer dock. The density current at high water does not seem to be postponed much, although the low water density current is clearly postponed with a longer dock. Maybe a saline patch equivalent of the theory by Van Maren (2009) occurs as well between high water and low water where a saline patch travels near the bed towards the back of the dock and is reflected back to the entrance arriving near low water. In case of a shorter dock this would stimulate the earlier start of low water density currents with a more saline dock.

6.1.3.2. On a horizontal large eddy

In the first measurement campaigns (DGD1) a horizontal eddy has been observed at multiple through-tide measurements, while in the later campaigns it was mostly absent. The disappearance of the eddy during ebb happens simultaneously with the increase in dock length and is a consequence of the larger tidal prism, causing larger outflow during ebb and destruction of the eddy in most cases of mean or larger tidal amplitude.

6.1.4. Estimation of settling velocity from concentration profiles (SiltProfiler)?

An attempt has been made to draw conclusions in terms of settling velocity from the successive measurements of suspended sediment concentration profiles. In order to obtain this information from profiles an ultimate condition is that for at least the time between two successive profile-takings at the same spot only very limited advection and turbulent mixing is allowed. Under these conditions a settling column situation would give the opportunity to set up a very simple 1DV (1 vertical dimension) model in which a number of fractions with different settling velocity are included. If one or more successive profiles could be simulated with a certain distribution of settling velocity, it could be stated that the sediments in the water column at that time have these properties. However, that would involve a decrease of the total mass of sediment in the water column, and this situation has not been observed during slack tide. Probably density currents always keep the waters near the dock entrance in movement and no period of stagnant water is reached. Therefore, the conditions to perform this type of analysis are not fulfilled.

6.1.5. Trapping efficiency of the dock

During the three years of through-tide measurement campaigns the ADCP backscatter has been calibrated into suspended sediment concentration and as such at each transect the in- and outflux of sediments can be calculated, the net influx has been compared to the analytical model above. These datasets have also been used to calculate the total amount of sediments entering and leaving the dock during one tidal cycle. From these figures the trapping efficiency can be calculated as the ratio of sediments entering the dock to the total exchanged amount. In this way the dock showed a trapping efficiency of on average 0.39, with a relatively small standard deviation and no significant trend over the three years. This means that for every ton dry sediment that enters the dock, about 40% never leaves.

Table 6-1: Trapping efficiency statistics of 13 through-tide ADCP measurements

Mean	Min	Max	St. Dev.
0.39	0.16	0.53	0.09

A theoretical approach for the determination of the trapping efficiency p of a semi-enclosed basin is given by Eysink (1983):

Equation 6-1:

$$p = 1 - \exp\{-\frac{w}{h}\left(1 - \frac{u^2}{u_c^2}\right)T_r\}$$

Where w is the settling velocity, h is the water depth, u is the average flow velocity in the dock, u_c is the critical velocity for deposition and T_r is the retention time of the basin.

The settling velocity has been measured (IMDC 2005i) and a value of 0.5 mm/s has been used for the calculation of the trapping efficiency with a water depth of 15 m. The retention time has been calculated from the liquid exchange rate (Figure 5-13) where an average of 39 Mm^3 per tidal cycle of 12.4 hours and a total volume of the dock of 16.9 Mm^3 has been used to find a retention time of 5.4 hours.

Applying Equation 6-1 for a range of both the average flow velocity and the critical velocity for deposition lead to the result in Figure 6-4. For flow velocity between 1 and 10 cm/s and critical velocity between 10 and 30 cm/s the trapping efficiency is between 0.25 and 0.45. It is hard to determine an average flow velocity for the complete dock over the entire tidal cycle and it is even harder to determine a general critical velocity for deposition, but the measured value for the trapping efficiency of 0.39 corresponds to e.g. u equal to 5 cm/s and u_c equal to 12 cm/s or u equal to 9 cm/s and u_c equal to 21 cm/s.

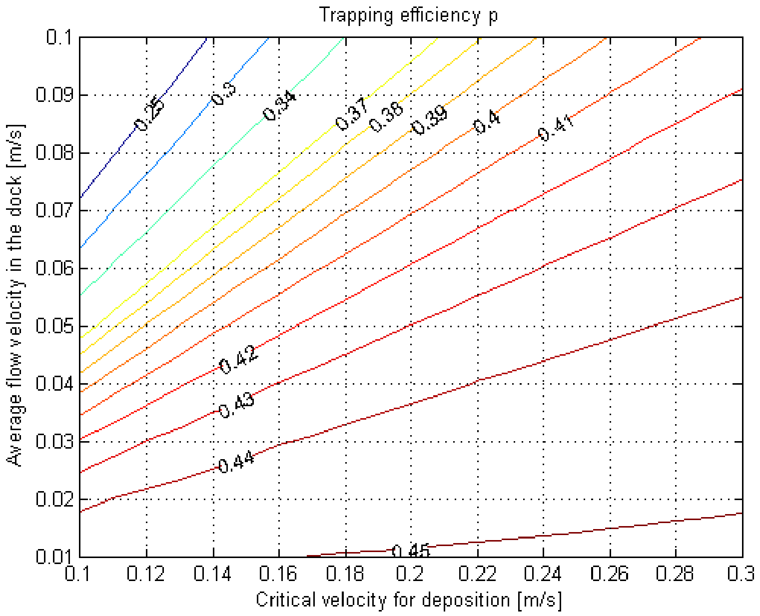


Figure 6-4: The trapping efficiency of Deurganckdok as a function of the average flow velocity in the dock and of the critical velocity for deposition. Calculation according to Eysink (1983).

6.1.6. Salinity and sediment concentration gradients

The hypothesis that a sediment laden eddy is located during rising tide on the north end of the dock some 200 m landward of the entrance and moves out to the entrance at high water is confirmed by the calculation of the average tidal cycles of a total of 23 months of measurements by 6 OBS equipments. Four of the equipments were installed at the entrance corners near the bed and near the surface. In these calculations also the average tidal cycle of horizontal and vertical gradients has been calculated for salinity, sediment concentration and temperature (IMDC 2006h,I,k; IMDC 2007o,p,t; IMDC2008m,n; IMDC 2009l,m). In these reports a great number of averaged tidal cycles have been calculated of salinity, temperature and sediment concentrations as well as of along-dock and across dock horizontal and vertical gradients of these parameters. For every single period or season analysed in these 10 reports the same pattern has shown up concerning the across-dock gradient of sediment concentration at the entrance: slightly higher concentrations at the south end of the entrance throughout flood –due to the eddy moving the turbid river waters over there- and a reversal and strengthening of the horizontal gradient between high water and 1 hour after high water –because the eddy moves from the north quay inside the dock towards the entrance (Figure 6-5). The same has been observed by the equipment near the bed and by the OBS equipment higher in the water column, during neap tides, average tides and spring tides, although more pronounced during spring tides.

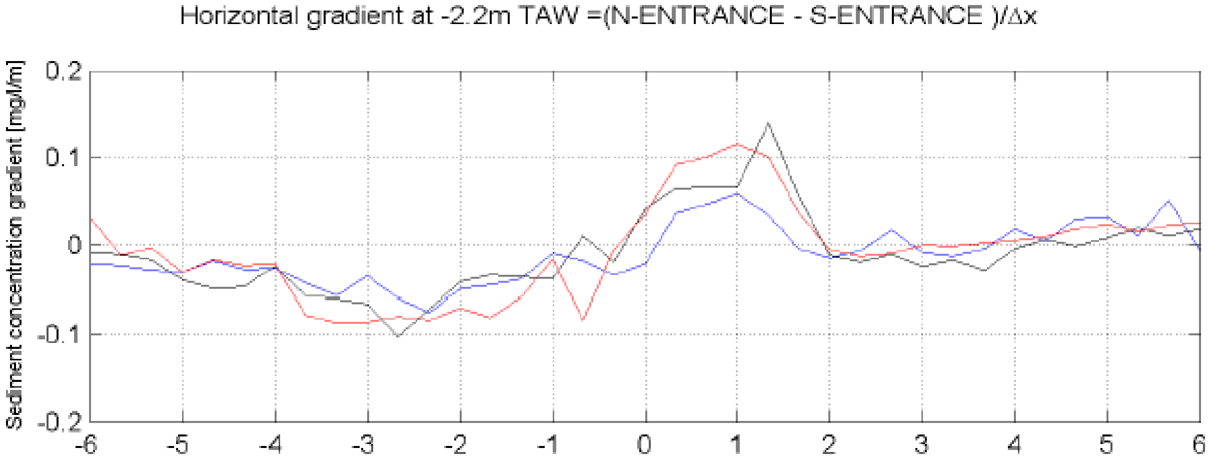


Figure 6-5: Averaged tidal cycle (275 cycles between April and October 2008) of the horizontal sediment concentration gradient along the dock's entrance. Red: spring tides; Black: average tides, Blue: Neap tides.

Vertical sediment concentration gradients near the entrance show as expected a small value except during high water slack when the gradient reaches 0.8 mg/l/m at south entrance and 3 mg/l/m at the north end of the entrance (spring tides, Figure 6-6). Other campaigns during winter, spring and autumn showed similar figures.

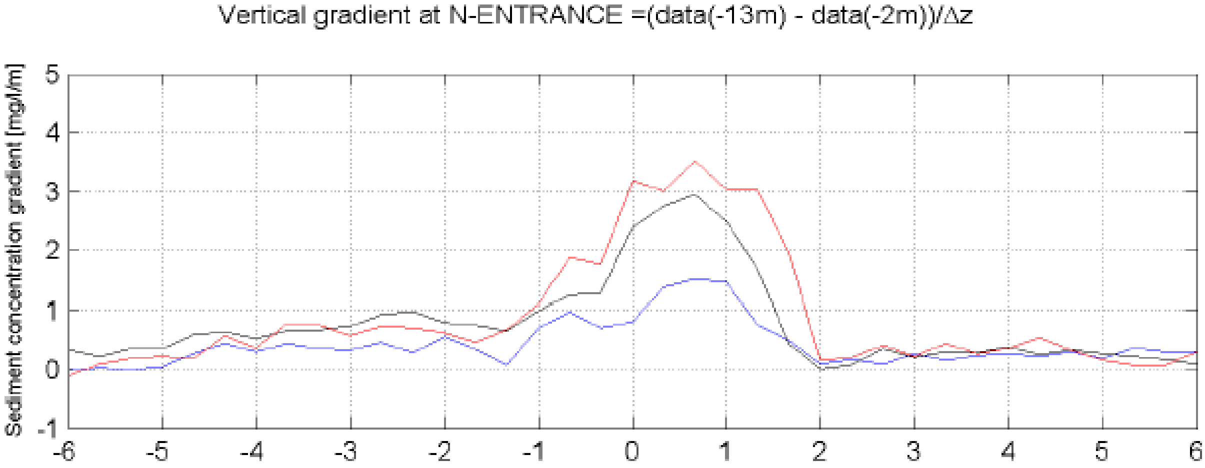


Figure 6-6: Averaged tidal cycle (275 cycles between April and October 2008) of the vertical sediment concentration gradient at North-entrance. Red: spring tides; Black: average tides, Blue: Neap tides.

The same analysis has been made for the measurements from October 2008 to April 2009, in which the average tidal cycle shows a negative (downward) gradient in sediment concentration from 1 to four hours after low water (Figure 6-7). In this phase of the tidal cycle density currents drive surface waters from the river into the dock and saline dock water out of the dock near the bed. Apparently the surface water from the river was even more turbid than the bottom waters in the dock during most of this winter period. This period is typically characterised by high sediment concentrations in the Scheldt Estuary.

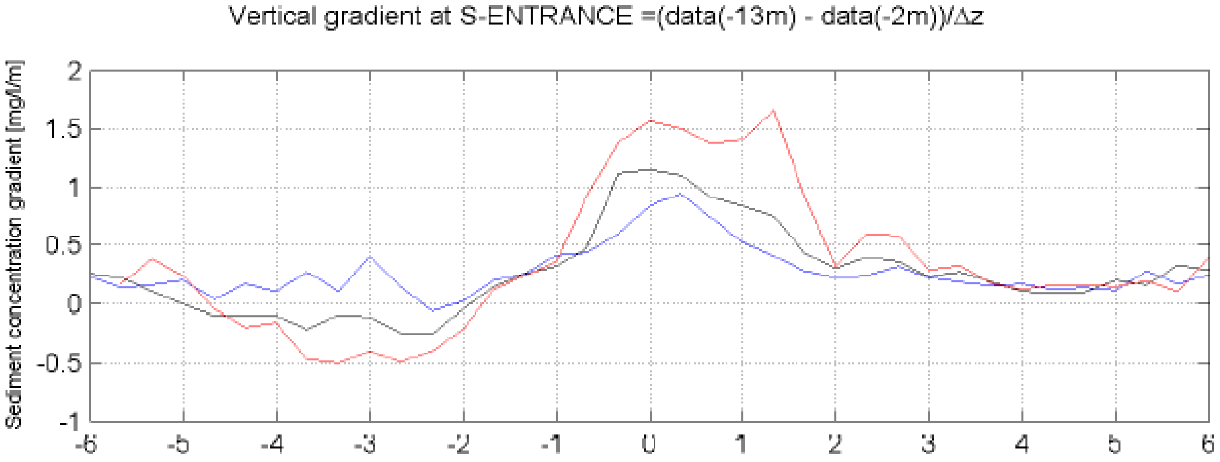


Figure 6-7: Averaged tidal cycle (290 cycles between October 2008 and April 2009) of the vertical sediment concentration gradient at North-entrance. Red: spring tides; Black: average tides, Blue: Neap tides.

Since middle 2008 not two but three OBS equipments have been deployed in long-term monitoring along the southern quay wall of the dock. When the average tidal cycles of the sediment concentration are compared, it can be seen that a peak in sediment concentration comes in near the entrance around high water, as observed in many other measurements. In the middle of the dock the near-bed concentration peaks around 2h30 after high water and at the back of the dock the peak comes at 4h after high water. This means that the saline, turbid cloud entering at the bed at high water decelerates and takes about 4 hours to reach the back of the dock. There is no indication that it is reflected on the back end of the dock.

The same has been looked at in the measurements in the spring of 2006, when the dock was still at about 60% of it’s today 2500 m length. Here we see the same turbid internal wave needs about 2.5 hours to travel to the back of the dock.

6.1.7. Salinity-fresh water discharge relation

An increase in upstream fresh water 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 6-8). 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.

The Scheldt river fresh water discharge counteracts the tidal pumping mechanism moving sediments upriver due to higher flow velocity during flood than during ebb. When the river discharge increases more sediments are entered in the estuarine system, but more importantly, the turbidity maximum (located at the tip of the salt intrusion where near bed stagnation causes sediment trapping) moves downstream. During the analyses of the measurements it has been showed that maximum turbidity occurred during periods with high runoff, when the turbidity maximum is located near Deurganckdok. During long periods of very high runoff the turbidity decreased again, probably because the turbidity maximum was pushed further downstream towards Prosperpolder, which is in literature defined as the most downstream location of the turbidity maximum (Fettweis et al, 1999).

This effect is combined with the fact that when the tip of the salt intrusion (and thus turbidity maximium) is nearby the salinity gradients decrease due to the fresh water dominating the estuary. This leads in turn to a decrease in density currents reducing the sediment influx into the dock.

So, both consequences of the river runoff rate have an important effect on the sedimentation rate of the dock but are at least partially counterproductive.

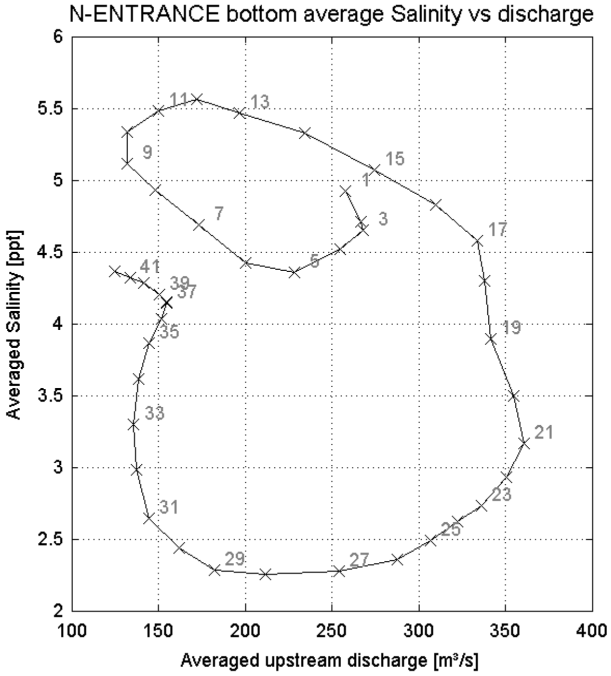


Figure 6-8: Hysteresis loop of salinity at the entrance of Deurganckdok under influence of river runoff. Data is filtered with a window of 7 days, numbers represent days after start of the measurements.

6.2. Three years siltation calculation

6.2.1. Results

The analytical model calculation of the three years have been merged and are shown in Figure 6-9.

Over the course of the three years of calculated sediment influx an average value of 1100 TDS per tidal cycle has been obtained, with a standard deviation of 420 TDS/tide. When it can be assumed that the influx has a normal probability distribution this would mean that 68% of the tides the influx is between about 700 and 1500 TDS.

Due to the change in the way input data has been gathered between DGD1/2 and DGD3 calculations, the standard deviation in the DGD3 calculations increased significantly, since the set of equations was reduced and the number of measured input variables increased. The equations used in DGD1 and 2 to determine year-round sediment concentration and salinity amplitude introduced a bounding of the obtained values for sediment influx rate (Figure 6-10). Especially the upper bounds of sediment influx rates have been removed by introducing measured sediment concentrations in the model input. This makes that the standard deviation on model results increased from 311 and 301 TDS/tide in DGD1 and 2 respectively to 592 TDS/tide for DGD3 calculations.

The mean sediment influx is equal for all three project years at neap tide (3 m tidal amplitude), but the increase in influx with increasing tidal amplitude is higher for the DGD3 calculations compared to the 2 previous years. This results in a higher average for the DGD3 calculations. This increase is due to the higher dock surface area and due to higher sediment concentrations measured during the third year compared to the estimated values for years 1 and 2. Especially in January-February 2009 sediment concentrations measured at the dock's entrance have been high.

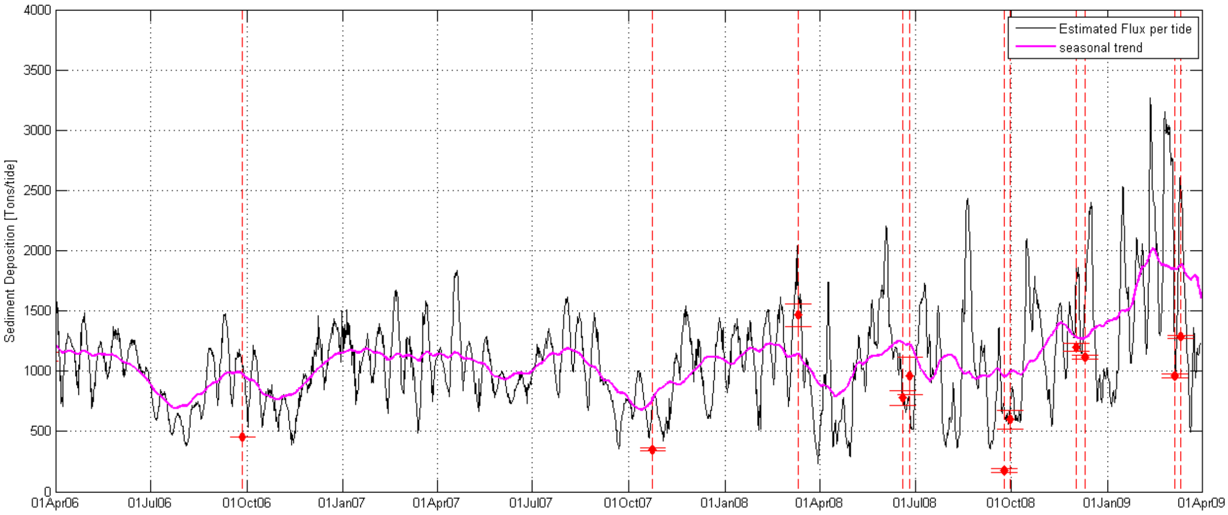


Figure 6-9: Calculated sediment influx per tide (black), seasonal trend (magenta) and ADCP backscatter observed sediment influx (red markers) over three years between April 2006 and March 2009.

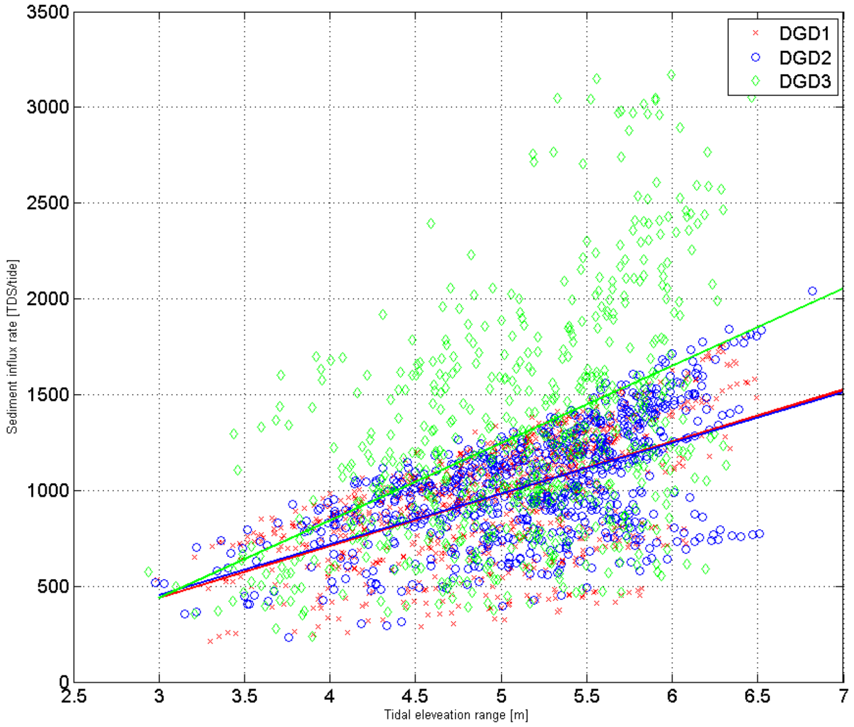


Figure 6-10: Scatter plot and linear fit for the relation between tidal amplitude and sediment influx. Three project years processed independently.

However, the probability distribution shows some skewness and is tail-heavy (Figure 6-11). In Figure 6-12 the cumulative probability function of the sediment influx rate is shown. From this distribution the probability of exceedence can be tabulated:

Table 6-2: Probability of exceedence of sediment influx rate.

Probability of exceedence (%)	Sediment influx rate (TDS/tide)
99	375
90	600
75	800
50	1050
25	1300
10	1600
1	2700

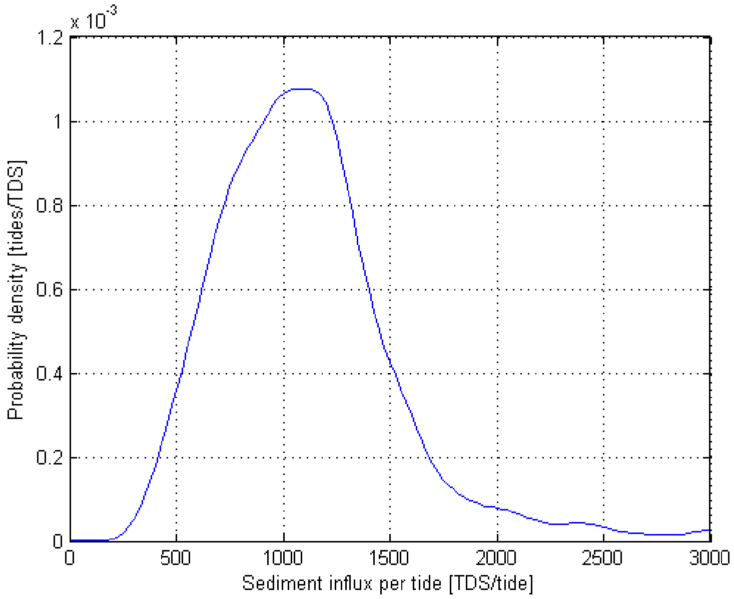


Figure 6-11: Probability distribution of sediment influx per tide.

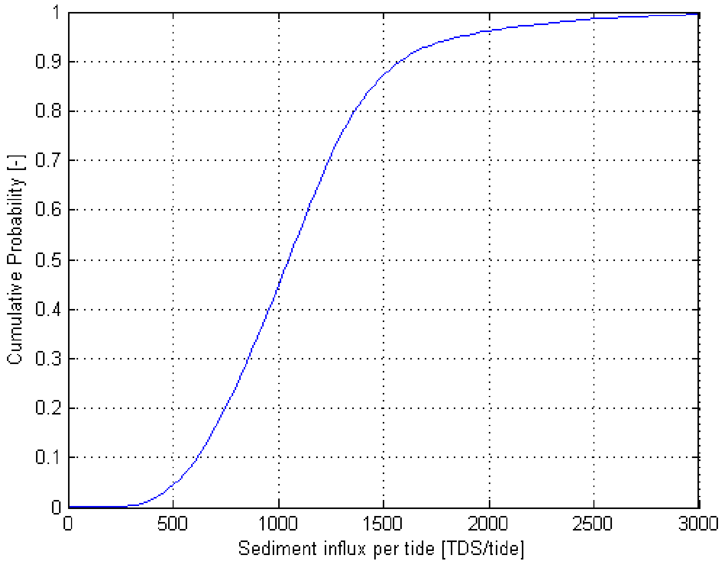


Figure 6-12: Cumulative probability function of the sediment influx rate [TDS/tide].

6.2.2. Notes on methods

During the course of three years of measurements at the entrance of the dock, a method has been developed to estimate the actual sediment influx per tidal cycle throughout the year by means of a conceptual model (Chapter 5). Initially the input data needed for the model (salinity amplitude and tidal average sediment concentration at the dock entrance) were determined through an empirical relationship between these magnitudes at the dock and at two buoys located a few kilometres from DGD (Figure 6-13). This approach was followed because no year-round data was available at the dock (for the method used see IMDC 2009o).

Before the start of the DGD3 project year it was decided to remove this limitation by increasing the OBS measurement effort to year-round observations at the entrance of the dock, both ends at two depths. Measurement data is continuous from 28th of April 2008 to September 2009 and ongoing. Since the DGD1 and DGD2 data involved transforming data from two locations on either side of the dock kilometres away a filtering operation had to be executed on the data to remove peaks related to local events. The low-pass filter set up for this purpose had a cut-off of 5 days. Obviously this filtering operation is no longer needed when measurements are available directly at the dock. Only tidal averaging of sediment concentration and calculation of the salinity amplitude per tide has to be executed. Due to this difference in approach the result of the calculated influx of sediments has a pronounced neap-spring tidal variation after April 2008 compared to before that date (Figure 6-9).

Some of the different coefficients used in the model have been calculated in slightly different ways in the preliminary report compared to this final report. The settled ratio for sediment exchange rates due to eddies and density currents has been computed with an updated formula in the present work compared to the DGD1 and DGD2 reports (IMDC, 2008b, 2008s). An overview of the coefficients used in the provisional reports after the first and second year into the project and the coefficients used in the present work –for computation of the full series of three years- have been listed in Table 6-3.

Table 6-3: Overview of coefficients in provisionally and finally reported results

Component	***Year***	***Provisional report***	***Present final report***
Tidal prism	DGD1	$c_1 = 0.9$; L_{dock}=1500 m	$c_1 = 0.66$; L_{dock}=1500 m
	DGD2	$c_1 = 0.9$; L_{dock}=1500 m	$c_1 = 0.66$; L_{dock}=1500 m
	DGD3	n/a	$c_1 = 0.66$; L_{dock}=2500 m
Density current	DGD1	$\alpha_{set,dens} = 0.36$	$\alpha_{set,dens} = 0.36$
	DGD2	$\alpha_{set,dens} = 0.30$	$\alpha_{set,dens} = 0.30$
	DGD3	n/a	$\alpha_{set,dens} = 0.35$
Eddy	DGD1	$\alpha_{set,eddy} = 0.6$; $\beta = 0.0$	$\alpha_{set,eddy} = 0.15$; $\beta = 0.05$
	DGD2	$\alpha_{set,eddy} = 0.1$; $\beta = 0.1$	$\alpha_{set,eddy} = 0.15$; $\beta = 0.05$
	DGD3	n/a	$\alpha_{set,eddy} = 0.14$; $\beta = 0.05$

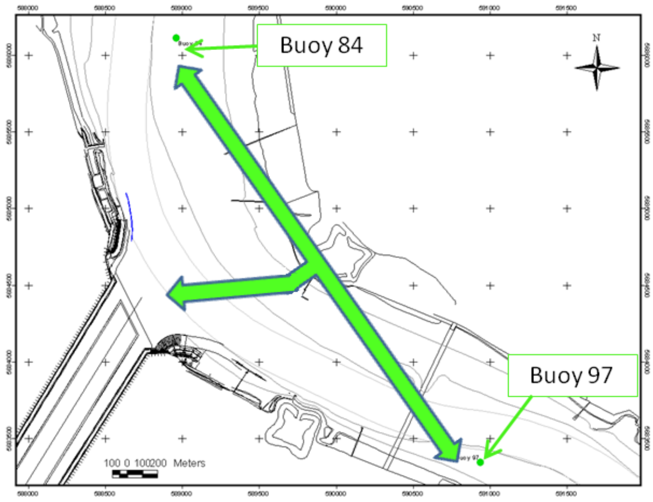


Figure 6-13: Determination of quantities at DGD through empirical relationships with quantities at nearby locations.

During the second yearly data analysis some small modifications in the calculation methods have been introduced after analysis of the new data series. One of the modifications is the calculation of the ratio of exchanged sediments settling out in the dock based on measurements (IMDC 2009o).

For the calculation of the siltation of the third year the procedures have been kept unchanged compared to the second year.

6.2.3. Comparison with dredging

Additionally, 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 2009. When the sediment mass present in the dock at April 1st 2006 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 6-14).

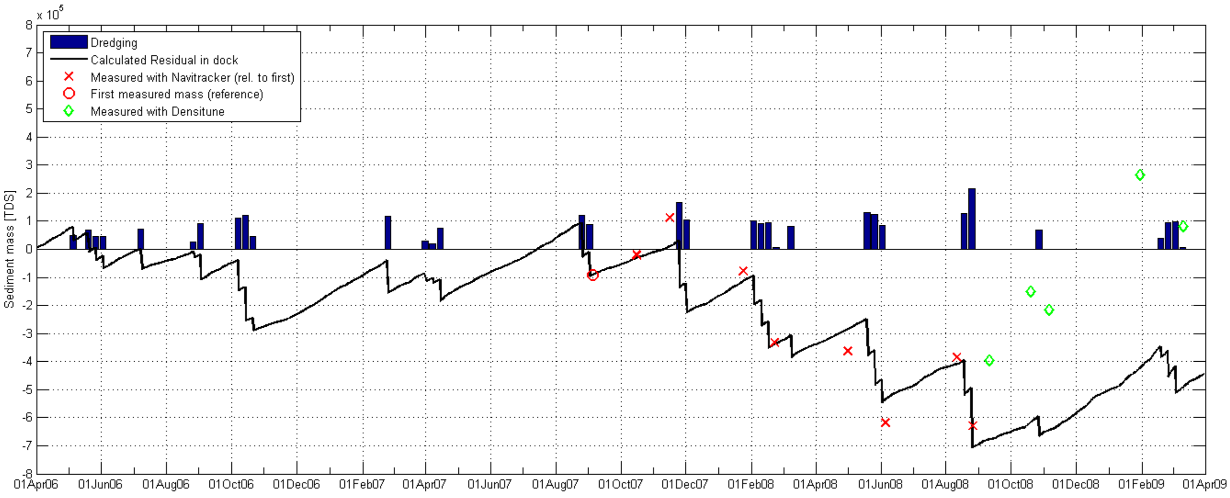


Figure 6-14: Dredged mass (TDS) per week, cumulative calculated inflow of sediments and residual sediments in the dock. Sediment mass present in the dock at April 1st is the reference and is set to zero. Red markers indicate the sediment mass measured by bed density profiling. The red circle is the first measurement in the DGD1 period and is used as reference the following measurements (red crosses).

A total of 990,000 TDS has been dredged from the dock in the DGD3 measurement year, compared to 800,000 in the DGD1 year and 950,000 TDS in the DGD2 project year. That means the mass of sediment inflow calculated above is 107,000 TDS lower than the dredged mass.

When the complete period of three years between April 1st 2006 and March 31st 2009 is considered a total of 2,310,000 TDS of sediment influx has been calculated. Compared to the total dredged mass of 2,760,000 TDS the net balance of the dock according to analytical model and dredging information system data stands at **minus 450,000 TDS**.

An extra input in the sediment balance set up for Deurganckdok is the possible contribution of capital dredging stirring up sediments which end up in the other parts of the dock. It is very hard to quantify this input, neither is the information available to determine whether it is significant or not.

6.2.4. Comparison with measured mass balance

During the second and third year of the project a series of area covering density profiling campaigns have been executed (IMDC2007r,s, 2008c,d,e, 2009g,h). Integration of the density profiles over the bed thickness leads to a mass in the bed per unit of area. Integration over the dock's area leads directly to the mass present in the bed. When the mass removed by dredging is added, an estimate is obtained of the sediment mass inflow over the year. This totally different method should be compared to what is obtained by the calculations in this report.

In periods without disturbance by maintenance dredging the mass growth rate was on average 2 to 7 kg/m²/day. When this value is converted to the complete dock area (full dock = 425x2500 m), a value is obtained of 2125-7400 TDS per day or 1100-3800 TDS per tide. These values are slightly higher but in good agreement with the results obtained with the empirical model above, where the sediment influx was calculated between 500 and 3000 TDS/tide.

Table 6-4: Overview of measured bed sediments in TDS/m² (left), covered area during measurement (middle) and Total measured mass in the bed in 10,000 TDS (right). Right below the area weighted average sediment weight per unit of area is shown. Campaigns from September 07 to February 08.

	Measured mass (TDS/m²)					Covered area (ha)					Absolute mass (10,000 TDS)				
	05-09-07	**16-10-07**	**16-11-07**	**24-01-08**	**22-02-08**	**05-09-07**	**16-10-07**	**16-11-07**	**24-01-08**	**22-02-08**	**05-09-07**	**16-10-07**	**16-11-07**	**24-01-08**	**22-02-08**
1															
2															
3a	1.403	1.727	1.936	1.715	1.185	9.92	9.92	9.92	9.92	8.64	13.9	17.1	19.2	17.0	10.2
3b	1.133	1.336	1.501	1.324	0.911	11	11	11	11	11	12.5	14.7	16.5	14.6	10.0
3c	1.279	1.399	1.463	1.25	1.027	9.88	9.88	9.65	8.93	9.88	12.6	13.8	14.1	11.2	10.1
3d	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
3e	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
4Na	1.166	1.036	1.197	0.941	0.744	3.67	3.67	3.29	3.31	3.2	4.3	3.8	3.9	3.1	2.4
4Nb	0.951	0.861	0.942	0.82	0.576	3.08	3.08	3.08	3.08	3.08	2.9	2.7	2.9	2.5	1.8
4Nc	0.748	0.769	0.82	0.748	0.621	2.54	2.59	2.45	2.29	2.59	1.9	2.0	2.0	1.7	1.6
4Nd	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
4Ne	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
4Za	1.018	0.877	1.053	0.938	1.003	2.43	2.43	2.43	2.43	1.64	2.5	2.1	2.6	2.3	1.6
4Zb	0.929	0.767	0.909	0.75	0.682	3.15	3.15	3.15	3.15	3.15	2.9	2.4	2.9	2.4	2.1
4Zc	0.74	0.741	0.785	0.545	0.624	2.23	2.59	2.39	2.34	2.59	1.7	1.9	1.9	1.3	1.6
4Zd	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
4Ze	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
5Na	1.238	0.878	0	0.842	0	1.94	1.87	0	1.31	0	2.4	1.6	0.0	1.1	0.0
5Nb	1.133	0.889	0	0.7	0	1.67	1.55	0	1.22	0	1.9	1.4	0.0	0.9	0.0
5Nc	0.896	1.113	0	0	0	1.26	1.33	0	0	0	1.1	1.5	0.0	0.0	0.0
5Nd	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
5Ne	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
5Za	0.809	0	0.842	0.681	0	1.04	0	0.97	0.9	0	0.8	0.0	0.8	0.6	0.0
5Zb	0.905	0.609	0.712	0.693	0	1.04	1.06	1.04	1.13	0	0.9	0.6	0.7	0.8	0.0
5Zc	0	0.591	0	0	0	0	0.97	0	0	0	0.0	0.6	0.0	0.0	0.0
5Zd	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
5Ze	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
						TOTAL AREA OF ZONES ACCOUNTED FOR:					AREA WEIGHTED MEAN TDS/m²				
						54.85	55.09	49.37	51.01	45.77	1.1373	1.2031	1.3680	1.1637	0.9084

Table 6-5: Overview of measured bed sediments in TDS/m² (left), covered area during measurement (middle) and Total measured mass in the bed in 10,000 TDS (right). Right below the area weighted average sediment weight per unit of area is shown. Campaigns from April 08 to March 08.

	Measured mass (TDS/m²)				Covered area (ha)				Absolute mass (10,000 TDS)			
	28-04-08	**05-06-08**	**11-08-08**	**26-08-08**	**28-04-08**	**05-06-08**	**11-08-08**	**26-08-08**	**28-04-08**	**05-06-08**	**11-08-08**	**26-08-08**
1	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0
2	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0
3a	1.68	1.00	1.62	0.88	8.56	8.35	8.46	8.21	14.37224	8.34165	13.6629	7.18375
3b	1.31	0.87	1.24	0.83	10.99	10.99	10.99	10.99	14.40789	9.5613	13.63859	9.1217
3c	1.22	0.86	1.12	0.82	9.91	9.91	9.91	9.91	12.04065	8.53251	11.07938	8.09647
3d	0.90	0.85	0.86	0.82	13.06	13.06	13.06	13.06	11.6887	11.0357	11.21854	10.67002
3e	0.00	0.00	0.00	0.00	4.89	4.94	4.8	4.97	0	0	0	0
4Na	0.98	0.70	0.98	0.60	3.24	3.14	3.22	3.28	3.16872	2.18858	3.1556	1.96472
4Nb	0.81	0.50	0.74	0.59	3.12	3.12	3.12	3.12	2.53656	1.55688	2.31504	1.82832
4Nc	0.68	0.51	0.68	0.59	2.57	2.57	2.57	2.57	1.73475	1.29785	1.75788	1.52144
4Nd	0.48	0.39	0.55	0.60	3.28	3.28	3.28	3.28	1.56128	1.28248	1.804	1.968
4Ne	0.00	0.00	0.00	0.00	1.20	1.25	1.21	1.21	0	0	0	0
4Za	1.07	0.60	0.97	0.56	1.60	1.56	1.59	1.44	1.712	0.93132	1.5423	0.80784
4Zb	0.79	0.53	0.69	0.52	3.12	3.12	3.12	3.12	2.47104	1.65048	2.15592	1.61928
4Zc	0.72	0.50	0.62	0.62	2.59	2.59	2.59	2.59	1.8648	1.28982	1.61616	1.61357
4Zd	0.54	0.42	0.54	0.52	3.23	3.23	3.23	3.23	1.73451	1.3566	1.75389	1.66991
4Ze	0.00	0.00	0.00	0.00	1.20	1.17	1.16	1.21	0	0	0	0
5Na	0.00	0.00	0.00	0.00	0.92	0.87	1	0.7	0	0	0	0
5Nb	0.82	0.52	0.81	0.00	1.04	1.13	1.11	0.91	0.85488	0.58195	0.89799	0
5Nc	0.55	0.46	0.74	0.84	1.01	1.10	1.06	0.92	0.55449	0.5082	0.7844	0.76912
5Nd	0.32	0.23	0.51	0.00	1.26	1.32	1.31	1.16	0.40068	0.30888	0.66941	0
5Ne	0.00	0.00	0.00	0.00	0.39	0.30	0.42	0.3	0	0	0	0
5Za	0.00	0.00	0.00	0.00	0.39	0.38	0.44	0.28	0	0	0	0
5Zb	0.62	0.73	0.83	0.87	1.46	1.10	1.13	1.1	0.90374	0.8008	0.93903	0.9526
5Zc	0.59	0.44	0.68	0.73	1.26	1.04	0.99	0.91	0.73962	0.45552	0.67023	0.6643
5Zd	0.32	0.23	0.51	0.00	1.50	1.20	1.24	1	0.4755	0.2736	0.6262	0
5Ze	0.00	0.00	0.00	0.00	0.52	0.36	0.44	0.32	0	0	0	0
					TOTAL AREA OF ZONES ACCOUNTED FOR:				AREA WEIGHTED MEAN TDS/m²			
					82.31	81.08	81.45	79.79	0.8896	0.6408	0.8630	0.6323

In Table 6-4 and Table 6-5 the area weighted average sediment mass per unit of area has been calculated for each of the measurement campaigns executed with Navitracker bed density profiling technique. This has been done by dividing the measured mass per zone by the total area, using only these zones which have been covered by the measurements by more than 50%. When these values are then applied to the complete dock's area (about 106 ha) an estimate for the complete dock is obtained. During some campaigns only zones with code A,B and C have been covered while in other campaigns zones with code D have been covered as well. The data from zones D has not been included in order to keep the figures comparable because zones with code D and E are located further from the dock's entrance and are likely to show smaller siltation rates. Therefore data from zones A, B and C only have been used from all campaigns. Expanding these data to the complete dock will lead to a slight overestimation, again due to decreasing siltation with distance from the river, but it is the best way to visualise the evolution over time of the sediment mass present in the dock.

In Figure 6-14 a comparison is included of the measured sediment mass in the dock and the residual sediment mass calculated by the empirical model presented above. The measured data has to be referenced to the same level as the calculated values because the calculations start with a value of zero TDS in the dock at the start of the period (April 1st 2006) and the measurements use a reference in space (the initial bed level after construction of the dock). This has been done by taking the measured mass for the 5 campaigns and subtracting the measured mass on September the 5th and adding the calculated mass on September 5th. In effect, the subsequent measured changes in mass are added to the calculated residual sediment mass on September 5th. In this way the calculations between September 5th 2007 and August 26th 2008 could be compared to the measured mass since this is the last campaign executed with the Navitracker equipment.

The calculated residual mass in the dock over a period of roughly one year shows a good agreement with the measured mass present in the dock and obtains the same trends. At the end of the year, at the time of the last Navitracker mass measurement, the calculated residual mass is almost equal to the observed mass.

After August 2008, though, the measurement technique has been changed by the client to the Densitune system. This system is based on a completely different principle (eigenfrequency of a mud parcel) compared to the Navitracker (gamma ray extinction). It is clear that the measurements with the Densitune technique show a significantly different onset and trend compared to the Navitracker data (green markers in Figure 6-14).

The last Navitracker measurements and the first Densitune campaign have been a period of 15 days away. According to the measurements of September 11th the average mass density increased from 0.83 TDS/m² (Navitracker) on August 26th to 1.04 TDS/m² in 15 days. When a mean bed density of 1.15 is assumed this would amount to a siltation of about 10 cm/day. Values observed during numerous analyses of bathymetric data are an order of magnitude lower. This means that both measurement techniques are not comparable. Also, the increase in measured mass during subsequent campaigns is roughly double of the siltation rates observed with the Navitracker density profiling and calculated with the analytical model.

A waterproof explanation cannot be found for the different results, although it is clear that the Densitune equipment does not penetrate as deep in the muddy bed as the heavier Navitracker equipment and leaves as such a significant part of the bed layers unmeasured and open for extrapolation. An analysis of the penetration has been made of the three last Navitracker campaigns and the first three Densitune campaigns. This shows that for the technique used initially in the project (Navitracker) about 16 % of the mass is due to extrapolations of the bed density profiles towards the reference level used because the equipment could not reach that depth, which is acceptable since the very deepest layers consolidate slower For the first three Densitune campaigns this figure has increased to 49 %, which means that almost half of the mass in the data comes from the very inaccurate extrapolations towards deeper unmeasured parts of the bed.

6.3. Influence factors

When the hysteresis loop of the fresh water discharge influence on sediment influx rates is produced the following pattern shows up after three month moving averaging: increasing discharge and sediment influx during fall, high discharge and sediment influx during winter, high sediment influx with decreasing discharge in early spring, decreasing sediment influx and discharge during summer (Figure 6-15, left panel). The same type of processing on the salinity data gives the result shown in the right panel of Figure 6-15. A less pronounced hysteresis lag effect is observed, this is due to the fact that salinity measured in Scheldt near the dock already includes the time lag between upstream discharge variations and Lower Sea-Scheldt salinity. The inverse proportionality between salinity and sediment influx can be at least partially explained by the position of the tip of the estuarine salt wedge and related mixing zone (and ETM). When the salinity is low near DGD the tip of the salt wedge and ETM is near so the sediment concentration is likely to be high. Furthermore, the salinity gradients are high due the presence of the salt-fresh water mixing zone, and therefore the local salinity amplitude is high which induces stronger density currents and hence higher exchange rates and higher sediment influx.

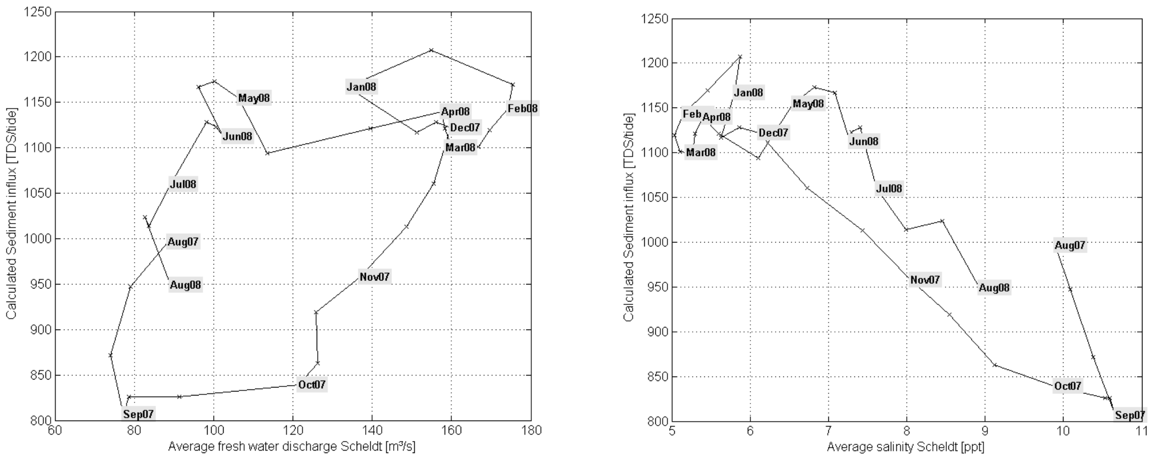


Figure 6-15: Hysteresis loop of fresh water discharge (left) and average salinity (right) against calculated sediment influx rate, after seasonal (90 days) filtering of the data between summer ’07 and summer ’08.

Another way of representing the situation is by means of time series comparison (Figure 6-16), where the period of DGD3 is a good case since it covers a continuous period of measurements at the dock’s entrance walls. Figure 6-16a shows the upstream Scheldt fresh water discharge, with pronounced low in summer - early fall and a high in late winter, physically directly linked is the salinity amplitude measured at DGD entrance (Figure 6-16b) which shows an inverse proportionality, again due the fact that the upstream discharge steers the position of the marine salinity front. Figure 6-16c shows the filtered sediment concentration, revealing a rather proportional relation with river discharge.

When the effect of both salinity amplitude and sediment concentration is compared to the computed sediment influx in DGD Figure 6-16d, it is clear that mainly the sediment concentration is of influence, the salinity amplitude is a secondary influence superimposed on the influx through the intensity of density currents.

When the unfiltered tidal average values of influx per tide, salinity amplitude and sediment concentration are considered, a scatter plot shows the largest part in the variation of the sediment influx is explained by the sediment concentration. Some variation, but a much smaller amount is explained by the salinity amplitude. This is no surprise as all three components in the calculated sediment influx are directly proportional to the sediment concentration near the dock's entrance.

It can be concluded that the river discharge is of main influence through the sediment concentration rather than the salinity gradients (i.e. salinity amplitude). In other words: a high sediment influx will nearly always occur when sediment concentration is high, while salinity amplitude can be both very low or very high. The salinity amplitude will only increase or decrease slightly the effect of sediment concentration on sedimentation (sediment influx).

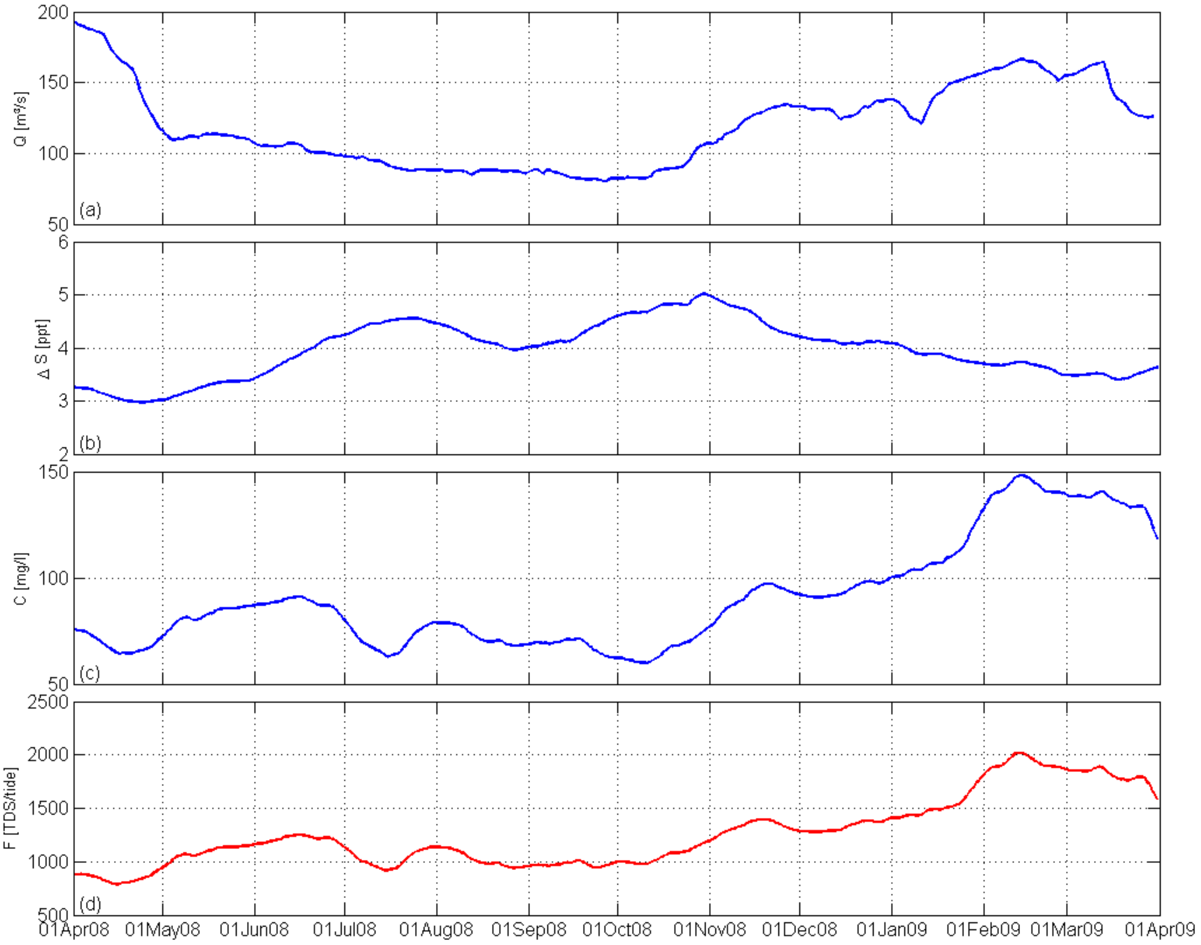


Figure 6-16: Time series of filtered fresh water discharge (a), salinity amplitude (b), sediment concentration (c) and computed sediment in flux per tide (d). Filter window: 60 days.

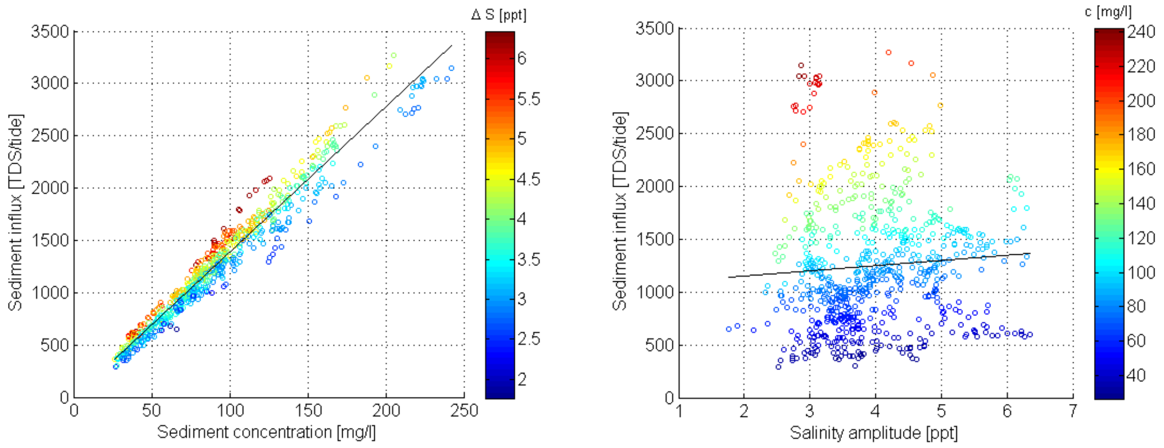


Figure 6-17: Proportionality of sediment concentration to calculated sediment influx per tide (left). Linear regression shows a coefficient of determination R² equal to 0.96. Proportionality of salinity amplitude to calculated sediment influx (right). Linear regression shows a coefficient of determination of less than 0.01.

A parameter which is certainly related to the sediment concentration and thus the sediment influx is the tidal elevation range. In the Scheldt estuary near DGD the tidal range can vary from 3 m during neap tide to 6 m during spring tide. Consequently, a much higher amount of kinetic energy is available from tidal flows during spring tide. Turbulence then converts kinetic energy to sediment potential energy (increased suspension) through mixing, i.e. the sediment concentrations are much higher.

As a result we see that up to 19% of the variation in sediment influx is explained by the tidal range (Figure 6-18).

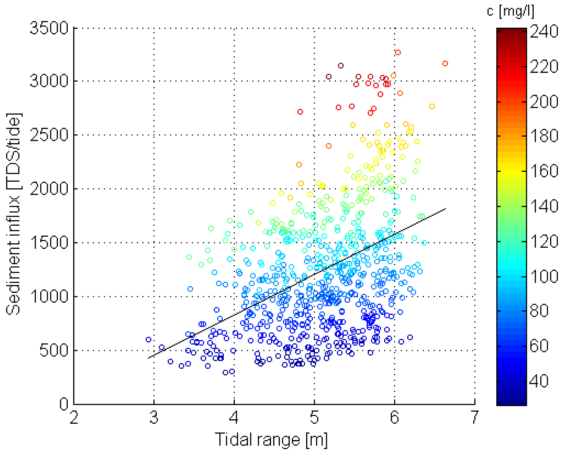


Figure 6-18: Proportionality of tidal range to calculated sediment influx per tide. Linear regression shows a coefficient of determination R² equal to 0.19.

For the river discharge, a coefficient of determination of only 0.11 is obtained when the unfiltered data is used. However, when the both the discharge and the sediment flux is filtered with a window of 60 days, an R² of 0.86 is obtained, corresponding to the correlation already visually derived from Figure 6-16. When now the discharge data is shifted forward in time, first a gradual increase in correlation is obtained, after which a maximum occurs (Figure 6-19). The maximum in correlation occurs after 15 tidal cycles, which is equal to about 7 to 8 days, indicating that the influence of fresh water discharge at the boundary of the tidal region is transported to DGD in about 7-8 days .

This is equivalent to the conclusion drawn from the hysteresis loop in Figure 6-8, where a delay of about one week was shown between river discharge and salinity near DGD.

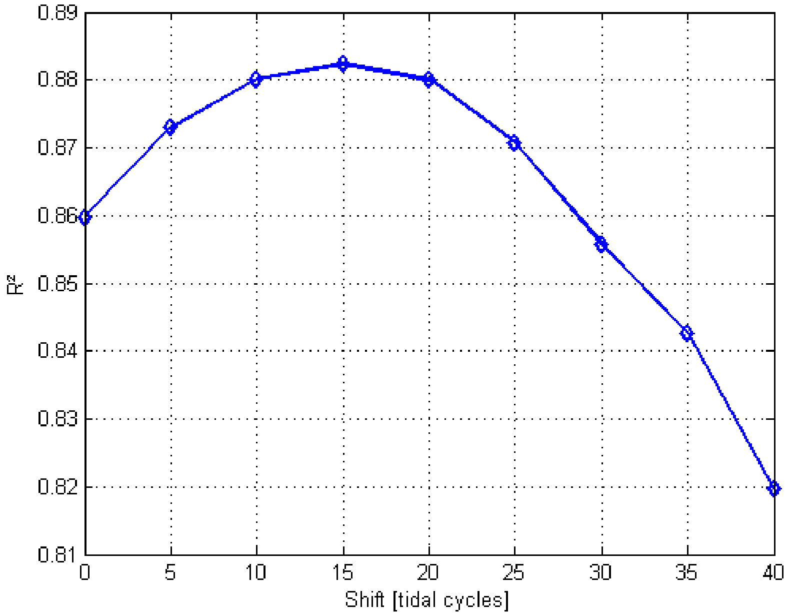


Figure 6-19: Coefficient of determination of the proportionality of upstream River discharge to computed sediment influx in DGD, as a function of the time shift applied to the discharge data.

It can be concluded that no unique influence factor can be determined for sedimentation rates at DGD. We see that sediment concentration levels are largely responsible for the amount of influx per tide, but sediment concentration is in turn a result of many influence factors. Both tidal range and upstream discharge are important, but also seasonal effects (biology) and flocculation are important, as well as the position of the estuarine turbidity maximum. The latter is in turn dependent on the upstream discharge while spring tides tend to be stronger in March-April, coinciding with the period of the highest river discharge. Therefore, the complexity of the system makes that no unique external influence factor determining the rate of sedimentation in Deurganckdok exists. The main external factors are –in order of importance- tidal range, upstream discharge and seasonal effects.

7. CONCLUSIONS

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 and semi-analytical model resulted in an estimated inflow of sediments due to natural phenomena of 702,000 TDS in the first year, 730,000 TDS in the second and 880,000 TDS in the third year. This corresponds to an average of 964 TDS/tide for the first, 1030 TDS/tide for the second and 1291 TDS/tide for the third year into the project. Note that the figures for the first two years are obtained after re-analysis and modifications of the model and are thus different from preliminary figures in the previous reports.

Over three years between April 1st 2006 and March 31st 2009 a total of 2,310,000 TDS sediment influx has been calculated against a total of 2,760,000 TDS dredged mass reported in BIS data. The calculated sediment mass in the dock shows a decrease of about 450,000 TDS, corresponding to -370 kg/m². This means that the sediment mass removal reported by BIS data was higher than the calculated influx.

Over the course of the three years of calculated sediment influx an average value of 1100 TDS per tidal cycle has been obtained, with a standard deviation of 420 TDS/tide.

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. This 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 which removed material by dredging has been taken into account have shown sedimentation rates in the dock of 600 to 1550 TDS per tide. New analyses of through-tide measurement campaigns using ADCP backscatter have shown similar net sediment import figures of 200 to 1500 TDS per tide.

The breakdown of the three main mechanisms causing sediment intrusion is as follows: 65% due to density currents, 25% due to tidal filling and 10% due to eddy exchange.

8. RECOMMENDATIONS

8.1. Post-CDW

A new analysis and calculation of sediment influx rate is foreseen after the construction of a Current Deflecting Wall (CDW) at the North end of the dock entrance. After completion of the CDW the flow pattern at the entrance of Deurganckdok as well as the phasing of the sediment structure through a tidal cycle will be altered. Therefore, sufficient measurements should be executed to observe and analyse the behaviour of the system afterwards:

- 3D flow pattern along dock axis (ADCP; neap tide and spring tide)
- 3D flow pattern along dock entrance (ADCP; neap tide and spring tide)
- 3D suspended sediment distribution along dock entrance (ADCP+Sediview; neap tide and spring tide, summer and winter conditions)
- Long term salinity and suspended sediment at the dock entrance quay walls (OBS; near-bed and near-surface; North and South end of the dock entrance)
- In case of non-continuous monitoring of the latter, additional salinity and suspended sediment concentration measurements at the Scheldt near DGD (e.g. Buoy 84).

In that case the analytical siltation model of Deurganckdok can be modified for the introduction of a CDW to make suitable prognoses of the sedimentation volumes in Deurganckdok.

The knowledge of the deposited tonnes dry solid (TDS) in Deurganckdok is utmost important. In the past the Densitune probe proved to produce density data in a different range compared to the long-time dataset generated by previous techniques (Navitracker). It is therefore recommended to resume density profiling with the latter instrument. Furthermore the frequency of the density measurements must increase and efforts should be made to investigate and understand the consolidation process of mud deposits in Deurganckdok.

For the future application of the semi-analytical sediment exchange model used in the present study, the continuation of long term monitoring of salinity and turbidity on both quay walls at the entrance of the dock (at two depths) is required.

8.2. Lower Sea-Scheldt suspended sediment re-analysis

The current study has illustrated that the sedimentation rate in Deurganckdok depends on the salinity gradients between the river Scheldt and the dock and on the other hand on the suspended sediment concentration in front of Deurganckdok. As such it is important to analyse the relationship between fresh water discharge from the Scheldt catchment, the position of the salinity gradients and the estuarine turbidity maximum (ETM) in order to understand the variability of suspended sediment concentration (SSC) near Deurganckdok and the subsequent siltation rates in the dock.

The ETM is a zone of high suspended sediment concentration which can vary in shape, size and intensity. Therefore it is important to analyse whether the position of the ETM can be determined from time series of suspended sediment measured at a number of fixed positions.

Since river conditions are highly variable and the different quantities vary with periods up to decades, it is evident that for such a task long time series of measurements are required. A number of sources can be applied:

- OMES turbidity measurements along the Scheldt estuary dating from 1996 – 2007. The spatial variation of turbidity over a long period can reveal the response of the turbidity maximum to changes in fresh water discharge.

- Turbidity measurements executed by Flanders Hydraulics at Oosterweel and Buoy 84 (2000-2009)
- Turbidity measurements at buoy 84, buoy 97, Prosperpolder, Deurganckdok, Boerenschans, Lillo and Oosterweel executed by IMDC
- The numerical model LTV Slib (maintained at Flanders Hydraulics) can be used to evaluate the hypothesis regarding the relation ETM- fresh water discharge as well as the sensitivity of the ETM characteristics to variations in fresh water discharge boundary conditions.

In the 2008 overview of MONEOS monitoring (Taverniers et al, 2009), the dynamic character of the ETM has been described by the observation that in times of high river discharge the estuarine salt wedge and accompanying ETM moves downstream and passes by Oosterweel, resulting in temporally higher turbidity. The data has to be analysed further to reveal the interaction between ETM and river discharge.

REFERENCES

Dyer, K.R. (1995): Sediment Transport Processes in Estuaries. In: Geomorphology and Sedimentology in Estuaries (Ed. GME Perillo), Elsevier Science, Oxford, 423-449.

Eysink, WD (1989): Sedimentation in harbour basins – small density differences may cause serious effects, Proceedings of the 9th International Harbour Congress, Antwerp, Belgium, June 1988; also: Delft Hydraulics, Publication No 417.

Fettweiss M, Sas M, Smitz H & Thibaut W (1999): Mud deposition in the new tidal dock (Deurganckdock), harbour of Antwerp, 12th International Harbour Congress, Antwerp.

IMDC (1998): Containerdock West, Hydrodynamic-sedimentological study, final report, (I/RA/11128/98.029/MFE).

IMDC (2005a). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 1: Test survey 17/02/2005, I/RA/11265/05.008/MSA.

IMDC (2005b). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.1: Deurganckdok 17/02/2005, I/RA/11265/05.009/MSA.

IMDC (2005c). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.2: Zandvliet 17/02/2005, I/RA/11265/05.010/MSA.

IMDC (2005d). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.3: Liefkenshoek 17/02/2005, I/RA/11265/05.0011/MSA.

IMDC (2005e). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.4: Schelle 17/02/2005, I/RA/11265/05.0012/MSA.

IMDC (2005f). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.5: Deurganckdok 16/02/2005, I/RA/11265/05.013/MSA.

IMDC (2005g). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.6: Kallosluis 18/02/2005, I/RA/11265/05.014/MSA.

IMDC (2005h). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.7: Near bed continious monitoring: february 2005, I/RA/11265/05.015/MSA.

IMDC (2005i). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 3: Settling velocity INSSEV february 2005, I/RA/11265/05.016/MSA.

IMDC (2005j). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 4: Cohesive sediment properties february 2005, I/RA/11265/05.017/MSA

IMDC (2005k). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 5.1: Overview of ambient conditions in the river Scheldt January-June 2005, I/RA/11265/05.018/MSA.

IMDC (2005l). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 5.2: Overview of ambient conditions in the river Scheldt July-December 2005, I/RA/11265/05.019/MSA.

IMDC (2006a) Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 6.1 Calibration Winter 15 March & 14 April 2006? I/RA/11291/06.092/MSA.

IMDC (2006b) Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 7.1 21 March 2006 Scheldewacht – Deurganckdok, I/RA/11291/06.094/MSA.

IMDC (2006c) Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 7.2 22 March 2006 Parel 2 – Deurganckdok (downstream), I/RA/11291/06.095/MSA.

IMDC (2006d) Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 7.3 22 March 2006 Laure Marie – Liefkenshoek, I/RA/11291/06.096/MSA.

IMDC (2006e) Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 7.4 23 March 2006 Parel 2 – Schelle, I/RA/11291/06.097/MSA.

IMDC (2006f) Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 7.5 23 March 2006 Laure Marie – Deurganckdok (downstream), I/RA/11291/06.098/MSA.

IMDC (2006g) Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 7.6 23 March 2006 Veremans – Waarde, I/RA/11291/06.099/MSA.

IMDC(2006h) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.1 Opmeting stroming en zout- en sedimentbeweging aan de ingang van het Deurganckdok (SiltProfiler), I/RA/11283/06.087/WGO.

IMDC(2006i) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.3. Opmeting stroming en zout-en sedimentbeweging aan de ingang van het Deurganckdok (ADCP), I/RA/11283/06.110/BDC

IMDC (2006j). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 8.1: Vaste meetopstelling in zake bodemgedrag, I/RA/11291/06.100/MSA.

IMDC (2006k) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.6 Zout en slibverdeling Deurganckdok 17/03/2006 – 23/05/2006, I/RA/11283/06.121/MSA.

IMDC (2006l) Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 5.3 Overview of ambient conditions in the river Scheldt – Januari-June 2006 (I/RA/11291/06.089/MSA).

IMDC(2006m): Studie van de stromingsvelden en sedimentuitwisseling aan de ingang van Deurganckdok. Current and Sediment flux measurements November 17th 2005 (I/RA/15030/06.021/BDC).

IMDC (2006n). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 9: Valsnelheid slib – INSSEV, I/RA/11291/06.102/MSA.

IMDC (2006o). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.7: Silt distribution and frame measurements 15/07/2006 – 31/10/2006. (I/RA/11291/06.122/MSA).

IMDC (2006p). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 12: Report concerning the presence of HCBS layers in the Scheldt river (I/RA/11291/06.109/MSA)

IMDC (2006q) measurements 15/07/2006 – 31/10/2006. (I/RA/11291/06.122/MSA).

IMDC (2006r). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 10: Cohesive sediment properties summer 2006 (I/RA/11291/06.103/MSA)

IMDC (2006s). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 5.3: Overview of ambient conditions in the river Scheldt – January-June 2006 (I/RA/11291/06.088/MSA)

IMDC (2006t). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 5.4: Overview of ambient conditions in the river Scheldt – July-December 2006 (I/RA/11291/06.089/MSA)

IMDC (2006u). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 5.5: Overview of ambient conditions in the river Scheldt : RCM-9 buoy 84 & 97 (1/1/2007 -31/3/2007) (I/RA/11291/06.090/MSA)

IMDC (2006v). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 5.6: Analysis of ambient conditions in the river Scheldt, September 2005 – March 2007 (I/RA/11291/06.091/MSA)

IMDC (2007a) Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 6.2 Summer calibration and Final report, I/RA/11291/06.093/MSA.

IMDC (2007b). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 5.4 Overview of ambient conditions in the river Scheldt – July-December 2006 (I/RA/11291/06.089/MSA).

IMDC (2007c). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 11.1 Through tide Measurement Sediview & Siltprofiler 27/9 Stream - Liefkenshoek (I/RA/11291/06.104/MSA).

IMDC (2007d). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 11.2 Through tide Measurement Sediview 27/9 Veremans - Raai K (I/RA/11291/06.105/MSA).

IMDC (2007e). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 11.3 Through tide Measurement Sediview & Siltprofiler 28/9 Stream - Raai K (I/RA/11291/06.106/MSA).

IMDC (2007f). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 11.4 Through tide Measurement Sediview 28/9 Veremans - Waarde(I/RA/11291/06.107/MSA).

IMDC (2007g). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 11.5 Through tide Measurement Sediview 28/9 Parel 2 - Schelle (I/RA/11291/06.108/MSA).

IMDC (2007h). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 11.6 Through tide Measurement Salinity Distribution 26/9 Scheldewacht – Deurganckdok in opdracht van AWZ.

IMDC (2007i) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 1.1 Sediment Balance: Three monthly report 1/4/2006 – 30/06/2006 (I/RA/11283/06.113/MSA)

IMDC (2007j) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 1.2 Sediment Balance: Three monthly report 1/7/2006 – 30/09/2006 (I/RA/11283/06.114/MSA)

IMDC (2007k) 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)

IMDC (2007l) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 1.4 Sediment Balance: Three monthly report 1/1/2007 – 31/03/2007 (I/RA/11283/06.116/MSA)

IMDC (2007m) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 1.5 Annual Sediment Balance (I/RA/11283/06.117/MSA)

IMDC (2007n) 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 (2007o) 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 (2007p) 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 (2007q) 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)

IMDC (2007r) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing 2. Deelrapport 1.10: Sediment Balance: Three monthly report 1/4/2007 – 30/06/2007 (I/RA/11283/07.081/MSA)

IMDC (2007s) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing 2. Deelrapport 1.11: Sediment Balance: Three monthly report 1/7/2007 – 30/09/2007 (I/RA/11283/07.082/MSA)

IMDC (2007t) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing 2. Deelrapport 2.16: Salt-Silt distribution Deurganckdok summer (21/6/2007 – 30/07/2007) (I/RA/11283/07.092/MSA)

IMDC (2007v) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing 2. Deelrapport 3.10: Boundary conditions: Three monthly report 1/04/2007 – 30/06/2007 (I/RA/11283/07.097/MSA)

IMDC (2007w) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing 2. Deelrapport 3.11: Boundary conditions: Three monthly report 1/07/2007 – 30/09/2007 (I/RA/11283/07.098/MSA)

IMDC (2007x). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.4: Through tide measurement Sediview average tide 27/09/2006 Parel 2 (I/RA/11283/06.119/MSA)

IMDC (2007y). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.6: Salinity-Silt distribution & Frame Measurements Deurganckdok 17/3/2006 – 23/05/2006 (I/RA/11283/06.121/MSA)

IMDC (2007z). Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 2.8: Salinity-Silt distribution & Frame Measurements Deurganckdok 15/01/2007 – 15/03/2007 (I/RA/11283/06.123/MSA)

IMDC (2008a) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.5: Through tide measurement Sediview average tide 24/10/2007 (I/RA/11283/06.120/MSA)

IMDC (2008b) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 4.1: Analysis of siltation Processes and Factors (I/RA/11283/06.129/MSA)

IMDC (2008c) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 1.12: Sediment Balance: Four monthly report 1/9/2007 – 31/12/2007 (I/RA/11283/07.083/MSA)

IMDC (2008d) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 1.13: Sediment Balance: Four monthly report 1/01/2007 – 31/03/2007 (I/RA/11283/07.084/MSA)

IMDC (2008e) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 1.14: Annual Sediment Balance. (I/RA/11283/07.085/MSA)

IMDC (2008f) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.09: Calibration stationary equipment autumn (I/RA/11283/07.095/MSA)

IMDC (2008g) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.10: Through tide measurement SiltProfiler 23 October 2007 (I/RA/11283/07.086/MSA)

IMDC (2008h) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.11: Through tide measurement Salinity Profiling winter 12 March 2008 (I/RA/11283/07.087/MSA)

IMDC (2008i) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.12: Through tide measurement Sediview winter 11 March 2008 – Transect I (I/RA/11283/07.088/MSA)

IMDC (2008j) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.13: Through tide measurement Sediview winter 11 March 2008 – Transect K (I/RA/11283/07.089/MSA)

IMDC (2008k) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.14: Through tide measurement Sediview winter 11 March 2008 – Transect DGD (I/RA/11283/07.090/MSA)

IMDC (2008l) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.15: Through tide measurement SiltProfiler winter 12 March 2008 (I/RA/11283/07.091/MSA)

IMDC (2008m) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.17: Salt-Silt distribution & Frame Measurements Deurganckdok autumn (17/9/2007-10/12/2007) (I/RA/11283/07.093/MSA)

IMDC (2008n) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.18: Salt-Silt distribution & Frame Measurements Deurganckdok winter (18/02/2007-31/03/2008) (I/RA/11283/07.094/MSA)

IMDC (2008o) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.19: Calibration stationary & mobile equipment winter (I/RA/11283/07.096/MSA)

IMDC (2008p) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 3.12: Boundary conditions: Three monthly report 1/9/2007 – 31/12/2007 (I/RA/11283/07.099/MSA)

IMDC (2008q) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 3.13: Boundary conditions: Three monthly report 1/1/2008 – 31/3/2007 (I/RA/11283/07.100/MSA)

IMDC (2008r) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 3.14: Boundary conditions: Annual report (I/RA/11283/07.101/MSA)

IMDC (2008s) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 4.10: Analysis of siltation Processes and Factors (I/RA/11283/07.102/MSA)

IMDC (2008t) Uitbreiding studie densiteitsstromingen in de Beneden Zeeschelde in het kader van LTV Meetcampagne naar hooggeconcentreerde slibsuspensies Deelrapport 5.6 Analysis of the ambient conditions in the river Scheldt – September 2005 - March 2007 (I/RA/11291/06.091/MSA).

IMDC (2009a) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.23: Through tide measurement Sediview during spring tide Summer 2008 – 30 September 2008 (I/RA/11283/08.084/MSA)

IMDC (2009b) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.29: Through tide measurement SiltProfiler summer 2008 – 29 September 2008 (I/RA/11283/07.090/MSA)

IMDC (2009c) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.34: Calibration stationary & mobile equipment autumn 2008 (I/RA/11283/08.095/MSA)

IMDC (2009d) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing Deelrapport 1.22: Sediment Balance: Three monthly report 1/10/2008 – 31/12/2008 (I/RA/11283/08.078/MSA)

IMDC (2009e) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.24: Through tide measurement Sediview during neap tide Autumn 2008 (I/RA/11283/08.085/MSA)

IMDC (2009f) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.25: Through tide measurement Sediview during spring tide Autumn 2008 (I/RA/11283/08.086/MSA)

IMDC (2009g) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing Deelrapport 1.23: Sediment Balance: Three monthly report 1/01/2009 – 31/03/2009 (I/RA/11283/08.079/MSA)

IMDC (2009h) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing Deelrapport 1.24: Annual Sediment Balance (I/RA/11283/08.080/MSA)

IMDC (2009i) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.26: Through tide measurement Sediview during neap tide Winter 2009 (I/RA/11283/08.087/MSA)

IMDC (2009j) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.30: Through tide measurement SiltProfiler winter 2009 (I/RA/11283/08.091/MSA)

IMDC (2009k) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.31: Through tide measurement Salinity Profiling winter 2009 (I/RA/11283/08.092/MSA)

IMDC (2009l) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.33: Salt-Silt distribution Deurganckdok: six monthly report 1/10/2008 – 31/3/2009 (I/RA/11283/08.094/MSA)

IMDC (2009m) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 3.21: Boundary conditions: Six monthly report 1/10/2008 – 31/03/2009 (I/RA/11283/08.097/MSA)

IMDC (2009n) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.27: Through tide measurement Sediview during spring tide Winter 2009 (I/RA/11283/08.088/MSA)

IMDC (2009o) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 4.20: Analysis of siltation Processes and Factors (I/RA/11283/08.098/MSA)

IMDC (2009p) Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing. Deelrapport 2.28: Through tide measurement ADCP eddy DGD Summer 2008 (I/RA/11283/08.089/MSA)

PIANC (2008): Minimising Harbour Siltation. Report of PIANC Working Group n° 43.

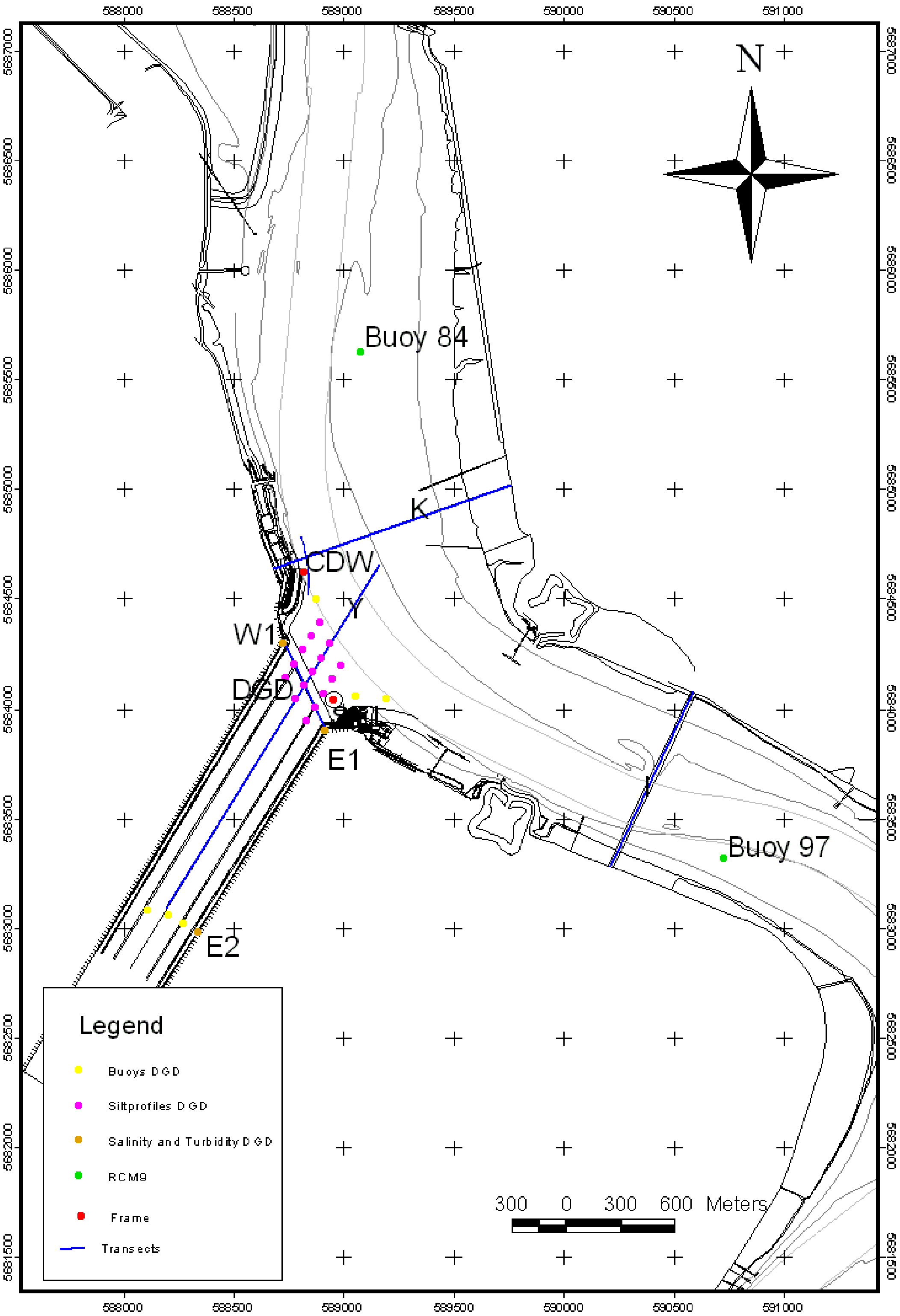
Taverniers, E., Mostaert, F. (2009) MONEOS – jaarboek monitoring WL 2008: Overzicht monitoring hydrodynamiek en fysische parameters zoals door WL in 2008 in het Zeescheldebekken gemeten. Versie 4_0. WL Rapporten, 833_07. Waterbouwkundig Laboratorium Antwerpen, België.

Van Maren, DS (2006): 3D Mud transport model Zeeschelde, Scenario 4, Effect CDW on sedimentation Deurganckdok, WL Delft Hydraulics, Report Z3824, November 2006.

Van Maren DS., Winterwerp H., Sas M. and Vanlede J. (2009): The effect of dock length on harbour siltation. Continental Shelf research, doi: 10.1016/j.csr.2009.03.003.

Wollast & Marijns (1981): Zwevende stof en chemische en fysische toestand in het Westerschelde estuarium. Ministerie Van Volksgezondheid.

APPENDIX A. LOCATION IN SITU MEASUREMENT SITES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5682000
5681500
N
Buoy 84
K
CDW
Y
W1
DGD
Sill
E1
Buoy 97
E2
Legend
Buoys DGD
Siltprofiles DGD
Salinity and Turbidity DGD
RCM9
Frame
Transects
300 0 300 600 Meters

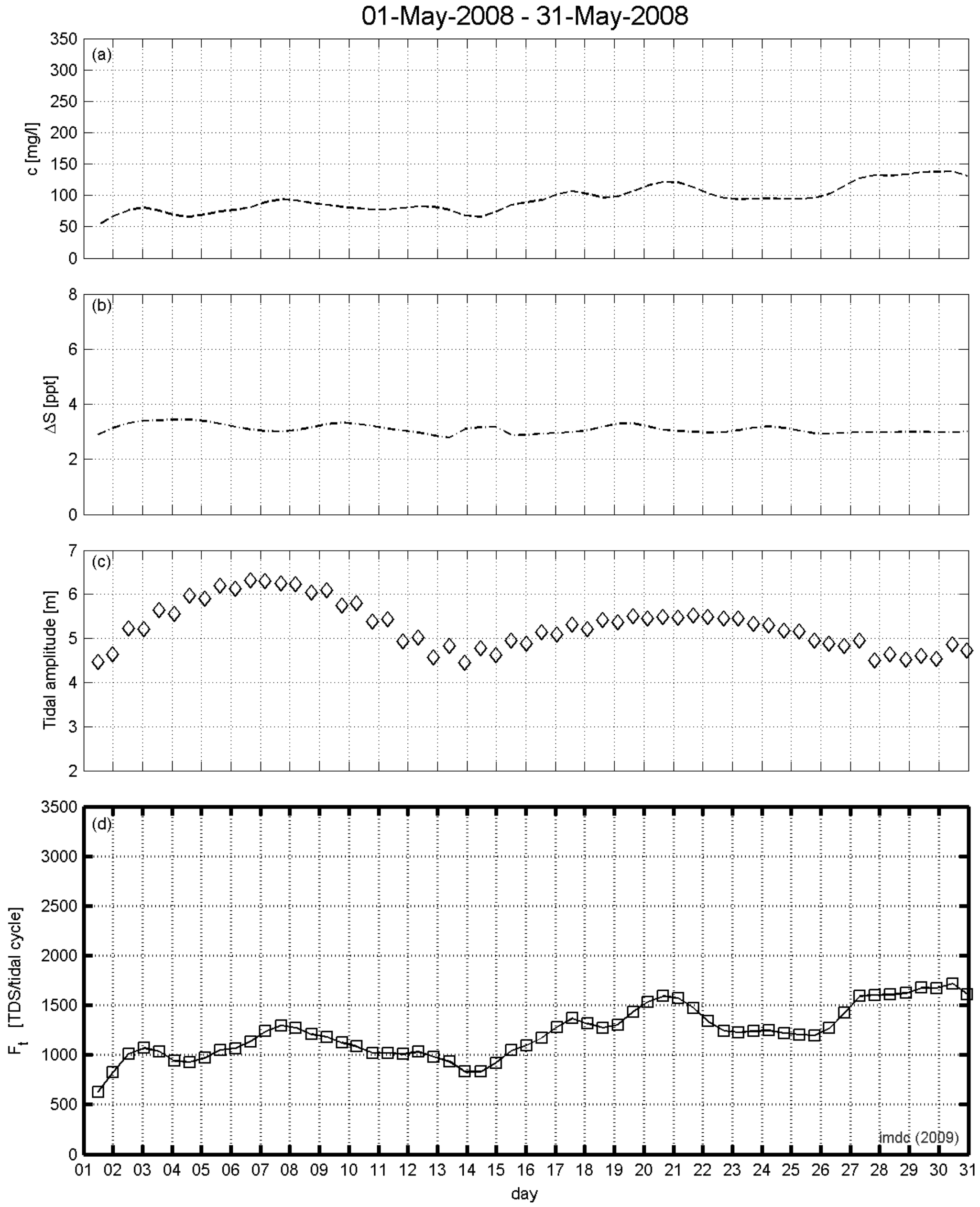
APPENDIX B. SILTATION RATES PER MONTH

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).

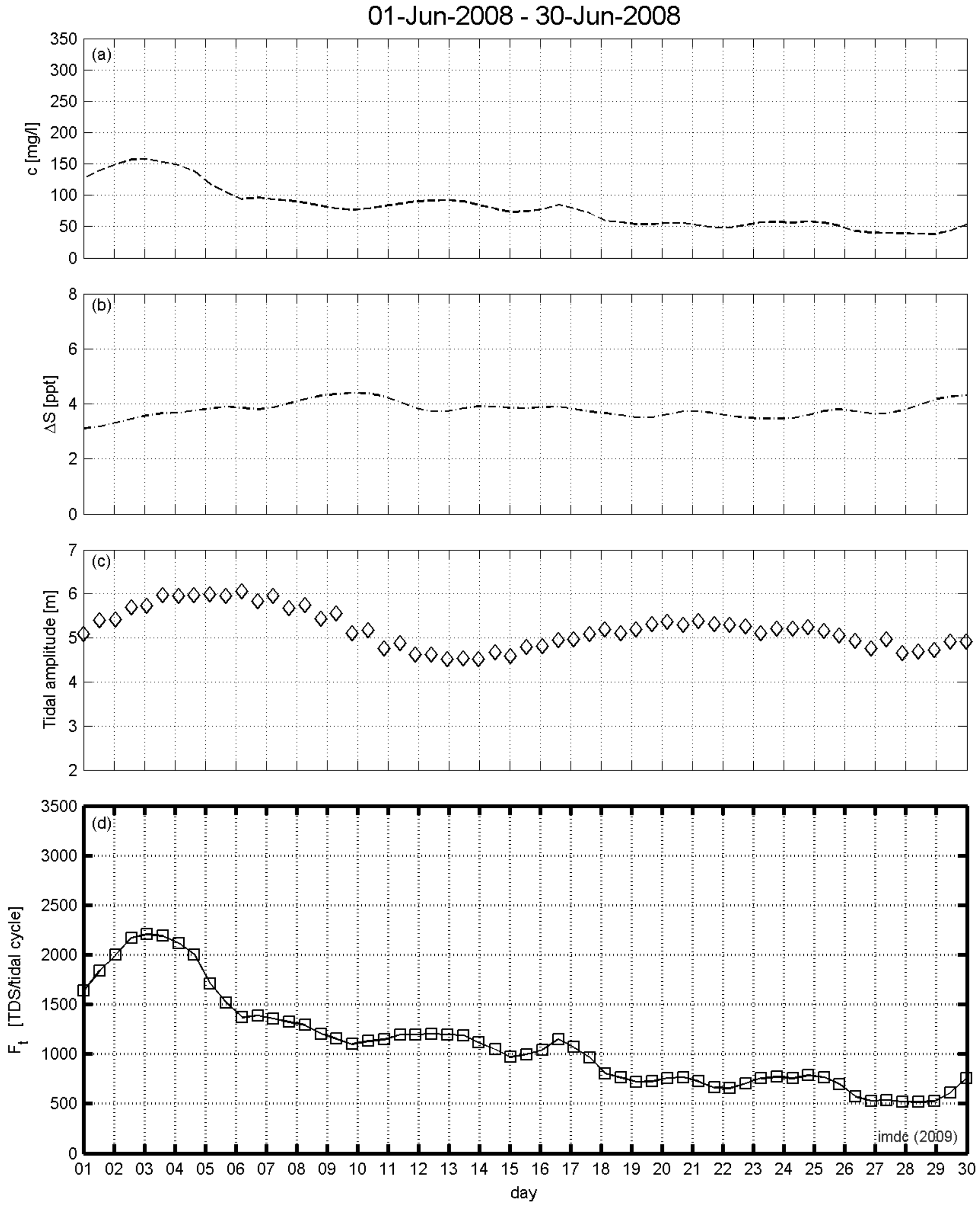
I/RA/11283/07.102/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

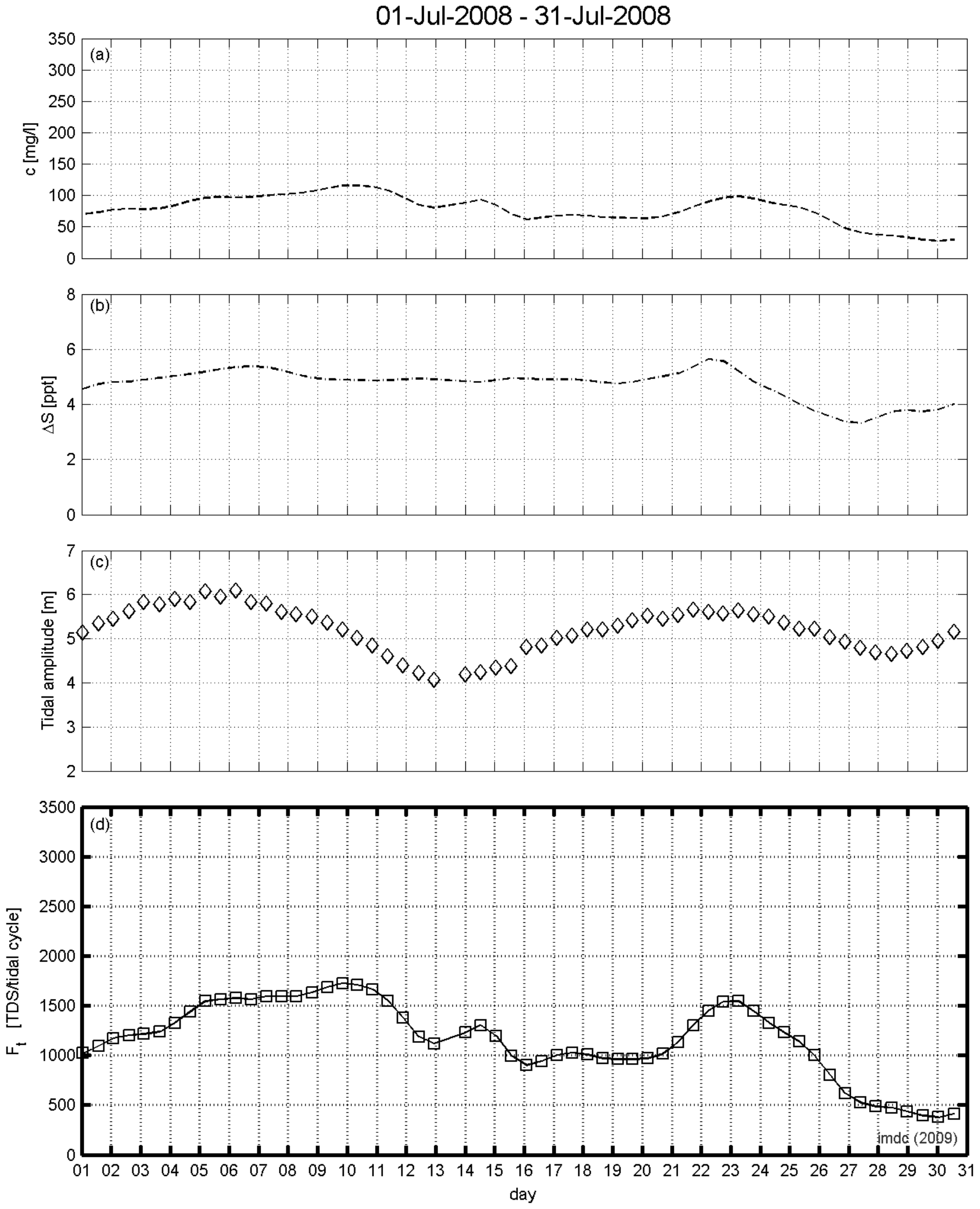
Deurganckdok



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

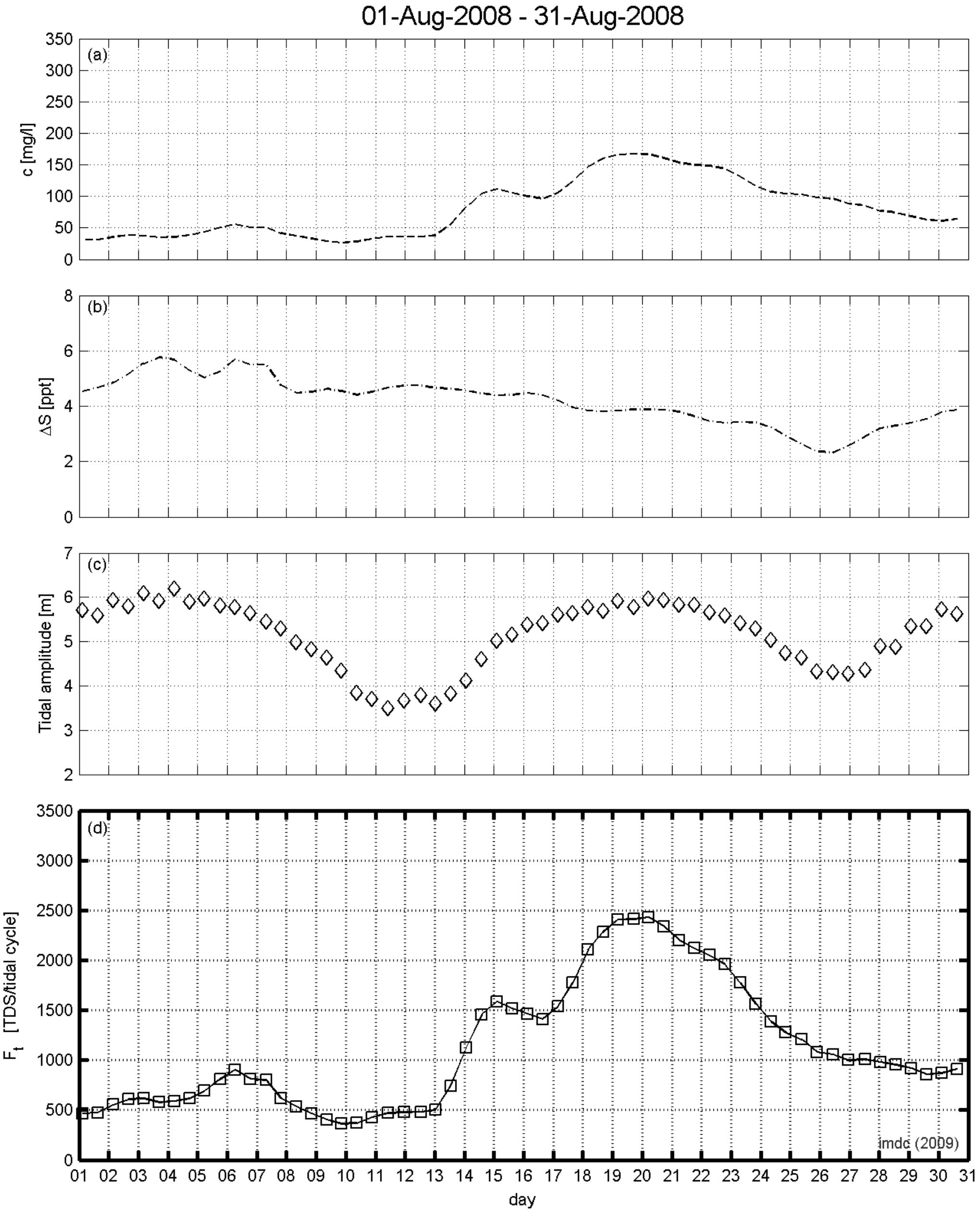
I/RA/11283/07.102/MSA

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).	IMDC International Marine & Dredging Consultants I/RA/11283/07.102/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).

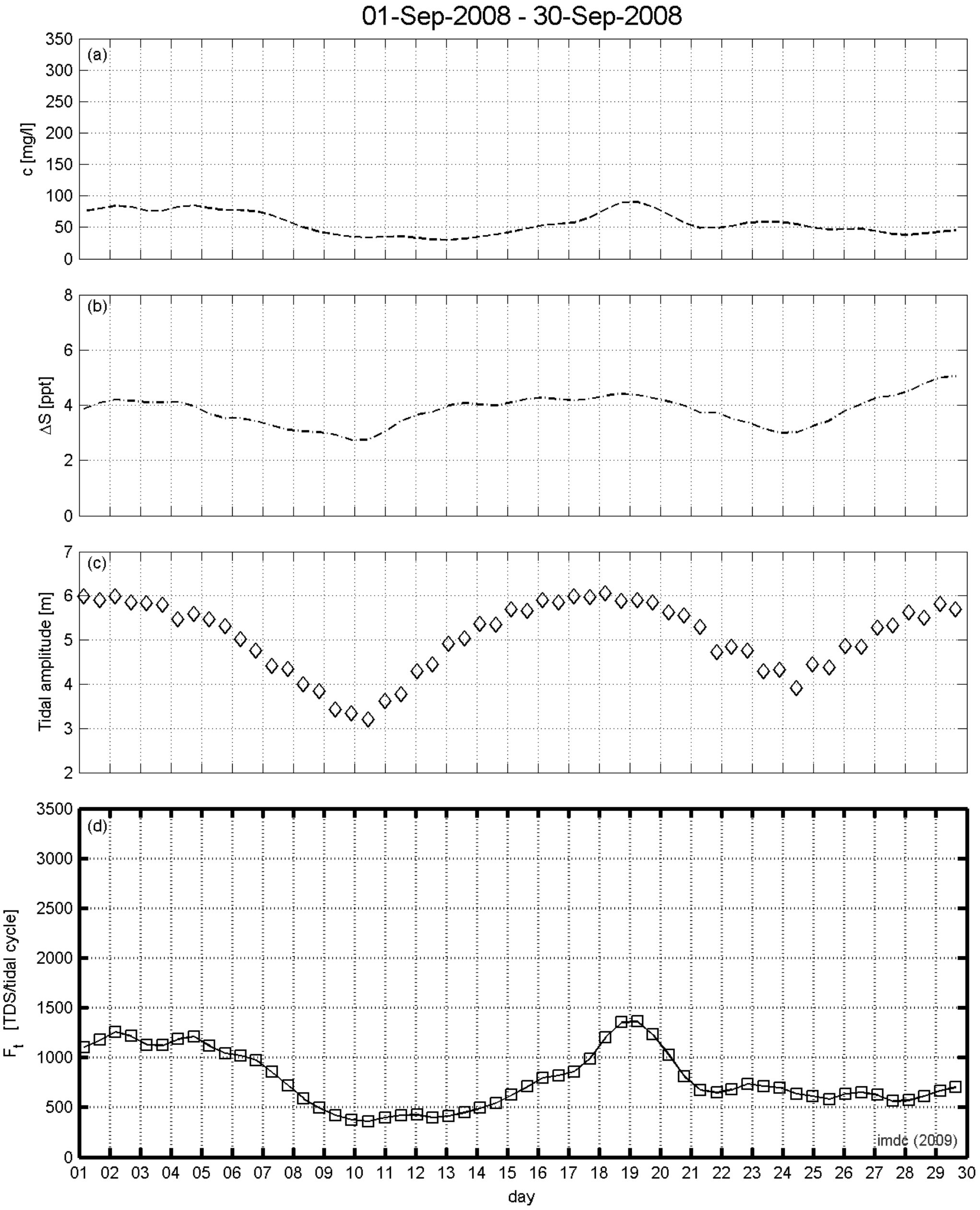
I/RA/11283/07.102/MSA

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).

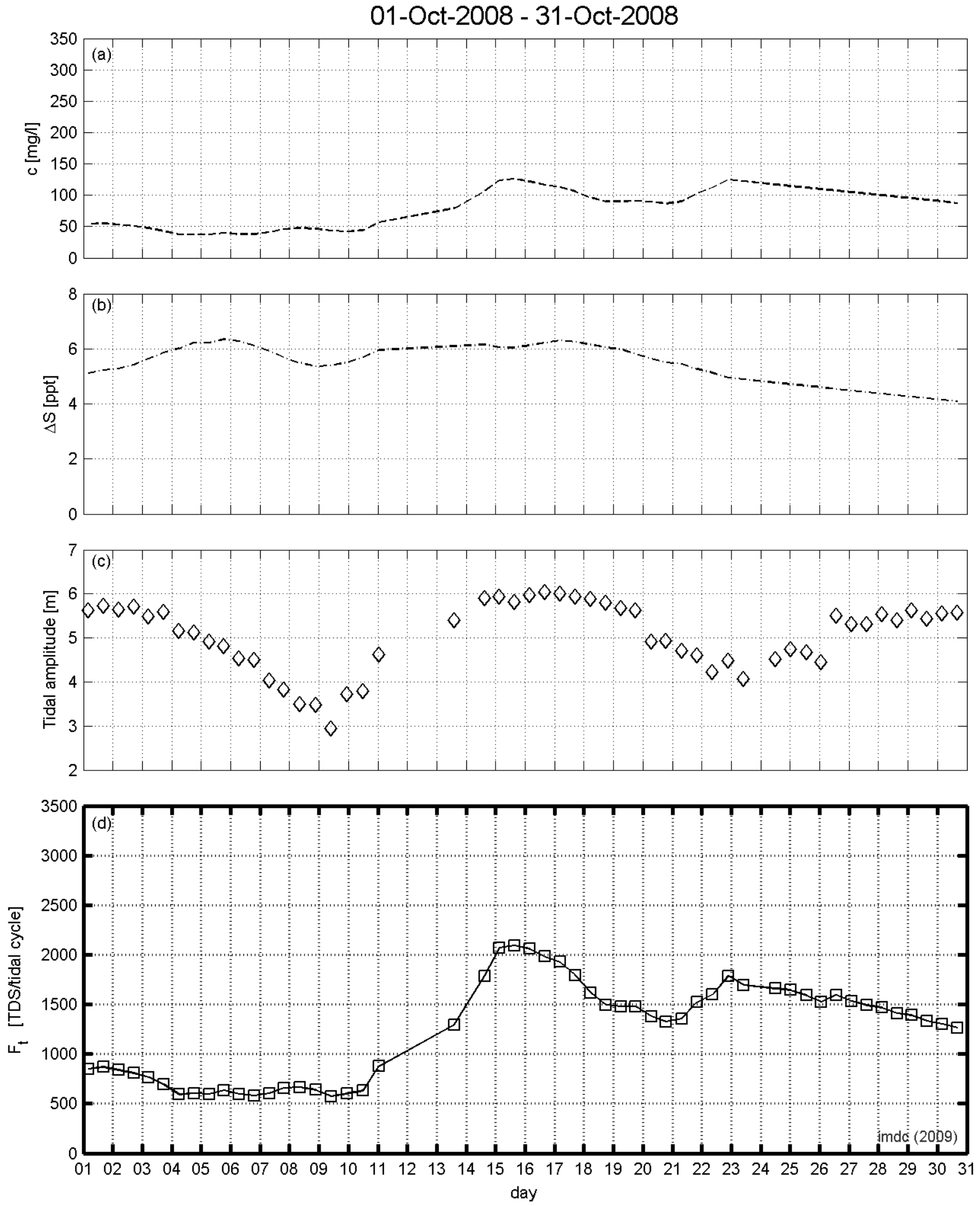
I/RA/11283/07.102/MSA

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).

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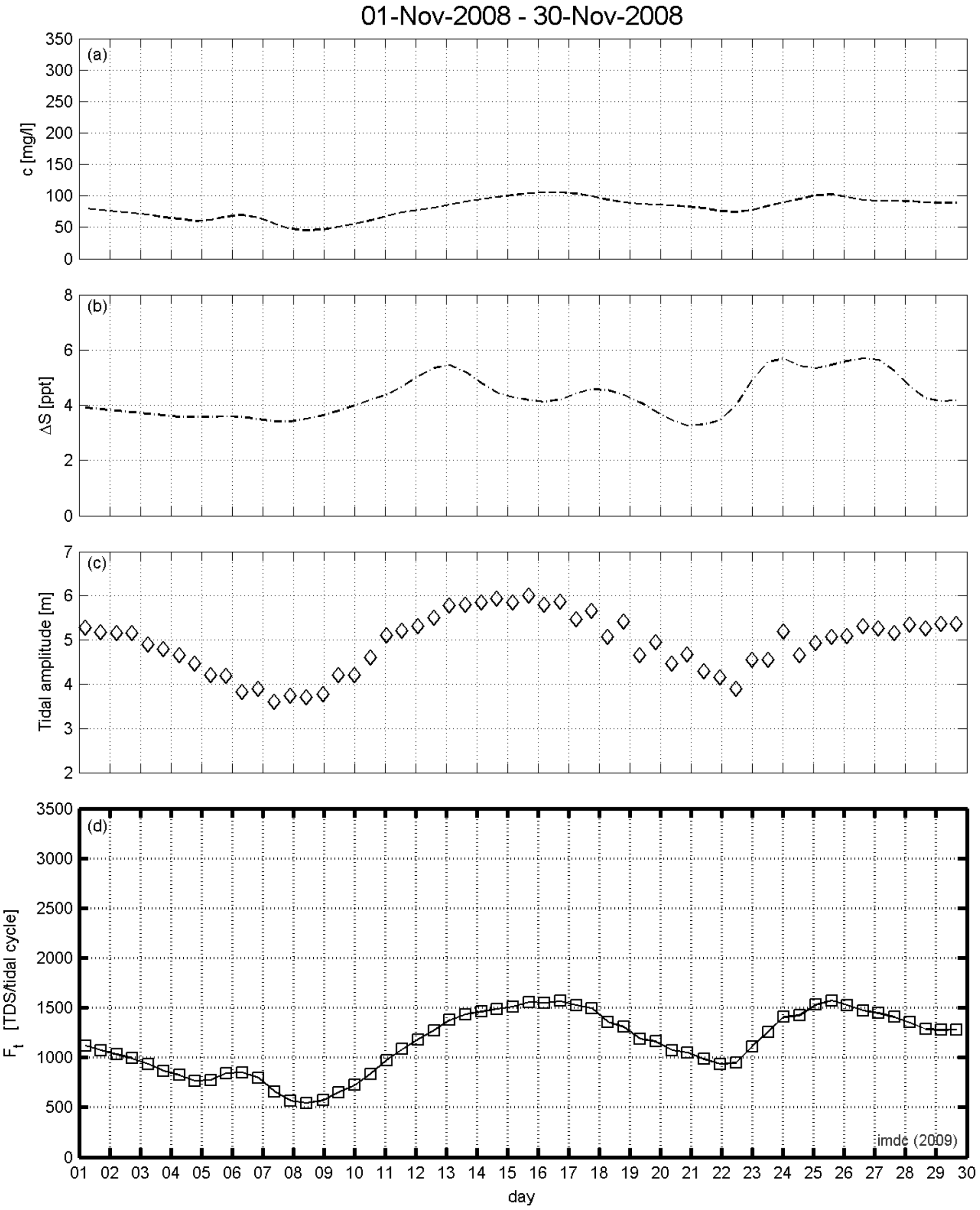
Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



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

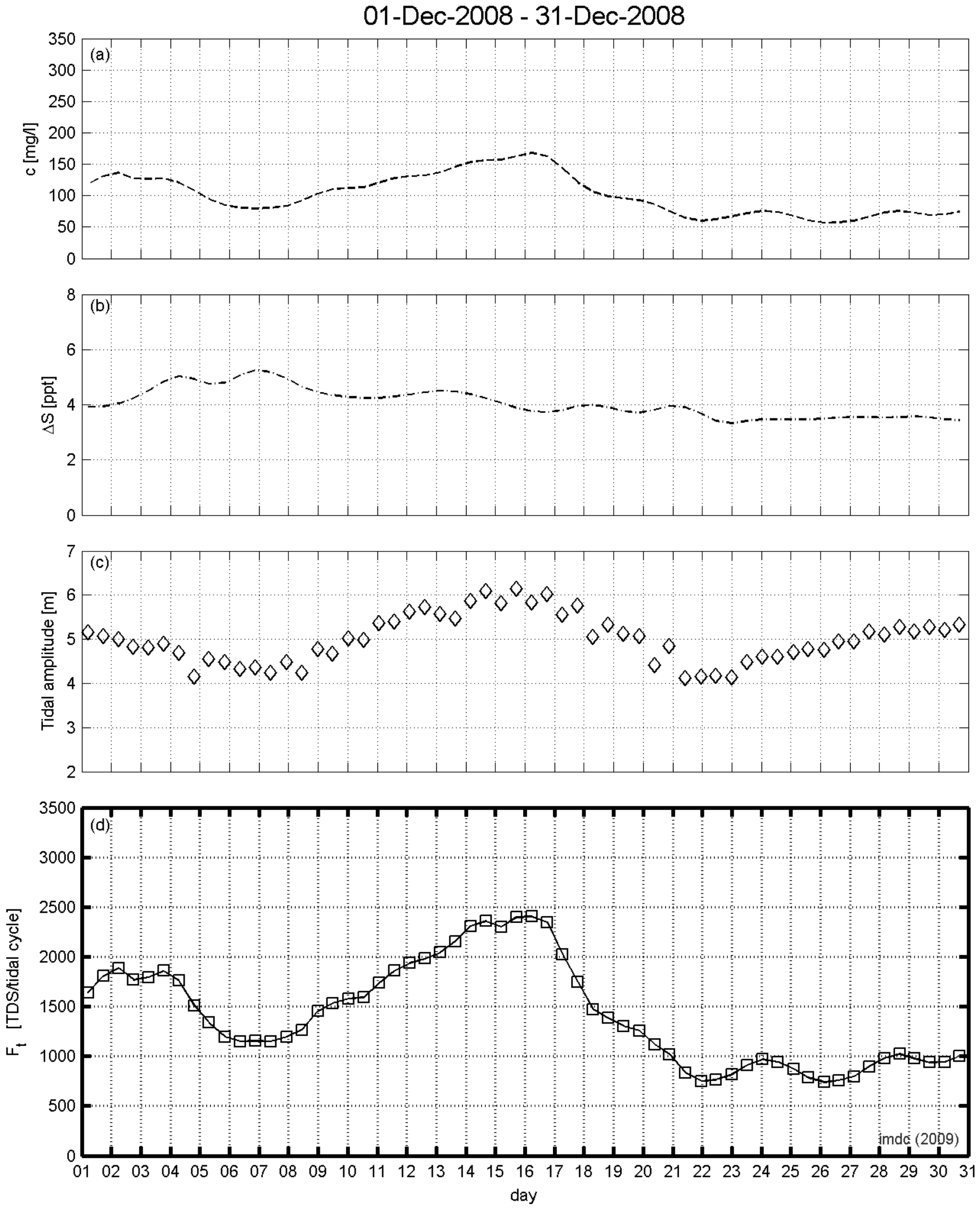
I/RA/11283/07.102/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok

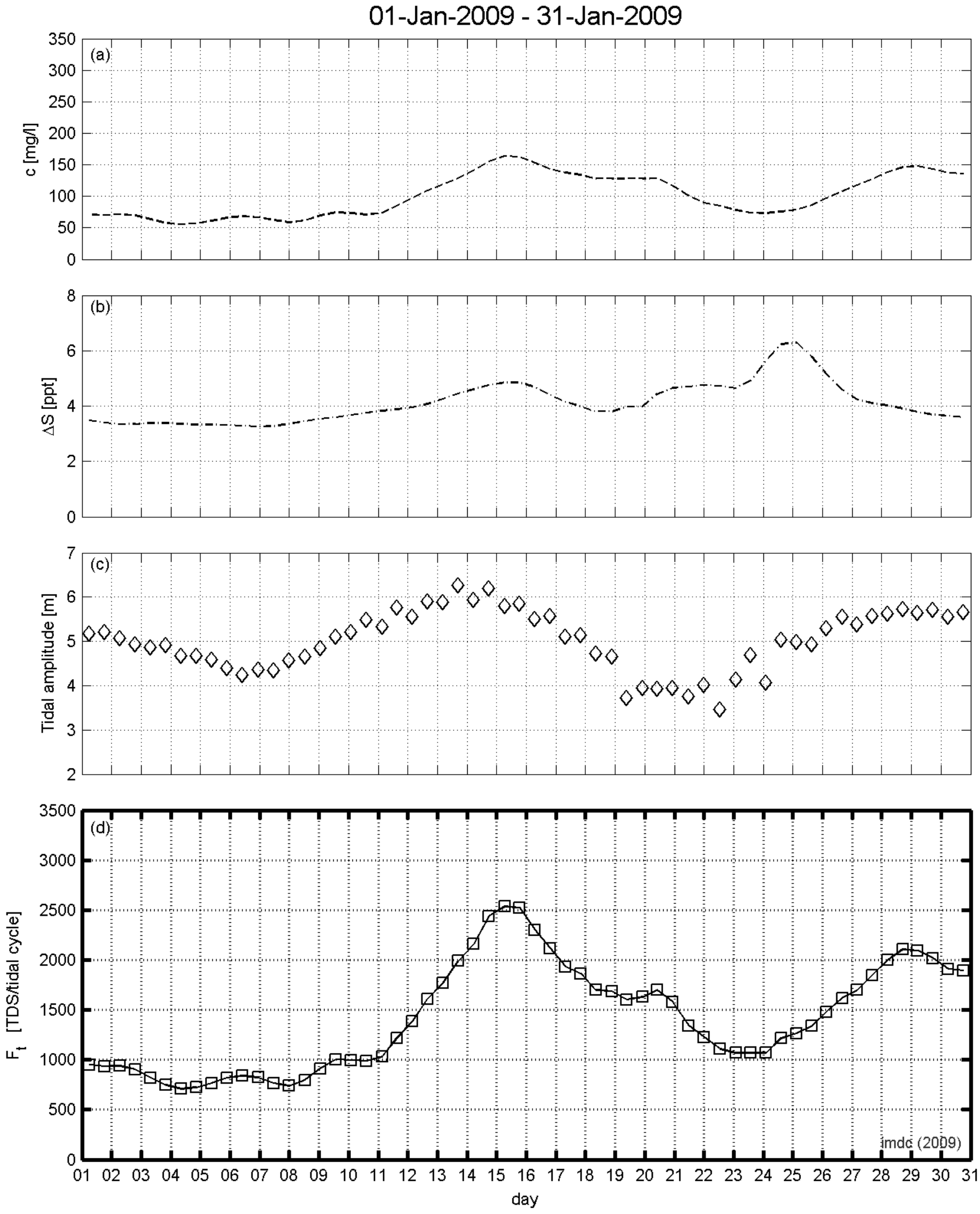


Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

I/RA/11283/07.102/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).

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I/RA/11283/07.102/MSA

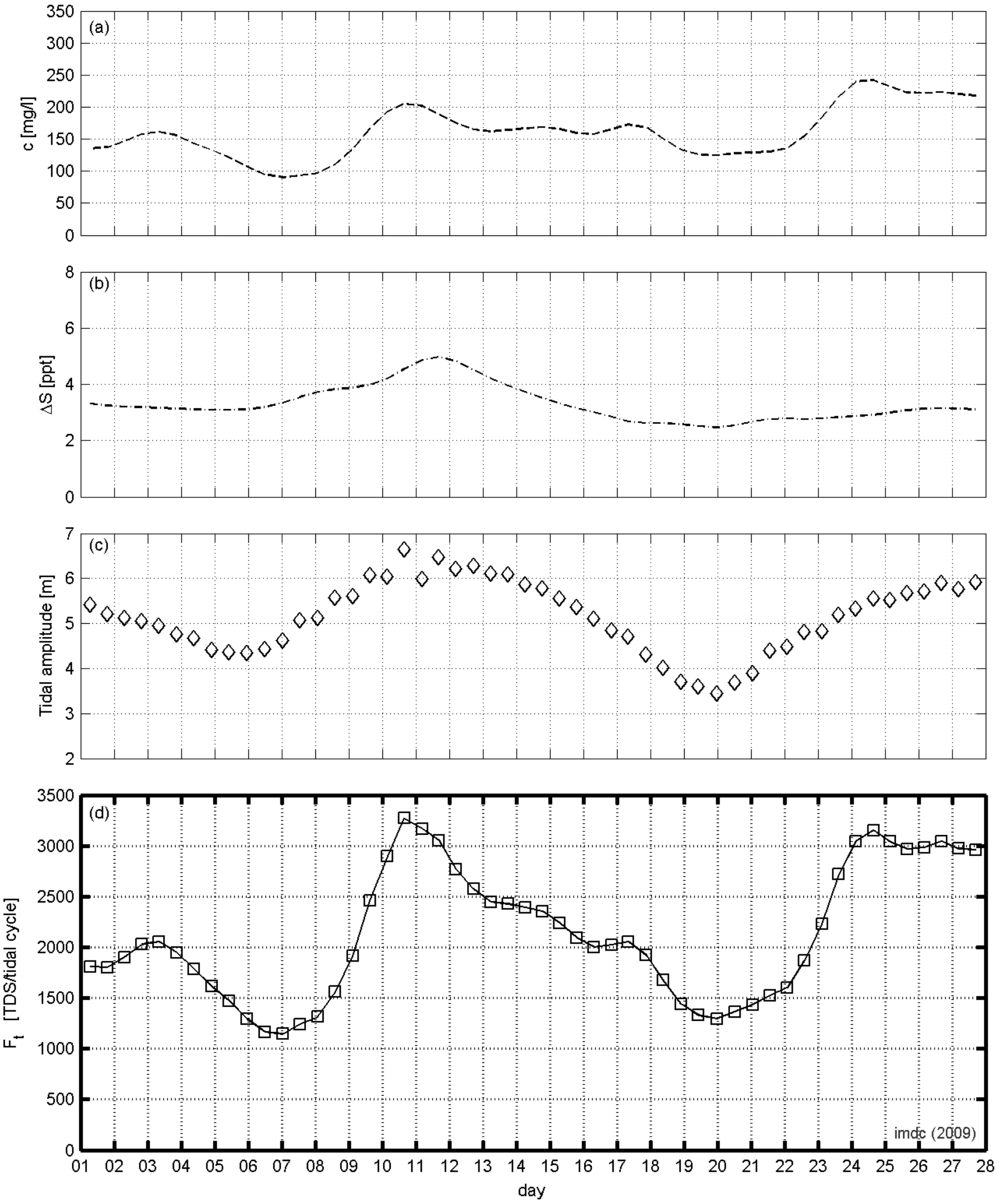
Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok

01-Feb-2009 - 28-Feb-2009



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

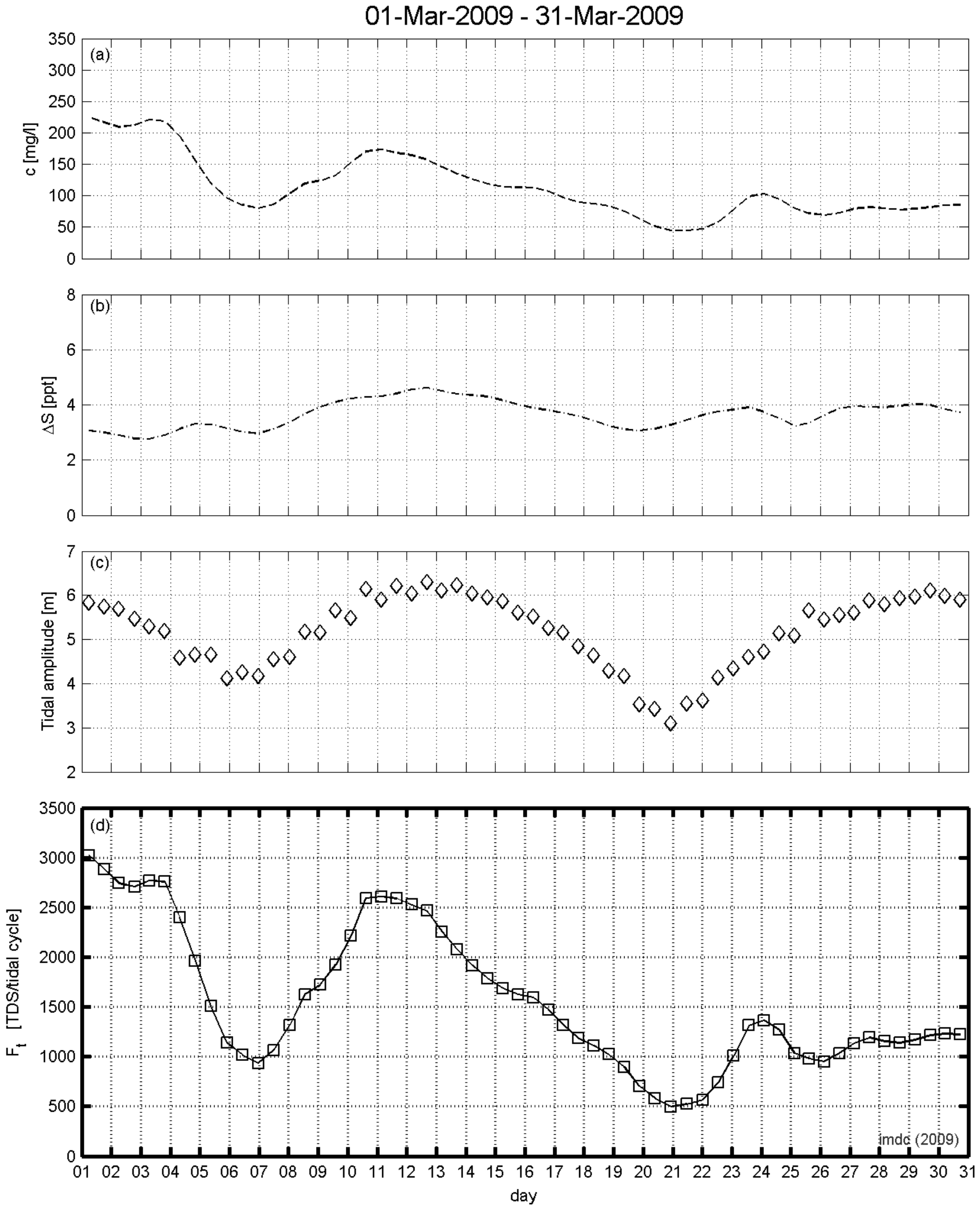
I/RA/11283/07.102/MSA

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).

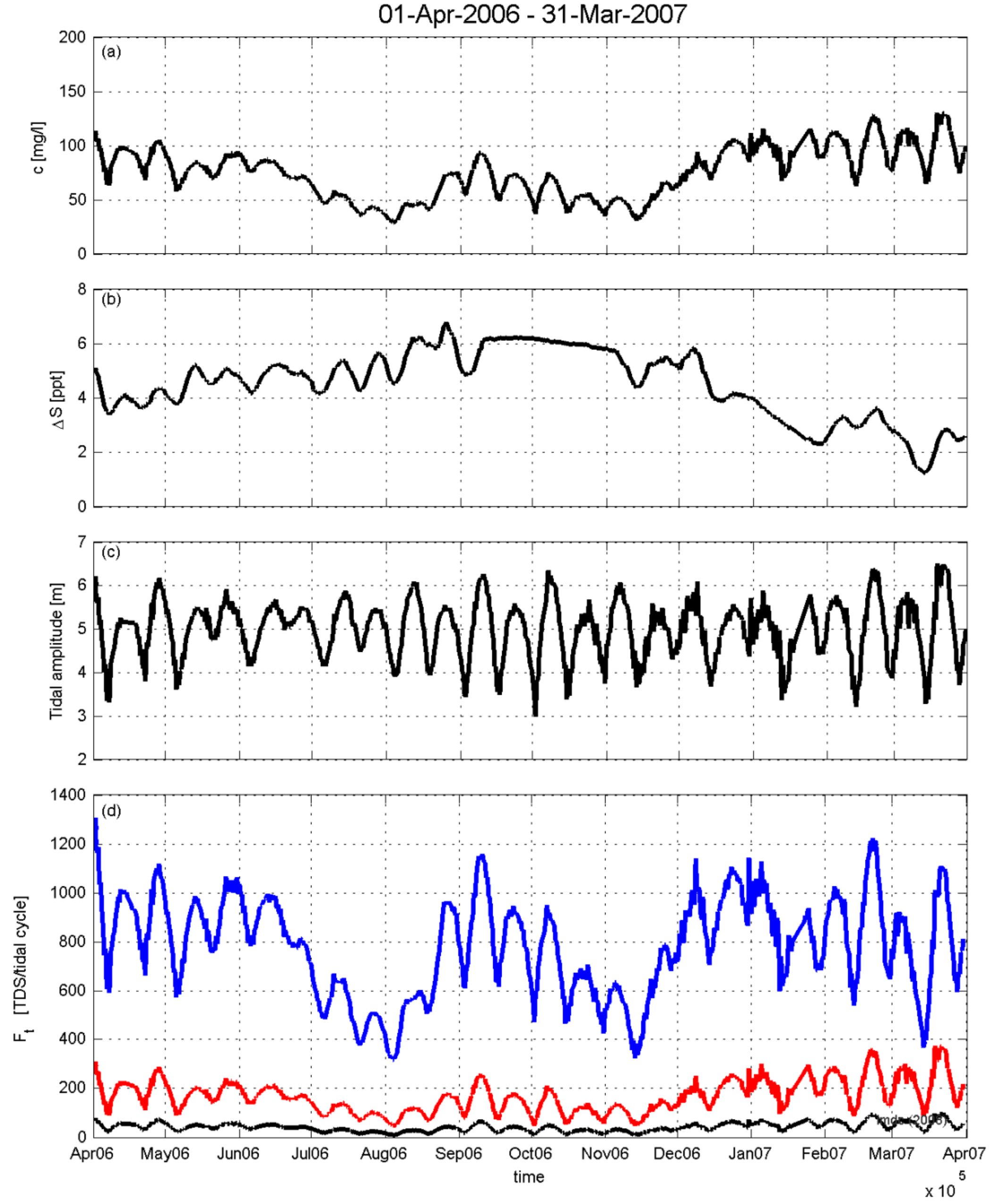
I/RA/11283/07.102/MSA

APPENDIX C. MAIN AMBIENT CONDITIONS VERSUS 3 COMPONENTS

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:
Deurganckdok



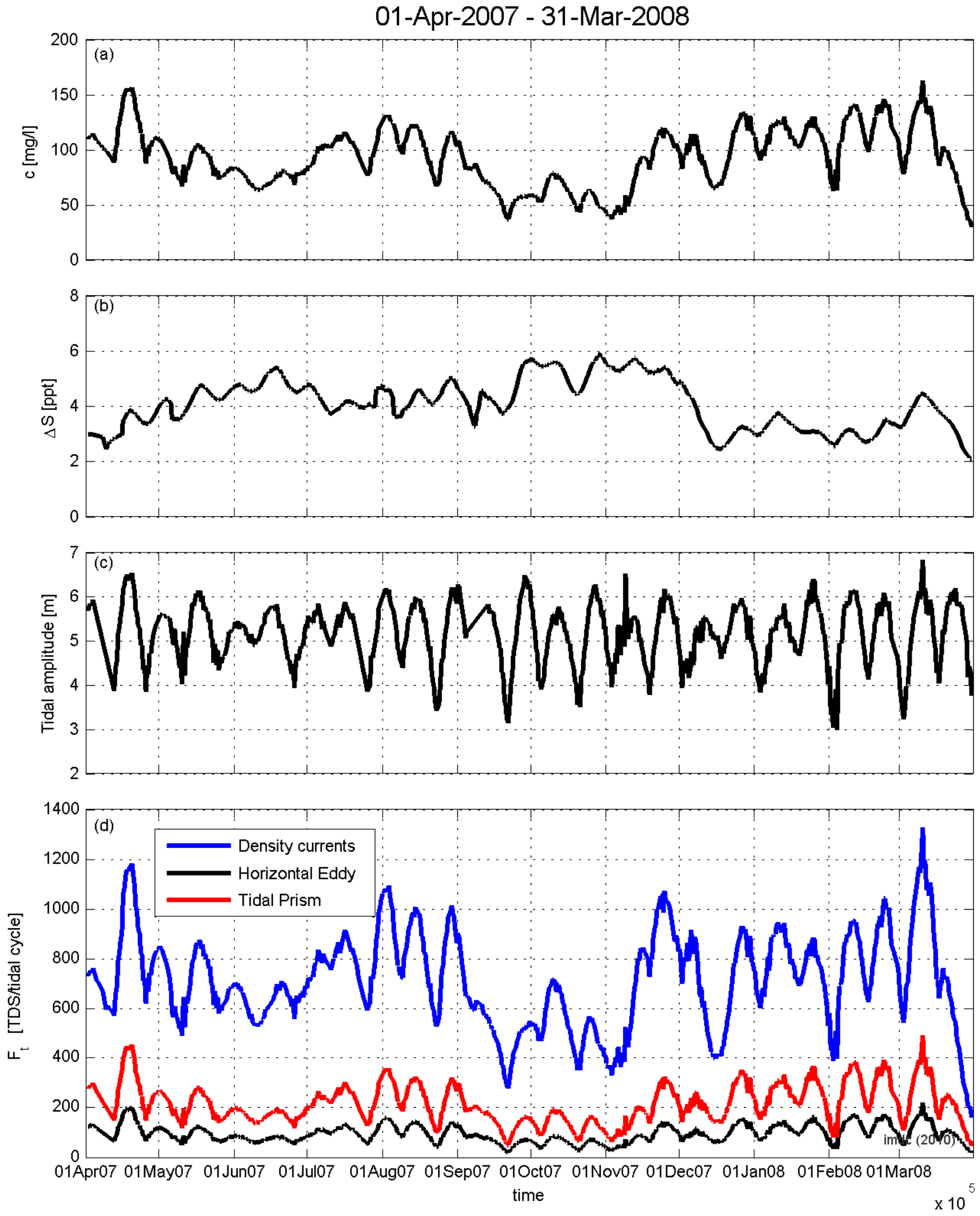
Suspended sediment concentration (a), salinity amplitude (b),
tidal range (c) and estimated sediment influx per tidal cycle (d),
due to density currents (blue), tidal amplitude (red) and eddy (black).

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 (red) and eddy's (black).

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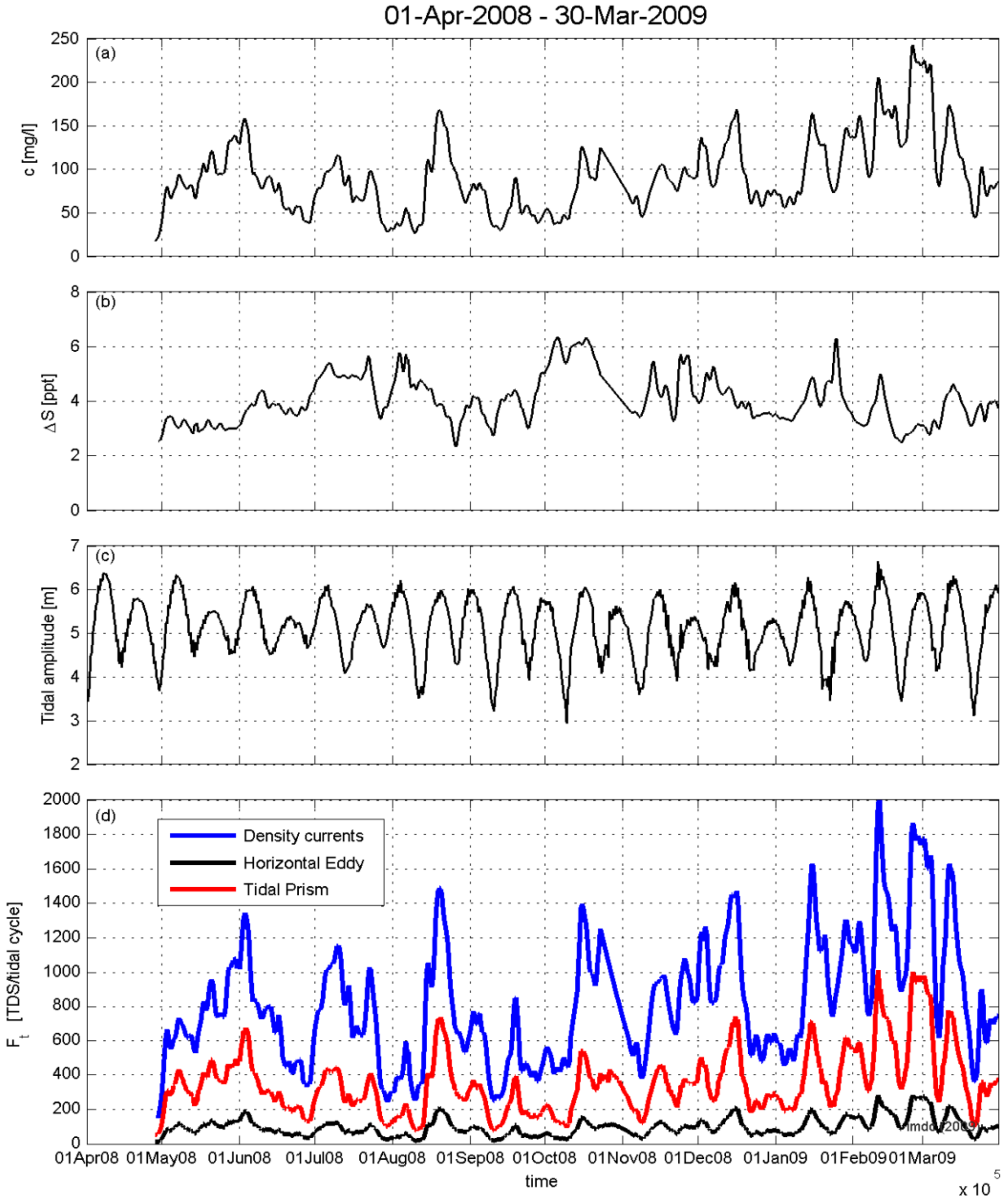
Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

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 (red) and eddy (black).