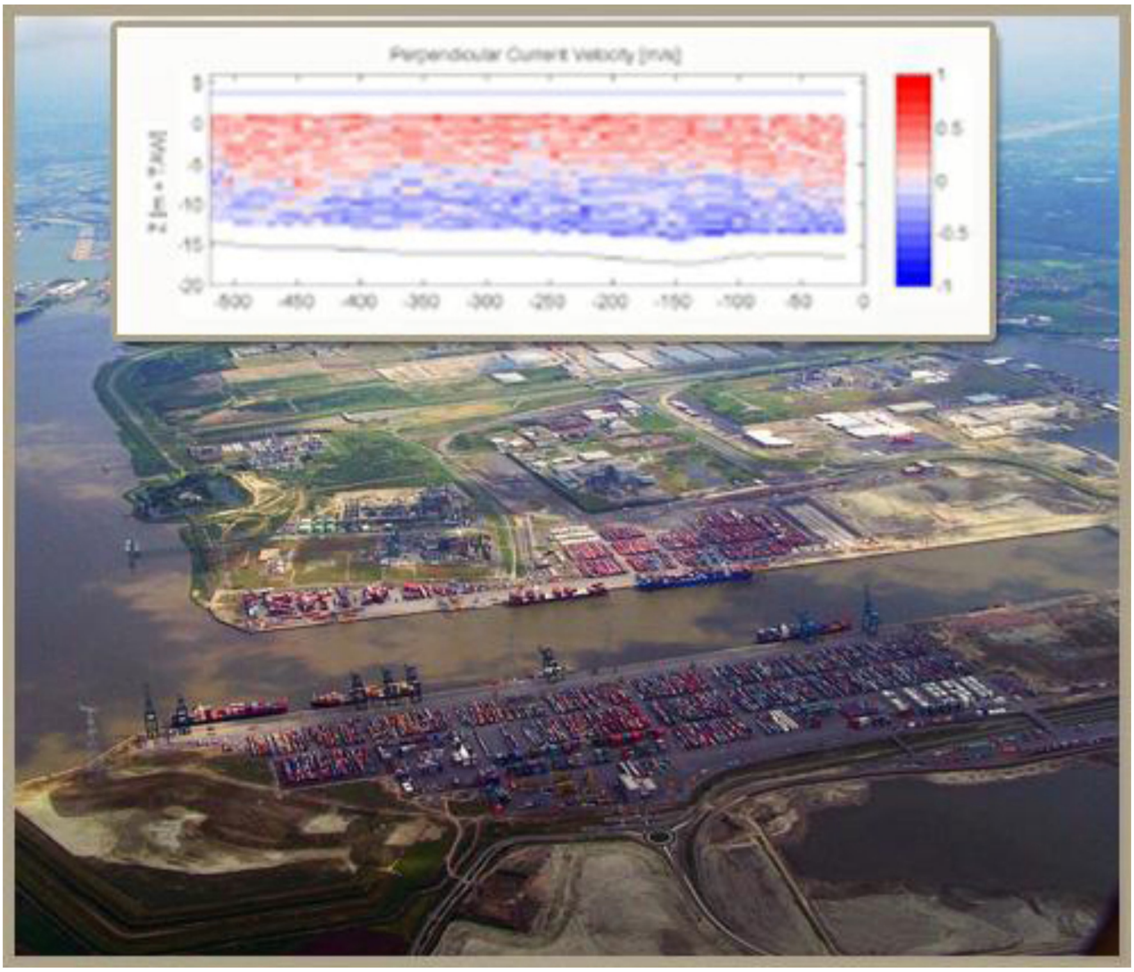
VLAAMSE OVERHEID

DEPARTEMENT MOBILITEIT EN OPENBARE WERKEN
WATERBOUWKUNDIG LABORATORIUM

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Bestek 16EB/05/04



Deelrapport 4.10 : Analyse van aanslibbingsprocessen en -invloeden

Report 4.10 : Analysis of siltation processes and factors:

April 2007 – March 2008

July 13th, 2009

I/RA/11283/07.102/MSA

IMDC International Marine & Dredging Consultants i.s.m. WL | delft hydraulics en GEMS International

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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

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
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 spring tide 27/09/2006 Parel 2 (I/RA/11283/06.119/MSA)
2.5	Through tide measurement Sediview neap tide (to be scheduled) (I/RA/11283/06.120/MSA)
2.6	Salinity-Silt distribution & Frame Measurements Deurganckdok 13/3/2006 – 31/05/2006 (I/RA/11283/06.121/MSA)
2.7	Salinity-Silt distribution & Frame Measurements Deurganckdok 15/07/2006 – 31/10/2006 (I/RA/11283/06.122/MSA)
2.8	Salinity-Silt distribution & Frame Measurements Deurganckdok 15/01/2007 – 15/03/2007 (I/RA/11283/06.123/MSA)
2.9	Calibration stationary equipment autumn (I/RA/11283/07.095/MSA)
2.10	Through tide measurement Siltprofiler winter (I/RA/11283/07.086/MSA)
2.11	Through tide measurement Salinity Profiling winter (I/RA/11283/07.087/MSA)
2.12	Through tide measurement Sediview winter (I/RA/11283/07.088/MSA)
2.13	Through tide measurement Sediview winter (I/RA/11283/07.089/MSA)
2.14	Through tide measurement Sediview winter (I/RA/11283/07.090/MSA)
2.15	Through tide measurement Siltprofiler (to be scheduled) (I/RA/11283/07.091/MSA)
2.16	Salt-Silt distribution Deurganckdok summer (21/6/2007 – 30/07/2007) (I/RA/11283/07.092/MSA)
2.17	Salt-Silt distribution & Frame Measurements Deurganckdok autumn (17/09/2007 - 10/12/2007) (I/RA/11283/07.093/MSA)
2.18	Salt-Silt distribution & Frame Measurements Deurganckdok winter (18/02/2008 - 31/3/2008) (I/RA/11283/07.094/MSA)
2.20	Calibration stationary & mobile equipment winter (I/RA/11283/07.096/MSA)
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

Report	Description
	(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)
Analysis	
4.1	Analysis of Siltation Processes and Factors, 4/'06 – 3/'07 (I/RA/11283/06.129/MSA)
4.10	Analysis of Siltation Processes and Factors, 4/'07 – 3/'08 (I/RA/11283/07.102/MSA)
HCBS: Ambient conditions in theriver Scheldt	
5.3	Overview of ambient conditions in the river Scheldt: Januari – June 2006
5.4	Overview of ambient conditions in the river Scheldt: July – December 2006

1.3.2. Measurement actions

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

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

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

1.4. Structure of the report

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

2. BASICS OF SEDIMENTATION IN DEURGANCKDOK

2.1. Project Area: Deurganckdok

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

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

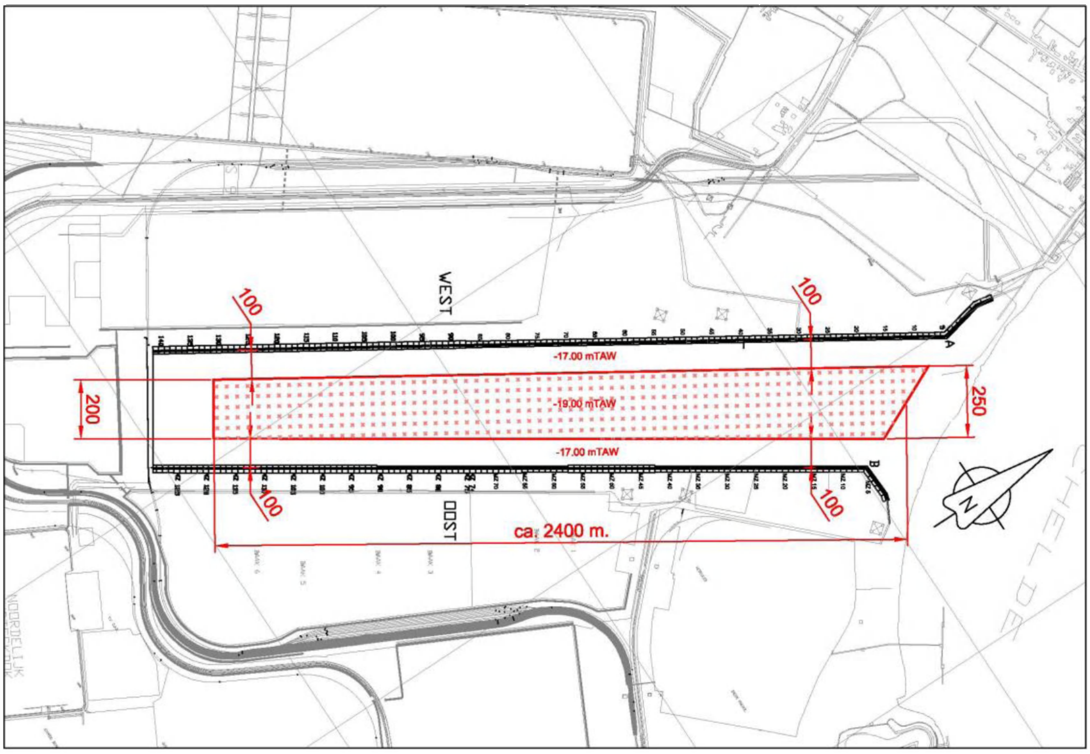


Figure 2-1: Overview of Deurganckdok

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

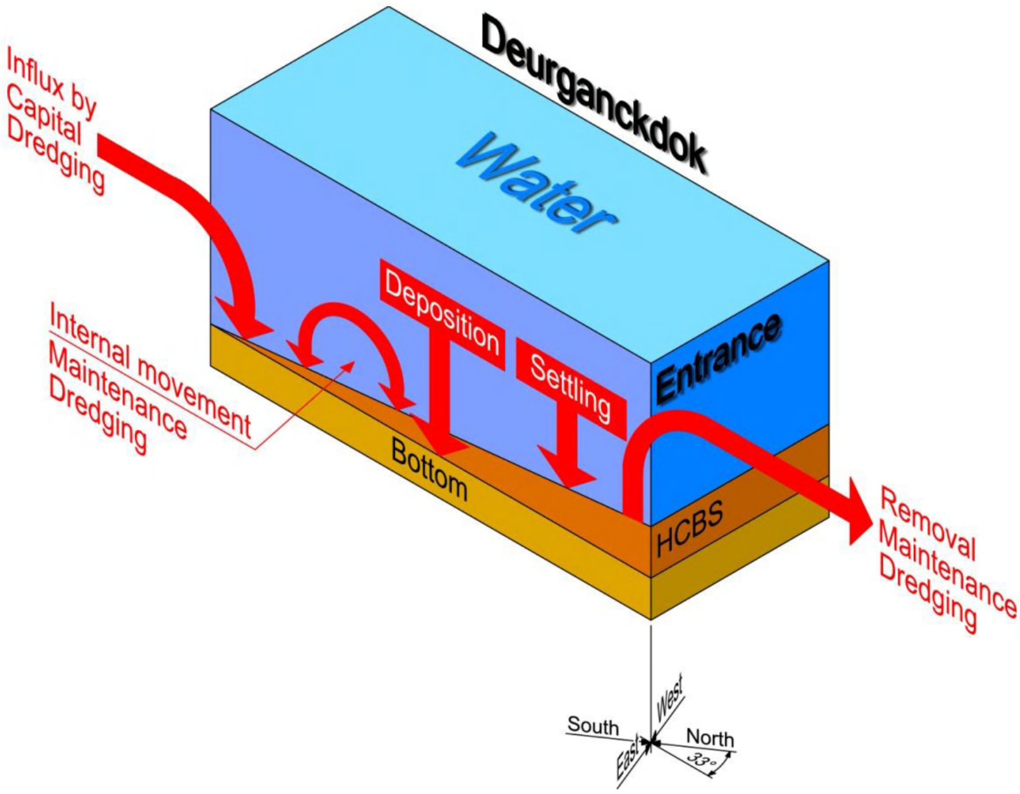


Figure 2-2: Elements of the sediment balance

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.

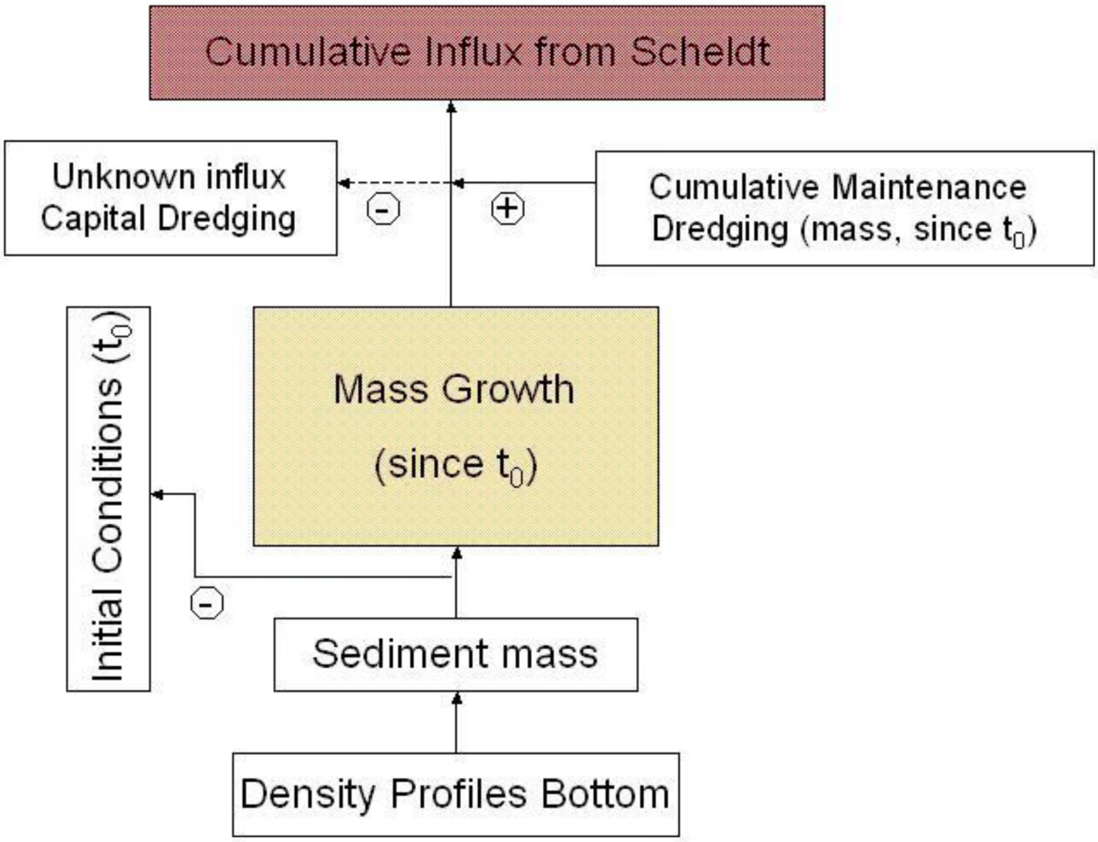


Figure 2-3: Determining a sediment balance with bed density profile data

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

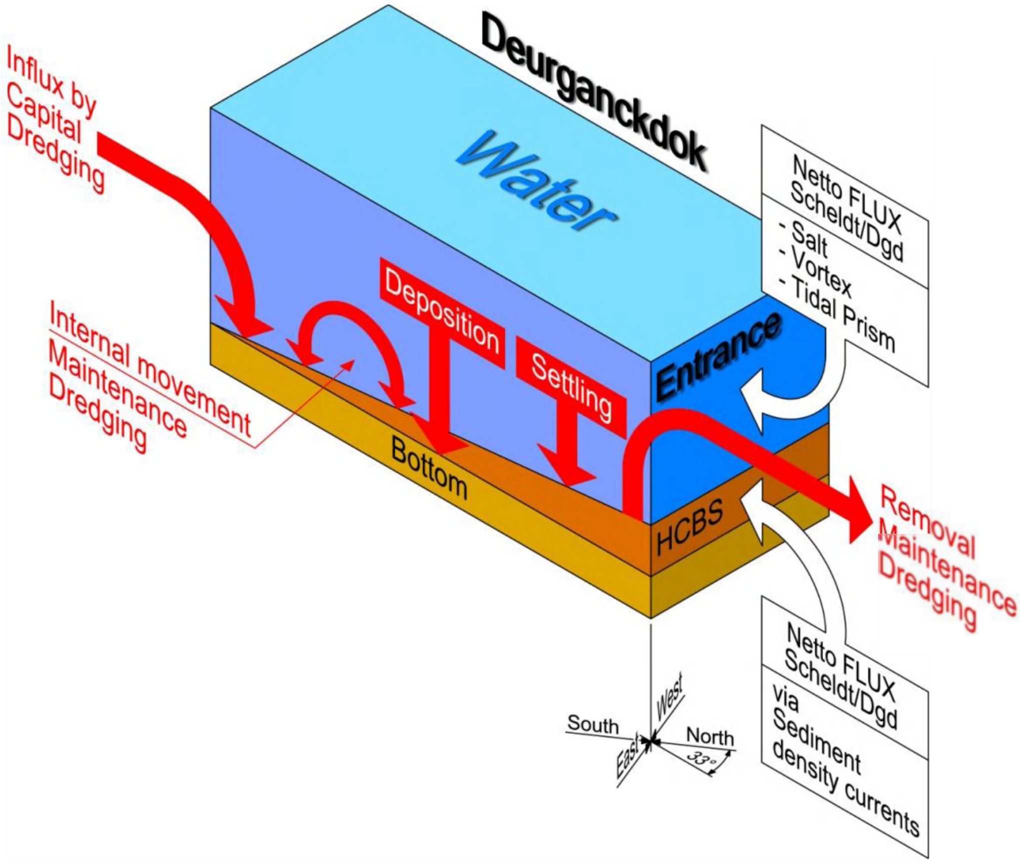


Figure 2-4: Transport mechanisms

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 second year of measurements. For a map of equipment locations outside Deurganckdok of which data has been used please refer to APPENDIX A.

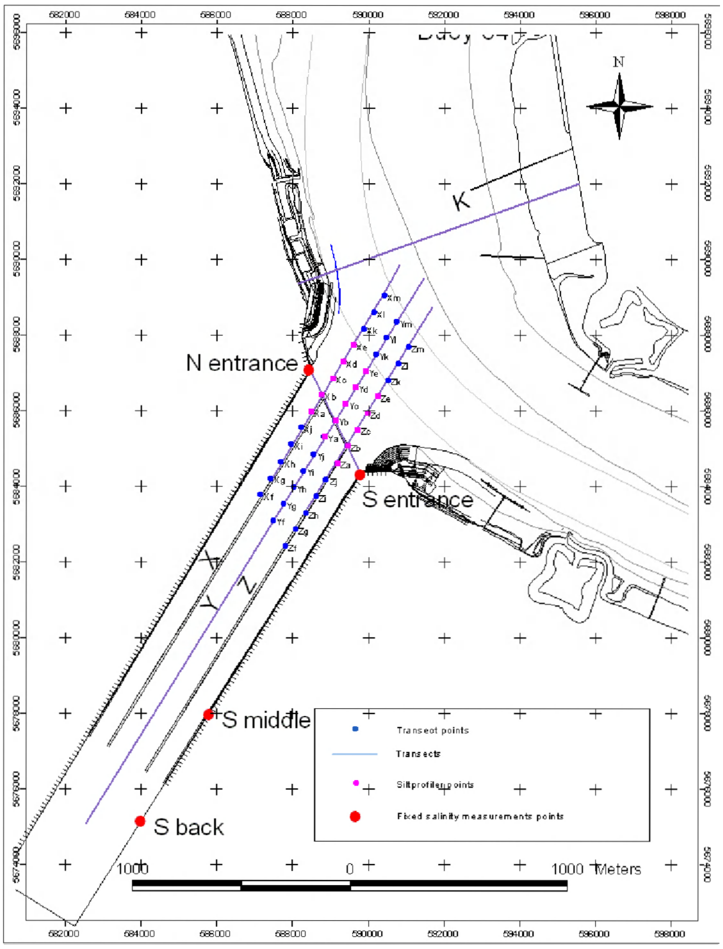


Figure 3-1: Location of measurement equipment and sailed tracks at Deurganckdock

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

activity	April 07		May 07		June 07		July 07		August 07		September 07	
	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												

activity	October 07		November 07		December 07		January 08		February 08		March 08	
	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 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
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
	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

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

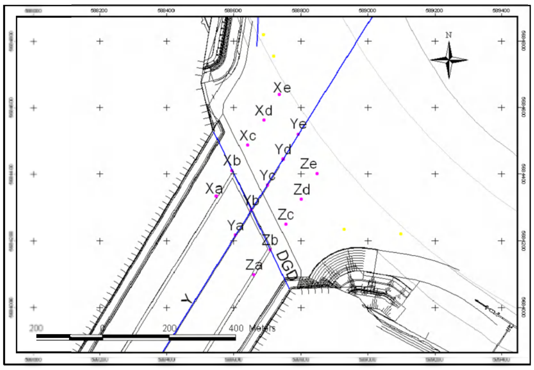


Figure 3-2: Through tide SiltProfiler measurements – Entrance Deurganckdok

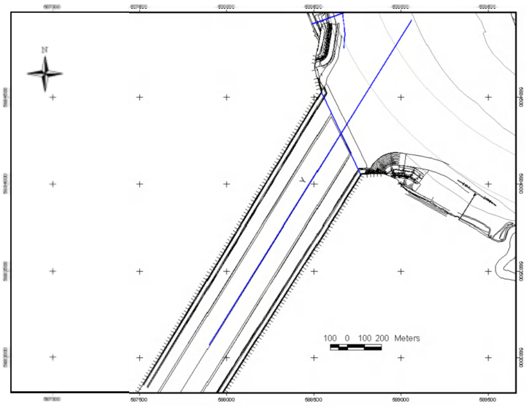


Figure 3-3: Through tide Salinity measurements – Deurganckdok (transect Y)

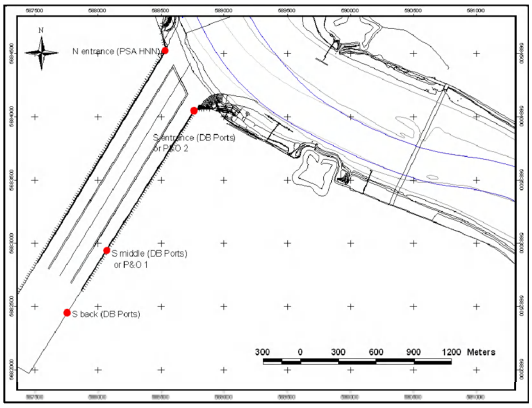


Figure 3-4: Long term salinity measurements Deurganckdok

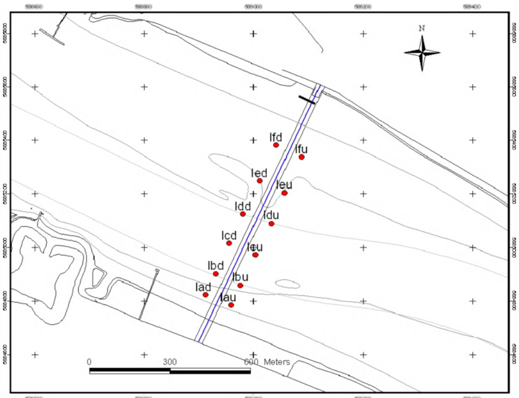


Figure 3-5: Through tide ADCP & SiltProfiler measurements – Upstream Deurganckdok (transect I)

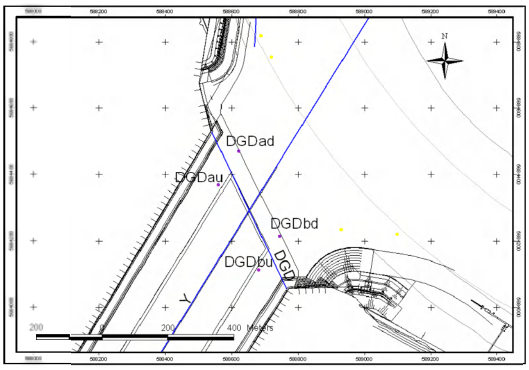


Figure 3-6: Through tide ADCP measurements – Entrance Deurganckdok (transect DGD)

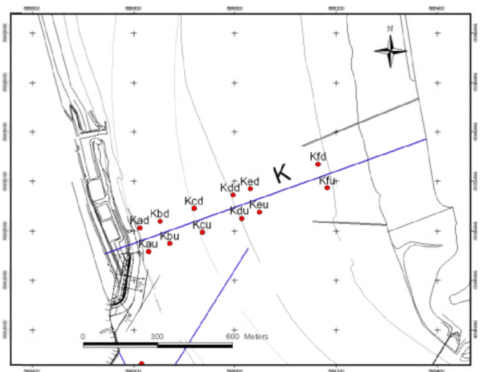


Figure 3-7: Through tide ADCP & SiltProfiler measurements – Downstream Deurganckdok (Transect K)

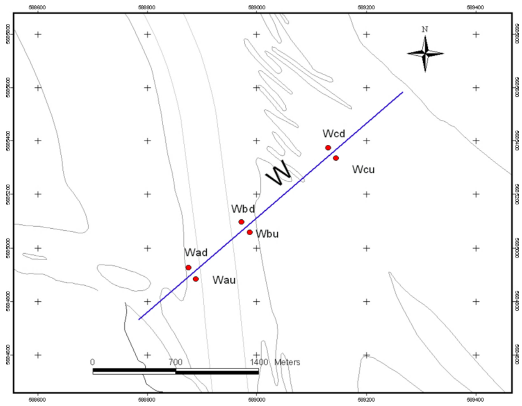


Figure 3-8: Through tide ADCP measurements - Waarde (transect W)

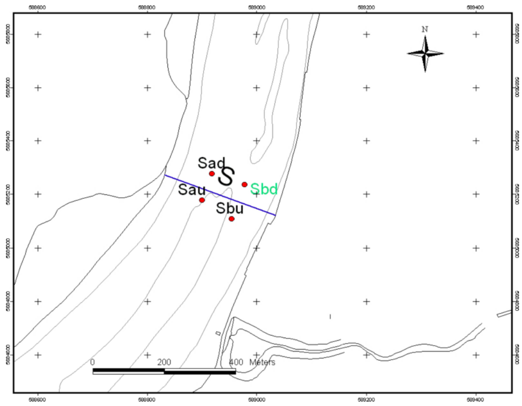


Figure 3-9: Through tide ADCP measurements - Schelle (transect S)

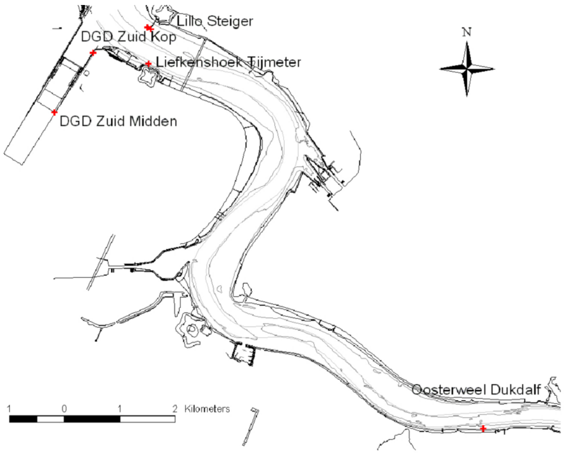


Figure 3-10: Calibration measurements - 15/03/2006 & 14/04/2006

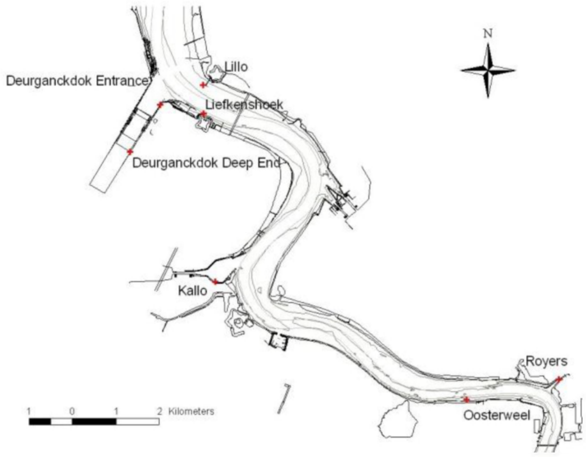


Figure 3-11: Calibration measurements – 23/06/2006 & 18/09/2006

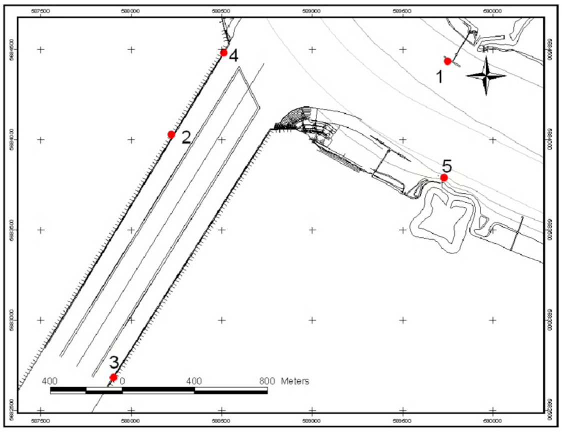


Figure 3-12:Calibration measurements – 10/09/2008

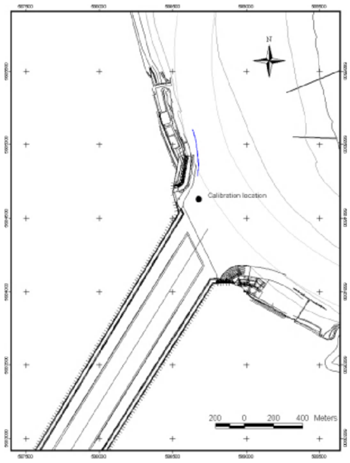


Figure 3-13:Calibration measurements – 04/02/2008 & 05/02/2008

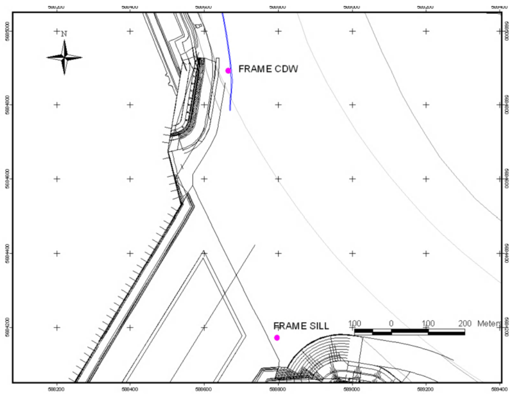


Figure 3-14:Near bed continuous monitoring

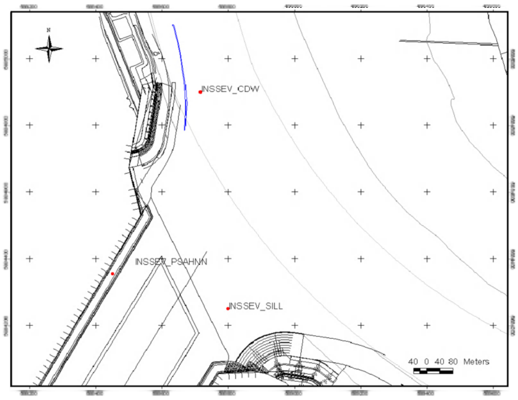


Figure 3-15: Settling velocity (INSSEV) 05/09/2006 – 07/09/2006

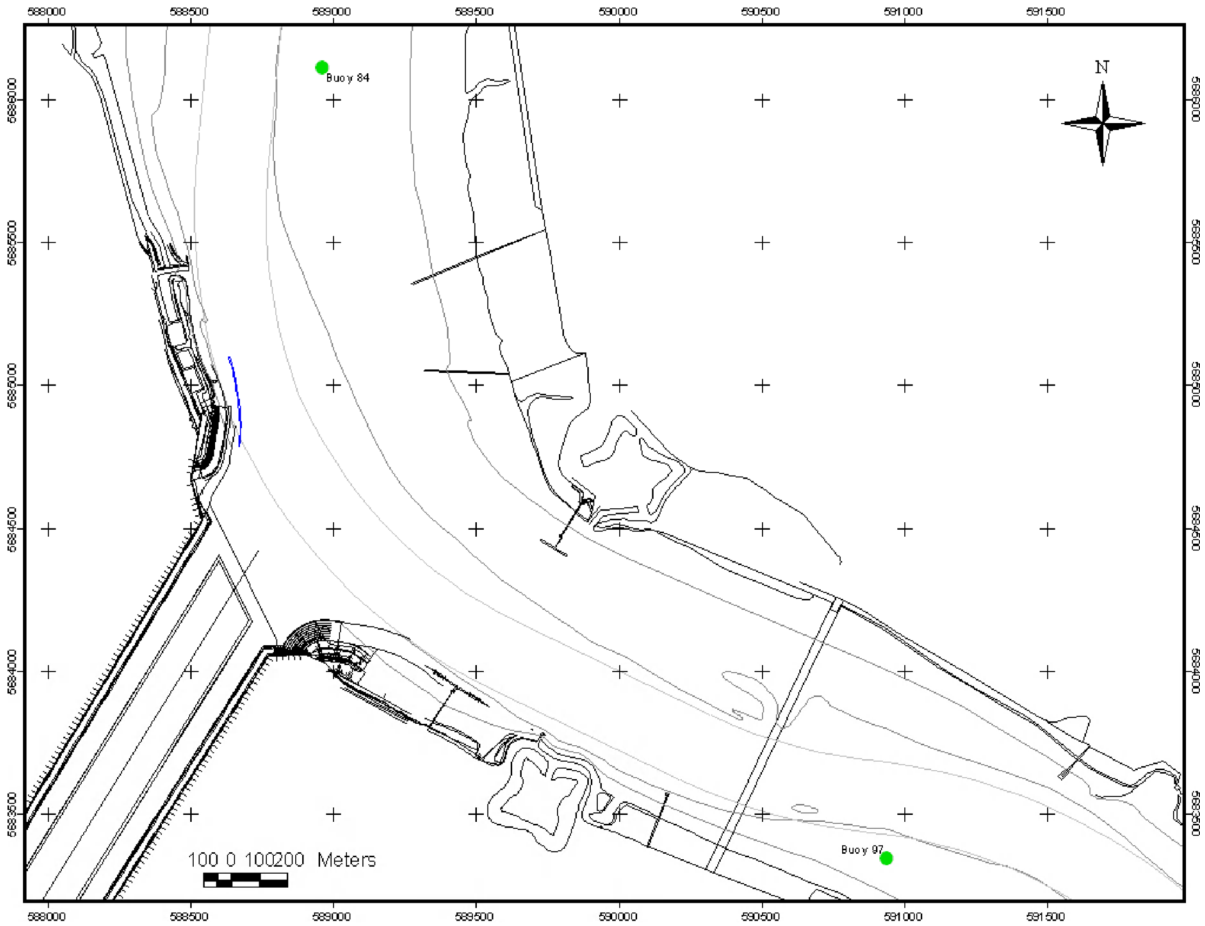


Figure 3-16: Long term measurements in the Lower Sea Scheldt

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

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

- averaged values of suspended sediment concentration, salinity and temperature for the entire water column, and the top and bottom 50% of the water column

- Dock entrance (transect along sill)
  - transects of suspended sediment concentration, velocity and sediment mass flux
  - time series of discharge and sediment mass flux
- Dock entrance (transects X, Y and Z perpendicular to dock's axis)
  - Transects of vertical flow velocity profiles
  - Depth averaged flow velocity in top 12m: vector fields
- Buoy 84 and 97
  - time series of suspended sediment concentration, local velocity, temperature and water level: measured near bottom and at half of the water column
  - monthly and three-monthly averages, minima and maxima in relation of the tide
- Scheldt area around Deurganckdok
  - transects of suspended sediment concentration, velocity and sediment mass flux
- Deurganckdock: inside and entrance area
  - particle size distribution of both bed and suspended sediment
  - bed: sediment composition, zeta potential, consolidation, shear strength, capillary suction time
  - water column: settling velocity
  - velocity: local and profile

3.2.2. Supplementary analyses

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

4. CONCEPT OF A SEDIMENTATION MODEL WITH DATA-ASSIMILATION

4.1. Introduction

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

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

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

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

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

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

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

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 2007 – March 2008 data has been collected, as summarized in §3.

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

- buoys 84 and 97, located in the Scheldt river (locations shown in Appendix A);
- both sides of dock entrance;
- 13-hours intensive measurement campaigns at dock entrance returning the local and total sediment mass flux (IMDC 2008g,l).

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

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

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

Assume the following measurement periods:

- short-term at dock's entrance cross-section (13 h): $\left[t_{ST,s}, t_{ST,e}\right]$
- 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): $\left[t_{LT,B,s}, t_{LT,B,e}\right]$

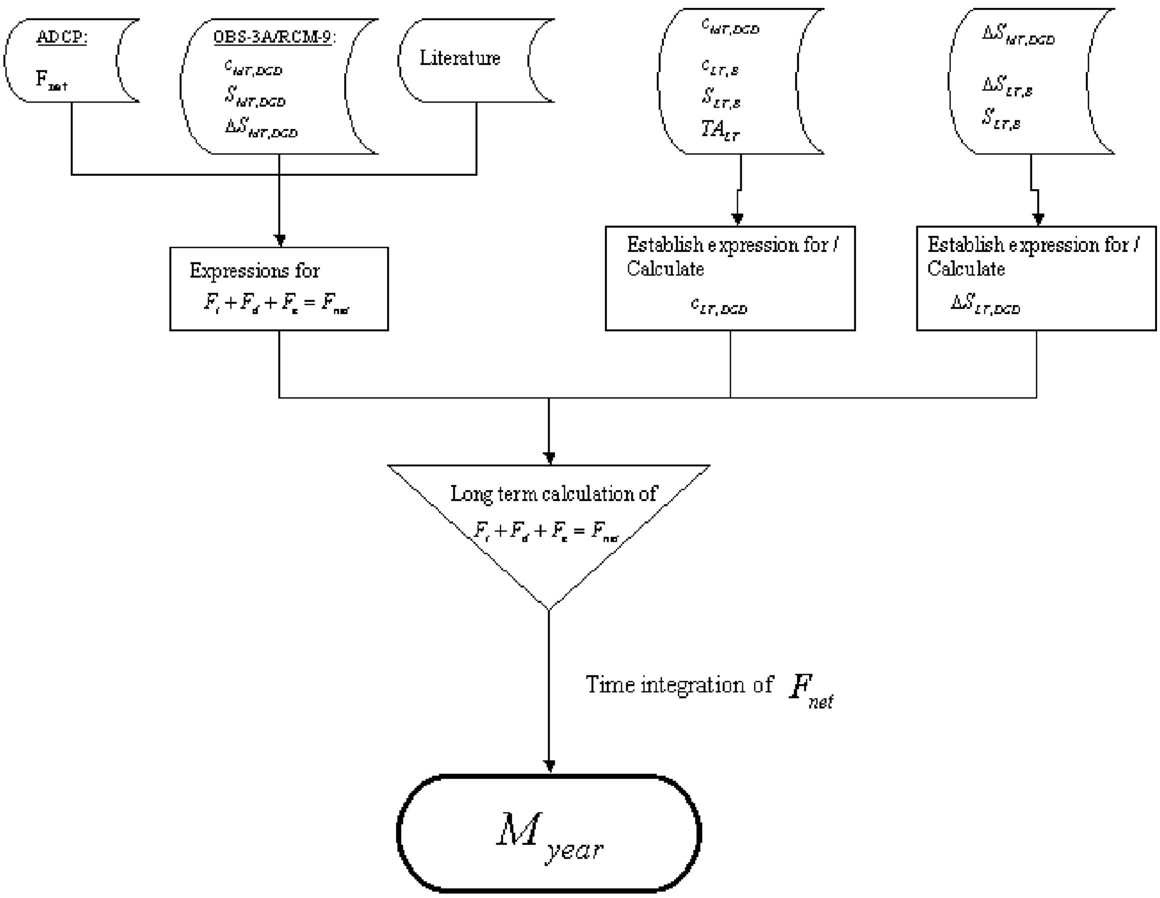


Figure 4-1: Overall method for empirical model of sedimentation in Deurganckdok with data-assimilation.

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.

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

5. IMPLEMENTATION OF A SEDIMENTATION MODEL WITH DATA-ASSIMILATION

5.1. Introduction

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

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

Secondly, the year-round measurements at buoy 84 and buoy 97 can be used as a basis for the determination of the first level of estimations: from three mid-term measurement campaigns at the entrance of Deurganckdok (salinity and suspended sediment concentration) and the measurements of salinity at the buoys in both directions at about 2 km from the dock an empirical relation can be established to estimate the measured parameters near the dock in between the measured periods.
In the first year of measurements in this project (DGD1) an initial parameterisation has been set up for estimation of year-round salinity amplitude and sediment concentration at the dock's entrance. Since these data are not measured directly during the full year they have to be determined otherwise. In this report the measurements of the second year in the project (DGD2) will be used to check the relationships for parameterisation established after DGD1, and where necessary make small adaptations. These adaptations will be checked finally after the third year of measurements (DGD3) which is still ongoing at the time of writing.

Thirdly, a semi-analytical solution can be determined for the sediment accumulation in the dock based on the continuous series obtained in the second step. 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.

In the analysis of the second year into the project (DGD2) presented in this report 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 is 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. That is out of the DGD2 project year analysed in this report, but the flow fields visualised during the campaign are already used as input. It has been observed that the eddy along the entrance is very weak and is probably not of major importance in the sediment exchange with the estuary. The main reason for this might be found in the interaction between eddy formation and the advective tidal flows hampering them.

Please note that all long term data has been transformed to a series of tidal averages and that the timeseries used for buoy 84 is measured at -5.8m TAW and for buoy 97 at -7.5m TAW.

5.2. Parameters needed for influx estimate

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

5.3. Determination of relationships between physical parameters

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

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

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

5.3.1. Salinity amplitude

In this section the function mentioned higher is established:

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

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

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

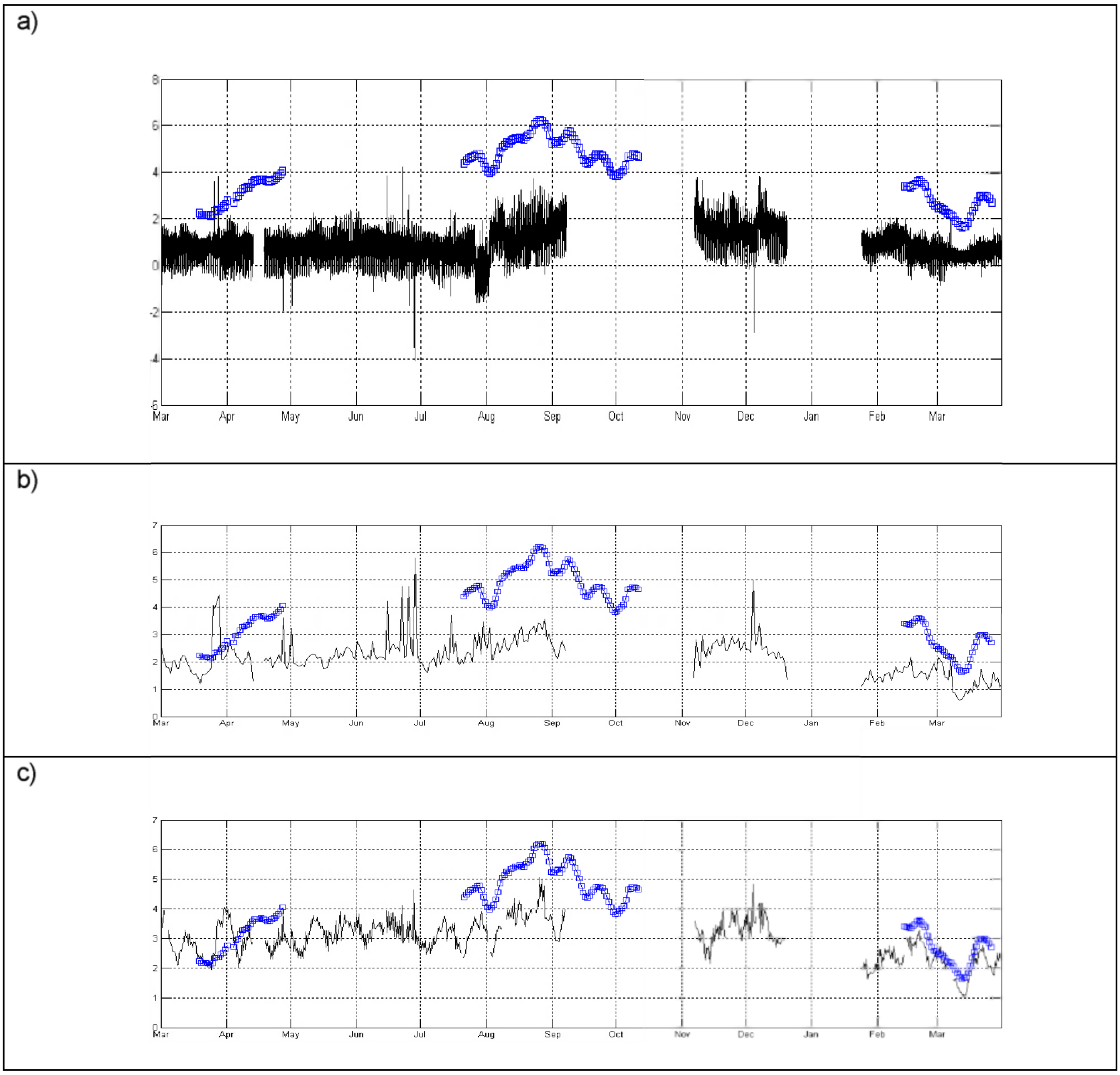


Figure 5-1: a) Salinity difference (unfiltered, buoy 84 – buoy97) in black and salinity amplitude at DGD in blue with markers; b) Range per tide in salinity difference between buoy 84 and buoy 97 in black and salinity amplitude at DGD in blue with markers; c) Average salinity amplitude (buoy 84 and buoy 97) in black and salinity amplitude at DGD in blue with markers. March 2006 – March 2007

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

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

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

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

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

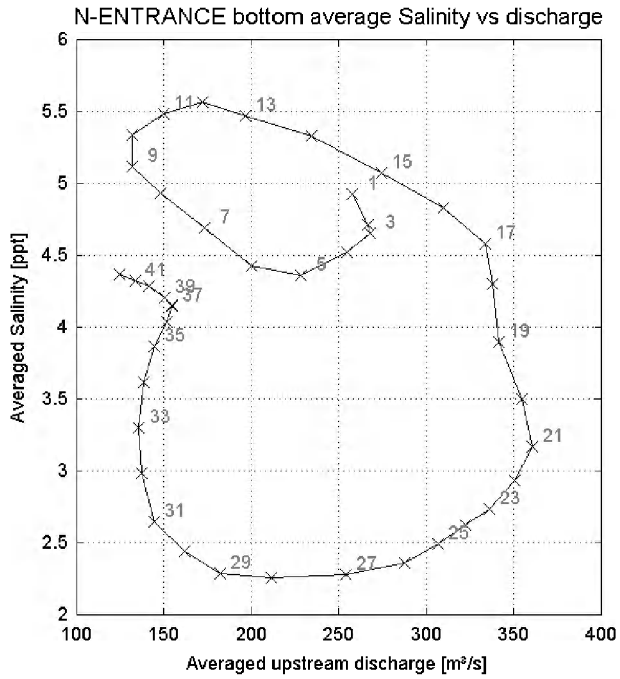


Figure 5-2: Hysteresis loop of salinity at the entrance of Deurganckdok under influence of river runoff. Data is filtered with a window of 7 days, numbers represent days after start of the measurements.

Therefore, an amplification coefficient c_{ss} dependent on average salinity of buoy 84 and buoy 97 is used (Equation 5-1):

Equation 5-1:

$$c_{ss} = 1 + 0.00029\overline{S}^3$$

Where: $\bar{s}$ is the average salinity.

Experimentally, the best fit has been with another function (shown in black in Figure 5-3) for the first period of measurements (DGD1) between April 2006 and april 2007. After comparison of measured salinity amplitude at buoys 84 and 97 and at the dock's entrance during the second measurement period (DGD2) a different function has been used. This results in an amplification factor lower than the one found for the first period of measurements. This change in behaviour might be due to the ongoing capital dredging in the dock still going on throughout the year.

The existence of the amplification in itself is rather surprising and is therefore investigated by finding a relationships between salinity amplitude in Deurganckdok, salinity amplitude in the river (buoys), mean salinity and season. During the year of measurements a wide range of mean salinity levels have occurred in the Scheldt estuary near the dock. During the first campaign in the summer of 2007 the average salinity was about 9 ppt, towards the end of the summer and fall it increased steadily to 11 ppt before a very sharp decrease early December to 4ppt. By the end of February 2008 salinity levels have risen to 7 ppt again to decrease gradually to 2 ppt by the end of March 2008, which is the end of the measurement year DGD2. As shown in the hysteresis loop in Figure 5-2 this is due to the effect of variations in fresh water river discharge. In Figure 5-3 is shown that the expression for c_{ss} as a function of the mean salinity can be confirmed.

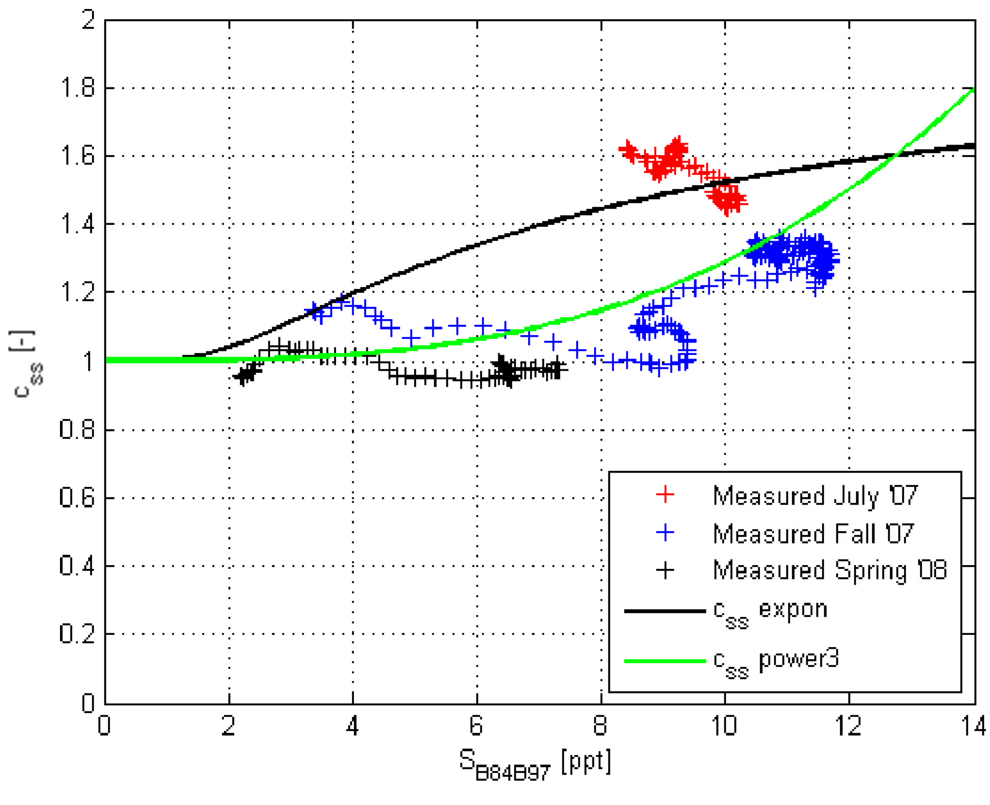


Figure 5-3: Relation between $c_{ss,}$ mean salinity and season, with the amplification coefficient c_{ss} used in the prediction shown in green and the function used for DGD1 in black.

Although the exponential relation of the amplification coefficient does not explain all the variation the trend is captured fairly good. The measured amplification starts high, at 1.5 to 1.6 during the summer of 2007 (red marks), at the start of the fall 2007 campaign the amplification has dropped to 1.3 but salinity levels are still higher. During the campaign salinity levels drop significantly to 3 ppt

and so does the amplification of salinity amplitude (1.1). At the start of the spring 2008 campaign (black marks) the salinity has risen to 7 ppt but the amplification did not change much. Finally, at the end of the spring campaign salinity has decreased to 2 ppt but amplification has suddenly increased to 1.4, which is not covered by the exponential relation.
An increase in salinity variation can lead to an increase in sediment exchange by density currents, but so far it is unclear whether this increase in salinity variation is due to a physical phenomenon within the dock or due to a different elevation of measurement equipment relative to the bottom and height of the water column. However, Figure 5-4 shows that it is not the case that a measurement at the bottom (buoy 97 data) and a measurement near the top (buoy 84 data) result in significant differences in salinity amplitude, at least not in the range of the difference with salinity amplitude at the dock's entrance.

The application of the c_{ss} coefficient has resulted in the evolution over time of salinity amplitude measured at the dock (mid-term) and the predicted salinity amplitude (long-term) shown in Figure 5-4. Also shown is the time series of the tidal salinity amplitude at buoys 84 and 97 and their low-pass filtered average (red). Here is again shown when the differences occur between the salinity amplitude at the dock's entrance and the salinity amplitude in the river.

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

Equation 5-2:

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

where: $c_{ss} = 1 + 0.00029\overline{S}^{3}$ and $\overline{S} = 0.5\left[\overline{S_{LT,B84}} + \overline{S_{LT,B97}}\right]$

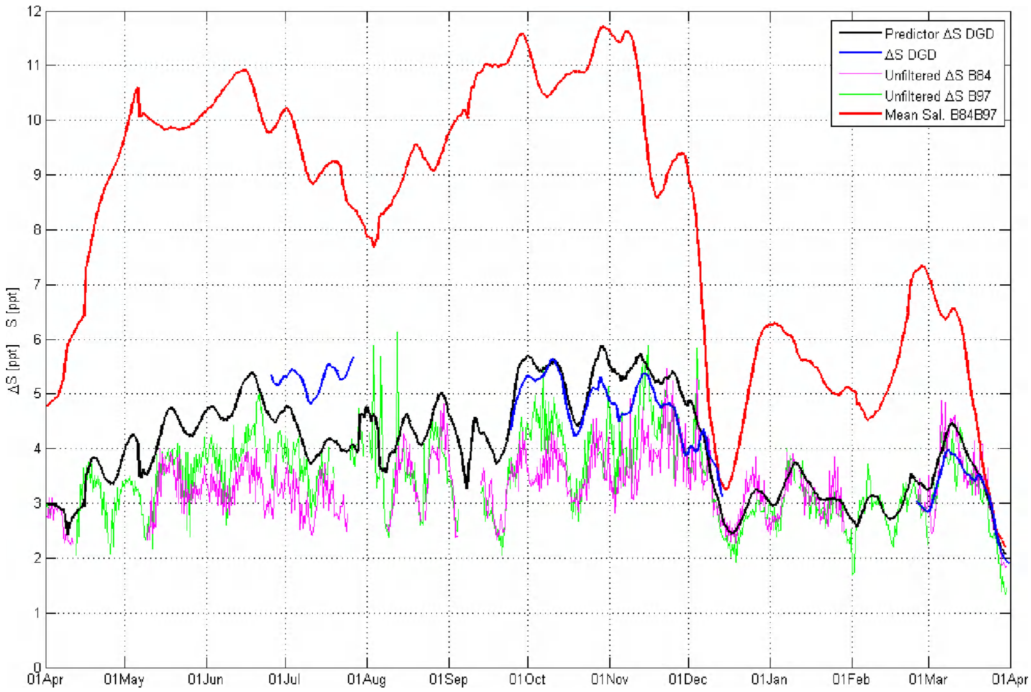


Figure 5-4: Measured salinity amplitude at DGD in blue and estimated salinity amplitude (yearround) in black using the amplification coefficient c_{ss} .Also shown is the unfiltered salinity amplitude at buoys 84 and 97 and the mean salinity in the estuary near the dock.

The normalised root-mean-square error (NRMSE) has been calculated to be 0.14 for this relationship and the error distribution is shown below. Although some difference between the estimated and measured salinity amplitude at the dock's entrance occurs the mean error is less than 15%.

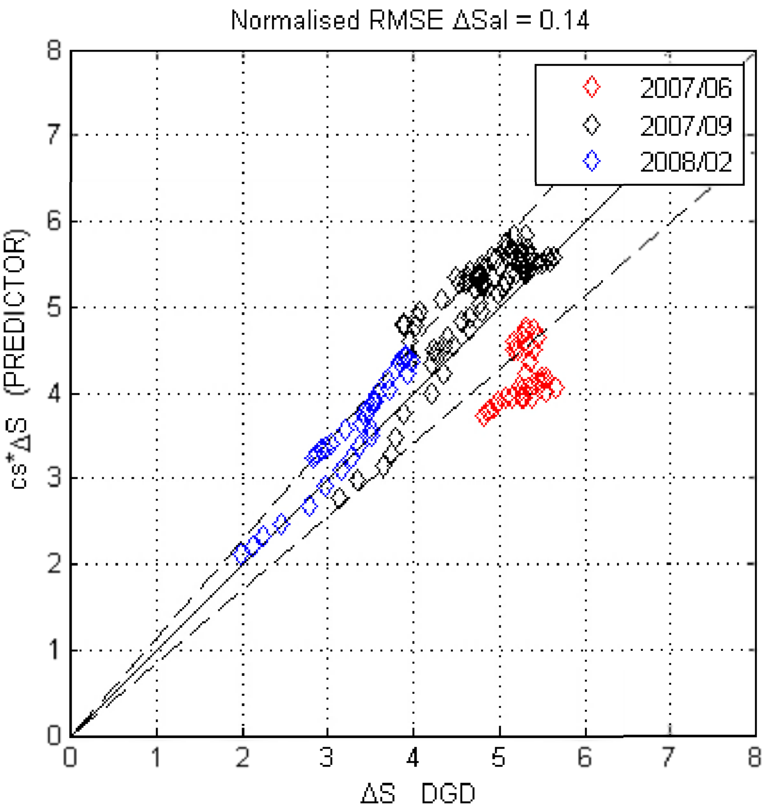


Figure 5-5: Calibrated model results for estimation of salinity amplitude (ppt) at DGD from long-term measurements at buoys 84 and 97.

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

5.3.2. Suspended Sediment Concentration

In this paragraph the following function will be established:

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

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

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

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

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

Equation 5-3:

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

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

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

Since gaps were present in the time series of salinity of the buoys, but at no instance data for both buoys was missing at the same time, a special interpolation has been applied. Otherwise too many linear interpolations in between the start and end points would distort the signal of the mean salinity of buoy 84 and buoy 97. This method is based on the running average of the ratio of filtered salinities at both buoys. In other words: a time series of the salinity at buoy 84 divided by the salinity at buoy 97 (between 1.1 and 1.25, since buoy 84 is closer to the estuary mouth). When buoy 97 data was missing it has been replaced with the salinity at buoy 84 multiplied by the ratio. Similarly, when buoy 84 salinity was missing it has been replaced by buoy 97 data divided by the ratio. The result is smooth curve for the average of salinity at both buoys with low pass filtering with a window of 7 days (Figure 5-6).

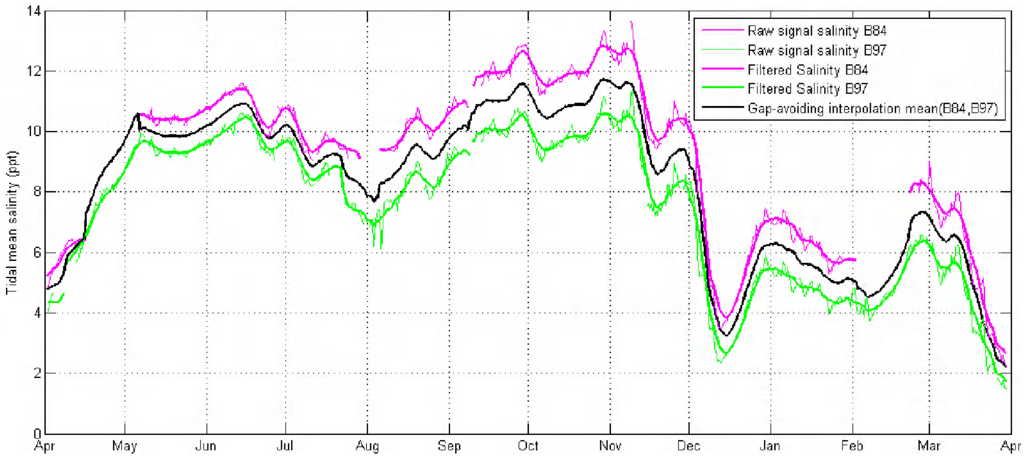
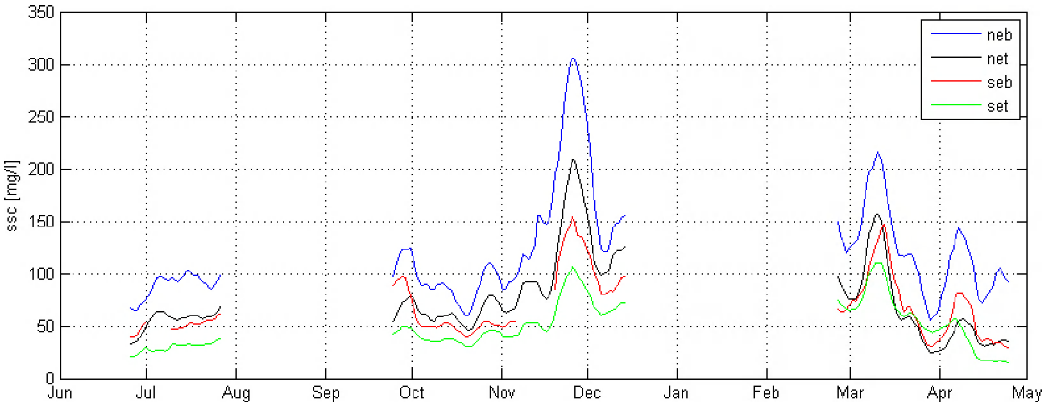


Figure 5-6: Gap-avoiding interpolation of salinity levels at the Scheldt estuary near Deurganckdok.

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

During the DGD1 analysis it was assumed that the ETM is around the position where the average salinity is about 3 ppt, any value less than 3 ppt indicates the ETM is slightly downstream, but not far. Any value higher means that the ETM is upstream, the higher the salinity the more upstream.

During the analysis of the DGD2 data this value needed adjusted. During the one year period between April 1st 2007 and March 31st 2008, two pronounced sediment concentration peaks have been observed at the dock's entrance as well as at the buoys: end of November and early March, which can be seen in Figure 5-7, but also in the extensive reports on the analysis of ambient conditions (IMDC 2008r). A secondary peak occurs in some data towards the end of August. Looking back at Figure 5-7 it can be seen that the peak in end November occurs about a week before the drastic decrease in salinity and that the second peak (early March) occurs a bit after the salinity levels reach temporary higher values near 7 ppt. This indicates that the ETM was moving towards the estuary mouth and passed Deurganckdok near the end of November, followed by the tip of the salt wedge. Then, the tip of the salt wedge arrived again near the dock somewhere in the last week of February, travelling towards the estuary head as indicated by the increasing salinity. About one week later the ETM passes as well.



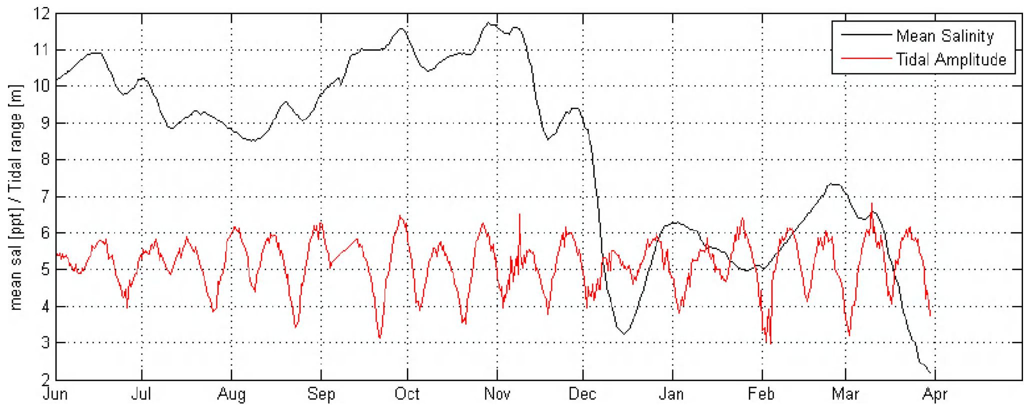


Figure 5-7: Comparison of salinity level, tidal amplitude and sediment concentrations at the four OBS equipments at entrance of the dock. n=North; s=South; e=entrance; t=top; b=bottom.

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

Equation 5-4:

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

Where $\overline{S}$ is the mean of the tidally averaged salinities at buoys 84 and 97, $\overline{S} = 0.5\left[\overline{S_{LT,B84}} + \overline{S_{LT,B97}}\right]$ and S_{tm} is the assumed salinity at the location of the turbidity maximum. This function has been chosen from four candidates for the best correlation with measurements (Figure 5-8) in the first measurement year and can be confirmed after evaluation with the measurements of the second year.

After the analysis of salinity and suspended sediment concentration levels described above it is clear that the ETM has been around the dock at least two times, although the mean salinity rarely dropped as low as 3 ppt (the salinity associated with the turbidity maximum in the DGD1 analysis).

Therefore it has been decided to adjust the S_{tm} value. With an optimization algorithm the best value for both the S_{tm} , a and b parameters has been determined based on the best RMSE performance after comparison with measurements of suspended sediment concentration at the dock's entrance.

Graphically the function looks as follows with a fixed value of b and variation of S_{tm} (left) and with a fixed value of S_{tm} and variation of b (right):

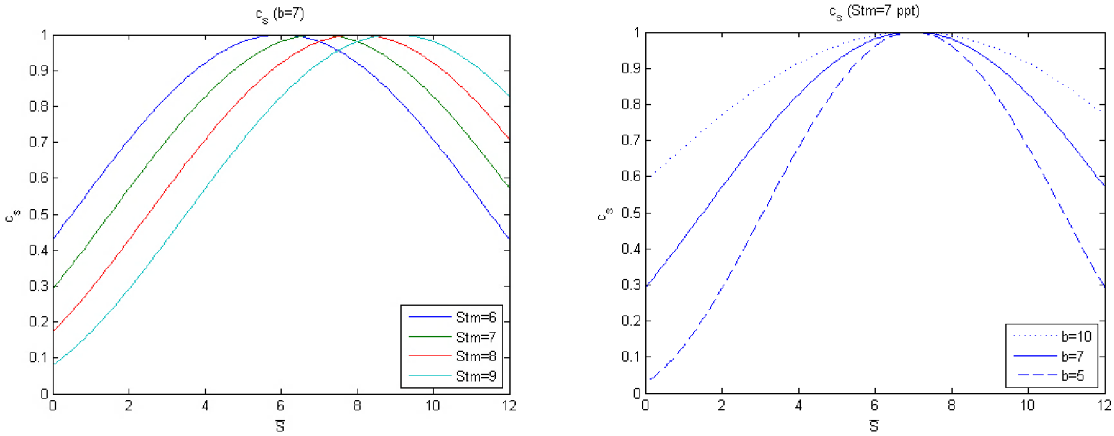


Figure 5-8: Possible functions for a coefficient representing the proximity of the turbidity maximum.

In order to make a qualitative assessment of the cosine square function for sediment concentration as function of the salinity, a new analysis has been done on the year-round data on buoy 84 and 97. For both locations the same pattern is found; on the low end and on the high end of the salinity range sediment concentrations tend to be lower than in the centre of the salinity range (Figure 5-9). For buoy 84 this maximum concentration sits at higher salinity (8 ppt - 10 ppt) compared to buoy 97 (6 ppt – 8 ppt). Buoy 84 is closer to the sea and thus the location of the ETM might be associated with higher salinity when it is moving closer to the estuary mouth than when it is located upstream. Moreover, since in each plot two disconnected peaks occur, the salinity associated with the ETM looks to be dependent on the direction in which the ETM and salt wedge are moving. Deurganckdok is situated in between both, hence S_{tm} should be in the range of the values above.

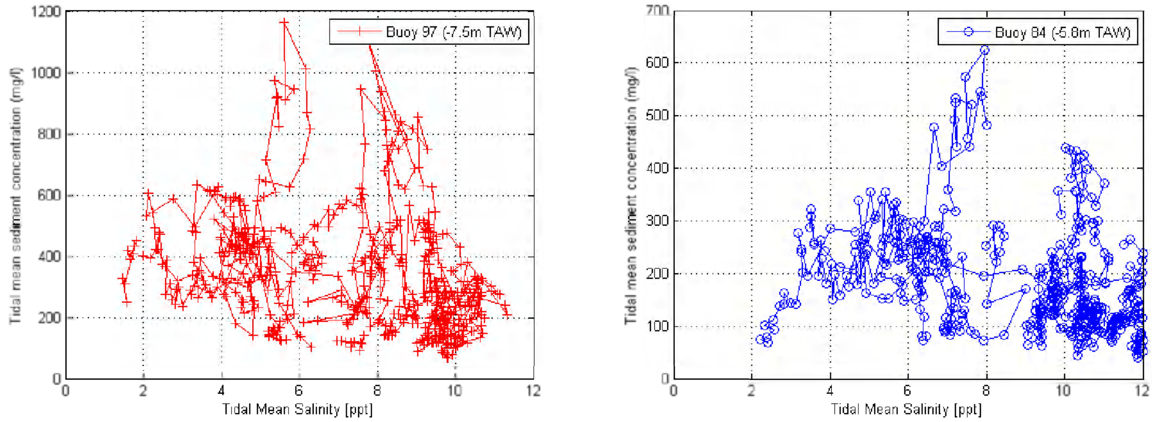


Figure 5-9: Analysis of the relation between salinity (measure of distance to turbidity maximum) and suspended sediment concentration at buoys 84 and 97

Finally the best result has been found for the values found in the table below.

Table 5-1: Optimized values for sediment estimator

Parameter	Value
S_{tm}	7 ppt
a	1.2
b	5 ppt

The multiplication of these two factors and the tuning of coefficients have lead to the relatively good prediction of the average suspended sediment concentration $\bar{c}$ near the entrance of Deurganckdok (Figure 5-10):

Equation 5-5:

$$\bar{c} = 100.c_t c_s$$

Measured series are more limited in time-span and are thus estimated with this technique. Gaps in the estimated series are avoided due to the special interpolation technique used for the salinity data at buoys 84 and 97. The estimated tidal average sediment concentration near the entrance of the dock is fairly well correlated with the measured data for the three measurements (Figure 5-10). The very pronounced peak end of November is not reproduced and might have been due to influences on the sediment distribution in the estuary other than the position of the ETM or tidal amplitude. When compared with other measurements in the estuary the overall trend is properly reproduced with low concentrations in June and October and peaks in April, early August, end November and early March.

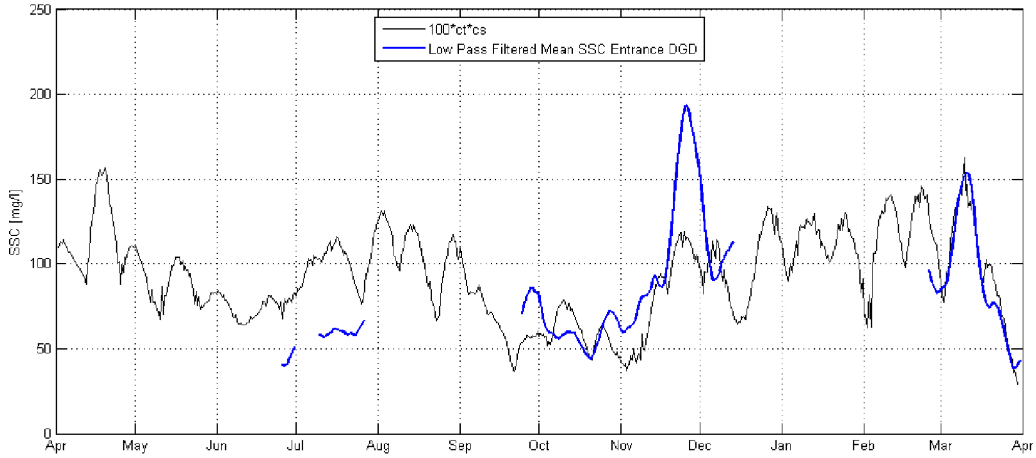


Figure 5-10: Low pass filtered suspended sediment concentration measured at DGD (blue) versus the estimated mean suspended sediment concentration year-round.

Here the model has an NRMSE of 0.18. Again, the higher and lower estimate will be the middle estimate multiplied by 1+NRMSE and 1-NRMSE respectively (Figure 5-11). It can be seen in this plot that the data in July is overestimated with about 40 mg/l.

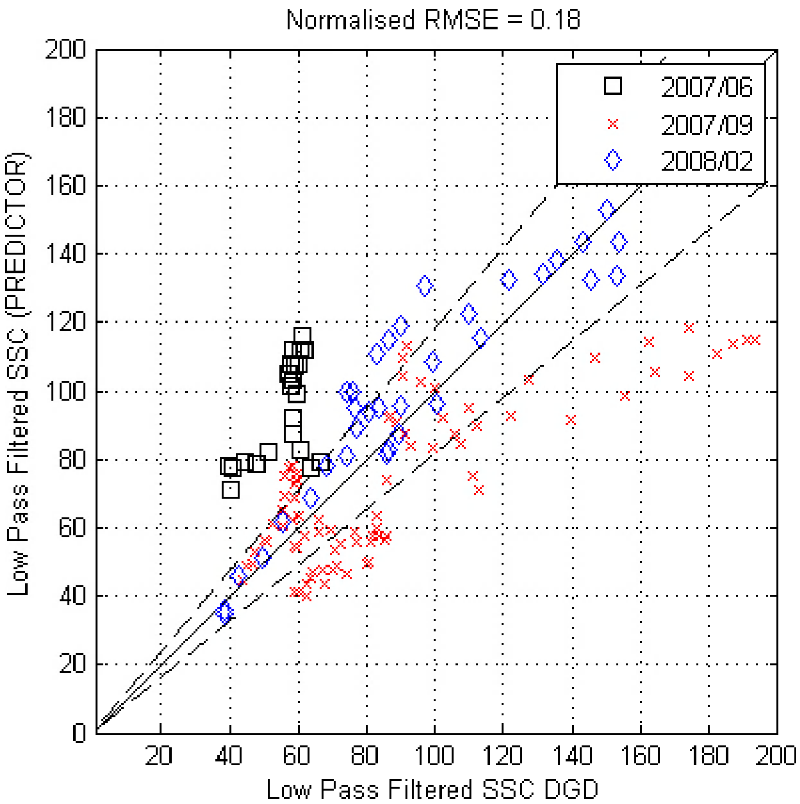


Figure 5-11: Performance of suspended sediment concentration predictor (mg/l).

5.4. Estimation of long term sedimentation

Since the momentum of currents in the dock is very limited the amount of sediment deposited in the dock will always be strongly dependent on the amount entering the dock, i.e. the fraction of suspended sediment entering and 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 5-6, the convention for velocity v being positive downstream or outbound the dock. The total flux can be decomposed into three components. (i) the flux due to the average velocity over the entrance section of the dock, meaning the tidal filling and emptying of the dock with a volume equal to its tidal prism (first term in Equation 5-7); (ii) the flux due to mixing effects induced by density currents, typically characterised by velocity stratification; (iii) flux generated by eddies along the entrance of the dock (horizontal entrainment).

Equation 5-6:

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

Equation 5-7:

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

$$= F_t + F_d + F_e$$

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

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

c is the suspended sediment concentration

T is the tidal cycle period

T_{dens} is the duration of density currents

T_{eddy} is the duration of eddy circulation

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

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

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

F_t is the tide induced sediment influx

F_d is the sediment influx due to density currents

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

5.4.1. Tidal Filling

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

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

Equation 5-8:

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

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

The constant c_1 in Equation 5-8 is a measure of the fraction of the sediment entering due to tidal filling remaining in the dock after settling. Since an extensive measurement campaign on sediment properties and settling has been carried out in the dock from 5 to 7th of September 2006 a good amount of information is present about the settling velocity, floc size and settling fluxes near the bottom (IMDC, 2006g). Floc size and floc settling velocity spectra were measured using the INSSEV equipment. Floc settling velocity has been found in the range of 0.5 to 1.5 mm/s for microflocs and of 2 to over 5 mm/s for macroflocs. Concerning residence time of a floc in the dock –only taking into 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 sediments suspended in water entering the dock due to tidal filling must be settled out almost completely. The fraction c_1 has been taken at 0.9.

5.4.2. Density Currents

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

The integral could be approximated by a function of average sediment concentration (available by estimate) and the intensity of the density currents / eddies, the latter being unavailable throughout the whole year. Therefore it will be assumed that the salinity amplitude at the dock's entrance is a measure for the intensity of the density current, as it is the driving force for exchange between high and low density volumes resulting in stratified current profiles. The tidal amplitude is a measure for flood and ebb velocities in the Scheldt River; in turn inducing shear along the open entrance to the dock, resulting in large eddies at the entrance. The vorticity of the eddy has an opposite sign during flood compared to during ebb (vorticity is calculated as the rotor of the velocity field, its sign determined with the 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 5-12). The fraction of the sediment in the inflowing water that is settled out and deposited in the dock multiplied by the exchanged liquid discharge times the average sediment concentration is a measure for the net sediment influx due to density currents. The average sediment concentration is available through estimate, the average exchanged liquid discharge is proportional to the salinity amplitude, but the fraction of sediment settled out is unknown.

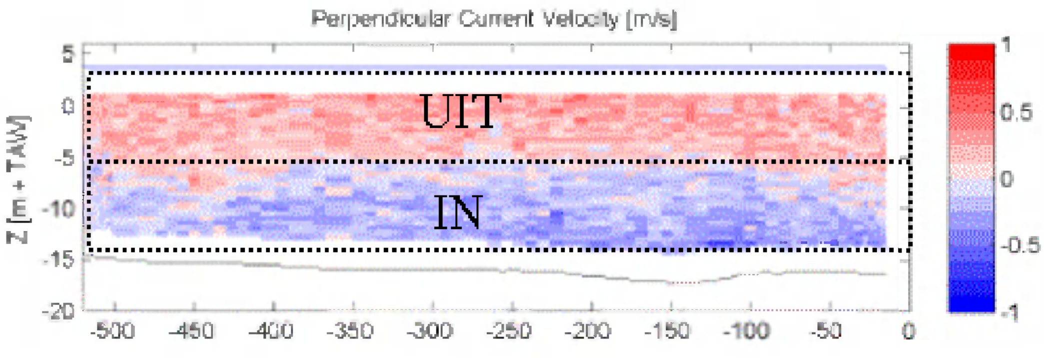


Figure 5-12: Example of density current at high water, denser, more saline water flows in the dock (v<0) in the lower half of the water column and fresher water flows out in the upper half. Schematisation in black.

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 5-12), 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.

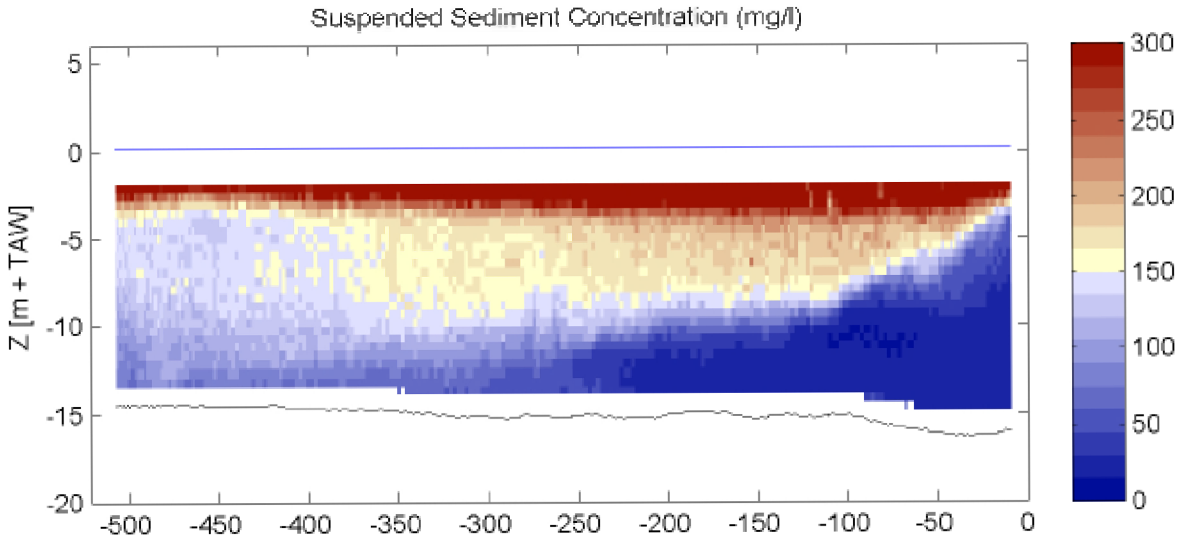


Figure 5-13: inverse sediment concentration profile during low water density current.

The relative difference of vertical gradient between the high tide case (Figure 5-12) and the low water case can be taken as a measure for the unknown settled fraction during a tidal cycle (Equation 5-9). In the case of Deurganckdok density currents have been found to have a higher vertical sediment concentration gradient during the high water case -when estuarine water flows in the dock near the bottom- compared to the low water situation –when water from the 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 5-13). 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 (2 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 5-9:

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

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

Equation 5-10:

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

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 this 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 5-14). 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 balls). This value varies between 0 and 0.6 and will be used in the calculations with a constant value (average) of 0.3. The use of the constant average value is chosen for this analysis but could be improved in a later stage by trying to find a relationship with ambient conditions like tidal coefficient since there seems to be a relation between alpha and the tidal amplitude.

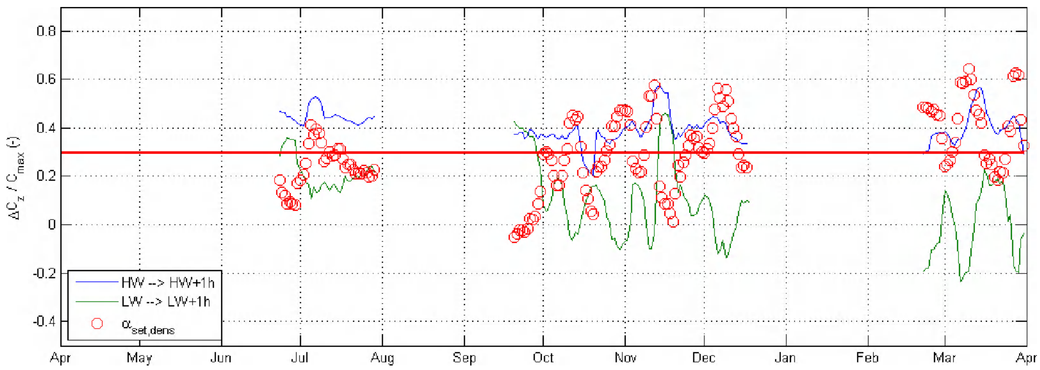


Figure 5-14: Net imported fraction at high water density current and net exported fraction during low water density current. The overall imported fraction over one tide is difference between both.

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 5-11:

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

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

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 5-12:

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

where: 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.

Coefficient c_2 is dimensionless and has been used to calibrate the suspended sediment flux against available observations from through-tide measurements. From Equation 5-11 its values should be close to 0.5, here it has been set to 0.55 after comparison of estimated density current in Equation 5-12 and observed density current magnitude during through-tide measurements with ADCP equipment.

Additionally, the effect of tidal filling and emptying on the density current should be taken into account. In Figure 5-15 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.

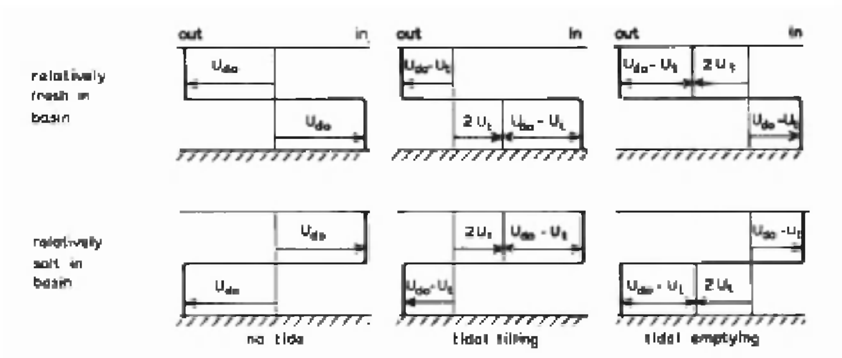


Figure 5-15: Influence of tidal filling and emptying on a density current (Eysink, 1983). Where U_{do} is the exchange velocity without influence of tidal in- and outflow, U_t is the flow velocity related with tidal prism.

An estimate of 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 saline water wave from the back of the dock. The effect of this reflection can be damping or limitation in time period of the density current (Van Maren et al, 2009).

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 mid December and 0.45 m/s in June and November (Figure 5-16).

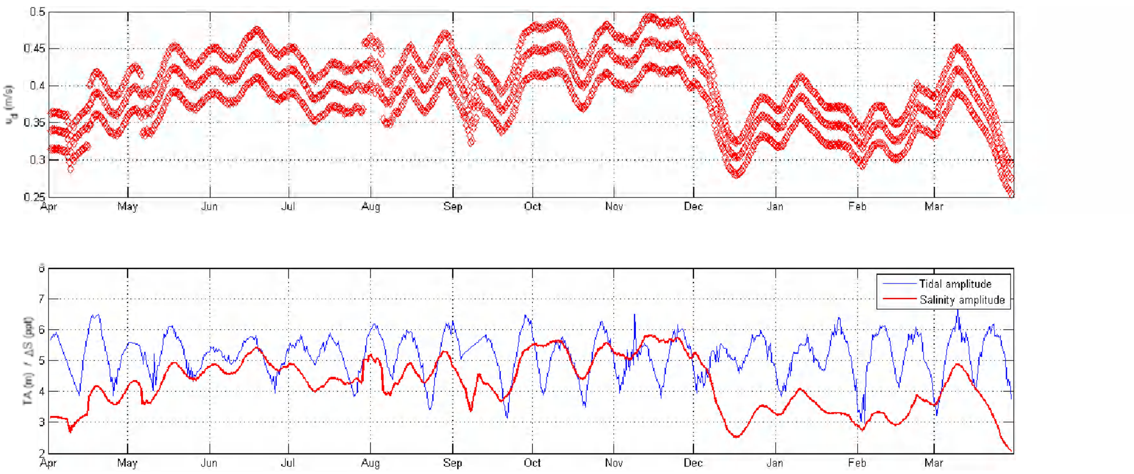


Figure 5-16: Calculated velocity related to density differences, with low, mid and high estimate (top) and the influence factors: salinity amplitude and tidal range (bottom).

5.4.3. Large Horizontal Eddy

A similar approach could be adopted for schematisation and estimation of the effect of large horizontal eddy formation and related turbulent exchange along the entrance on sediment influx. During flood current in the Scheldt River shear induces clockwise eddy circulation (Figure 5-17), during ebb current anti-clockwise. A consideration should be made about the difference in flood velocity and ebb velocity.

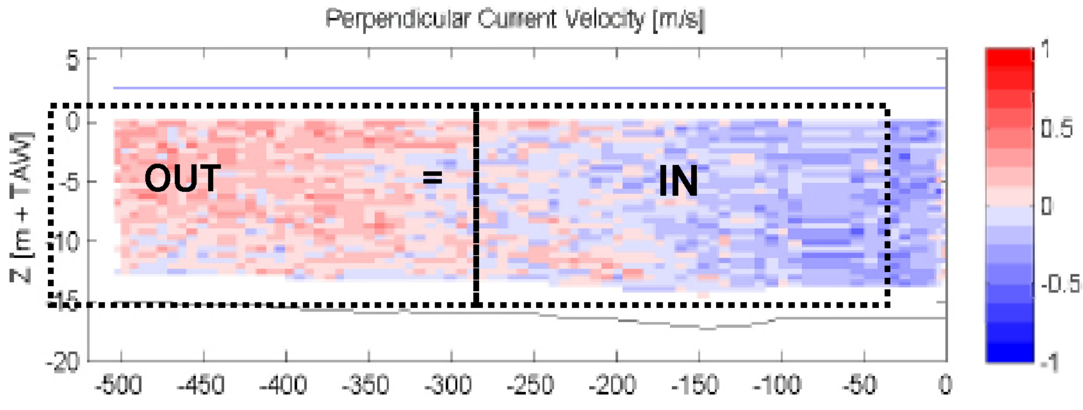


Figure 5-17: Example of eddy circulation flow at the entrance of the dock during flood: at the inland end water flows in (v<0) at the seaward end water flows out, view towards the Scheldt. Schematisation in black.

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

Information from measurements useful for an approximation of this fraction is the suspended sediment concentration gradient along the entrance measured during three campaigns, again, it is impossible to calculate for periods in between measurement campaign at DGD based on long term measurements at buoys 84 and 97. Therefore an approximation is based on the relative gradients during ebb and during flood. Considering the gradient is calculated as the concentration at the left quay (North-Entrance), minus the concentration at the right quay (South-Entrance) divided by the distance and the rotational direction of the eddy (flood: clockwise, ebb: anti-clockwise) the following is true, temporally provided ebb and flood velocities are equal (Table 5-2):

Table 5-2: 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	NEGATIVE
Ebb	Anti-clockwise	positive	LW-3h to LW = 3 hours	POSITIVE

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. The reason we consider only positive gradients in the example is that in most cases the gradient remains positive throughout the tidal cycle.

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. 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 5-13).

The coefficient representing the fraction of circulated sediment remaining in the dock is calculated as follows:

Equation 5-13:

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

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 5-14:

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

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 5-18). It is clear that the horizontal gradient is predominantly positive, and higher during ebb than during flood.

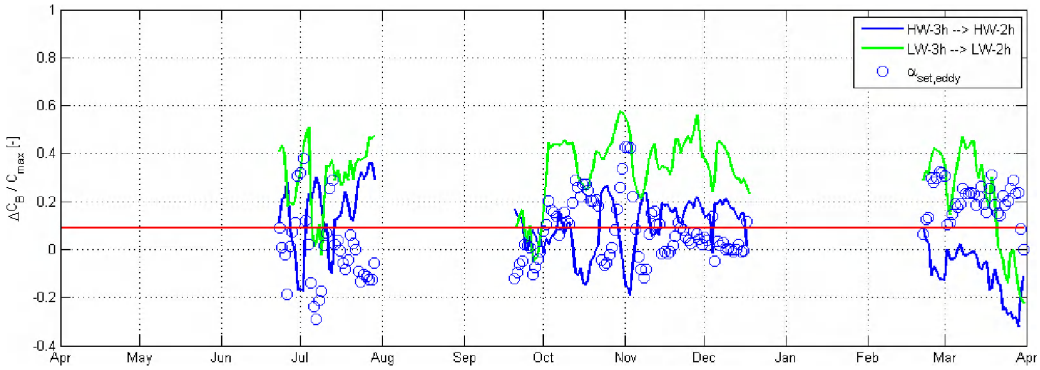


Figure 5-18: Relative sediment gradients along the entrance of the dock.

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.

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 5-15:

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

where: 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 (0.1), $\overline{c(t)}$ 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 turbulent exchange Equation 5-15 becomes:

Equation 5-16:

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

Where β is dimensionless and equal to 0.05.

5.4.4. Overall net sediment inflow per tidal cycle

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

Table 5-3: Value of coefficient representing settled fraction

parameter	Value [-]
$\alpha_{set,dens}$	0.3
$\alpha_{set,eddy}$	0.1

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

The total net influx of suspended sediment into DGD is calculated as the sum of influx due to tidal prism (F_t), the influx due to density currents (F_d) and the flux due to eddy circulation currents, F_e. 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 400 to 1000 Tons Dry Matter (TDS) per tide followed by tidal prism exchange (200-400 TDS per tide) and horizontal eddy circulation (20-120 TDS per tide).

After executing all required calculations sediment fluxes are in the range of 500 to 2500 TDS per tide have been obtained (Figure 5-20). Since large uncertainties remain in the estimates a low and high estimate have been calculated leading to an uncertainty interval around the calculated flux values.

The variation in net sediment inflow is relatively limited throughout the year, with a slight decrease during the summer. The reason is that for example during winter the sediment concentration is higher (Figure 5-10) while the salinity amplitude is lower (Figure 5-4) due to the higher river runoff. Both effects partially single out each other. The highest sedimentation rates are found mid March 2008 during extreme spring tide conditions combined with storm and as a consequence high salinity amplitude and sediment concentrations. The cumulative natural siltation is shown in Figure 5-21. 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.

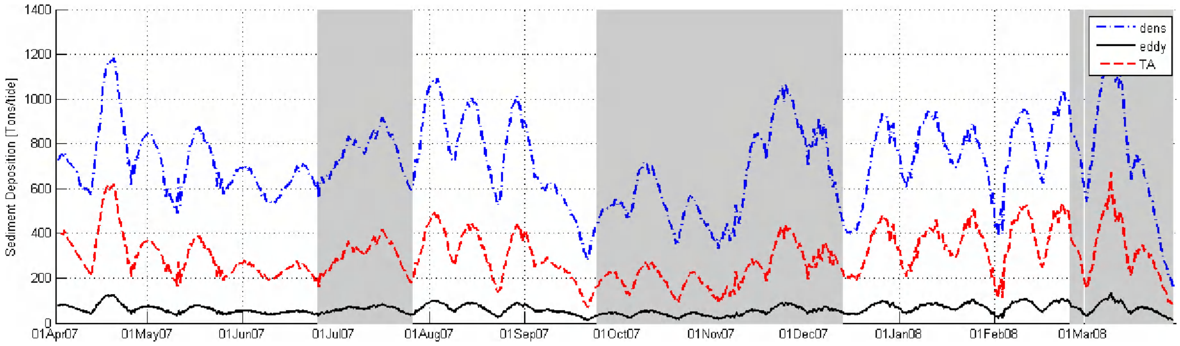


Figure 5-19: Sediment influx due to density currents, eddy circulation and tidal amplitude (tidal prism).

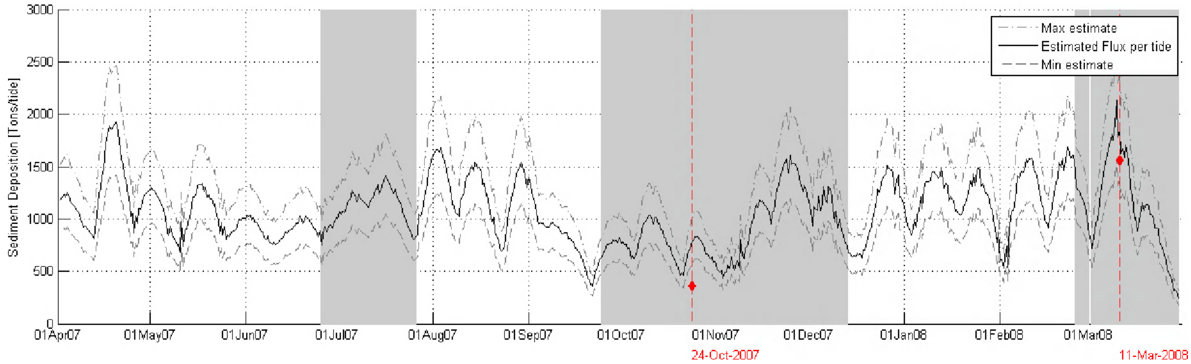


Figure 5-20: Time series of estimated sediment influx (with uncertainty interval), grey zones indicate periods of measurement in DGD, red dots indicate through-tide measurements of which the observed suspended sediment influx is available.

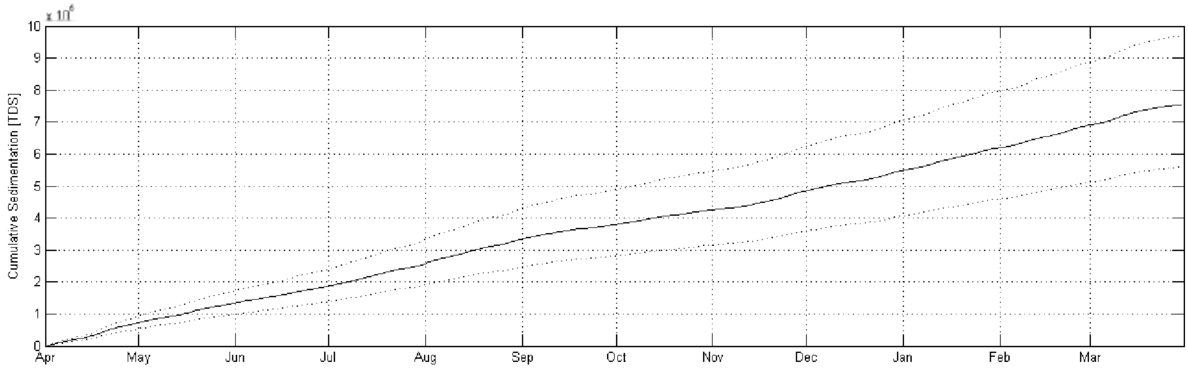


Figure 5-21: Cumulative natural sedimentation in black (x100,000 TDS) with zero at April 1st 2007, uncertainty band in grey. Average sedimentation rate varies with seasons, lowest rates in September and October.

After calculation of an estimate for each tide from 1st of April 2007 to 31st of March 2008 the time integral has been calculated (Table 5-4). The main estimate shows a value of 753,000 tons dry matter net inflow of suspended sediments in 12 months. The uncertainty on these values should be taken as high as 30-40% according to the low and high estimates.

In the table influx values for the three main contributing components of sedimentation have been listed separately. However, these phenomena do not always exist independently and interact during many tidal phases. By consequence these values are not to be evaluated individually either.

Table 5-4: Yearly suspended sediment influx estimate Deurganckdok (x1000 TDS)

	Low estimate	Mid estimate	High estimate
Tidal prism influx	170	**209**	249
Density current influx	377	**502**	638
Eddy circulation influx	12	**42**	82
Total sediment influx	559	**753**	970

The lower sediment influx due to the large eddy at the entrance is the main difference with previous 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 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. 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.

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

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

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

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

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

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

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

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

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

$$\overline{c(t)} = 100.\left[\frac{h(t)}{\bar{h}}\right].\left[a\cos^2\left(\frac{\overline{S(t)} - S_{TM}}{b}\right)\right]$$

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

$$\Delta S(t) = \frac{1}{2}\left[1 + 1.00029\overline{S_f(t)}^3\right]\left[\Delta S_{f,B84}(t) + \Delta S_{f,B97}(t)\right]$$

$$\overline{S(t)} = 0.5\left[\overline{S_{f,B84}} + \overline{S_{f,B97}}\right]$$

With:

$c_1 = 0.9$

$c_2 = 0.55$

$A_h = 1500x450m^2 = 6.75e5m^2$

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

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

$T_{eddy} = 6.3600s = 2.16e4s$

$\alpha_{set,dens} = 0.3$

$\alpha_{set,eddy} = 0.1$

$v_{eddy} = [1\ 2\ 3].0.05m/s$ (Low-mid-high estimate)

$\beta = 0.05$

$\rho = 1010kg/m^3$

$S_{Tm} = 7ppt$

$a = 1.2$

$b = 5ppt$

Time indication t is an index and not a continuous time since t indicates the discrete times of each tidal cycle. The subscript ‘f’ indicates that the data has been filtered with a low pass filter with window 7 days.

5.5. Comparison with dredging

Additionnally, the results have been compared to dredged sediment mass in the same period. From BIS data obtained from Afdeling Maritieme Toegang the sediment mass in TDS has been calculated for every week between April 1st 2007 and March 31st 2008. When the sediment mass present in the dock at April 1st is set to zero the evolution of the cumulative natural inflow of sediments per tide has been has been deduced with the mass of sediments removed by dredging (Figure 5-22).

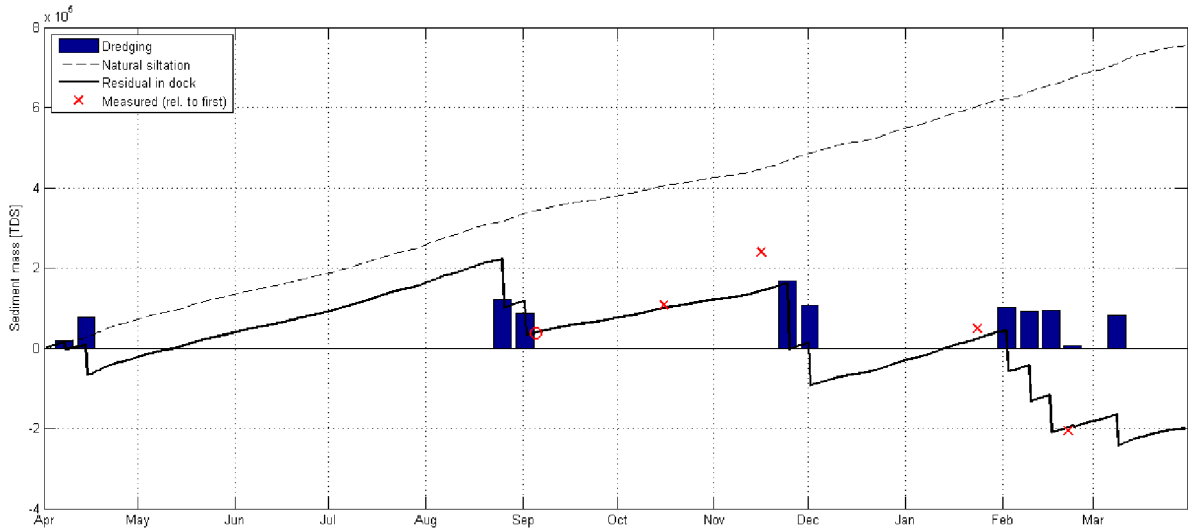


Figure 5-22: Dredged mass (TDS) per week, cumulative calculated inflow of sediments and residual sediments in the dock. Sediment mass present in the dock at April 1st is the reference and is set to zero. Red markers indicate the sediment mass measured by bed density profiling. The red circle is the first measurement in the DGD2 period is used as reference the four following measurements (red crosses).

A total of 954,000 TDS has been dredged from the dock in the DGD2 measurement year (IMDC2008e). That means the mass of sediment inflow calculated above is 201,000 TDS lower than the dredged mass. The results from the density profiling suggest that the actual mass in the bed of the dock near the end of February was 20% lower (-0.25 TDS/m²) compared to early September, which is in reasonable agreement with the results of the model applied for this study.

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 it possible to determined whether it is significant or not.

5.6. Comparison with measured mass balance

During the second year of the project a series of area covering density profiling campaigns have been executed (IMDC2007r,s & 2008c,d,e). Integration of the density profiles over the bed thickness leads to a mass in the bed per unit of area. Interpolation 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 5 kg/m²/day. When this value is converted to the complete dock area, a value is obtained of 1200-3000 TDS per day or 620-1550 TDS per tide. These values are in good agreement with the results obtained with the empirical model above.

Table 5-5: 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.

	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

In Table 5-5 the area weighted average sediment mass per unit of area has been calculated for each of the measurement campaigns. 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. Since deviations are possible due to differences in coverage between measurement campaigns, a sixth campaign on December 5th has not been taken into account since only the central trench was covered. 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 5-22 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 2007) 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 February 22nd 2008 could be compared to the measured mass (determined by bed density profiling).

Three out of the four remaining datasets show a consistent residual sediment mass calculated by the model and one period (mid October to mid November) shows a higher mass growth in the measurements than in the calculations. Again, a complete set of measurement campaigns executed over the completely finished dock will become available in the third measurement campaign (DGD3) and will give the possibility for verification of the model.

6. CONCLUSIONS AND RECOMMENDATIONS

The annual sediment influx in Deurganckdok has been estimated after synthesis of extensive measurement campaigns at short, mid and long term durations. Extensive use of the available data has led to an estimated inflow of sediments due to natural phenomena of 753,000 TDS in twelve months between 1st of April 2007 and 31st of March 2008. An uncertainty of 30 to 40% should be taken into account due to interpolations and linearization of interactions between different flow and exchange phenomena. Sedimentation rates per tide range 400-800 TDS for neap tides and 700-2000 TDS for spring tides.

Numerical modelling efforts in the past have shown results of similar magnitude with sedimentation rates at 1200 TDS per neap tide and 1700 TDS per spring tide (IMDC, 1998; Fettweiss et al., 1999). New modelling efforts with highly detailed 3D models being carried out by Van Maren (2006) show results of 700 to 1500 TDS per tide. 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 360 to 1500 TDS per tide.

When the obtained estimate (753,000 TDS) is compared to the balance of the dredged mass of about 954,000 TDS in the same period and the reduced amount of sediments present in the dock (measured, -20%) at the end of the year they are in good agreement.

The new data available in measurement year 2 (DGD2) has proven the semi-analytical model can provide accurate results in terms of mass sedimentation rates per tidal cycle and per year. Furthermore, the seasonal variation in sedimentation is revealed. Some of the methods for calculation were slightly modified. The main difference with analyses of the first year DGD1 is that the direct influence of an eddy on the siltation is rather limited, about 6%. Tidal prism and density currents account for 27% and 67% respectively.

Therefore, it is important for an analysis of year DGD3 that data acquisitions at both buoy 84 and buoy 97 are to be continued, resumed or replaced by nearby measurements. These data sets - combined with simultaneous measurements in the dock– will then allow further tuning and uncertainty reduction of the present model.

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IMDC (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.

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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), in opdracht van AWZ.

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, in opdracht van AWZ.

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 (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), in opdracht van AWZ.

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), in opdracht van AWZ.

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), in opdracht van AWZ.

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), in opdracht van AWZ.

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), in opdracht van AWZ.

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), in opdracht van AWZ.

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 (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), in opdracht van AWZ.

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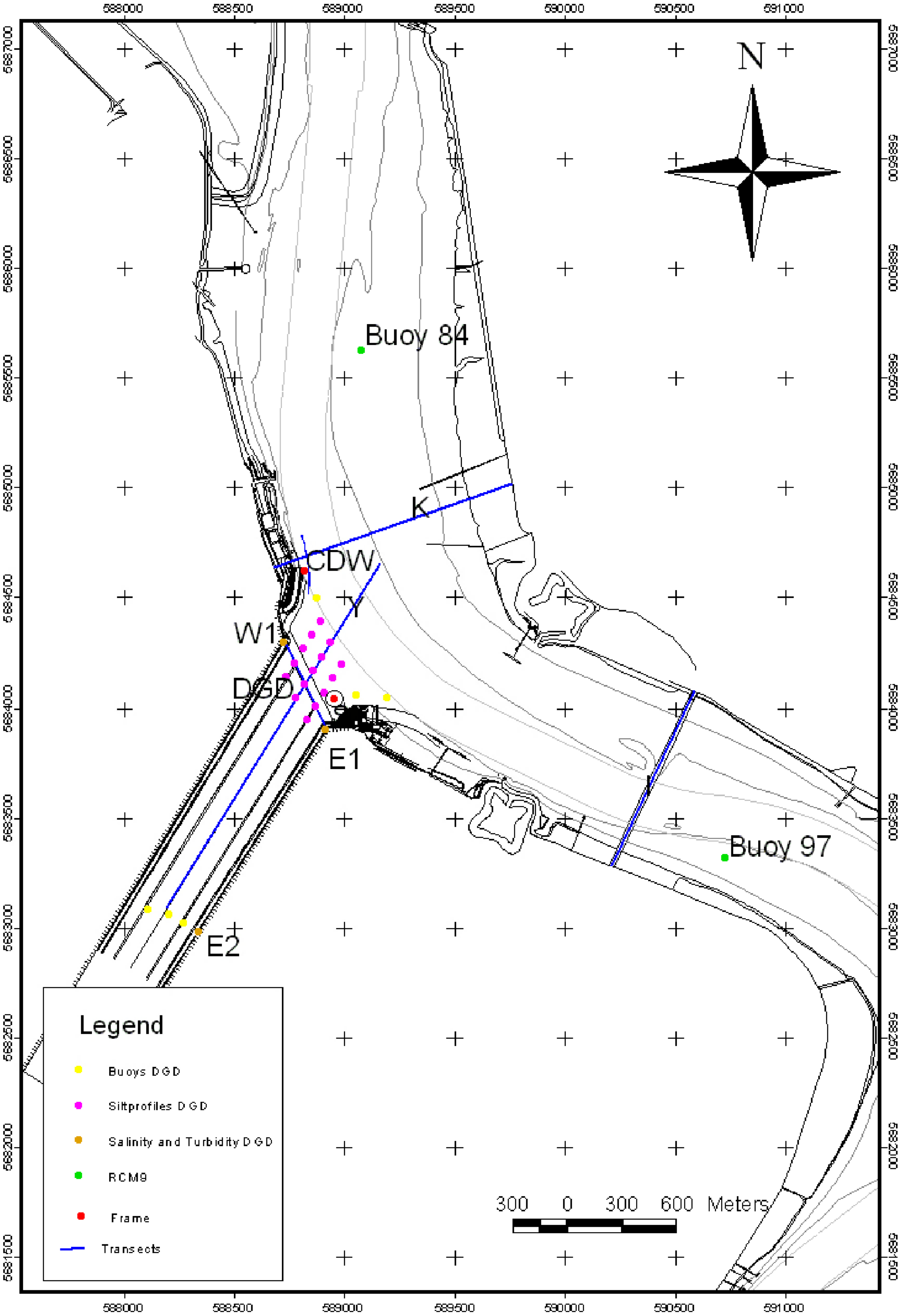
APPENDIX A. LOCATION IN SITU MEASUREMENT SITES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N
Buoy 84
K
CDW
Y
W1
DGD
E1
E2
Buoy 97
Legend
Buoys DGD
Siltprofiles DGD
Salinity and Turbidity DGD
RCM9
Frame
Transects
300 0 300 600 Meters

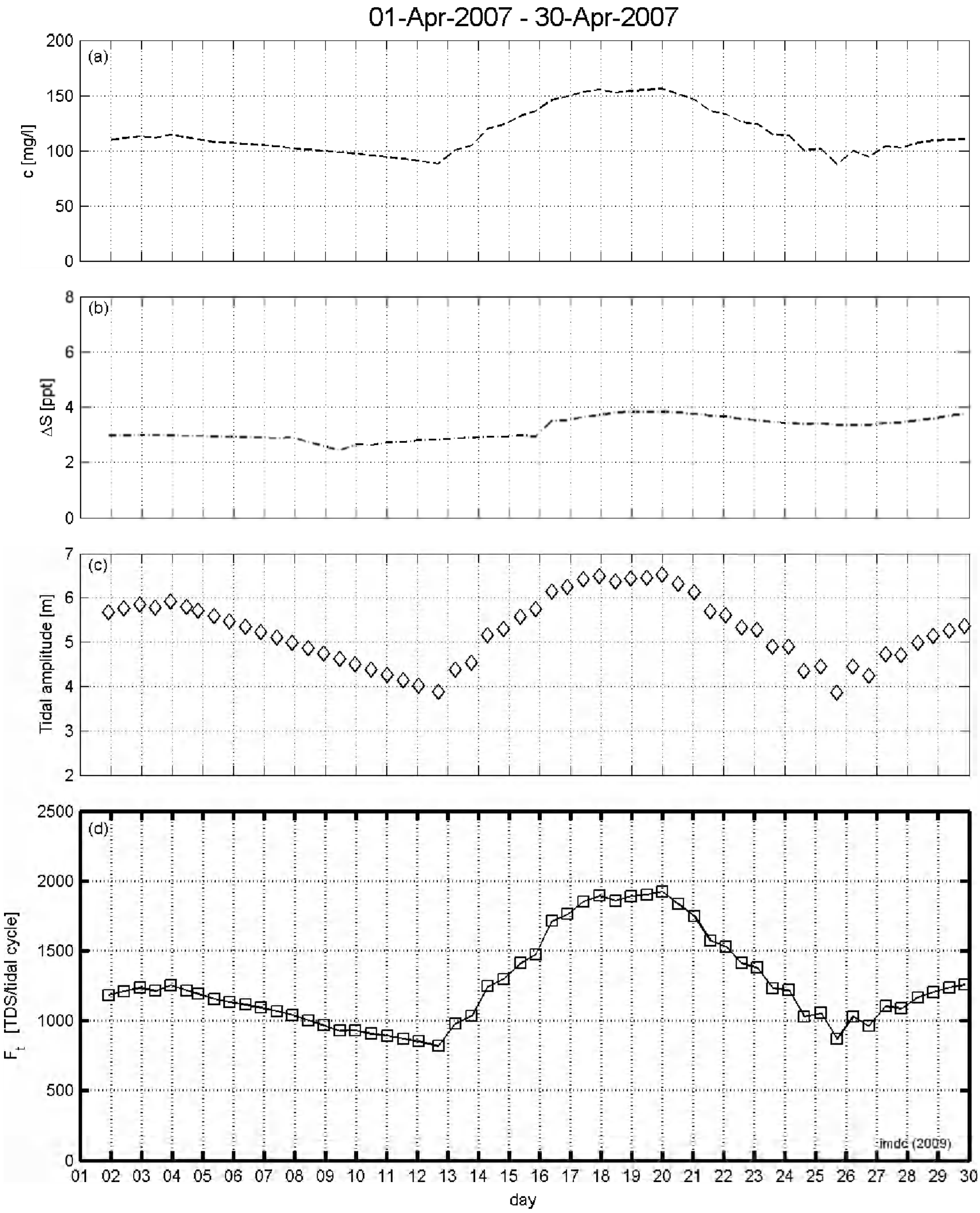
APPENDIX B. SILTATION RATES PER MONTH

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).

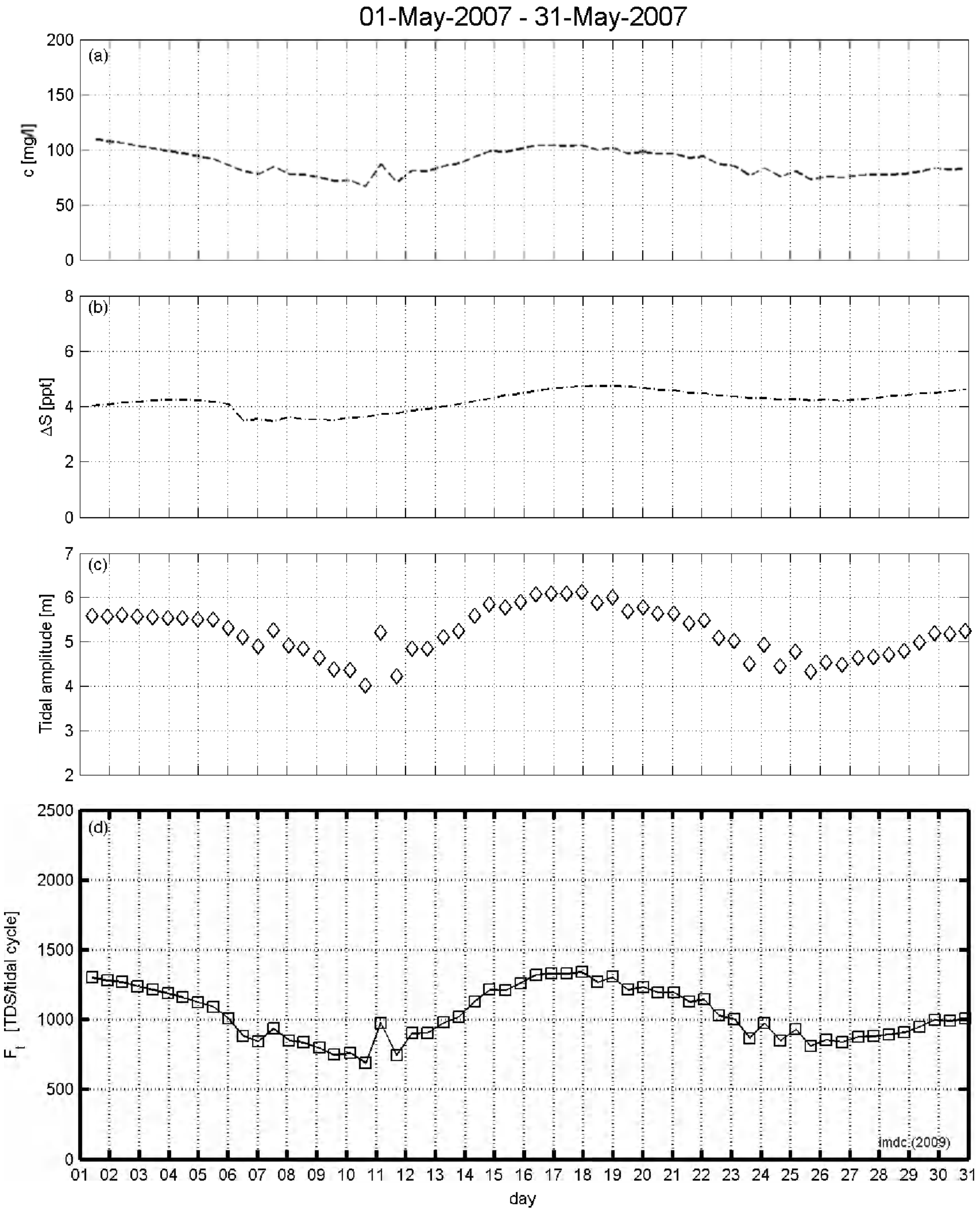
I/RA/11283/07.102/MSA

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).

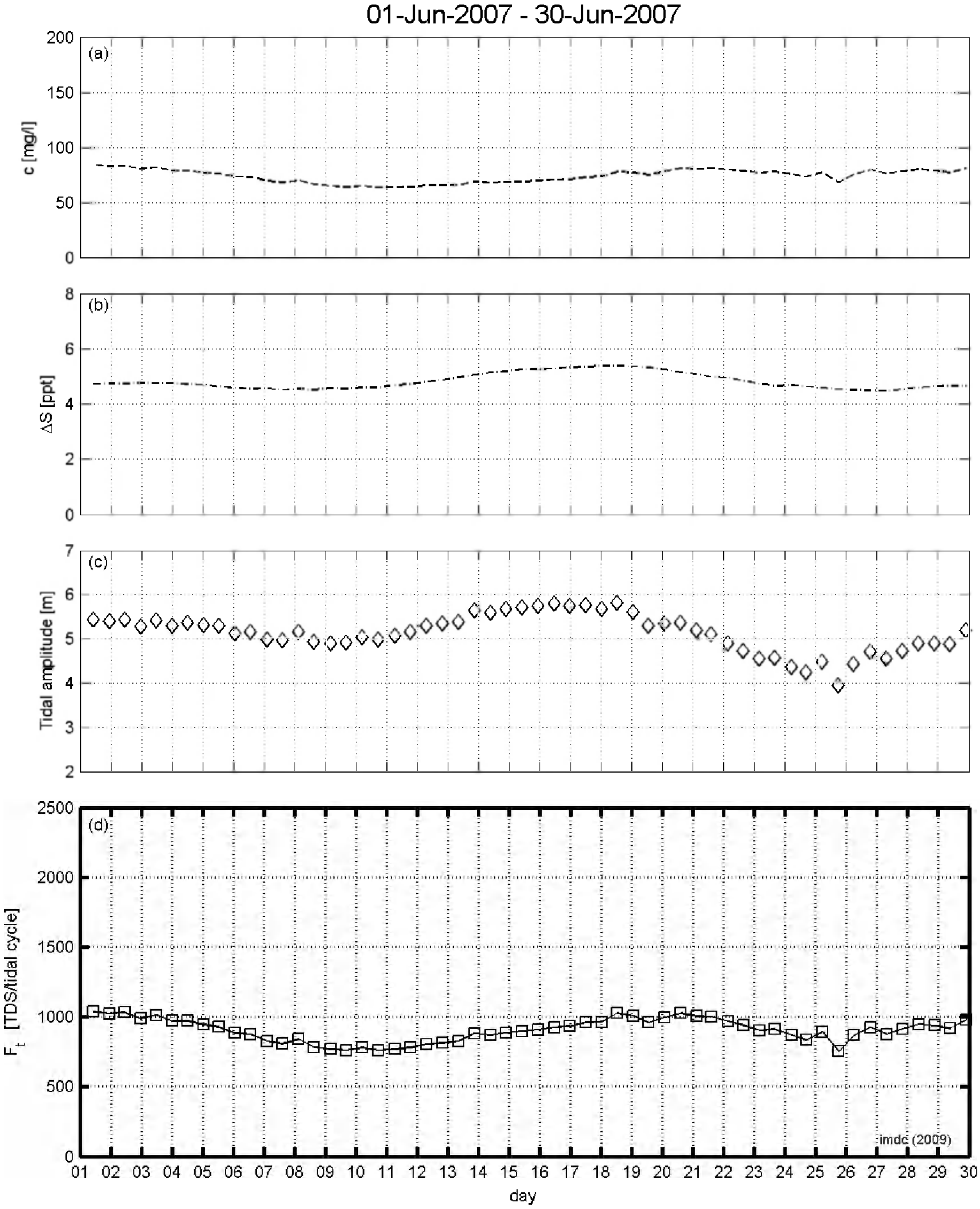
I/RA/11283/07.102/MSA

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).

I/RA/11283/07.102/MSA

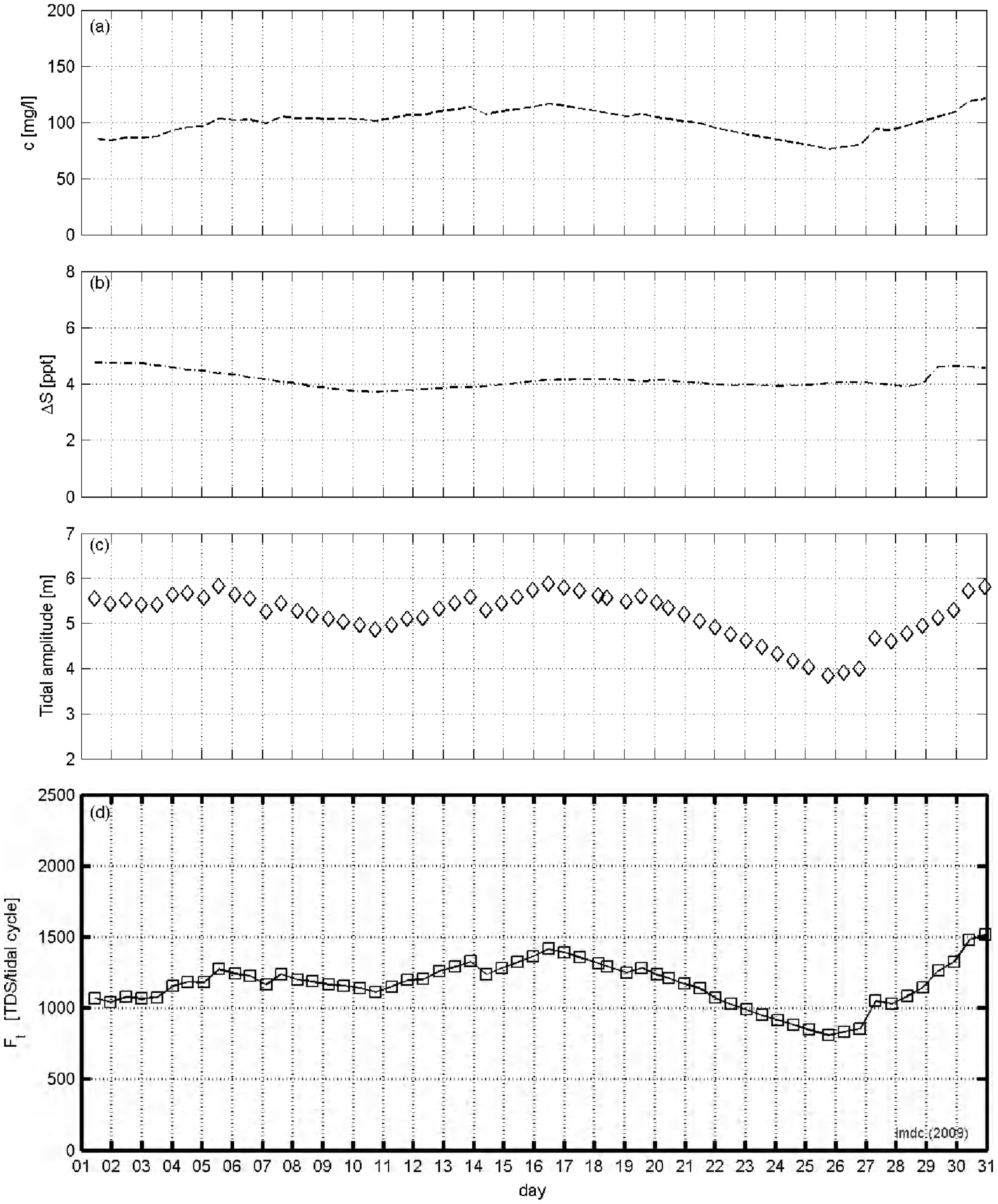
Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok

01-Jul-2007 - 31-Jul-2007



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

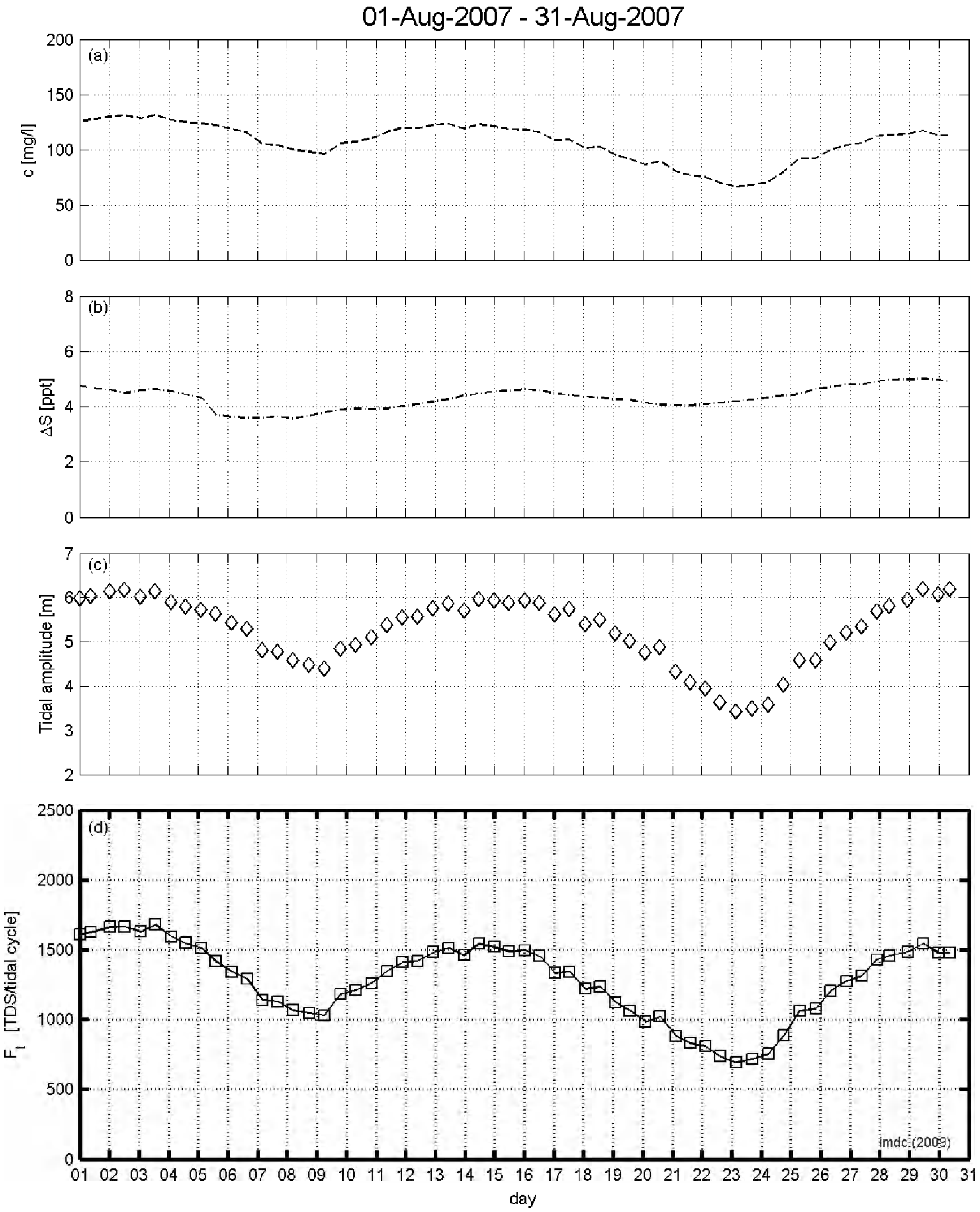
I/RA/11283/07.102/MSA

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).

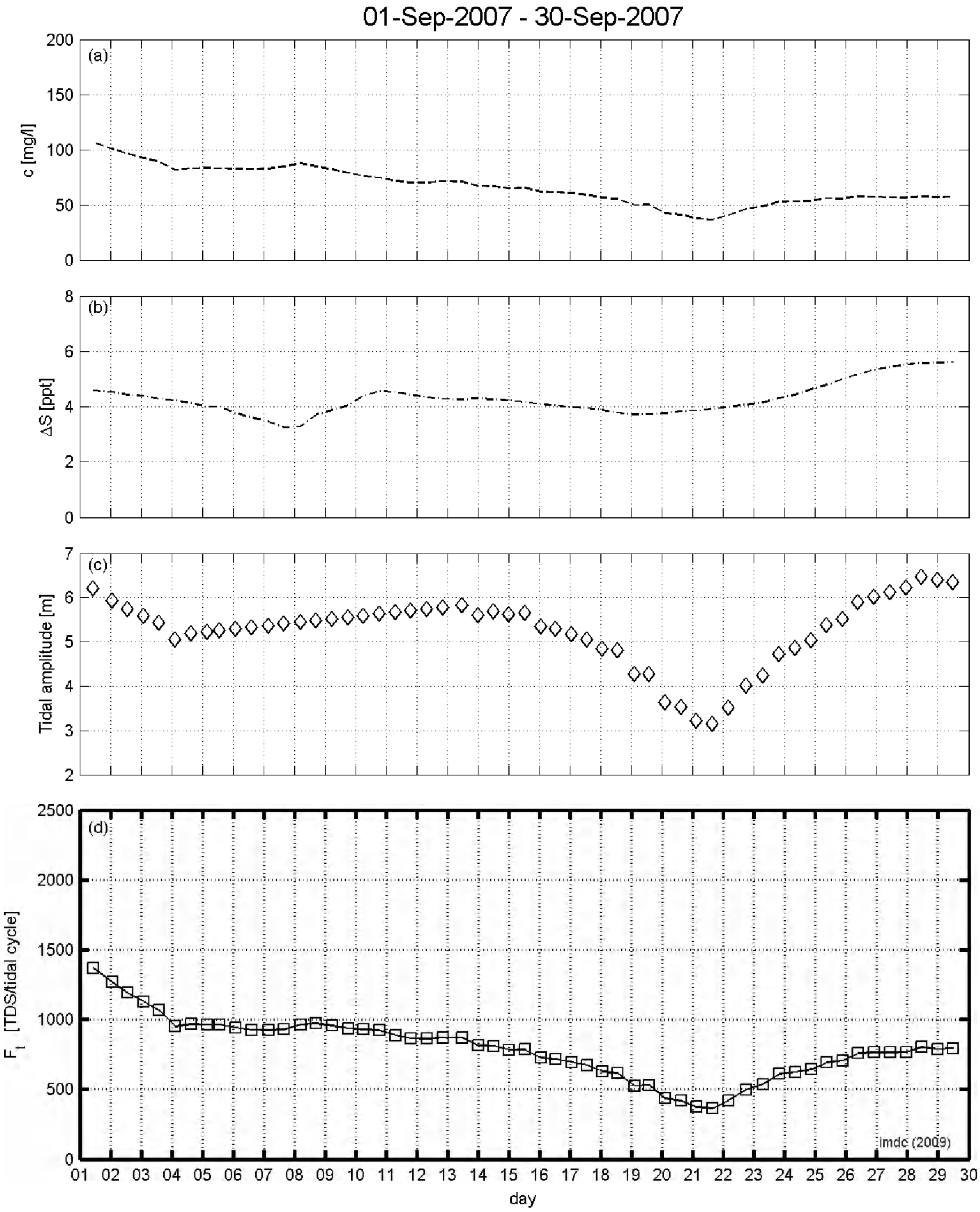
I/RA/11283/07.102/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok

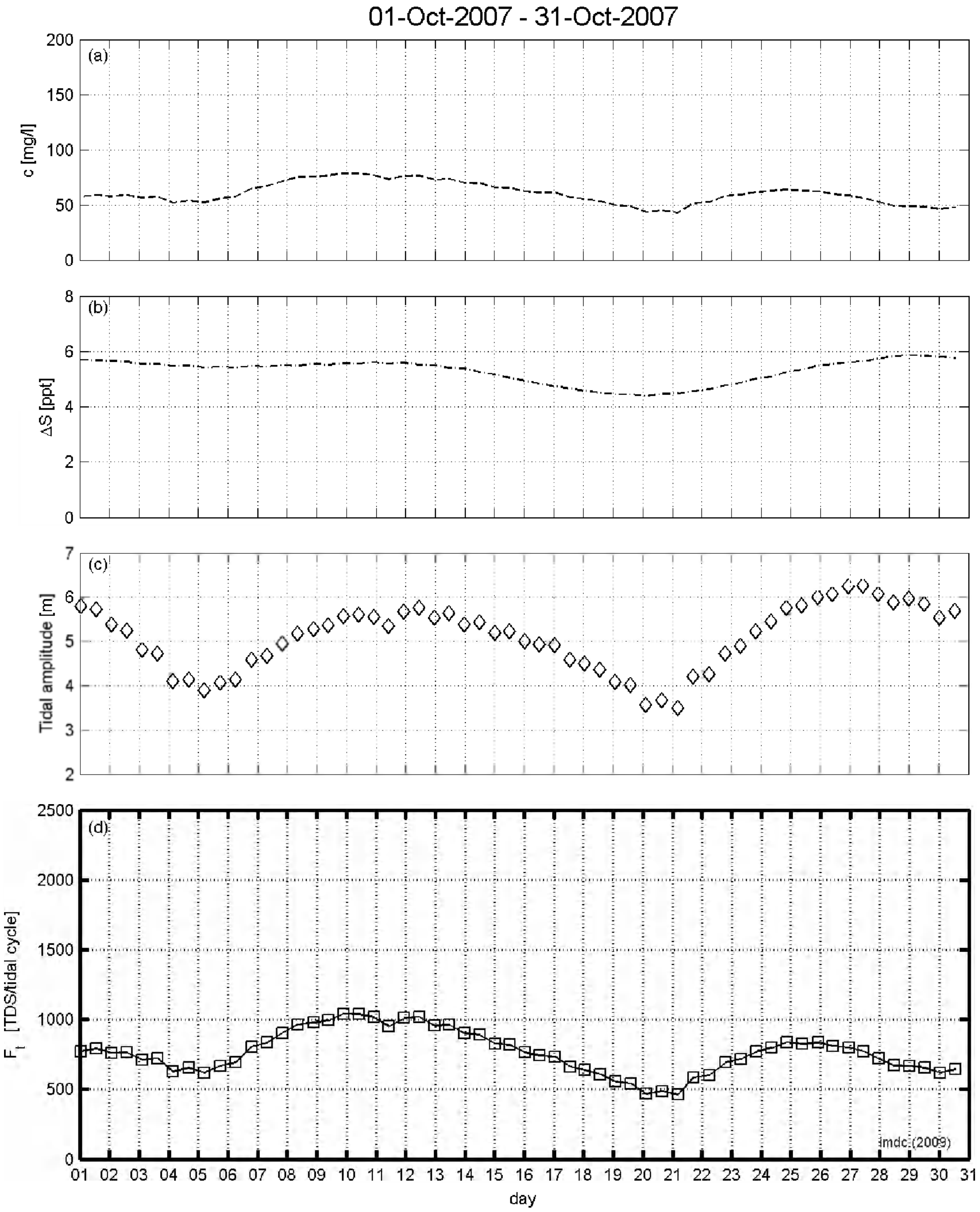


Suspended sediment concentration (a), salinity amplitude (b), tidal range (c) and estimated sediment influx per tidal cycle (d).

I/RA/11283/07.102/MSA

Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

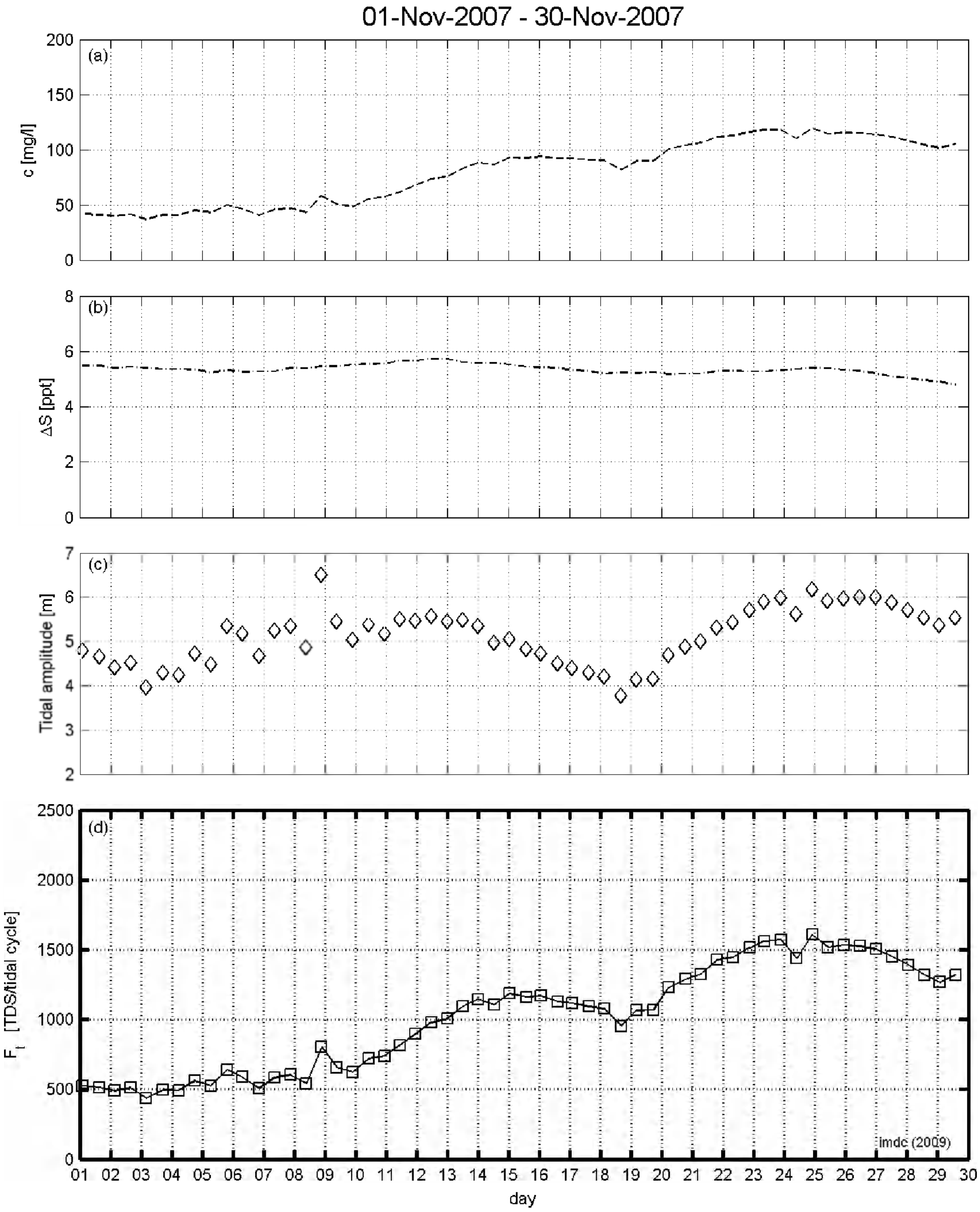
Analysis Siltation Processes	
	Location: Deurganckdok



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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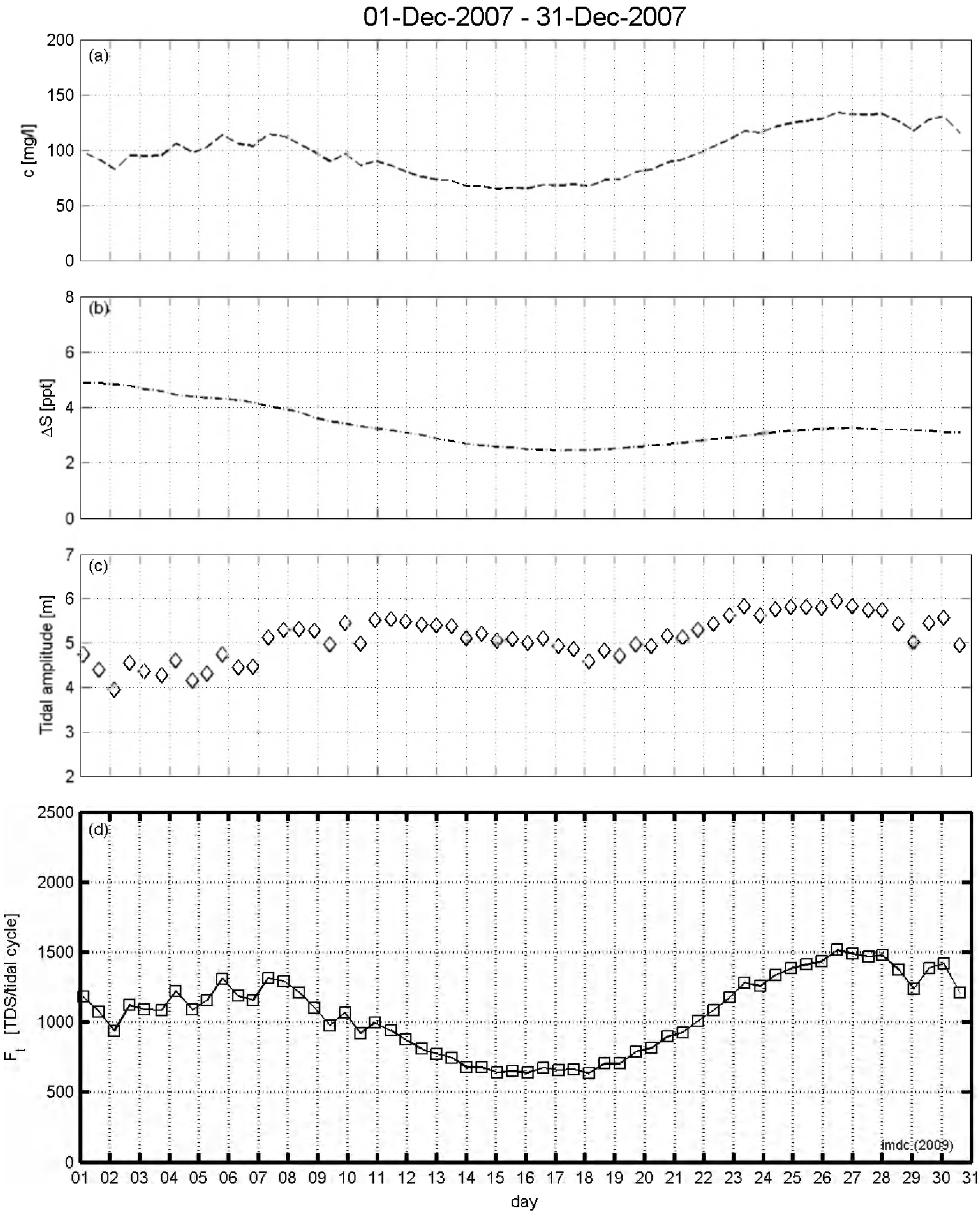
Langdurige metingen Deurganckdok: Opvolging en analyse aanslibbing

Analysis Siltation Processes

Location:

Deurganckdok



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

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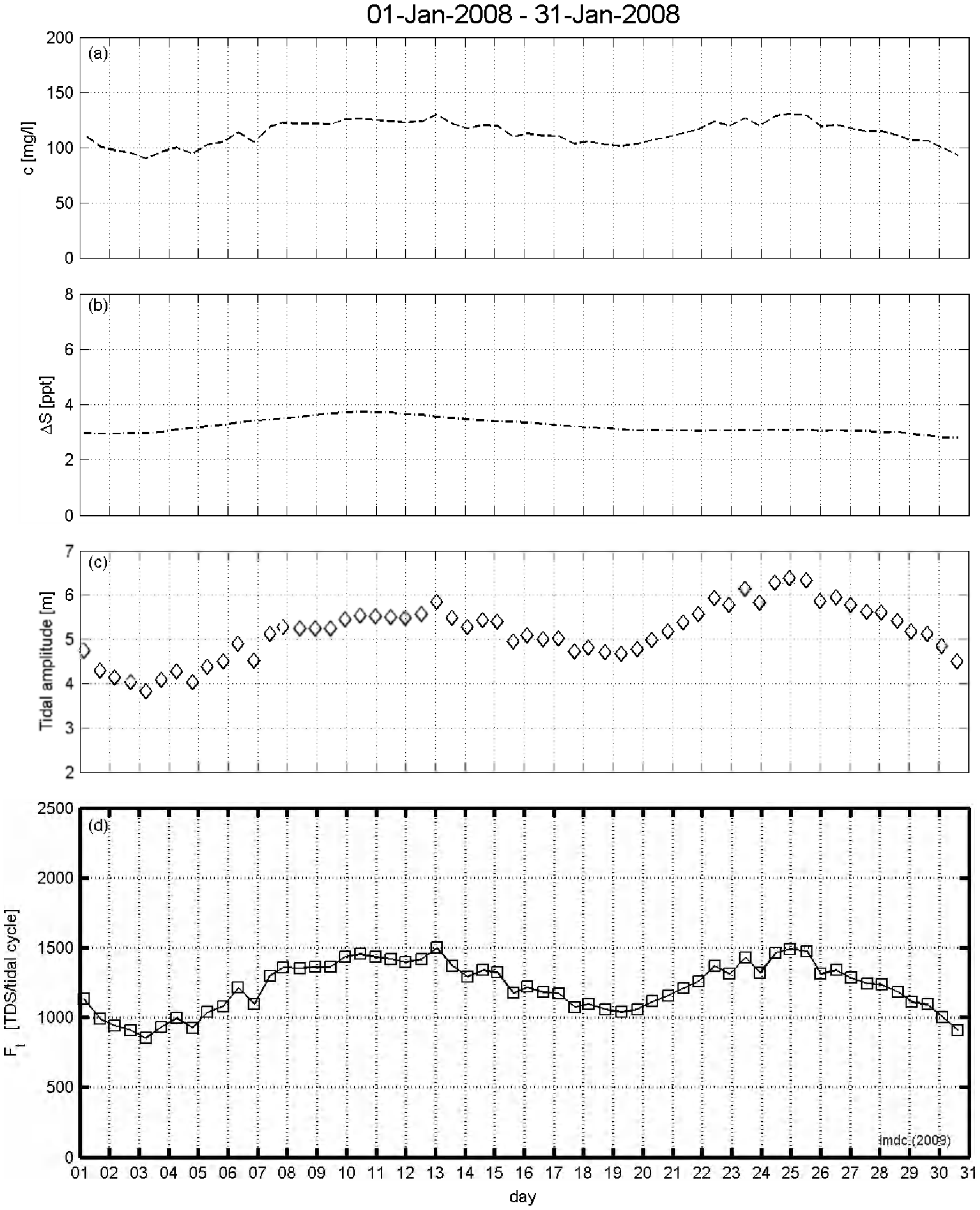
I/RA/11283/07.102/MSA

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).

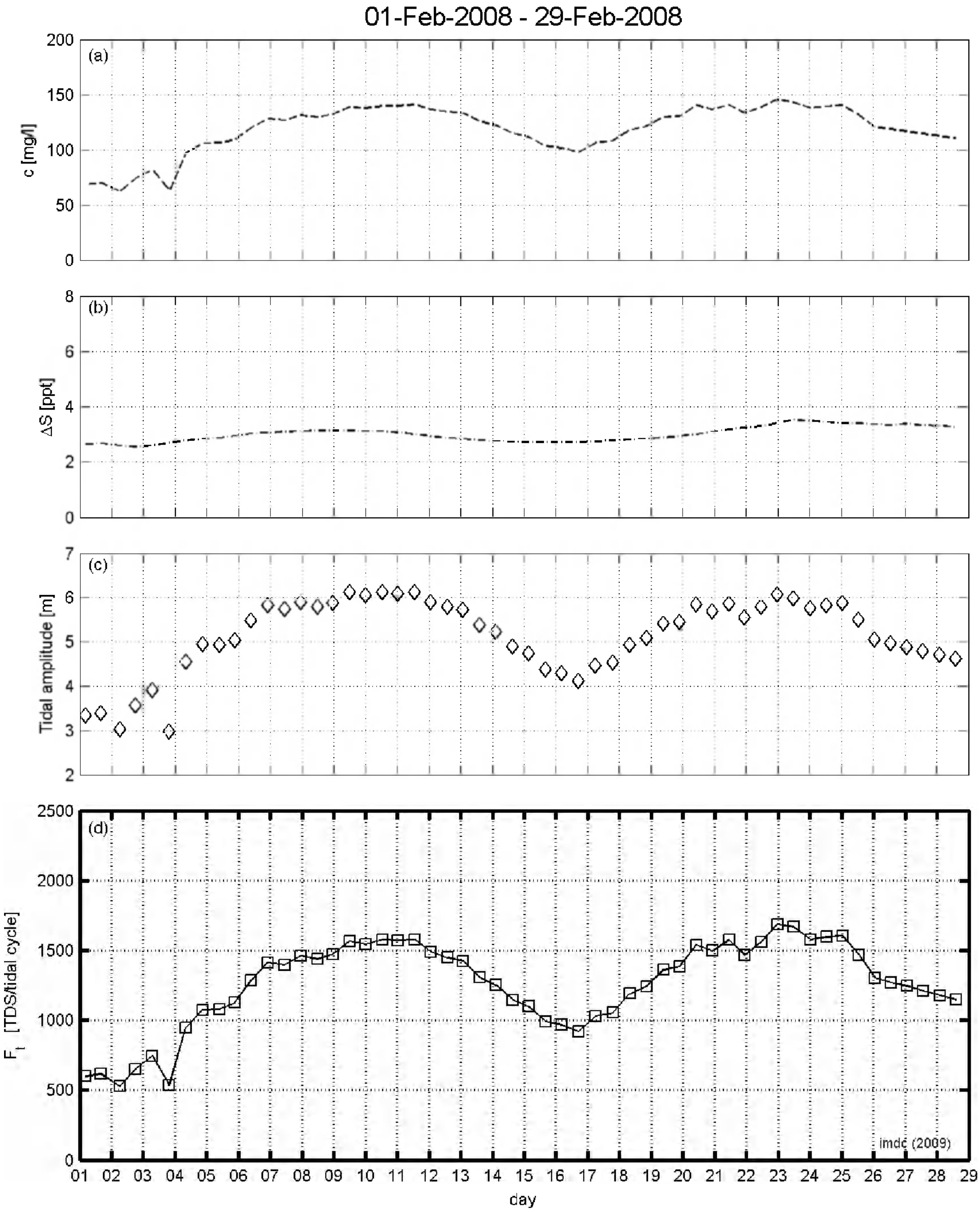
I/RA/11283/07.102/MSA

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).

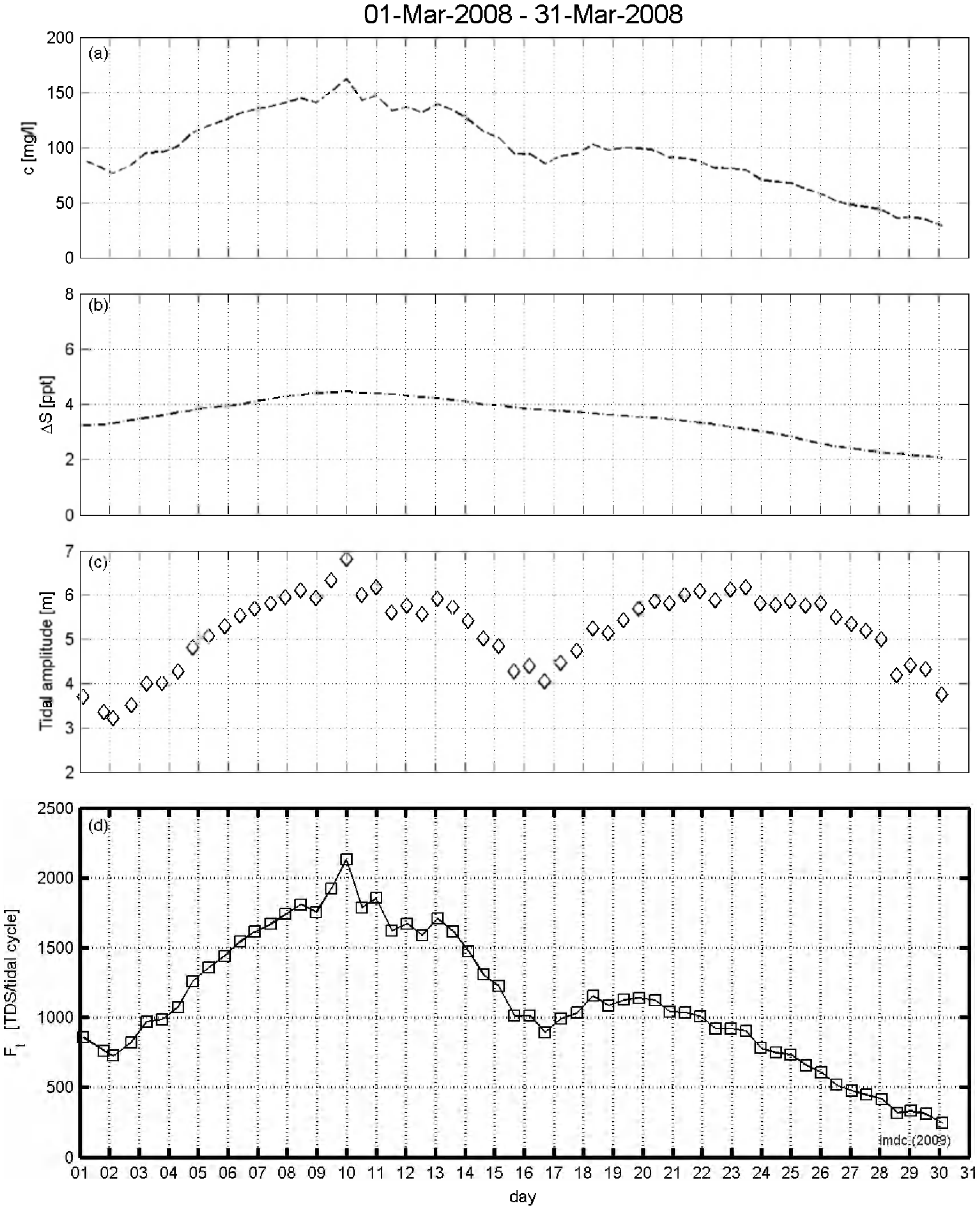
I/RA/11283/07.102/MSA

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).

I/RA/11283/07.102/MSA

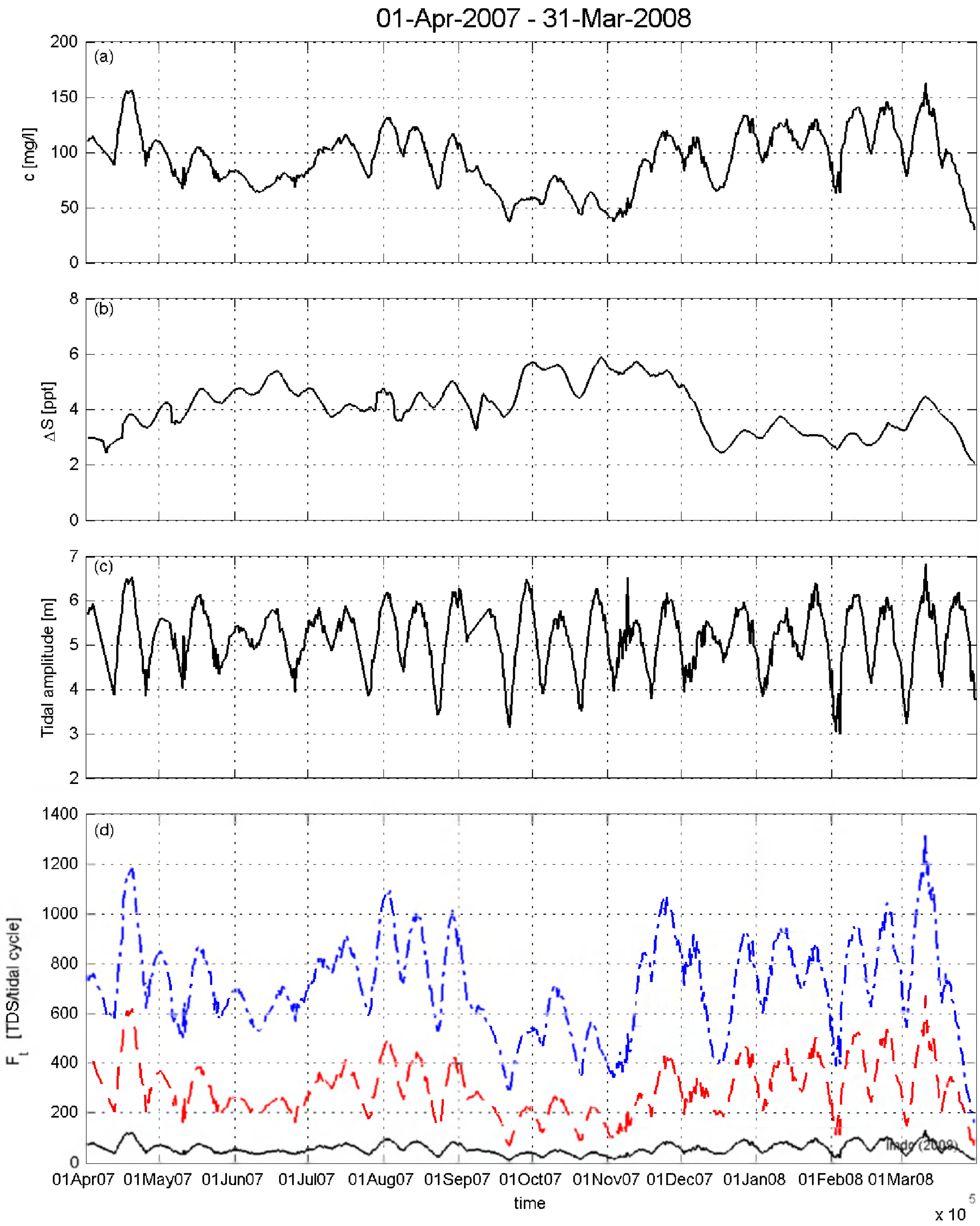
APPENDIX C. MAIN AMBIENT CONDITIONS VERSUS 3 COMPONENTS

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's (black).