REPORT

Flemish Government - Department of Mobility and Public Works

Maritime Access Division

Evaluation of the external effect on the siltation in Deurganckdok (2012 - 2014)

Report 1.16: Analysis of external effects on siltation processes and factors

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IMDC

International Marine & Dredging Consultants

in collaboration with

Deltares

Enabling Delta Life

Colophon

International Marine & Dredging Consultants

Address: Van Immerseelstraat 66, 2018 Antwerp, Belgium

☎: + 32 3 270 92 95

: + 32 3 235 67 11

Email: info@imdc.be

Website: www.imdc.be

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Contact within IMDC

Name **Jan Claus**
Phone number +32 3 287 25 26
Email jan.claus@imdc.be

Distribution List

3	Hardcopy	Mr. Roose (Maritime Access Division)
3	Hardcopy	Mr. Vanlede (Flanders Hydraulics)

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1. INTRODUCTION

1.1 THE ASSIGNMENT

This report is part of a set of reports concerning the project ‘Evaluation of the external effects on the siltation in Deurganckdok (2012 - 2014)’. The terms of reference were prepared by ‘Department of Mobility and Public Works of the Flemish Government, Maritime Access Division’ (16EF/2011/28). Part 1 of the study was awarded to International Marine and Dredging Consultants NV in association with Deltares on February 3rd 2012.

This study is a follow-up study on the study ‘Evaluation of the external effects on the siltation in Deurganckdok’ (2009 - 2012) and the study ‘Siltation Deurganckdok (2006 -2009)’.

The data and information that are used in this project are provided or collected by Flanders Hydraulics Research, Maritime Access Division and the Agency for Maritime Services and Coast. Flanders Hydraulics Research provided data on discharge, tide, salinity and turbidity along the river Scheldt. Maritime Access Division provided maintenance dredging data. Agency for Maritime Services and Coast – Coast Division provided depth sounding and density profile measurements.

1.2 AIM OF THE STUDY

The purpose of this study is to evaluate the external effects on the siltation in the Deurganckdok (DGD). External effects are those effects caused by recent human interventions in and around Deurganckdok:

- The deepening and widening of the navigational channel in the Lower Sea Scheldt between the entrance of the Deurganckdok and the access channels to the locks of Zandvliet-Berendrecht (2008–2010) (a.k.a. Drempel van Frederik);
- The deepening of the entrance to the Deurganckdok by removing the sill at the entrance (2009–2010);
- The construction of the Current Deflecting Wall (CDW) downstream of the entrance of the Deurganckdok (2010–2011);
- The change in maintenance depth or strategy of the Deurganckdock (2011);
- The construction of the Kieldrecht lock at the landward end of Deurganckdok (2011-2016)

It is noted that investigating the consequences of the changes in the dock (maintenance) on the sediment concentrations in the river is not part of this scope.

1.3 OVERVIEW OF THE STUDY

This study is composed of 2 parts:

- Reporting and analysis of existing documents and delivered measurement data.
- Execution of specific measurement campaign to determine the siltation and salinity rates at the entrance of DGD.

Reports of the project 'Evaluation of the external effects on the siltation in the Deurganckdok (2012 -2014)' are summarized in Table 1-1 (p. 13). The numbering of the reports follows the numbering of the previous project running between 2009 and 2012.

This report is a sequel to the set of analysis reports executed during the previous projects: IMDC (2009a) and IMDC (2013a) and is a final report to evaluate external effects on the siltation processes, concerning the period 2012-2014.

1.4 SCOPE OF THIS REPORT (RESEARCH QUESTIONS)

The specific research questions pertain to the observed sedimentation and maintenance dredging in the Deurganckdok, in terms of (influence of the changes in the) external factors (water quality in the river, dock geometry, …).

The long term monitoring and project measurements have been designed and carried out to capture and explain specific processes. Concerning these processes, research questions can be formulated that will be investigated through the analysis of the data and investigation with a sedimentation model.

1. Which influence does the CDW have on the long-term water exchange and sedimentation processes between the dock and the river?
2. If changes in processes are observed, can they be attributed to a specific year, and thus correlate to one of following specific external effects or interventions: Scheldt deepening, sill removal, CDW construction, maintenance depth changes, Kieldrecht lock construction? Or do we rather see a cumulated effect of all interventions?
3. Is the observed increase of the dredging volume, besides the effect of the sill dredging, related to:
    a. Changes in the water exchange processes or duration of processes since CDW construction, leading to longer (more) sedimentation per tide? Or,
    b. Changes in (external) sediment concentrations in the river?
    c. Changes in dredging strategy in the dock, i.e. the change in maintenance depth?

1.5 STRUCTURE OF THE REPORT

Chapter 2 provides a general summarizing description of the project and previous research. Chapter 3 gives an overview of all measurements executed in and near Deurganckdok, the performed analysis methods and the setup of a sedimentation model. In Chapter 4, data analysis will be carried out and the application to the sedimentation model will be discussed. Chapter 5 contains a discussion of the results. Conclusions are presented in Chapter 6.

Table 1-1: Overview of the project "Evaluation of external effects on the siltation in Deurganckdok (2012–2014)".

Report	Description
I.	**Analysis and Reporting**
I.1 Annual Sediment Balance: Bathymetry surveys, Density measurements, Maintenance and construction dredging activities	
1.09	Annual Sediment Balance in survey year 7: 01/04/2012-31/03/2013 (IMDC, 2013b)
1.10	Annual Sediment Balance in survey year 8: 01/04/2013-31/03/2014 (IMDC, 2014a)
I.2 Boundary Conditions: Upriver Discharge, Salt concentration Scheldt, Bathymetric evolution in access channels, dredging activities in Lower Sea Scheldt and access channels	
1.11	Boundary Conditions in survey year 7: 01/04/2012 – 31/03/2013 (IMDC, 2013c)
1.12	Boundary Conditions in survey year 8: 01/04/2013 – 31/03/2014 (IMDC, 2014b)
I.3 Analysis of the boundary conditions	
1.13	Analysis of the boundary conditions in survey years 3 and 4: 01/04/2008 – 31/03/2010 (IMDC, 2013d)
1.14	Analysis of the boundary conditions in survey years 5 and 6: 01/04/2010 - 31/03/2012 (IMDC, 2013e)
1.15	Analysis of the boundary conditions in survey years 7 and 8: 01/04/2012 – 31/03/2014 (IMDC, 2014c)
I.4 Analysis: evaluation of external effects on siltation in Deurganckdok	
1.16	***Analysis of external effects on siltation processes and factors (I/RA/11406/13.148/JCA)***
II.	**Long-term salinity and turbidity measurement campaign at the entrance Deurganckdok**
II.1 Salinity Siltation Distribution at the entrance of Deurganckdok	
2.14	Salinity-Siltation distribution Deurganckdok in survey year 7: 01/04/2012 - 31/03/2013 (AnteaGroup, 2013a)
2.15	Salinity-Siltation distribution Deurganckdok in survey year 8: 01/04/2013 – 31/03/2014 (AnteaGroup, 2014a)
II.5 Quality Control instruments	
2.16	Calibration stationary equipment 2012 (AnteaGroup, 2013b)
2.17	Calibration stationary equipment 2013 (AnteaGroup, 2014b)

2. SEDIMENTATION IN DEURGANCKDOK

2.1 PROJECT AREA

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

- 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.
- The bottom of Deurganckdok is located at a depth of -17 m TAW in the transition zones between the quay walls and the central trench and of -19 m TAW in the central trench.
- The quay walls reach up to +9 m TAW.

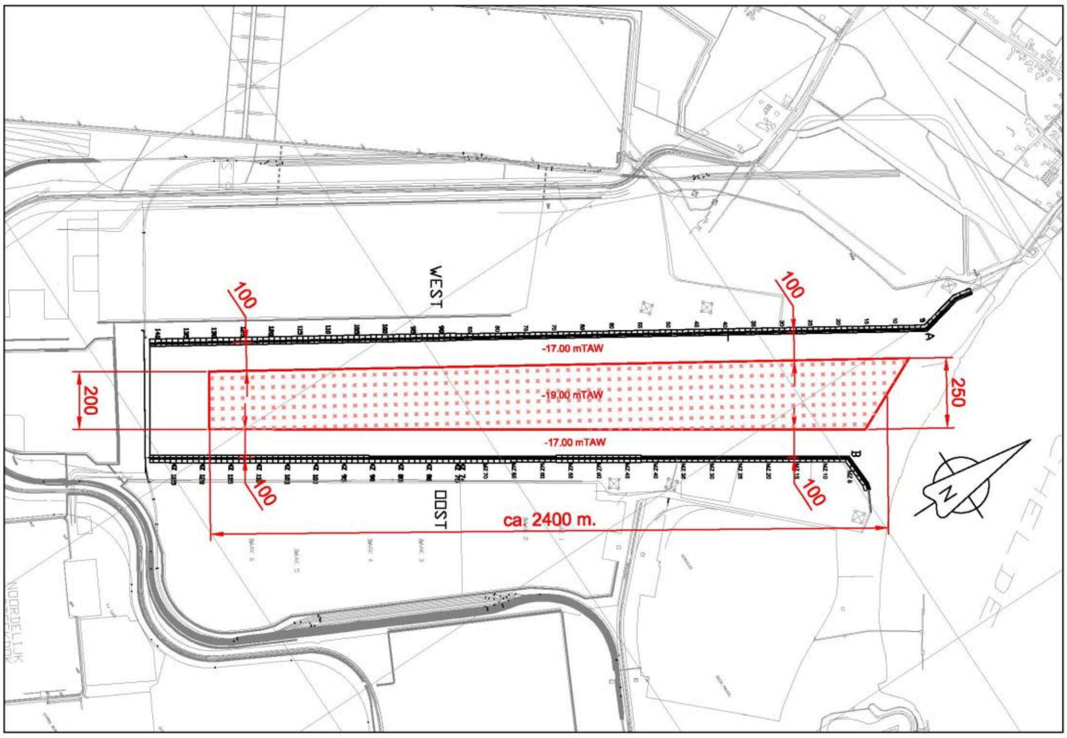

Figure 2-1: Overview of Deurganckdok

The dredging of the dock was performed in 3 phases between the start on February 2005 and finalization on February 2008. A Current Deflecting Wall (CDW) was constructed at the entrance of Deurganckdok between 2010 and 2011 with the objective to reduce the yearly sedimentation in the dock. The CDW was completed in August 2011. Between October 2011 and June 2016, the sealock 'Kieldrecht lock' was built to connect the tidal dock with the rear docks of Waaslandhaven.

Other main construction works which have been carried out near the dock since the opening of Deurganckdok are summarized in Table 2-1.

Table 2-1: Overview of construction works since the opening of Deurganckdok.

Date	Description
18th February 2005	Deurganckdok dike between the Scheldt and the dock was opened
18th Feb 2005 – 1st Aug 2005	Dredging Phase 2 (end)
Feb 2007 – Feb 2008	Dredging Phase 3, dock extended from 1500 to 2500m
Jul 2008 – Aug 2010	Deepening and widening of the Scheldt navigation channel in Belgium (spread over a long period, exact timing not known)
Nov 2009 – Jun 2010	Dredging of the entrance sill
Dec 2009 – Mar 2014	Using TSH Dredger for maintenance dredging of the entrance sill (before and after this period the sill sediment is swept into the river Scheldt)
Apr 2010 – Aug 2011	Construction of the Current Deflecting Wall (CDW)
> Mar 2011	Change of maintenance depth -16.6m / -18.2m / -15.9m TAW in quays / trench / entrance (included in maintenance dredging)
Nov 2011 – June 2016	Construction of the Kieldrecht lock at the landward end of DGD
April 2015	Filling of the Kieldrecht lock

2.2 DREDGING INTENSITY

The cumulative maintenance dredging mass (TDS) till 2014 in the Deurganckdok (Figure 2-2) can be divided in two periods, roughly split in 2010.

The average dredging intensity in the dock is higher since 2010 (solid line) than before 2010 (striped line): in the period up to 1/1/2010, an average dredging intensity of 2600 TDS/day is observed. From 2010 till 2014, the average increases by 1600 TDS/day to 4200 TDS/day.

Part of the increase can be attributed to dredging of the sill since November 2009 that is now in the volumes, (avg. 600 TDS/day) instead of sweepbeam dredging. Before November 2009 a sweepbeam dredger swept the sill sediments into the river Scheldt where it was disposed.

Regarding the mud dredging volumes in the entire Lower Seascheldt (Figure 2-3), the role of Deurganckdok in the overall volume is clear. Also, the volume dredged at the in the river, at the sill ‘Drempel van Frederik’, appears to be somewhat higher the past years. Relatively speaking, about 30 % of the mud volume is originating from the Deurganckdok.

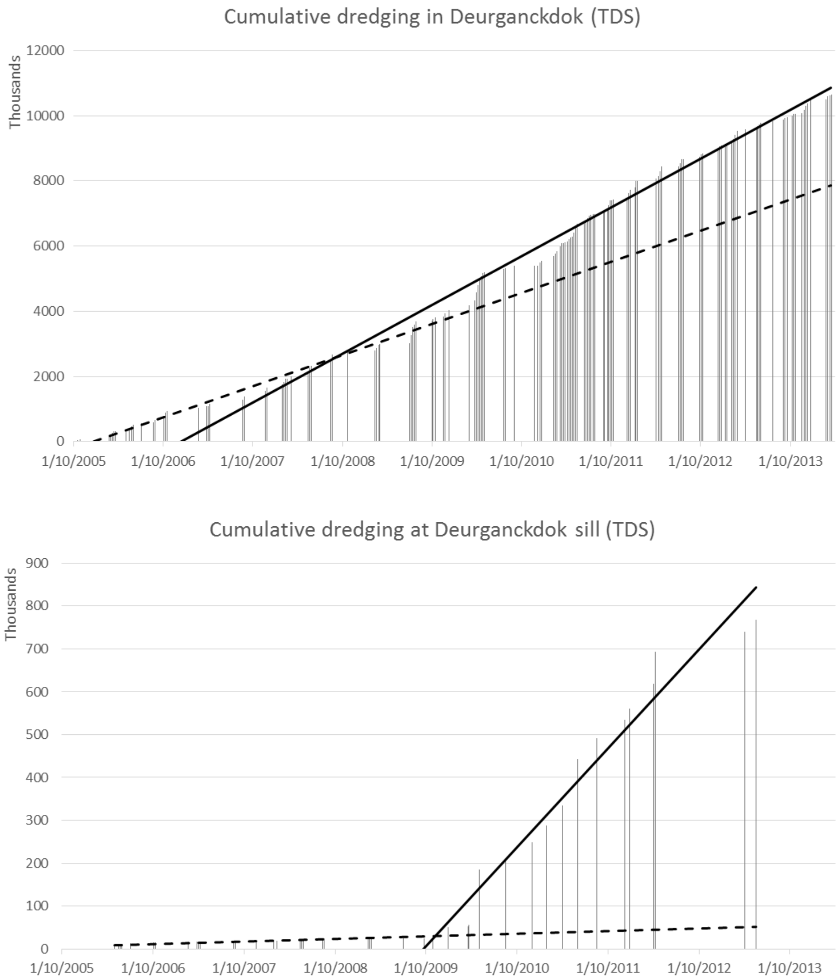

Figure 2-2: Cumulative dredging mass in Deurganckdock (total) and entrance sill. Striped line: linear trend 2005-2009; solid line: linear trend 2010-2014. Striped line: linear regression up to 31/12/2009; Full line: linear regression starting from 1/1/2010.

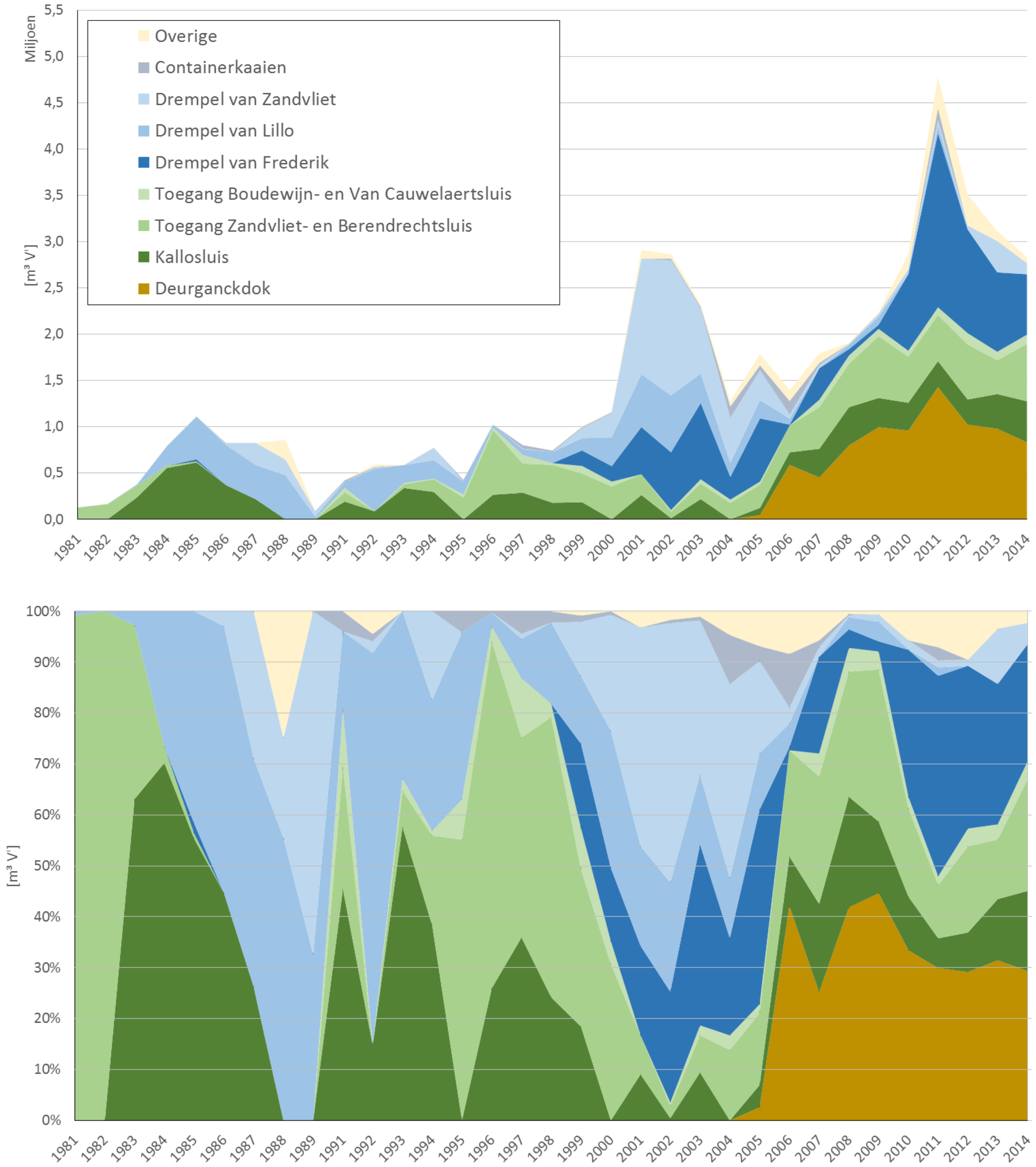

Figure 2-3: Absolute (upper graph) and relative (lower graph) mud dreding volumes (m³ V') in the Lower Sea Scheldt.

2.3 OVERVIEW OF STUDIED PARAMETERS

The purpose of this study is to evaluate the external effects on the siltation in the Deurganckdok (DGD). The evaluation is based on the analysis of reported measurement data. The analysis of the measurement data contains two main investigations:

- Description and analysis of the collected observations; and
- Application of a conceptual sedimentation model, which uses results from the mass balance, boundary conditions and measurement data at the entrance of Deurganckdock.

In addition, analysis and reporting of the natural processes and human activities in the Lower Sea Scheldt (boundary conditions) was also investigated during this project to provide more insight into the mechanisms causing the siltation in Deurganckdok.

The sedimentation in Deurganckdok comprises a number of sediment transport modes: deposition, influx from capital dredging works, internal replacement and removal of sediments due to maintenance dredging. (Figure 2-4).

The net deposition is calculated from a comparison with a chosen initial condition t_0 (Figure 2-5). 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 river Scheldt since t_0.

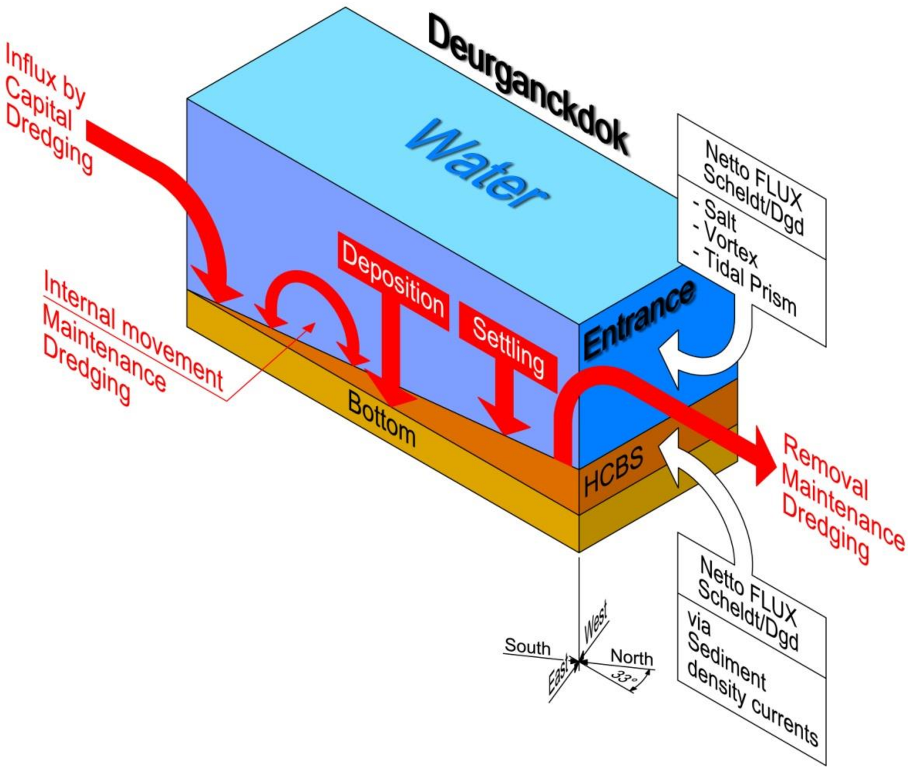

Figure 2-4: Elements of the sediment balance and transport mechanism.

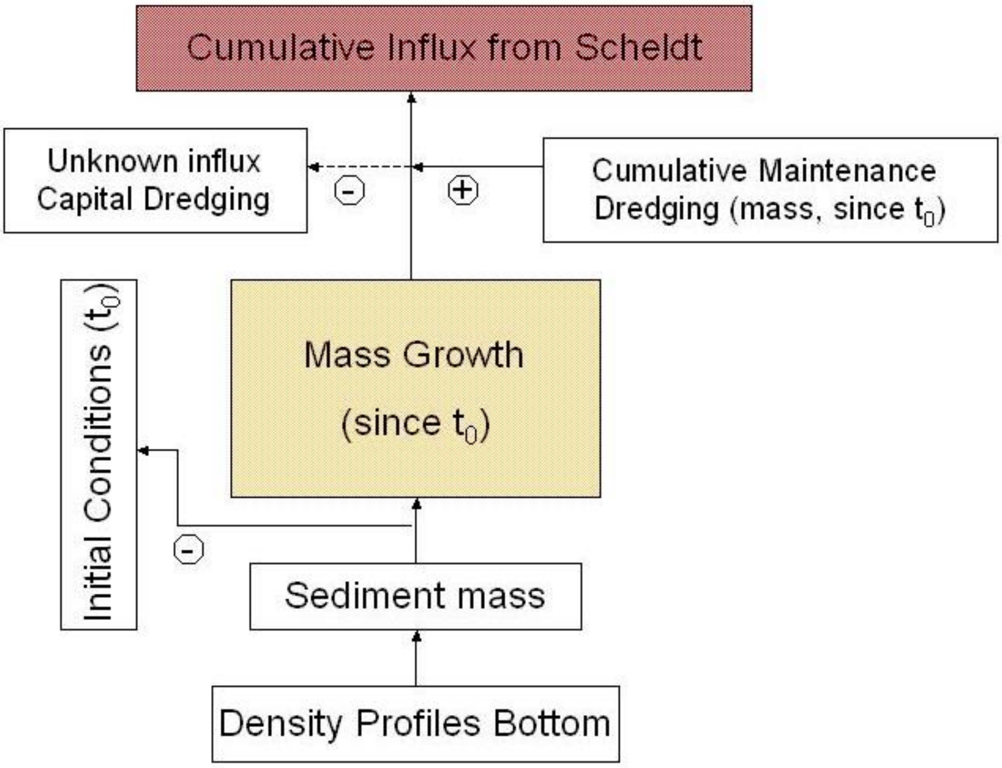

Figure 2-5: Determining a sediment balance.

Concerning the sediment exchange, the following mechanisms will be aimed in this study:

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

These aspects of hydrodynamics and sediment transport have been landmark in determining the parameters to be measured during the project. Measurements have focused on three types of timescales: 1/ one tidal cycle, 2/ one neap-spring cycle and 3/ seasonal variation within one year.

The following data have been collected to understand these mechanisms:

- Monitoring upstream discharge of the River Scheldt.
- Monitoring salinity and sediment concentration in the Lower Seascheldt, up and downstream of the Deurganckdok, at permanent measurement locations at Oosterweel, Liefkenshoek (only salinity) and Buoy 84.
- Long-term measurements of salinity and suspended sediment distribution at the entrance of Deurganckdok.
- 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.

Noteworthy is that ADCP (13 hour) measurements have not been carried out within this analysis period (2012-2014), in contrast to the past analysis periods.

2.4 PREVIOUS RESEARCH

During the course of the Deurganckdok projects the collected data has been described in a series of reports. The next sections give a specific overview and references of which data analyses have been performed, and which (preliminary) conclusions about the external effects on the siltation have been drawn.

2.4.1 Previously reported data analyses

An overview is given of the analyses executed on Deurganckdok data in the past.

Annual Sediment balance reports (IMDC, 2006a, 2007a, 2008a, 2009b, 2010a, 2011a, 2012a, 2013b, 2014a):

- 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 rates (siltation rates from periods without dredging activities)
    - average net mass evolution (from density measurements)
    - 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

Annual Boundary conditions analysis reports (IMDC, 2007b, 2013d, 2013e, 2014c):

- Analysis on the long-term continuous measurements on the Lower-Sea Scheldt and at entrance of Deurganckdok on several time scales (seasonally, tidal cycle and long-term variation) on following parameters:
    - Current velocity and direction;
    - Salinity;
    - Temperature;
    - Sediment concentration.

Analysis reports to evaluate the external effects on the siltation processes of Deurganckdok (IMDC, 2009a, 2013a):

- Data analysis of the collected measurements data to gain insight of the siltation processes (density and eddy currents);

- Sedimentation model set-up.

2.4.2 Previously reported conclusions about the effect of the CDW

The development and construction of the CDW (Figure 2-6) is a long process dating back to 1997.

A synthesis of the development process of the CDW has been given in IMDC report (2010b). The main expected impacts of the CDW, as described in that synthesis report, are:

- During flood the CDW should divert the surface flow inside the dock and the bottom flow towards the Scheldt River.
- By streamlining the flow, the CDW mainly reduces the eddy component of the total water exchange at the dock (and affects only indirectly the tidal and density components). This explains the lower expected efficiency compared to the port of Hamburg, where density currents are not an issue.
- The sedimentation in the dock is expected to reduce by 10 to 20 % based on numerical results. This has to be compared to the total water and sediment exchange before building the CDW. The water exchange between the dock and the Scheldt is due to tidal filling for 15 %, to eddy formation for 20 % and to density currents for 65 % (total around 45 Mm³/tide). The sediment exchange is due to tidal filling for 25 %, to eddy formation for 10 % and to density currents for 65 % according to the previous application of the conceptual sedimentation model (IMDC, 2009a), for a mean total of 1200 TDS/tide.
- Based on numerical results, a slight increase by 8 % of the sedimentation rate can be expected from removing the entrance sill.

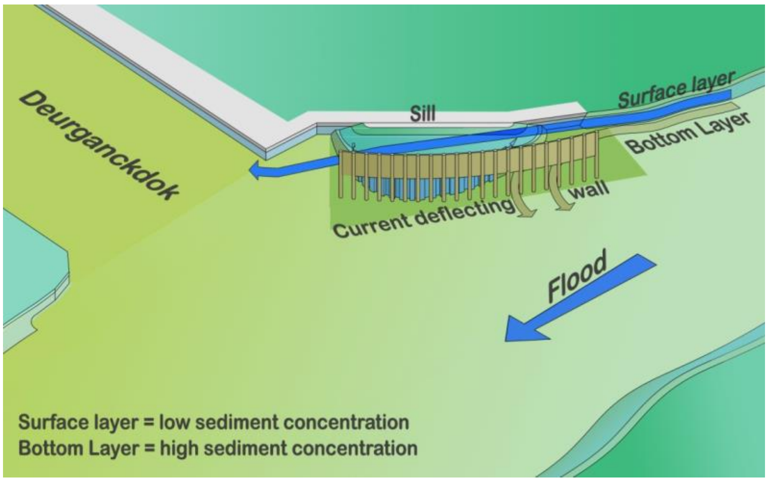

Figure 2-6: Schematisation of the Current Deflecting Wall.

In the data reports posterior to August 2014, an attempt has been made to compare measurements with those prior to the construction of the CDW. The following preliminary conclusions have been made:

- Mass balance:
  - The year after completion of the CDW (2011-2012) has been marked by intense dredging activity and a deeper maintenance depth. As a consequence natural siltation rates cannot be reliably estimated and no reliable comparison with previous years is possible (2012a).

  - 2012-2013: The siltation rates during the periods without dredging activity is smaller compared to previous years. 21 % less sediment mass was dredged compared to the previous year. Important dredging activities took place from end of March 2012 to end of May 2012, and accounted for 28.0 % of the total dredged mass (IMDC, 2013b)
  - 2013-2014: The natural siltation rate (estimated to be 1 – 3 cm/day) is smaller compared to previous years. 30 % less sediment mass was dredged compared to the previous year. Important dredging activities took place from end of September 2013 to the middle of December 2013, and accounted for 50.0 % of the total dredged mass (IMDC, 2014a).
  - No conclusion can be made about the effect of the CDW to the siltation rates since these years were marked by a lot of dredging activity and thus limited data with regards to the natural siltation rate (during periods without dredging) is available.

- Through tide measurements :
  - Cross dock ADCP: A comparison of spring tide measurements (IMDC, 2011b, 2012b) before and after CDW shows a clear reduction of the eddy at two moments during the tide (HW-3h and HW-1). Neap tide measurements (IMDC, 2011c, 2012c) also suggest such a reduction but less clearly. The effect of the CDW on the SSC cannot be assessed due to the high temporal variability of the SSC depending on external conditions. Both low and high SSC, net deposition and trapping efficiency have been measured with the CDW (500 and 900 TDS/tide during neap tide, 2300 and 3400 TDS/tide during spring tide, trapping between 28 % and 56 %).
  - Along dock ADCP: A comparison of velocity maps without and with CDW at HW-1h of spring tide suggests no clear change in flow pattern (IMDC, 2011d, 2012d).
  - There are no new ADCP measurements available since 2012.

- Near bed monitoring :
  - Frames: The measured SSC at the sill (South entrance) is comparable with and without CDW both during summer/autumn conditions (IMDC, 2011e) and during winter/spring conditions (IMDC, 2012e). The measurements at the CDW downstream frame show a clear tidal variation, with a SSC peak during flood, while the two other frames display a less clear pattern due to local effects. Despite these local effects, measurements still suggest the presence of a flood eddy and density currents at the dock entrance with CDW (IMDC, 2011e). A lower SSC is reported at the South station (sill frame) except during HW and LW when it is higher than the North station (CDW upstream frame): this is the opposite of what is usually observed in long-term salinity measurements before the CDW, but these differences may be due to different measurement locations compared to the sensors along the quays.

- SiltProfiler: SSC measurements are high for autumn 2011 measurements (IMDC, 2011e) and low for winter 2012 measurements (IMDC, 2012e) compared to without CDW. The SSC is generally higher South than North: this is the opposite of what is usually observed in long-term salinity measurements before CDW but it may be due to different locations. No clear decrease of the SSC due to the CDW is visible during flood.

In the analysis report of external effects on the siltation in Deurganckdok for the period 2006-2012 (IMDC, 2013d) long term salinity and SSC measurements as well as 13h measurement data before and after CDW were compared, in order to understand the effect of the CDW on the current pattern and on the sedimentation regime.

- **Results show that the CDW has the expected effect on the water exchange.**
  A strong reduction of the flood eddy is qualitatively visible in the 13h measurements. Important changes in the tidal phasing are clearly visible from average tidal cycles derived from long time series at the dock entrance. It seems to delay the sediment-laden bottom flow and to allow the surface flow to enter the dock faster via the CDW channel. As expected, the largest effects are visible at the North entrance. The results suggest a clear reduction of the eddy and locally weaker density currents. ADCP measurements do however not allow to extrapolate these local measurements to the entire entrance cross-section, because they clearly show stronger and longer lasting density currents, in particular around LW. However this change in density currents may be due to other human impacts (deepening or SSC increase).
- **The effect of the CDW on sedimentation is less clear.**
  Measurements up to now suggest a decrease of the SSC by 20 % to 30 % near the bottom, both North and South of the entrance from HW-1h to HW+2h. However, the average SSC slightly increases during the rest of the tidal cycle. Over the same periods, the average SSC in the Scheldt is equally unchanged.
- **The increase in maintenance dredging volumes was found starting from spring 2011.**
  This corresponds to the finalisation of the CDW. However, at the same time, many other human interventions happened such as the increase in maintenance depth, the more frequent dredging activity and a change in reporting of dredging volumes at the entrance sill. The impact of CDW itself on the changes in dredging volumes cannot be distinguished from other factors at this moment. Given the earlier conclusions about water exchange, it is however suggested that the larger maintenance depth and the more frequent dredging play a more important role in the increased maintenance dredging than the CDW itself.
- **In the numerical model Slib3D, the CDW results in a decrease of the sedimentation.**
  The reduction amounts to 0% at neap tide and 30 to 40% at spring tide, with an average of about -15 % over a spring-neap cycle. This is of the same order of magnitude than previously reported (Van Maren, 2007).
- **Other human activity in the river Scheldt has a potentially non-linear effects.**
  Such effects can easily overshadow the positive effect of the CDW.

3. DATA, METHODS AND MODELS

3.1 DATA & MEASUREMENTS

3.1.1 Overview

In the scope of earlier siltation studies and projects at Deurganckdok and this project, several measurements campaigns have been organized in the vicinity of Deurganckdok: at the entrance, down- and upstream of Deurganckdok, and in the dock itself. The measurements were performed during several tidal cycles (neap, average and spring tide) and on long-term time scale. A list of campaigns with references is given in Annex A.

The different types of measurements are discussed in the next sections:

- Depth soundings and density measurements for calculation of the sediment mass balance in the dock;
- Settling velocity measurements;
- Through-tide measurements with ADCP
- Long-term salinity and SSC measurements in Deurganckdok
- Long-term (continuous) monitoring in the Lower Sea Scheldt.

3.1.2 Depth soundings and density measurements

Depth soundings and density measurements are necessary to calculate a sediment balance of mass volumes or the dry weight of sediment per surface unit. In order to measure bulk densities, four devices were used over the time, i.e. the Navitracker, the Densitune, the RheoTune and the GraviProbe.

During the measurement years 2010-2012 the Navitracker has been used all the time except for the measurement of March 20th 2010 which has still been done with the Densitune. During the measurement year 2012-2013 all three instruments have been used (the Navitracker, the Densitune and the GraviProbe). From May 20th 2013 onward the RheoTune was used. A correlation between devices is shown in section 3.2.2.

3.1.3 Settling velocity measurements

To obtain information of the particle characteristics of the sediment, measurements were performed in the dock in 2005 and 2006 (IMDC, 2005a, 2006b). Following parameters were obtained:

- 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

3.1.4 Through-tide measurements

Through-tide measurements were executed during the earlier projects to provide insight in the water and sediment dynamics in vicinity or at the entrance of Deurganckdok using SiltProfiler or/and Acoustic Doppler Current Profiler (ADCP). Those devices determine:

- Dynamic measurements of flow pattern, salinity and sediment transport at the entrance of Deurganckdok.
- Obtain vertical sediment concentration profiles -including near bed high concentrated benthic suspensions.

These observations were crucial to investigate the water exchange and sedimentation processes at the entrance of Deurganckdok and to set-up the sedimentation model (section 3.3). It must be noted that no ADCP measurements have been executed in the period 2012-2014. In the next period (2014-2017) ADCP measurements are foreseen at the entrance of Deurganckdok in autumn of 2015 and 2016 to establish changes caused by the construction of the Kieldrecht lock.

3.1.5 Long-term salinity and SSC measurements

Since 2006, long-term SSC and salinity measurements at the entrance of Deurganckdok were executed on irregular basis. The measurement frequency of all the instruments was 10 minutes. Continuous measurements are available from March 2008 excluding the construction phase of CDW (2010 - 2011). At some periods a turbidity sensor till 500NTU was deployed at the nearest location to the water bed. In those cases the sensor reaches their maximum value of 500NTU and underestimates the turbidity value. The sediment concentrations are derived from in-situ calibration campaigns of the turbidity meters (see section 3.1.2). The measurement locations are shown in Figure 3-1.

Data measured at the entrance of Deurganckdok will be used to set up the sedimentation model (section 3.3) and to provide insight to the water and sediment exchange between the dock and the river Scheldt.

3.1.6 Continuous monitoring in the Lower Sea Scheldt

Continuous long-term measurements were carried out in the Lower Sea Scheldt (Figure 3-1) on fixed location at Oosterweel (left bank), Liefkenshoek, Prosperpolder, Buoy 84. In the past, other locations were maintained at Boerenschans, Buoy 97 and Lillo. Boerenschans and Lillo are respectively removed in 2005 and Buoy 97 in 2008. The measurement frequency of the instruments is 10 minutes.

An Aanderaa RCM9 device was used to measure the flow velocity and direction, temperature, pressure, conductivity and turbidity at Buoy84 and Oosterweel. Between 2009 and 2012, the Aandera RCM-9 was replaced by the new generation AADI instrument Seaguard RCM which has an influence on the turbidity data. Since installing the Seaguard RCM several times the maximum level of the turbidity sensor of 500 FTU was reached. If the sediment concentrations are higher than the saturation value, the actual turbidity value is unknown. Due to this reason the turbidity sensors of 500FTU were replaced by a turbidity sensors of 2500FTU between 2012 and 2013.

A CTD-instrument manufactured by Valeport Ltd was used to measure salinity at Liefkenshoek and Prosperpolder.

Tidal data were provided by Flanders Hydraulics Research in the form of water level readings taken every 10 minutes in Prosperpolder, Liefkenshoek and Antwerp. Prosperpolder was used as a tidal station for the measurement location Prosperpolder, Liefkenshoek for Buoy 84 and measurement location Liefkenshoek, and Antwerp for the measurement location Oosterweel.

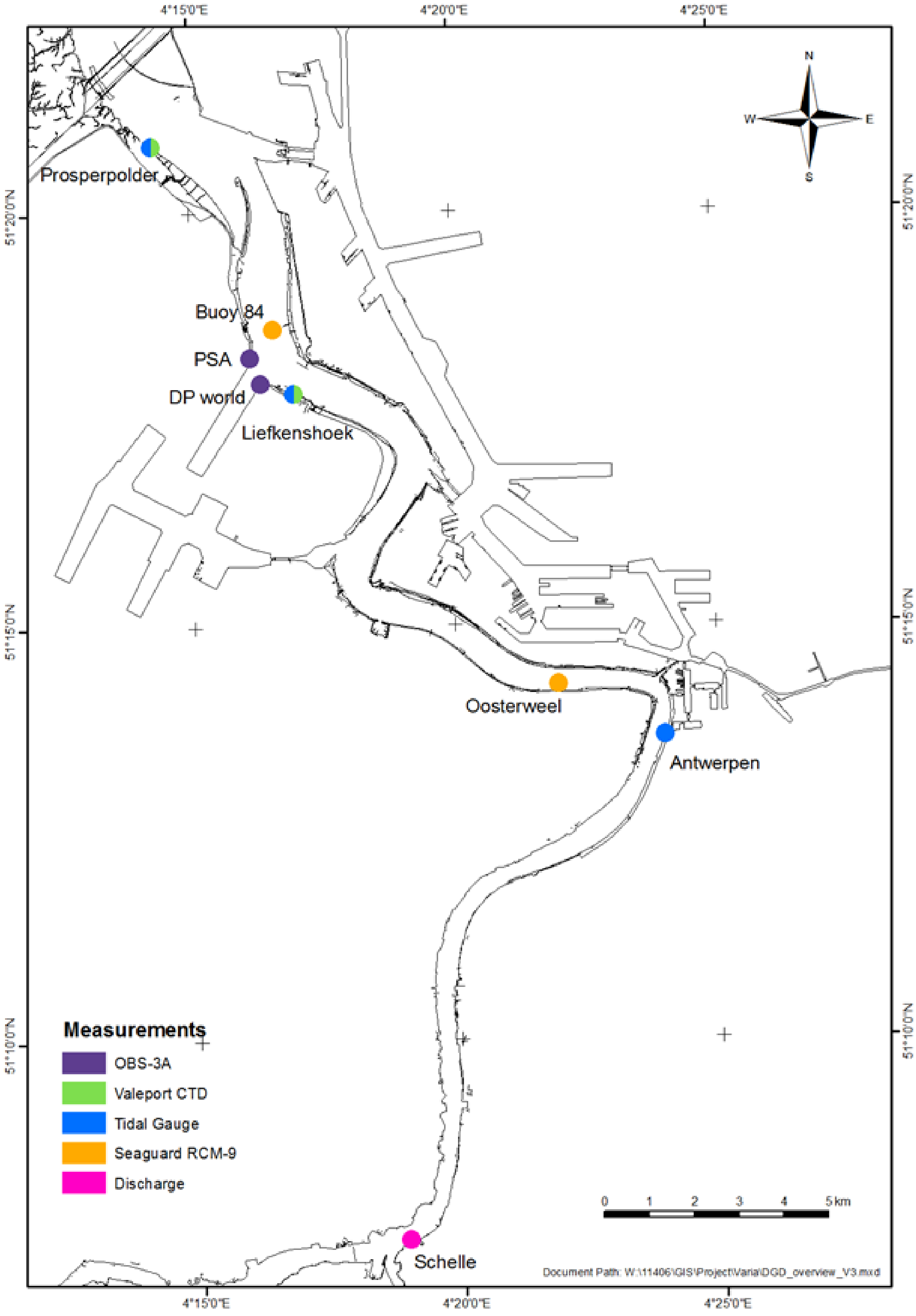

Figure 3-1: Continuous long-term measurement locations (green dots) on the Lower Sea Scheldt and at Deurganckdok entrance since 2006.

3.2 CALIBRATION AND PROCESSING

3.2.1 Turbidity to SSC calibration

For the two measurement locations at the **entrance of Deurganckdok** (DPW and PSA, or South and North entrance respectively), the turbidity has been measured by two different companies in two different periods (period 1 up to May 2012; period 2 between June 2012 and April 2014). The same devices were used but were positioned 2m deeper during the second period.

The measured turbidity values have been converted to SSC using calibration curves which are based on in-situ calibration campagnes. A new calibration curve for the time series in period 1 is set up based on the calibration curves shown in Table 3-1, retrieved in period 2. This operation is motivated by the larger sampled SSC variability in the second period and should thus provide more confidence in the calibration curve and the SSC time series, especially for the higher concentrations (the error produced by extrapolation to the higher range will be smaller) (IMDC, 2014c). The operation is validated by the similarity of (recalibrated) SSC results measured in an overlap period in May 2012 (data not shown).

Table 3-1: Averaged calibration curves produced for 4 sensors at the entrance of DGD (AnteaGroup, 2014a).

Instrument number of OBS-3A (Campbell Scientific)	**Calibration curve SSC (mg/l) = a x *turb* + b**
580	SSC = 2.408 *turb* – 9.96
581	SSC = 1.612 *turb* – 28.51
582	SSC = 2.517 *turb* – 21.66
583	SSC = 2.384 *turb* – 21.31
584	SSC = 2.351 *turb* – 14.85
596	SSC = 2.327 *turb* – 14.91
AVG	**SSC = 2.368 *turb* – 15.26**

For the stations on the **Lower Sea Scheldt** (Buoy 84 and Oosterweel), the calibration conversion was set up by Flanders Hydraulics Research, based on water samples collected during calibration and through-tide campaigns (Vanlierde *et al.*, 2014). To produce a consistent time series of sediment concentrations for the whole period, new time series were provided by Flanders Hydraulics Research using new calibration curves as described in MONEOS report of survey year 2014 (Vanlierde *et al.*, 2015). Table 3-2 presents the new calibration relations derived by Flanders Hydraulics Research at Buoy84 and Oosterweel for the three types of devices.

Some caution is necessary during the SSC interpretation for the RCM Seaguard with a turbidity range up to 500 FTU (2009-2012). Not the whole turbidity range was covered with water samples during the calculation of conversion curves. SSC data larger than respectively 1000 mg/l (800 FTU) at Buoy84 and 850 mg/l (550 FTU) at Oosterweel were extrapolated and must be treated with care. For the conversion curves of the RCM Seaguard (till 2500 FTU) the total range was covered.

Table 3-2: Summary table of new calibration curves at Buoy84 and Oosterweel (Vanlierde et al., 2015)

Buoy 84	**Regression model [SSC ~ FTU]**
Aanderaa RCM-9	$y = 0.00253x^2 + 2.22831x$
Aanderaa SeaGuard (500 FTU)	$y = 0.000776x^2 + 1.133978x$
Aanderaa SeaGuard (2500 FTU)	$y = 1.232555x$
Oosterweel	**Regression model** [SSC ~ FTU]
Aanderaa RCM-9	$y = 0.004096x^2 + 1.869836x$
Aanderaa SeaGuard (500 FTU)	$y = 0.000227x^2 + 1.237918x$
Aanderaa SeaGuard (2500 FTU)	$y = 1.397138x$

It is thus noted that in the factual data reports of the boundary conditions (IMDC, 2013c, 2014b) and in the previous analysis report (IMDC, 2013a), different calibration curves were used, which may lead to differences in representation and interpretation.

Because of this operation, decided in collaboration with the client, the SSC time series after CDW results in higher SSC values at the entrance of the dock compared to the previous analysis report (IMDC, 2013a).

Figure 3-2 illustrates the effect of the new, unified calibration curves on the SBOT turbidity data.

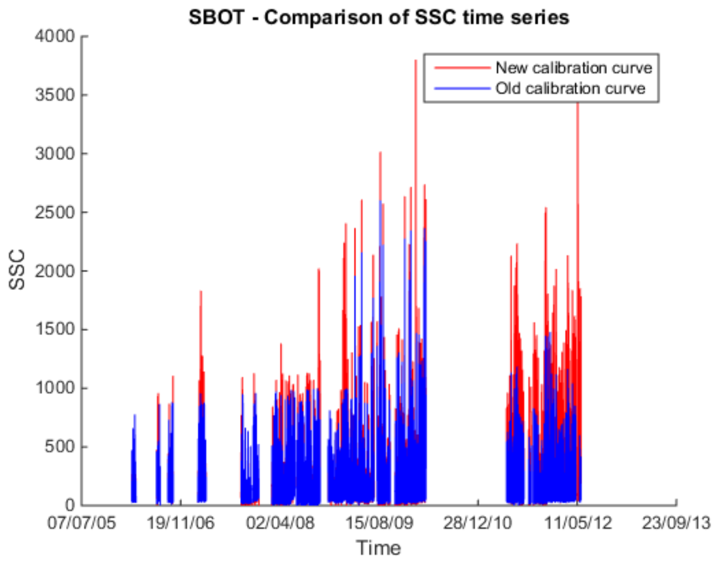

Figure 3-2: Example of the effect of the difference between calibration curves (old, vs new) for the SBOT timeseries.

3.2.2 Density measurements intercalibration

The DensiTune and the RheoTune measurements yield higher densities at a specific depth in comparison to the Navitracker.

In IMDC (2009c), both density profilers (the Navitracker and the Rheotune) were compared in the harbour of Zeebrugge. A correlation was then determined between dry mass measured using Rheotune (RT) and using Navitracker (NT): NT = 0.75 RT. No similar dataset measured at Deurganckdock is available to compare the different instruments.

Therefore, the aforementioned relation is used as a correction factor to the measured mass in the sedimentation model (see section 3.3).

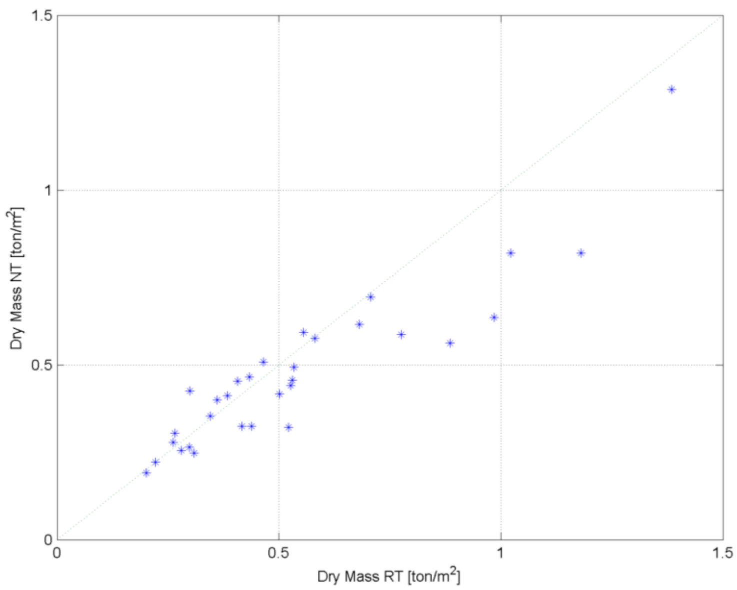

Figure 3-3: Total dry mass measured using Rheotune vs. the total dry mass measured using Navitracker in the harbour of Zeebrugge (IMDC, 2009c).

3.2.3 Data processing

3.2.3.1 Time-series setup

For the setup of the integrated timeseries, the data processing has been done in several steps:

- First all data has been merged into single time series from 2006 to 2014 per location;
- The data was cleaned, based on a visual assessment of each full time series;
- Based on an inter-comparison of time series at different locations, additional periods have been identified during which some data has been judged doubtful and has been removed:
    - Removed salinity at STOP from 18/6/2008 to 23/10/2008 (drifting compared to other sensors at the dock entrance)
    - Removed salinity at NBOT, NTOP, SBOT and STOP from 1/7/2006 to 1/11/2006 (up to 8ppt higher than at buoy B84 despite good match between sensors over the remaining time series)

- Removed salinity at NTOP from 01/05/2013 to 31/07/2013 (3 ppt lower compared to other sensors at the dock entrance)
- Removed salinity at B84TOP from 26/7/2008 to 11/2/2009 (drifting compared to B84BOT)
- Removed salinity at B84TOP from 16/6/2009 to 9/9/2009 (drifting compared to B84BOT)

The post-processed data is available to the client as text-format file (IMDC uniform format with 12 columns including all parameters), merged in a single timeseries per measurement station. The stations and abbreviations given below are used in the rest of the report to identify a particular sensor:

- North entrance bottom sensor (NBOT)
- North entrance top sensor (NTOP)
- South entrance bottom sensor (SBOT)
- South entrance top sensor (STOP)
- Buoy 84 bottom sensor (B84BOT)
- Buoy 84 top sensor (B84TOP)
- Oosterweel bottom sensor (OWBOT)
- Oosterweel top sensor (OWTOP)
- Prosperpolder sensor (PROSP)
- Liefkenshoek sensor (LIEF)

Similar time series have been generated for the boundary conditions:

- Tide (at Liefkenshoek)
- Discharge (at Schelle ; daily values)
- Dredging (from BIS (Dredging Information System) and weekly reports)

Figures of the time-series can be found in annex B.1.

3.2.3.2 Daily statistics

Daily statistics have been derived from the timeseries: median, mean, minimum and maximum daily values, maximum daily range (or delta values) and number of data values measured per day.

The salinity and tidal amplitudes are necessary for the sedimentation model (delta values, see section 3.3.1).

The daily averaged SSC is also easier to interpret at longer timescales than its instantaneous value. Strictly speaking, averaging intervals of two tidal cycles would be better (24h 50min), however the impact of the use of daily values has been deemed acceptable.

It is also noted in sections 3.1.5 and 3.1.6 that saturation occurs at different sensors and times. The effect of this saturation is that the turbidity (or the derived SSC) timeseries show clipping. As a consequence, average calculations underestimate the true average in these periods, and may lead to false interpretations of trends or changes in turbidity or SSC evolution over time.

To circumvent this, the median values instead of average values have been used in further presentations. It is noted that this is a change to the preceding reporting.

The comparison of median and average for the data in which clipping does not occur shows a good correlation (Figure 3-4).

The resulting daily median statistics graphs are presented in annex B.2.

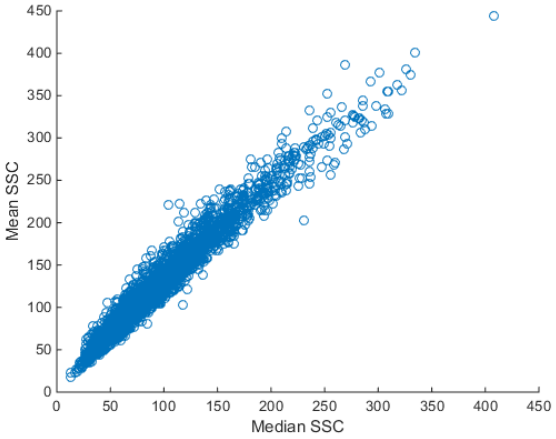

Figure 3-4: Correlation the daily median and the daily mean SSC at DGD entrance.

3.2.3.3 Filling of gaps for sedimentation model input

The sedimentation model (section 3.3) requires complete time series over the entire period. Therefore gaps in salinity and SSC at the dock entrance have been filled by correlations with other available observations in the Scheldt:

- For the salinity, all sensors listed above cross-correlate well (correlation coefficient R=0.82 in Figure 3-5), except with Oosterweel which is further upstream and thus shows different salinity variation properties. Gaps at all stations are filled with a linear regression with B84BOT data (largest dataset available), remaining gaps with a linear regression with B84TOP.
- For the turbidity and the SSC, correlations are much weaker due to the high local variability at the dock entrance. Nonetheless, periods of high daily mean SSC correlate reasonably well between the Buoy 84 sensors[1] and those near the dock entrance (correlation coefficient R=0.57). Gaps of data at the sensors at the dock entrance have been filled with a linear regression with B84BOT at the bottom, and with B84TOP at the top.

[1] Buoy 97 data was not applied for correlation because there is no record after 2008 at this station.

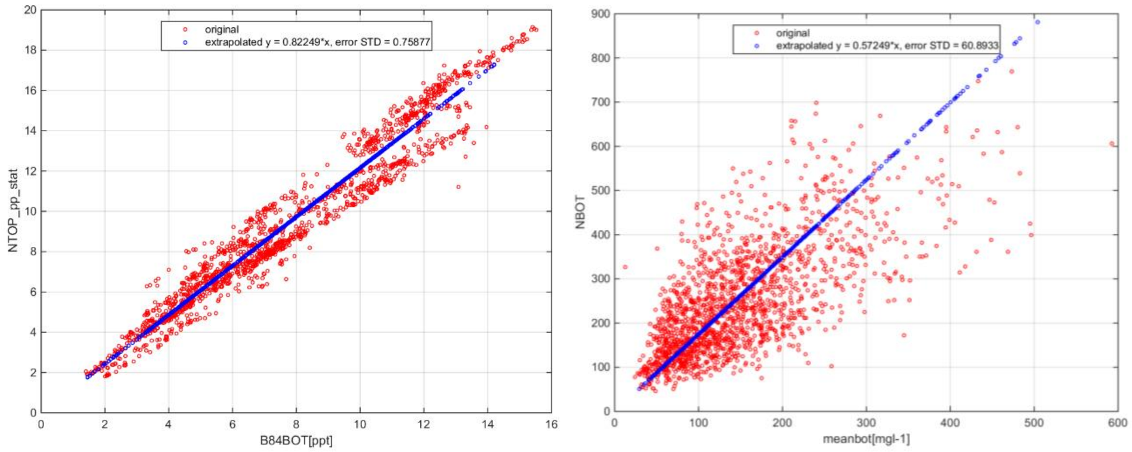

Figure 3-5: Example of linear regression used to fill salinity gaps (left) at NTOP from data at B84BOT and SSC gaps (right) at NBOT from B84BOT.

3.2.3.4 Intratidal variations

Based on the full time series, tidal average representations have been produced as well (similarly using the median instead of the mean values to circumvent clipping in the SSC data). The representation shows the evolution of the parameter through the course of one tide, centred on the moment of high water. The representation is split in several graphs, as function of the

- Neap-spring phase: neap vs. mean vs. spring tide;
- Timing with regard to CDW construction: before vs. after CDW construction.

The images are reproduced in Annex C.

3.3 SEDIMENTATION MODEL SETUP

A conceptual sedimentation model based on data assimilation has been developed to estimate the sediment influx and deposition due to the three main water exchange mechanisms at the dock entrance: tidal filling, density currents and eddy currents (IMDC, 2007c, 2008b, 2009a). This model was further developed in IMDC (2013a) to estimate the sedimentation in the dock since its construction and in particular to model the impact of the CDW on the sedimentation.

In the next sections, a concise overview of the current state of the model and relevant past assumptions is presented below. Furthermore, modifications applied in this project are explained and justified.

3.3.1 Model concept

The model assumes that the water exchange can be split into three water exchange components: tidal filling, density currents and eddy currents. The sedimentation in the dock is computed as the sum of net sediment fluxes for each exchange mechanism.

$$F_{total} = F_{tide} + F_{density} + F_{eddy}$$

The expression used for each net flux has been chosen based on a mix of physics and observations. While ideally fluxes are computed as the space and time integral of the instantaneous velocity times the sediment concentration, limited data and ease of use require to reduce these integrals which are highly variable in time to single values for one tidal cycle. In that way the expressions reduce to well-identified forcing factors with few calibration parameters.

The main data sources used in this chapter are the long-term measurements of salinity and SSC and the 13h measurements at the dock entrance. However, no13h measurements has been performed between 2012 and 2014.

3.3.1.1 Tidal filling

Tidal filling brings a known amount of water into the dock with a given concentration. The influx of sediment during flood is then defined as the tidal prism times a tidally-averaged concentration (variable at a larger time scale). Of this influx a fraction $\alpha_{set,tide}$ settles and is not evacuated during ebb. The net sediment flux due to tidal filling is then defined as:

$$F_{tide} = \alpha_{set,tide} V_{prism} c(t) = \alpha_{set,tide} h(t) A_h c(t)$$

where

- $\alpha_{set,tide}$ is the fraction of the influx settling in the dock
- $h(t)$ is the tidal amplitude
- A_h is the horizontal dock area
- $c(t)$ is the tidally averaged sediment concentration

The sediment concentration is computed per day as the spatial average of the daily average of the four measuring stations at the entrance.

3.3.1.2 Density currents

Density currents arise from an initially horizontal difference in density which is compensated by a water level gradient. The imbalance of hydrostatic forces over the vertical drives a two-layer current with the near-bed current towards the lower density region and the surface current in opposing direction.

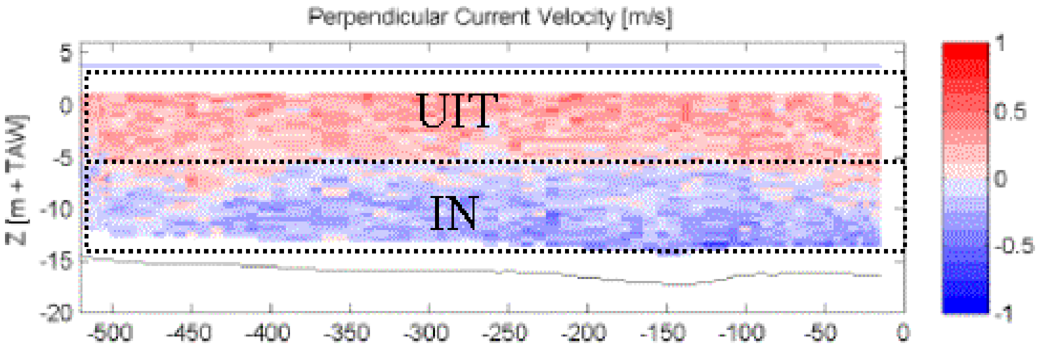

Figure 3-6: Example of density current at high water at the dock entrance (v>0 leaves the dock). Measurement before CDW.

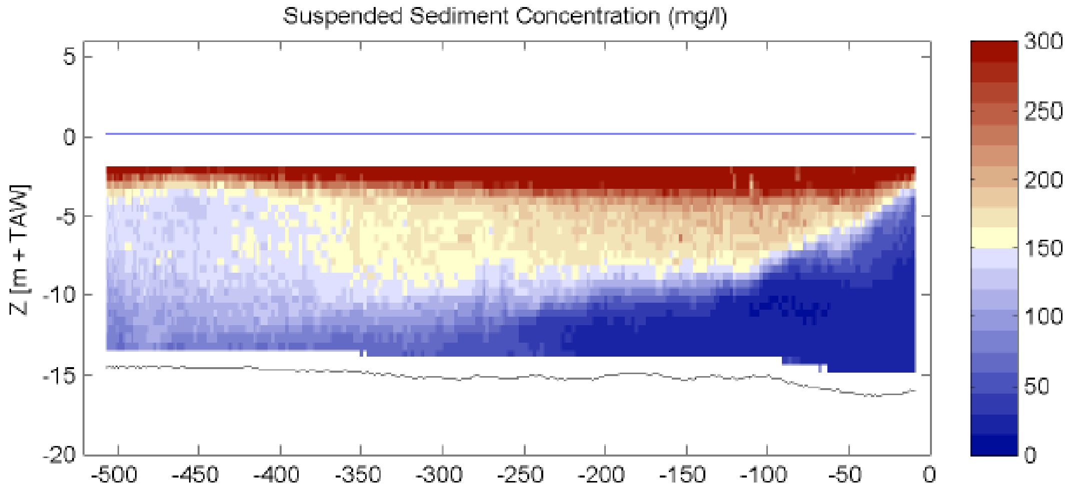

Figure 3-7: Example of inverse sediment concentration profile during low water density current at the dock entrance, when water from the Scheldt enters the dock near the surface. Measurement before CDW (not related to Figure 3-6).

The density current velocity could be expressed as (Kranenburg, 1998):

$$v_{dens} = 0.5\sqrt{\frac{\Delta\rho}{\rho} g H_{dock}} = 0.5\sqrt{\varepsilon(t)\ g\ H_{dock}}$$

where

- ρ is the density
- $\Delta\rho$ is the density difference between the two layers (so vertical or horizontal)
- $\varepsilon(t) = \frac{\Delta\rho}{\rho}$ is the relative density difference (computed from salinity difference)
- g is the gravity constant
- H_{dock} is the depth of the dock

The two layers of the density current are assumed to be of the same thickness and the current in each layer of equal magnitude. The density current distribution is assumed to be uniform over the entire dock cross-section and to last a certain duration during the tidal cycle in order to yield a volume of water exchanged in a tidal cycle. Like tidal filling, the net sediment flux is given by multiplying the influx with a tidally-averaged concentration and only a fraction $\alpha_{set,dens}$ settles in the dock :

$$F_{dens} = \alpha_{set,dens} \, V_{dens} \, c(t) = \alpha_{set,dens} \frac{A_{cs}}{4} \sqrt{(\varepsilon(t) \, g \, H_{dock})} \, T_{dens} \, c(t)$$

where

- $\alpha_{set,dens}$ is the fraction of the influx settling in the dock
- A_{cs} is the cross-sectional entrance area
- T_{dens} is the measured duration of the density currents

The salinity amplitude used to compute density currents has been computed as the maximum daily value of all four sensors at the dock entrance minus their minimum. It is hence larger than the salinity amplitude at a given single location.

3.3.1.3 Eddy currents

The tidal eddy during flood results in water entering the dock via the Southern half of the entrance and leaving it via the Northern half. This process is reversed during ebb.

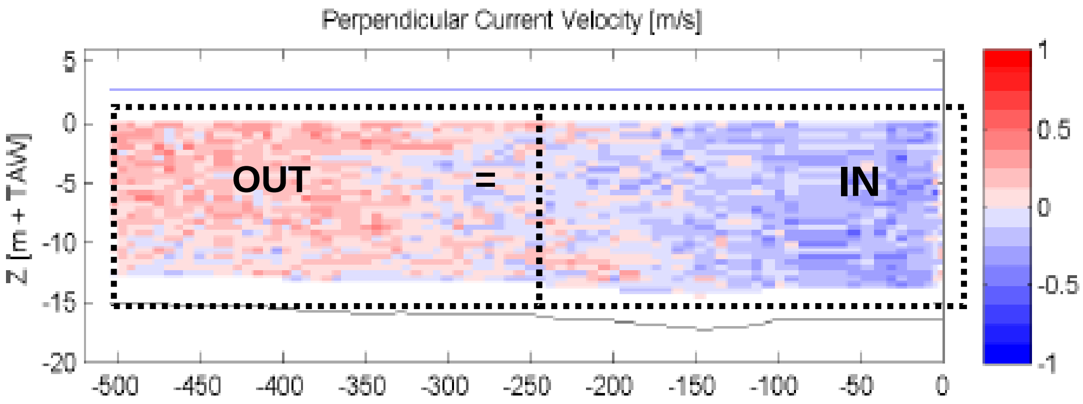

Figure 3-8: Example of eddy circulation during flood at the dock entrance (v>0 leaves the dock). Measurement before CDW.

The eddy current velocity is taken as a measured average value modulated by the tidal coefficient. Like the density current, the eddy current is assumed to be equally strong in the two halves of the entrance but with an opposing sign, and it is assumed to last a certain duration (T_{dens}) during the tidal cycle. The net sediment flux is given by multiplying the influx with a tidally-averaged concentration and only a fraction $\alpha_{set,eddy}$ settles in the dock:

$$F_{eddy} = \alpha_{set,eddy} \, V_{eddy} \, c(t) = \alpha_{set,eddy} \frac{A_{cs}}{2} \, v_{eddy} \frac{h(t)}{\bar{h}} T_{eddy} \, c(t)$$

Where

- $\alpha_{set,eddy}$ is the fraction of the influx settling in the dock
- v_{eddy} is the measured mean eddy velocity
- $\bar{h}$ and $h(t)$ are respectively the average and the daily tidal amplitude
- T_{eddy} is the measured duration of the eddy

In theory the mean eddy velocity depends on the tidal amplitude, with a stronger eddy during spring tide. Here a constant average value is taken and a lower and higher values are used to determine the uncertainty band.

The previous version of the sedimentation model in IMDC (2009a) also includes a correction factor to account for the fact that the mixing zone (and the eddy) is moving in and out of the dock during the tidal cycle. According to Eysink (1989), this effect reduces the water exchange (velocity) due to the eddy by a fraction β of the tidal exchange (velocity). However, according to the 2006-2012 report (IMDC, 2013a), this correction is negligible in the present case ($v_{eddy} \gg \beta v_{tide}$). Therefore in the present report, we neglect this correction.

3.3.1.4 Settling coefficients

The settling coefficients can be interpreted as the trapping efficiency of the individual exchange mechanisms. They are determined in the following way:

- For <u>density currents</u>, the settling coefficient is calculated from the vertical SSC gradient. Strictly speaking it is equal to the influx minus the outflux divided by the influx:

$$\alpha_{set,dens} = \frac{F_{dens,in} - F_{dens,out}}{F_{dens,in}}$$

  With the previous assumptions that the two layers of the density current are assumed to be of the same thickness and the current in each layer of equal magnitude, the following expression is valid:

$$\alpha_{set,dens} = \frac{\overline{\Delta c_{z,HW}} - \overline{\Delta c_{z,LW}}}{c_{NBOT,HW} + c_{SBOT,HW} + c_{NTOP,LW} + c_{STOP,LW}}$$

  However because these assumptions are sometimes violated, unrealistic values of $\alpha_{set,dens}$ are sometimes obtained (above 1 or below 0). To reduce this, the denominator was replaced by the maximum SSC during flood and ebb in previous reports:

$$\alpha_{set,dens} = \frac{\overline{\Delta c_{z,HW}}}{\max(\overline{c_{NBOT,HW}}, \overline{c_{SBOT,HW}})} - \frac{\overline{\Delta c_{z,LW}}}{\max(\overline{c_{NTOP,LW}}, \overline{c_{STOP,LW}})}$$

  where the overbar denotes the mean over North and South for $\overline{\Delta c_{z,\dots}}$ and the mean over both bottom or both top sensors for $c_{.BOT,\dots}$ and $c_{.TOP,\dots}$ respectively.

- For eddy currents, the settling coefficient is calculated from the horizontal SSC gradient. A correction factor 0.5 is applied on the ebb contribution to account for the weaker eddy during ebb than during flood. Similar to the density currents, the correct and the original formulae respectively read :

$$\alpha_{set,dens} = \frac{0.5\,\overline{\Delta c_{B,eb}} - \overline{\Delta c_{B,flood}}}{0.5\,(c_{NBOT,ebb} + c_{NTOP,ebb}) + c_{SBOT,flood} + c_{STOP,flood})}$$

  and

$$\alpha_{set,eddy} = \frac{0.5\,\overline{\Delta c_{B,ebb}}}{\max(\overline{c_{S,ebb}}, \overline{c_{N,ebb}})} - \frac{\overline{\Delta c_{B,flood}}}{\max(\overline{c_{S,flood}}, \overline{c_{N,flood}})}$$

  where the overbar denotes the mean over bottom and top for $\overline{\Delta c_B}$ and the mean over both South or both North sensors for $c_S$and c_N respectively.

- For tidal filling, the remaining settling coefficient is derived such that the global trapping efficiency derived from the 13h measurement campaigns is reproduced, given the relative importance of each sediment exchange mechanism (tidal filling, eddy current, density current) estimated from the previous application of the conceptual sedimentation model:

$$\omega_{dens}\alpha_{set,dens} + \omega_{eddy}\alpha_{set,eddy} + \omega_{tide}\alpha_{set,tide} = \alpha_{global}$$

  where the three first weights below have themselves been estimated with the sedimentation model (IMDC, 2009a) and the global trapping efficiency has been measured :
  - ω_{dens} = 66 %
  - ω_{eddy} = 10 %
  - ω_{tide} = 24 %
  - α_{global} = 39 % (global trapping efficiency, e_s in report IMDC (2009a))

The settling coefficients are calculated during a certain period in each tidal cycle during which the relevant exchange mechanism exists independently from the other mechanisms: from HW to HW+1 (HW) and from LW to LW+1 (LW) for density currents, from HW-3 to HW-2 (flood) and from LW-3 to LW-2 (ebb) for the eddy.

The settling coefficients have been found very sensitive to the way they are calculated and the way the data has been pre-processed. It was hence suggested to consider these settling coefficients as potential calibration coefficients (IMDC, 2013a), but to use the same processing and calculation method before and after the construction of the CDW.

As data is available since the construction of the dock, the pre-processing has been done again using the entire available dataset to obtain extra insight on multiyear variability. This data analysis is presented in the next chapter together with the application of the sedimentation model.

3.3.2 Model setup

3.3.2.1 Input timeseries

The input data for the sedimentation model consists of different timeseries (tide, salinity and SSC), and displayed in Figure 3-9:

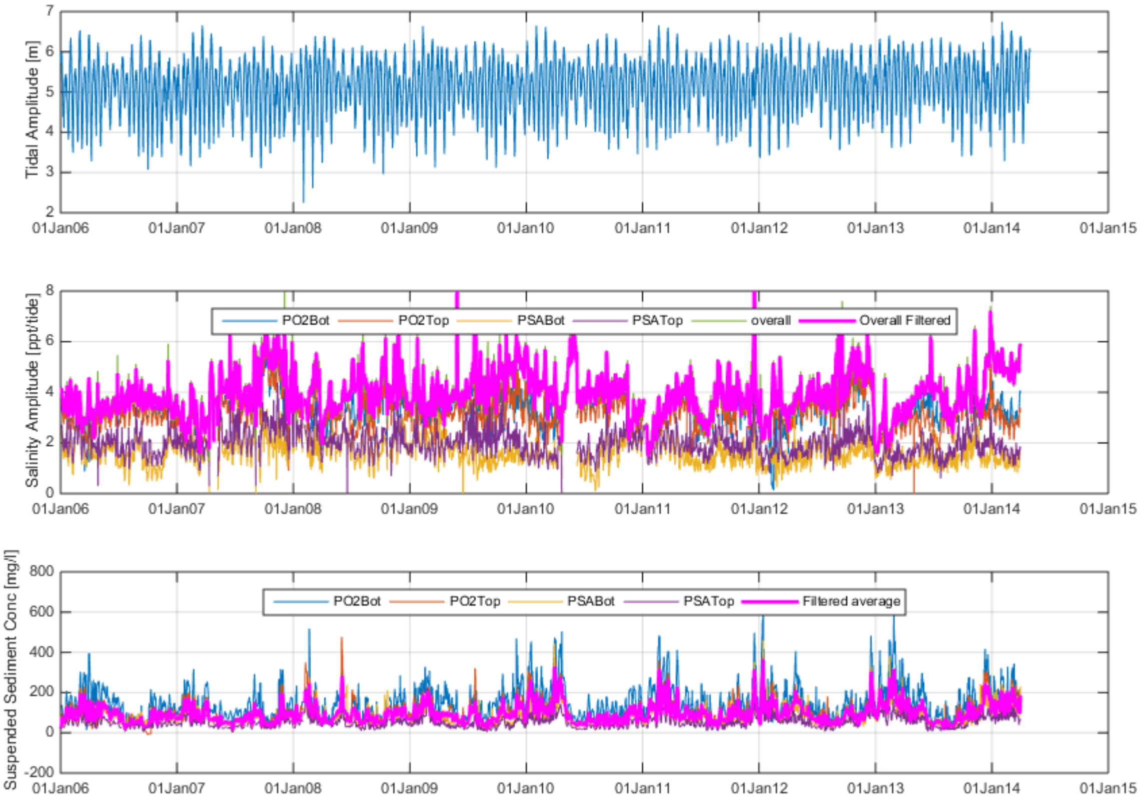

Figure 3-9: Sedimentation model input timeseries of water level, salinity and SSC.

3.3.2.2 Schematisation of the human impacts

Lengthening of the dock

The dock length has been increased in the model from 1500m to 2500m starting from April 2008 to account for the dock extension.

Removal of the entrance sill

The effect of the removal of the entrance sill has been modelled by increasing the dock depth from 16m to 18m starting from July 2010 (Figure 3-10). The depth is measured over the sill because the water exchange is computed at the entrance.

Increase of the maintenance depth

Table 3-3 presents an overview of the maintenance depths in Deurganckdok over time. The depth of the dock has been increased simultaneously to the removal of the sill as of March 2011. It can be seen that the period with full dock, deeper entrance depth and without CDW is very short compared to the model period. Furthermore, the effect of construction work comes progressively with the construction work.

Therefore, the end date of the construction of CDW is chosen as the same as the starting date of deepen depth of the dock as well as maintenance depth (1st April 2011), to simplify the model.

No additional schematisation has been applied for the larger depth after October 2012. Note that the maintenance depth is relative to the 33 kHz signal of the echosounder, while the 210 kHz signal gives the top of the mud layer.

The increase in the maintenance depth can have an impact to the density currents. An increase in duration of density currents of 20 % has been applied starting from April 2011 to reflect this observation through ADCP measurements (IMDC, 2013a).

Note that the deepening of the Scheldt is affecting the dock only indirectly via the boundary conditions and thus no schematization has been applied to account for this.

Current Deflecting Wall

Overall the effect of the CDW is therefore just modelled with a shorter eddy duration and a longer density duration starting from September 2011 as suggested in (IMDC, 2013a).

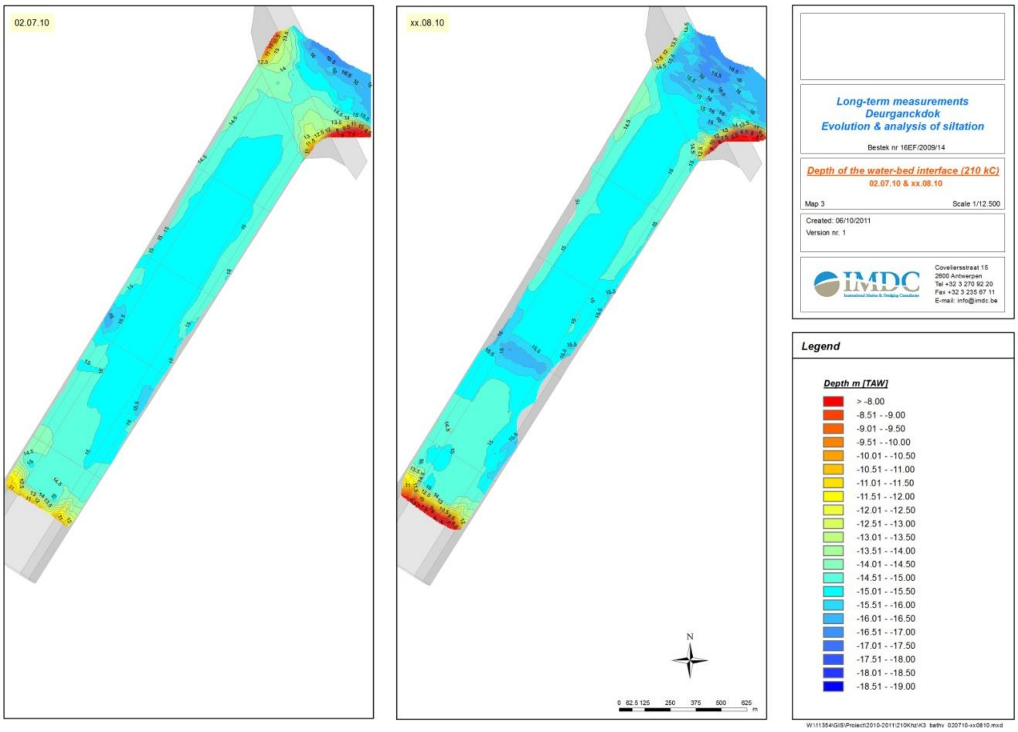

Figure 3-10: Bathymetry of the dock before (left, July 2nd 2010) and after dredging the entrance sill (right, August 2010). Note that the sill can be much shallower after a long period without maintenance.

Table 3-3: Overview of maintenance depths in Deurganckdok over time.

Date	Maintenance depth quays [m LAT]	Maintenance depth trench [m LAT]	Maintenance depth sill [m LAT]
May 2008 - December 2010	14.8 – 15.7 m (variable)	15.0 – 17.0 m (variable)	No maintenance of sill except sweepbeam
December 2010	|	|	14.8 – 15.5 m (variable)
March 2011	**15.9 m**	**17.5 m**	**15.2 m**
October 2012	|	**18.0 m**	|

Summary of the schematization changes

The schematization through time has been carried out as presented in Table 3-4.

Table 3-4: Variable parameter values per period.

Period	Dock length L_{dock}	Dock/entrance depth H_{dock}	Duration eddy T_{eddy}	Duration density currents T_{dens}
1/7/2005 to 1/4/2008 (short dock)	1500 m	16 m	6 hours	5 hours
1/4/2008 to 1/7/2010 (long dock)	2500 m	16 m	6 hours	5 hours
1/7/2010 to 1/4/2011 (long dock, no sill)	2500 m	18 m	6 hours	5 hours
1/4/2011 to 1/4/2014 (long dock, no sill, CDW, deeper dock)	2500 m	18 m	1 hour	6 hours

3.3.2.3 Sediment properties and strategy

There is some uncertainty surrounding the values of the settling coefficients depending on the calculation method and on the data set used for the analysis.

The global trapping efficiency has been derived from many 13h campaigns (IMDC, 2013a) and is assumed to be reliable. It was shown that the average trapping efficiency is very comparable between without (39 %) and with the CDW (42 %) (IMDC, 2013a).

No ADCP measurement data are available to support a specific change of the trapping efficiency inside the dock after the deepening of the maintenance depth in October 2012 to 18.0 m TAW.

Flocculation effect: updated formulation

It was suggested in the previous analysis report (IMDC, 2013a) that the trapping under high SSC conditions can be higher due to increased flocculation in the low-turbulence environment of the dock. Increased flocculation under high SSC can be modelled by modulating the trapping efficiency with the SSC for each trapping coefficient:

$$\alpha_{floc} = \frac{SSC(t)}{\overline{SSC}}$$

Flocculation is a very complex process but in the absence of data it is difficult to introduce more dependencies. The fall velocity reacts positively to an increase in SSC (IMDC, 2005a, 2006b). A linear law is chosen in first instance for simplicity. Previous fall velocity measurements (e.g. Thorn, 1981) support this assumption but do not specify the type of relation between fall velocity and SSC. The Manning flocculation model seems to suggest a non-linear response of the fall velocity to the SSC with a power greater than one, in particular above a SSC of 500mg/l (IMDC, 2005a, Fig. 6-37). An optimal turbulence level can also strongly increase the flocculation and fall velocity.

However, for larger concentrations (around 1 g/l), a transition occurs, and the settling velocity of the suspension decreases with concentration higher than this transition value.

In order to take into account this effect in the calculation, it is then proposed to modify the formula of flocculation factor by the following one:

$$\alpha_{floc} = \max(1, \frac{SSC(t)}{SSC})$$

In the application of the sedimentation model (section 4.2), the flocculation effect is first calculated using the original formula proposed in (IMDC, 2013a), in order to compare with the results from previous report (IMDC, 2013a).

Dredging volumes

Dredging volumes are obtained from the BIS system and measured mass have been converted from the values reported in the annual mass balances to a weighted area mean, as in the previous analysis report.

3.3.3 Model application overview

The model has finally been applied with 4 different settings:

- Setting “0”, using the settings of the previous analysis report and original timeseries (with old calibration curves)
- Setting “1”, using the RheoTune and Densitune scaling factor, the updated timeseries (new calibration curves) and a lower global trapping efficiency to compensate for the higher SSC values after recalibration of the turbidity.
- Setting “2”, similar to Setting “1”, but using the new flocculation formula
- Setting “3”, similar to Setting “2” but with an increased global trapping efficiency during an SSC peak in April 2010.

Additional settings “4” to “10” are also introduced to model to estimate the external effects (CDW and change in maintenance depth) on the sedimentation rates of Deurganckdok. The several settings are presented in Annex D.1 on the similar manner as Table 3-4. The results are presented in section 4.2.7

Table 3-5: Parameters used in the global sedimentation model.

Parameter	Description	Setting 0: previous report	Setting 1: new timeseries and reduced trapping	Setting 2: add new flocculation factor	Setting 3: increased trapping efficiency
α_{global}	Global trapping efficiency (corresponding to settling coefficients for density, eddy and tidal filling of 0.35, 0.14 and 0.66)	**0.39**	**0.32**	**0.32**	**0.32 before 1/4/2010** **0.64 between 1/4 and 1/7/2010** **0.32 after 1/7/2010**
α_{floc}	Flocculation factor	$\alpha_{floc} = \frac{SSC(t)}{\overline{SSC}}$	$\alpha_{floc} = \frac{SSC(t)}{\overline{SSC}}$	$\alpha_{floc} = \max(1, \frac{SSC(t)}{\overline{SSC}})$	$\alpha_{floc} = \max(1, \frac{SSC(t)}{\overline{SSC}})$
L_{dock}	Dock length	1500 m before April 2008, 2500 m after			
B_{dock}	Dock width	450m			
H_{dock}	Average dock depth	16m / 18m before / after July 2010			
T_{dens}	Duration of density currents during flood or ebb (calibration parameter for relative importance of water exchange due to density currents)	5 hours before April 2011, 6 hour after (as result of change in maintenance depth)			
T_{eddy}	Duration of eddy currents during flood or ebb (calibration parameter for relative importance of water exchange due to eddy currents)	6 hours before April 2011, 1 hour after (as result of CDW construction)			
v_{eddy}	Mean value of average eddy velocity	0.1 m/s, 0.05 – 0.15 m/s for uncertainty			
h	Average tidal amplitude	5.14 m			
ρ	Water density	1010 kg/m³			
T_{tide}	Tidal period	12h 25 min			
g	Gravity constant	9.81 s^{-2}			

4. ANALYSIS

In this chapter, the **analysis** will consist of a description of the timeseries (section 4.1.1), the daily statistics (section 4.1.2) and the mean tidal cycles (section 4.1.3). In section 4.1.4 the 13-hour measurements are briefly considered. After the data description, the sedimentation model will be applied and the results described (section 4.2).

During the description (and discussion in the next chapter), attention will be given specifically related to the hypotheses and research questions formulated in Chapter 1.

4.1 DATA DESCRIPTION

4.1.1 Full time series

The full time series figures can be found in Annex B.1. The following visual observations can be made from the full time series 2006-2014:

Temperature

- All sensors cover quite well the time span and show a clear seasonal variability, with maximum temperatures of 20 to 25°C in July and August and minimum temperatures of 0 to 5°C in December to February.

Salinity

- The salinity measurements at the dock entrance are discontinuous and display gaps in 2006-2007 and a long gap between April 2010 and May 2011. The measurements at Buoy 84 and Oosterweel are fairly continuous. Liefkenshoek is available as station since 2009.
- At Buoy 84, a maximum salinity of 14 to 20 ppt is typically found in September and a minimum salinity of 0 to 4 ppt between December and February.
- Oosterweel shows a lower salinity (up to 15 ppt) and a larger salinity amplitude within the tidal cycle because it is situated further upstream and more central in the salinity transition zone (more freshwater influence).
- In 2009 through 2011 the salinity is significantly higher in B84BOT than in B84TOP, which is not observed since 2012. Since 2012 a new sensor was deployed at B84BOT (IMDC, 2013c) and lies more in line in period for 2009. This indicates suspected absolute salinity observations in the period 2009-2011 in the B84TOP sensor.
- The NBOT sensor displays higher salinity than the other sensors at the entrance since 2014.
- During periods with high fresh water discharge, the salinity drops fast as fresh water pushes the salinity wedge downstream. Events such as in November 2010 or December 2011 cause the salinity to drop suddenly from more than 10ppt to their minimum observed values. After such an event, the salinity gradually increases again. This effect is observed in all stations.

Turbidity and SSC

- The turbidity measurements at the dock entrance are discontinuous and display gaps in 2006-2007 and a long gap between April 2010 and May 2011. The measurements at Buoy 84 and Oosterweel are fairly continuous.
- At Buoy 84, there were some periods that the Seaguard RCM 500FTU was used in which the turbidity peaks could not captured, e.g.
    - March 2009 – March 2012 at B84TOP
    - January 2012 – December 2012 at B84BOT
- At Oosterweel, the Seaguard RCM 500FTU was also used from December 2010 until December 2012 at OWBOT, and in 2012 at OWTOP.
- The SSC time series at the entrance of DGD and Oosterweel show an increasing trend.

4.1.2 Daily values

The SSC time series of daily median values can be found in A4 format in Annex B.2. The following additional visual observations can be drawn from the time series of daily values:

- A stable and clear seasonal variation of the SSC is visible at B84. In IMDC (2016) is proved statistically that the main factor of this seasonality is the seasonal variation in fresh water discharge. In combination with other factors the seasonality could be reinforced or weakened. Those additional factors could be :
    - Extreme spring tides around the annual equinoxes
    - A spatial shift of the ETM and the salt wedge (due to the variation of fresh water discharge);
    - a higher sediment load in the winter due to winter floods;
    - more intense dredging in the winter;
    - a seasonal algal bloom in the water and/or microorganisms such as diatoms stabilizing the tidal flats leading to less mud being released in the water column in the summer.
- At Oosterweel, however, the SSC values tend to increases without any obvious seasonal variation.
- The SSC variations remain strongly variable near the dock entrance.
- A rising trend can be observed in the SSC at two sensors near the bottom (NBOT & SBOT), especially after 2010.

It has been noted in IMDC (2009a) that the SSC is the main controlling parameter of the modelled sedimentation in Deurganckdok. Although out of the scope of the report, an additional figure has been made to relate the SSC to human activities (two last figures in Annex B.2) for the sake of the discussion that follows.

- It suggests a relation between maintenance dredging activity at Deurganckdok and measured SSC at B84. A larger SSC at B84 corresponds to more sedimentation in Deurganckdok, which requires more dredging. The dredged material is then deposited near Oosterweel.
- Since September 2011, the (trends in) SSC have become more comparable between the river (B84) and the dock than before. Before 2010, the SSC values at the dock entrance are lower than at B84. This confirms that fact that the SSC at the dock entrance has increased since 2010.
- In contrast, the salinity amplitude, the second parameter used in the sedimentation model (see sections 3.3 and 4.2), remains relatively constant over the entire period 2006-2013 and is comparable between the river and the dock. From October 2013, the salinity amplitude at the entrance of the dock tend to increase to 2ppt higher than at the river which can be an error due to sensor drifting at NBOT.
- The SSC in Oosterweel suggests a relation with the disposal activity around Oosterweel with increasing SSC while there is an increase in the disposal activity. Starting from September 2009 which coincides with the period of river and dock deepening, the disposal volume is much higher than the period before. This can also be observed in the SSC time series and relationship is statistical confirmed in IMDC (2013f, 2016).
- The impact of dredging works at other locations, in particular at the Drempel van Frederik, has not been investigated. It should be noted that since 2011 mainly silt instead of sand is dredged at the Drempel van Frederik (IMDC *et al.*, 2013a).

4.1.3 Mean tidal cycle

The figures in the previous sections are not expected to show any qualitative effect of the CDW because other forcing factors and effects are expected to be far more influential. The effect of the CDW is expected to be local and intra-tidal.

To evaluate this small-scale and short-term effect, mean tidal cycles of salinity and SSC centred on HW and divided into neap, mean and spring tides have been computed comparable to the reports about long-term salinity measurements (e.g. IMDC, 2010c). Cycles before (1/4/2006 to 1/4/2010) and after the construction of the CDW (1/9/2011 to 30/3/2014) have been computed separately. **It is noted that the number of tides and winter seasons**, **before CDW construction (4 years) and after CDW construction (2.5 years, with 2 spring and summers, and 3 fall and winter seasons) is not comparable and may also influence the statistical distribution of the results.** This effect is also obvious by the fact that preliminary results in the IMDC (2013a) report may have shown different results.

To compare the data before and after CDW construction, the relative mean tidal cycles are calculated dividing each cycle by its average value.

In addition, compared to the previous analysis report, mean tidal cycles have also been computed for the B84 and Oosterweel stations to illustrate the system evolution at a bigger scale in order to identify the effect of the CDW on the sedimentation around the dock compared to larger-scale effects.

Mean tidal cycles and (gradients of) salinity, SSC and temperature can be found in Annex C.

Salinity gradients can be used as weak proxies for the intensity of density and eddy currents. Density currents are caused by horizontal density gradients. However these density currents subsequently move and mix the two water bodies in such a way that the density will relatively increase near-bed and decrease near the surface. The vertical density gradient can hence be an indirect measure of the strength of density currents and an inverse measure of vertical mixing: a larger gradient is a sign that a stronger density current is currently present, and/or that vertical mixing is weaker (stronger stratification).

Similarly in the case of an eddy circulation, the density of the river water entering near the South entrance during flood is higher than that of the water flowing out near the North entrance. The horizontal density gradient across the entrance can hence be an indirect measure of the strength of eddy currents.

The following observations can be made from the comparison of the tidal cycle with and without CDW at individual locations (all comparisons are “with CDW” relative to the situation “without CDW”):

- North entrance bottom (NBOT):
  - The salinity values are lower after CDW during neap, mean and spring tide.
  - The SSC has higher values during LW and flood, and a 10% lower peak from HW to HW +1 for mean and spring tide, but higher peak at HW+1. The SSC peak at HW thus builds up slower after 2011. Relative SSC shows lower SSC at HW which means that the peaks have not increased as much as the lower values.
- North entrance top (NTOP) :
  - The salinity values are lower after CDW during neap, mean and spring tide (similar to NBOT).
  - The SSC is similar in evolution but has higher values after CDW during flood and around HW and LW; during ebb the difference is neglectable. Differences are particularly observed during spring tide, and somewhat during neap and mean tide.
- South entrance bottom (SBOT) :
  - The salinity values are lower after CDW during neap, mean and spring tide (similar to NBOT, NTOP).
  - After CDW construction, the SSC is slightly higher during LW and slightly lower during HW. A smaller peak can be observed from HW+1 to HW+2. Relative SSC shows a much lower peak during HW.
- South entrance top (STOP) :
  - The salinity values are lower after CDW during neap, mean and spring tide. It displays a slightly flatter negative peak around LW (HW-4).
  - The SSC has higher SSC after CDW but no more peak at HW.
- Buoy 84 bottom (B84BOT):
  - Due to suspected data in the period 2009-2011, no valid interpretation can be done for B84BOT with respect to CDW construction.The SSC has lower values. After CDW, the peak in SSC occur 30 minutes earlier than before.

- Buoy 84 top (B84TOP) :
    - The salinity values are slightly lower after CDW during mean and spring tide, and similar to slightly higher during neap tide.
    - The SSC signal mostly shows lower values, except the time shortly after HW and around LW, where values are similar to the pre-CDW situation. During onset of the ebb current, values are slightly higher, but the peak SSC after HW is lower than before CDW. A small phase shift may also be observed in the SSC.
- Oosterweel bottom (OWBOT):
    - The salinity field is similar before and after CDW around LW, but slightly lower during mean and spring tide during flood and around HW.
    - The SSC has significantly higher values after 2011 during the whole tidal cycle.
- Oosterweel top (OWTOP) :
    - The salinity field is similar before and after CDW around LW, but slightly lower during mean and spring tide during flood and around HW.
    - The SSC has significantly higher values after 2011 during the whole tidal cycle.

Apart from the mean cycles, **gradients** can also be analysed (also presented in Annex C). Gradients are presented as differences between two sensors. Vertical gradients are calculated as the difference between bottom and top sensors; horizontal gradients are calculated as differences between sensors from the north and south entrance.

- Bottom sensors horizontal gradient (eddy ; NBOT-SBOT) :
    - Over a tidal cycle, the horizontal salinity gradient is getting closer to 0 which means that the eddy current becomes weaker. Except around HW+2, the gradient increases slightly.
    - The SSC gradient is higher during LW and lower during HW, in particular at spring tide.
- Top sensors horizontal gradient (eddy ; NTOP-STOP) :
    - The horizontal salinity gradient is around 0 and flatter during flood, which indicates a decrease of a flood eddy current at the surface. During the ebb onset (between HW and HW+3), however, the gradient becomes higher.
    - The SSC gradient is higher during spring tide around HW, and somewhat higher during LW at mean and spring tide.
- North entrance vertical gradient (density ; NBOT-NTOP) :
    - The salinity gradient shows similar trend between before and after CDW. At neap tide, the salinity difference is slightly lower at HW-6 to HW-5. The salinity gradient buildup during the onset of the flood flow appears to be delayed (~ 10 minutes).
    - The SSC gradient has slightly higher values during low water, but the main change is a 20 % to 40 % lower peak from HW to HW+2.

- South entrance vertical gradient (density ; SBOT-STOP) :
  - The vertical salinity gradient at the South entrance is almost the same after CDW.
  - The SSC gradient is almost the same along the cycle, with a higher difference at HW to HW+2 during spring tide.

Also the vertical gradients in the river are considered.

- B84 vertical gradient (density: B84BOT-B84TOP):
  - Due to suspected data in the period 2009-2011, no valid interpretation can be done for B84BOT with respect to CDW construction.
  - The SSC gradient is also decreased. An exception occurs at HW+3.
- Oosterweel vertical gradient (density: OWBOT-OWTOP)
  - The salinity gradient is nearly exactly the same as before.
  - The SSC gradient is in general lower suggest a more uniform environment, except at HW-5 and HW+1 (onset of ebb resp. flood currents), mostly during neap tide.

The temperature gradients are also different with the CDW, however their amplitude is so small that no significant conclusions can be drawn.

In comparison to the previous analysis report (IMDC, 2013a), it can be stated that:

- The salinity values are strikingly different; here the seasonal effect of different time series length is brought forward as an explanation;
- The result for the SSC data are fairly similar, except that the new data shows increased SSC background signal (during flood, e.g.), whereas this was not visible in the previous analysis.
- The vertical salinity gradients now show less difference than in the previous analysis report, however the horizontal salinity gradients show similar behaviour although the differences are also less pronounced.
- The vertical and horizontal SSC gradients generally show similar results.

4.1.4 13h measurement campaigns (up to 2012)

In view of absence of new 13h measurement data between 2012 and 2014, main conclusions from previous report (IMDC, 2013a) will be shortly restated:

First, a quantitative assessment on the effect of the CDW to density currents and eddy currents was performed. Flow patterns were compared against each other by plotting selected campaigns on the same time axis, from 6h before to 6h after HW. The observations showed that:

- At spring tide, the flood eddy at HW-1 is less strong after the CDW, that density currents both around HW and LW are stronger after the CDW.
- At neap tide, the flood eddy at HW-1 is less strong after the CDW, the ebb eddy is more pronounced, density currents are comparable.

Another method adapted from Christiansen (Van Maren, 2005) was also used to assess the density currents and eddy currents after the CDW. The following conclusion was deducted from the observations made by comparing two Christiansen figures before and after the CDW:

- The flood eddy is visibly shorter, but the presence of a weak ebb eddy makes the total eddy duration decreased from around 5-6h to 4-5h.
- The density currents have progressively become both stronger and longer since 2007. Their duration increased from around 6-7h before the CDW to 6-7h after the CDW.

4.1.5 Interpretation and application

All timeseries show a decrease in **salinity** through the tidal variation. As indicated in the introduction of section 4.1.3, the different covering of seasons combined with the strong seasonal variation in salinity, is considered to be the explanation for this.

Unaffected by this variation in analysis periods remain the **salinity gradients** between sensors however, since these gradients act at smaller spatial and temporal scales than the seasonal variations. The gradients suggests that

- the horizontal eddy has become weaker (NBOT-SBOT) most of the time (since the horizontal gradient value is closer to zero); the horizontal gradient at the top shows a somewhat stronger eddy around high water and ebb onset, but weaker eddy elsewhere;
- The vertical gradient at the north entrance shows a small timing difference at the onset of flood, suggesting that the bottom flow is delayed (or deflected). Later in time, the salinity gradient evolves as before. At the south entrance, no clear effect on vertical gradient is observed.

In general, an increase in 'background' **SSC** is observed (e.g. during flood). This may be related to the evolution of SSC in the river and will be discussed further. The SSC gradients show different patterns:

- The bottom horizontal gradients show slightly lower gradients during and shortly after high water, but slightly higher gradients at LW. The top horizontal gradient has become stronger during LW and HW.
- The vertical SSC gradient at the north entrance is decreased and thus suggests more vertical mixing, or bottom flow deflection. At the south entrance, there is rather an indication of slightly stronger density current action (or less mixing) at spring tide.

The data thus suggest a weaker flood eddy and a somewhat stronger ebb eddy. This corroborates with the results from the previous analysis report. The effect on the density current is not clearly derived from the salinity measurements and SSC data suggest a decrease at the north side, and slight increase at the south side.

There are no new ADCP measurement data to interpret the point measurements and their horizontal and vertical gradients in terms of the complete dock entrance section.

Based on the fact that the general description and interpretation of the new time series and their gradients do not show fundamentally different effects compared to the old timeseries, there are no strong arguments to alter the assumptions and schematizations applied in the sedimentation model in IMDC (IMDC, 2013a)

4.2 SEDIMENTATION MODEL APPLICATION

The conceptual sedimentation model developed in 2009 is applied to the period 2006-2014 and (stepwise) modifications are made as introduced in Chapter 3. Factors that may influence the model results compared to previous applications, and described in Chapter 3, are:

- Recalibration of the turbidity to SSC data and
- Use of median instead of mean averages to reduce effect of turbidity data clipping;
- Different instruments for density measurements, using scaling based on intercalibration.

In view of the interpretation in the previous section, the absence of new 13h ADCP measurement campaigns and of the uncertainty pertaining to the individual trapping coefficients (IMDC, 2013a), these coefficients were not recalculated. They will be kept as in the previous analysis report. However, the global trapping efficiency will be reviewed as part of the recalibration effort.

4.2.1 Setting 0: Application of IMDC (2013a) model

For the sake of comparison, the model result using the old SSC time series and calibrated parameters for the period of 2006-2012 from report (IMDC, 2013a) is shown in Figure 4-1. The DensiTune based measurements (green crosses) are significantly higher than the sediment mass model (black line) because of the higher densities at a specific depth in comparison to the Navitracker.

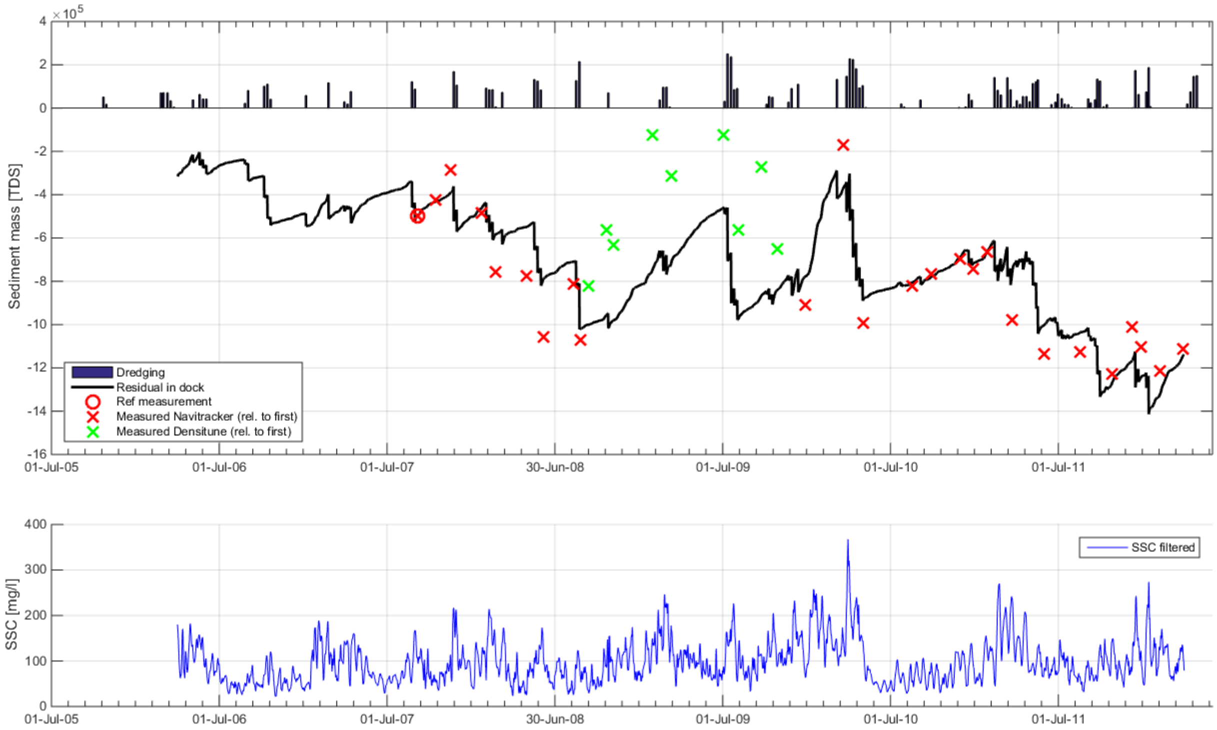

Figure 4-1: Dredging intensity (upper graph), sedimentation model (middle graph) and averaged SSC at the entrance, SSC time series and calibrated parameters from previous analysis report (equal to Figure 5-35 in IMDC (2013a)).

4.2.2 Setting 1: Model adaptations for new SSC calibration curves

For this and the subsequent model applications, the scaling factor shown in section 3.2.2 will be applied to the sediment masses based on the RheoTune and DensiTune measurements. It appears that the DensiTune based observations are indeed closer to the model than before.

Also, the updated SSC time series are used as model input but compensated for the change in calibration by a scaling factor of 0.83, which corresponds to the decrease in global trapping efficiency as shown in Table 3-5 (from 0.39 to 0.32). Other settings are unchanged.

After application, it appeared that for the period April 2006 - April 2010, the agreement between predicted mass and measured mass is comparable to the initial model result. This is expected because the model settings mainly remain the same. After April 2010 the model underestimates the observed sediment mass. This period corresponds to the starting of the construction of the CDW (April 2010) and the increased maintenance depth (visible from March to May 2011). The entrance sill has been dredged on July 1st 2010 in the model.

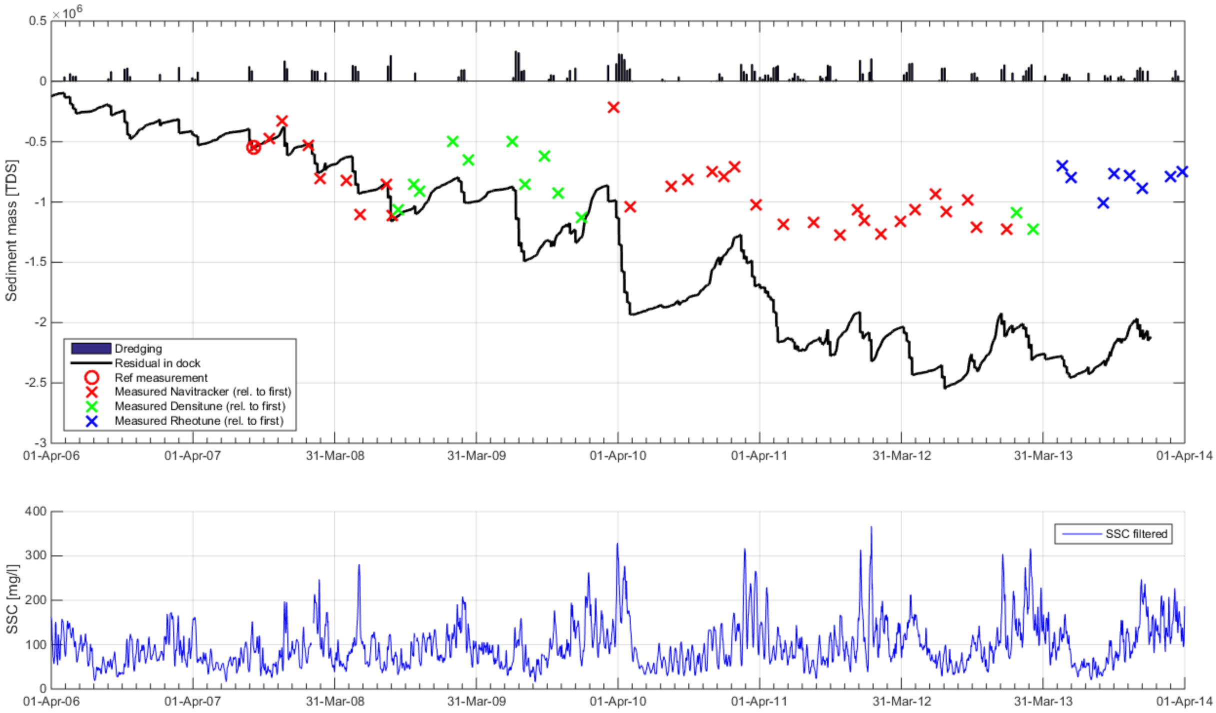

Figure 4-2: Dredging intensity (upper graph), sedimentation model (middle graph) based on updated daily median SSC time series (lower graph) including a scaling factor of 0.83.

4.2.3 Setting 2: Model adaptations for new flocculation formulation

The change to the flocculation process in the model has been applied in the subsequent model application.

With the new flocculation formula, the model gives better agreement between the predicted sedimentation and the measured mass before April 2010. After April 2010, the model still gives lower computed sediment mass than the measurement but the total mass difference is smaller (in the order of 0.5 million TDS). With the updated flocculation, the α_{floc} cannot be smaller than 1, which results in a higher sedimentation than in the preceding model versions.

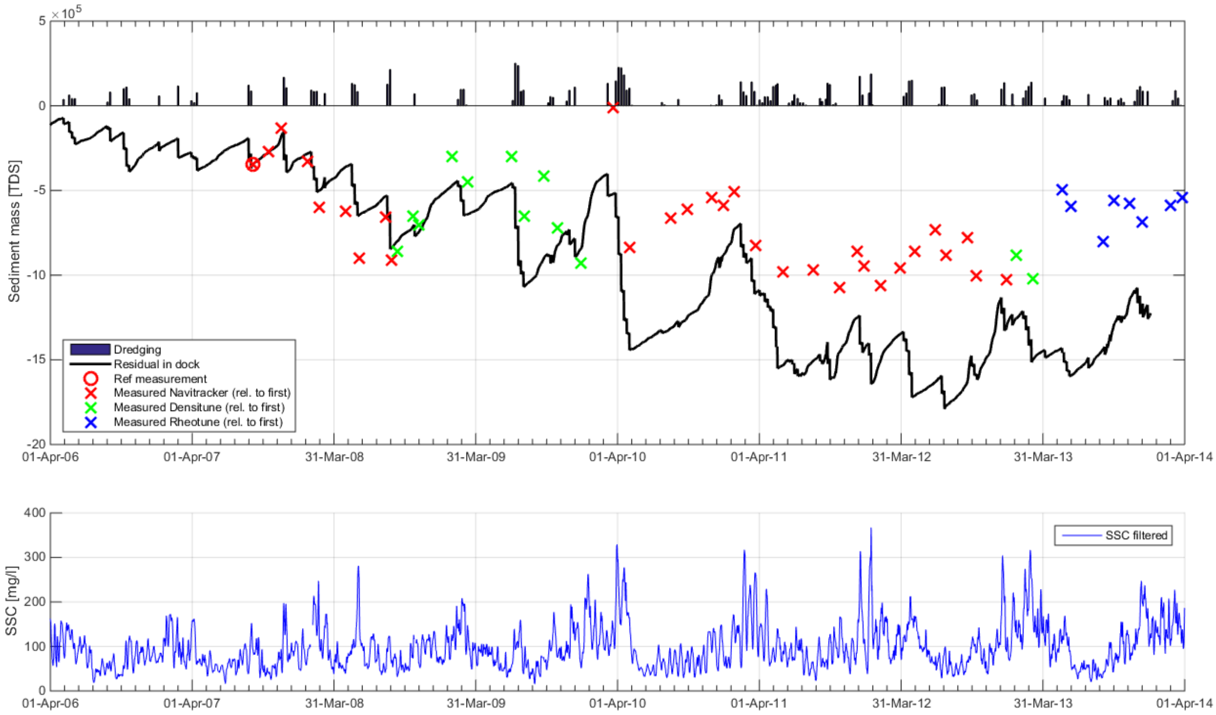

Figure 4-3: Dredging intensity (upper graph), sedimentation model (lower graph) based on updated SSC time series (lower graph) including a scaling factor of 0.83 and an updated flocculation formulation.

4.2.4 Setting 3: Increased global trapping efficiency (April-June 2010)

In model version Setting 2', the increase of the sediment mass is not completely captured (Figure 4-4). From April 9th 2011 to May 10th 2011, the SSC timeseries has been filled by SSC timeseries based on B84 SSC data. Because there may be an underestimation (especially of the higher SSC values) and possibly an influence of CDW works and sill dredging, the global trapping efficiency is increased by a factor 2 during the period 1/4/2010 – 1/7/2010 to increase the sedimentation effect of the high SSC values in April 2010.

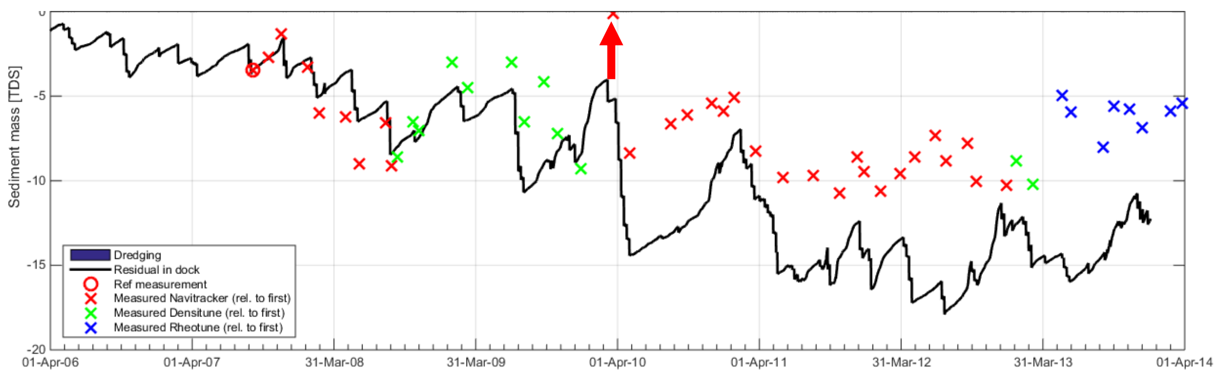

Figure 4-4: Sedimentation model (Setting 2) with indication of the underestimation of the sedimentation in April 2010 (red arrow).

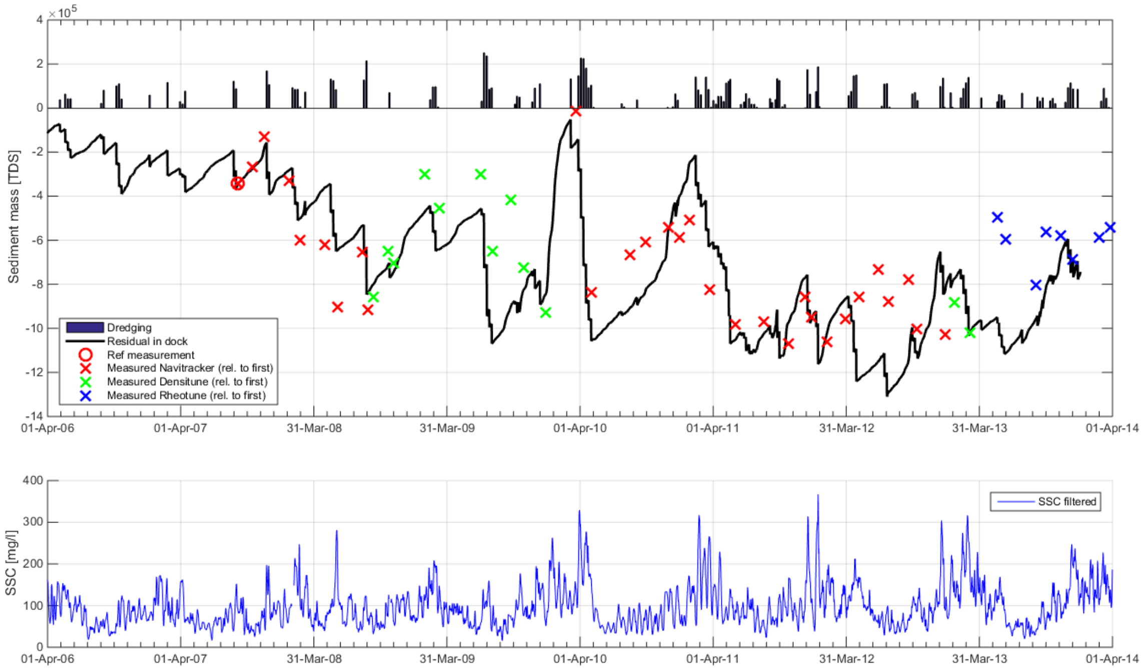

Figure 4-5: Dredging intensity (upper graph), sedimentation model (lower graph) based on updated SSC time series (lower graph) including a scaling factor of 0.83 and an updated flocculation formulation and an increased trapping efficiency between 04/2010 and 07/2010.

The effect of this short term increase in trapping efficiency is that the measured sedimentation peak of April 2010 is captured (Figure 4-5), and the subsequent cumulative sedimentation corresponds rather well to the observed volumes in terms of magnitude. The cumulated error at the beginning of 2014 is less than 2 million TDS which is (given the fact that errors are cumulated over a period of more than 5 years), relatively small.

It must be noted that the trapping efficiency in the model after 07/2010 is otherwise identical to the trapping efficiency before 04/2010. Factors that change are identical in all presented model settings: dock depth, duration of density and eddy currents.

The modelled sedimentation shortly after April 2010 does not entirely follows the observations, but this may be due to differences in the proxy SSC based on B84 data that is used. As of May 2011, the model is closer to the observations again.

Two periods in spring 2012 and spring 2013 show lower sedimentation rates that in the observations. At the moment, there is no explanation for this.

4.2.5 Water and sediment fluxes

The partial and total **water fluxes** derived from the model are shown in Figure 4-6. The changes in schematization have a clear impact on the eddy and tidal current fluxes (times indicated by vertical arrows). The increase of the dock length leads to higher tidal fluxes. The change of current durations (decrease in eddy current and increase in density current duration) lead to higher density current fluxes and lower eddy current fluxes. On the long term, a clear increase of the typical water exchange volume is observed, from 30 to 40 Mm³ per tide to 40 to 50 Mm³ per tide.

Most of this change is due to dock lengthening and deepening, as little increase is observed after 2011. Indeed, the current schematization more or less leads to cancelling of the effect of longer density currents vs. shorter eddy currents.

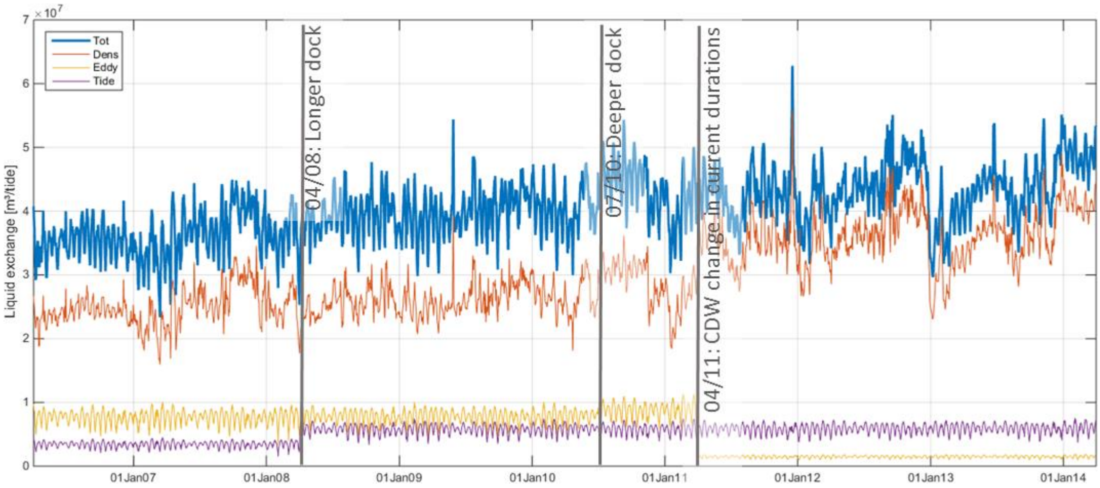

Figure 4-6: Calculated total and partial water fluxes into the dock. Vertical arrows and text indicate main schematization changes. Horizontal arrow indicates SSC timeseries filling with B84 data.

The **net sediment influx per tide** (Figure 4-7) is impacted by the selected calibration method. With the model in IMDC (2009a), the net influx is generally comprised between 500 and 2000 TDS/tide, in line with 13h measurements and numerical modelling results before construction of the CDW. With the model in IMDC (2013a) and in this report, the variation is amplified, with a net influx generally comprised between 200 and 4000 TDS. Although the calibrated model reproduces good total sedimentation, such a large variation has not been observed in the 13h measurements (up to 2012).

Overall, an increase of peak sediment influx is observed, which is the product of increased water exchange volume and sediment concentrations through time. This will be further discussed in Chapter 5.

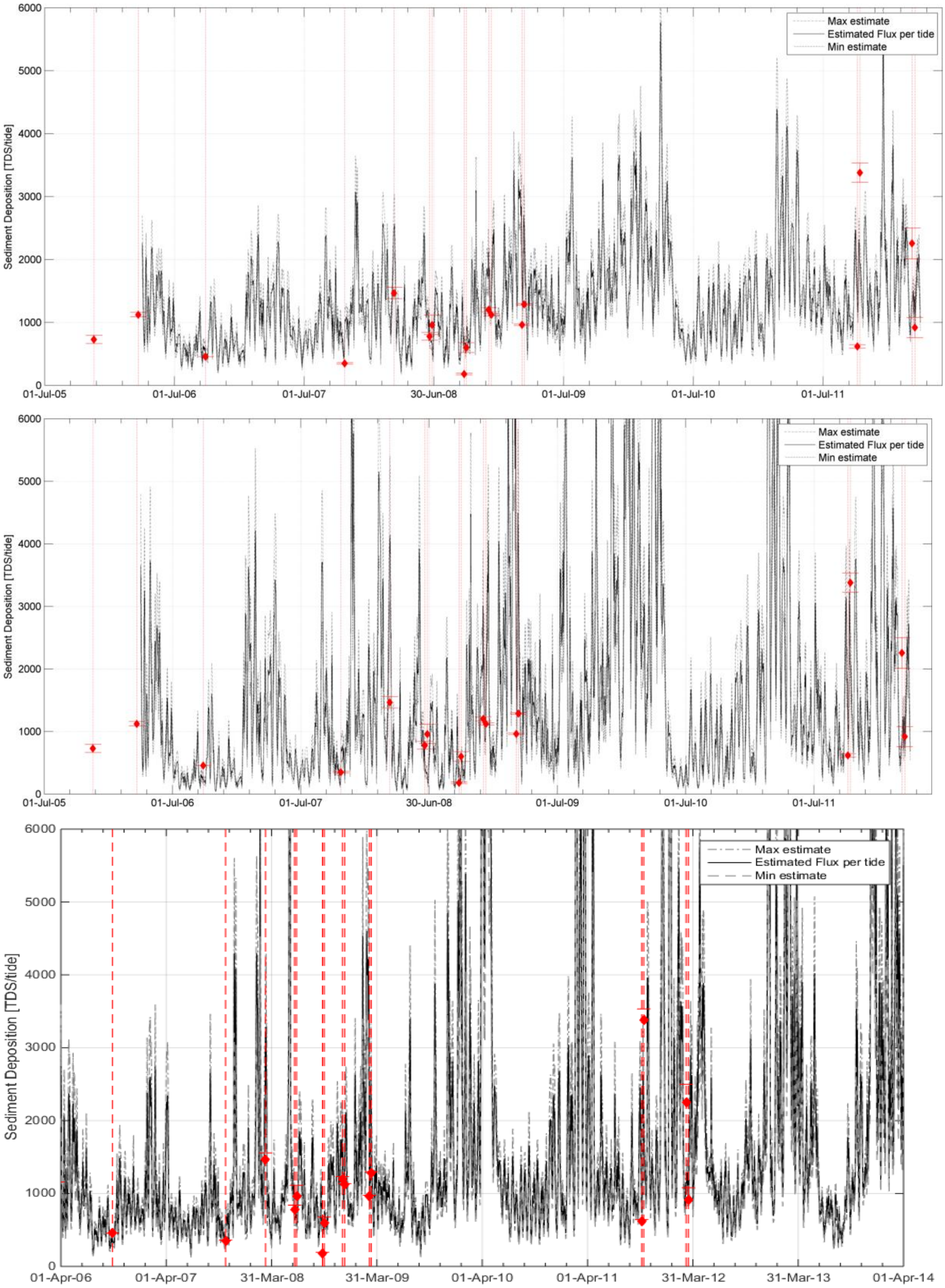

Figure 4-7: Sediment deposition per tide compared to the estimates derived from 13h measurements. Top: based on calibration period 2006-2009 parameters (IMDC, 2009a); Middle: calibration for period 2006-2012 (IMDC, 2013a); Bottom: calibrated for period 2006-2014. Red lines: ADCP measurements.

The contribution of the different exchange components to the sediment flux is obtained by the individual water exchange volumes and sediment concentrations. As imposed by the model schematization, we observe from the relative contributions that

- The dock lengthening leads to a stronger tidal prism driven sediment flux (2008)
- The dock deepening does not strongly influence the sediment fluxes
- The different current durations lead to a strong decrease of eddy flux contribution and increase of density current contribution.

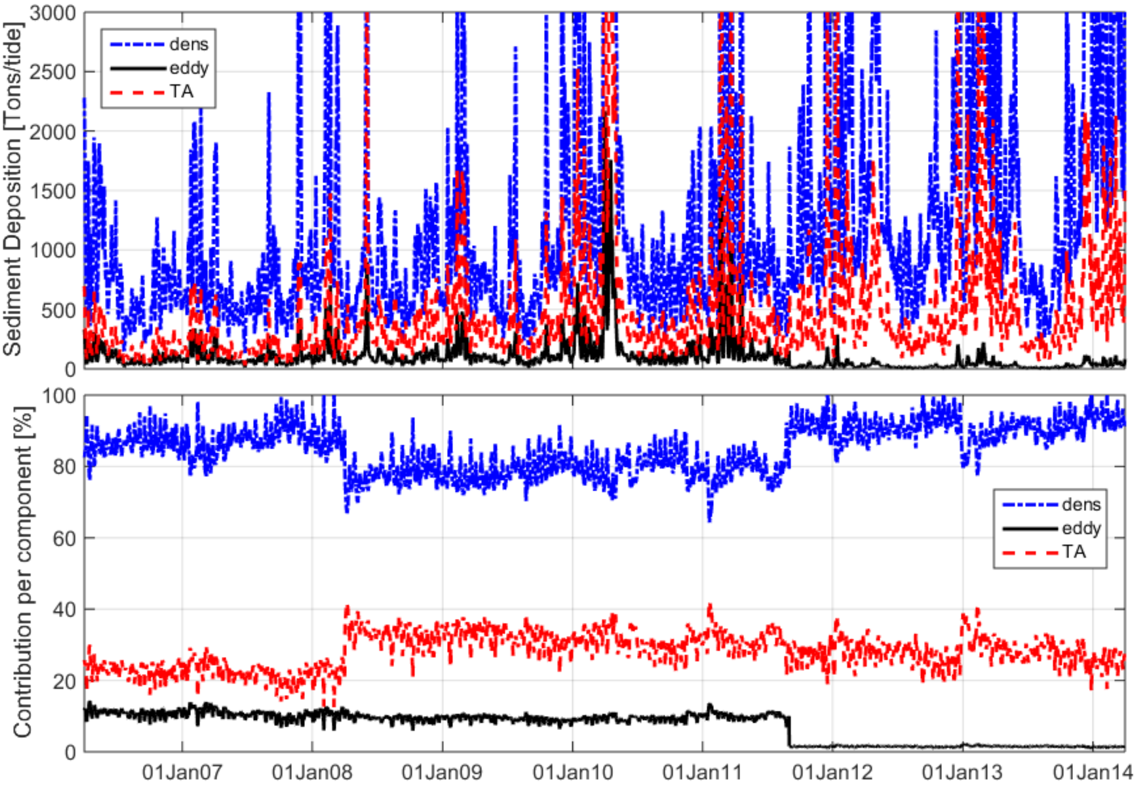

Figure 4-8: Sediment flux per component (absolute, top; relative, bottom).

4.2.6 Sedimentation volumes

In the previous analysis report (IMDC, 2009a), it was suggested that the reported dredging volumes should not include dredging of the sill at the dock entrance. This impacts the total dredged volumes reported in the yearly mass balance. Table 4-1 presents “corrected” volumes which are the weekly dredging reports minus the dredged sill volumes at the entrance of the dock and calculated sedimentation volumes from the conceptual model for the period of 2006-2012 (IMDC, 2013a) and for the period of 2006-2014 (this report).

Table 4-1: BIS dredging volumes negatively corrected for dredging of the entrance sill.

Period	Project	Reported volumes weekly data [TDS]	Corrected volumes weekly data [TDS]	Modelled sedim. [TDS] in (IMDC, 2013a)	Modelled sedim. [TDS] in this report
Apr2006-Apr2007	DGD1	690 000	690 000	590 000	553 200
Apr2007-Apr2008	DGD2	980 000	980 000	820 000	795 800
Apr2008-Apr2009	DGD3	990 000	990 000	910 000	797 700
Apr2009-Apr2010	CDW1	1 580 000	1 550 000	1 610 000	1 664 700
Apr2010-Apr2011	CDW2	1 560 000	1 330 000	1 160 000	1 170 500
Apr2011-Apr2012	CDW3	1 880 000	1 610 000	1 210 000	1 383 000
Apr2012-Apr2013	CDW9	1 511 000	1 279 000	-	1 427 000
Apr2013-Apr2014	CDW10	1 192 000	1 051 000	-	1 150 000
Total		**10 343 000**	**9 480 000**	**-**	**8 941 900**

Table 4-1 shows that yearly dredging volumes have increased from around 1 M TDS in 2008-2009 to 1.9 M TDS in 2011-2012 (reported volumes). The large increase of 500 000 TDS in 2009-2010 corresponds to part of the strong sedimentation event of winter 2010 that was considered in model Setting 3 (section 4.2.4).

In report (IMDC, 2013a), this increase of TDS from 1M to 1.9M TDS/year were attributed for:

- around 25-30 % to a change in reporting of dredging amounts (250 000 TDS to 300 000 TDS),
- around 40 % to a one-time deepening of the dock in 2011-2012 (400 000 TDS),
- around 10 % to an increase of the entrance cross-section (100 000 TDS),
- around 15 % to longer density currents excluding the larger cross-section (150 000 TDS)
- The modulation of the trapping efficiency by the SSC also has a strong impact on the sedimentation volumes, increasing it respectively by around 400 000 TDS in 2009-2010, 200 000 TDS in 2010-2011 and 100 000 TDS in 2011-2012 due – in particular in the winter 2010 – to occasional peaks in SSC.

It was then concluded in report (IMDC, 2013a) that sedimentation volumes excluding strong sedimentation events like the one of winter 2010 probably lie around 1.2 M TDS/year in 2011-2012 compared to 1 M/year in 2008-2009. This is, interestingly, in line with the measured volumes (corrected volumes) in 2012-2013 (1 279 000) and in 2013-2014 (1 051 000). Or it means that the model from report (IMDC, 2013a) is able to simulate the sedimentation volumes in the near future.

The cumulative sedimentation simulated by the model with setting 3 is presented in Figure 4-9. The total volume in Table 4-1 shows a good match between the measured dredging (9.5 million TDS after correction for sill dredging) and the predicted volumes (ca. 9 million TDS). The uncertainty band shown on Figure 4-9 is computed like in IMDC (2009a) by assuming a measurement uncertainty of the SSC of ±10 % and of ±0.05 m/s for the mean eddy velocity which leads to an error margin of ca. 2 million TDS.

The modelled cumulative sedimentation in Figure 4-9 shows roughly two increasing trends. The year 2010 marks the change between these two lines. The second line (2012-2014) presents a steeper slope than the first line (2006-2010). This will be further discussed in Chapter 5.

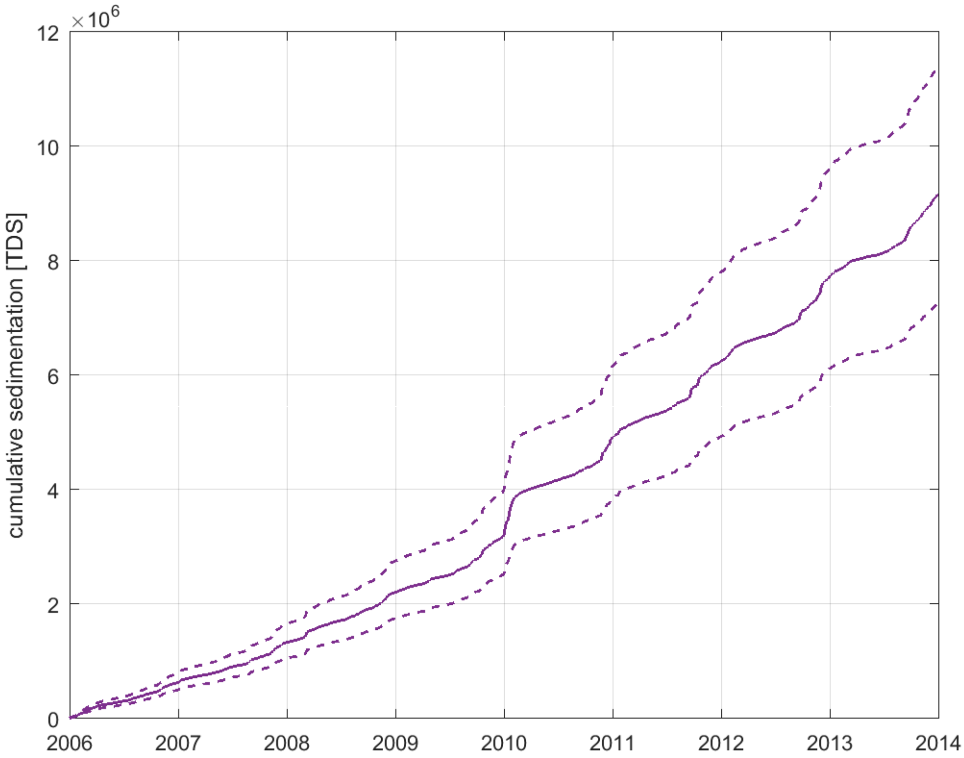

Figure 4-9: Cumulative sedimentation modelled with calibrated parameters (setting 3). Uncertainty band derived like as in IMDC (2009a).

4.2.7 External effects

Overall, the external effects are included in the model (from settings 0 to 3). To determine the external effects on the sedimentation rate of Deurganckdok, the empirical model is running several times excluding (some) external effects. This is applied by resetting the variable parameters (as described in Table 3-4) and using settings as shown in Annex D. Following conditions are used to rerun the model:

- Setting 4: Without construction of CDW (since 04/2011);
- Setting 5: Without dock deepening in 04/2011;
- Setting 6: Without construction of CDW and dock deepening;
- Setting 7: Without sill removal in 07/2010;
- Setting 8: Without sill removal, construction of CDW and dock deepening;
- Setting 9: Without dock enlargement in 04/2008;
- Setting 10: The same conditions as during the opening of the dock in 07/2005.

All the results are shown in Annex D and an overview in Table 4-2. To determine the **effect of the CDW construction** on the sedimentation rate of Deurganckdok, the model has been rerun after resetting the shorter eddy duration (setting 4). As result (Figure 4-10), the modelled cumulative sedimentation is increasing faster from April 2011 for model without CDW (setting 4) compared to with CDW (setting 3). The averaged sedimentation rate (TDS/day) from 04/2011 till 01/2014 is calculated in Annex table D-9 for the two settings (with/without CDW) to derive the effect of CDW. Finally, the difference between the two modelled rates suggests an increase without CDW between 104 and 443 TDS/day or between **3 and 9 %.**

The same method is also applied to determine the effect of **change in maintenance depth** (setting 5) and suggests a reduction of the sedimentation rate between **12 and 1 3%** (or 391 and 611 TDS/day) in case of no depth change in 04/2011.

Since 07/2010, **the sill of the dock** is removed which will have an effect on the sedimentation rate of the dock. To determine this effect the model has run again with setting 7 and has been compared to model with setting 3 (Figure 4-11). The effect could be derived in the short period 07/2010 till 04/2011 (where other effects do 'not' influence the removal) and suggest a reduction between 12 and 14 % compared to rate of setting 3 of this period. To confirm this order of reduction after 04/2011, sedimentation rates between model with setting 6 and setting 8 have been compared. This result suggests also a reduction of the sedimentation rate between 11 and 12 %, or in total between **11 and 14 %**, if the sill of dock was not removed.

The effect of **the enlargement of the dock** has estimated on the similar manner as the sill removal comparing the model results of setting 3 and setting 9 for period 04/2008 and 07/2010; and setting 8 and 10 after 07/2010 (Figure 4-12). Both estimations result in a reduction between **9 and 12 %** if the dock was not enlarged.

Table 4-2: Overview of the impact of the external effects by comparing several model settings of empirical model

<table>
<tr><th>External effect</th><th>Comparison model settings</th><th>Reduction [%]</th></tr>
<tr><td>CDW</td><td>3-4</td><td>3 and 9</td></tr>
<tr><td>Change in maintenance depth</td><td>3-5</td><td>-13 and -12</td></tr>
<tr><td rowspan="2">Sill removal</td><td>3-7</td><td>-14 and -12</td></tr>
<tr><td>6-8</td><td>-12 and -11</td></tr>
<tr><td rowspan="2">Dock enlargement</td><td>3-9</td><td>-12 and -9</td></tr>
<tr><td>8-10</td><td>-12 and -10</td></tr>
</table>

All those results of external effect are derived from the empirical model using the salinity and SSC field measurements. Those measurements are observed in condition where the external effects act. While resetting external effects in the model will still use those input observations and will introduce a certain bias. Also a change of an input parameter could have a cumulative effect with another parameter(s) influencing the model result. **Due to these reasons the results in Annex D must be handled with any care.**

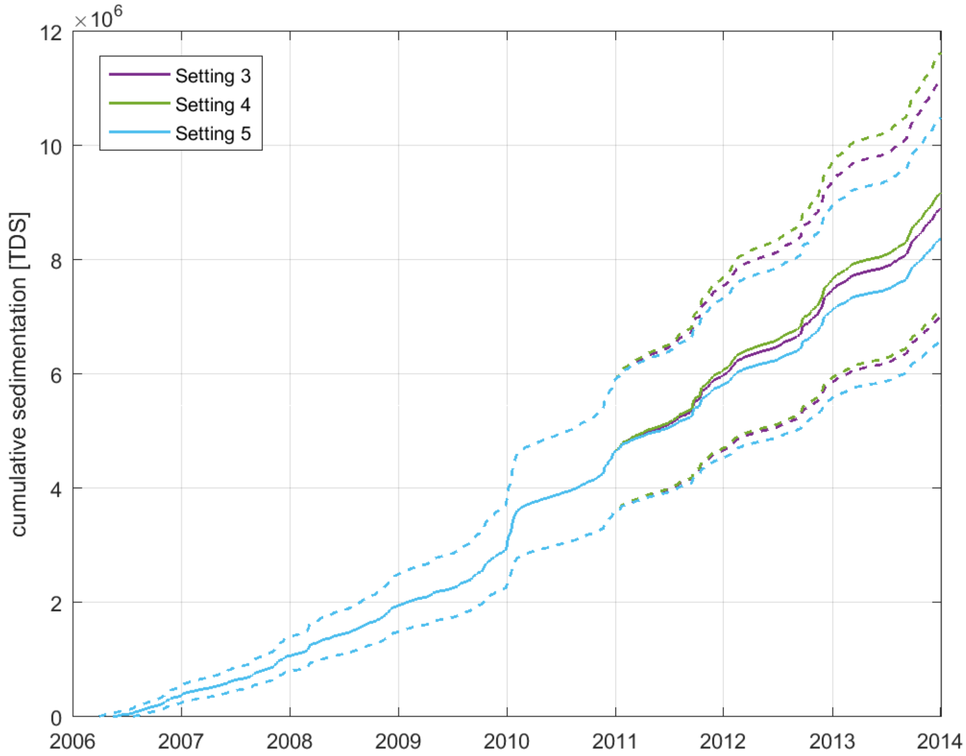

Figure 4-10: Cumulative sedimentation modelled with the settings 3 till 5 to estimate the effect of the CDW construction and dock deepening.

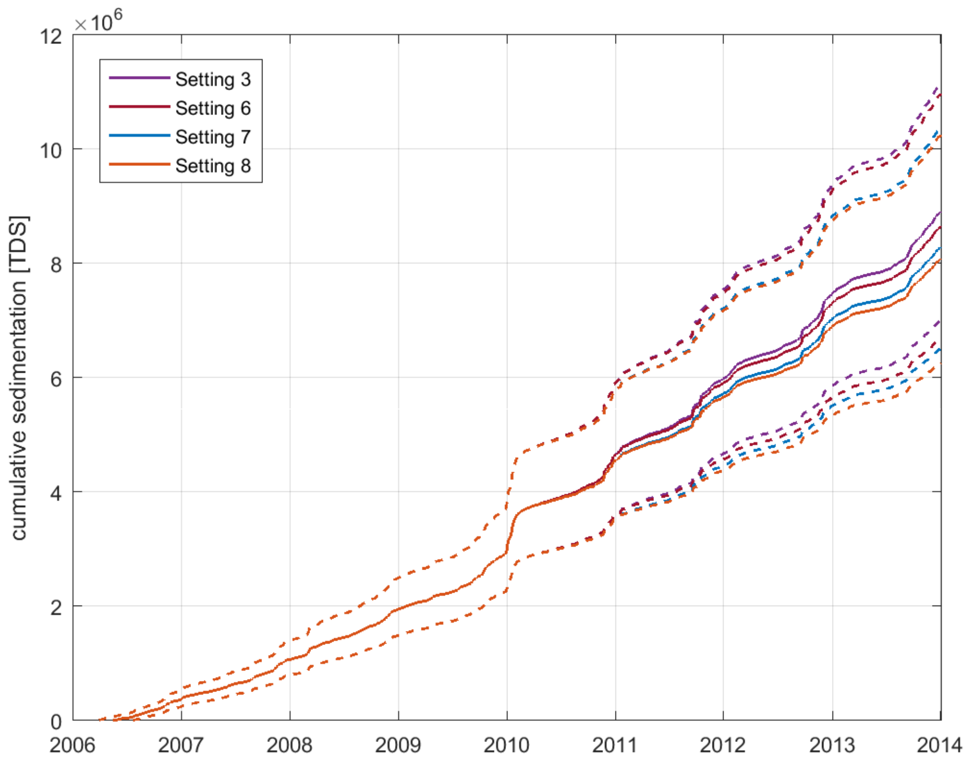

Figure 4-11: Cumulative sedimentation modelled with the settings 3, 6, 7 and 8 to estimate the effect of the sill removal.

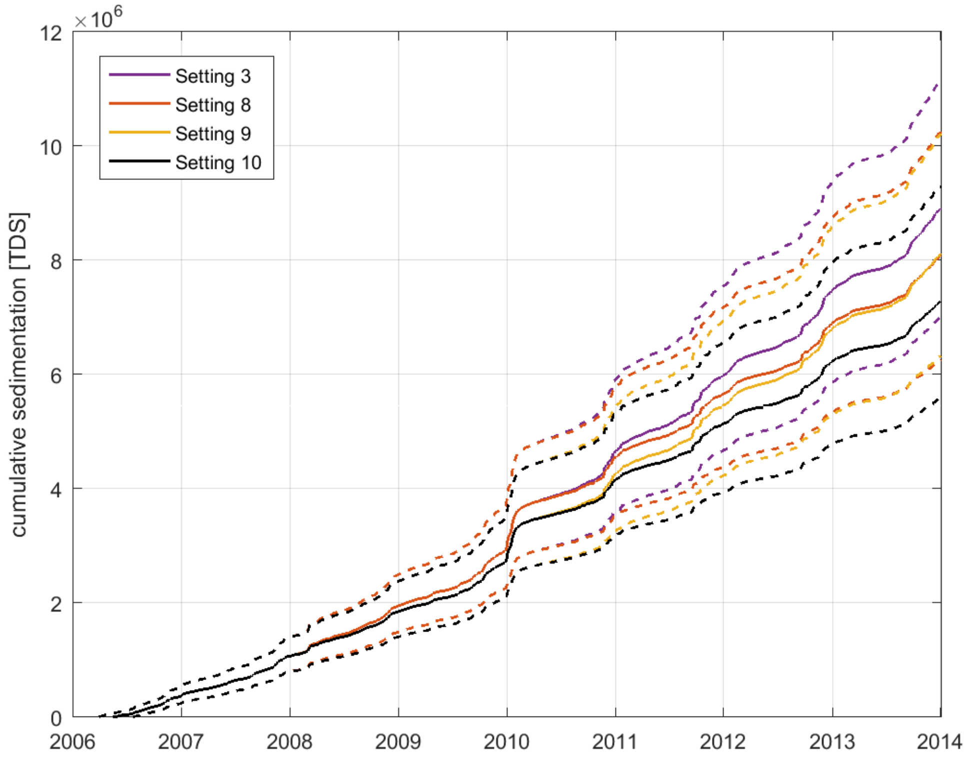

Figure 4-12: Cumulative sedimentation modelled with the settings 3, 8, 9 and 10 to estimate the effect of the dock enlargement.

5. DISCUSSION

The **research questions** formulated in Chapter 1 are repeated for the convenience of the reader and the clarity of this chapter. Each of the questions will be addressed in the subsequent sections.

1. Which influence does the CDW have on the long-term water exchange and sedimentation processes between the dock and the river?
2. If changes in processes are observed, can they be attributed to a specific year, and thus correlate to one of following specific external effects or interventions: Scheldt deepening, sill removal, CDW construction, maintenance depth changes, Kieldrecht lock construction? Or do we rather see a cumulated effect of all interventions?
3. Is the observed increase of the dredging volume, besides the effect of the sill dredging, related to:
   a. Changes in the water exchange processes or duration of processes since CDW construction, leading to longer (more) sedimentation per tide? Or,
   b. Changes in (external) sediment concentrations in the river?
   c. Changes in dredging strategy in the dock, i.e. the change in maintenance depth?

5.1 LONG-TERM WATER EXCHANGE VOLUME AND SEDIMENT FLUXES

Main observations and interpretation

For the long-term evolution of water exchange volumes and sediment fluxes, the timeseries, the intra-tidal cycles and the sedimentation model results need to be addressed.

The **salinity** data at the Buoy 84 and Liefkenshoek stations and the dock entrance show similar seasonal variations. Discharge events cause steep drops of salinity and slower but steady climbing salinity towards the normal observed range.

In general, the intra-tidal variation of salinity shows lower values after 1/9/11 (‘after CDW construction’) than before 1/4/10 (‘before CDW construction’). This is attributed to the difference in seasonal coverage of the two underlying timeseries: one runs from 1/4/06 to 1/4/2010 (4 years, 16 seasons) while the other runs from 1/9/2011 to 1/4/14 (2.5 years, with 2 spring and summers, and 3 fall and winter seasons). As the lowest salinities are recorded in November-February, the difference may be due to the dataset itself.

The **salinity gradients** though undergo similar variations and thus should have less effect of this difference. The salinity differences indicate:

- Weaker deep eddy circulation, except around HW+2 hours (based on NBOT-SBOT);
- Weaker shallow eddy circulation except during ebb onset (HW to HW+3 hours) (based on NTOP-STOP);
- No significant difference in vertical gradients before and after CDW construction.

Thus, the salinity gradients suggest that the eddy strength has decreased, which corroborates with earlier observations and conclusions.

The **suspended sediment concentration** shows an increasing trend at the dock entrance and at Oosterweel, whereas the data from Buoy 84 does not display such a trend. The mean tidal cycles confirm this behaviour and even indicate a decrease of SSC at B84BOT. The time series data at the entrance also suggests a relation with increased dredging intensity at Deurganckdok.

The **suspended sediment concentration gradients** at the dock entrance indicates slightly lower horizontal gradients during and shortly after HW, but slightly higher gradients at LW. The top horizontal gradient has become stronger during LW and HW. The vertical SSC gradient at the north entrance is decreased and thus suggests more vertical mixing, or bottom flow deflection. At the south entrance, there is rather an indication of slightly stronger density at spring tide.

These results currently suggest that the CDW has the expected albeit minor effect: at the North entrance it seems to deflect and so to delay the sediment-laden bottom flow and to allow the surface flow to enter the dock faster via the CDW channel. At the South entrance, however, the effect is negligible. The results hence also suggest a slight reduction of the eddy and locally weaker density currents at the North entrance during flood because the delay effect decreases vertical salinity gradients. It is unclear however whether these conclusions based on local measurements can be extrapolated to the entire entrance cross-section. For this purpose, ADCP measurements are needed at the entrance of Deurganckdok.

The **water exchange and sediment fluxes** in the sedimentation model are strongly controlled by the model schematization settings. The density flux is the most important flux and shows a strong increase after increase of the density current duration (based on ADCP measurements, in IMDC (2013a)). The total water exchange shows an increase through time (Figure 4-6).

With increased water exchange and sediment concentrations at the dock entrance, it is obvious that sediment flux to the dock increases as well. The increased flux, balanced by increased dredging in the dock, is well captured by the sedimentation model (cumulative error in the order of 0.5 million TDS).

Influence of lunar nodal cycle on tidal amplitude

The water exchange volume is partly externally controlled, i.e. by the tidal prism. This is influenced on the long term however by the lunar nodal cycle with a periodicty of 18.6 years (among other cycles) with a an amplitude of 5 to 10 cm. Late 2015, the cycle’s maximum was reached, after a previous maximum in 1997 and minimum in 2006. The observed mean tidal range in the period 2008-2014 increased by 18 cm at Prosperpolder which is somewhat larger than the expected increase by the nodal cycle alone. Indeed, a positive linear trend in the water levels of 0.5 cm per year at Prosperpolder (IMDC, 2014d) is also known.

The magnitude of the tidal range is ca. 510 cm. Taking into account an increase of 18 cm equals a relative increase of the tidal prism (and related fluxes) of 3.5 %. To estimate the overall importance, this has to be multiplied with the relative importance of the tidally driven flux (Figure 4-8) which is in the order of 20 to 30 %.

It can be estimated that the 18.6 year cycle and trend of the tidal range, only influences the sediment flux to the dock by 1 % (order of magnitude) and can thus be neglected.

Effect of the CDW on the long-term fluxes

The CDW has been built from April 2010 to August 2011. By streamlining the flow, the CDW should mainly **reduce the eddy component** of the total water exchange at the dock entrance. This is effectively observed in the ADCP measurements and supported by the decrease in horizontal salinity gradient (sensors). A strong reduction of the flood eddy is qualitatively visible in the 13h measurements (section 4.1.4 of IMDC report (2013a)).

Also, the mean tidal cycles suggest a less strong stratification, or more mixing. Density current could thus be weaker, although ADCP data would be needed to confirm this suggestion. The change in density currents may be due to other human impacts (deepening of the dock; see further).

The sedimentation in the dock was expected to reduce by 10 to 20 % based on numerical results for a comparable dock (section 2.4.2). This is not observed in the field observations because the (potential) effect is overshadowed by the increased overall sediment flux due to increased SSC at the entrance and total water exchange (as discussed above).

5.2 EFFECTS OF DIFFERENT INTERVENTIONS

Capital dredging works

Deepening and widening of the Lower Sea Scheldt occurred over an extensive period, from July 2008 to August 2010. Since 2010, elevated maintenance dredging (of mud) is observed at Drempel van Frederik (see section 2.2). No clear impact is visible in the data and the sedimentation model.

The Deurganckdok entrance sill has been dredged over a relatively short period, from November 2009 to June 2010. The maintenance depth of the dock has been increased from March to May 2011.

The period from January to March 2010, has been characterised by a very strong sedimentation event in Deurganckdok, followed by maintenance dredging of around 800 000 TDS from March to May 2010. The SSC measured is higher than usual during that timeframe, and could be partly caused by the capital dredging but the effect of the sill removal alone on the SSC data cannot be distinguished due to the overlapping interventions.

After the entrance sill has been dredged, larger yearly maintenance volumes have been reported at the dock entrance (21 000 TDS/month between April 2010 and April 2012 compared to 1 000 TDS/month between April 2006 and April 2010). This is partly due to a change in reporting conventions: maintenance of the sill was until 12/2010 done by sweepbeam dredging and was not included in the BIS dredging data.

However, as shown in Figure 2-2, the sill dredging alone does not explain the overall observed dredging intensity increase. Removing the sill increases the entrance cross-section which could linearly increase the exchanged water volumes and potentially increase the sedimentation in Deurganckdok. The sedimentation model suggests an increase between 10-14% which is rather high compared to the numerical model (Slib3D) result of maximum 7% (2013a). This would then have an effect on the subsequent maintenance dredging.

Maintenance dredging works

Maintenance dredging works in Deurganckdok appear to relate to the SSC measured at the entrance of the dock (section 4.1.2). A higher SSC at the dock entrance leads to more sedimentation in Deurganckdok, which requires more dredging. It has not been investigated whether the dredging activity itself also leads to a direct impact (higher SSC measurement) at the entrance itself.

The dredged material is deposited near Oosterweel and is resuspended again by the (tidal) currents. It is known from a multivariate analysis (IMDC, 2016) that the disposal intensity at Oosterweel controls the SSC at Oosterweel. Figure 5-1 shows the covariation of SSC and disposal volumes at short timescale (weekly), seasonal timescale and long term timescale. A statistically significant correlation with the Buoy 84 signals also exists. Therefore, it can be expected that the measured SSC variation at Deurganckdok also has a partial influence from the Oosterweel disposal volumes.

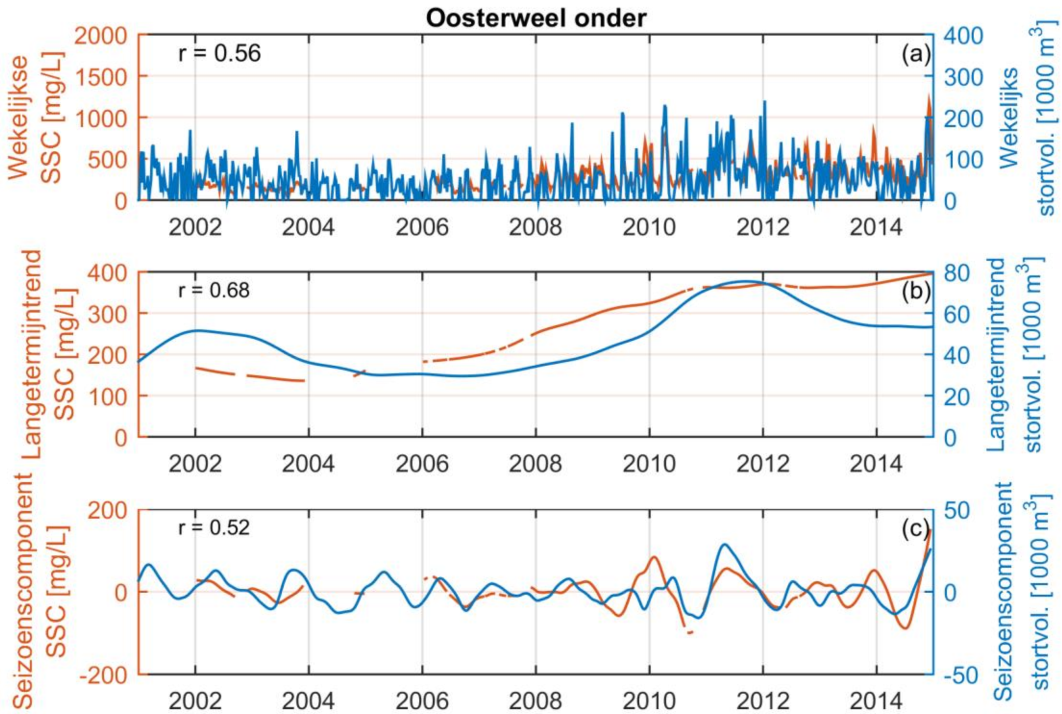

Figure 5-1: Correlating trends in mud disposal and SSC observation at Oosterweel lower sensor (IMDC, 2016) at weekly scale (upper graph), long-term scale (middle graph) and seasonal scale (lower graph).

SSC observations at Buoy 84 indicates a decrease over time. This appears to be contrary to the observed increase of SSC at the dock entrance, which is only a few km upstream. However, this observation corroborates with earlier conclusion in IMDC (2013b) that the Deurganckdok with maintenance leads to elevated SSC in the Lower Seascheldt and lowered SSC in the Western Scheldt. The conceptual mechanism behind this is that the dock acts as a strong sink that prevents a part of the suspended sediments to disperse further downstream.

Also, the deepening of Drempel van Frederik and Deurganckdok (including sill removal) strengthens the sediment sinks (or traps). Increased sedimentation rates at Drempel van Frederik and Deurganckdok are effective for lowering the sediment concentration further downstream (at Buoy 84).

Ultimately, this could indicate that the retour flux between the disposal site (Oosterweel) and the main dredging locations (Deurganckdok and Drempel van Frederik) has become stronger over time.

Construction of the Current Deflecting Wall

The CDW was constructed between April 2010 and August 2011. The intratidal cycles suggest that the eddy current strength (and related fluxes) have decreased after CDW construction. However, stronger and longer density currents were observed from earlier ADCP measurements (IMDC, 2013a). Additional ADCP data would be needed to confirm the recent most suggestion that density current has become weaker. Furthermore, the vertical variation in SSC measurement location before and after June 2012, further adds to the uncertainty of this latter observation.

In view of this uncertainty and of the subjective choice of the parameterisation of the CDW in the sedimentation model, the exact effect of the CDW on the sedimentation cannot be reliable quantified at this moment, although the effect on hydrodynamics is confirmed. Nevertheless, the effect of the CDW is estimated between 3 and 9 % after rerunning the model with shorter eddy duration. This result is lower than the expected reduction of 10 to 20 % based on numerical Slib3D model. Other model reruns estimate the other external effects (dock enlargement, dock deepening and sill removal) between 10-14 % per intervention.

Those model estimations must be handled with any care due to the subject choice of the model parameterisation, use of field measurements (which includes the external effects), cumulative effect with another parameters and unknown (cumulative) effects of other external intervention on the river Scheldt.

Cumulative effects

Ultimately, the observed changes in the system cannot be uniquely coupled to an individual intervention on the long run because

- The deepening of the Scheldt may have altered the mud sedimentation at the shoals such as Drempel van Frederik;
- The sill removal and deepening of the Deurganckdok can have increased the overall sediment influx into the dock (estimation of approximately 12% per intervention);
- The construction of the CDW has decreased the eddy current strength, but changes in density current duration are uncertain (both positive and negative arguments);
- The total maintenance mud disposal at Oosterweel has increased over time and has locally increased the SSC which is quantifiable at Buoy 84 as well.
- The system itself can react as well by working towards a new equilibrium situation in which the role of mud flats as buffer capacity cannot be overlooked, but remains unknown at the moment.

Since the interventions were all executed in a relative short time (2009-2011) in a small spatial domain, the observations are mainly to be interpreted as a cumulative effect of all interventions.

5.3 CAUSE OF THE INCREASED DREDGING INTENSITY

The increased dredging intensity is a consequence of the increased sediment flux into the dock, which is caused by two elements, as the flux is the product of sediment concentration and water volume exchange.

On one hand, the sedimentation model indicates that the **total water exchange volume has increased**. Of course, this result depends on the imposed schematization: the eddy weakening is confirmed by recent measurements, but the measured longer density current duration is not confirmed by more recent ADCP measurements (after 2012) and is derived from the ADCP measurments reported earlier. The dock lengthening and deepening also lead to changes of the modelled water fluxes, but less than the CDW construction.

On the other hand, observations of SSC time series at the entrance of the dock show that **sediment concentration increased after April 2010**. This is supported by the conclusions from the intra - tidal cycle analysis. The SSC increase may be due to increased disposal at Oosterweel, and thus form a positive feedback loop which could lead to further increasing sedimentation in the dock.

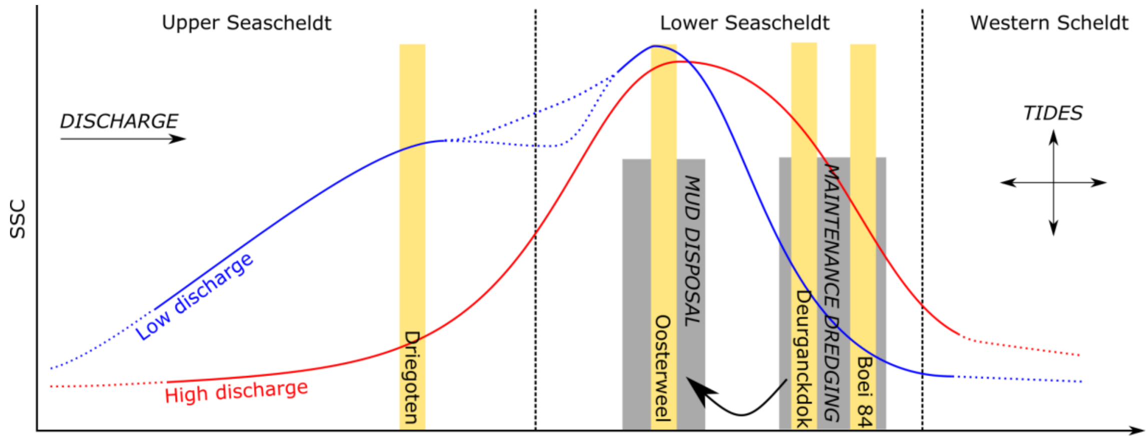

Figure 5-2: Conceptual model after IMDC (2016), modified with the indication of the maintenance dredging site and the Deurganckdok.

As a consequence of the increased sediment flux into the dock after 2010, the dredging volumes have become larger. As higher amounts of mud are disposed at Oosterweel, the sediment concentrations have increased near that site. It is known that a positive correlation exists with the SSC measurements at Buoy 84; it is expected that this is true for Deurganckdok entrance as well.

The more effective trapping of sediment at the Deurganckdok can explain the decreased SSC downstream.

We therefore summarize that the combined effect of:

- The deepening of the Schelde and the increased size and depth of Deurganckdok;
- The removal of the entrance sill of the dock;
- The construction of the CDW;

have influenced the water exchange and/or altered the relative contributions of the fluxes of water and sediment into the dock, which lead to an increased dredging requirement. It is hypothesized that the sediment concentration at the dock entrance have increased as a consequence of the increased disposal near Oosterweel (Figure 5-2). This ultimately further enhances the flux of sediment towards the dock and may or may not evolve towards a new equilibrium state.

The aforementioned assumption needs to be validated, which can be done by application of the multivariate regression as shown in IMDC (2016) to the Deurganckdok SSC dataset. Further support to the interpretations can be given by performing additional ADCP measurements through tide (13-hour measurements) at the entrance and on the river Scheldt. Four ADCP measurements at the entrance are foreseen in autumn 2015 and autumn 2016, yet none on the river

6. CONCLUSIONS

6.1 MAIN OBSERVATIONS AND INTERPRETATIONS

Salinity data from all measurment stations in the river and at the dock entrance show similar seasonal variations. Discharge events cause steep drops of salinity and slower but steady climbing salinity towards the normal observed range.

The intra-tidal salinity variation calculated before the start and after the end of the CDW construction, suggests lowered salinity. However, this is attributed to different time series length and different coverage of seasons before and after the construction of the CDW and not an effect of the CDW.

The **salinity gradients** (the difference between the bottom and top sensor for vertical gradients, and the difference between south and north sensor for horizontal gradients) undergo similar variations and thus are expected to cancel out this offset. Based on gradients, it is derived that the eddy circulation has generally become weaker since the CDW is in place. The effect on vertical gradients is unclear at the moment, although it is known from ADCP measurements (reported in the previous analysis report), that the duration of the density current should have increased.

The **suspended sediment concentration** shows an increasing trend at the dock entrance and at Oosterweel, whereas the data from Buoy 84 does not display such a trend. The mean tidal cycles confirm this behaviour and even indicate a decrease of SSC at B84BOT.

The **suspended sediment concentration gradients** (similar definition as salinity gradients) indicates slightly weaker horizontal gradients during and shortly after high water, but slightly higher gradients at LW. The top horizontal gradient has become stronger during LW and HW. The vertical SSC gradient at the north entrance is decreased and thus suggests more vertical mixing, or bottom flow deflection. At the south entrance, there is rather an indication of slightly stronger density at spring tide. Also here, the signal is mixed and the large-scale effect remains unclear.

The **sedimentation model** has been further adapted and includes an updated flocculation schematization. In general, schematizations have remained unchanged compared to the preceding analysis report and include:

- Increase of maintenance depth at the sill;
- Increase of the dock length;
- Increase of maintenance depth of quays and trench;
- Shortening of eddy current duration and lengthening the density current duration to simulate the effect of the CDW construction.

With such schematization, the sedimentation model is able to reproduce the total sediment volume signal over the years, with a cumulated error of 0.5 million TDS (on a total volume of 9 million TDS).

The model has been applied to quantify the absolute and relative importance of the water exchange trough tidal filling, eddy currents and density currents. These exchange volumes are multiplied with the outside SSC values to estimate the net sediment fluxes into the dock (sediment trapping). From the model it is concluded that the total water exchange has increased over the years, mainly before 2011, which thus indicates that the dock deepening, lengthening and sill removal influenced the water exchange more than the CDW construction.

The **mud dredging mass** indicates that the average dredging intensity up to 1/1/2010 is about 2600 TDS/day, whereas after this date, the average increases to 4200 TDS/day.

The water exchange flux alone does not explain this increase, but also the **sediment concentration in the river** has increased at the dock entrance. The sediment concentration in the river is assumed to be related to the increased mud disposal at Oosterweel. This is an aspect that needs further investigation.

6.2 IMPACT OF EXTERNAL EFFECTS ON THE SEDIMENTATION IN DEURGANCKDOK

The **impact on the sedimentation of Deurganckdok** due to different external, or anthropogenic effects, is summarized as follows.

1. The total water flux into the dock is mostly controlled by the changes to the geometry of the dock: **lengthening, deepening and increase of the entrance cross-section** by removing the entrance sill. The sedimentation model suggests a sedimentation increase between **10 and 14% per change.**
2. The **construction of the CDW** has influenced the relative contributions of tidal, eddy and density current water fluxes and thus has a clear effect on hydrodynamics. Measurements show that the CDW has the expected, albeit smaller, effect. The sedimentation model suggests a sedimentation reduction between **3 and 9%.**
3. The increase of **sediment concentrations outside the dock** may be an external effect caused by the mud disposal at Oosterweel, which has also shown an increase over time.
4. The **cumulative** effect of the geometric changes to the dock and the elevated sediment concentration, result in increased sediment trapping in the dock. The effect on the CDW be quantified at this moment. It is noted that the increased sediment trapping in the dock may explain the decreased SSC near Buoy 84, downstream.

7. RECOMMENDATIONS

This study does not fully allow to conclude on the effect of the CDW on the sedimentation of Deurganckdok. However, from the data analysis, it could be concluded that the larger maintenance depth and the more frequent dredging play a more important role to the sedimentation of Deurganckdok, and has shadowed the effect of the CDW.

The slight decrease of SSC at Buoy 84 could indicate that a deepened Drempel van Frederik and Deurganckdok now act as better sediment sinks (or traps). Increased sedimentation rates are effective for lowering the sediment concentration further downstream. Ultimately, this could indicate that the retour flux between the disposal site (Oosterweel) and the dredging locations (Deurganckdok and Drempel van Frederik) has become stronger. To study these hypotheses, it is recommended to:

- Continue and/or expand the measurements:
    - Redeploy the Buoy 97 measuring station to elucidate the SSC evolution situated between the Deurgankdock and the Oosterweel site;
    - Or alternatively, deploy a SSC measuring device at the Liefkenshoek station where salinity and temperature are already recorded for the same purpose.
    - Perform 13 hour ADCP measurements in order to further clarify the relative contributions of tidal filling, density currents and eddy currents through tide, preferably at different tidal amplitude and discharge conditions.
    - Repeat the 13 hours ADCP measurements at the entrance and on the river Scheldt at same tidal event (transect DGD, I and K) to determine SSC evolution down- and upstream from the entrance.
- Changes in dredging frequency and relocation strategy may have a noticeable positive impact on the yearly maintenance volumes. It is hence advised to investigate alternative maintenance dredging strategies and to closely monitor their effect.
- Set up a multivariate statistical model of the SSC variations from the Deurganckdok sensor, similar to the analysis performed in IMDC (2013f, 2016) for the Oosterweel, Buoy 84 and Driegoten SSC time series.
- A process based model (e.g. Slib3D or a new detailed model) of Deurganckdok could be used with the new insights and with the large amount of data collected over the year to refine the estimates of the effect of the CDW on sedimentation.

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IMDC (2009g). Long-term siltation monitoring Deurganckdok: analyses and measurements. Report 2.24: Through tide Sediview measurements during neap tide and winter at Deurganckdok (transect DGD): 10/12/2008. I/RA/11283/08.085/MSA, Flemish Government, Department of Mobility and Public Works, Flanders Hydraulics Research.

IMDC (2009h). Long-term siltation monitoring Deurganckdok: analyses and measurements. Report 2.25: Through tide Sediview measurements during spring tide and winter at Deurganckdok (transect DGD): 02/12/2008. I/RA/11283/08.086/MSA, Flemish Government, Department of Mobility and Public Works, Flanders Hydraulics Research.

IMDC (2009i). Long-term siltation monitoring Deurganckdok: analyses and measurements. Report 2.26: Through tide Sediview measurements during neap tide and spring at Deurganckdok (transect DGD): 06/03/2009. I/RA/11283/08.087/MSA, Flemish Government, Department of Mobility and Public Works, Flanders Hydraulics Research.

IMDC (2009j). Long-term siltation monitoring Deurganckdok: analyses and measurements. Report 2.27: Through tide Sediview measurements during neap tide and spring at Deurganckdok (transect DGD): 12/03/2009. I/RA/11283/08.088/MSA, Flemish Government, Department of Mobility and Public Works, Flanders Hydraulics Research.

IMDC (2009k). Long-term siltation monitoring Deurganckdok: analyses and measurements. Report 2.33: Salt-Silt distribution measurements at Deurganckdok: 01/10/2008 - 31/09/2009. I/RA/11283/08.094/MSA, Flemish Government, Department of Mobility and Public Works, Flanders Hydraulics Research.

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IMDC (2010c). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.8: Salt-Silt distribution Deurganckdok: April 2009 - March 2010. I/RA/11354/10.068/NZI, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2010d). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.5: Through tide measurement: Eddy Currents DGD - 02/03/2010. I/RA/11283/10.051/MSA, Flemish Government, Department of Mobility and Public Works, Flanders Hydraulics Research.

IMDC (2010e). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 1.4: Boundary Conditions year 1: April 2009 - March 2010. I/RA/11354/10.102/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2011a). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 1.2: Annual Sediment Balance year 2: April 2010 - March 2011. I/RA/11354/10.100/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2011b). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.1: Through tide Sediview measurement: Entrance DGD during spring tide autumn 2011. I/RA/11354/10.106/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2011c). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.2: Through tide Sediview measurement: Entrance DGD during neap tide autumn 2011. I/RA/11354/10.107/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2011d). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.6: Through tide measurement: Eddy Currents DGD spring tide - Autumn 2011. I/RA/11354/10.110/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2011e). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.10: Salt-Silt & current distribution at entrance Deurganckdok: Frame and through-tide measurements - Autumn 2011. I/RA/11354/11.131/BQU, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2011f). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.12: Calibration of mobile and stationary instruments on 16/03/2011. I/RA/11354/10.113/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2011g). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 1.5: Boundary Conditions year 2: April 2010 - March 2011. I/RA/11354/10.103/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2012a). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 1.3: Annual Sediment Balance year 3: April 2011 - March 2012. I/RA/11354/10.101/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2012b). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.3: Through tide Sediview measurement: Entrance DGD during spring tide winter 2012. I/RA/11354/10.108/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2012c). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.4: Through tide Sediview measurement: DGD during neap tide winter 2012. I/RA/11354/10.109/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2012d). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.7: Through tide measurement: Eddy Currents DGD spring tide - Winter 2012. I/RA/11354/10.111/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2012e). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.11: Salt-Silt & current distribution at entrance Deurganckdok: Frame and through-tide measurements - Winter 2012. I/RA/11354/10.114/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2012f). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.13: Calibration of stationary instruments on 01/06/2012. I/RA/11354/12.011/JCA, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2012g). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 2.9: Salt-silt distribution Deurganckdok: June 2011 - May 2012. I/RA/11354/10.112/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2012h). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 1.6: Boundary Conditions year 3: April 2011 - March 2012. I/RA/11354/10.104/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2013a). Evaluation of the external effects on siltation in Deurganckdok (2009 - 2012). Report 1.8: Analysis of external effects on siltation processes and factors. I/RA/11354/10.105/MBO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2013b). Evaluation of the external effects on siltation in Deurganckdok (2012 - 2014). Report 1.09: Annual sediment balance in survey year 7: April 2012 - March 2013. I/RA/11406/13.143/JCA, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2013c). Evaluation of the external effects on siltation in Deurganckdok (2012 - 2014). Report 1.11: Boundary conditions survey year 7 : April 2012 - March 2013. I/RA/11406/13.145/JCA, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2013d). Evaluation of the external effects on siltation in Deurganckdok (2012 - 2014). Report 1.13: Analysis of the boundary conditions in survey years 3 and 4: April 2008 - March 2010. I/RA/11406/13.054/MGO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

IMDC (2013e). Evaluation of the external effects on siltation in Deurganckdok (2012 - 2014). Report 1.14: Analysis of the boundary conditions in survey years 5 and 6: April 2010 - March 2012. I/RA/11406/13.062/MGO, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

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IMDC (2014b). Evaluation of the external effects on siltation in Deurganckdok (2012 - 2014). Report 1.12: Boundary conditions in survey year 8: April 2013 - March 2014. I/RA/11406/13.146/JCA, Flemish Government, Department of Mobility and Public Works, Maritime Access Division.

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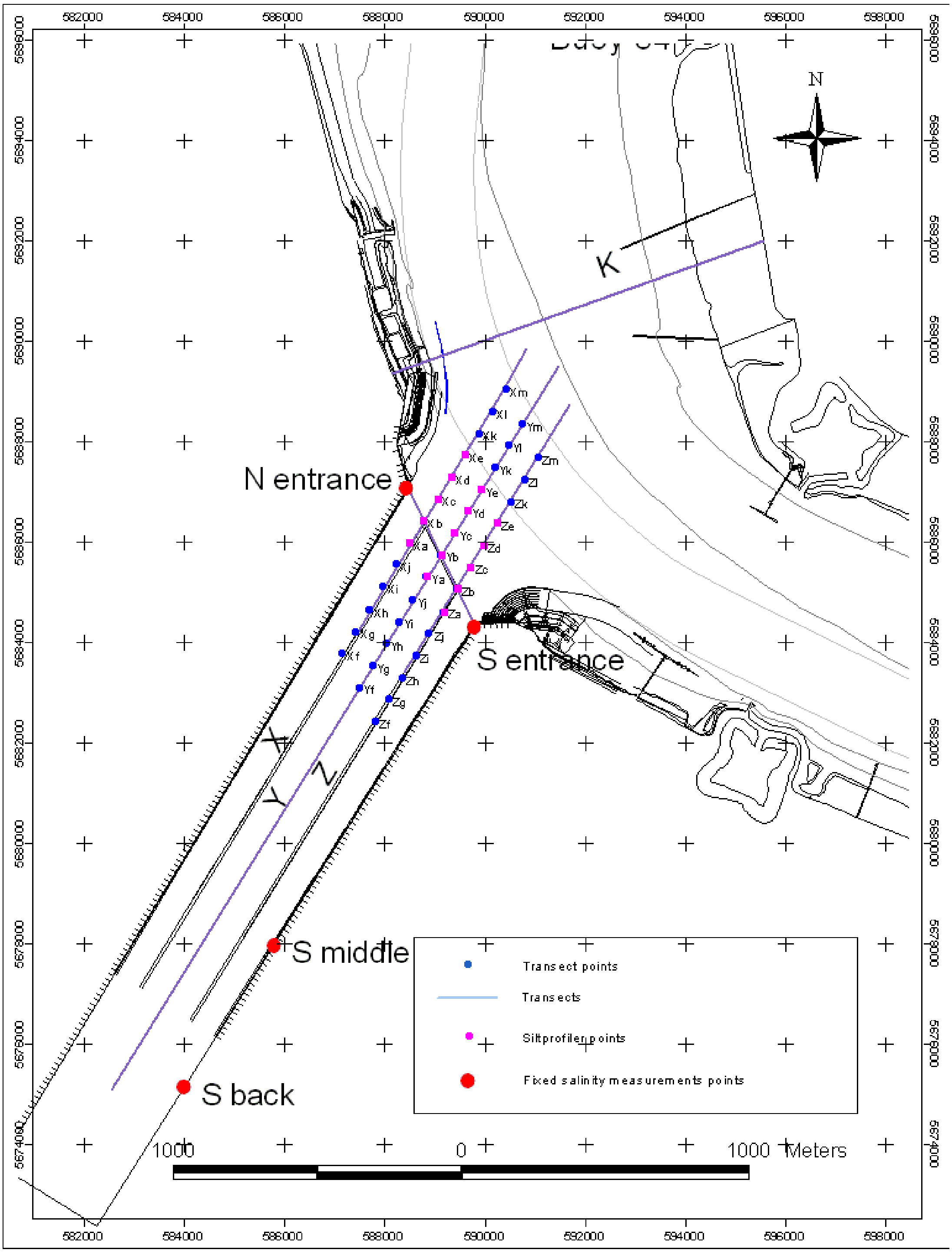
9. ANNEXES

Annex A Measurements campaign overview

Annex Table A-1 to Annex Table A-4 give a global overview of all executed measurement campaigns in vicinity or in of Deurganckdok since the opening of the dock. The map in Annex Figure A-1 shows the sailed measurement tracks and stationary measurement locations in the Deurganckdok.



Annex Figure A-1: Location of measurement equipment and sailed tracks at Deurganckdok

Annex Table A-1: An overview of the executed depth soundings and density measurements in Deurganckdok provided by Agency for Maritime Services and Coast – Coast division.

<table>
<tr><th colspan="4">Depth soundings and density measurements</th></tr>
<tr><th>Type</th><th>Description</th><th>Date(s)</th><th>Report(s)</th></tr>
<tr><td>Depth soundings</td><td>Measuring the depth using dual frequency 210-33 kHz</td><td rowspan="2">07/2005 – 03/2006
04/2006 – 03/2007
04/2007 – 03/2008
04/2008 – 03/2009
04/2009 – 03/2010
04/2010 – 03/2011
04/2011 – 03/2012
04/2012 – 03/2013
04/2013 – 03/2014</td><td rowspan="2">(IMDC, 2006a)
(IMDC, 2007a)
(IMDC, 2008a)
(IMDC, 2009b)
(IMDC, 2010a)
(IMDC, 2011a)
(IMDC, 2012a)
(IMDC, 2013b)
(IMDC, 2014a)</td></tr>
<tr><td>Density measurements</td><td>Measuring bed density profiles at a spatial grid covering the dock</td></tr>
</table>

Annex Table A-2: An overview of in-situ settling velocity and calibration campaigns on the River Scheldt in the environment of Deurganckdok since project HCBS (2005)

<table>
<tr><th colspan="4">Settling velocity/ calibration campaigns</th></tr>
<tr><th>Type</th><th>Description</th><th>Date(s)</th><th>Report(s)</th></tr>
<tr><td>Settling velocity</td><td>Measuring the in-situ settling velocity of a sediment particle in Deurganckdok (CDW/SILL/Western qua) based on the INSSEV-protocol</td><td>17-19/02/2005
05-07/09/2006</td><td>(IMDC, 2005a)
(IMDC, 2006b)</td></tr>
<tr><td>Calibration campaign</td><td>An in-situ calibration of the instruments in the environment of Deurganckdok with focus on turbidity conversion to sediment concentration (based on water samples)</td><td>15/03+14/04/2006
23/06+18/09/2006
10/09/2007
4-5/02/2008
27-28/10/2008
16/03/2011
01/06/2012
21/08/2012
24/07/2013</td><td>(IMDC, 2006c)
(IMDC, 2006d)
(IMDC, 2007d)
(IMDC, 2008c)
(IMDC, 2008d)
(IMDC, 2011f)
(IMDC, 2012f)
(AnteaGroup, 2013b)
(AnteaGroup, 2014b)</td></tr>
</table>

Annex Table A-3: An overview of the through tide measurements on the River Scheldt in the environment of Deurganckdok since project HCBS (2005)

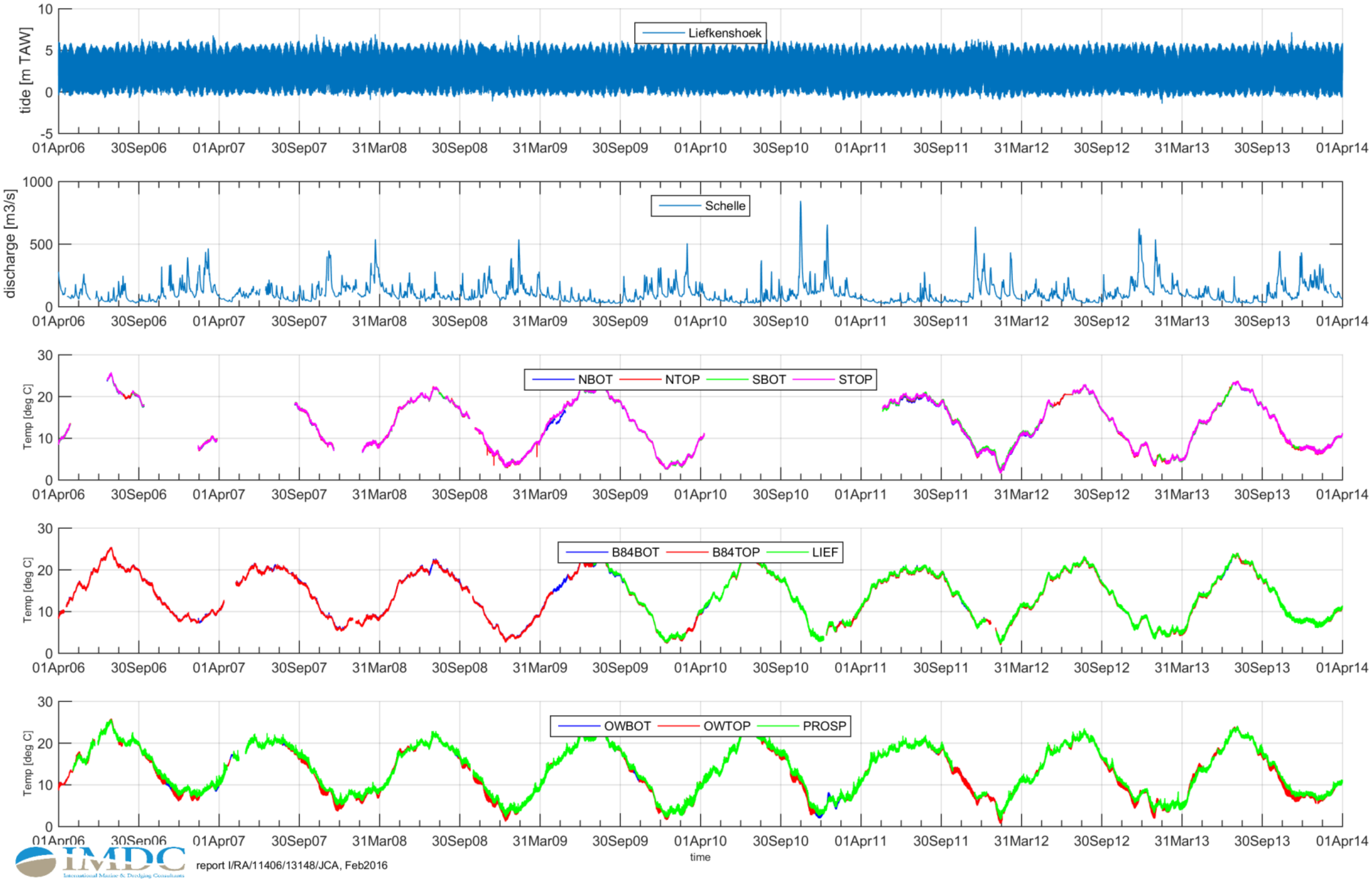
Through tide measurements			
Type (Location)	**Description**	**Date(s)**	**Report(s)**
SiltProfiler	Sediment and salinity measurements on 15 fixed gauging points at the entrance of DGD using the very fast IMDC vertical SiltProfiler.	21/03/2006 26/09/2006 23/10/2007 12/03/2008 29/09/2008 13/03/2009 27/09/2011 09/03/2012	(IMDC, 2006e) (IMDC, 2006f) (IMDC, 2007e) (IMDC, 2008e) (IMDC, 2009d) (IMDC, 2009e) (IMDC, 2011e) (IMDC, 2012e)
Longitudinal salinity measurements (Transect Y)	Measuring the longitudinal salinity distribution in Deurganckdok on several depths.	21/03/2006 26/09/2006 12/03/2008 11/03/2009	(IMDC, 2006g) (IMDC, 2006h) (IMDC, 2008f) (IMDC, 2009f)
Eddy measurements ([1]Transect X, Y, Z [2]Transect 1-4)	Measuring the spatial flow pattern and magnitudes of eddy currents at the entrance of Deurganckdok by using an ADCP	01/10/2008[1] 02/03/2010[2] 29/09/2011[2] 12/03/2012[2]	(IMDC, 2008g) (IMDC, 2010d) (IMDC, 2011d) (IMDC, 2012d)
Transect measurements at Deurganckdok (Transect DGD)	Measuring the spatial current and sediment distribution, water flux and sediment flux at the entrance of Deurganckdok by using ADCP and SEDIVIEW procedure (*incl. SiltProfiles)	17/11/2005* 22/03/2006 27/09/2006 24/10/2007 11/03/2008 19-26/06/2008 24-30/09/2008 2-10/12/2008 6-12/03/2009 6-13/10/2011 8-16/03/2012	(IMDC, 2006i, 2006j) (IMDC, 2006k) (IMDC, 2006l) (IMDC, 2007f) (IMDC, 2008h) (IMDC, 2008i, 2008j) (IMDC, 2008k, 2008l) (IMDC, 2009g, 2009h) (IMDC, 2009i, 2009j) (IMDC, 2011b, 2011c) (IMDC, 2012b, 2012c)
Transect measurements at Waarde (Transect W)	Measuring the spatial current and sediment distribution, water flux and sediment flux at several locations on the River Scheldt by using ADCP and SEDIVIEW procedure (*incl. SiltProfiles)	23/03/2006 28/09/2006	(IMDC, 2006m) (IMDC, 2006n)
Transect measurements at Zandvliet		17/02/2005	(IMDC, 2005b)
Transect measurements at downstream Deurganckdok (Transect K)		17/02/2005 22-23/03/2006 27-28*/09/2006 11/03/2008	(IMDC, 2005c) (IMDC, 2006k, 2006o) (IMDC, 2006p, 2006q) (IMDC, 2008m)
Transect measurements at Liefkenshoek (Transect I)		17/02/2005* 22/03/2006* 27/09/2006* 11/03/2008	(IMDC, 2005d) (IMDC, 2006r) (IMDC, 2006s) (IMDC, 2008n)
Transect measurements at Kallo		18/02/2005*	(IMDC, 2005e)
Transect measurements at Schelle (Transect S)		17/02/2005 23/03/2006 28/09/2006	(IMDC, 2005f) (IMDC, 2006t) (IMDC, 2006u)

Annex Table A-4: An overview of the long-term measurements on the River Scheldt in the environment of Deurganckdok since project HCBS (2005)

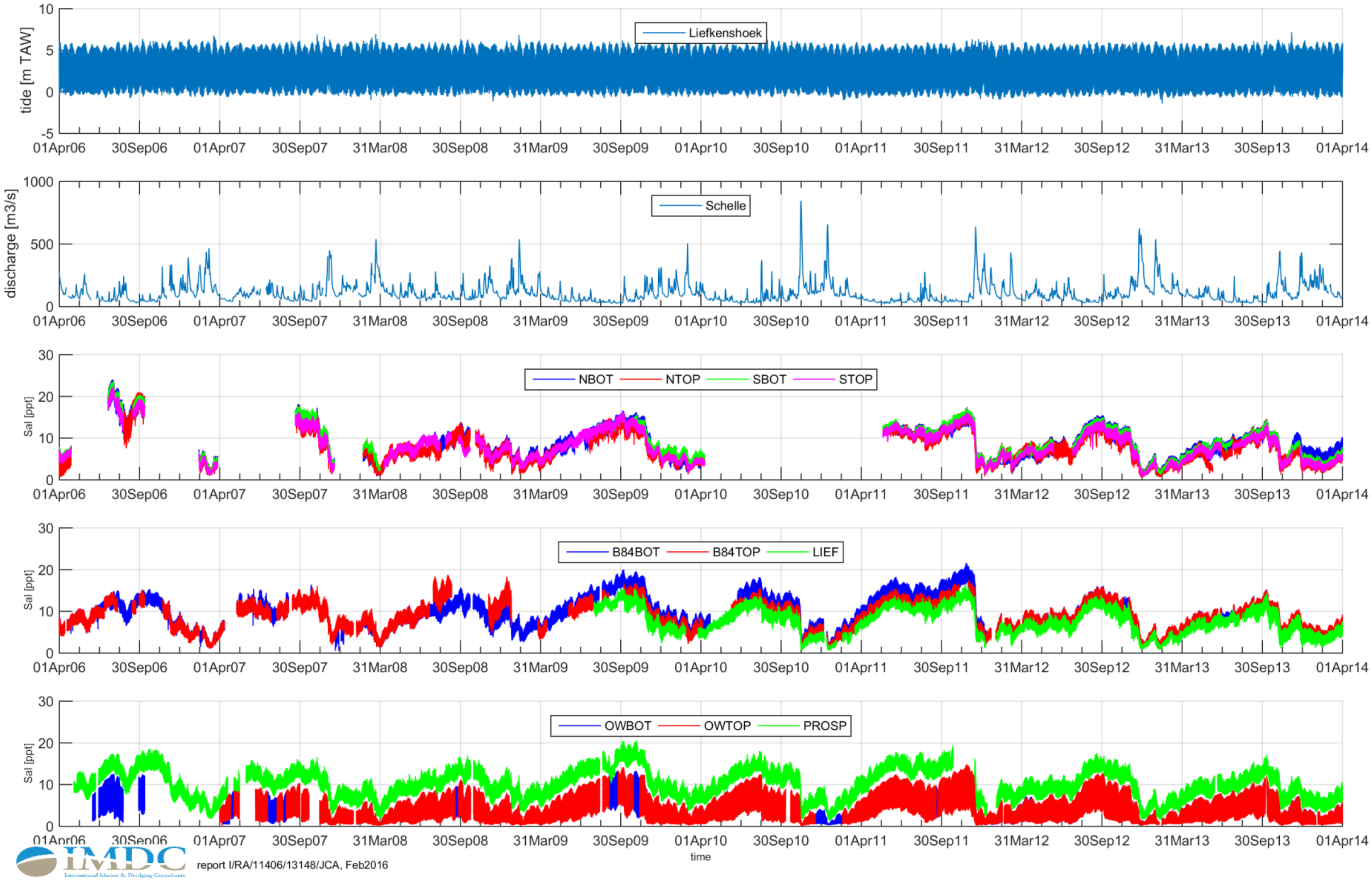
Long-term measurements				
Type	**Description**	**Location**	**Period(s)**	**Report(s)**
Near bed continuous monitoring	Measuring the tidal variation in current velocity, sediment concentration, salinity and bottom elevation near the bottom at the entrance of Deurganckdok by using an special designed frame	DGDdown, DGDup	02/2005	(IMDC, 2005g)
		CDW (North side)	03-04/2006	I(IMDC, 2006v)
		CDW (North side) & SILL (South side)	04-05/2006 07-10/2006 03-04/2007 09-12/2007 02-04/2008	(IMDC, 2006w) (IMDC, 2006x) (IMDC, 2007g) (IMDC, 2008o) (IMDC, 2008p)
	Analogously to a near bed monitoring but extended with an ADCP to measure current and sediment pattern in the water column after the building of CDW	CDWdown (downstream CDW) CDWop (upstream CDW) SILL (South side)	09-10/2011 02-03/2012	(IMDC, 2011e) (IMDC, 2012e)
Salinity and siltation monitoring in Deurganckdok	Measuring the salinity and sediment variation on long-term scale in Deurganckdok at 2 fixed depths	PSA, P&O1 and P&O2	03-04/2006 07-10/2006 02-04/2007 06-07/2007 09-12/2007	(IMDC, 2006w) (IMDC, 2006x) (IMDC, 2007g) (IMDC, 2007h) (IMDC, 2008o)
		N entrance S entrance S middle S back	02-03/2008 04-09/2008 10/2008-3/2009	(IMDC, 2008p) (IMDC, 2008q) (IMDC, 2009k)
		N entrance S entrance	04/2009-05/2010 05/2011-05/2012 05/2012-03/2013 04/2013-03/2014	(IMDC, 2010c) (IMDC, 2012g) (AnteaGroup, 2013a) (AnteaGroup, 2014a)
Ambient condition monitoring	Measuring the ambient conditions nearby Deurganckdok: currents, salinity and sediment concentration	Lillo Oosterweel Hoboken Boerenschans	01-06/2005 07-12/2005	(IMDC, 2005h) (IMDC, 2006y)
		Prosperpolder Buoy84 Buoy97 Oosterweel	01-06/2006 07-12/2006 01/2007-03/2008 04-09/2008	(IMDC, 2006z) (IMDC, 2007i) (IMDC, 2008r) (IMDC, 2008s)
		Prosperpolder Buoy84 Oosterweel	10/2008-03/2009 04/2009-03/2010 04/2010-03/2011 04/2011-03/2012	(IMDC, 2009l) (IMDC, 2010e) (IMDC, 2011g) (IMDC, 2012h)
		Prosperpolder Buoy84 Liefkenshoek Oosterweel	04/2012-03/2013 04/2013-03/2014	(IMDC, 2013c) (IMDC, 2014b)

Annex B **Time series from 2006-2014**

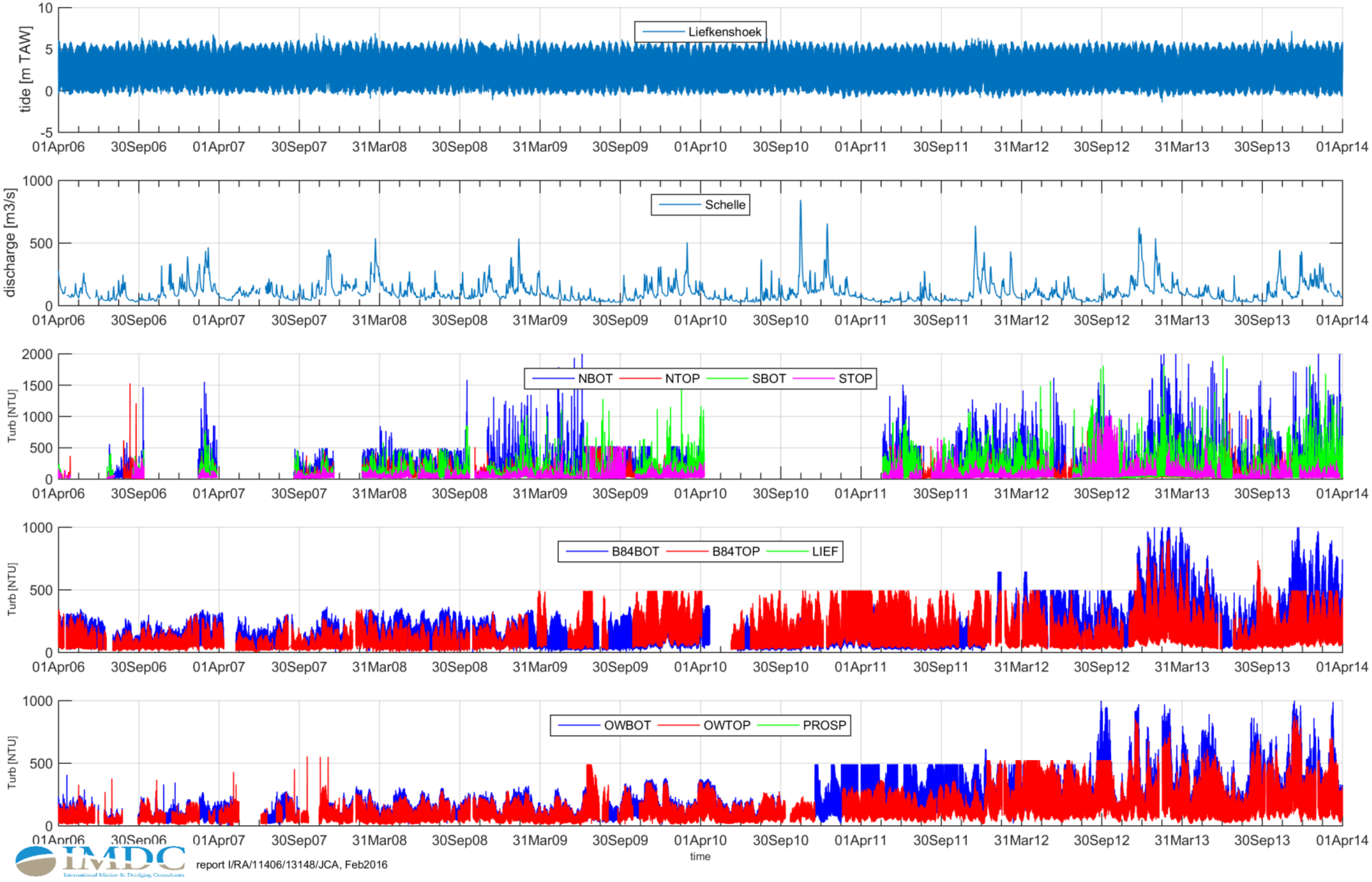
B.1 Time series of instantaneous values



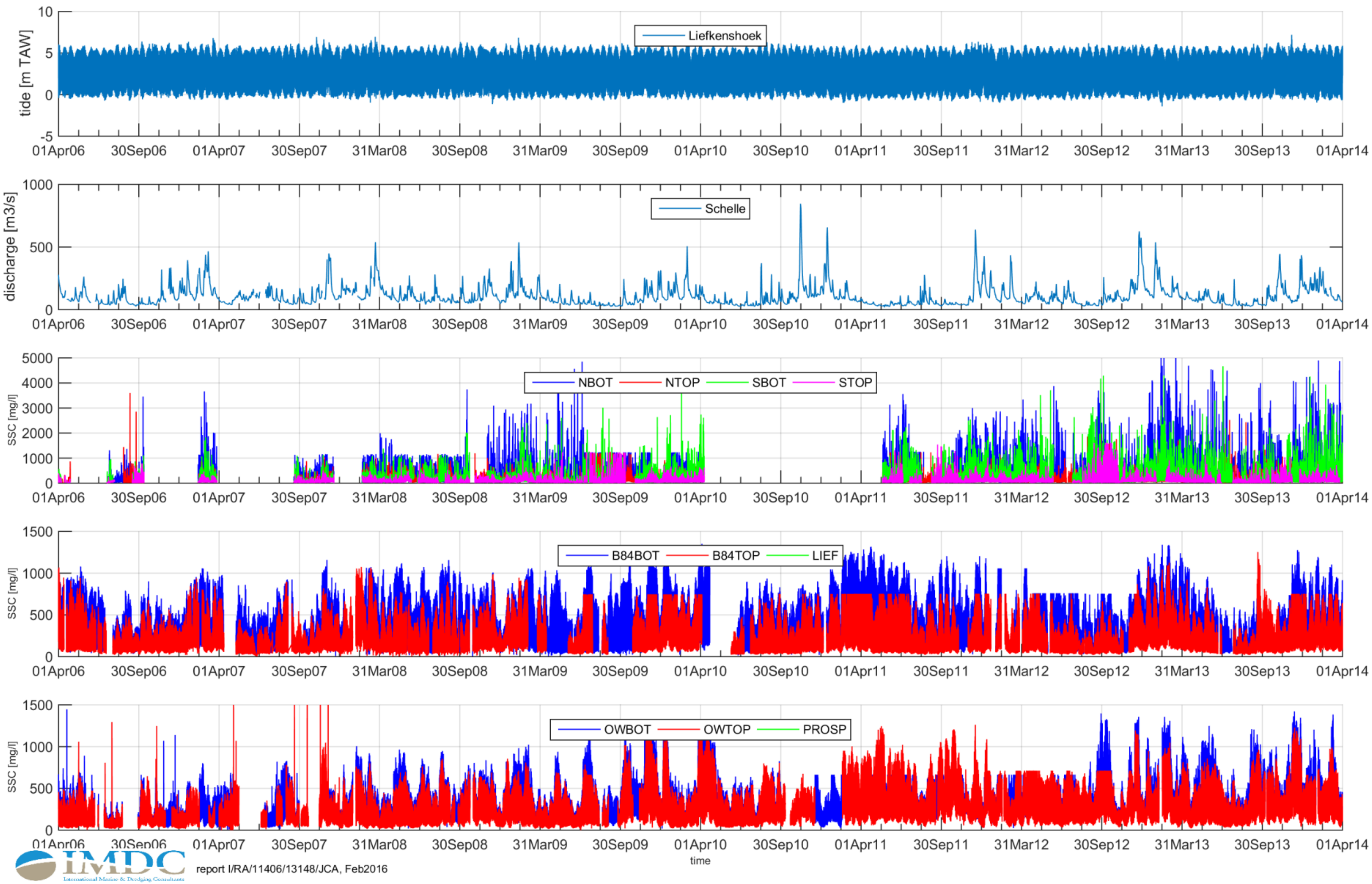
Annex Figure B-1: Time series of temperature including fresh water discharge (Schelle) and tide (Liefkenshoek)



Annex Figure B-2: Time series of salinity including fresh water discharge (Schelle) and tide (Liefkenshoek)

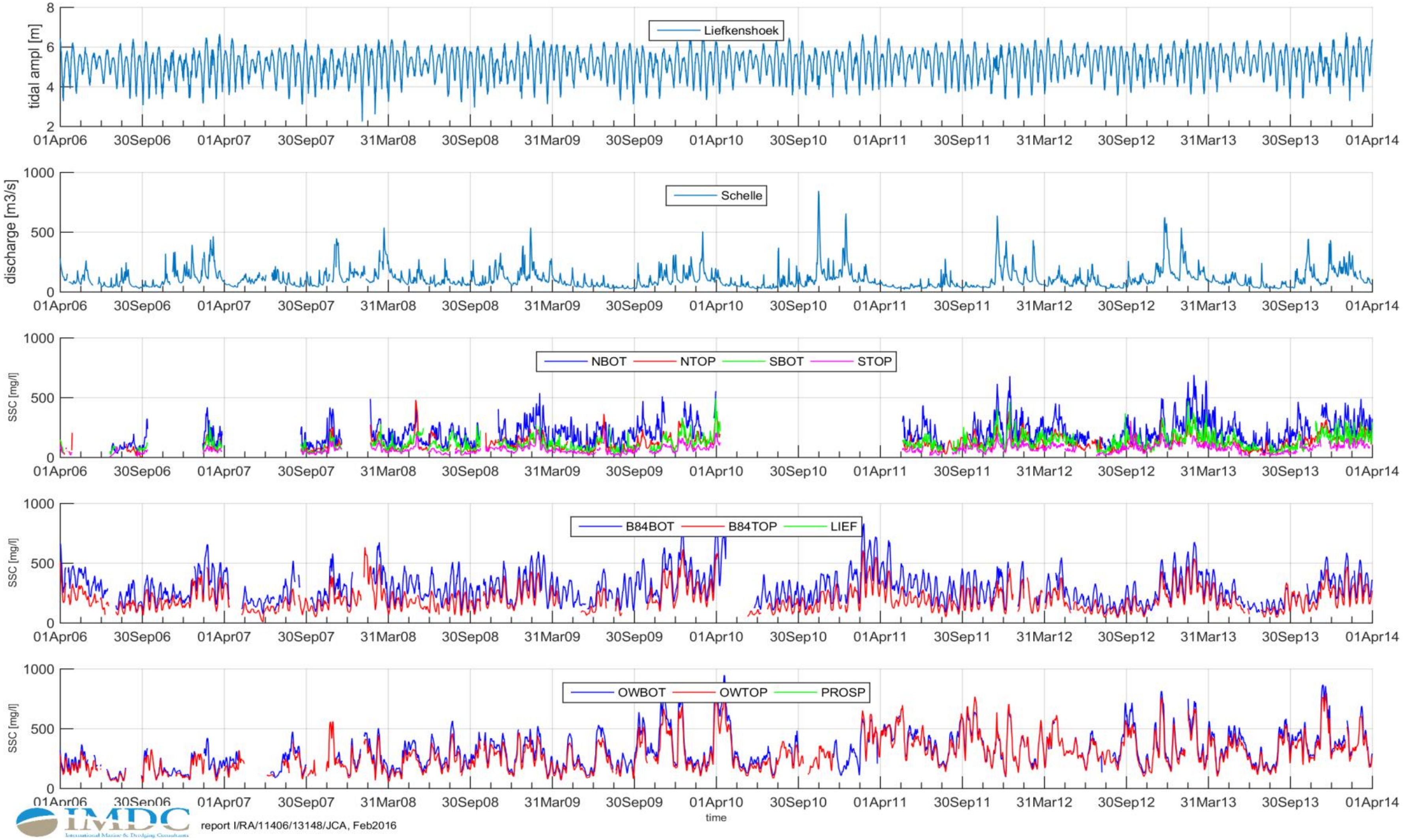


Annex Figure B-3: Time series of turbidity including fresh water discharge (Schelle) and tide (Liefkenshoek).

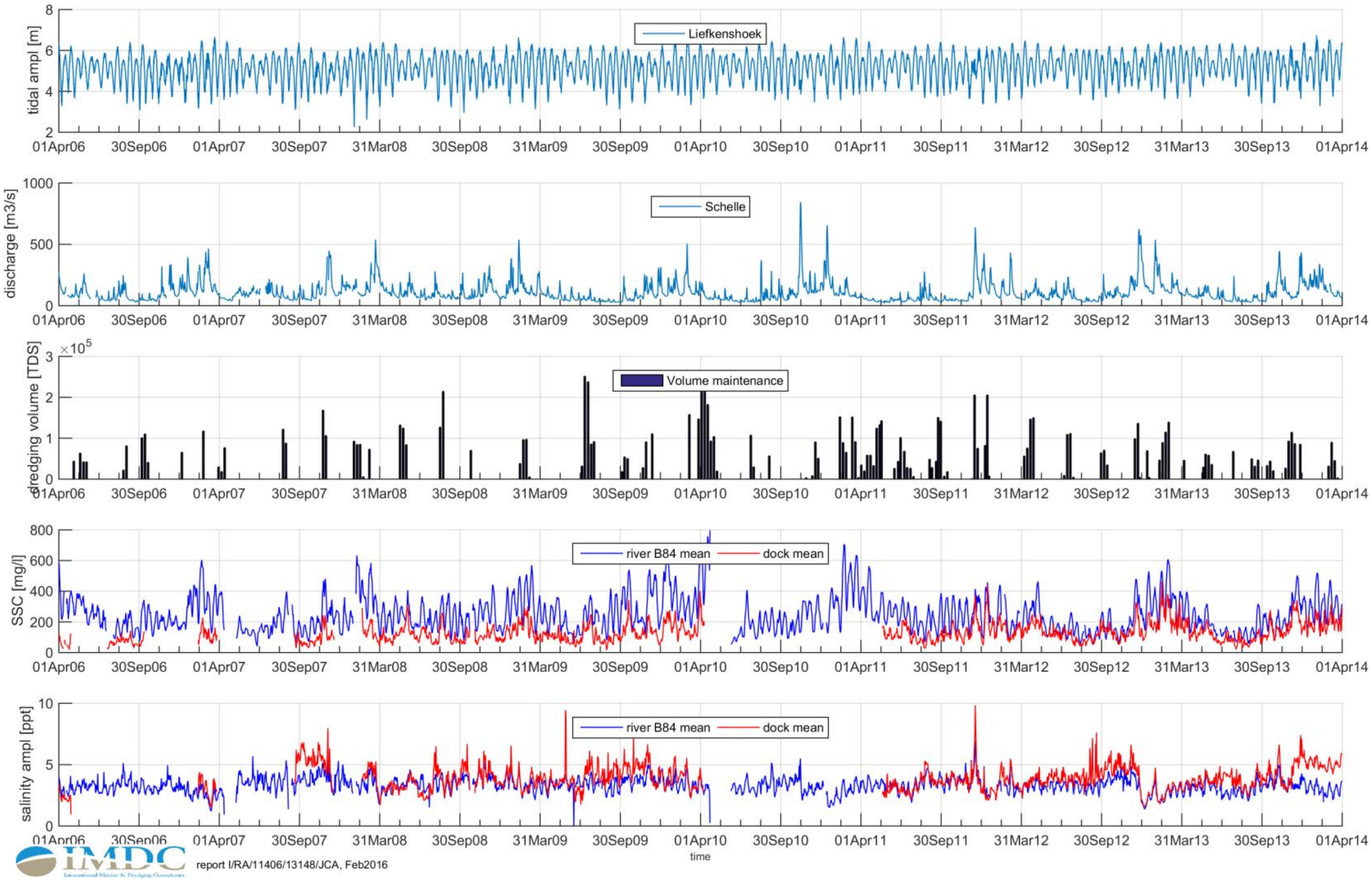


Annex Figure B-4: Time series of SSC including fresh water discharge (Schelle) and tide (Liefkenshoek).

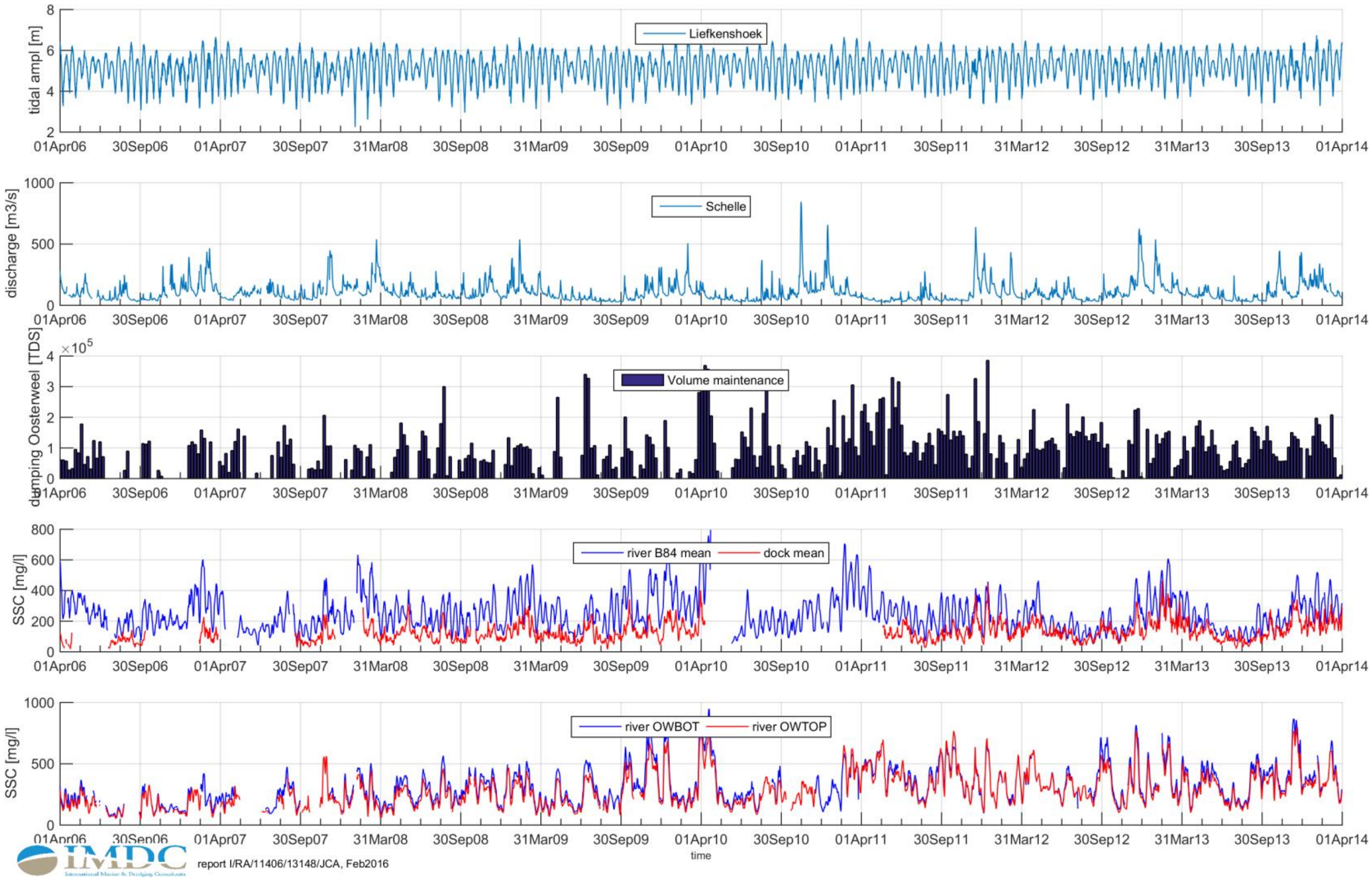
B.2 Time series of daily values



Annex Figure B-5: Daily averaged time series of SSC including fresh water discharge (Schelle) and tidal amplitude (Liefkenshoek).



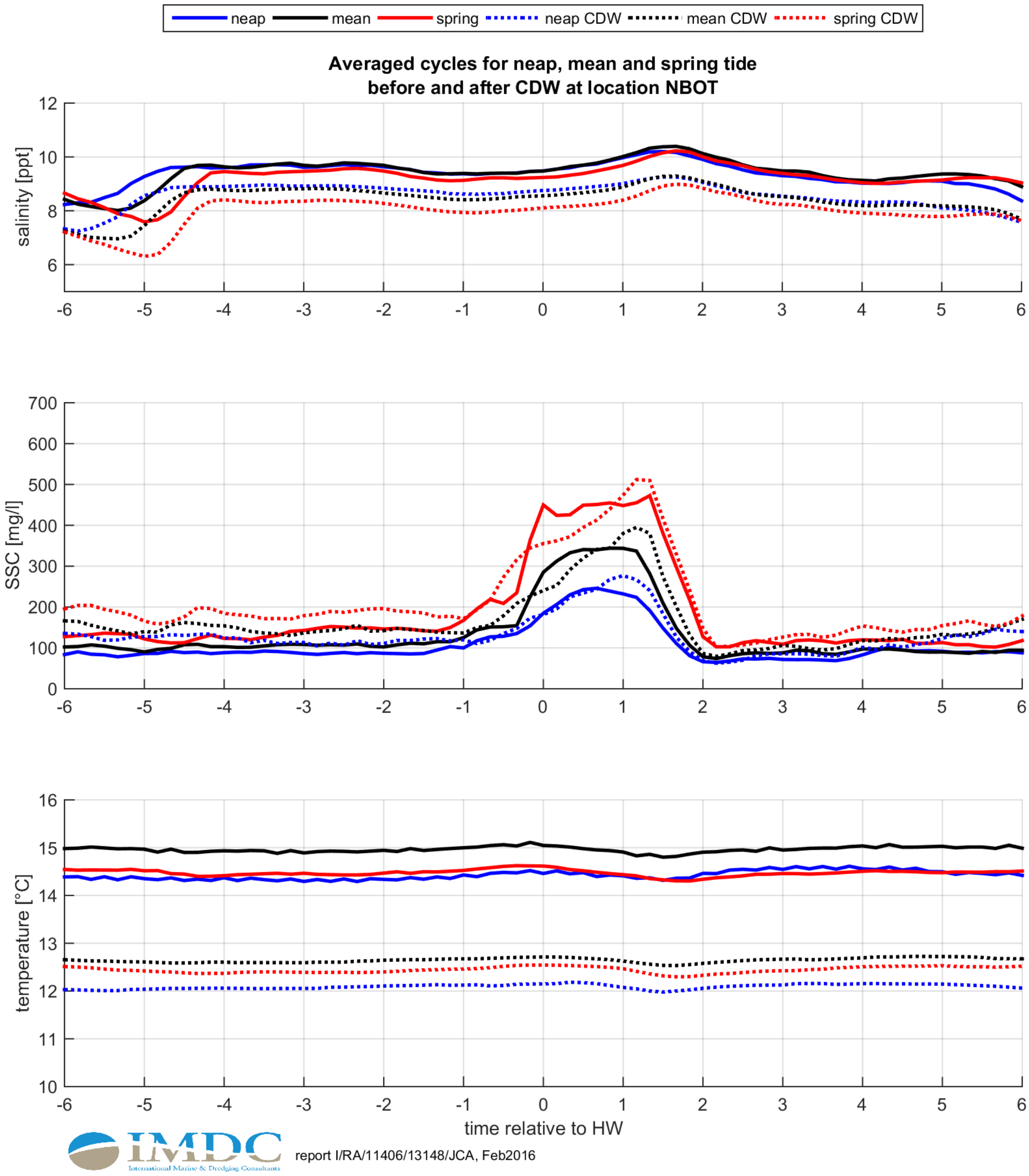
Annex Figure B-6: Daily averaged time series of SSC and salinity including fresh water discharge (Schelle), tidal amplitude (Liefkenshoek) and dredging volumes of Deurganckdok.



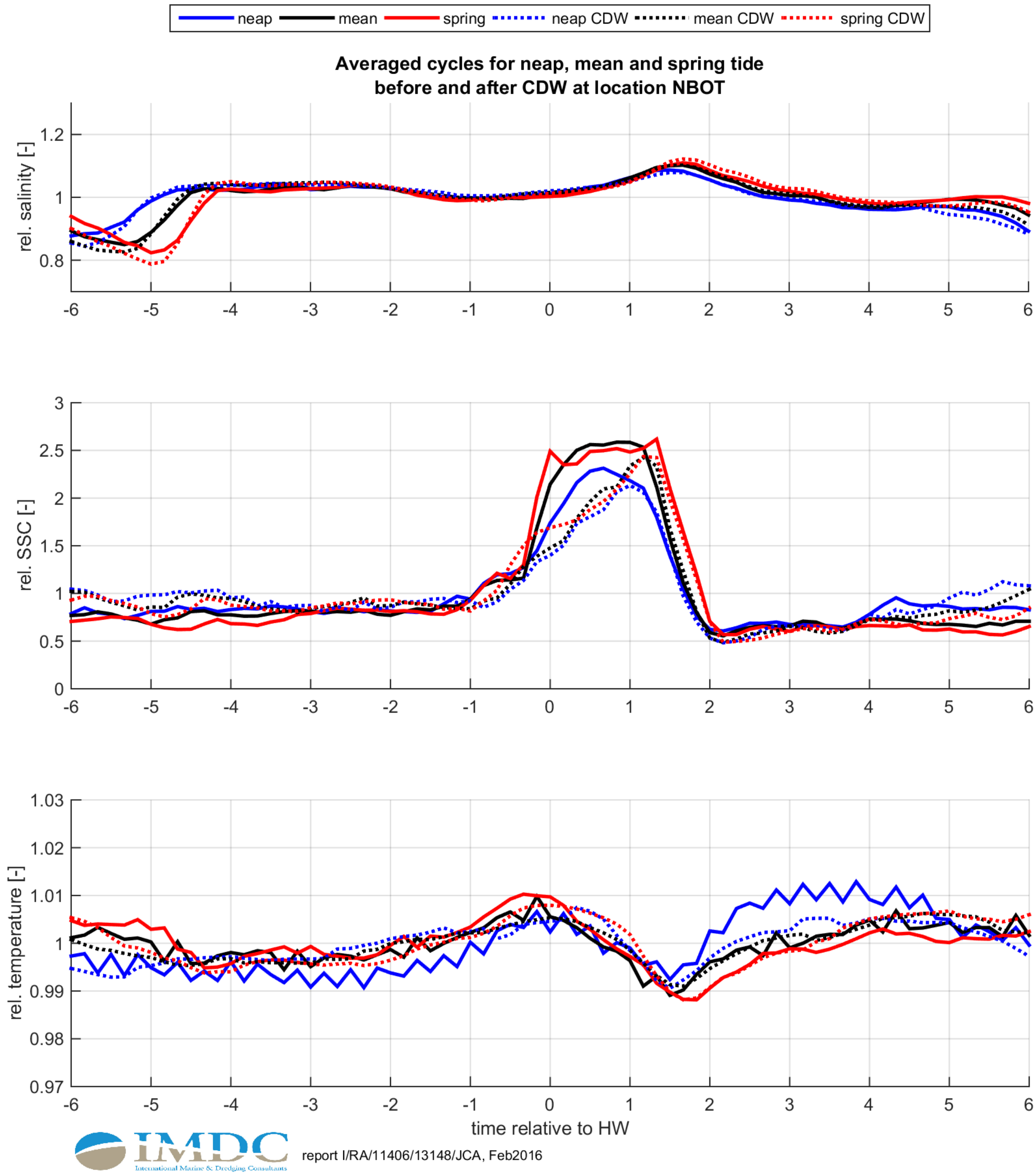
Annex Figure B-7: Daily averaged time series of SSC including fresh water discharge (Schelle), tidal amplitude (Liefkenshoek) and disposal volumes at site Oosterweel.

Annex C Mean tidal cycles

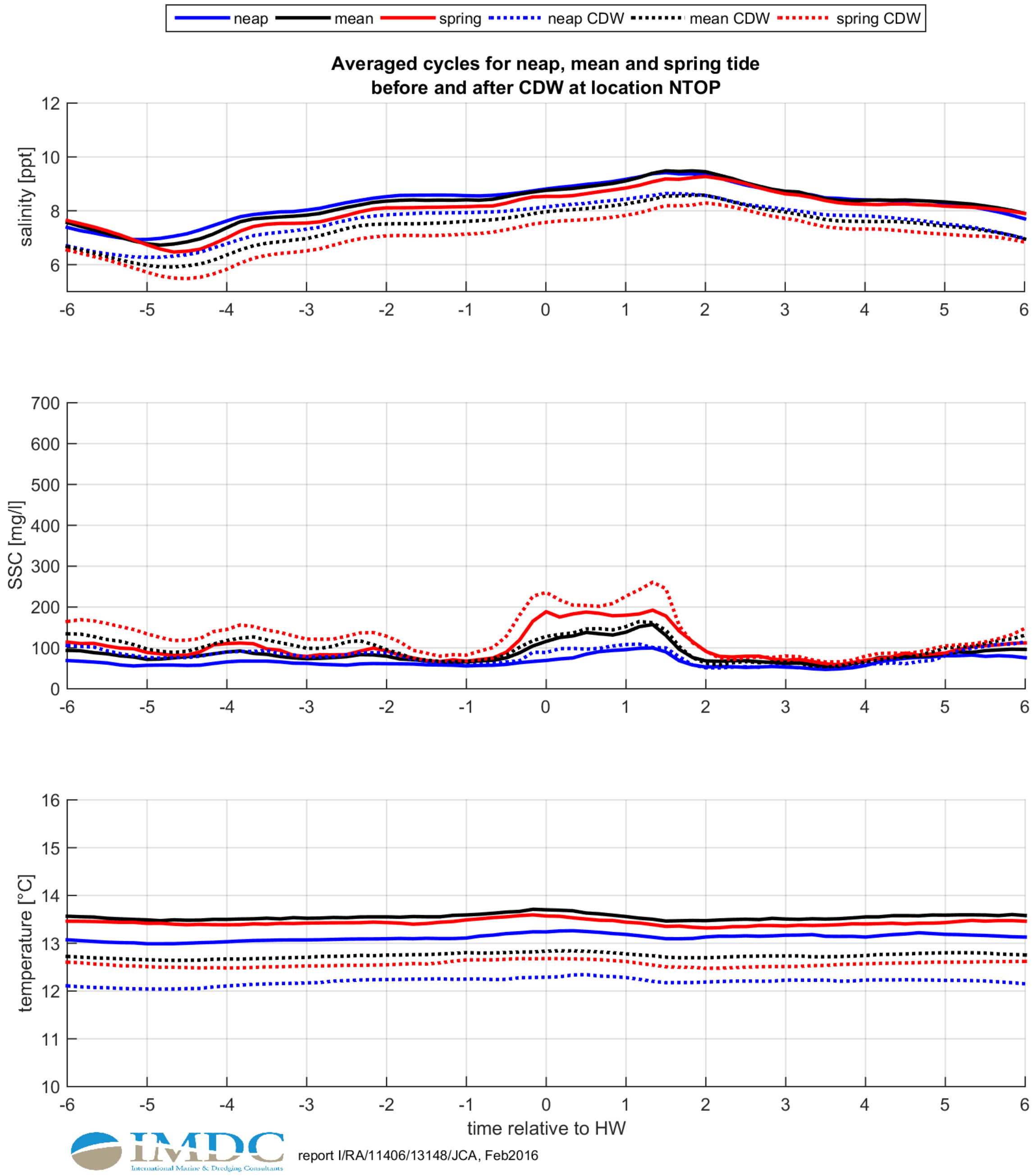
C.1 Per location



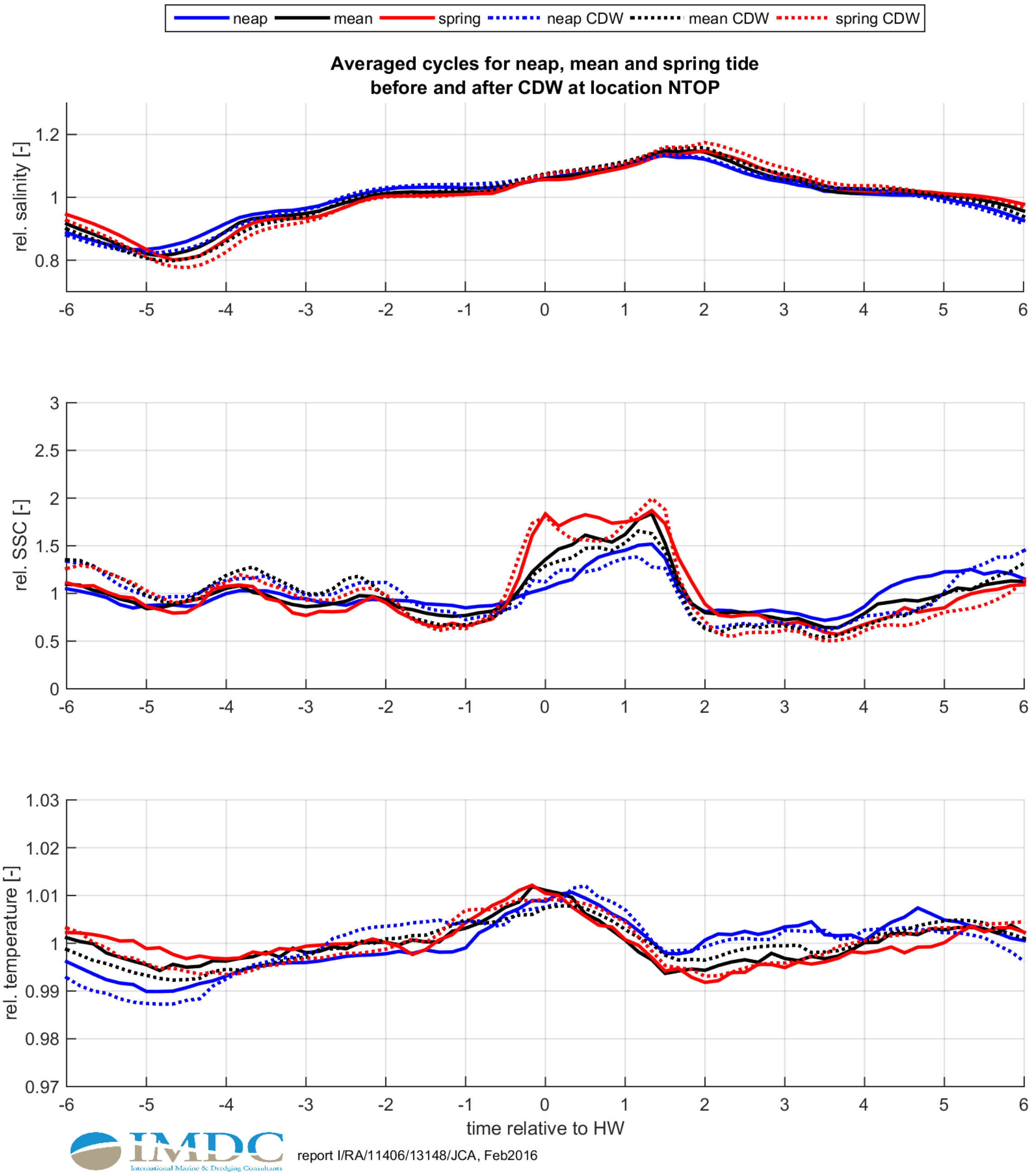
Annex Figure C-1: Mean tidal cycles at NBOT



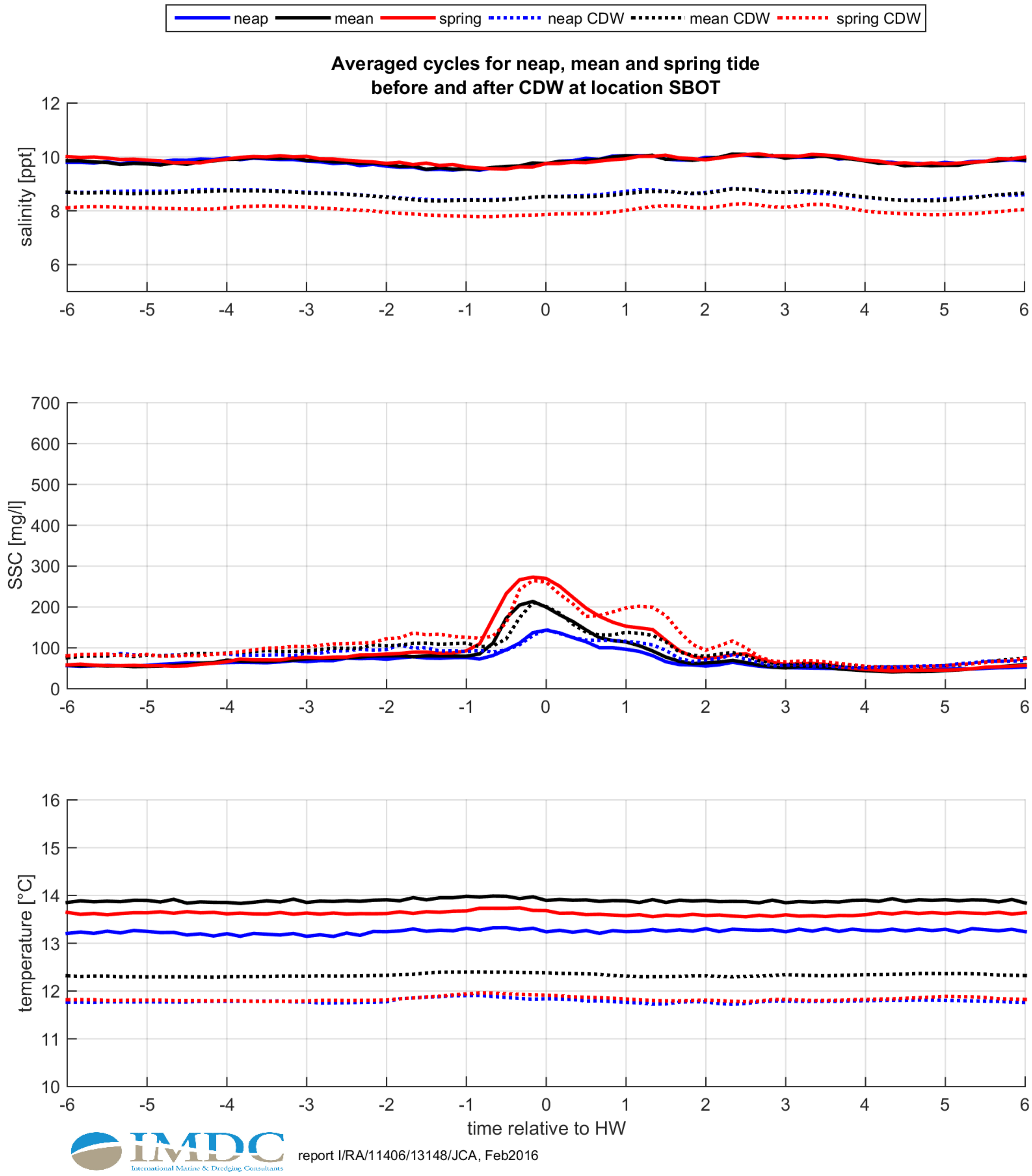
Annex Figure C-2: Relative mean tidal cycles at NBOT



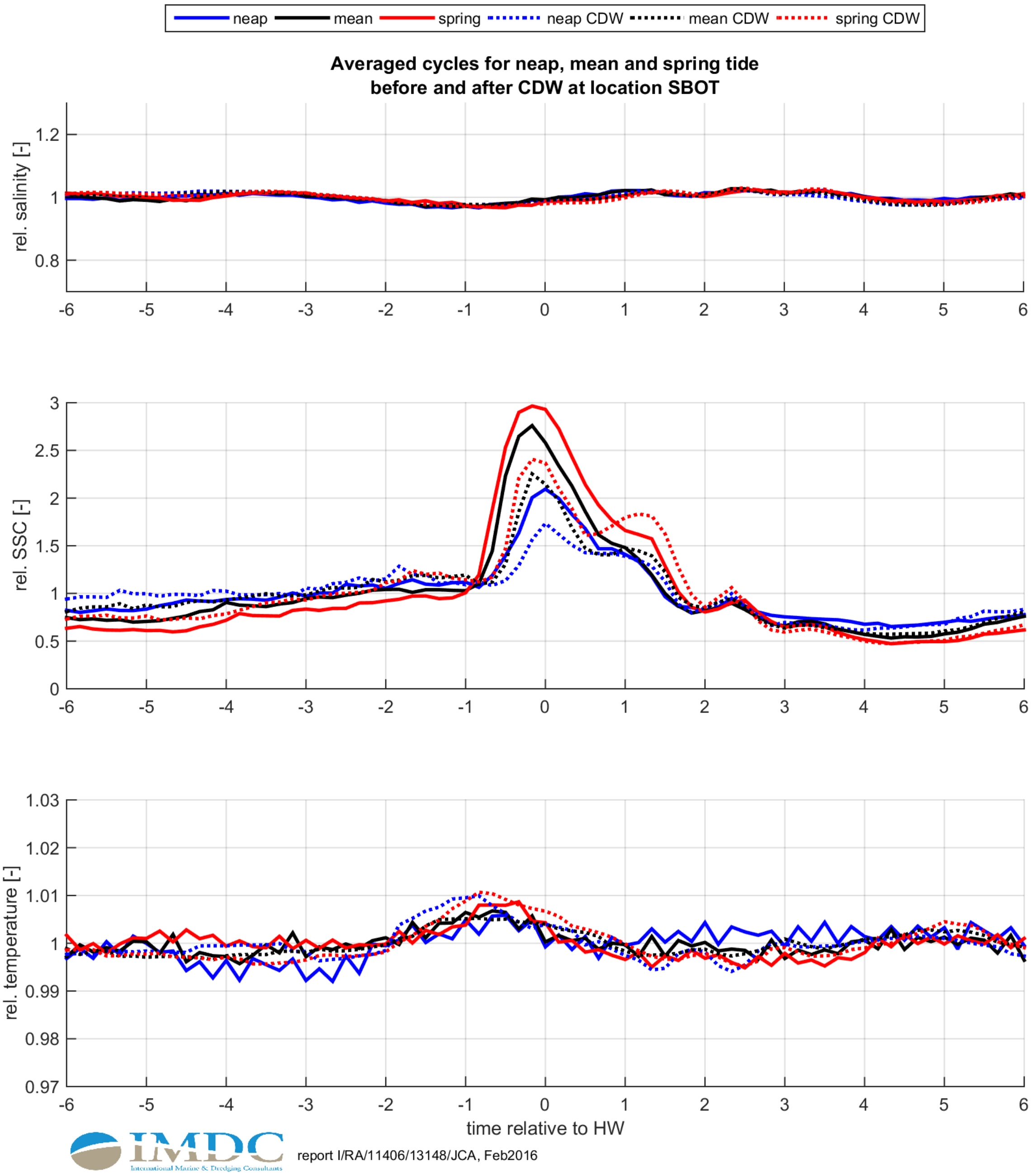
Annex Figure C-3: Mean tidal cycles at NTOP



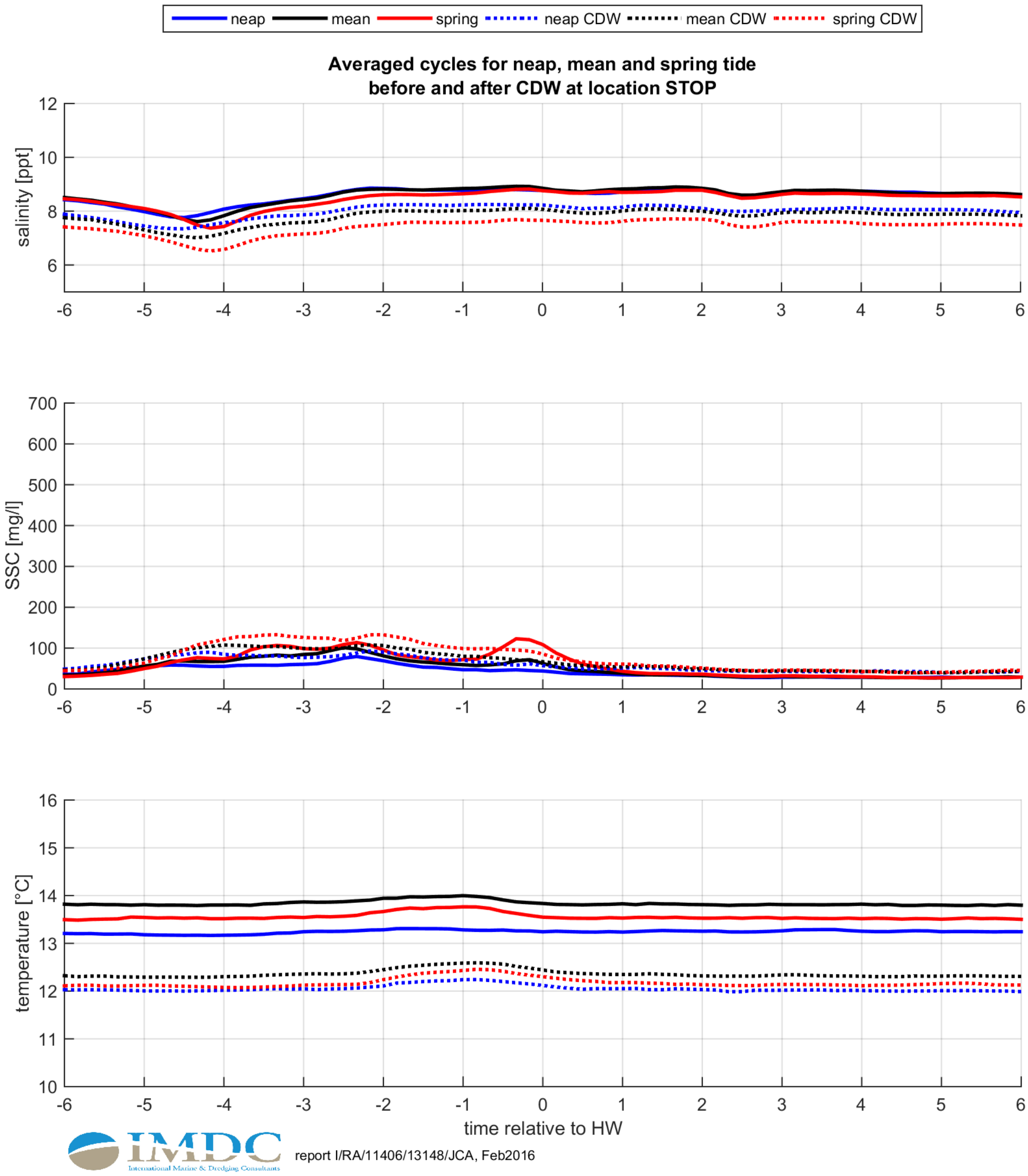
Annex Figure C-4: Relative mean tidal cycles at NTOP



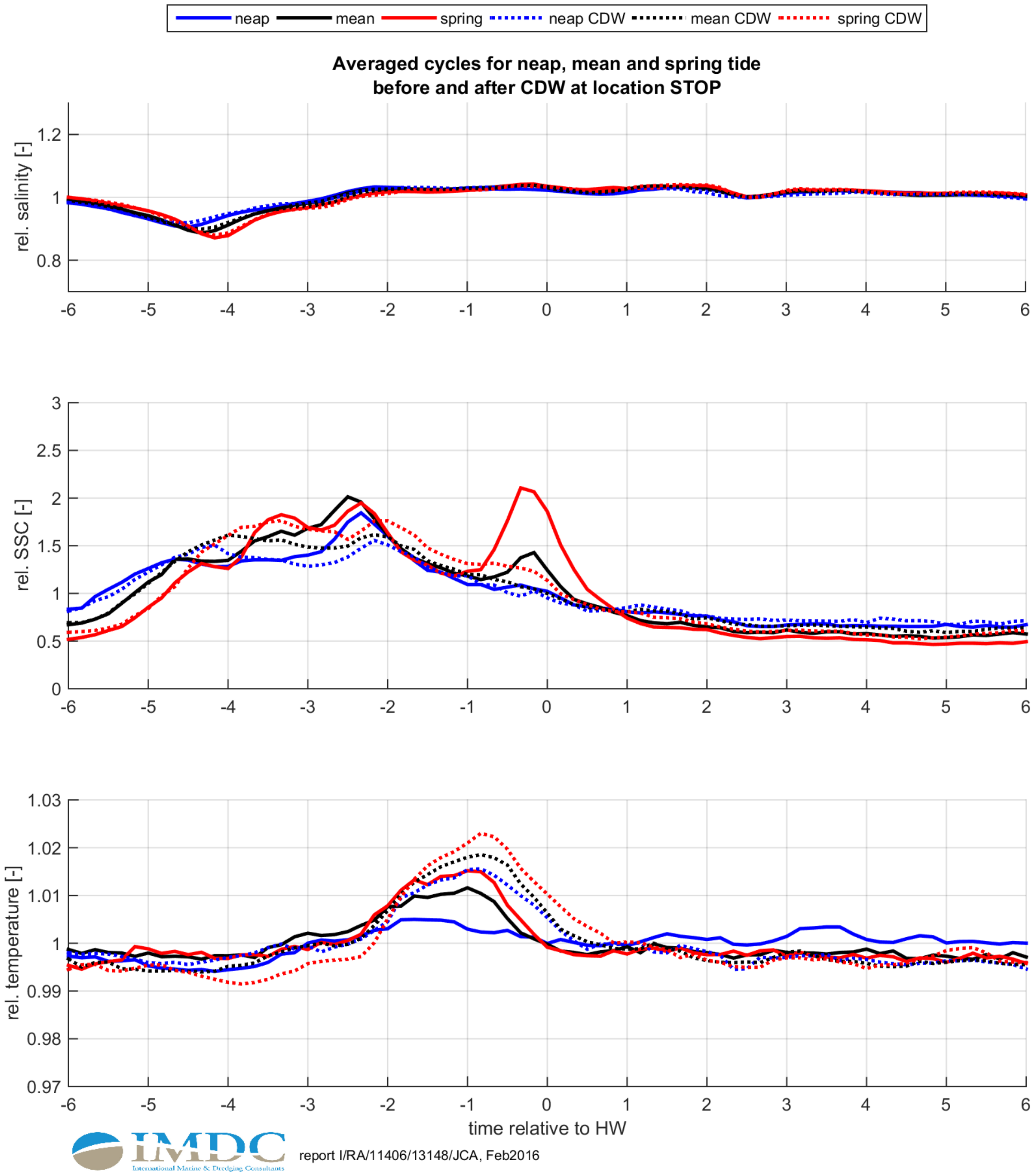
Annex Figure C-5: Mean tidal cycles at SBOT



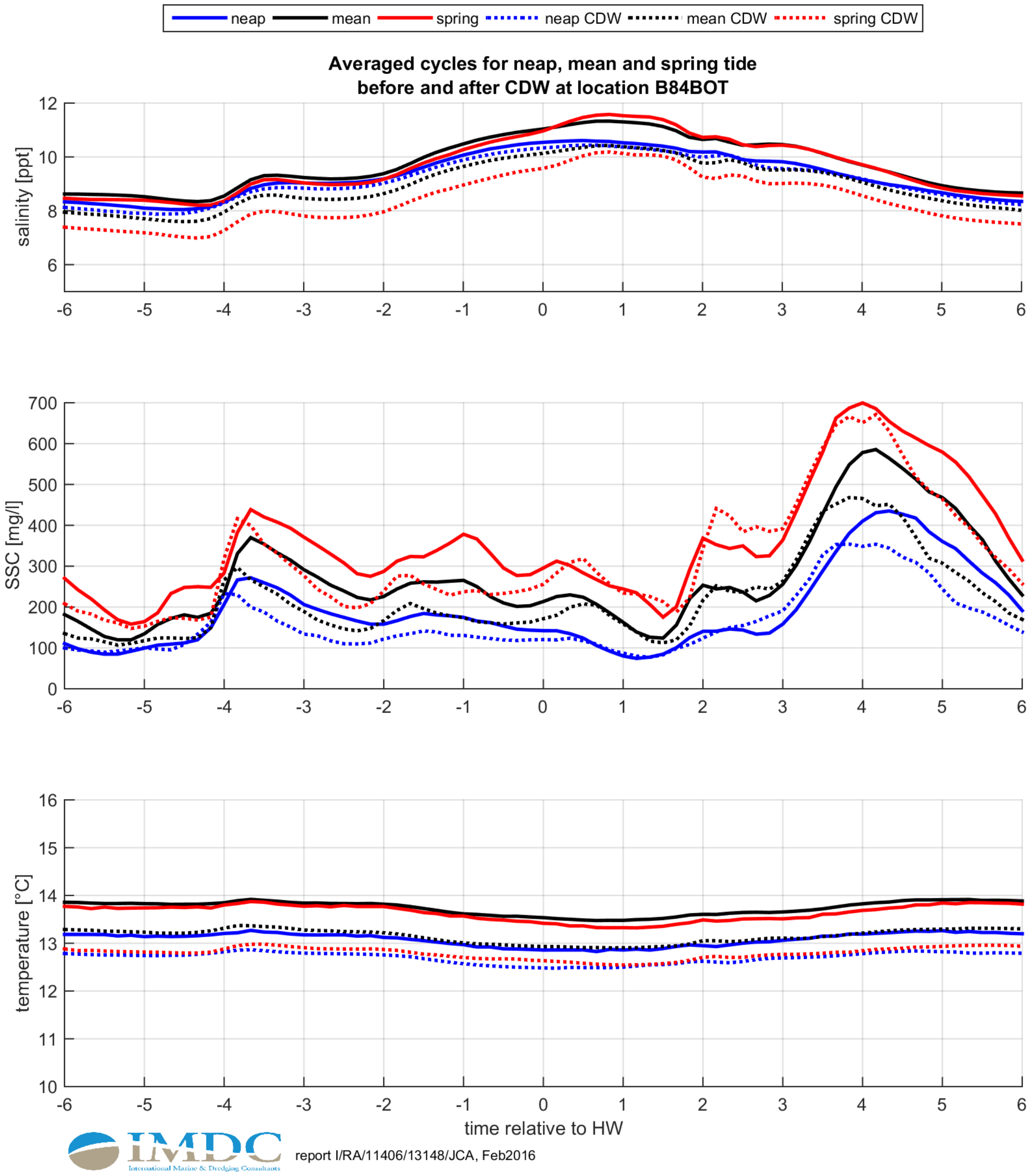
Annex Figure C-6: Relative mean tidal cycles at SBOT



Annex Figure C-7: Mean tidal cycles at STOP

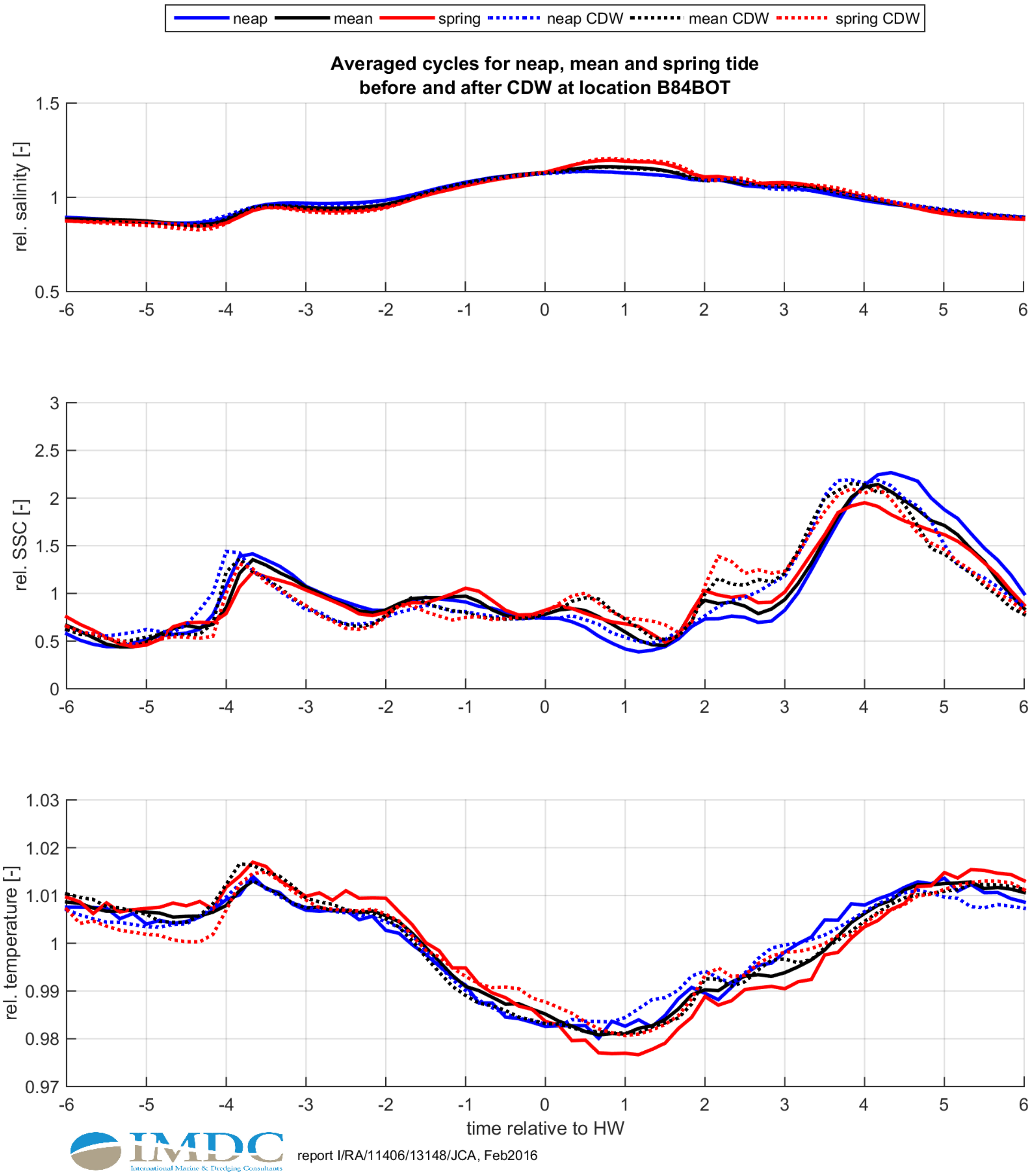


Annex Figure C-8: Relative mean tidal cycles at STOP

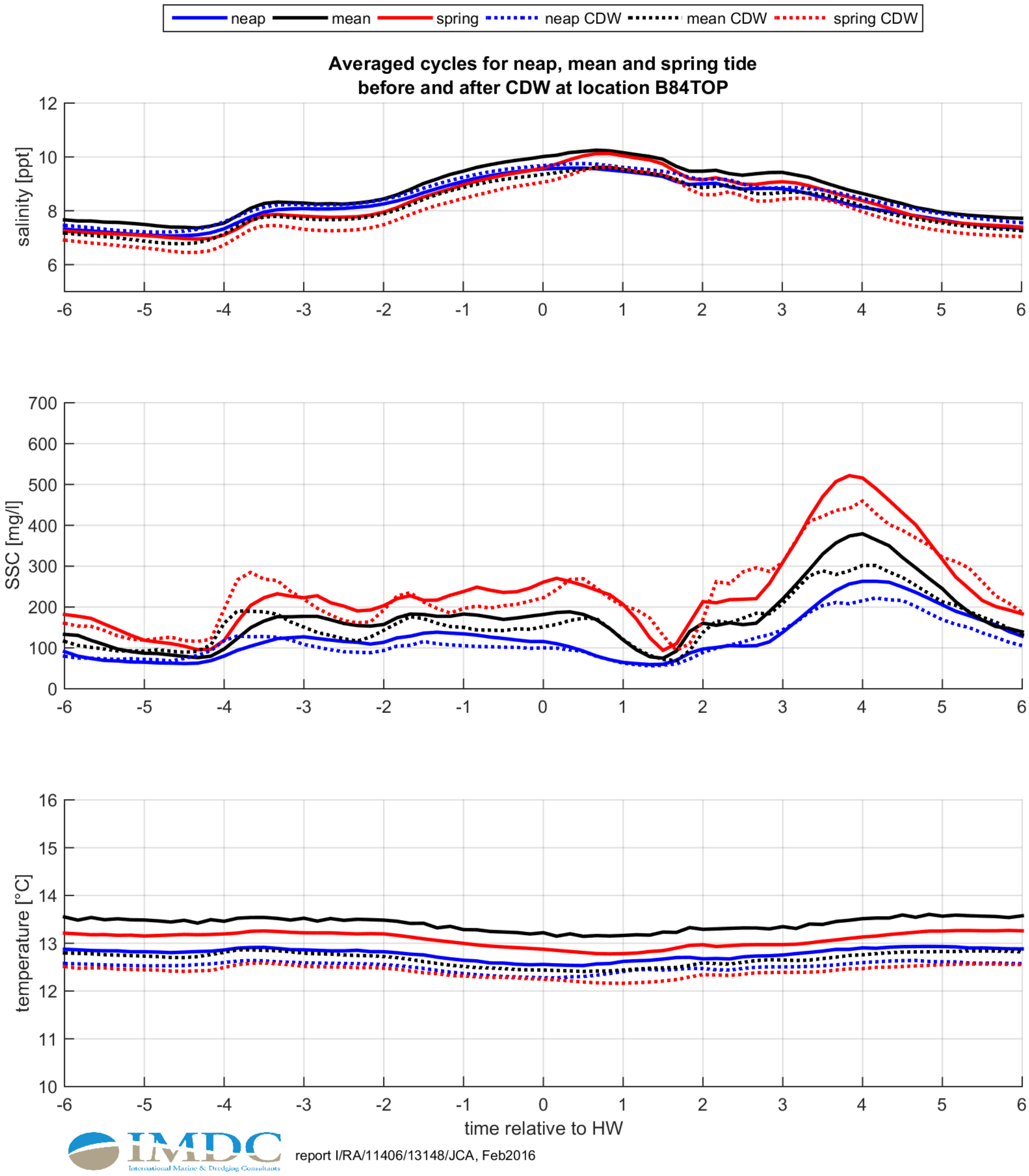


Annex Figure C-9: Mean tidal cycles at B84BOT

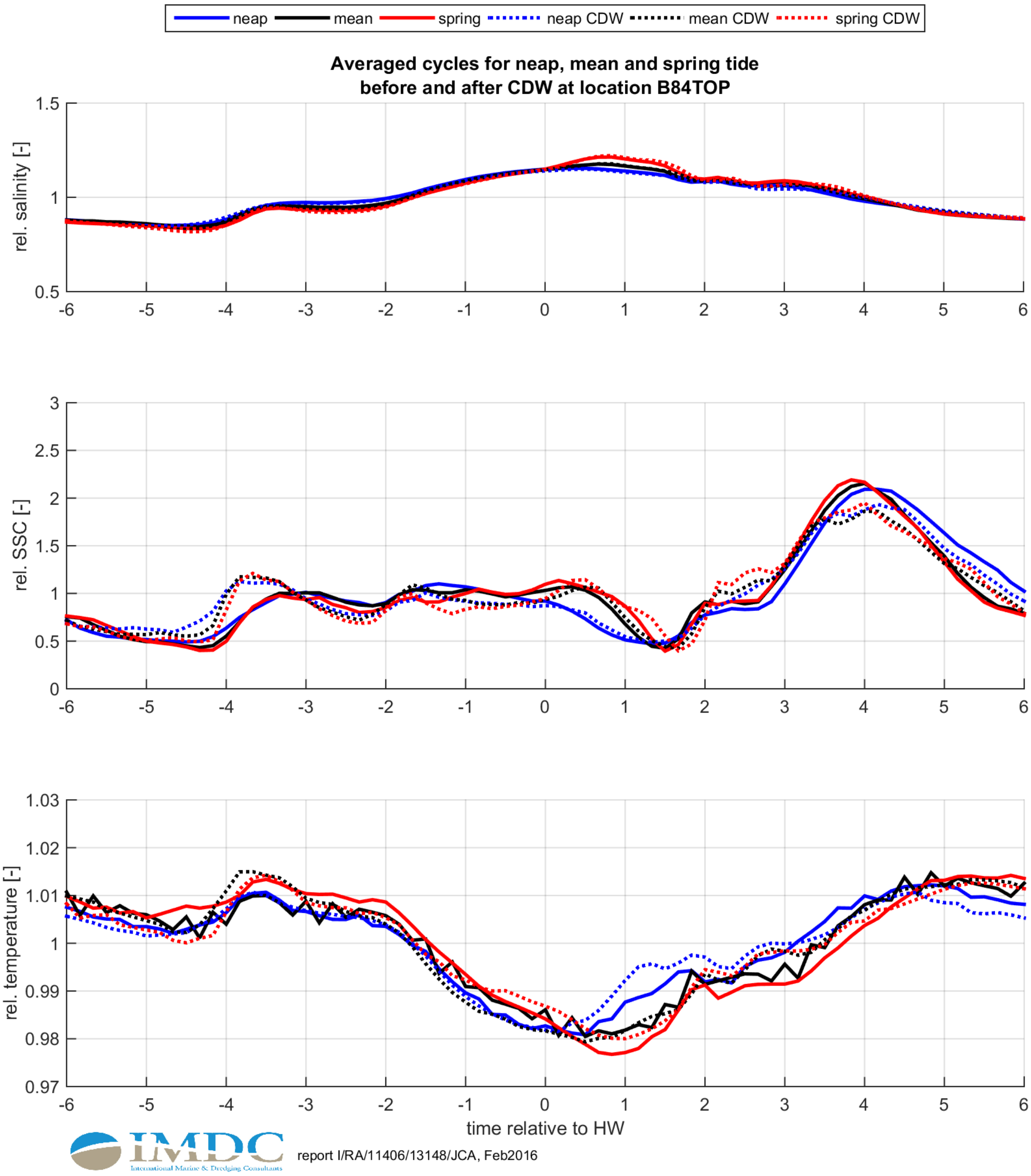
[Note: The suspicious salinity data at B84BOT between 2009 and 2011 is used for processing this figure and will overestimate the absolute salinity results before CDW].



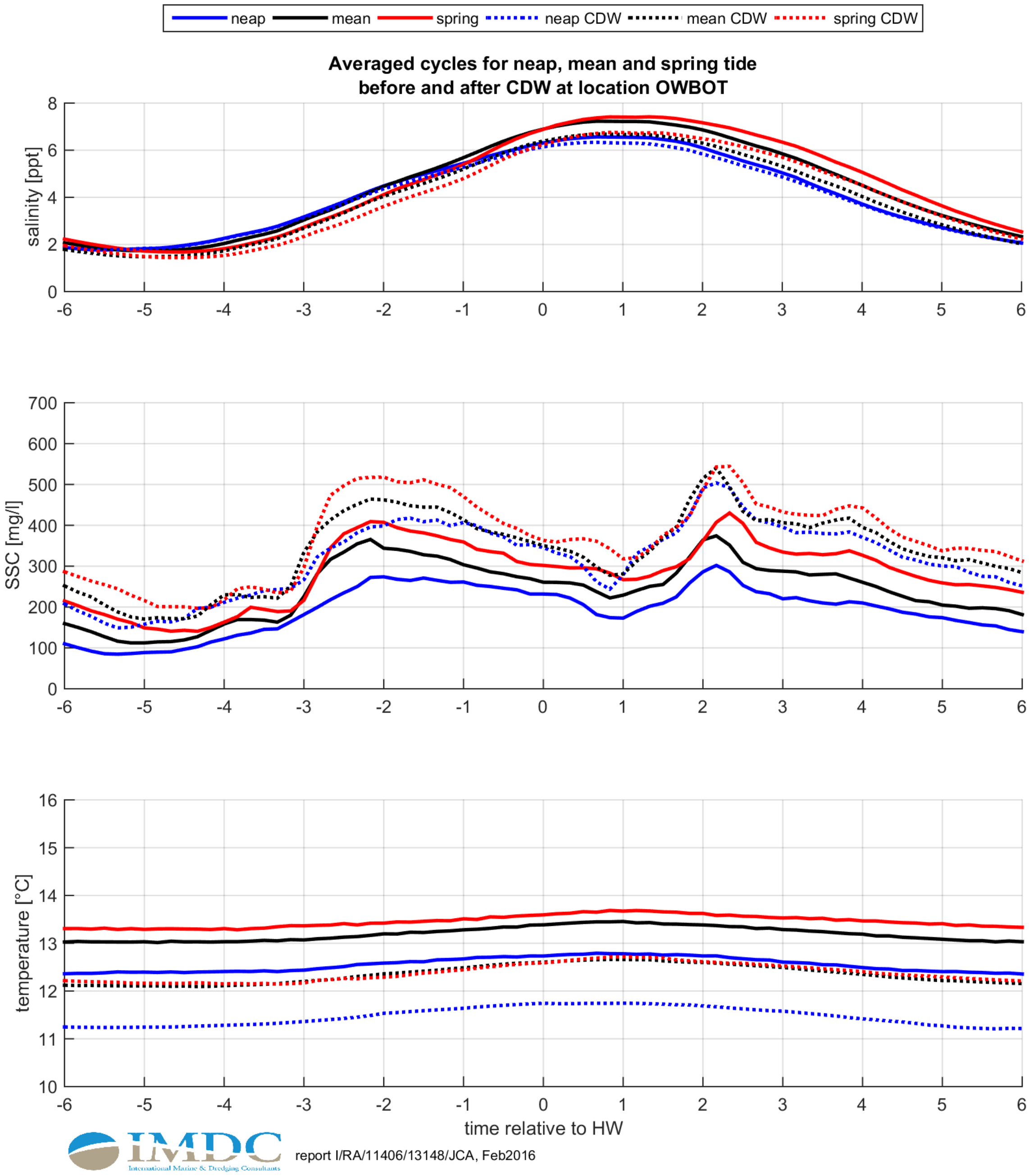
Annex Figure C-10: Relative mean tidal cycles at B84BOT



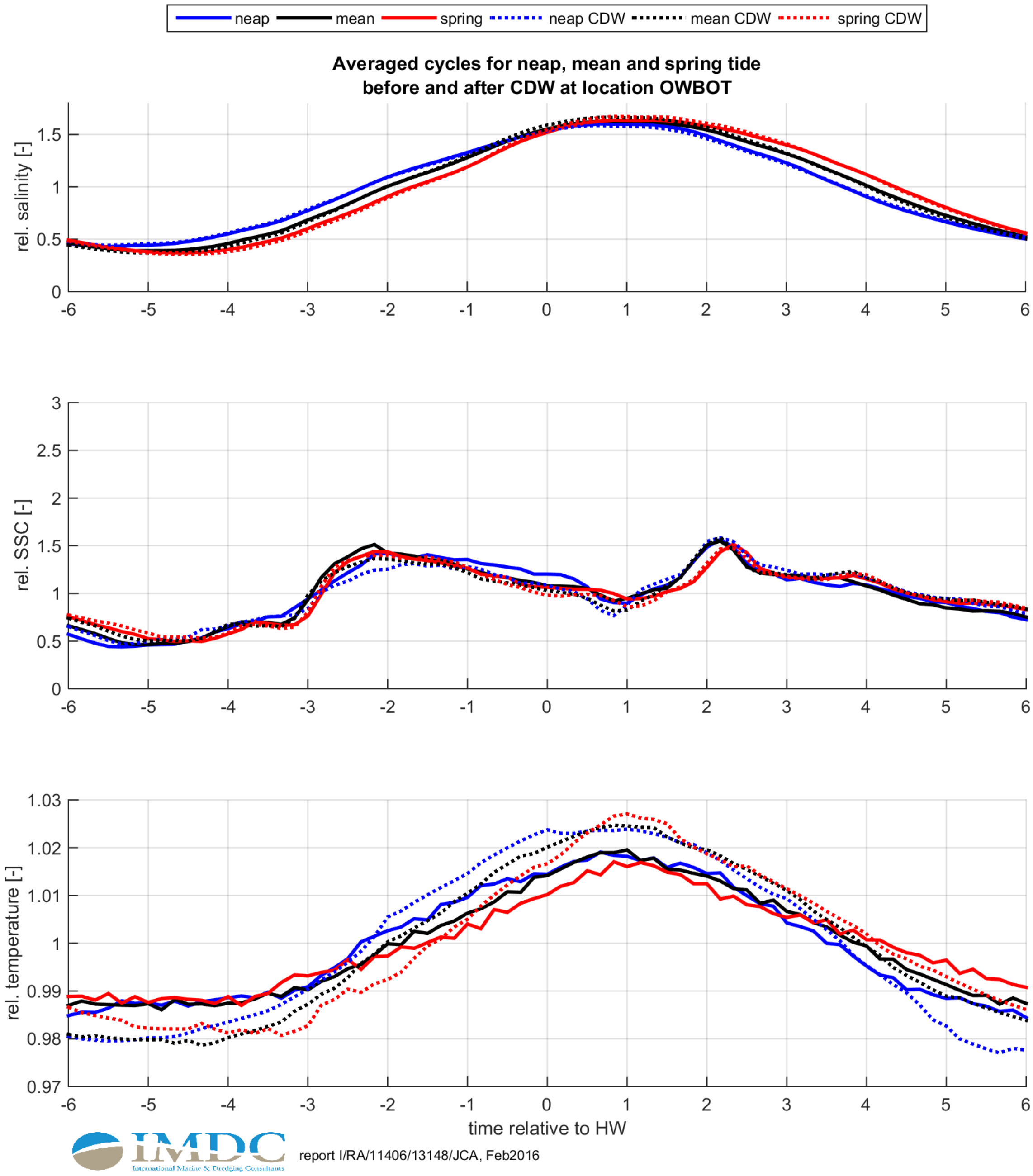
Annex Figure C-11: Mean tidal cycles at B84TOP



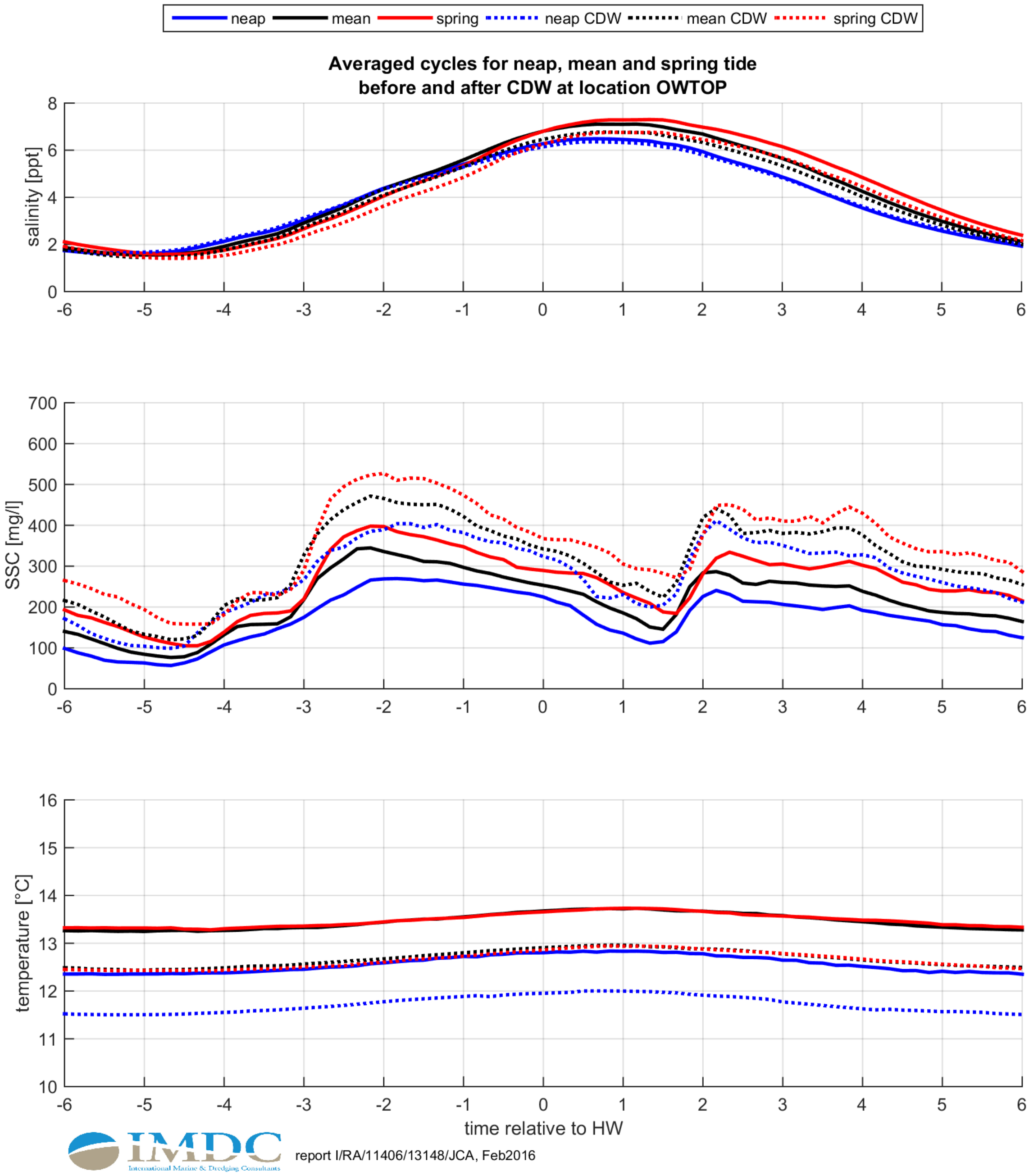
Annex Figure C-12: Relative mean tidal cycles at B84TOP



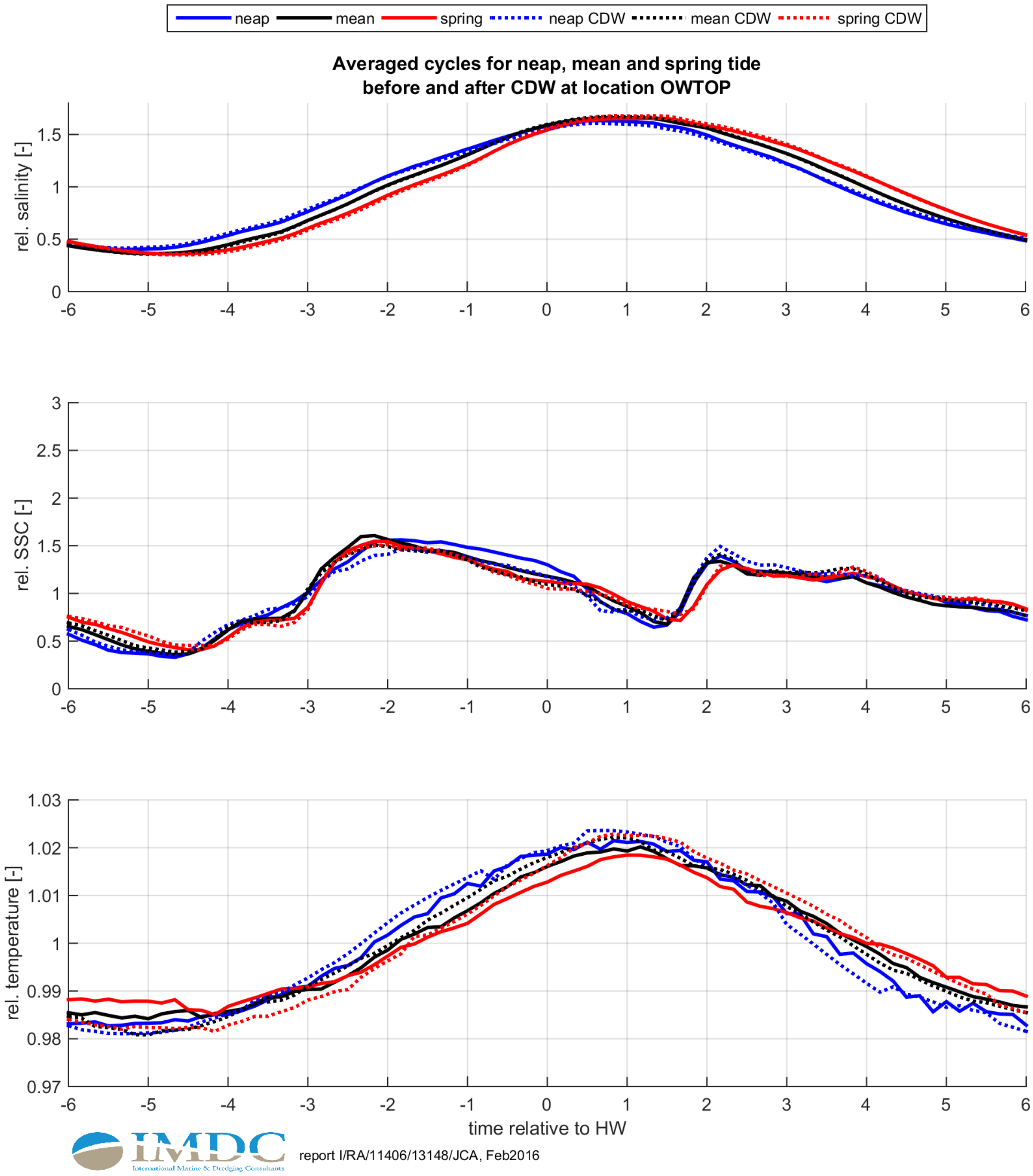
Annex Figure C-13: Mean tidal cycles at OWBOT



Annex Figure C-14: Relative mean tidal cycles at OWBOT

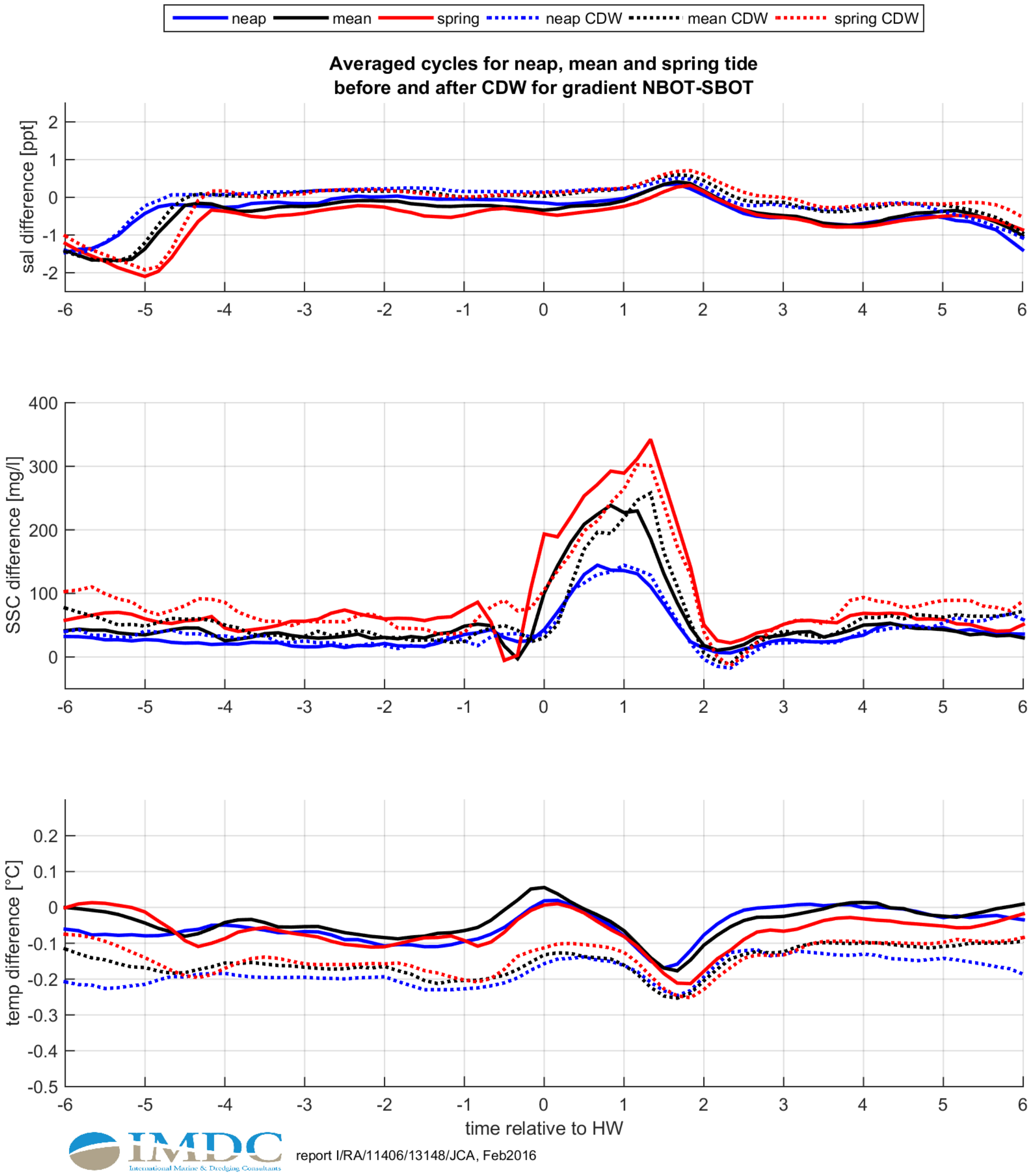


Annex Figure C-15: Mean tidal cycles at OWTOP

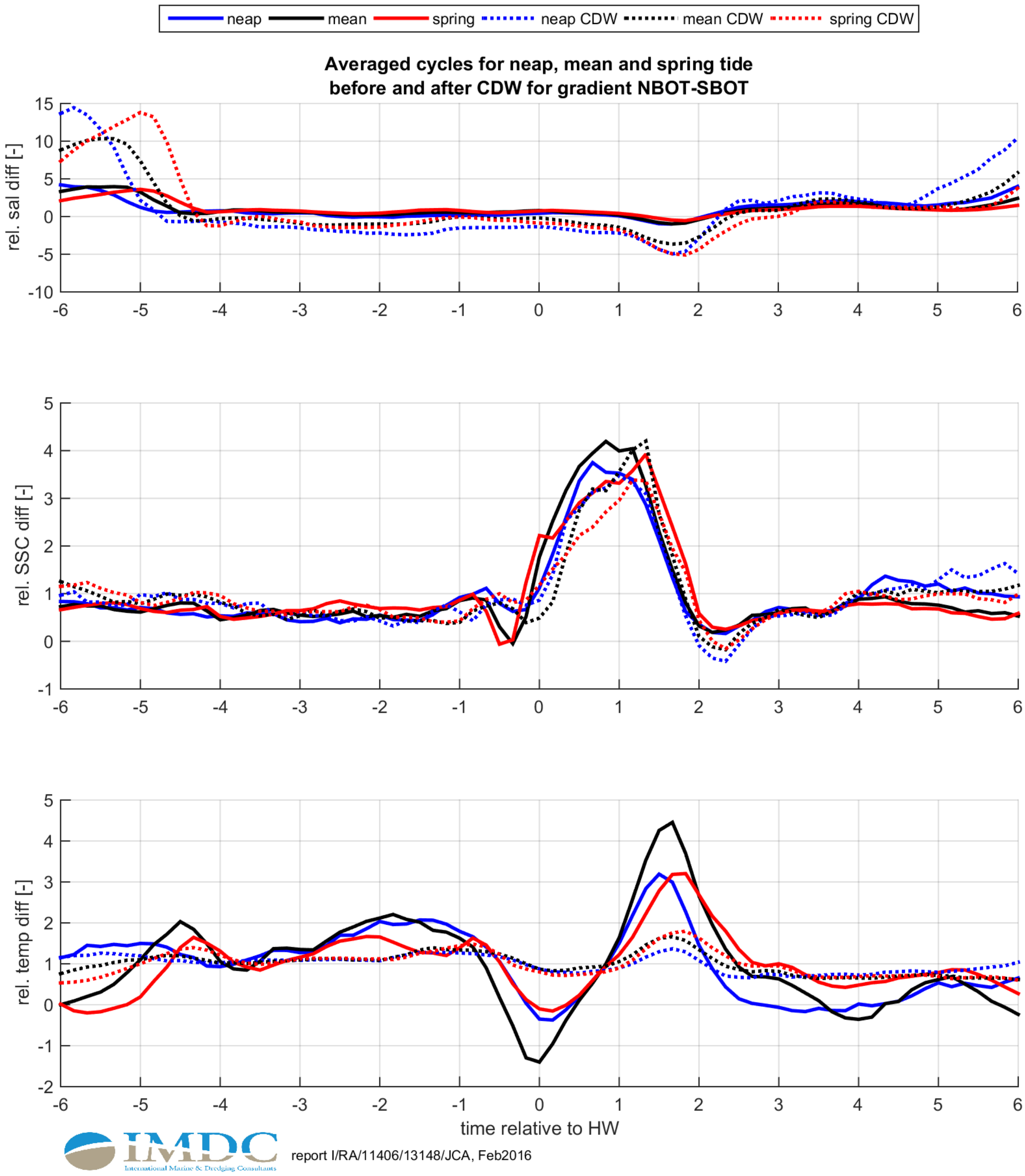


Annex Figure C-16: Relative mean tidal cycles at OWTOP

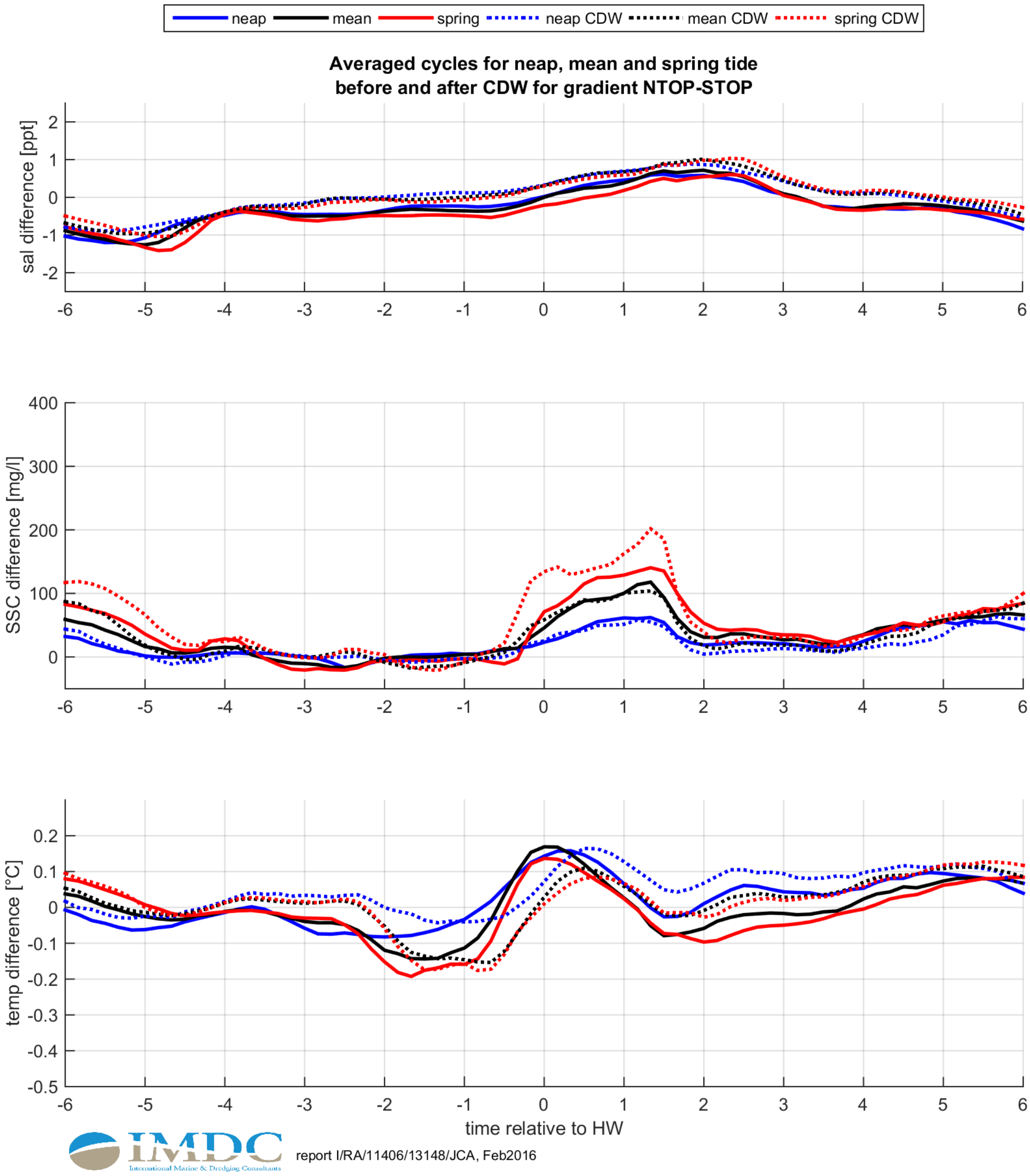
C.2 Gradients



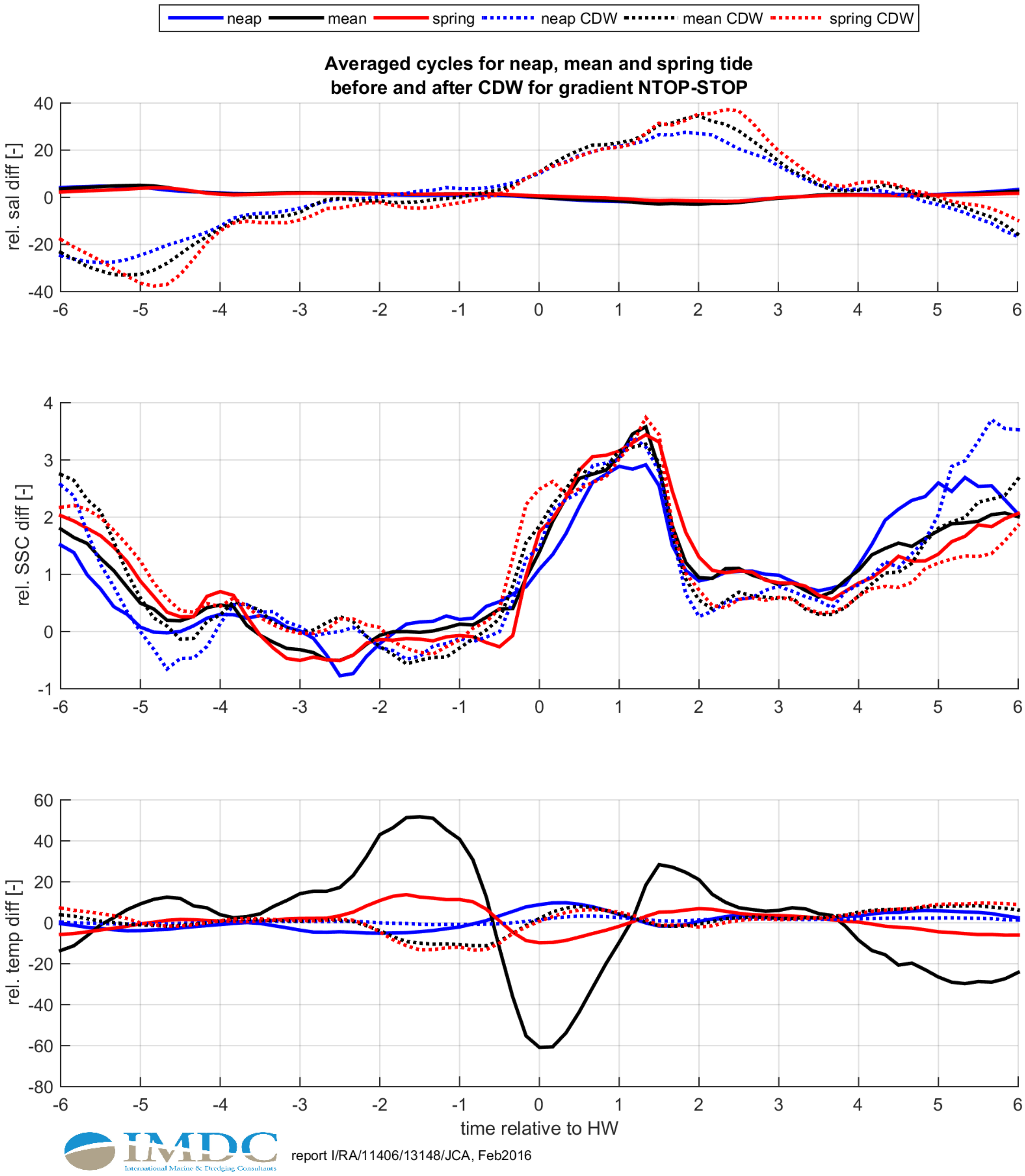
Annex Figure C-17: Horizontal differences of tidal cycles, bottom sensors



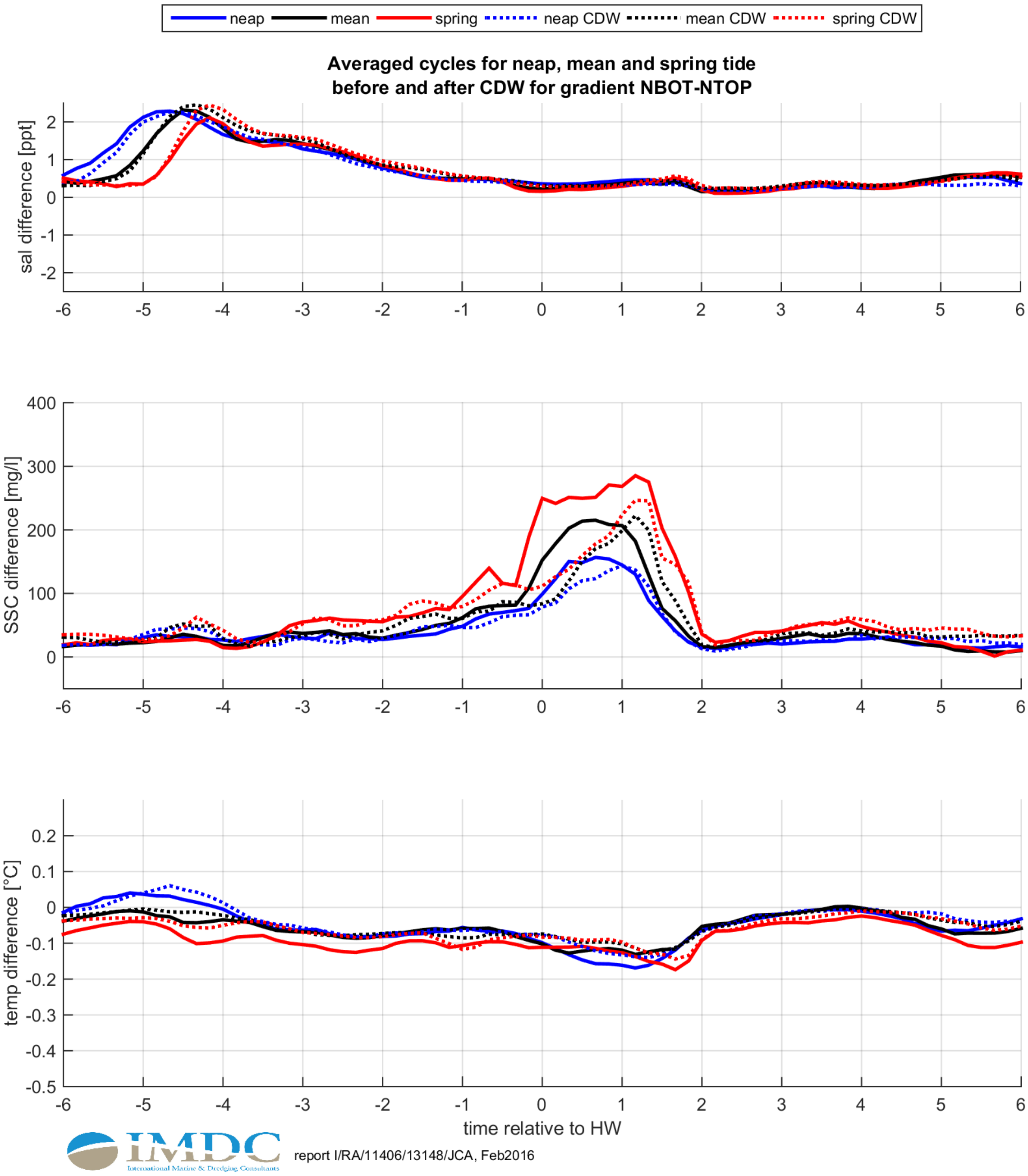
Annex Figure C-18: Horizontal relative differences of tidal cycles, bottom sensors



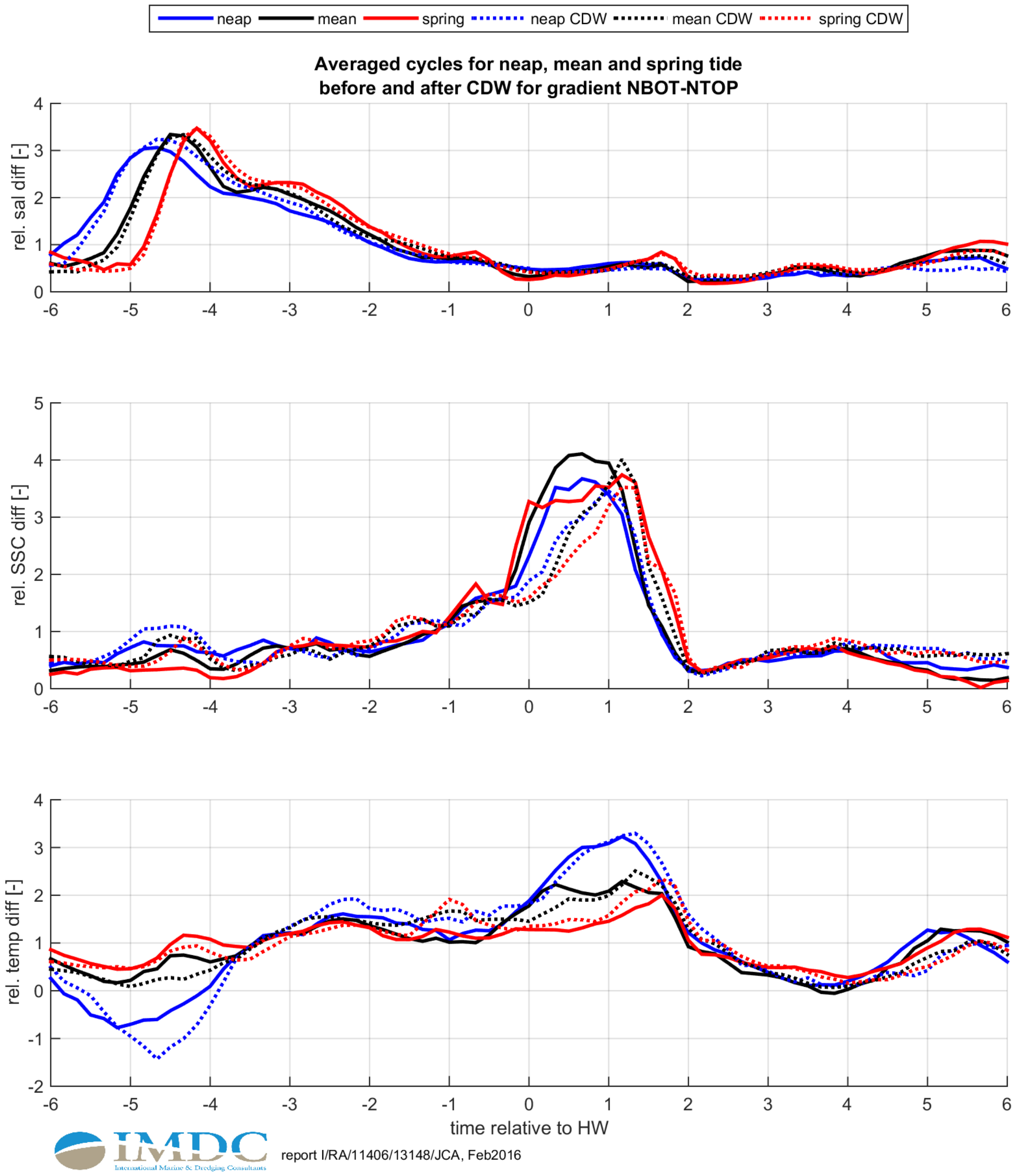
Annex Figure C-19: Horizontal differences of tidal cycles, top sensors



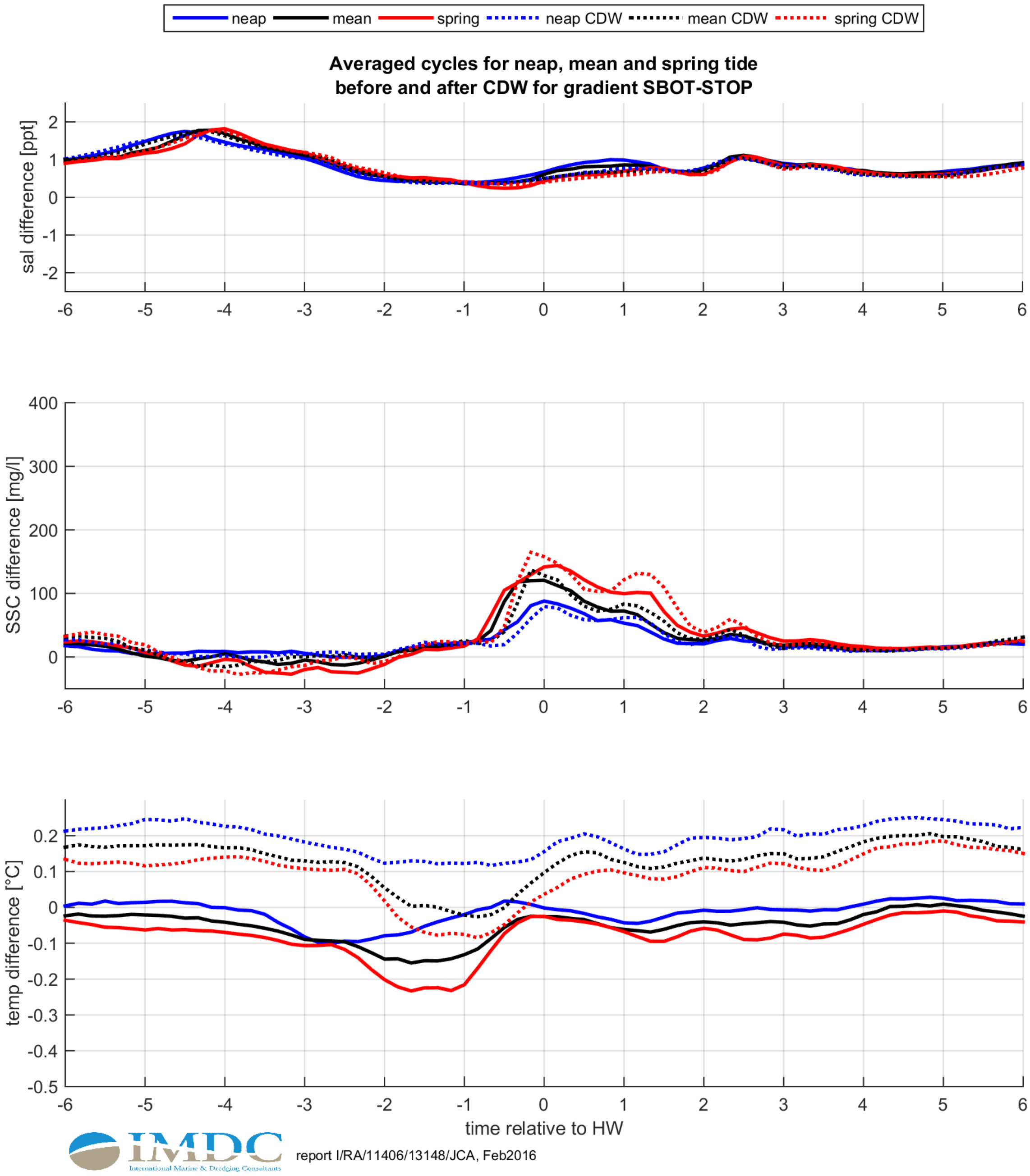
Annex Figure C-20: Relative horizontal differences of tidal cycles, top sensors



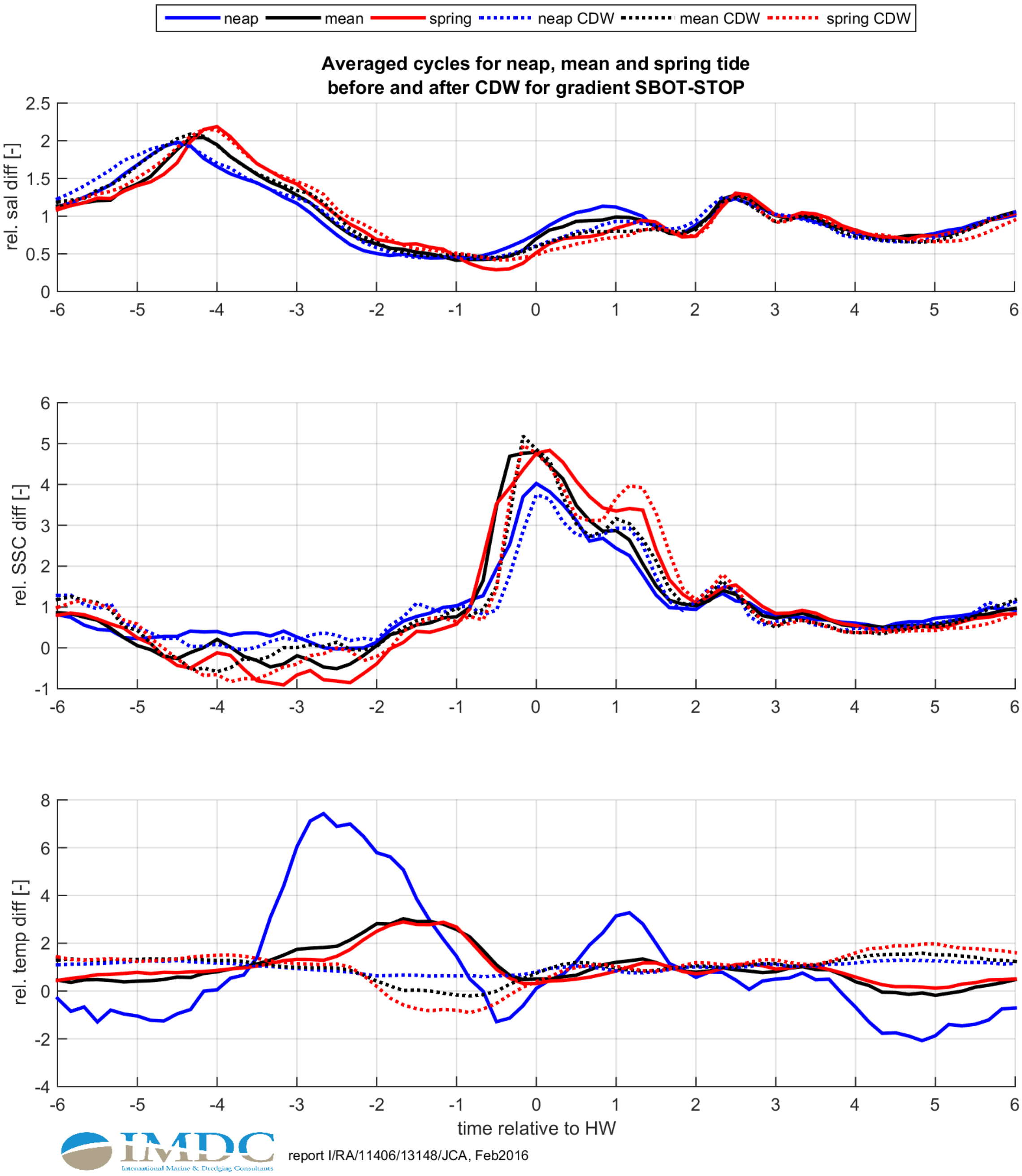
Annex Figure C-21: Vertical differences of tidal cycles, North sensors



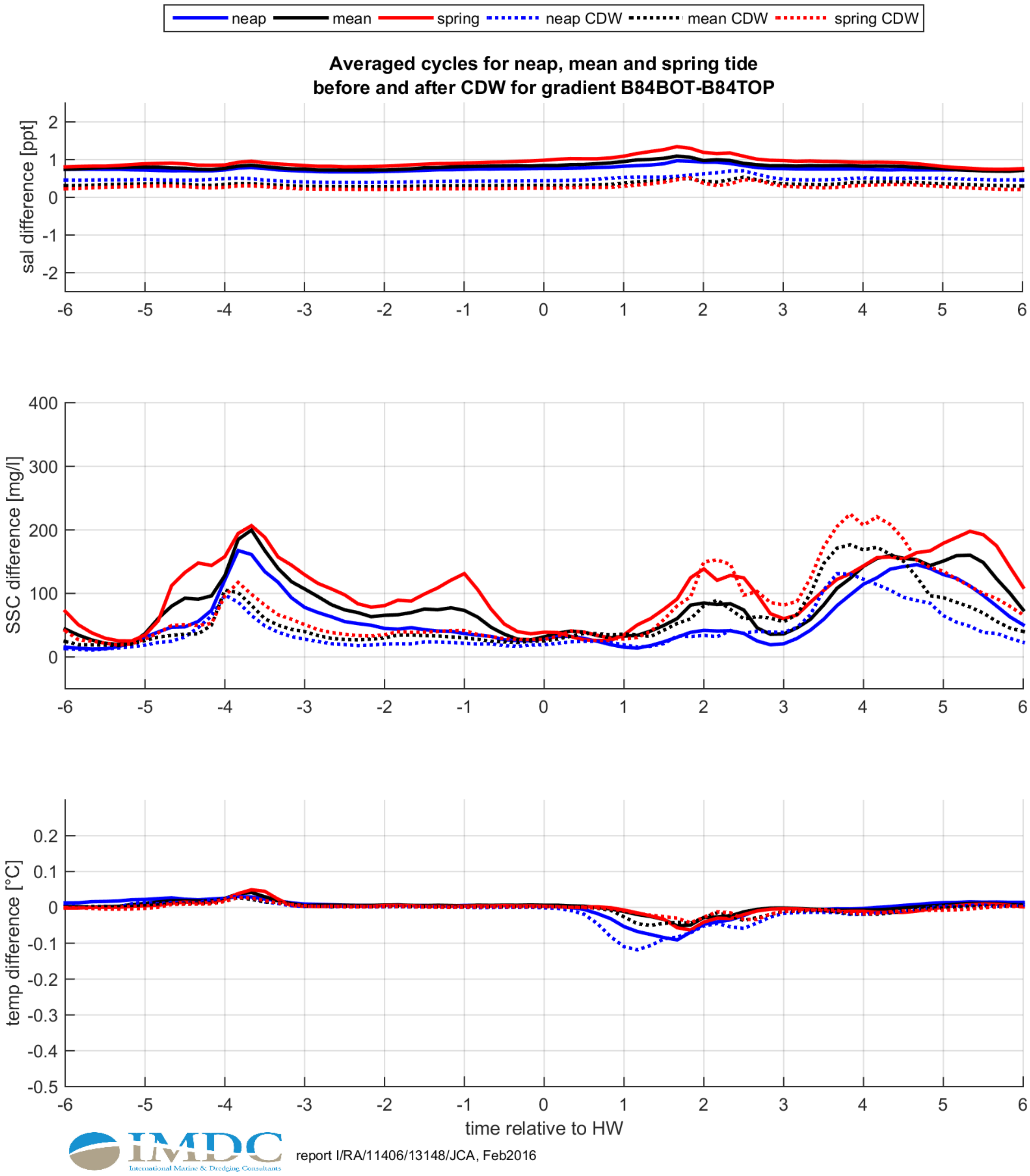
Annex Figure C-22: Relative vertical differences of tidal cycles, North sensors



Annex Figure C-23: Vertical differences of tidal cycles, South sensors

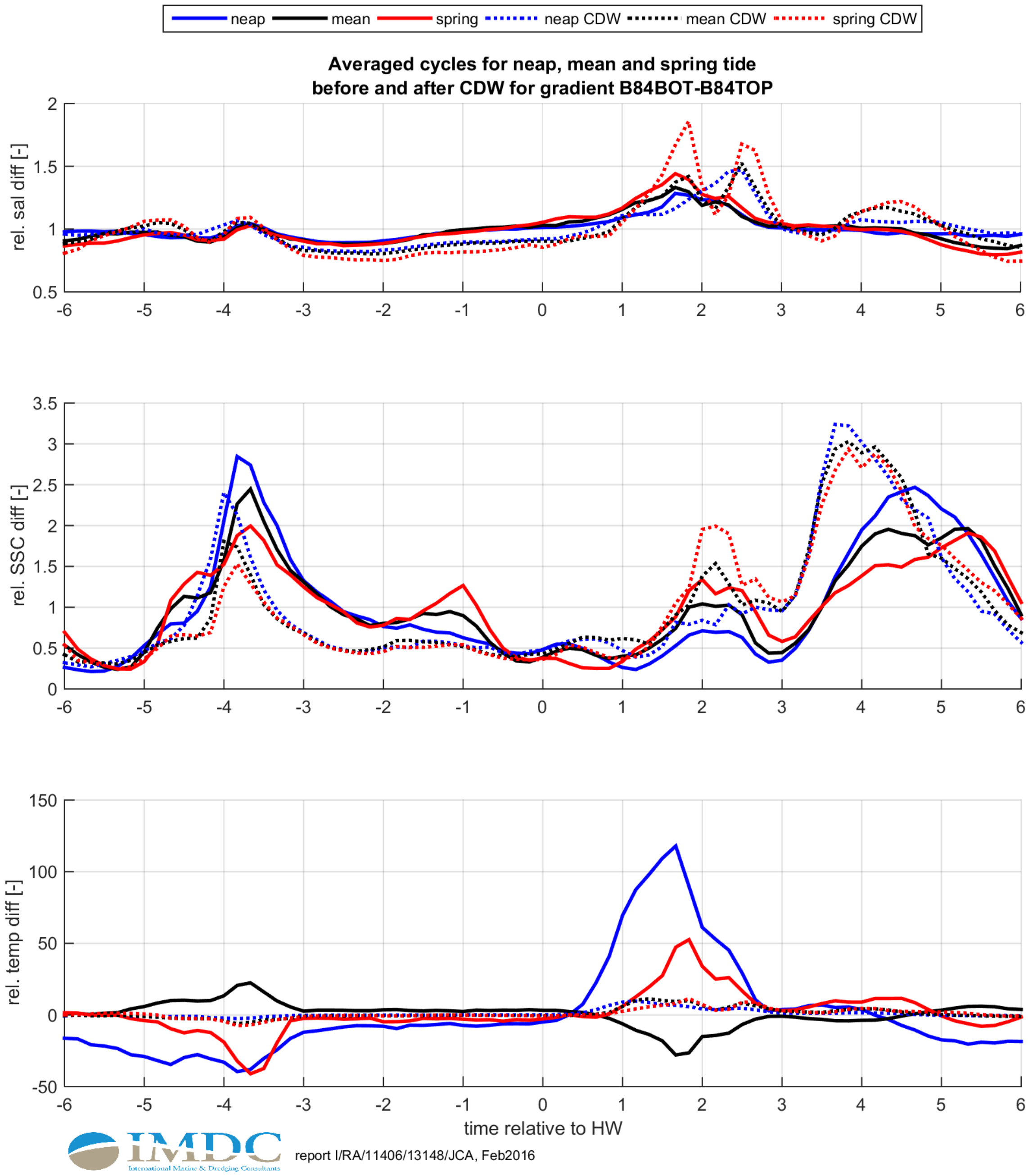


Annex Figure C-24: Relative vertical differences of tidal cycles, South sensors

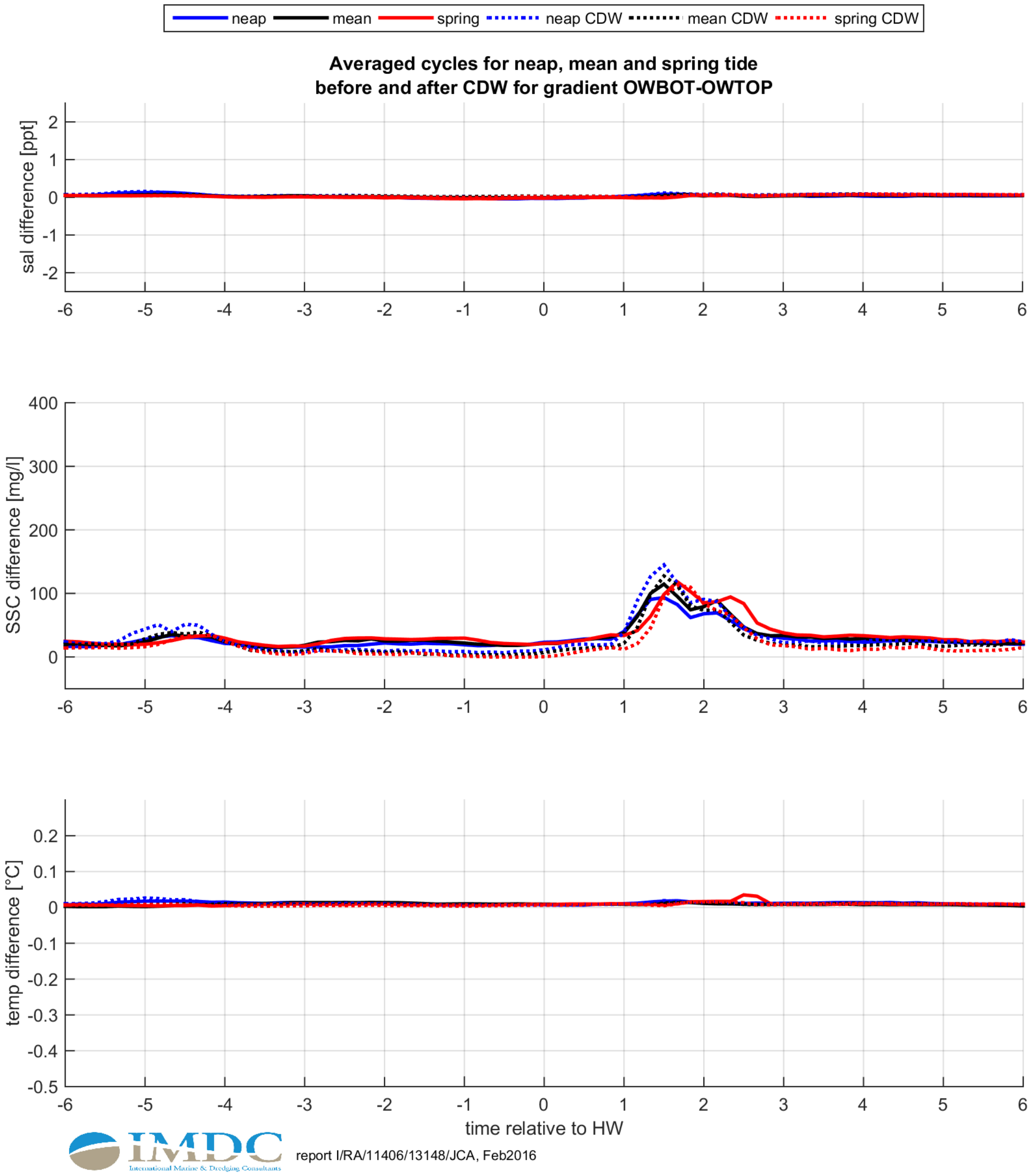


Annex Figure C-25: Vertical differences of tidal cycles, Buoy 84

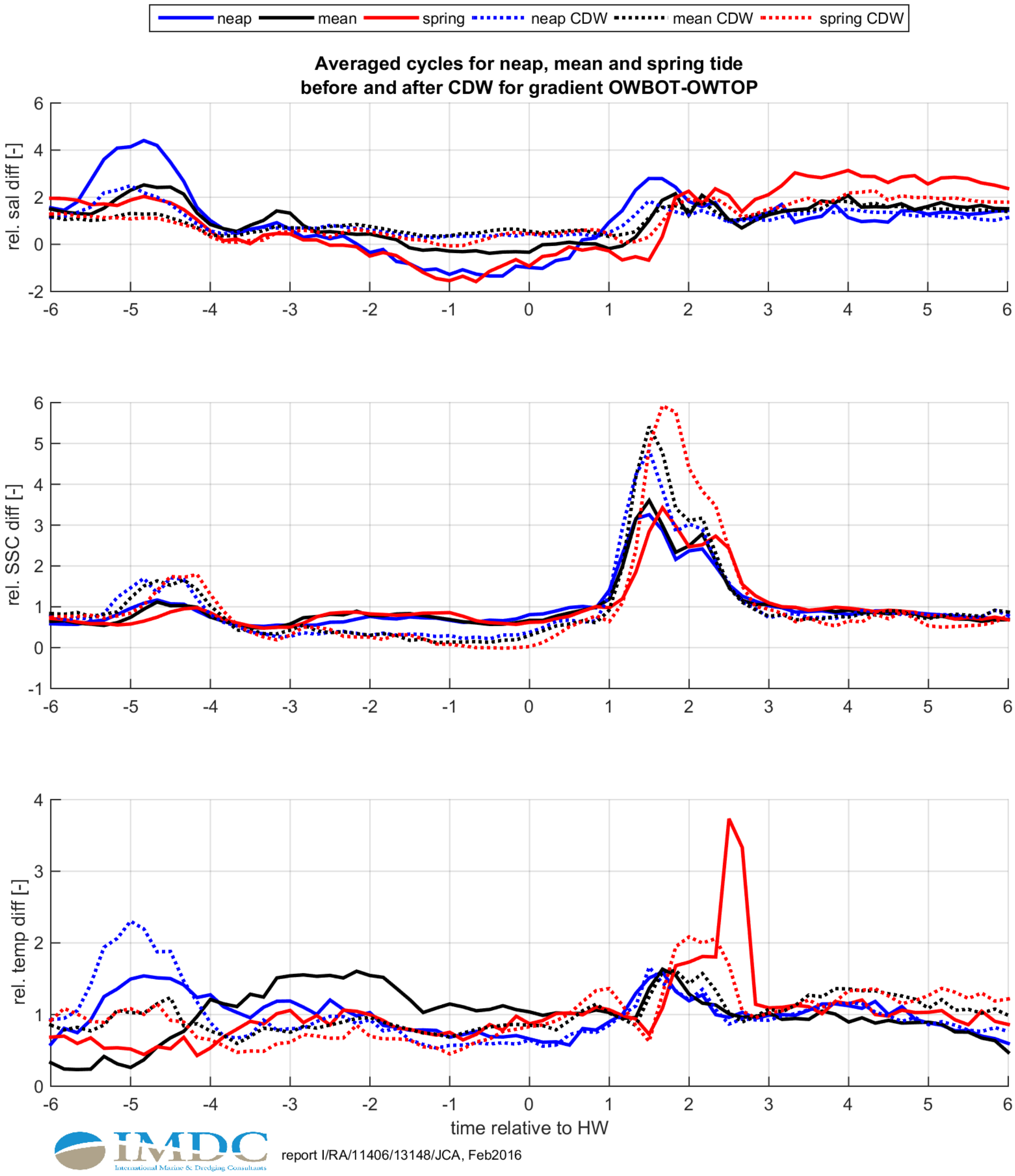
[Note: The suspicious salinity data at B84BOT between 2009 and 2011 is used for processing this figure and will overestimate the vertical gradient before CDW].



Annex Figure C-26: Relative vertical differences of tidal cycles, Buoy 84



Annex Figure C-27: Vertical differences *of tidal cycles, Oosterweel*



Annex Figure C-28: Relative vertical differences of tidal cycles, Oosterweel

Annex D Impact tables of external effects on sedimentation rates

D.1 Variable parameters

Annex table D-1: Variable parameters for model settings 0 till 3

Period	Dock length L_{dock}	Dock/entrance depth H_{dock}	Duration eddy T_{eddy}	Duration density currents T_{dens}
1/7/2005 to 1/4/2008 (short dock)	1500 m	16 m	6 hours	5 hours
1/4/2008 to 1/7/2010 (long dock)	2500 m	16 m	6 hours	5 hours
1/7/2010 to 1/4/2011 (long dock, no sill)	2500 m	18 m	6 hours	5 hours
1/4/2011 to 1/4/2014 (long dock, no sill, CDW, deeper dock)	2500 m	18 m	1 hour	6 hours

Annex table D-2: Variable parameters for model settings 4: Without CDW construction

Period	Dock length L_{dock}	Dock/entrance depth H_{dock}	Duration eddy T_{eddy}	Duration density currents T_{dens}
1/7/2005 to 1/4/2008 (short dock)	1500 m	16 m	6 hours	5 hours
1/4/2008 to 1/7/2010 (long dock)	2500 m	16 m	6 hours	5 hours
1/7/2010 to 1/4/2011 (long dock, no sill)	2500 m	18 m	6 hours	5 hours
1/4/2011 to 1/4/2014 (long dock, no sill, no CDW, deeper dock)	2500 m	18 m	<u>6 hours</u>	6 hours

Annex table D-3: Variable parameters for model settings 5: Without change in depth

Period	Dock length L_{dock}	Dock/entrance depth H_{dock}	Duration eddy T_{eddy}	Duration density currents T_{dens}
1/7/2005 to 1/4/2008 (short dock)	1500 m	16 m	6 hours	5 hours
1/4/2008 to 1/7/2010 (long dock)	2500 m	16 m	6 hours	5 hours
1/7/2010 to 1/4/2011 (long dock, no sill)	2500 m	18 m	6 hours	5 hours
1/4/2011 to 1/4/2014 (long dock, no sill, CDW)	2500 m	18 m	1 hour	<u>5 hours</u>

*Annex table D-4: Variable parameters for model settings 6:
Without CDW construction and change in maintenance depth.*

Period	Dock length L_{dock}	Dock/entrance depth H_{dock}	Duration eddy T_{eddy}	Duration density currents T_{dens}
1/7/2005 to 1/4/2008 (short dock)	1500 m	16 m	6 hours	5 hours
1/4/2008 to 1/7/2010 (long dock)	2500 m	16 m	6 hours	5 hours
1/7/2010 to 1/4/2011 (long dock, no sill)	2500 m	18 m	6 hours	5 hours
1/4/2011 to 1/4/2014 (long dock, no sill, no CDW)	2500 m	18 m	<u>6 hours</u>	<u>5 hours</u>

Annex table D-5: Variable parameters for model settings 7: Without sill removal

Period	Dock length L_{dock}	Dock/entrance depth H_{dock}	Duration eddy T_{eddy}	Duration density currents T_{dens}
1/7/2005 to 1/4/2008 (short dock)	1500 m	16 m	6 hours	5 hours
1/4/2008 to 1/7/2010 (long dock)	2500 m	16 m	6 hours	5 hours
1/7/2010 to 1/4/2011 (long dock, with sill)	2500 m	16 m	6 hours	5 hours
1/4/2011 to 1/4/2014 (long dock, with sill, CDW, deeper dock)	2500 m	16 m	1 hour	6 hours

Annex table D-6: Variable parameters for model settings 8: Conditions as before 04/2008

Period	Dock length L_{dock}	Dock/entrance depth H_{dock}	Duration eddy T_{eddy}	Duration density currents T_{dens}
1/7/2005 to 1/4/2008 (short dock)	1500 m	16 m	6 hours	5 hours
1/4/2008 to 1/7/2010 (long dock)	2500 m	16 m	6 hours	5 hours
1/7/2010 to 1/4/2011 (long dock)	2500 m	16 m	6 hours	5 hours
1/4/2011 to 1/4/2014 (long dock)	2500 m	16 m	6 hours	5 hours

Annex table D-7: Variable parameters for model settings 9: Without dock enlargement.

Period	Dock length L_{dock}	Dock/entrance depth H_{dock}	Duration eddy T_{eddy}	Duration density currents T_{dens}
1/7/2005 to 1/4/2008 (short dock)	1500 m	16 m	6 hours	5 hours
1/4/2008 to 1/7/2010 (short dock)	1500 m	16 m	6 hours	5 hours
1/7/2010 to 1/4/2011 (short dock, no sill)	1500 m	18 m	6 hours	5 hours
1/4/2011 to 1/4/2014 (short dock, no sill, no CDW, deeper dock)	1500 m	18 m	1 hour	6 hours

Annex table D-8: Variable parameters for model settings 10:.Conditions as from the opening

Period	Dock length L_{dock}	Dock/entrance depth H_{dock}	Duration eddy T_{eddy}	Duration density currents T_{dens}
1/7/2005 to 1/4/2008 (short dock)	1500 m	16 m	6 hours	5 hours
1/4/2008 to 1/7/2010 (short dock)	1500 m	16 m	6 hours	5 hours
1/7/2010 to 1/4/2011 (short dock)	1500 m	16 m	6 hours	5 hours
1/4/2011 to 1/4/2014 (short dock)	1500 m	16 m	6 hours	5 hours

D.2 Sedimentation rates per external effect

D.2.1 CDW and change in maintenance depth

Annex table D-9: Averaged modelled sedimentation rate of Deurganckdok to determine the effect of construction of CDW (including uncertainty).

	04/2011 – 04/2014
Sed. Rate with CDW (setting 3) [TDS/day]	3935 (3145 – 4857)
Sed. Rate without CDW (setting 4) [TDS/day]	4185 (3249 – 5301)
Difference [TDS/day]	249 (104 – 443)
Estimated effect [%]	6 (3 – 9)

Annex table D-10: Averaged modelled sedimentation rate of Deurganckdok to determine the effect of change in maintenance depth (including uncertainty).

	04/2011 – 04/2014
Sed. Rate with deeper dock (setting 3) [TDS/day]	3935 (3145 – 4857)
Sed. Rate without deeper dock (setting 5) [TDS/day]	3443 (2754 – 4247)
Difference [TDS/day]	-492 (-611 / -391)
Estimated effect [%]	-13 (-13 / -12)

D.2.2 Sill removal

Annex table D-11: Averaged modelled sedimentation rate of Deurganckdok to determine the effect of sill removal (including uncertainty).

	07/2010 – 04/2011	04/2011 – 04/2014	07/2010 – 04/2014
Sed. Rate with sill removal (setting 3) [TDS/day]	3800 (2966 – 4785)	3935 (3145 – 4857)	3905 (3106 – 4841)
Sed. Rate without sill removal (setting 7) [TDS/day]	3360 (2627 – 4225)	3451 (2763 – 4254)	3431 (2733 – 4247)
Difference [TDS/day]	-440 (-560 / -339)	-483 (-603 / -382)	-475 (-594 / -373)
Estimated effect [%]	-13 (-14 / -12)	-12 (-12 / -12)	-12 (-12 / -12)

Annex table D-12: Averaged modelled sedimentation rate of Deurganckdok to determine the effect of sill removal (including uncertainty).

	07/2010 – 04/2011	04/2011 – 04/2014	07/2010 – 04/2014
Sed. Rate with sill removal and same conditions as before the removal (setting 6) [TDS/day]	3734 (2887 – 4741)	3692 (2858 – 4690)	3700 (2864 – 4700)
Sed. Rate without sill removal (setting 8) and same conditions as before the removal [TDS/day]	3308 (2561 – 4194)	3260 (2528 – 4136)	3270 (2534 – 4147)
Difference [TDS/day]	-426 (-546 / -325)	-432 (-554 / -330)	-431 (-552 / -329)
Estimated effect [%]	-11 (-11 / -11)	-12 (-12/-12)	-12 (-12/-11)

D.2.3 Enlargement of the dock

Annex table D-13: Averaged modelled sedimentation rate of Deurganckdok to determine the effect of the enlargement of the dock (including uncertainty).

	04/2008 – 07/2010	07/2010 – 04/2014	04/2008 – 04/2014
Sed. Rate with dock enlargement (setting 3) [TDS/day]	3182 (2499 – 3993)	3905 (3106 – 4841)	3623 (2869 – 4510)
Sed. Rate without dock enlargement (setting 9) [TDS/day]	2831 (2202 – 3581)	3527 (2790 – 4393)	3255 (2560 – 4076)
Difference [TDS/day]	-351 (-412 / -297)	-378 (-448 / -316)	-368 (-434 / -308)
Estimated effect [%]	-11 (-12/ -10)	-10 (-10 / -9)	-10 (-10 / -11)

Annex table D-14: Averaged modelled sedimentation rate of Deurganckdok to determine the effect of the enlargement of the dock (including uncertainty).

	04/2008 – 07/2010	07/2010 – 04/2014	04/2008 – 04/2014
Sed. Rate with dock enlargement as before the enlargement (setting 8) [TDS/day]	3162 (2483 – 3969)	3270 (2534 – 4147)	3227 (2514 – 4077)
Sed. Rate without dock enlargement (setting 10) and same conditions as before the removal [TDS/day]	2811 (2186 – 3557)	2891 (2218 – 3699)	2860 (2205 – 3643)
Difference [TDS/day]	-351 (-412 / -297)	-378 (-448 / -316)	-368 (-434 / -308)
Estimated effect [%]	-11 (-12/ -10)	-12 (-12/-11)	-11 (-12/ -11)