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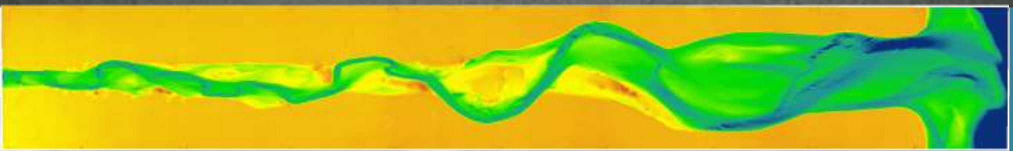
Effects of dredging and dumping in laboratory scale experiments of estuaries



Cox, J.R. (Jana)

Student number: 5821797

Utrecht University,

Department of Physical Geography

Faculty of Geosciences

March 2018 – final version

Master: Earth Surface and Water

Track: Coastal and fluvial morphodynamics

Supervisors: J.R.F.W Leuven & Prof. M.G. Kleinhans

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Abstract

Shipping fairways are continuously dredged to maintain and increase access of large ships to major ports located in estuaries, for example the port of Antwerp in the Western Scheldt. However, it has been shown in various estuaries worldwide that there are several adverse side effects of these actions including loss of ecologically valuable intertidal area, increased tidal range and increased wave propagation speeds which results in flooding. The Western Scheldt estuary is one such estuary which has undergone both channel deepening events (capital dredging) and maintenance dredging, which takes place on a continuous basis to maintain a minimum depth required for shipping. This thesis examines the effects of dredging and dumping on the morphology of estuaries at a variety of spatial and temporal scales. This was done using a scale experiment in combination with detailed analysis of the Western Scheldt estuary.

A scale experiment was designed with a dredging and dumping protocol based on past and current practices in the Western Scheldt. Information about these practices came from reports, papers and supporting literature, combined with detailed analysis of digital elevation models of the estuary (DEMs) from 1955-2015. A shipping fairway was dug with dimensions scaled on measures taken in the Western Scheldt and consequently maintained to a minimum depth requirement with removed material being dumped back in the system. Dumping locations were based on current practices in the Western Scheldt.

Results from the experiment are compared with a control experiment without dredging or dumping. The implications of dredging and dumping were seen on both an estuary wide scale and individual morphological features over a variety of temporal scales. The experiment replicated the processes occurring in the Western Scheldt and other estuaries worldwide including adverse effects such as decreased intertidal area, increased high waters, increased tidal range, increased tidal penetration and a tendency for the main channel to silt up more quickly. It also indicates which dumping locations result in sedimentation/erosion and the importance of distance along the estuary in determining this.

To maintain the sediment budget of sandy multi-channel systems such as the Western Scheldt and to combat negative and potentially dangerous effects (particularly with the threat of sea level rise) of dredging and dumping further human interference will be needed.

Key words: dredging, dumping, deepening, estuary, morphology, scale-experiment, shoals, channels, Western Scheldt

1. Introduction

Many estuaries worldwide have undergone severe anthropogenic changes, often spanning several hundred years with an acceleration of activity in recent years. Channels are deepened and widened by dredging material (sand and mud), to allow for access to ports located within estuaries. The material is then often relocated within the estuary (dumped) in an effort to maintain the natural morphology of the estuary and to maintain natural sediment transport and circulation. However, there are many adverse effects to dredging and dumping on the morphology of the estuaries. The main foci in the literature concerning dredging and dumping are twofold: the first focus is ecological, analysing the effects on specific organisms (flora and fauna), the second focus is sedimentary processes, mainly turbidity and suspended sediment concentration. There is a distinct lack of information about the impact of dredging and dumping on overall estuarine morphology and features within the estuary, including topics such as changing intertidal area and the response of shoals, side channels and holes when used as dumping locations.

This chapter outlines the general effects of dredging and dumping on estuaries worldwide and some suggested mechanisms and processes that cause these observed effects. Then it will discuss one estuary specifically: the Western Scheldt estuary which the basis for a scale experiment to test these effects. This estuary was chosen as a large data set was available for the estuary, particularly in terms of dredging and dumping protocol and volumes. The chapter continues to give a summary of the current state of knowledge of dredging and dumping in the Western Scheldt estuary which directly influenced the setup of the experiment in this study. This study aims to find out:

What are the effects of dredging and dumping on the morphology of estuaries and what are the proposed mechanisms that cause these effects?

More specifically, it looks at the response of features at a variety of scales: small-scale features such as individual shoals, side channels and scours, medium-scale features such as the main channel, water levels and large-scale features such as estuary width, estuary stability and intertidal area.

1.1 Review of the effects of dredging and dumping on estuaries & suggested mechanisms

Dredging estuaries can cause changes to the natural shape of the main channel by changing current speeds and modifying erosion and deposition rates in adjacent areas (Liria, Garel & Uriate, 2009). Dredging alters the bottom topography of the channel and alters patterns of water circulation within the main channel (Johnston, 1981). The bathymetry of the estuary is smoothed as obstructions such as shoals, bars and sills are removed and channels become straighter (Nichols, 2018). Dredging of channels often leads to more rapid infilling in these channels provoking further dredging (Monge-Ganuzas, Cearrata & Evans, 2013).

Blott et al., (2006) suggest that morphological changes in estuaries are highly dependent on location within the estuary, positing that at the seaward end where estuaries are often unconfined they have a high level of sensitivity to change, whilst upstream most estuaries are heavily confined limiting effects to redistribution of sediment between intertidal and subtidal zones.

Dredging is known to alter the tidal prism of estuaries due to infilling of intertidal areas leading to increased tidal range (Liria, Garel & Uriate, 2009, Yuan & Zhu, 2015). The same is true for deepening and widening of the main channel which leads to increased tidal range in these channels (Zhu, Weisberg & Zheng, 2014). The speed of tidal propagation is increased by dredging due to reduced friction on the channel bed (Nichols, 2018). The dynamics of ebb and flood flows including duration, asymmetry and peak discharges are also altered by dredging (Colby et al., 2010, Nichols, 2018).

The mobilization and circulation of sediment within the estuary due to dredging and dumping alters both the sediment transport dynamics in the estuary and the overall sediment budget (see section 1.4) of the estuary (Thomas, Spearman & Turnbull, 2002). Dredging often increases suspended sediment concentration (largely due to the modern dredging technique of trailer dredging which will be discussed in section 1.10). This increased suspended sediment concentration combined with increased turbidity limits primary production in estuaries by inhibiting light penetration (Johnston, 1981, van Maren et al., 2015). This is as previously mentioned the main focus of reports and literature pertaining to the effects of dredging and dumping.

Dredging often alters the overall planform of the estuary by changing the pattern and distribution of channels and shoals within estuaries (Monge-Ganuzas, Cearrata & Evans, 2013). Dredging also alters smaller features within the estuary such as the position and extent of individual intertidal sand banks (shoals) and channels (Blott et al., 2006). However, the effect of dredging and dumping on these smaller scale features represents a gap in the current literature. The main channel is generally deepened and widened whilst side channels are used as dumping sites often causing them to silt up. Smaller channels such as shortcuts or connecting channels form and disappear on a timescale of months to years (Jeuken, 2000). Shoals grow or erode depending on the balance between the flow of water in the channel and its erosive power and the amount of sediment dumped on the shoal. This alters the shape, size and relative location of the shoals.

Dumping sites within the estuary typically intertidal shoals, experience enhanced sedimentation which often causes intertidal area to decrease (Essink, 1999). The effect of dumping is to increase supratidal area by raising these shoals above high water level. This effect may be temporary if the sediment can be remobilized (which is strongly dependent on location within the estuary) or permanent if the sediment cannot be removed (Monge-Ganuzas, Cearrate & Evans, 2013). This issue is discussed in detail in this study.

Future problems facing dredged estuaries are controlling sediment management, improving ecological quality and habitats and keeping up with sea-level rise. The effect of rising sea-level on estuaries is a potential threat which may cause increased water depth, increased tidal prism and increased current velocities which would all increase sediment remobilization within estuaries (Blott et al., 2006). To accurately prepare for these problems the effects of dredging and dumping on the estuaries and the surrounding processes and mechanisms must be understood. This study aims to shed light on these effects by replicating them in an experimental setting. First, however, one estuary, the Western Scheldt estuary is studied in detail to further analyse the effects of dredging and dumping on the morphology of estuaries.

1.2 Description of the Western Scheldt estuary

The Scheldt River has its source in France, flows through Belgium and the Netherlands before emptying into the North Sea (Bolle et al., 2010). The Scheldt estuary stretches over Dutch and Belgian territories, but the Western Scheldt refers solely to the Dutch part of the Scheldt estuary (Dam et al., 2016). The Western Scheldt is 5km wide at its mouth and 60km long (Wang et al., 2015). The present-day formation of the Western Scheldt estuary (see Figure 1) is a funnel shape and the estuary is tide dominated (Bolle et al., 2010). The estuary can be morphologically divided into three zones, which from west to east develop as follows: the subtidal delta, the multi-channel system (containing elongated intertidal shoals which are typical for tide dominated estuaries) and the single tidal channel with bank attached bars (Jeuken, 2000). The estuary consists mainly of medium to fine grain sand with mud only found in the intertidal flats (Dam et al., 2015). There are also some erosion resistant peat and clay layers in the estuary which can be located directly at the bed surface (Dam et al., 2016).

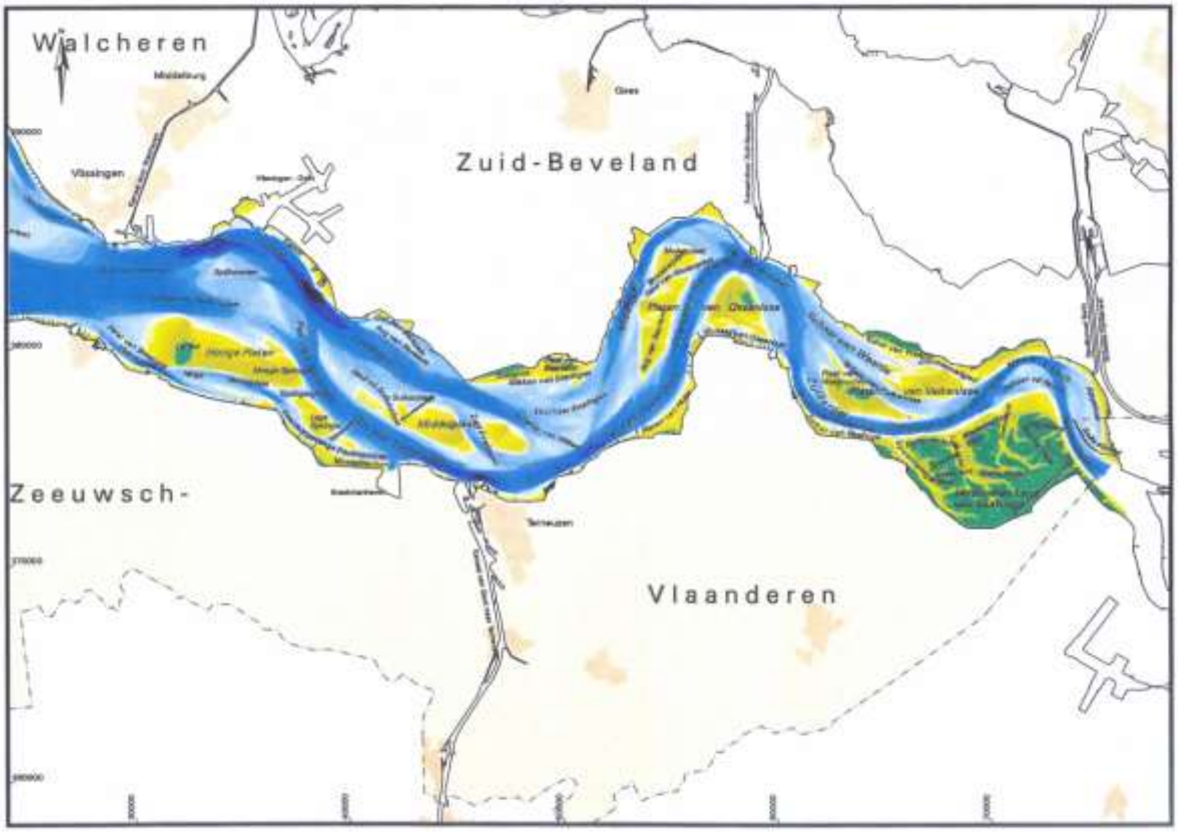


Figure 1: Map of the location of the Western Scheldt estuary. Source: VNSC (2013).

1.2.1 Geological history of the estuary

Sea level rise is identified as the key factor in forming tidal basins in the North Sea (Wang et al., 2015). Sea level rise at the end of the Last Glacial Maximum created several tidal basins during the Early Holocene in the lower region of the Netherlands (Beets et al., 1992). Rising sea level caused landward expansion of these basins and trapping of marine sediment (Van der Spek, 1997). These basins infilled with sand and mud when sea level rise later decelerated around 5500 years BP causing a stable prograding coastline (Beets et al., 1992). More specifically, the Scheldt estuary formed 1200-800 years BP, developing from a tidal intrusion (Ofori, 2009). The estuary formed due to sea flooding of a low relief river valley (Jeuken, 2000). Sediment import is now twice the amount needed to balance sea level rise and this excess sediment is a direct result of the closure (by humans) of the Zuiderzee and Lauwerszee which influenced the morphological development of tidal basins in the North Sea (Wang et al., 2015). This governed the amount and type of sediment in the estuary. This excess of sediment, determined by the geological setting caused the characteristic multi-channel system of the Western Scheldt. The Western Scheldt differs from others in Europe because of this sandy multi-channel system, making it ecologically unique and giving a wide range of features such as extensive intertidal shoals and side channels.

1.2.2 Morphological development of the Western Scheldt estuary

The first historical data concerning the Western Scheldt is from 1000AD when the estuary was both wider and shallower than present day and was named “De Honte” (Winterwerp et al., 2001). During the early Middle Ages, the tidal inlet Honte connected to the Scheldt River (Dam et al., 2016) and since then the channel has been expanding landward (Van der Spek, 1997).

For the following 500 years the estuary increased in size due to a combination of natural (storms and floods) and anthropogenic (peat mining and land reclamation) influences with the current main channel configuration forming during this period (Winterwerp et al., 2001). From 500AD to present there was an overall narrowing of the estuary due again, to a combination of natural (land formation, wetland development) and anthropogenic (poldering and embanking) influences which led to the current geometry of the estuary (Winterwerp et al., 2001). By the 14th century the Westerschelde had naturally scoured its channel to become a crucial shipping fairway to Antwerp harbour (Van der Spek, 1997). During the 17th century the estuary had its largest surface area with several side branches and connections to the Eastern Scheldt (Dam et al., 2016). The area also had extensive tidal-flat and salt-marsh areas during this time (Van der Spek, 1997).

Many of the side branches and connections silted up between the 17th and 19th centuries with the connections to the Eastern Scheldt closed off in 1867 and 1871 (Dam et al., 2016). Since 1860, the main channels migrated, shoals were eroded and created and secondary/side channels both appeared and disappeared (Dam et al., 2016). The tidal flats developed into salt marshes which were subsequently embanked causing a large decrease in intertidal storage area and an increase in the depth of the estuary due to the decreasing surface area of the tidal flats and scouring of the channels (Van der Spek, 1997).

Initially human interference in the Western Scheldt was focused on land reclamation, but at the beginning of the 20th century sand mining, dredging and dumping became the foci of human activity (Jeuken & Wang, 2010). Early land reclamation caused silting up of natural processes in the estuary (de Vriend et al., 2011). The last 60 years has seen an overall change in the morphology of the estuary from an irregular distribution of intertidal flats with branching channels and shallow areas towards smoother tidal flats in between main channels (Cleveringa & Taal, 2015).

This pattern of extensive human interaction is common in many estuaries worldwide, particularly in Europe. This means that there are no “clean” or completely natural estuaries left. The morphology of estuaries including location and presence of bars and shoals, amount of intertidal area, number of channels and side channels are directly determined by this human interaction with morphology. This study has the ability to compare these anthropogenically altered estuaries with a completely natural system by using scaled experiments.

1.3 Current morphology of the Western Scheldt

The system is often schematised (based on the original work of Winterwerp et al., (2001)) as a series of macro-cells consisting of a curved ebb channel, a straight flood channel and an intertidal or subtidal shoal separating the two (Swinkels et al., 2009, Jeuken & Wang, 2010). Six of these macro-cells (also called estuarine sections) have been recognised in the Western Scheldt based on their sediment circulation due to the asymmetric motion of the water (Swinkels et al., 2009). This asymmetry in flow in the ebb and flood channels means flood and ebb channels respond differently to dredging. . In the Western Scheldt the tendency is for the main meandering ebb channel to silt up due to dredging whilst the straight flood channels tend to erode (Jeuken, 2000).

These six cells reached their present-day alignment in 1905 (Jeuken, 2000) and the configuration of the main ebb and flood channels has remained unchanged since the 1930s (Bolle et al., 2010). The morphology can be summarized in Figure 2 from Jeuken (2000).

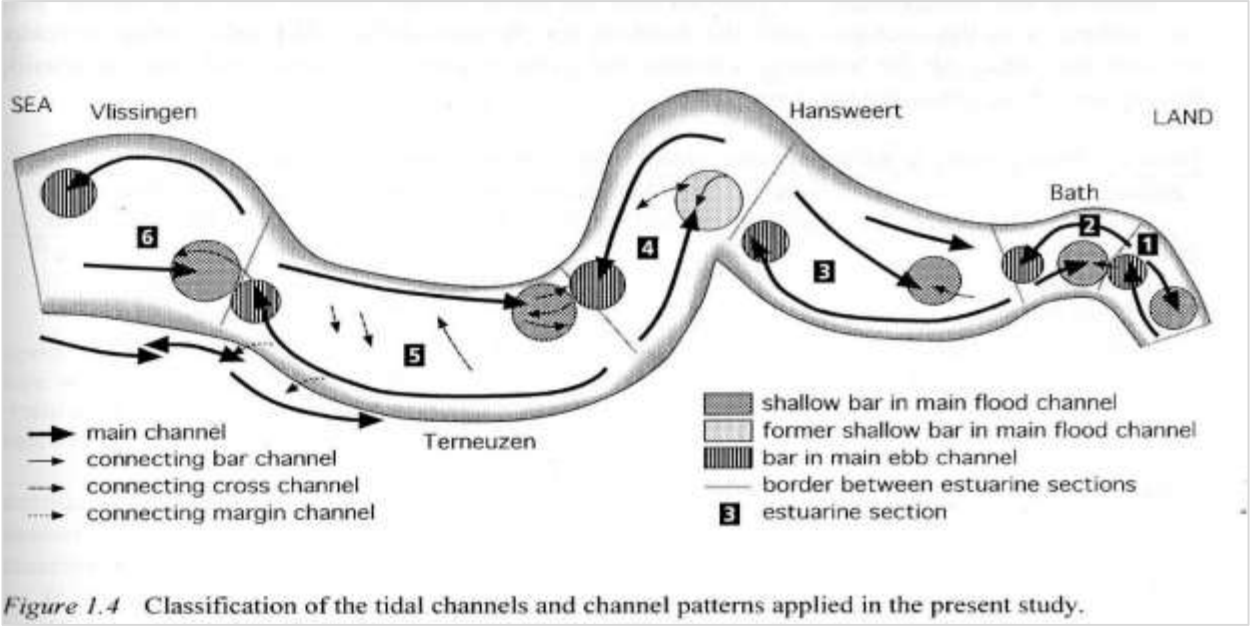


Figure 1.4 Classification of the tidal channels and channel patterns applied in the present study.

Figure 2: The morphology of the Western Scheldt estuary with channels, bars and shoals. Note: the 6 macro cells are called "estuarine sections" – this term is interchangeable with macro-cell depending on the author. Source: Jeuken (2000).

Each macro-cell contains a large meander shaped main ebb channel and a laterally bordering straight main flood channel which are separated by intertidal or subtidal shoals and linked with one or more types of connecting channels (Jeuken, 2000). The flood channel is open to the flood current with a sill present at its upstream end whilst the ebb channel is open to ebb current with a sill present at its downstream/seaward end (Swinkels et al., 2009). The ebb channels form a continuous meandering channel which is only constrained by manmade features such as dikes and harbours (Jeuken, 2000). The ebb channels are deeper than the flood channels and are therefore used as the main navigation route to the Port at Antwerp (Swinkels et al., 2009).

Connecting channels which cut through sub and intertidal areas link the flood and ebb channels and induce water exchange between the channels which redistributes the tidal flow in the system (Swinkels et al., 2009). These connecting channels create meso-cells. There are three main types of connecting channels: bar channels which link the two main channels by cutting through bar areas in the main flood channel, cross channels which link the main channels by cutting through intertidal shoals and margin channels which connect large main channels along the boundary of the estuary (Jeuken, 2000)

Water level difference between the ebb and flood channels drives the flow of water through these connecting channels and the connecting channels form where the difference in water levels is the largest, typically in bar areas at the landward end of the flood channel (Swinkels et al., 2009). These smaller connecting channels have quasi-cyclic morphological behaviour and experience channel origination, migration and termination on a timescale of years to decades (Jeuken, 2000, Wang, 2015).

1.4 Sediment balance of the Western Scheldt estuary

The sediment balance of the Western Scheldt is determined by the import or export of sediment at the mouth of the estuary and by sand mining, dredging and dumping throughout the entire estuary, fluvial input of sediment is almost nil (Wang et al., 2011). The amount of sediment annually imported naturally is of the same order as the amount of sediment removed by sand mining (Wang et al., 2015). The alterations made since the 17th century have resulted in an increase in net sediment import of sand and mud (Van der Spek, 1997). However, in the 1990s a change in sediment regime was recorded as the mouth of the estuary began exporting sediment rather than importing it (Bolle et al., 2010). This is believed to be due to the estuary crossing a threshold of critical depth of the estuary (Wang et al., 2015).

After sediment enters the system at the coast the majority of sandy material is transported through the main flood and ebb channels (Bolle et al., 2010). In recent decades the cumulative sediment budget of the Western Scheldt has been altered due to dredging and dumping. At the most seaward cells (5&6) and further inland cells (1&2) there has been a decreased sediment budget leading to export of sediment from these cells and consequently erosion, whilst the central part of the estuary has seen increased sediment budget, an import of sediment and net sedimentation (Wang et al., 2002). The decrease in cells 1&2 has been attributed almost exclusively to the effects of dredging and deepening (Ofori, 2009). In terms of the absolute balance of sand in the estuary there has been a drastic volume change since the 1970s due to sand extraction, deepening and dredging (Nedebragt,2006, Ofori, 2009).

The sediment balance of the estuary is a widely discussed topic in the field of estuary management and the literature pertaining to dredging and dumping with various policies, suggestions and tests in place to stop sediment starvation of the estuary as has already happened in cells 1&2 and around Antwerp. To keep the natural multi-channel system the sediment balance must be maintained to stop erosion of the intertidal shoals and bars in the estuary which is a constant challenge for the estuary.

1.5 History of dredging in the Western Scheldt

The following section outlines the various strategies used to remove material from the Western Scheldt estuary and how these strategies have changed over time. The reasons behind these strategies, any differences and likely effects on the morphology of the estuary are described.

1.5.1 Introduction to dredging in the Western Scheldt

The motivation behind the dredging works in the Western Scheldt has remained unchanged over time. This motivation is to maintain an appropriate navigable depth in all the shipping lanes (e.g. Figure 3) along the estuary to allow access to the main ports of Antwerp, Gent, Terneuzen and Vlissingen (Depreiter et al., 2010). Changes to the channel caused by dredging can cause erosion or deposition in otherwise stable estuarine channels (Bolle et al., 2010) and this has led to a myriad of problems in the Western Scheldt over time. The focus of most dredging is the sills present in the estuary. Sills are “shallow areas at the transition between channel bends/channel crossings” (Wang, Kornman, & Management, 2003). Two types of location are dredged in the Western Scheldt: the maritime fairway and ports/harbours; with most of the material dredged from the maritime fairway (Mow, 2013).

Figure 3: Large container ship crossing from Vlissingen to Breskens. Photo by Jana Cox (August 2017).

1.5.2 History of dredging in the Western Scheldt

Since the 1920s the estuary has been dredged to gain access to the ports along the Western Scheldt (Swinkels et al., 2009). The first dredging took place in 1922 and focused on the sections near the estuary head i.e. cells 1 & 2 at the Dutch/Belgian border and Bath respectively (Jeuken, 2000). Small scale dredging events then took place periodically until the 1970s. Before the 1970s dredging occurred only on sills in the eastern part of the estuary (Dam et al., 2015).

The estuary underwent three main deepening events: 1970-1975, 1997-1998 and 2010-2011. The first deepened the main channel to 9.5m , the second to 11.6m and currently the depth of the main channel is close to 14m in some parts (Swinkels et al., 2009). The focus of the two earlier events was the deepening of sills in the navigation route (Jeuken & Wang, 2010). A further deepening event took place in 2010-2011 to create a minimum channel depth of 13.1m which is independent of the tides (Wang, 2015). This deepening required both capital dredging and maintenance dredging every following year to keep the port accessible for large ships (Plancke & Vos, 2016).

The most intense dredging activities have taken place in the eastern part of the estuary where several shallow sills are the greatest obstruction to ships (Swinkels et al., 2009). These sills (drempels) have been periodically dredged over time with early dredging focused on Drempel van Bath and Drempel van Hansweert (see Figure 4) in the 1960s and the extension to include Drempel van Valkenisse and Drempel van Borssele during the 1970s and 1990s dredging events (Wang et al., 2003).

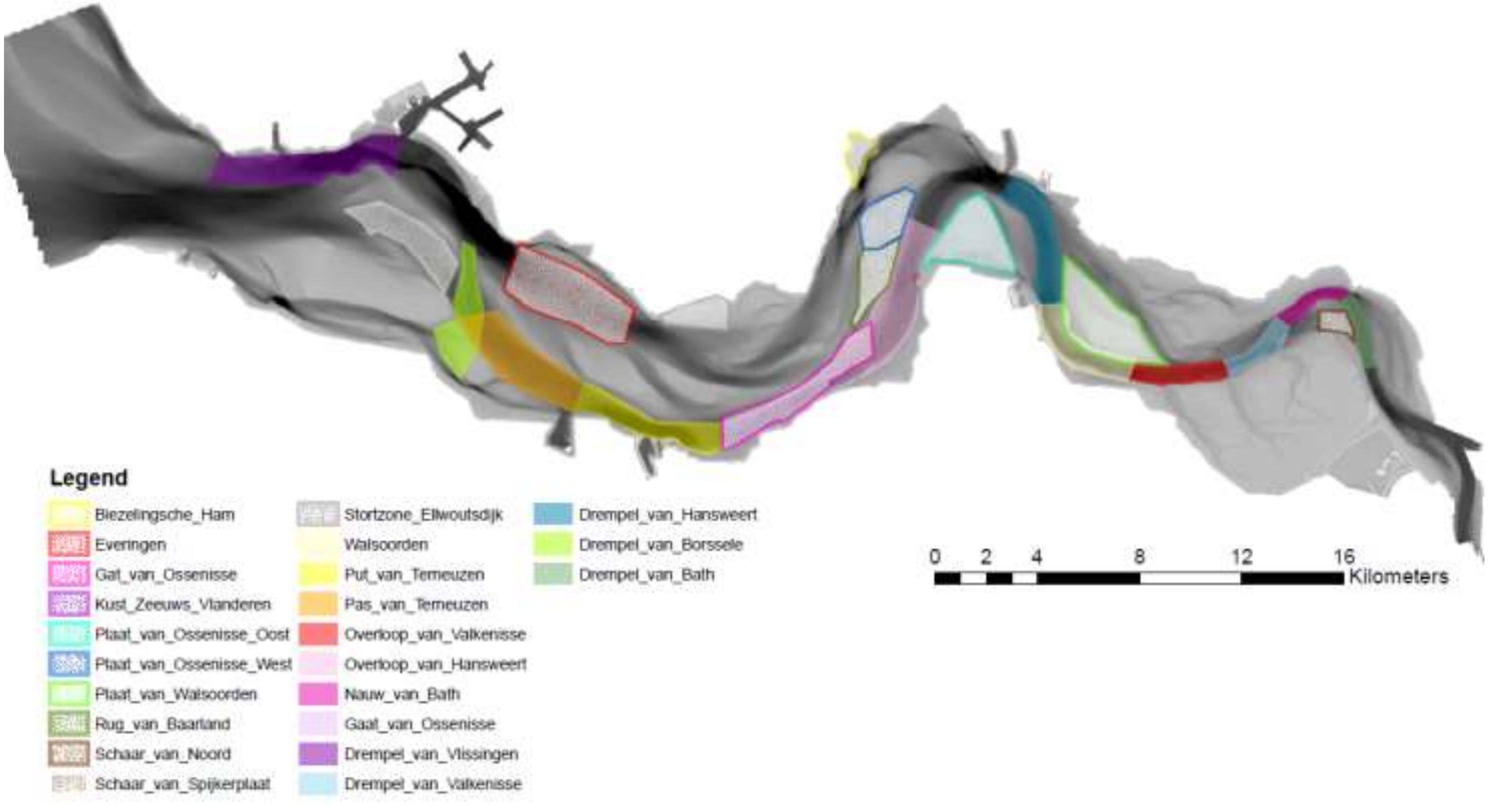


Figure 4: Locations of all dredging (plain colour) and dumping (speckled) sites in the Western Scheldt until 2010 based on VNSC reports (2015 & 2016).

The deepening of the estuary in the 1970s was focused on deepening the bars of the main ebb channels specifically in cells 1-3 (at the Dutch/Belgian border, Bath and Valkenisse) with the goal of inducing erosion of the main ebb channels to maintain the shipping line but also included the side effects of shoaling flood channels, extending shoals and the temporary disappearance of the connecting channels (Jeuken, 2000). The 1990s event focused on further deepening of the ebb channel bars but focused on the mouth of estuary (Jeuken, 2000). The goal of the 2010-11 deepening was to create a tide independent shipping fairway to Antwerp port for ships up to 13.1m draft (Depreiter et al., 2010). Since 2011 the maintenance dredging in the estuary has been focused on the shoals and sills along the main shipping channel to keep the main channel at a depth of 14.5m (Depreiter et al., 2010).

1.5.3 Volumes of dredged sediment

The amount of sediment dredged has varied over time as seen in Figure 5. When the deepening events occur, the largest overall volume of sediment is removed from the system (and consequently relocated within the estuary). Certain locations have had very high volumes of sediment removed from the system over time; these are sill areas such as Drempel van Bath, Drempel van Valkenisse and Drempel van Borssele. As seen in Figure 6, the most dredged area since the 1980s is Drempel van Hansweert.

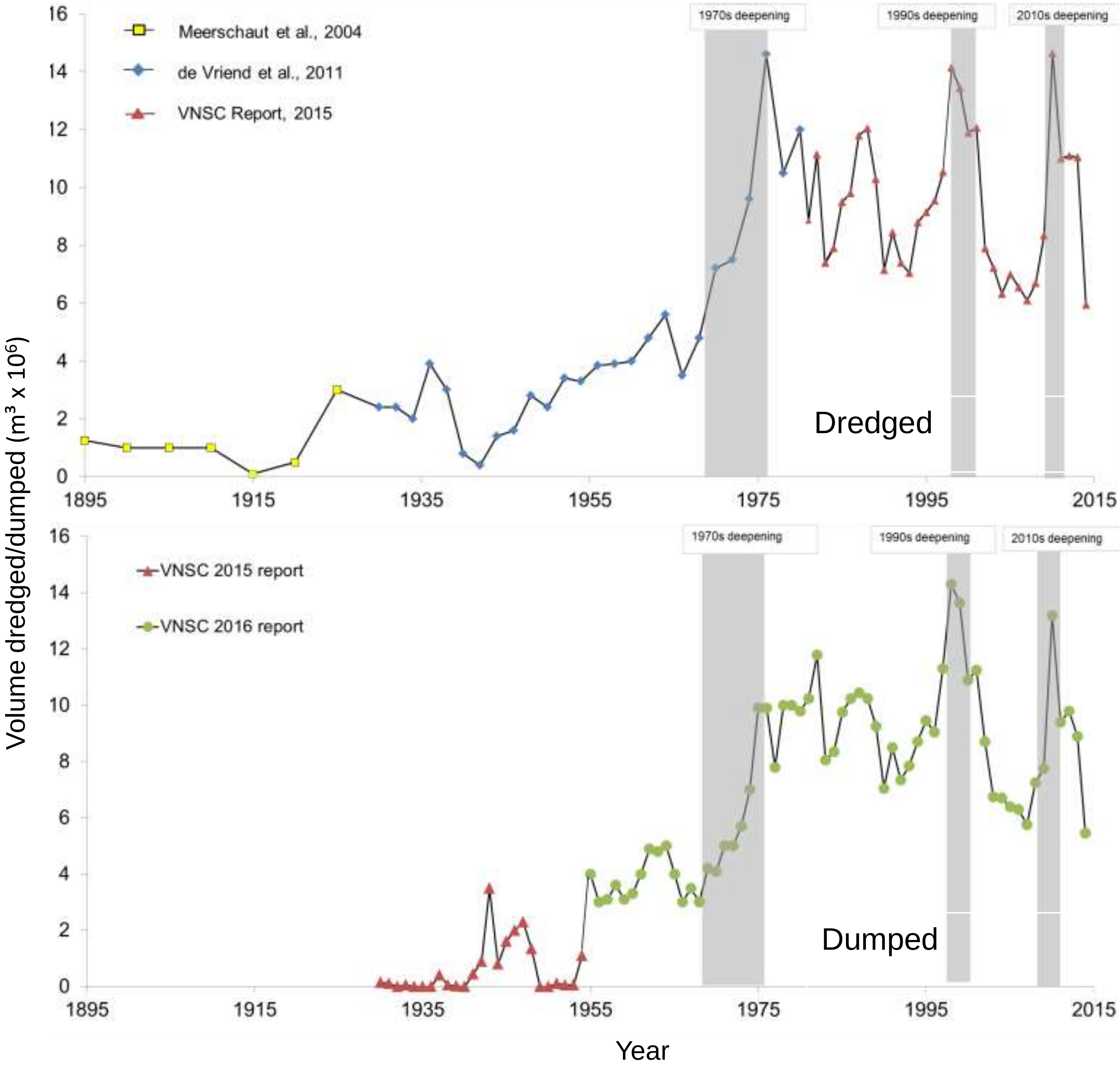


Figure 5: Volumes of dredged and dumped sediment in the Western Scheldt 1895-2014 (including data soureces), grey boxes indicate channel deepening events.

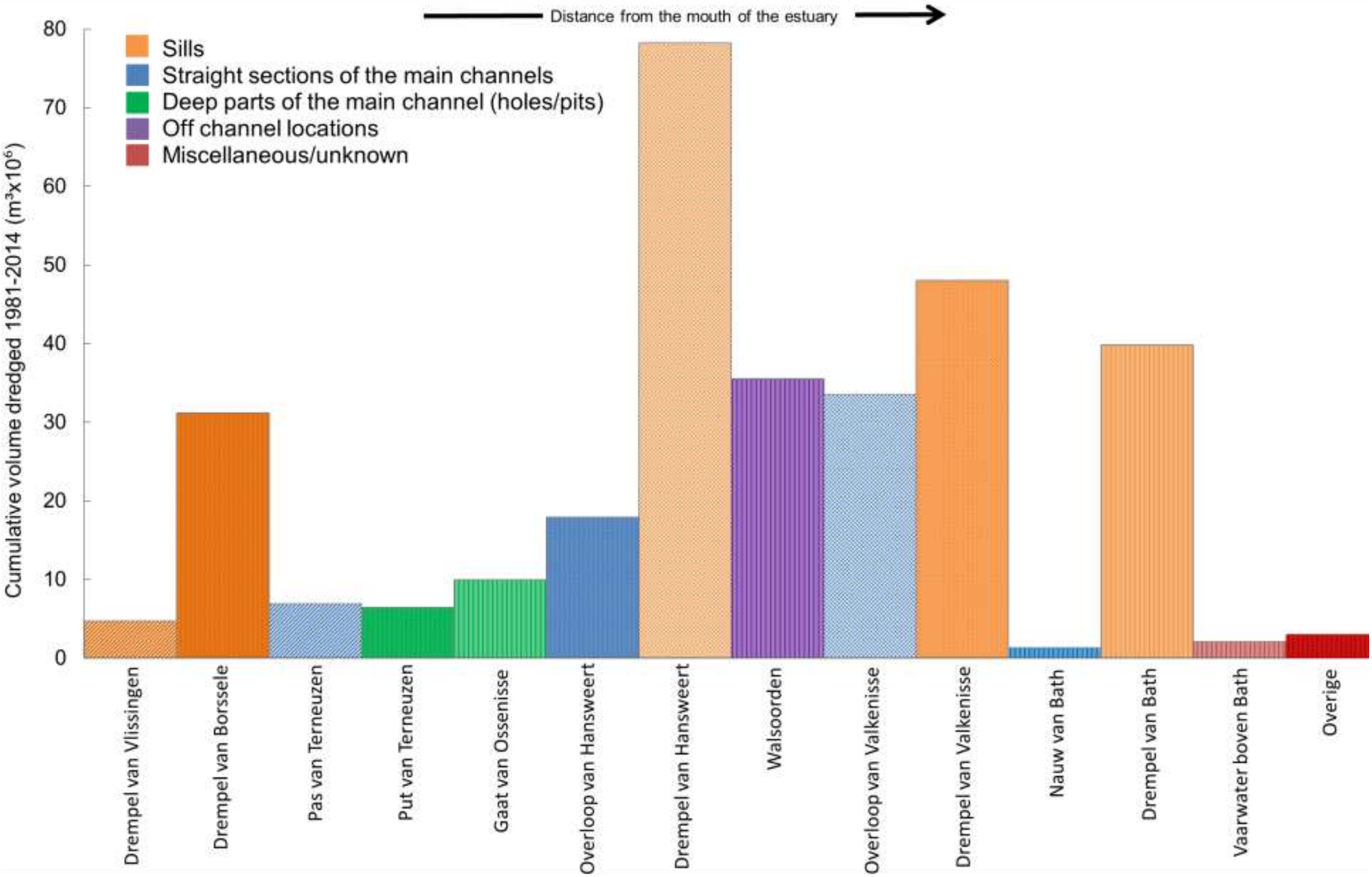


Figure 6: Cumulative volume of sediment dredged per location in the Western Scheldt 1981-2014 with volume figures taken from VNSC, (2015). Locations correspond with the map shown in Figure 4.

1.6 Effects of dredging on morphology evident in DEMs of the Western Scheldt

Analysis of DEMs of the Western Scheldt (see chapter 2 for data source and more information) indicate basic effects of dredging and dumping on the morphology of features within the estuary. The difference in elevation between 1955 and 2015 can be seen in Figure 7. The overall pattern indicates deepening of some sections of the main channel (particularly outer bends), filling in of side channels and a build-up of material on shoals/bars.

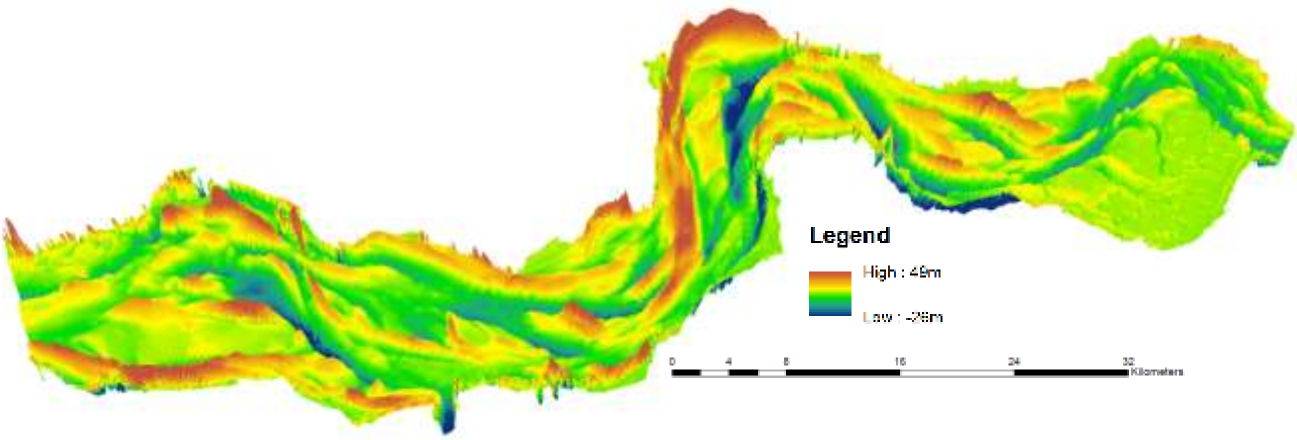


Figure 7: DEM of difference in elevation of the Western Scheldt estuary between 1955 and 2015.

Dredging in the Western Scheldt has caused deepening of the entire main channel over time. Figure 8 shows the change in depth of the main channel/shipping fairway over time. Some sections have become much deeper than others and all shallow sections have been removed. Several side channels and shortcuts have also been dredged and deepened for navigation focused on the seaward end of the estuary. However, most of the side channels have silted up and shallowed significantly including the side channel from Biezelingsche Ham to Eendragt (see Figure 10). For the three different capital dredging events the response of the system varies.

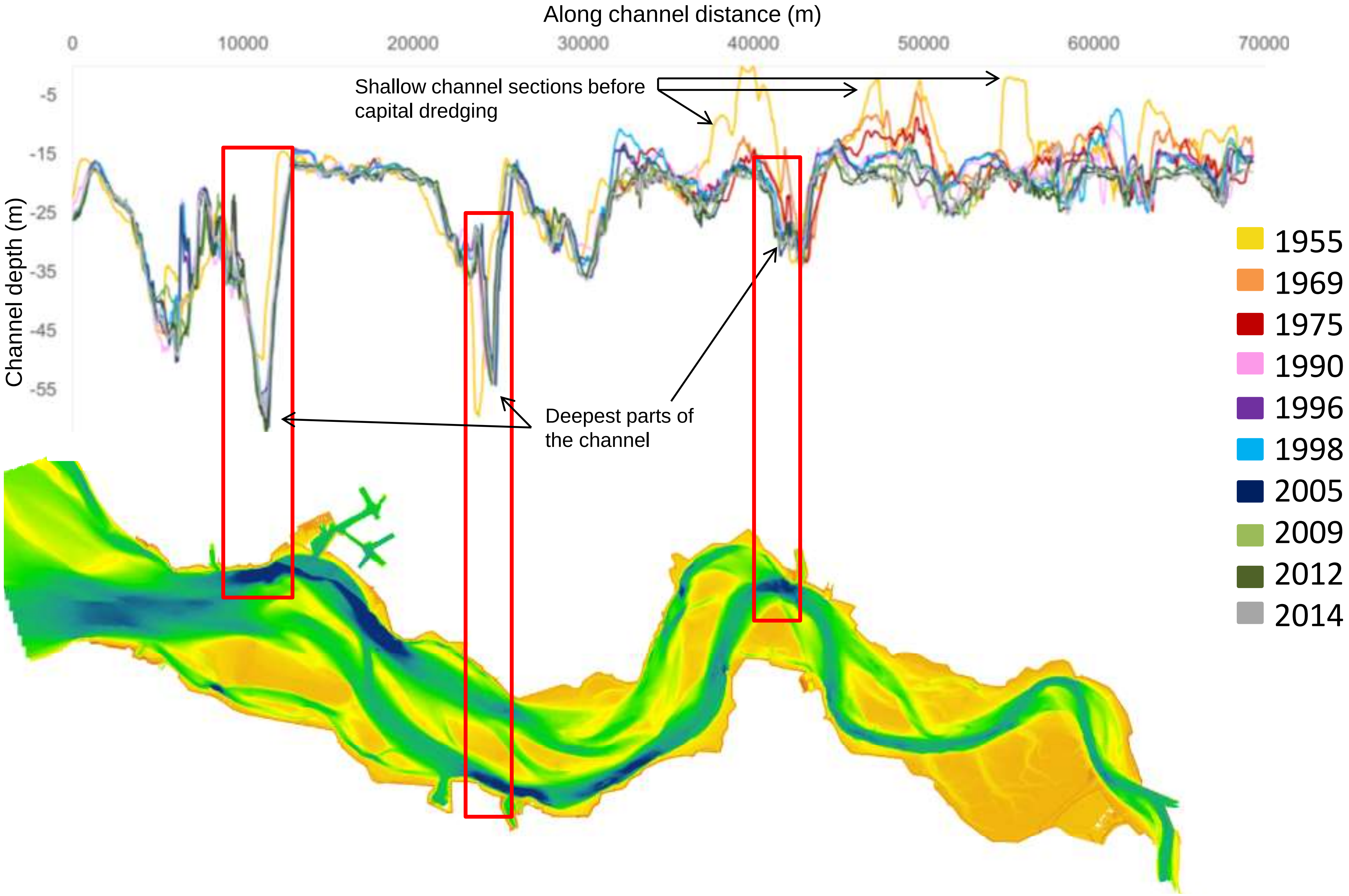
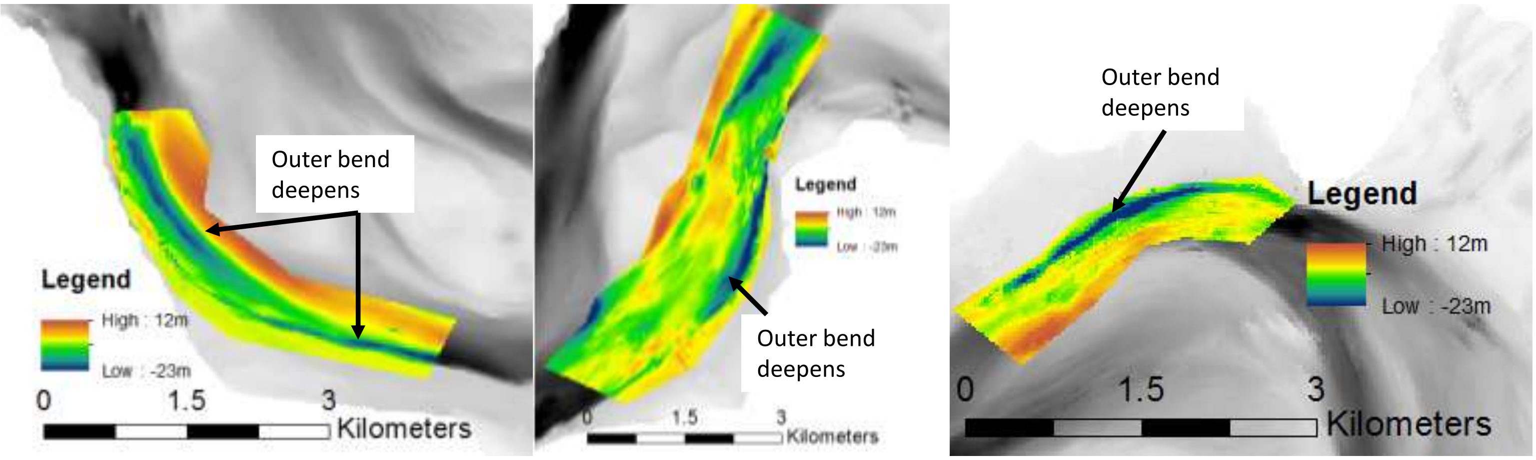


Figure 8: Elevation of the shipping fairway of the Western Scheldt over time.

Prior to the first channel deepening (1955-1970) the main channel deepened in response to dredging with the focus on the outer edges of bends (Figure 9). Side channels also deepened leading to a larger vertical difference between water levels and shoal edges. This led to the erosion of several shoals in the system.



Overloop van Hansweert

Walsoorden

Nauw van Bath

Figure 9: DEMs of difference between 1955 and 1970 (pre-capital dredging) for three main channel dredging sites in the Western Scheldt estuary, where red = increase in elevation, blue = decrease in elevation.

The first channel deepening (1970-1975) led to the silting up of one of the major side channels (see Figure 10) in the Western Scheldt whilst deepening the main channel by several metres. Once more shoal edges are eroded.

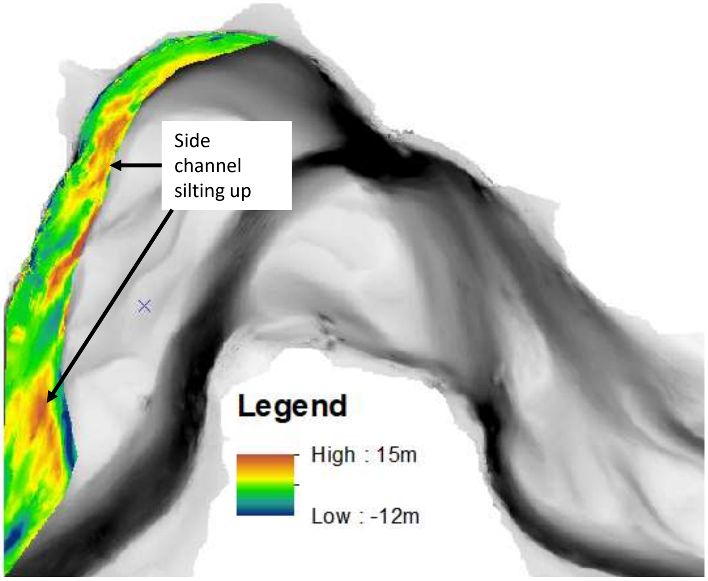
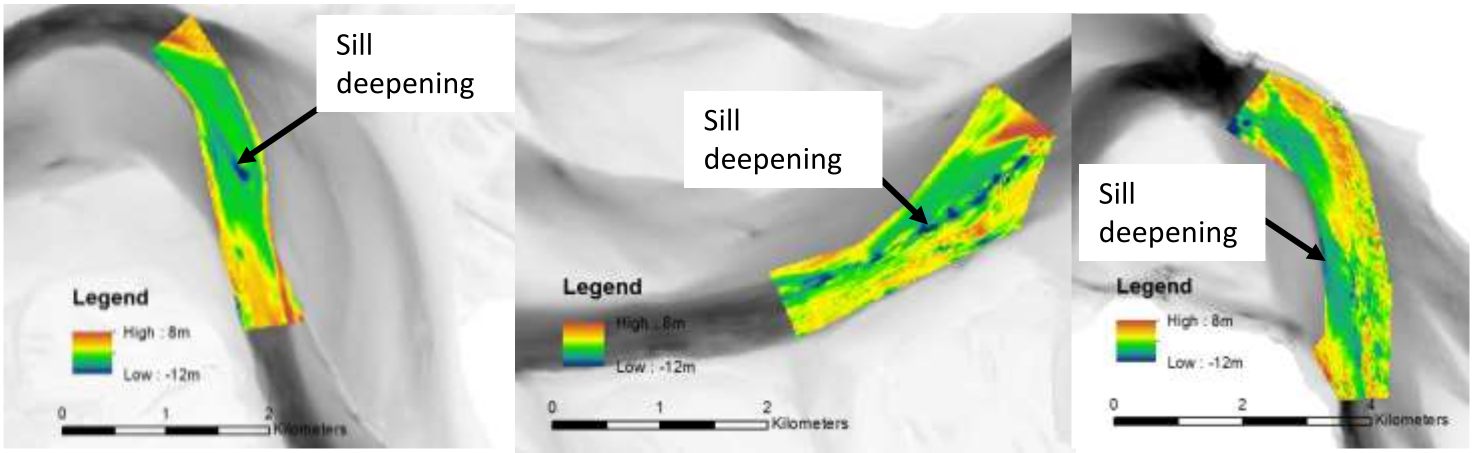


Figure 10: DEM of difference between 1970 and 1975 (before and after first capital dredging event) for the side channel between Biezelingsche Ham and Eendragt in the Western Scheldt estuary, where red = increase in elevation, blue = decrease in elevation.

Side channel between Biezelingsche Ham and Eendragt

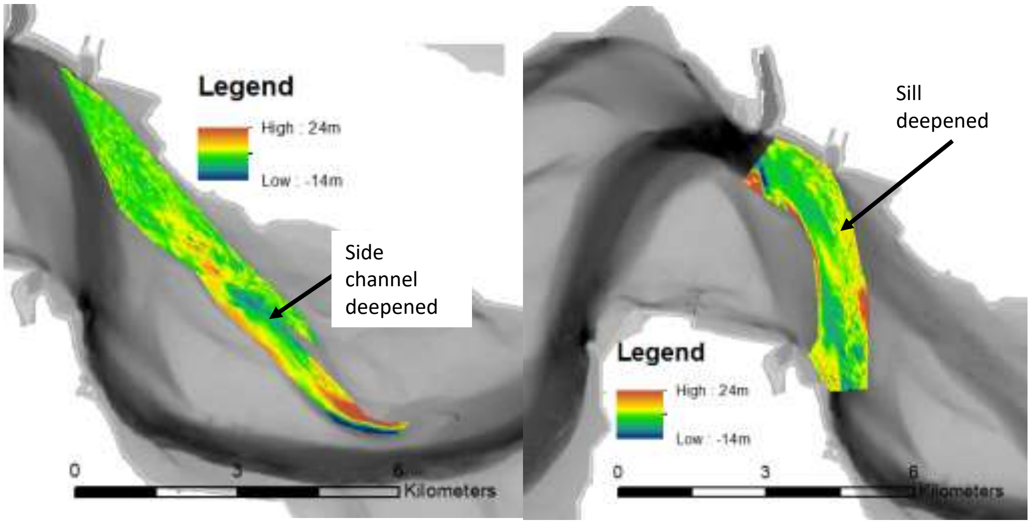
The second channel deepening (1996-1998) focused on deepening the sills (Figure 11) and these sections were lowered by 1-3m. In general, following channel deepening events, sills initially deepen rapidly, followed by a short shallowing before finally an overall deepening. When sills are left undredged they grow 1.5% year whilst dredging causes area to decrease by 0-5% per year. Some deep parts of the channel became naturally deeper as a side effect. Some side channels and shortcuts were also deepened.



Drempel van Bath Drempel van Valkenisse Drempel van Hansweert

Figure 11: DEMs of difference between 1996 and 1999 (before and after second capital dredging event) for 3 sills in the Western Scheldt estuary, where red = increase in elevation, blue = decrease in elevation.

The third deepening (2010-2011) again focussed on deepening sills however the entire channel was lowered by a few metres. Several side channels show extreme deepening (up to 10m in some parts). The response of side channels (Figure 12) varies considerably due to their use as both dredging and dumping locations.



Side channel at Valkenisse Overloop van Hansweert

Figure 12: DEMs of difference between 2009 and 2012 (before and after third channel deepening) for one side channel and one sill in the Western Scheldt, where red = increase in elevation, blue = decrease in elevation.

Maintenance dredging also took place in intermittent years with less severe effects. The main purpose of the maintenance dredging is to remove sediment in the shallowest parts of the channel, this led to the almost constant removal of sills. The effects of maintenance dredging were largely local and inconsistent and show a less strong signal than the capital dredging events. Usually maintenance dredging events just worked to compound the effects of the capital dredging.

The main effects of dredging in the Western Scheldt are to deepen the main channel, alter the depth of side channels (if they are dredged they will deepen, if not they silt up) and to cause erosion of shoal edges.

1.7 History of dumping in the Western Scheldt

The following section will describe different dumping locations within the Western Scheldt estuary and how the strategy for dumping this material has changed over time. The effects of dumping in these locations will also be discussed.

1.7.1 Introduction to dumping in the Western Scheldt

Not all sediment dredged in the Western Scheldt is dumped back within the system, less than 10% is extracted (sand mined) for use in construction and some of the sediment which is too highly contaminated to be returned to the system is treated and then disposed of outside the estuary since 2012 (Mow, 2013). However as seen in Figure 13, most of sediment since 2000 has been dumped back into the estuary. Dumping locations have changed over time and several strategies have been introduced over time to dispose of the material obtained by dredging. The total amount of sediment dumped in the estuary over time is seen in Figure 5.

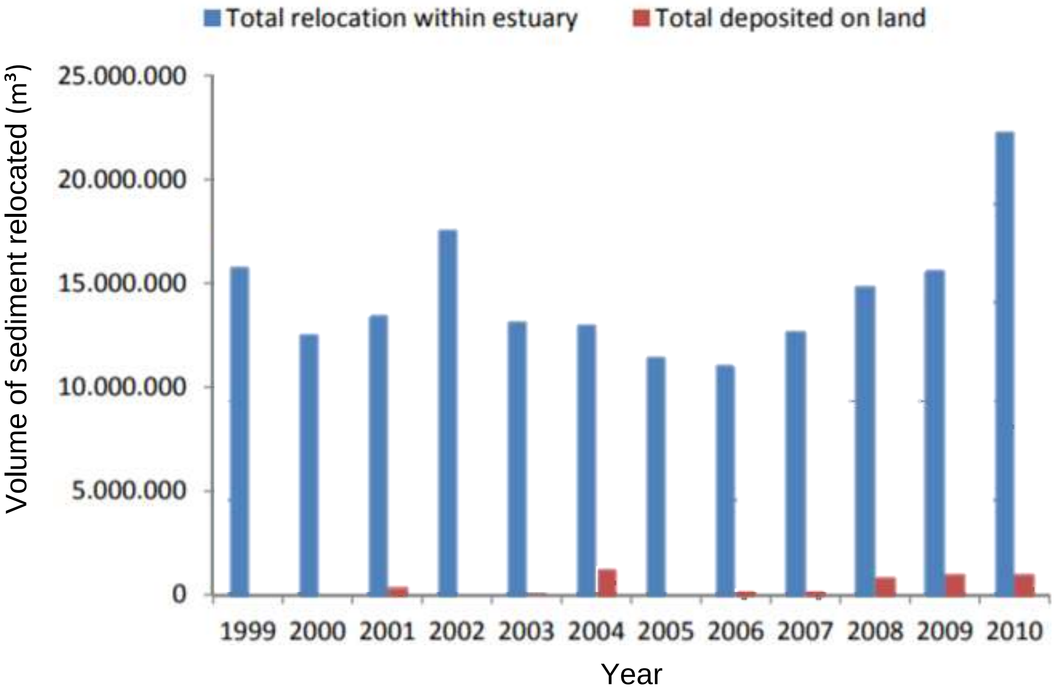


Figure 13: Volumes of sediment relocated within the Western Scheldt and their destinations. Altered from Mow (2013).

1.7.2 Dumping locations: how to choose?

The different amount of sediment dumped per dumping location in the Western Scheldt from 1981-2009 can be seen in Figure 14. The locations for dumping are often chosen to "minimise cost and effort" and are selected in the vicinity of dredging locations to avoid halting use of the shipping fairway (Mow, 2013). The locations used from 1981-2010 can be seen in Figure 15. However, the closer to the dredging site the more chance of recirculation (Verfaillie et al., 2005). Typical dumping locations for dredged material in the past were the shallower flood channels and connecting channels (Swinkels et al., 2009). Now, several new tried and tested strategies including flexible dumping have been introduced to dispose of the material. The 1970s deepening had no specific dumping strategy associated with it, with some material removed for construction and the rest relocated within the estuary into secondary channels close to dredging sites (Mow, 2013). After the negative effects of this dumping strategy were noticed, dumping began in the Western part of the estuary (Swinkels et al., 2009) and for the two following deepening events different dumping strategies were developed.

1.7.3 1990s: The East-West strategy

Following the 1990s deepening the dumped material was placed in the mouth of the estuary (Jeuken, 2000). The sediment dredged in the eastern part of the estuary was consequently dumped in the western part of the estuary to remobilise the sediment more evenly within the system as the mobility is high in the seaward sections of the estuary (Mow, 2013). This strategy was used for both the capital and maintenance dredging in the 1990s. However, this did not fit with the overall aim to reduce effort and costs, as transporting sediment for such long distances expended large amounts of time and fuel, therefore for the 2010-11 deepening a new strategy was devised.

1.7.4 The 2010 Strategy: flexible dumping

Included in the plans for the 2010 deepening was a clause to initiate a new "Flexible Dumping" strategy in the Westerschelde. This strategy aims to: preserve the multichannel system of the Western Scheldt, attain maximum ecological gain on the edges of intertidal flats and preserve the environmentally valuable surface area of the Western Scheldt (Depreiter et al., 2010). The goal of flexible dumping is to allow adaptability based on monitoring (Mow, 2013). Sites for dumping were chosen after several pilot projects were introduced. Dumping sites were secondary channels, subtidal areas near sandbars and in deep parts of the fairway (Mow, 2013). The methodology and reasoning behind the various dumping locations are described below. However, before any potential dumping site is used the area must be adopted into a current dumping permit and adjustments to any outlined plans are based on results of monitoring only (Wit, Meersschaut, & Sas, 2000). The amount of sediment dumped per location since 2010 can be seen in Figure 14 whilst the new dumping locations are displayed in Figure 16.

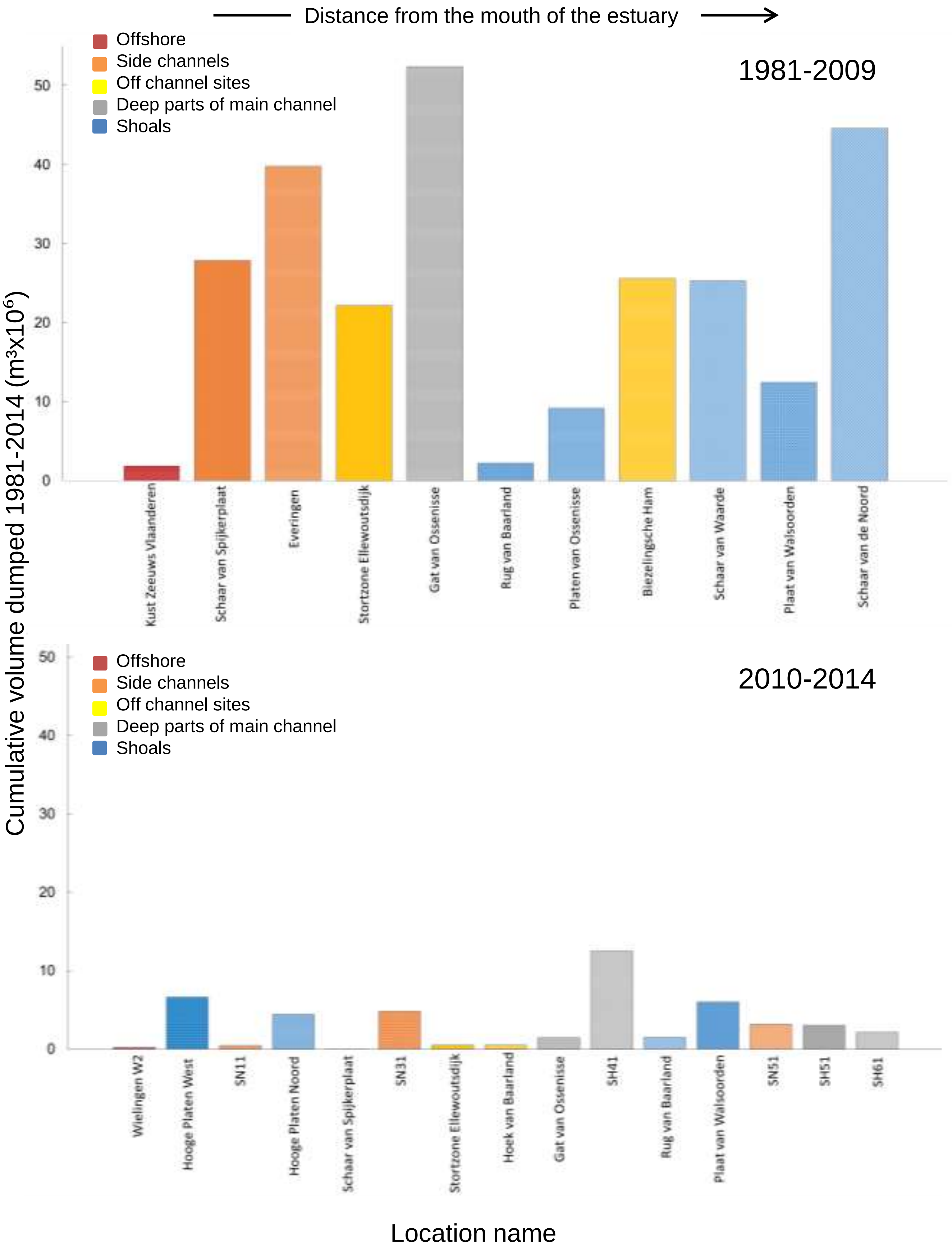


Figure 14: Cumulative amount of sediment dumped per location in the Western Scheldt for 1981-2009 (before flexible dumping) and 2010-2014 (with advent of flexible dumping) with volume figures from VNSC report (2015). Locations correspond with the map shown in

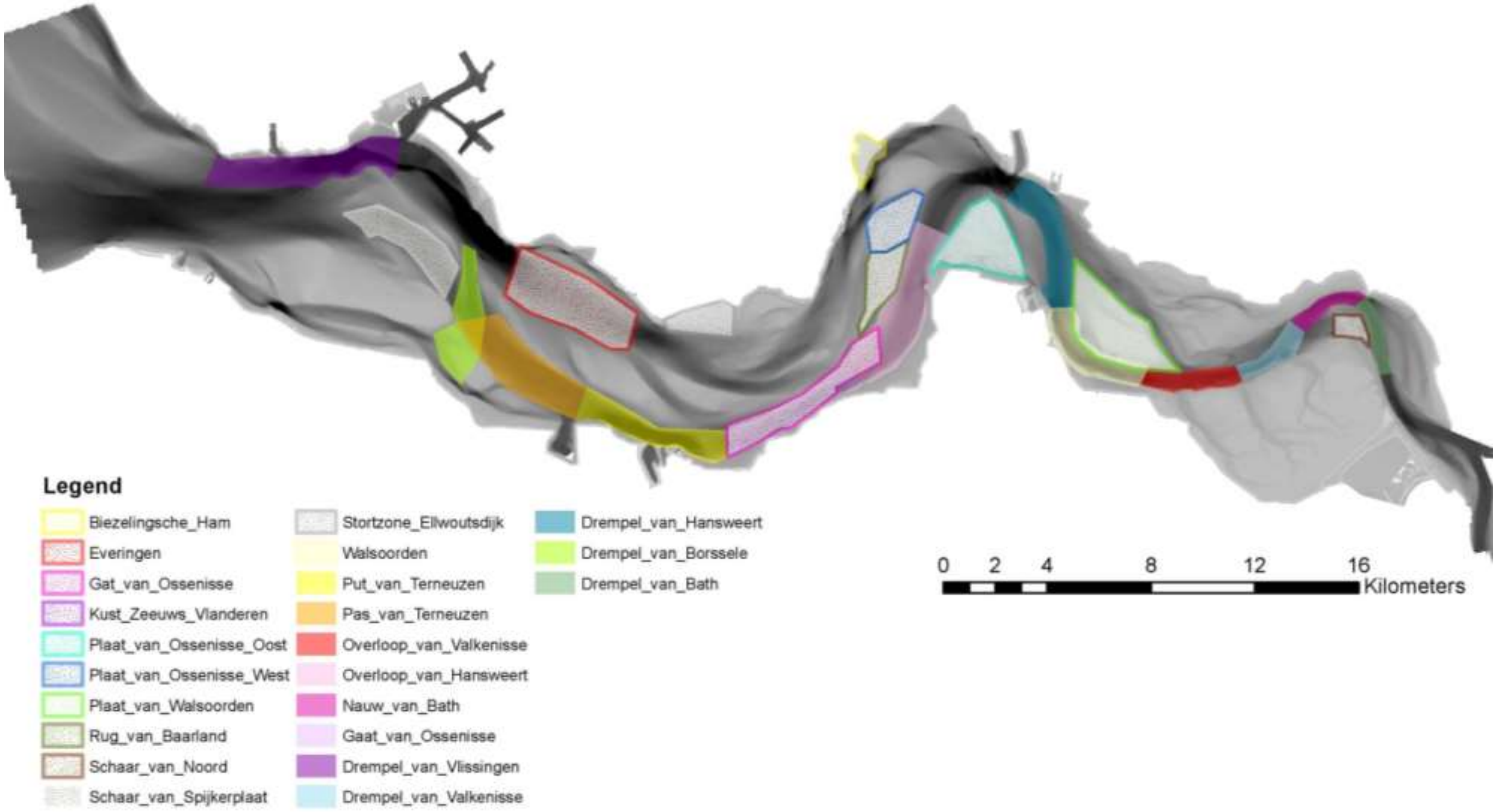


Figure 15: Locations of all dredging sites (plain colour) and dumping sites (speckled) in the Western Scheldt from 1981-2010 based on VNSC reports (2015 & 2016).

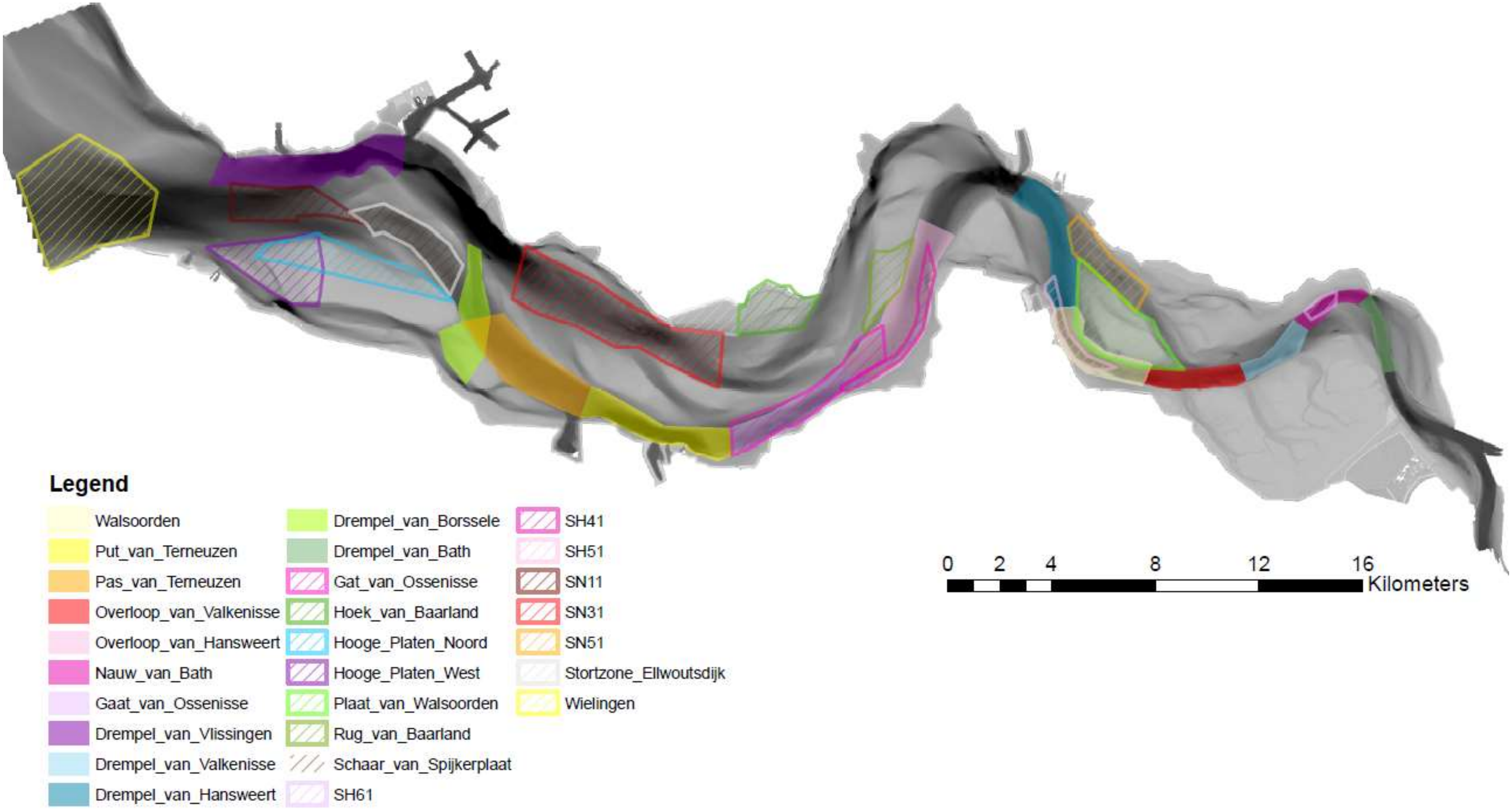


Figure 16: Locations of all dredging sites (plain colour) and new flexible dumping sites (hashed) in the Western Scheldt since 2010 based on VNSC reports (2015 & 2016).

1.7.5 Sediment exchange between cells in the Western Scheldt

Jeuken (2000) analysed the movement of sediment between the various cells of the Western Scheldt and found that disposal of large volumes of sediment in one cell induced sediment transport into other cells causing temporary large sediment exchanges. Dumping therefore alters the sediment transport dynamics and disturbs the volume of sediment present in each cell. The effect is particularly important if dumped in side channels as sediment is redistributed quickly due to constant flow and often causes sediment to return to the main channel (Palaiogianni, 2015).

1.7.6 Sandbar (shoal) dumping

In an effort to stop the conversion of the Western Scheldt into a single channel system, an alternative dumping method was proposed of dumping material near eroded tidal flats which allows slow movement of material towards the flats enhancing subtidal and intertidal habitats (de Vriend et al., 2011). In 2004 tests were undertaken and intensive monitoring for 5 years showed that part of the disposed sediment moved slowly and increased the subtidal and intertidal shoal areas however new ecological habitats were not created (van der Wal et al., 2011). Alongside the 2010-11 deepening agreed upon in the future plans for the estuary, a flexible dumping strategy was devised to help maintain equilibrium in the system (Depreiter et al., 2015). The sandy sediment had to be dumped in the system without putting the multi-channel system at risk, so a strategy was devised whereby the dredged material could be relocated near sandbars to create new ecological areas (Plancke et al., 2014). This strategy was investigated by Flanders Hydraulic Research and the investigation included desk research, field measurements, physical scale model tests, numerical simulations and in situ disposal tests at Plaat van Walsoorden. Shallow water sandbar slopes are proposed as disposal locations which would both enlarge shallow water habitats (and allow ecosystem development) and decrease disposal intensity in secondary channels (Roose, Plancke, & Ides, 2008). According to Roose et al., (2008) the Port of Antwerp Expert Team (PEAT) chose the Walsoorden bar specifically for a pilot project as the seaward tip of this sandbar has been eroded away over the past twenty years and it was proposed that the dredged material could be used to reshape the seaward tip of this sandbar. This in turn would lead to a more ecologically and morphologically stable estuary which would improve the self- erosive capacity of the flow on the crossing, leading to less future dredging. The result of this research was the beginning of a new dumping strategy encompassing Plaat van Walsoorden, Rug van Baarland, Hooge Platen Noord & Hooge Platen West as suitable locations for disposal of dredged sediment. This led to all of the capital dredged material from the 2010-11 dredging event to be disposed of at these four sites using “clapping” with hoppers in the deeper areas and trailing suction hopper dredgers in the shallower areas (Plancke et al., 2014). However, only 20% of the dredged material from the maintenance dredging which followed the deepening was placed in these four areas with the remaining material disposed of in main or secondary channels (Plancke et al., 2014).

1.7.7 Secondary (side) Channels

Before the advent of the sandbar dumping strategy the main disposal strategy for dredged material was the dumping of material into secondary channels (Roose et al., 2008). The reason for this was that the channels would redistribute the sediment in such a way as to keep the primary and secondary channels in balance (Taal, 2012). The capacity of these channels as dumping locations has been determined using the cell concept since 2007 (Mow, 2013). Sand mining has been used as a controlling measure to increase the storage capacity of these channels since the 1990s (Wit et al., 2000). It is proposed by Zimmerman(2009) that dumping in one channel causes erosion in the second channel in the same cell i.e. if you dump in the side channel you should see net erosion in the main channel and vice versa.

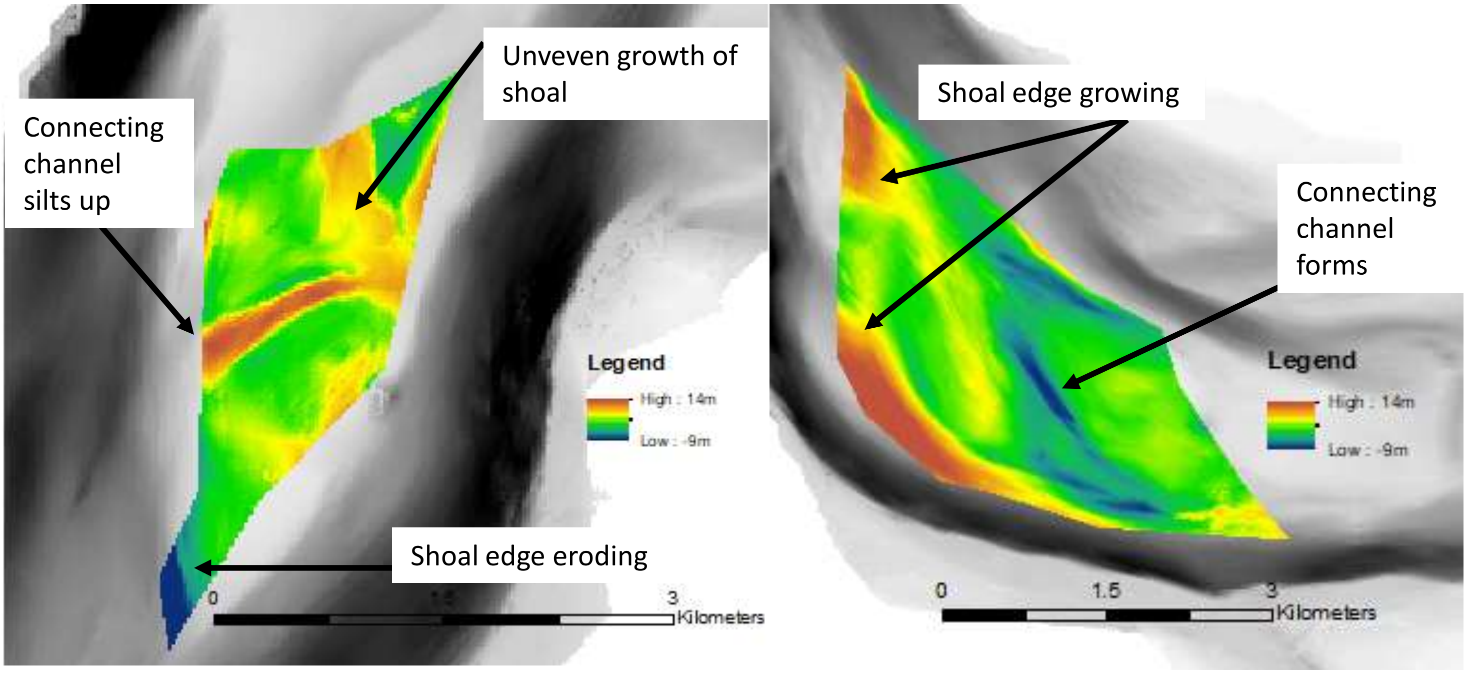
1.7.8 Deep parts of the fairway – scours

Sediment is often disposed of in deep parts of the main channel known as holes, pits or scours. The premise is that these sections of the channel naturally experience increased erosion so sediment dumped in these sections will be easily removed. Depreiter et al., (2010) performed tests on the speed of remobilisation and stability of sediment in these deep parts of the fairway in the Western Scheldt. They found that disposed sediment was most stable when dumped in one concentrated location (not sprayed or spread out). They also observed that the deepest holes were the most subject to erosion and suggest that shallower parts may see sedimentation but they were unable to prove this without further data. This study gives erosive half-lives to the sediment dumped in these deep sections of one half year to one year.

1.8 Effects of dumping on morphology evident in the DEMs of the Western Scheldt

Dumping in the Western Scheldt has different morphological effects depending on dumping regime. The effects seen during the three main channel deepening events and three different dumping strategies are now outlined.

Prior to any channel deepening events (1955-1970) dumping in side channels and shoals (Figure 17) led to silting up and shallowing of side channels and growth of shoals. The growth of shoals was uneven and varied with distance along estuary. Those seaward tended to grow whilst those landward tended to erode.



Rug van Baarland – seaward

Plaat van Walsoorden - landward

Figure 17: DEMs of difference between 1955 and 1969 (pre-capital dredging events) for two shoals in the Western Scheldt estuary, where red = increase in elevation, blue = decrease in elevation.

With the first channel deepening event, there was no clear dumping strategy with locations chosen to minimize efforts and costs only. This led to some shoals growing significantly particularly between Waarde and Valkenisse in the middle of the estuary (Figure 19). Due to extensive dumping in the side channel between Biezelingsche Ham and Eendragt, this side channel filled in rapidly as seen in section 1.7.

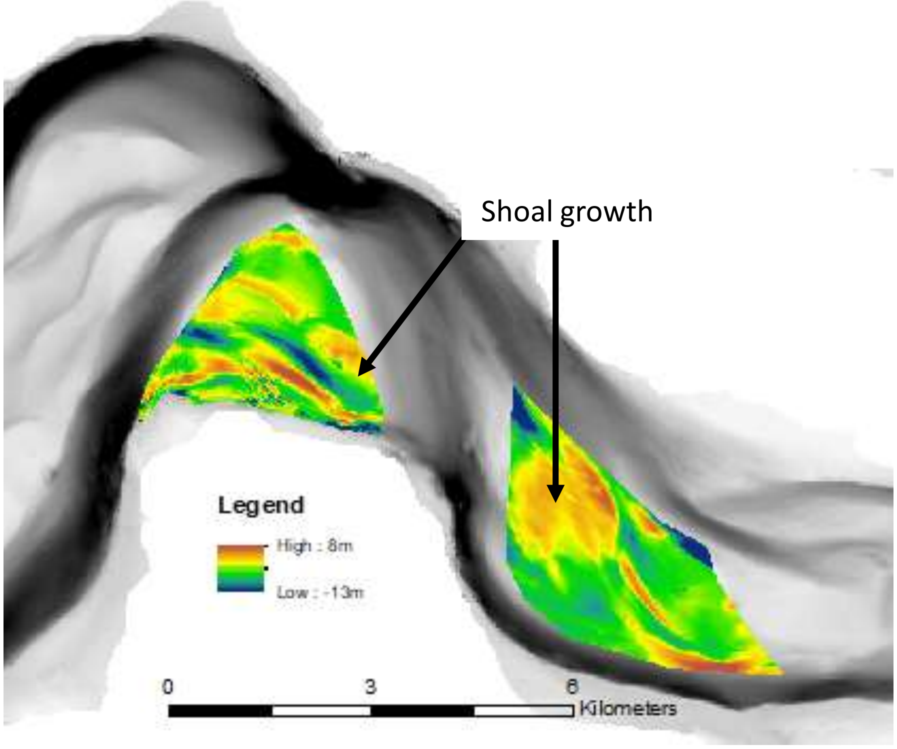
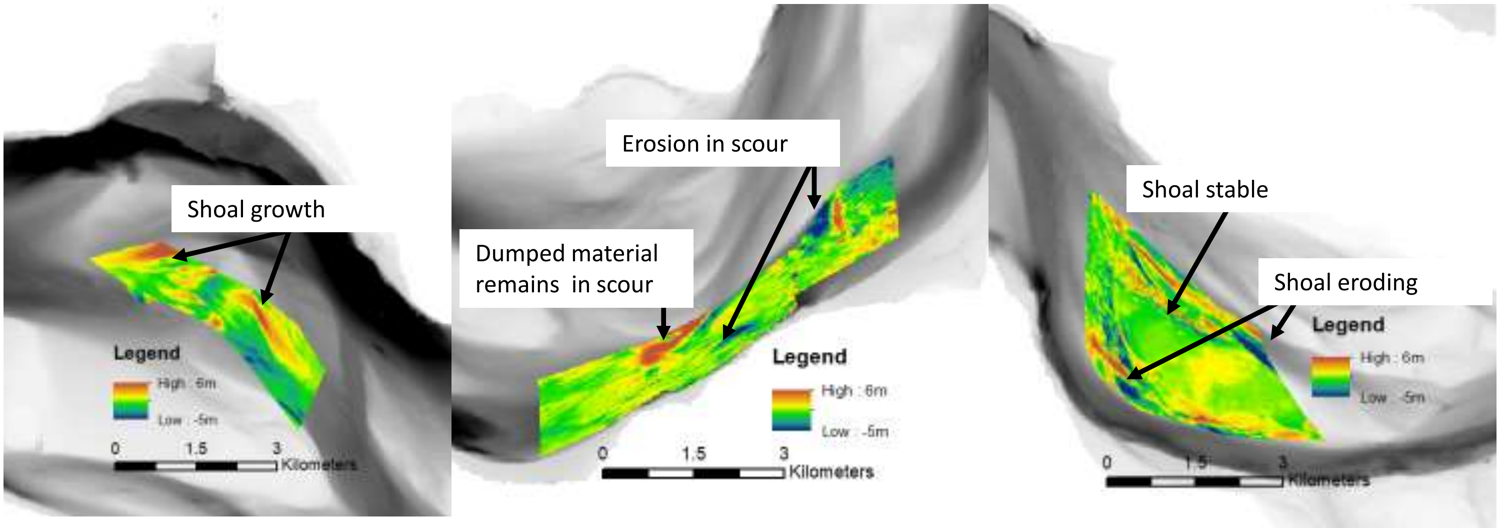


Figure 18: DEMs of difference between 1969 and 1975 (before and after first capital dredging event) for shoals betwen Warde and Valkenisse in the middle of the Western Scheldt estuary, where red = increase in elevation, blue = decrease in elevation.

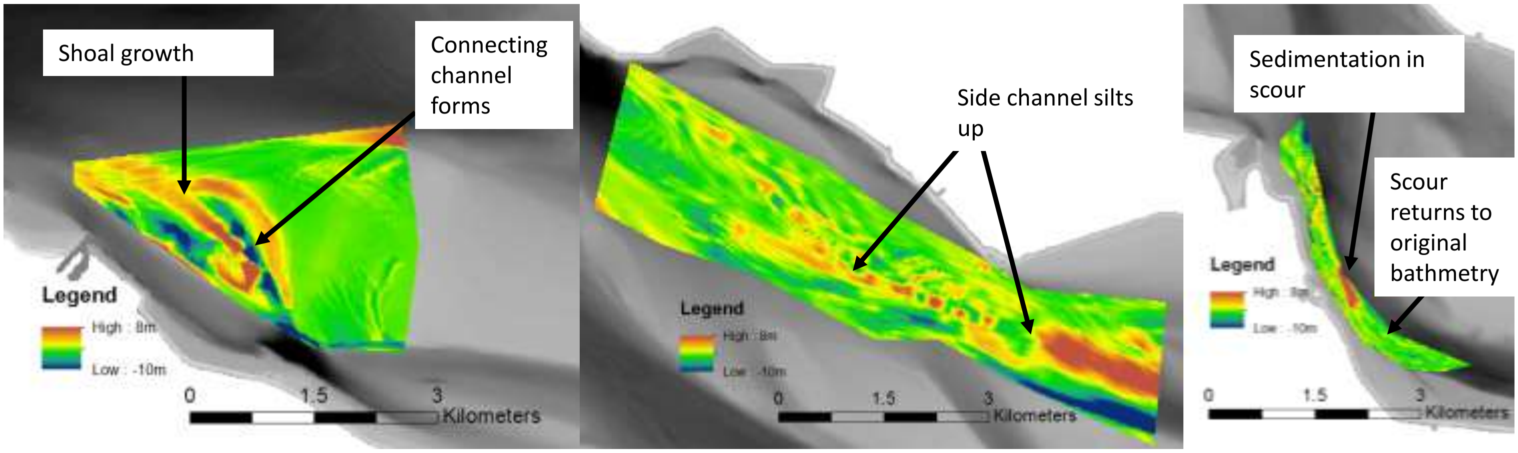
With the second channel deepening event the dumping strategy was the East to West strategy. Shoals at Gaat van Ossenisse, Stortzone Ellewoutsdijk, Everingen and Schaar van Spijkerplaat were the main dumping locations during this period. This led to concentrated growth of several of these shoals located in the Western, seaward part of the estuary (Figure 19). The sediment also begins to spread in the direction of the main channel after dumping. The shoals at the eastern side of the estuary either remain stable or erode. Material dumped in deep parts of the channel showed uneven mobilization with shallower sections unable to remobilize sediment and deeper sections not only removing sediment but experiencing erosion. Overall however, they largely returned to their original bathymetry.



Schaar van Spijkerplaat - seaward Gaat van Ossenisse Plaat van Walsoorden - landward

Figure 19: DEMs of difference between 1996 and 1998 (before and after the second capital dredging event) for seaward shoal, scour and landward shoal in the Western Scheldt estuary, where red = increase in elevation, blue = decrease in elevation.

For the third channel deepening event the dumping regime was flexible dumping. This included the addition of several new dumping locations as outlined in section 1.7.4. Figure 20 shows the difference in elevation for three different types of dumping location included in the flexible dumping plan. Shoal locations grew but again redistributed sediment into main and side channels nearby. New connecting channels and shortcuts cross cut shoals. Side channels used as dumping locations also silted up. Scours used as dumping location again had a variable response like with the 1996-1998 dumping with some sections experiencing erosion, others sections silted up but largely the bathymetry returned to its original state.



Hooge Platen West – shoal SN31 – side channel SH51 – scour

Figure 20: DEMs of difference between 2009 and 2012 (before and after third capital dredging event) for each type of flexible dumping location: shoals, side channels and scours, where red = increase in elevation, blue = decrease in elevation.

Once more, maintenance dumping also occurred in intermittent years with similar effects. In general, dumping caused shallowing of side channels, shoal growth, development and disappearance of connecting channels and erosion or sedimentation in the deep parts of the channel.

1.9 Future plans for the Western Scheldt

1.9.1 The Long-Term Vision

The Long-Term Vision (LTV) is: “a framework for sustainable management of the Scheldt estuary in a political context of Dutch-Flemish cooperation” (Depreiter et al., 2015). The aim of the LTV is the “development of a healthy and multifunctional estuary that is used for human needs in a sustainable way” (Roose et al., 2008). The LTV has governed all the reports from Deltares, Arcadis and the VNSC which provided data for this study.

The Long-Term Vision (LTV), has been recently updated and extended up to 2030. This LTV 2030 is combined with the “Development Sketch” or “Ontwikkelingsschets 2010” to give a set of measures that must be incorporated by 2010 which would accomplish the first phase of LTV 2030 (Taal & Meersschaut, 2015). As outlined by Taal and Meersschaut (2015) these two programmes have a threefold objective: to improve “Safety, Accessibility and Naturalness” whilst also preserving the physical characteristics of the estuary with the main measures agreed on being: deepening of the shipping fairway, nature restoration and a safety plan for the Sea Scheldt. This LTV governs all actions taken in the Westerschelde in the future and will play an important role in future policies of sediment management. For the LTV to preserve the multichannel system of the estuary and balance this with the need for dredging and dumping it is crucial that the negative effects of dredging and dumping are minimized and that the mechanisms are fully understood.

1.9.2 Building with Nature

Building with Nature, a term coined by Czech engineer Svašek has now become an integral part of the management of the Western Scheldt. The goal of Building with Nature is to better serve the environment and society and improve project implementation by considering environmental implications in the planning stages of any works along the estuary (Vikolainen, Bressers, & Lulofs, 2014). The programme was introduced by the Dutch dredging industry with the help of EcoShape in 2007 and the concept has driven the development of dredging and dumping action in the Westerschelde ever since. This will be an important aspect of any future sediment management in the Westerschelde moving forward. In particular this concept will govern the required amount of intertidal area and improvement of ecological quality of water (which has been altered due to suspended sediment concentration).

Figure 21: Intertidal salt marshes along the Western Scheldt estuary. Photo by Jana Cox (August 2017).

1.9.3 Future plans for sediment management

As of May 2016, the VNSC have placed sediment management in the Western Scheldt at the forefront of their activities. By 2021 the current licenses pertaining to dredging and dumping will expire, and a new management plan therefore must be developed for 2022, with a goal of development for the end of 2018 (VNSC website, 2017).

1.10 Summary of different dredging and dumping techniques: how do they dredge and dump?

The Scheldt estuary has long been the home for innovation in the field of dredging. In 1435 the scratcher or "krabbelaar" was built to undertake maintenance dredging in the Scheldt river by using the method of agitating dredging (Malan Jordaan & Bell, 2009). In 1589 new mud dredging machines were developed in the Netherlands called mud-mills which were a novel technique (Van Veen, 1948). By the 18th century mud-mills were in operation in Antwerp harbour originally using human treadmills and later using horses (Malan Jordaan & Bell, 2009). These were gradually replaced by steam driven bucket dredgers then modern diesel engine bucket dredgers. Nowadays the main type of dredger used both worldwide and in the Western Scheldt is a suction dredger. Since 2000 trailer suction hopper dredgers (TSHD) have been used to dredge material whilst a plough or silt scraper is used where these TSHD cannot operate (Mow, 2013). A TSHD is a self-propelling ship which fills its hull or hopper using one or two pipes which suck material from the bottom during dredging and is fully electronically controlled (Malan Jordaan & Bell, 2009). It is argued that trailer dredgers are the most effective and economically feasible type of dredgers however, these place large volumes of sediment into suspension which increases suspended sediment concentration by 4-20 times (Bai, Wang & Shen, 2003). This has large implications for sediment transport and sediment budgeting.

There are several modern methods of disposal of this material including dumping through bottom doors, rainbowing, spraying with spray pontoon and pumping ashore (Wit et al., 2000). The dumping of material generally takes place underneath the transport vessel when being dumped in a channel (Verfaillie et al., 2005). When dumping in shallower water at the edges of sandbars a diffuser linked to a spray pontoon has been used in the Western Scheldt (Plancke et al., 2014).

In the past empirical relations were used to predict both depth and volume of sediment required for maintenance dredging. This required plotting historically observed maintenance dredging over sill depth and extrapolating predictions for new maintenance dredging (Wang et al., 2003). The focus now has moved towards improving and updating 2D and 3D predictive models to accurately simulate sedimentation patterns at the sills and predict required maintenance dredging to avoid excess removal of sediment or incorrect dredging (Wang et al., 2003).

1.11 Hypotheses of the effects of dredging and dumping

The following hypotheses emerge from this chapter:

1. Dredging alters the overall pattern of the estuary by altering the location and extent of channels, bars and shoals
2. Dredging changes the natural shape of the main channel
3. Dredging causes smoothing of the bottom topography of the main channel
4. Dredging the main channel increases the rate of infill of the main channel
5. Response of estuary features to dredging is highly dependent on the location within the estuary: the seaward end has a higher sensitivity to change than other sections of the estuary

6. Dredging alters the tidal prism of estuaries
7. Dredging causes an increase speed of tidal propagation in estuaries
8. Dredging increases tidal range in the estuary
9. Dredging alters ebb and flood dynamics in the estuary including asymmetry, duration and peak ebb and flood
10. Dredging and dumping increase suspended sediment concentration and alter sediment transport and sediment budgets within the estuary
11. Dredging leads to the erosion of the sides of shoals
12. Dumping on shoals leads to increased sedimentation and loss of intertidal area
13. Dumping on shoals can lead to sediment becoming redistributed into both the main and side channels
14. Dredging and dumping leads to decreased intertidal area
15. Dumping in the side channels will cause erosion in the main channel whilst dumping in the main channel will lead to erosion in the side channels
16. Dumping in side channels will cause them to shallow and become less navigable
17. Dumping in deep scours will cause sediment to be eroded
18. Material dumped in scours is easily removed so the bathymetry of these areas usually remains stable

Dumping in shallower sections will cause sedimentation

Large scale experiment will be combined with data analysis of the Western Scheldt to test these hypotheses

2. Methods and materials

The scale experiments were designed based on the current dynamics and dredging and dumping practices used in the Scheldt Estuary. This was done using analysis of digital elevation models (DEMs) of the estuary and relevant academic papers and reports (particularly those of the Vlaams-Nederlanse Scheldecomissie) pertaining to dredging and dumping. Following this analysis, a dredging and dumping protocol was designed for use in the experimental facility: The Metronome. The following outlines the sources and use of the data used to design the experiments, the details of the experiment and the processing of the results of the experiment.

2.1 Western Scheldt data collection & analysis

DEMs from 1955-2015 of the topography and bathymetry of the Dutch coast were used to analyse the morphology and morphological changes in the Scheldt estuary. Dredge and dump sites were located using the reports of the Vlaams-Nederlandse Scheldecommissie (VNSC) and relevant literature. Volumes dredged and dumped per site were recorded from the same sources (see Figure 5). These sites were then located on the DEMs and investigated. Analysis of the DEMs using ArcGIS produced average depth changes per dredge/dump site and changes to the overall channel depth and width. This was done by extracting volume and area for the dredge and dump sites (individual polygons seen in Figure 4, Figure 15 & Figure 16). These were combined with the volume information from the VNSC reports to produce ratios and percentage changes for various types of dredge/dump sites (straights, crosses, sills, bends, shoals, side channels, holes) and the depth and width changes of the channel due to channel deepening events versus changes due to maintenance dredging.

2.2 Designing experiments for the Metronome

An overview of the timeline of the experiment including actions and measurements taken is provided in Figure 25.

2.2.1 What is the Metronome?

The Metronome is a large scale experimental tidal facility in Utrecht University which mimics reversing tidal flow by tilting periodically. It is 20 metres long and 3 metres wide with both a river input and tidal input. The facility specialises in creating sandy multi-channel estuaries like the Western Scheldt with complex morphological features. The facility also contains 7 overhead cameras along the flume used to record images. Figure 22 shows the geometry of the Metronome with a brief explanation of how it works. For further explanation see Kleinhans et al. (2017).

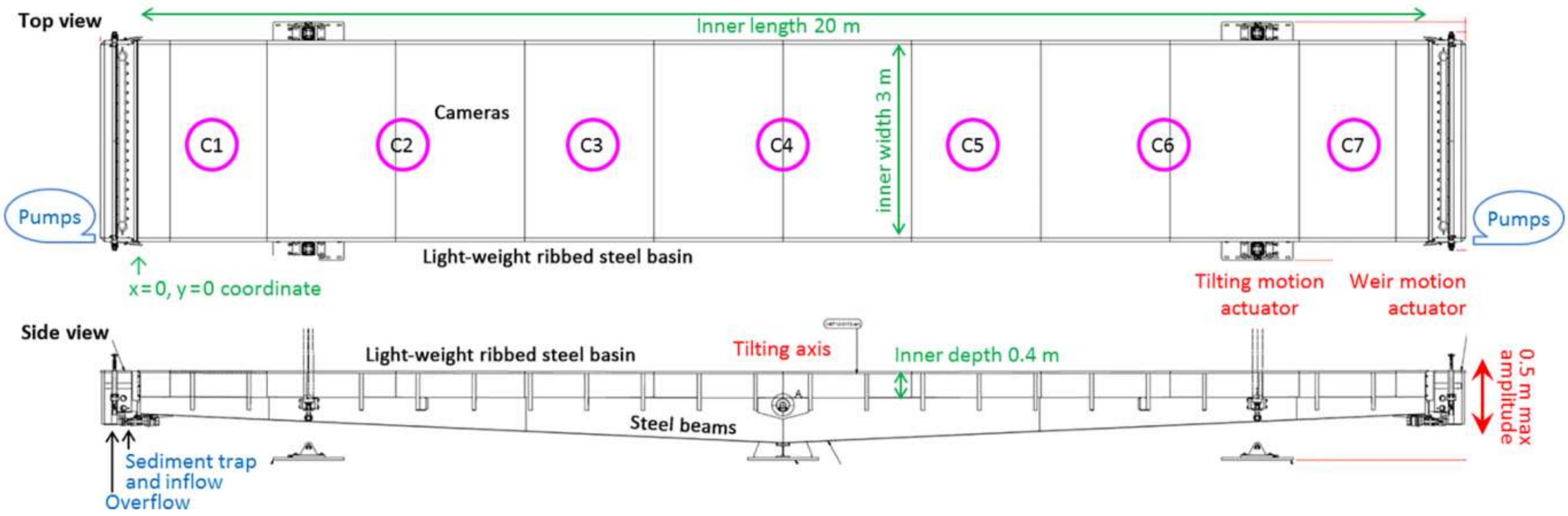


Figure 22: Geometry of the Metronome facility. The inner basin measures 20.00m in length, 3.00m in width and 0.40m in depth, and the maximum tilting amplitude is 0.5m at the end tank,, resulting in a tilting slope amplitude of 0.05 mm $^{-1}$. Both flume ends have end tanks with a 0.2m long stilling basin functioning as a sediment trap and pumped water inflow separated by a automated weird from the outside 0.2m long overflow basin with a 2mm mesh to capture PIV particles. Motion is controlled by four 20kN actuators for tilting and two small actuators for each end tank weir. Cameras C1-7 are mounted 3.7m above the flume floor. Source: Figure 3 from Kleinhans et al. (2017).

2.2.2 Experimental setup and settings – creating the shipping fairway

This experiment used a sand-only setup with mixed particle size sand and no mud. The grain size distribution is displayed in Figure 23. There was no sediment feed (this closely matches the reality in the Western Scheldt as outlined in chapter 1) and sediment was net exported in a seaward direction. This closed system sediment regime was the case for both this experiment and the control experiment allowing for comparison. There was however, erosion from the banks of the sediment which did supply sediment to the system (this was the case in both the control experiment and the dredging experiment).

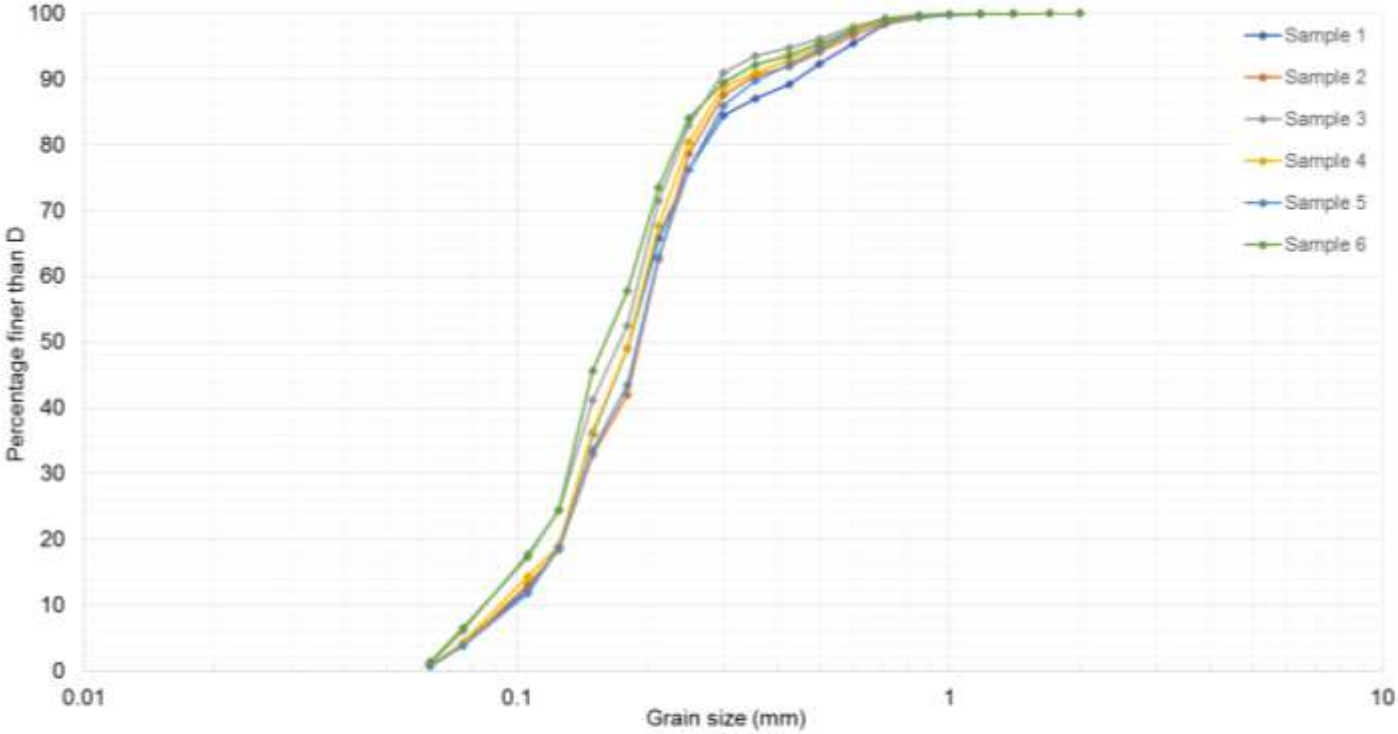


Figure 23: Grain size distribution for 6 samples of sand from the Metronome. Sample 1-3 represent dredged material whilst sample 4-6 represent dumped material.

For this experiment an initial trumpet shape estuary was cut and allowed to develop for 3000 tidal cycles. Each tidal cycle spans 40 seconds. Tidal amplitude was 75mm. After this initial run, a Scheldt like estuary had developed with side channels, ebb and flood channels, shoals etc. An initial "shipping fairway" was then cut along the deepest natural course of the estuary (linking both ebb and flood channels where necessary).

This channel was lowered to about 1/5 of the original depth using a palette knife and removal of sediment by hand (from 2.5cm to a 3cm minimum depth) based on the channel deepening that occurred in the Western Scheldt (first channel deepening from 6.5m to 9.5m, the second from 9.5m to 11m and the third from 11m to 14m). A picture of the dry dredged channel can be seen in Figure 24. The width of the channel was proportional to the overall width of the estuary in the same ratios as the Western Scheldt. For the landward end this was approximately 10% of the overall estuary width, 15% moving into the middle reaches of the estuary and at the seaward end up to 20% of estuary width. The estuary was then dredged to create the "shipping fairway" and the material was removed from the estuary completely (it was not returned to the system).

Figure 24: Dry dredged channel at cycle 3000.

2.2.3 Dredging the shipping fairway

After this first capital dredging event, the Metronome was allowed to run for first 50 and then 100 cycles to determine how quickly the estuary would silt up and to allow the system to stabilize. After 100 cycles the first maintenance dredging event took place. This involved removing any sediment in the channel that was above the minimum depth requirements (3.5cm) or any sections which were below width requirements. These were located using DEMs of the channel after 3100 cycles. It was decided that after 50 cycles the shipping fairway was already becoming filled with sediment so for the remaining four maintenance dredging events of this first shipping fairway, dredging took place after 50 cycles. Once more, dredging locations were identified using DEMs. In reality the Western Scheldt is continuously dredged all year round, which was not possible to replicate in the experiment. The wet sediment was removed from the various locations and the volume and location details were recorded.

A second capital dredging was also undertaken on a new wider estuary: after the 5th maintenance dredging of the first channel the Metronome was run for 1000 more cycles to allow a wider estuary with more complex morphology to develop. This second capital dredging followed the same protocol as the first (minimum depth requirement of 3cm, width appropriate to the overall estuary width etc.). Again, the estuary was allowed to develop and silt in with measurements after 50 and 100 cycles. For this new wider estuary, maintenance dredging after 100 cycles was deemed more appropriate and thus 5 maintenance dredging events were then undertaken on this second channel after 100 cycles.

After the final maintenance dredging event the estuary was then allowed to run for a further 8000 cycles until it reached termination at 13000 tidal cycles.

2.2.4 Dumping locations

Resulting from the data about dumping protocol from the Western Scheldt and consultation with experts from ARCADIS (Jelmer Cleveringa & Nathanaël Geleynse), it was agreed that primarily shoals, side channels and deep pits or holes in the main channel would be used as dumping locations. When dumping on shoals, material was mainly dumped on the seaward side to allow for remobilization as was done at the test site at Plaat van Walsoorden (see section 1.7.6). Dumping in side channels took place at the entrances to the side channels to mimic how ships in the Western Scheldt would dump sediment in these side channels (avoiding going too far into these shallower side channels for fear of running aground). Dumping in holes or pits would take place in sections of the channel that were much deeper than the minimum depth (>4cm).

The appropriate dry volume of sediment was then dumped at locations close to the dredging sites at typical dumping locations for the Western Scheldt (i.e. side channels, shoals, pits) and these locations were recorded. Dry sediment was used to allow for easy “spraying” of the dumped material and to avoid any clumping of material which would hinder remobilization.

2.3 Data collection

2.3.1 DEMs & orthophotos

Photos were taken along the estuary for the purpose of creating DEMs. For each DEM 120-130 photos were taken at various angles in both directions along the estuary. DEMs and orthophotos were created using AGISOFT Photoscan software using control points every 2 metres along the estuary (20 tie points total). See Table 1 for a summary of timing of experimental DEMs and orthophotos. The DEMs were processed in ultra-high quality and standard default settings in AGISOFT. Using these DEMs and orthophotos the exact dredging and dumping locations were identified along with exact channel dimensions. These DEMs were also used for a range of calculations of depth, length, width, volume, area and the creation of cross sections.

Several tools in ArcGIS were used to quantify changes in height, area, width and volume. The estuary extent was defined as the border between the channels and shoals with the surrounding banks. Any width or cross section measurements were straight line distance from edge to edge of the given feature. The locations of features are specified according to along flume distance e.g. shoal at 10m along the flume. For measuring changes in depth along the main channel a thalweg (single line) was chosen in the centre of the fairway to represent the channel. Namely, GIS analysis of the DEMs was used to quantify the following (for dredged and non-dredged experiments at various tidal cycles):

- Changes to shoal height and creation of shoal cross sections
- Surface area of side channels, average depth of side channels and number of side channels
- Along channel profiles of the main channel
- Average channel depth of the main channel
- Estuary width and estuary shape
- Intertidal area (which was compared with an overhead imagery method)
- Speed of removal of sediment from scours

Cycle	Event	DEM & Orthophotos collected
3000	Pre-dredging	✓
3000	Capital dredge 1	✓ (dry and wet channel)
3050	50 cycles after capital dredge 1	✓
3150	100 cycles after capital dredge 1	✓ (dry and wet channel)
3150	Capital dredge 1 – maintenance dredge 1	✓
3200	Capital dredge 1 – maintenance dredge 1 – after 50 cycles	✓
3200	Capital dredge 1 – maintenance dredge 2	✓ (dry and wet channel)
3250	Capital dredge 1 – maintenance dredge 2 – after 50 cycles	✓
3250	Capital dredge 1 – maintenance dredge 3	✓ (dry and wet channel)
3300	Capital dredge 1 – maintenance dredge 3 – after 50 cycles	✓
3300	Capital dredge 1 – maintenance dredge 4	✓ (dry and wet channel)
3365	Capital dredge 1 – maintenance dredge 4 – after 65 cycles	✓
3365	Capital dredge 1 – maintenance dredge 5	✓ (dry and wet channel)
4600	Pre-dredging	✓
4600	Capital dredge 2	✓ (dry and wet channel)
4650	50 cycles after capital dredge 2	✓
4700	100 cycles after capital dredge 2	✓
4700	Capital dredge 2 – maintenance dredge 1	✓ (dry and wet channel)
4800	Capital dredge 2 – maintenance dredge 1 – after 100 cycles	✓
4800	Capital dredge 2 – maintenance dredge 2	✓ (dry and wet channel)
4900	Capital dredge 2 – maintenance dredge 2 – after 100 cycles	✓
4900	Capital dredge 2 – maintenance dredge 3	✓ (dry and wet channel)
5000	Capital dredge 2 – maintenance dredge 3 – after 100 cycles	✓
5000	Capital dredge 2 – maintenance dredge 4	✓ (dry and wet channel)
5100	Capital dredge 2 – maintenance dredge 4 – after 100 cycles	✓
5100	Capital dredge 2 – maintenance dredge 5	✓ (dry and wet channel)
5200	Capital dredge 2 – maintenance dredge 5 – after 100 cycles	✓
11000	After 11000 cycles	✓
13000	After 13000 cycles	✓

Table 1: List of instances where DEMs and orthophotos were created during the dredged experiment.

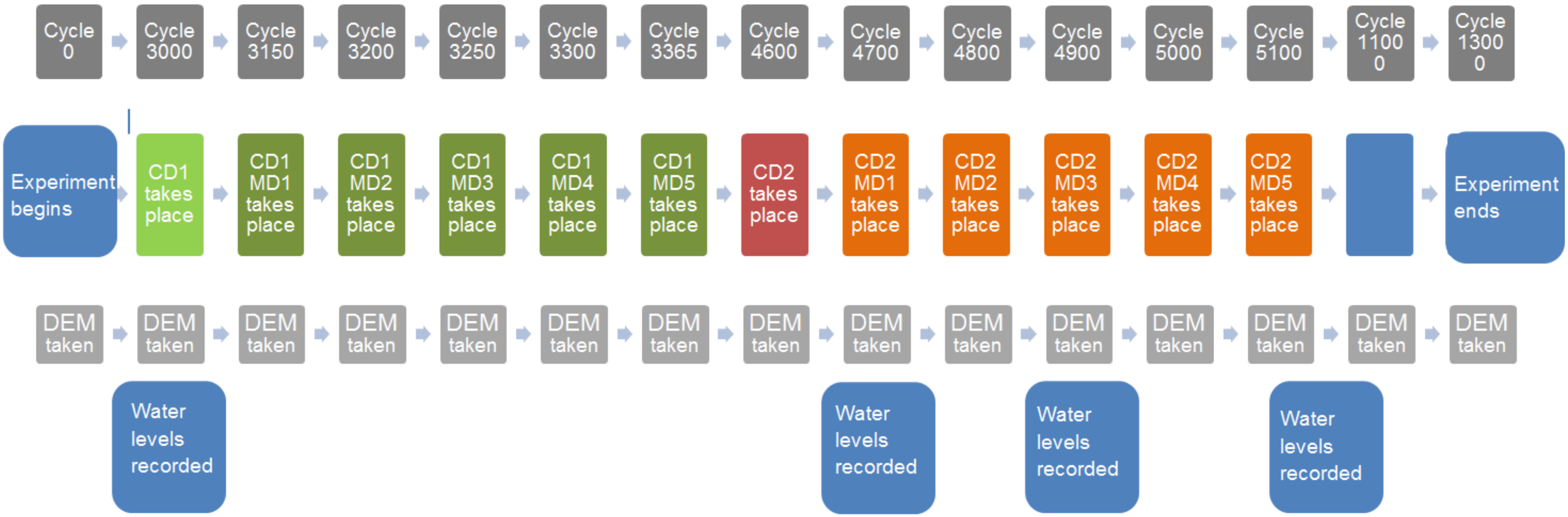


Figure 25: Timeline of the experiment.CD = capital dredge. MD = maintenance dredge. DEM = digital elevation model. Dark grey boxes indicate cycle number. Light green indicates capital dredging 1 whilst dark green represents maintenance dredging events. Red represents capital dredge 2 whilst orange represents successive maintenance dredging events. Light grey indicates period when DEM was taken, whilst blue represents times when water levels were recorded.

2.3.2 Time lapse imagery & blue colour photos

Overhead cameras continuously took photos once per tidal cycle over the entire estuary. These time lapse imagery photos are comparable with other experiments in the facility (non-dredged and dumped estuaries) and can be developed into short movies to show morphological development. These overhead cameras were also used to take images at various points in the tidal cycles to indicate which sections were submerged during ebb and flood. This allowed for quantification of intertidal area by indicating a threshold value for “wetness” or “dryness” and calculating how many pixels remained either totally wet (subtidal), totally dry (supratidal) or sometimes wet, sometimes dry (intertidal). This calculation was done using MATLAB.

2.3.3 Water levels & Particle Image Velocimetry (PIV) measurements

Water levels were recorded using sonar sensors for both still and moving water at various stages in the experiment. One sensor was over the main dredged channel while the other was placed over a side channel. These water levels were recorded before and after different events to allow for comparison. Still water levels or zero water levels were also recorded. This allowed for correction of the water levels between measurements.

Particle Image Velocimetry (PIV) was undertaken using the overhead cameras and physical seeding of plastic particles. This gave instantaneous velocity measurements along the estuary for various stages in the tidal cycles (during both flood and ebb). These were then processed in MATLAB to determine the maximum flow velocity in the estuary and create velocity maps for both the u (cross channel) velocity component and v (along channel) velocity component.

2. 3.4 Intertidal area calculation methods

To verify the method used to calculate and map the supratidal, intertidal and subtidal areas used (this technique combines GIS analysis of the DEMs with water level data), the overhead imagery from the Metronome was analysed. The LAB photos were used to determine a threshold value of wetness and any values that were not permanently wet or dry were determined to be intertidal. The difference in methods for the control experiment (no dredging or dumping) is seen in Figure 26. The use of LAB photos gives a smoother, less variable intertidal area. However, the differences were deemed small enough for the GIS method to still be valuable, particularly as it allows the plotting of maps which visualise the difference in supratidal, intertidal and subtidal area easily.

2.3.5 Control experiment

DEMs and water level data were available for a control experiment which featured the same setup with the exception of dredging and dumping.

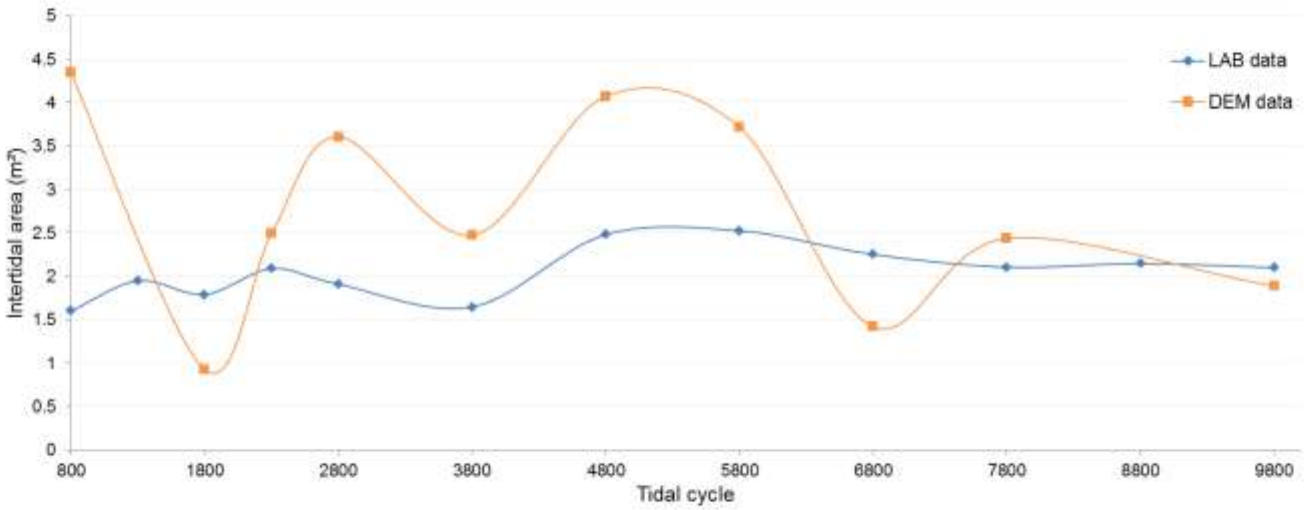


Figure 26: Variation in intertidal area based on method used for calculation for the control experiment (no dredging and no dumping).

3. Results

The following section outlines the main findings of the dredged experiment and compares these findings with the control experiment. Chapter 4 outlines the similarities and differences between the experimental results and the Western Scheldt. The differences and similarities are outlined at a variety of scales. Large-scale effects refer to estuary wide effects, those which affect the overall planform of the estuary or large scale patterns of shoals and channels. Medium scale effects refer to those which alter important along estuary characteristics such as the main channel and the water levels over the estuary. Small scale features refer to individual features such as shoals, side channels and scours. All three of these spatial scales are compared over time.

Typically in this facility, experiments run for 11,000-15,000 cycles beginning with a typical trumpet shape estuary which gets larger over time. In the case of the control experiment, it developed as an unconstrained estuary expanding laterally over time with numerous disconnected but distinctive ebb and flood channels, shoals and bars that migrate regularly and change in dimensions. Appendix 2 shows the DEMs documenting the development of the estuary collected for various stages in this experiment.

The dredged experiment also expanded laterally over time. Once dumping and dredging took place a main channel emerged with several side channels, shoals and bars, but these did not migrate as regularly and their dimensions stayed more stable over time as demonstrated in the following sections. When allowed to process without dredging and dumping the pattern became “messy” and dredging was required to return the shipping fairway to a single channel. Appendix 3 shows the DEMs taken for this experiment, including immediately before and after dredging and dumping events for each capital and maintenance dredging event.

3.1 Large scale effects of dredging and dumping

The estuary developed in a Western Scheldt manner including the three morphologically distinct zones outlined earlier: the subtidal delta, the multi-channel system and the single channel with bank attached bars (Figure 27). These are referred to as the seaward, middle and landward ends of the estuary respectively in the following sections of the study. Before dredging, the experiment had a typical van Veen (1948) structure with clear ebb and flood channels (

Figure 28). Moving through the experiment a Western Scheldt pattern developed with a continuous meandering channel with several stable side/secondary channels. Some connecting channels formed and migrated throughout the experiment cross cutting shoals and bars, acting in a similar fashion to those in the Western Scheldt although less distinctive likely due to scaling effects.

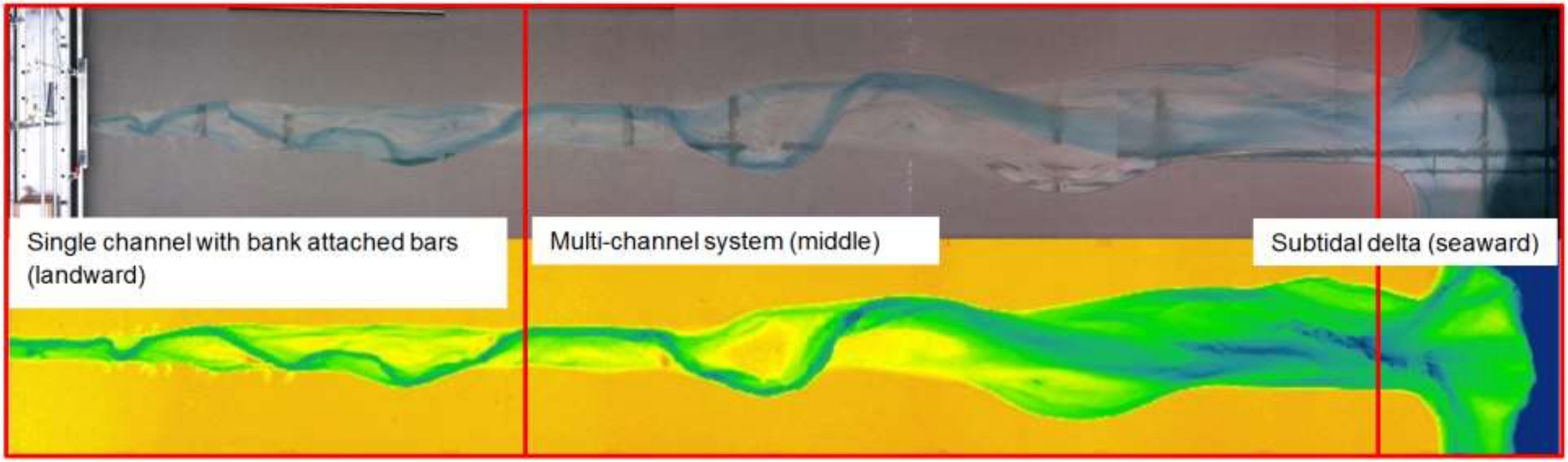


Figure 27: The three sections of the dredged estuary: 1. The single channel with bank attached bars also called the landward end, 2. The multi-channel system also known as the middle of the estuary, 3. The subtidal delta or seaward end. The top image is the overhead image of the estuary, the bottom is the DEM of the estuary.

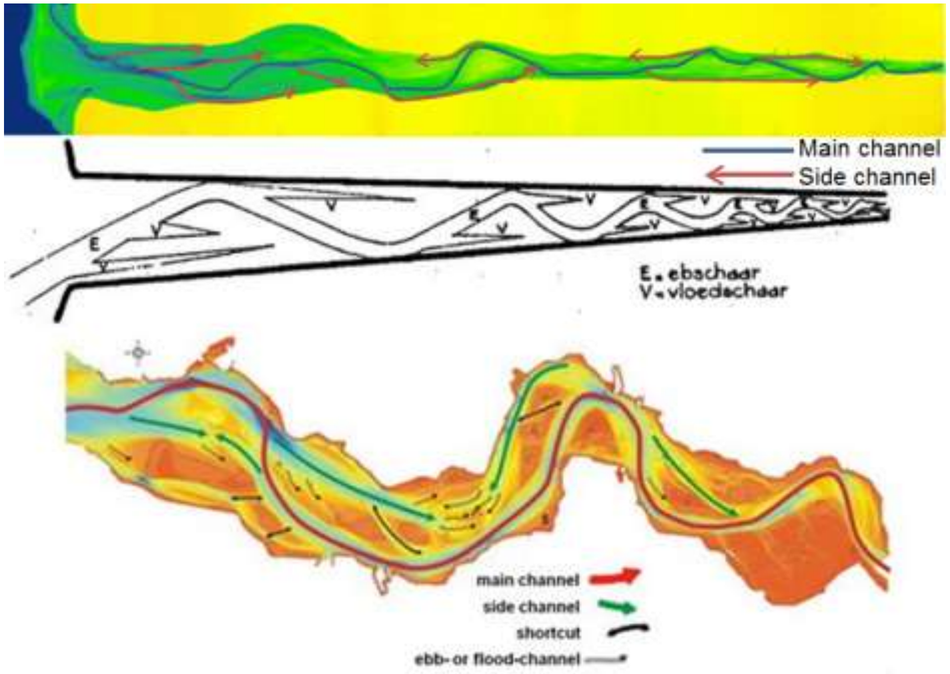


Figure 28: Comparison of the experiment at cycle 3000 (before any dredging or dumping takes place) with the typical van Veen structure of the Western Scheldt. Altered from van Veen (1948).

3.1.1 Estuary width and morphological composition

In comparing the overall estuary width of the dredged experiment with the non-dredged experiment a clear pattern emerges. Estuary width at the seaward end of the estuary is greater in the non-dredged experiment i.e. a wider more braided pattern occurs. In the dredged experiment the seaward end of the estuary is much narrower with fewer channels and shoals; it is on average, over time, 20% narrower than the non-dredged experiment over time (see Figure 29). Looking at width cross sections of the seaward end (see Figure 31) it is clear that the seaward end of the non-dredged estuary is composed of several channels and interim shoals whilst the dredged experiment displays one clear very deep channel and a higher elevation area.

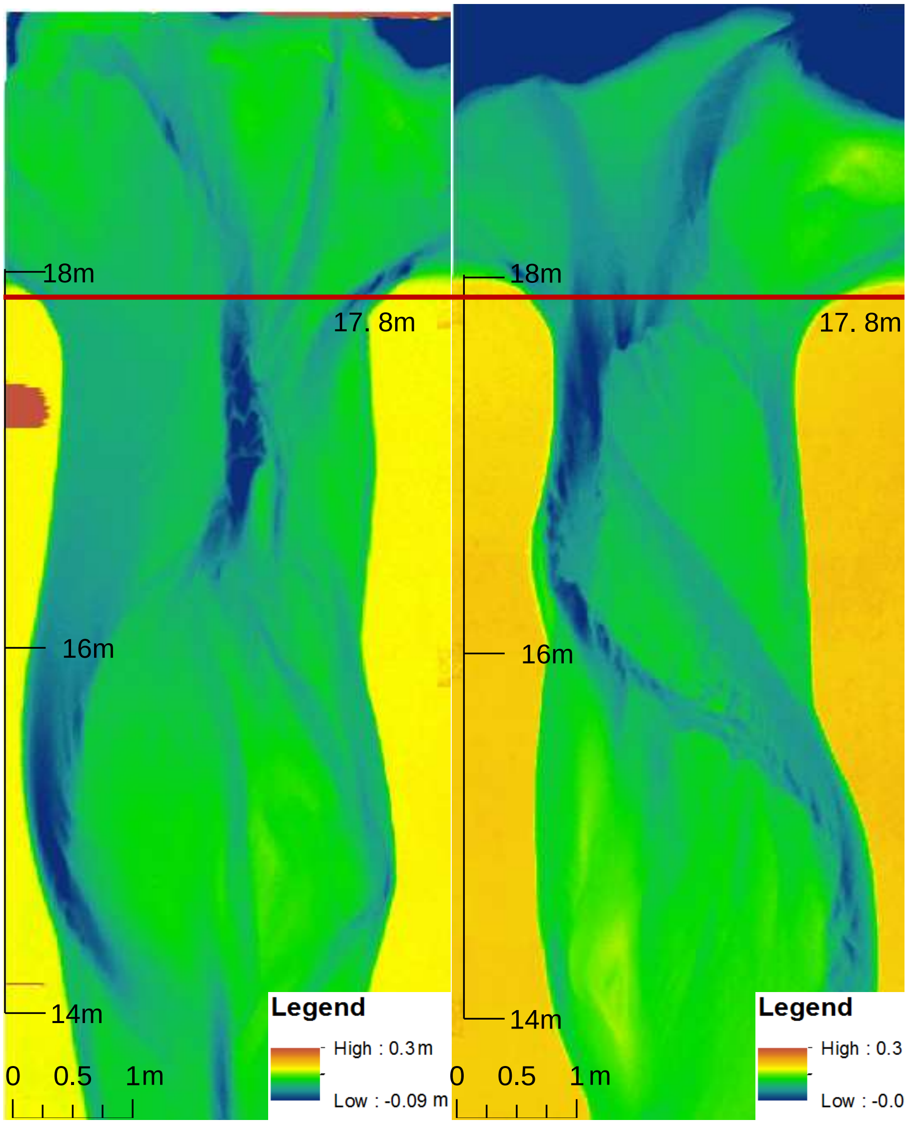


Figure 29: DEMs showing estuary width at location 14-18m of the estuary for the non-dredged experiment (left) at cycle 4899 and the dredged experiment (right) at cycle 4900. The red line at 17.8m indicates where cross-section was taken for following figure.

In the middle of the estuary, the converse is true, with the dredged experiment showing an averagely wider estuary, on average 32% wider over time, than the non-dredged experiment (see Figure 30). This is likely due to the stable main channel; shoal and side channel system in the dredged experiment which stabilised due to continuous dredging of the main channel and dumping on the shoal in the middle of the estuary which is clearly visible in Figure 31 of the cross sections of the middle of the estuary. The non-dredged experiment displays several channels and more than one shoal as the experiment progresses.

At the landward end of the estuary (Figure 30), the dredged estuary is 11% narrower over time than the non-dredged experiment. In this dredged experiment, the primary dredged channel remains even after progression of the experiment without dredging. Several shoals and bars surround this main channel which erode at a slower rate when used as dumping sites giving much higher bars and shoals. In the non-dredged experiment there are two main channels with several connecting channels and less distinctive bars and shoals than in the dredged experiment as seen in Figure 31.

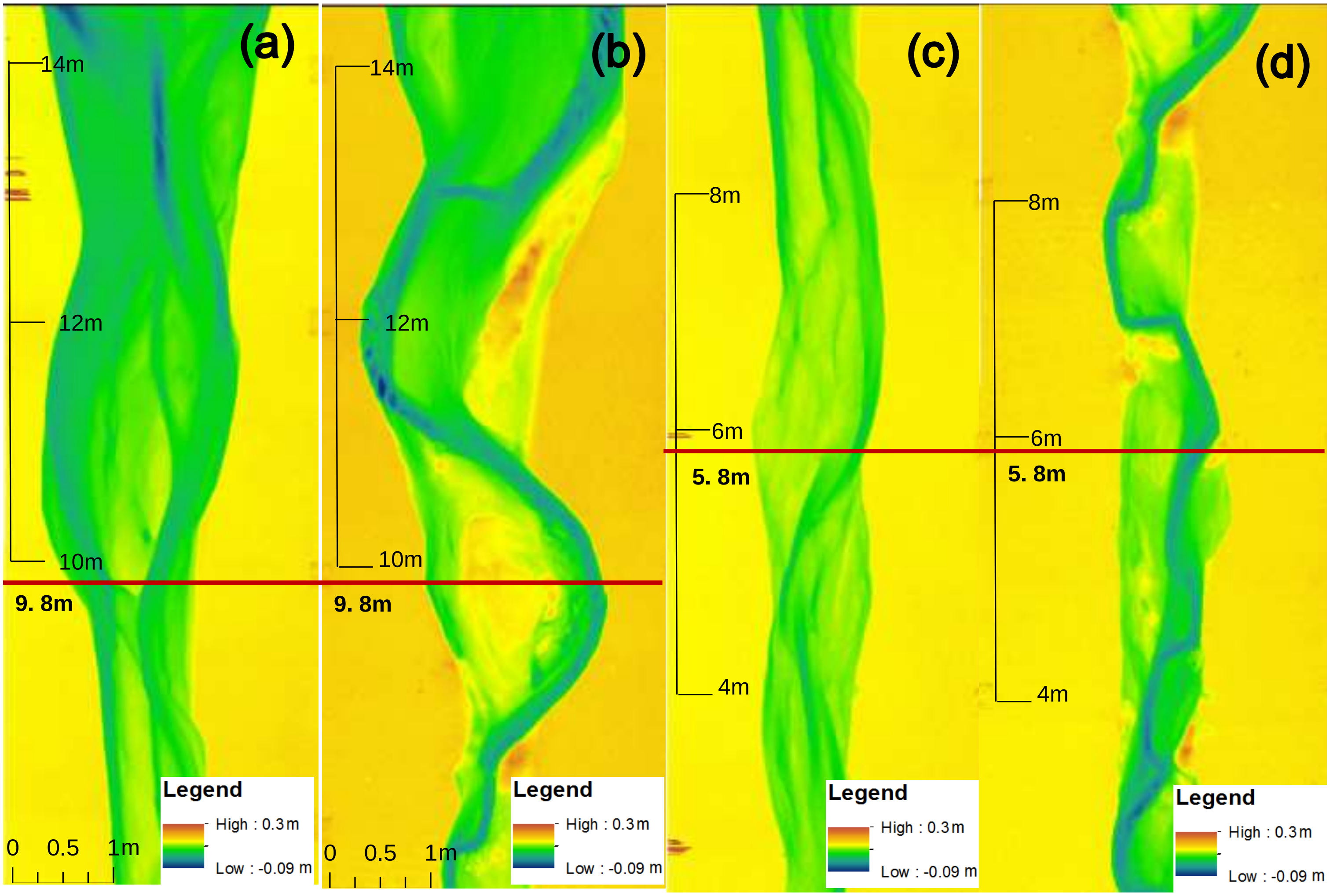


Figure 30: DEMs showing estuary width at (a) 10-14m for the non-dredged situation (b) 10-14m for the dredged situation (c) 4-8m for the non-dredged situation and (d) 4-8m for the dredged situation (Cycle 4899 for the non- dredged experiment and cycle 4900 for the dredged experiment).

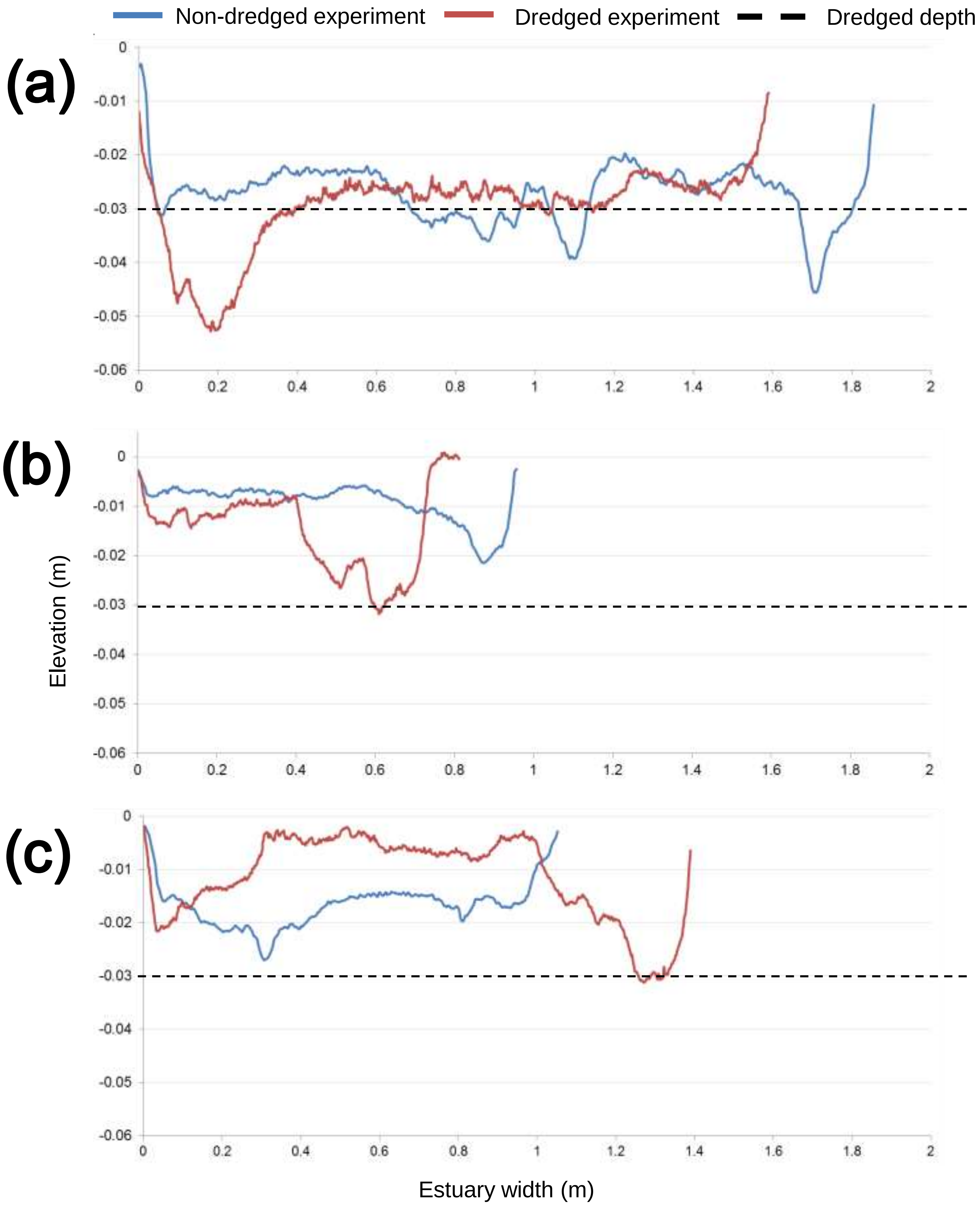


Figure 31: Cross section of the estuary at the seaward end at 17.8m (top) middle of the estuary at 9.8m (middle) and landward end of the estuary at 5.8m (bottom) for the non-dredged experiment (at cycle 5887) and dredged experiment (cycle 5200).

3.1.2 Estuary stability

Stability, for the purpose of this study, refers to the location of features within the estuary and the likelihood that they remain in that position without migrating. A "stable" estuary is one that maintains the same pattern of morphological features i.e. channels, bars and shoals remain in the same location over time.

Following each capital dredging a well-defined estuary shape emerges with a distinctive main channel, side channels, shoals and bars. The estuary retains the same dimensions and features remain in the same location in subsequent cycles. Indeed, the shape of the estuary maintains itself throughout the later cycles (apart from infilling of some of the crosses due to sill development). The main shipping fairway originally dug is clearly visible in the upstream and middle parts of the estuary even at 11000 and 13000 cycles several thousand cycles after last dredging and dumping events (Figure 32). This is particularly clear in the middle sections of the estuary where in the dredged experiment a very stable main channel, shoal and side channel form. At the seaward section of the estuary there is still high mobility and redistribution of sediment and flow and the system begins to revert back to a multi-channel system. The control experiment also sees the most migration and variation in the seaward sections where sediment and water mobility is highest.

Side channels are often non-migratory in the dredged experiment probably due to their use as typical dumping locations. Similarly, shoals often display great stability, remaining in the same locations throughout the experiment. When left undredged and undumped, side channels often silt up entirely in later cycles and are cut off at least at one end. Shoals often remain supratidal long after dredging finishes often sealing off any connecting or side channels surrounding them. The trend is for the estuary to silt up in both the landward and middle sections, whilst the action of the tides allows for mobility in the seaward section.

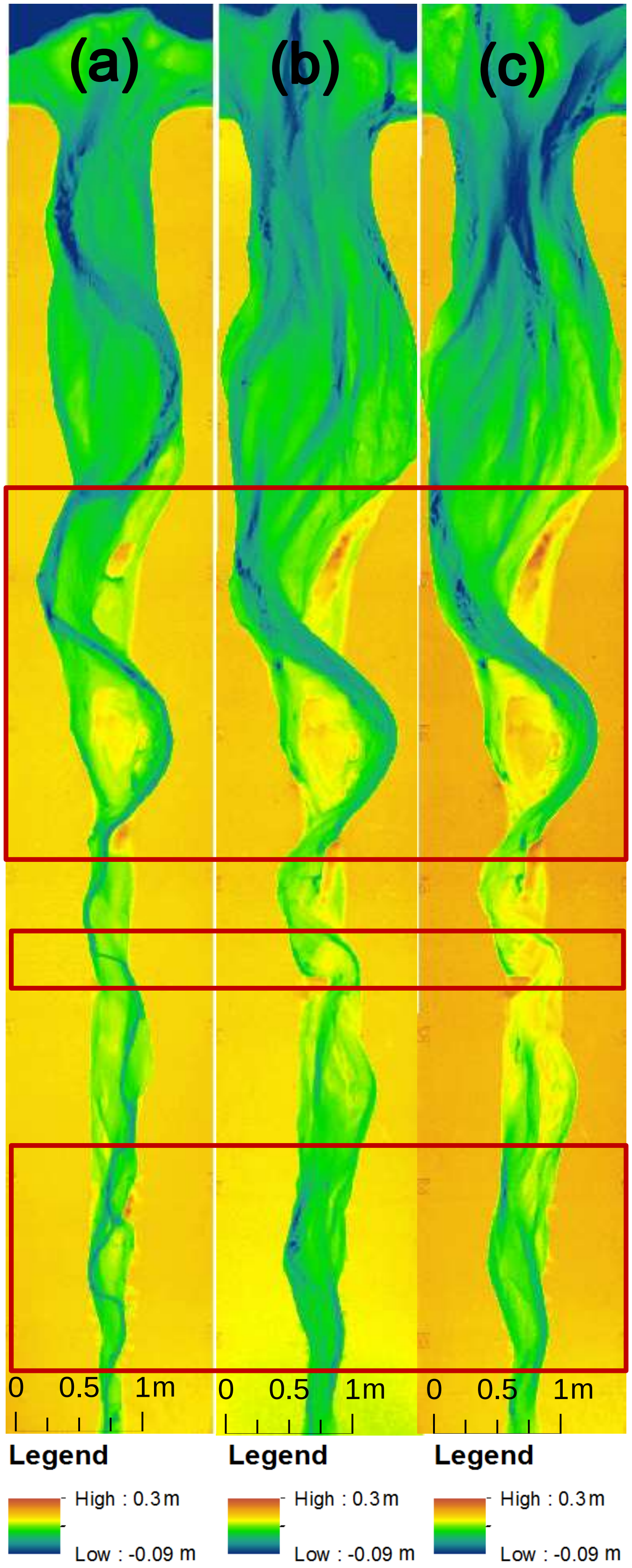


Figure 32: Estuary shape of the dredged experiment at (a) cycle 4600 (after CD2), (b) cycle 11000 and (c) cycle 13000. Red boxes indicate sections where cut channel can still be seen several thousand cycles after dredging and dumping have stopped.

3.1.3 Intertidal area, subtidal area and supratidal area

Figure 34 shows the change in supratidal, intertidal and subtidal area over time for both the dredged and non-dredged scenarios.

In the non-dredged experiment the subtidal area increases over time. Intertidal area initially decreases then increases before decreasing against towards the end of the experiment. The supratidal area follows a similar pattern. Over time there is relatively little variation in any of the areas (max $2m^2$).

In the dredged experiment subtidal area increases over time whilst intertidal and supratidal area both initially increase rapidly before decreasing towards the end of the experiment. The variation in area has a larger range than in the non-dredged experiment (max $5m^2$).

The absolute values for area indicate that the subtidal area is smaller due to dredging , intertidal area is similar in area and supratidal area is larger due to dredging. The trend due to dredging is to convert subtidal areas to intertidal areas by removing side channel area, then converting intertidal areas to supratidal areas due to dumping on these intertidal shoals. This effect is more severe in the upper and middle sections of the estuary as seen in Figure 33, whilst the seaward end of the estuary is still capable of mobilizing sediment due to the effects of the tides. However, the subtidal delta also becomes raised above the water level during low waters making it intertidal in parts.

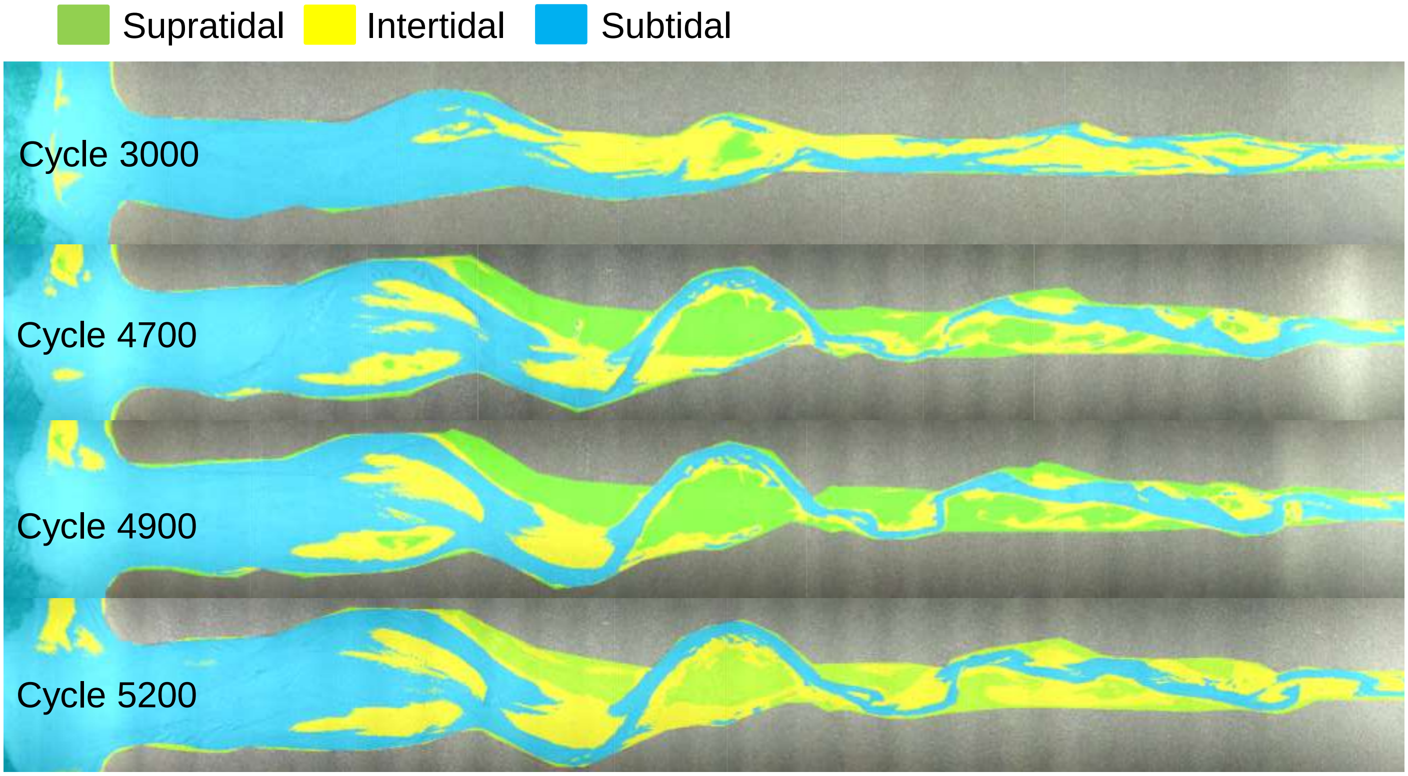


Figure 33: Change in supratidal (green), intertidal (yellow) and subtidal area (blue) for the dredged experiment at various time steps.

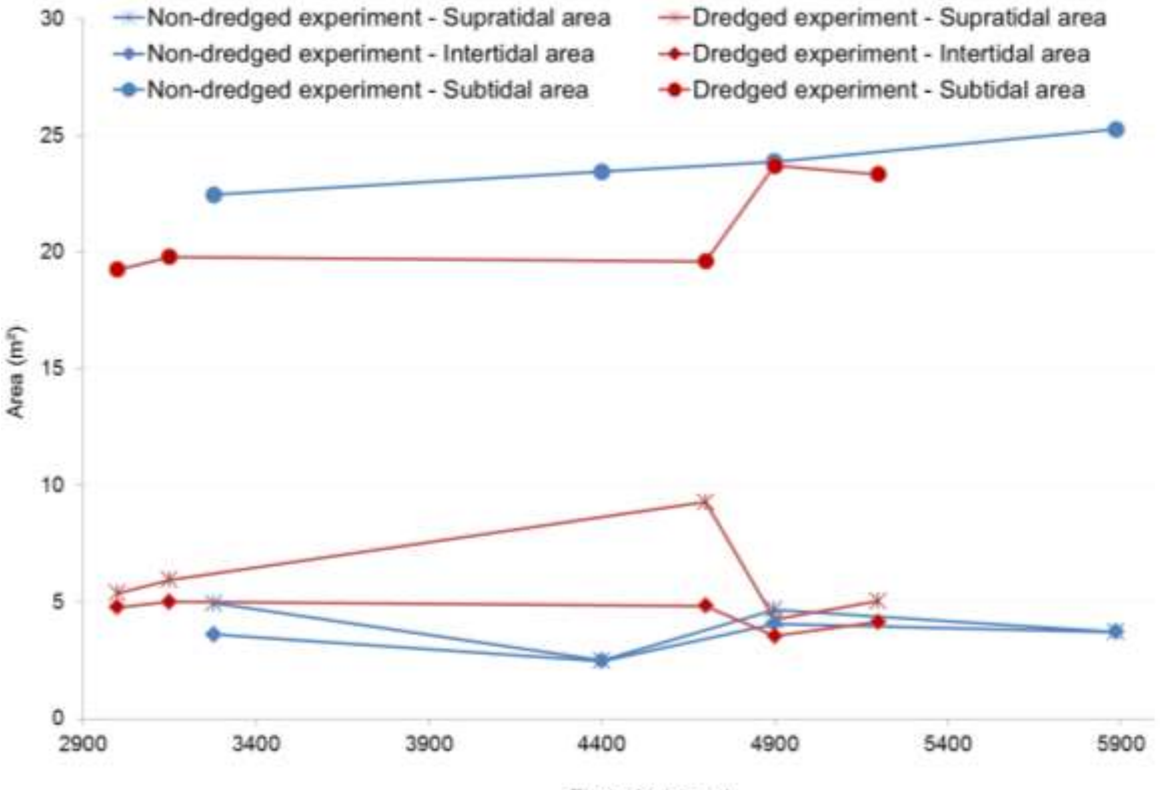


Figure 34: Change in supratidal, intertidal and subtidal area in both the non-dredged and dredged experiment over time

3.2 Medium scale effects of dredging and dumping

3.2.1 Main channel dimensions

The first capital dredging event created the “main channel” for this experiment which was maintained by successive maintenance dredging events. The path of this dredged main channel as compared with the non-dredged path can be seen in Figure 35. Along channel profiles of this main channel over various time steps can be seen below for both the non-dredged and dredged channels (Figure 36).

In the non-dredged experiment there is less variation in channel depth over time but there is variation in the along channel depth with various deeper sections and scours particularly in the later stages of the experiment (cycle 10915 for instance). Whilst both main channels show a deepening in the seaward direction, the effect of this is more severe in the non-dredged case. The depth variation over time is much greater in the dredged experiment, but the channel displays a lower range of depth along channel (less scours and pits) than the non-dredged experiment. During dredging (cycles 3300, 4600 and 4900) the main channel maintains its minimum target depth of -0.03m. When left to proceed without dredging or dumping the channel becomes highly variable in depth and begins to return to a shallower more variable channel like in the non-dredged experiment.

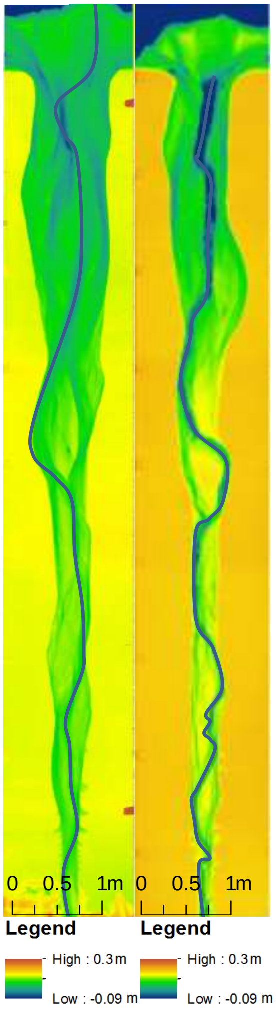


Figure 35: Main channel course in both the non-dredged (left) and dredged (right) experiments.

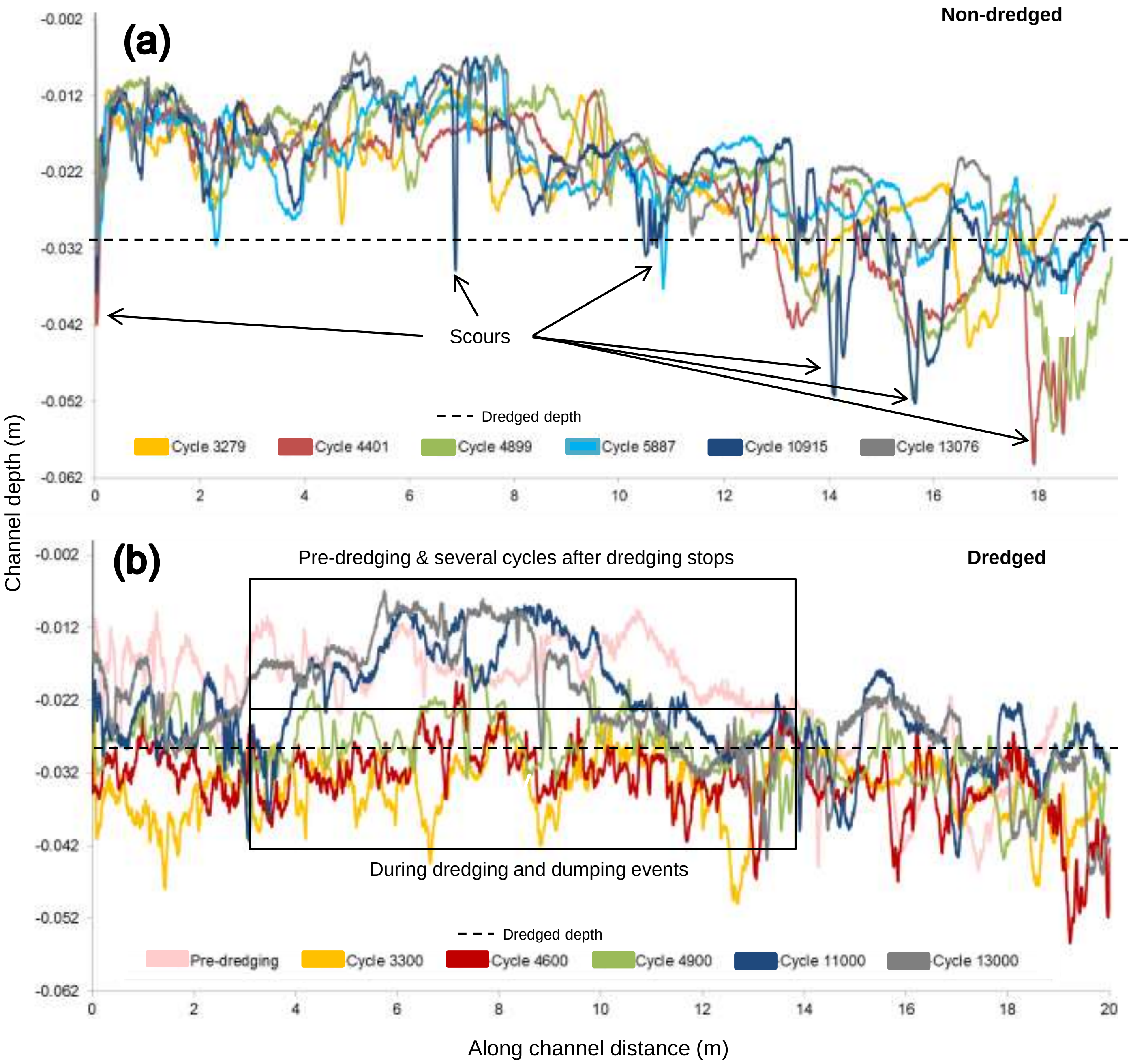


Figure 36: Along channel profiles of channel depth for (a) the non-dredged experiment and (b) the dredged experiment.

When the average depth of the channels over time (Figure 37) is compared it becomes clear that the tendency and trend of the dredged main channel is to infill and shallow at a more rapid rate than in the non-dredged experiment. To reiterate, both experiments are closed systems i.e. there is no fresh sediment input in either case, with the exception of the banks as previously mentioned. However, the movement of material in the dredging and dumping scenario leads to a channel with a quicker rate of infill over time.

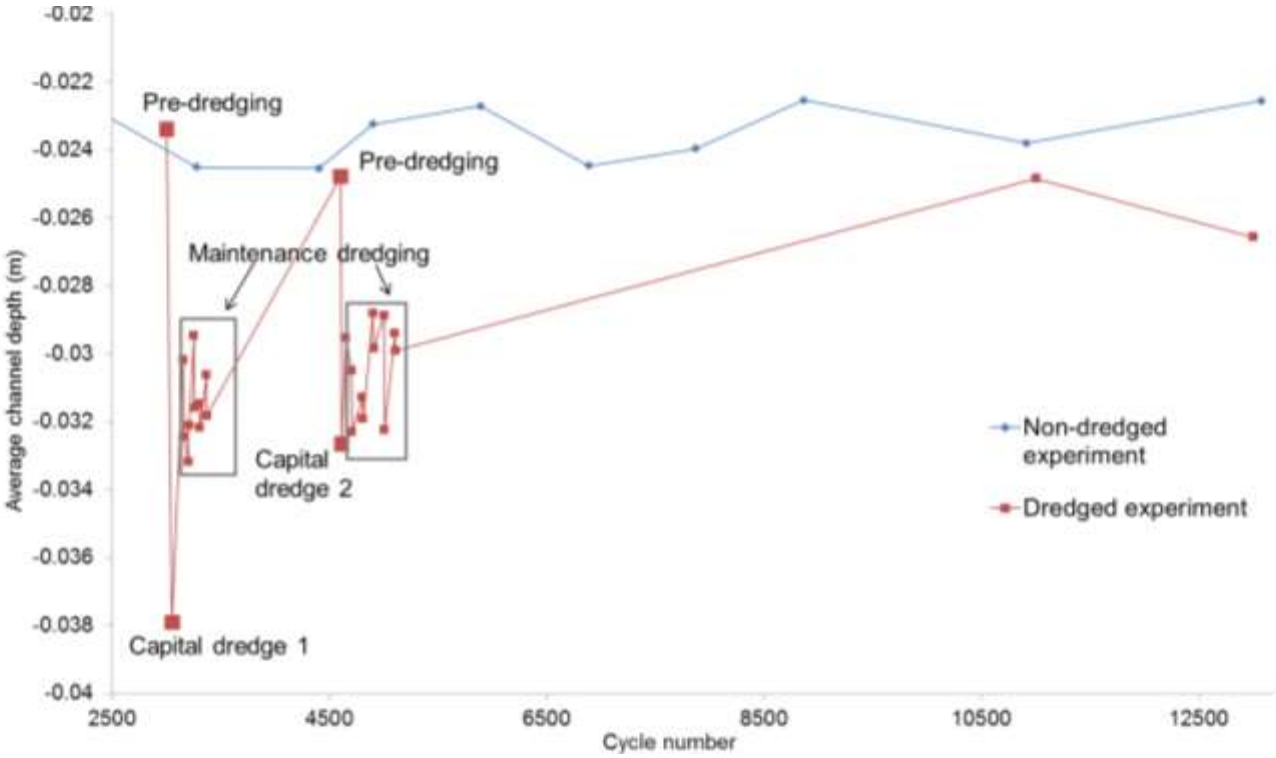


Figure 37: Average channel depth of the main channel over time for the dredged and non-dredged experiments.

When looking at individual dredging and dumping events in the dredged experiment (see Figure 38) it is clear that earlier in the experiment (following the first CD) dredging works to remove shallower sections (peaks) from the main channel to create a more uniform curve at the target minimum depth of -0.03m. For deeper sections of this main channel that go undredged, these shallow after dredging and dumping events which again causes a move towards a more uniform along channel curve.

With the shipping fairway of the wider estuary, formed by the second capital dredge (CD2) the effect of dredging and dumping is once more to remove high peaks i.e. shallow sections of the main channel. However, the deep sections of the channel do not shallow/fill in at the same rate; instead they shallow slower or remain at the same depth. This means that instead of the more uniform main channel given by the dredging and dumping of the narrower estuary, in the case of the wider estuary there is channel at the target depth of -0.03m with some much deeper sections (-0.04m to -0.055m).

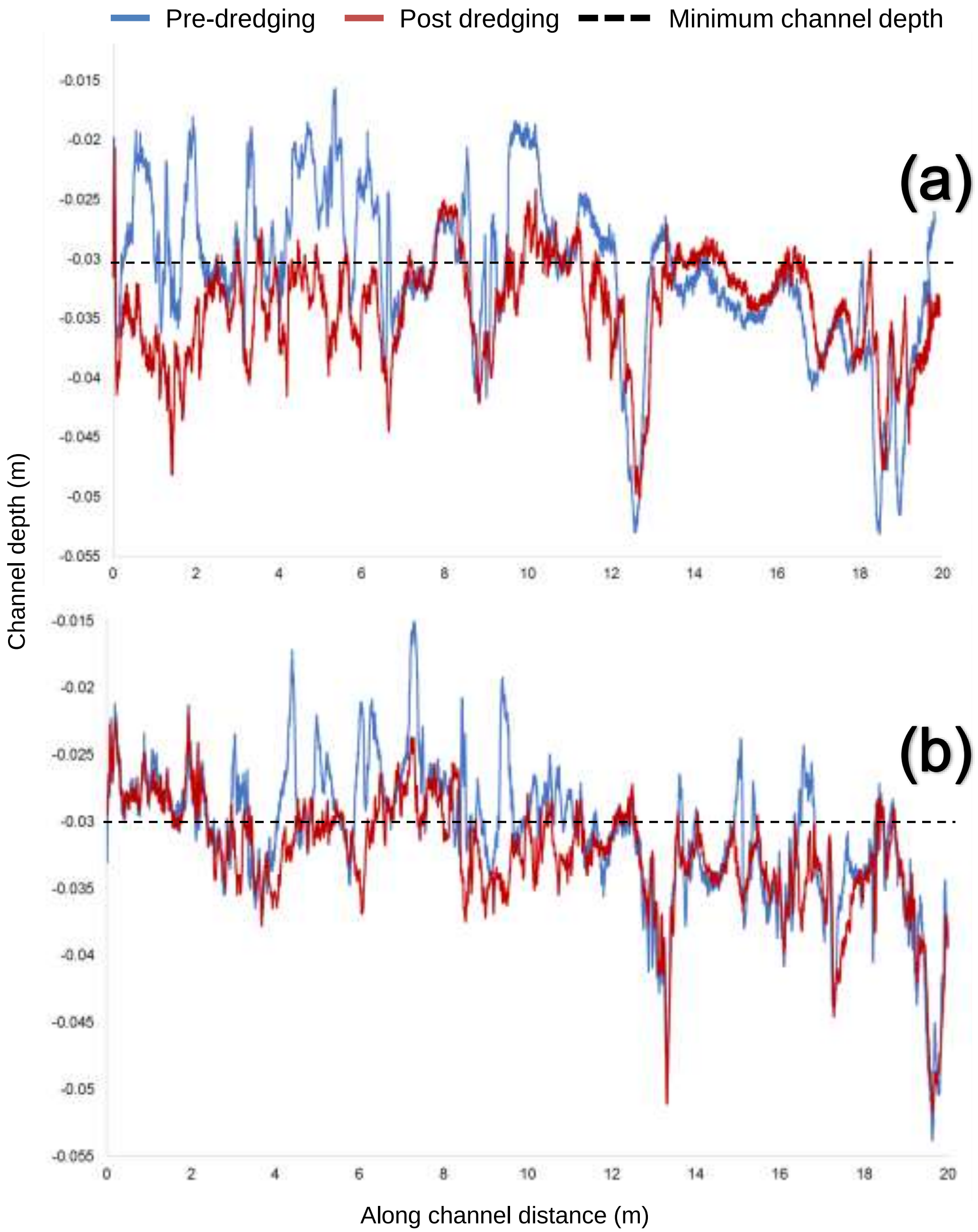


Figure 38: Along channel profiles of the main channel immediately before and after a maintenance dredging and dumping event for (a) the first capital dredging event and (b) the second capital dredging event.

3.3.1 Water levels

In the non-dredged experiment water levels in the main channel (Figure 39a) display a sinusoidal wave, with variation around the still water level. There are small differences over time in the absolute values of water levels (this may be due to inaccuracies in the measurements or actual differences due to changing channel planform) but the pattern of the wave (period, amplitude and frequency) remains similar over time.

Dredging alters the period, amplitude and frequency of the tidal wave and alters overall water levels. The water levels in the dredged experiment are shown in Figure 39b. There is an increase in frequency due to dredging. The water levels in the main channel increase due to dredging and continue to show a stepwise increase until dredging stops (cycle 5200). The amplitude of the tidal wave is clearly increased due to dredging. The shape of the tidal wave becomes more asymmetric and tends further towards ebb dominance than before dredging occurred. The ebb flow also increases in duration whilst flood duration stays constant.

In the non-dredged experiment the water levels in the side channels (Figure 39c) also show a sinusoidal pattern. They show larger variations in water level than the main channel with several extreme peaks (again however, this may be caused by the water level sensors). Resembling the main channel, it also shows some variation, however this variation is stronger than in the main channel. Unlike the dredged experiment, water levels for the non-dredged case were not taken over a clearly defined “main” and “side” channel, therefore variation in values may also be caused by this.

Evaluating the water levels in the side channels for the dredged experiment (Figure 39d), a similar pattern to the main channel emerges. Once more, dredging causes an increase in frequency and period. Similar to the main channel the side channel also exhibits a large increase in water levels. The tidal wave is once more increased due to dredging. There is a tendency once more to increase ebb dominance however, the effect is less severe in the side channels. Ebb and flood duration increase.

3.3.2 High water, low water and tidal range

Figure 40 displays the high water, low water and tidal range data for the main and side channels in the dredged and non-dredged experiments.

In the non-dredged experiment, high water, low water and tidal range all display a slight decrease over time in the main channel. In the side channel low water increases over time, tending from minus figures to close to the zero or still water mark. High water decreases over time also, leading to a decreased tidal range in the side channels over time in the non-dredged experiment.

In the dredged experiment, high water and low water increase over time in the main channel. Tidal range increases over time until dredging stops and after dredging stops it begins to decrease. In the side channel, high water and low water also both increase over time with the same pattern in tidal range as the main channel. The measurements taken at cycle 4900 show a large excursion from the rest of the data, this is likely a measurement issue or a problem with measuring still water levels.

Overall, the dredged experiment shows higher high water values and lower low water values than the non-dredged experiment in both the main and side channels. Tidal range is greater in the main channel due to dredging but smaller in the side channels.

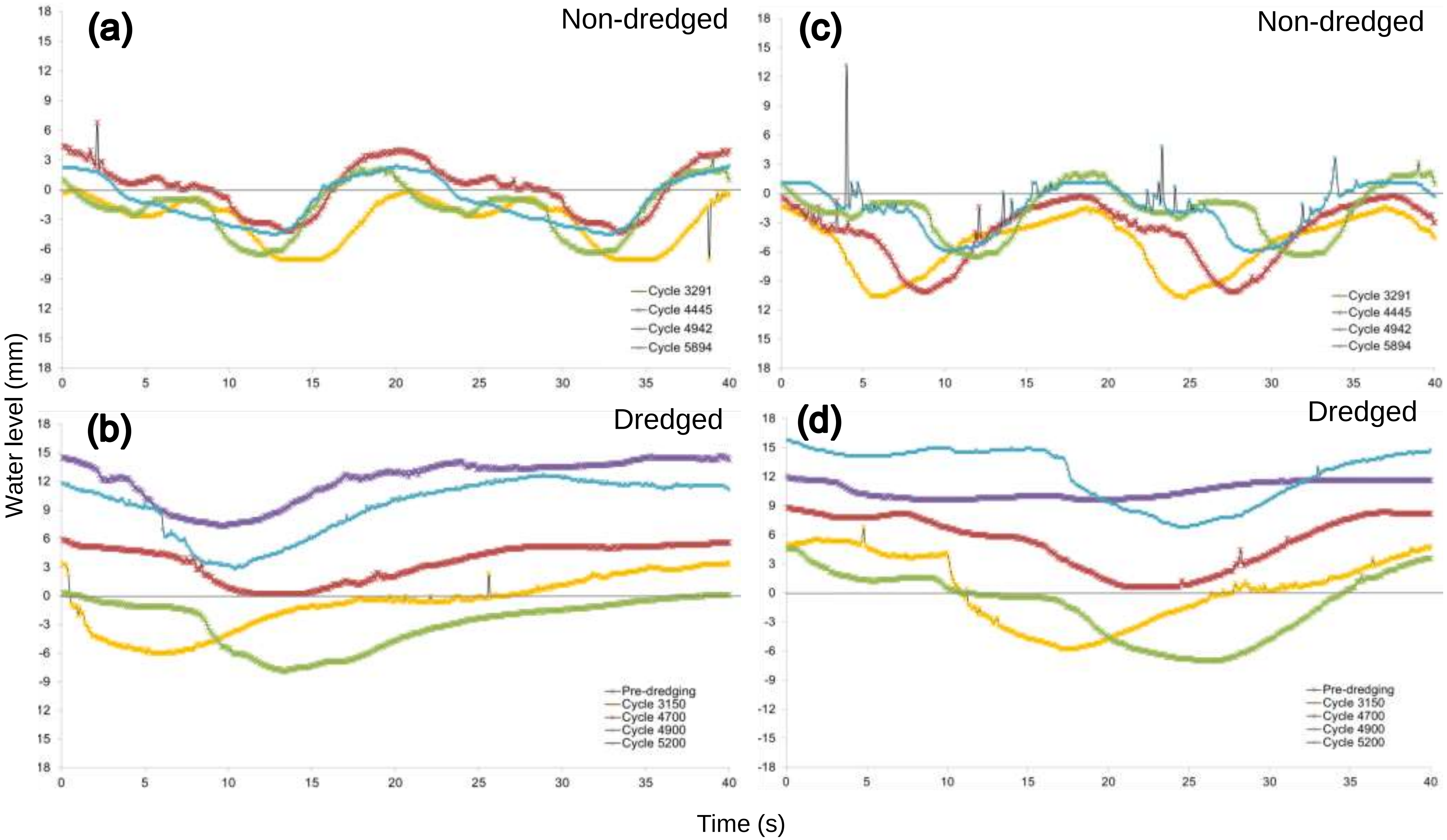


Figure 39: Water levels for (a) the main channel over 1 tidal cycle (40 seconds) for the non-dredged experiment, (b) the main channel over 1 tidal cycle for the dredged experiment, (c) the side channels over 1 tidal cycle for the non-dredged experiment and (d) the side channels over 1 tidal cycle for the dredged experiment.

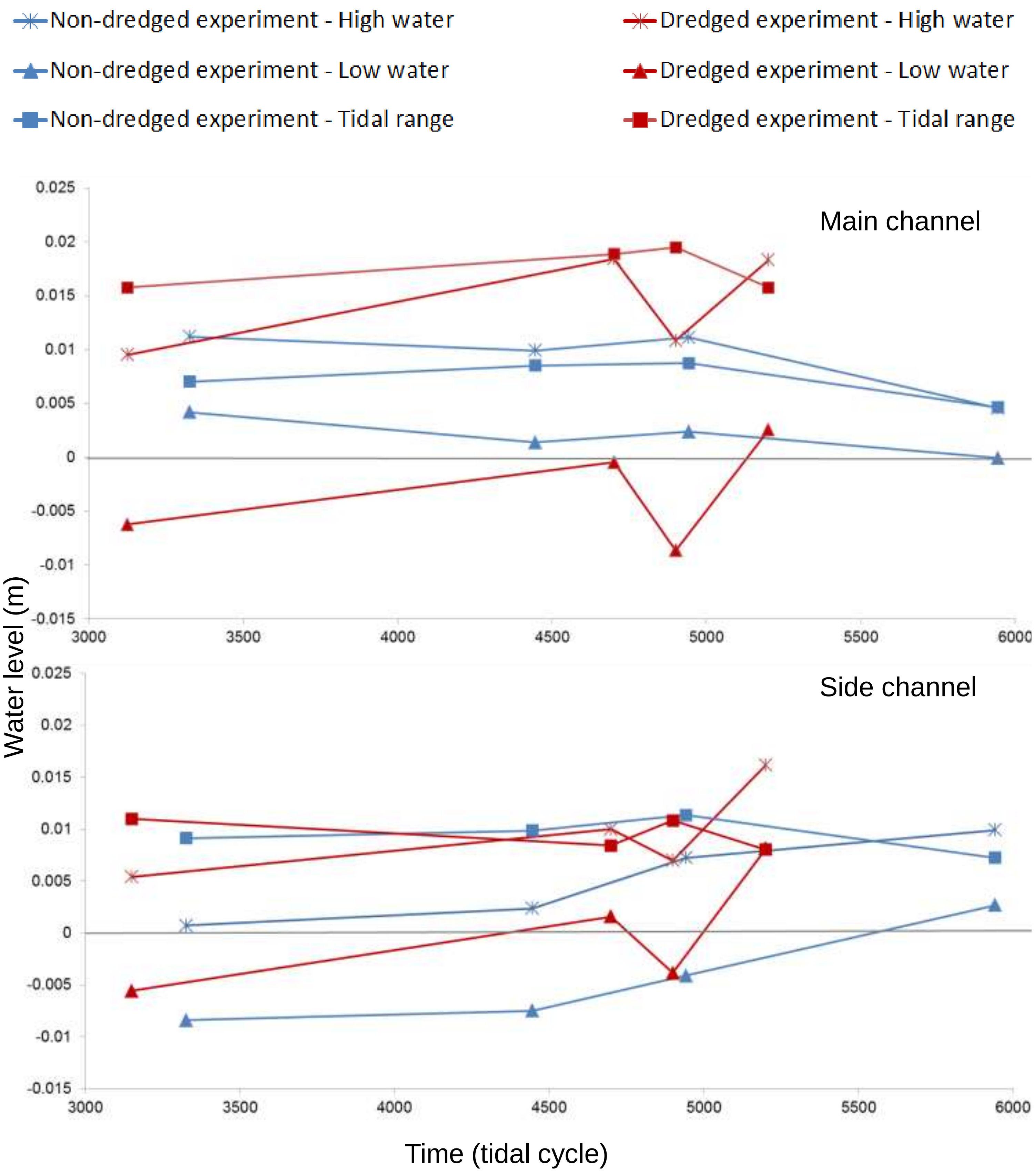


Figure 40: High water, low water and tidal range data for main channel (top) and side channels (bottom) for the non-dredged and dredged experiments.

3.5 Small (feature) scale effects of dredging and dumping

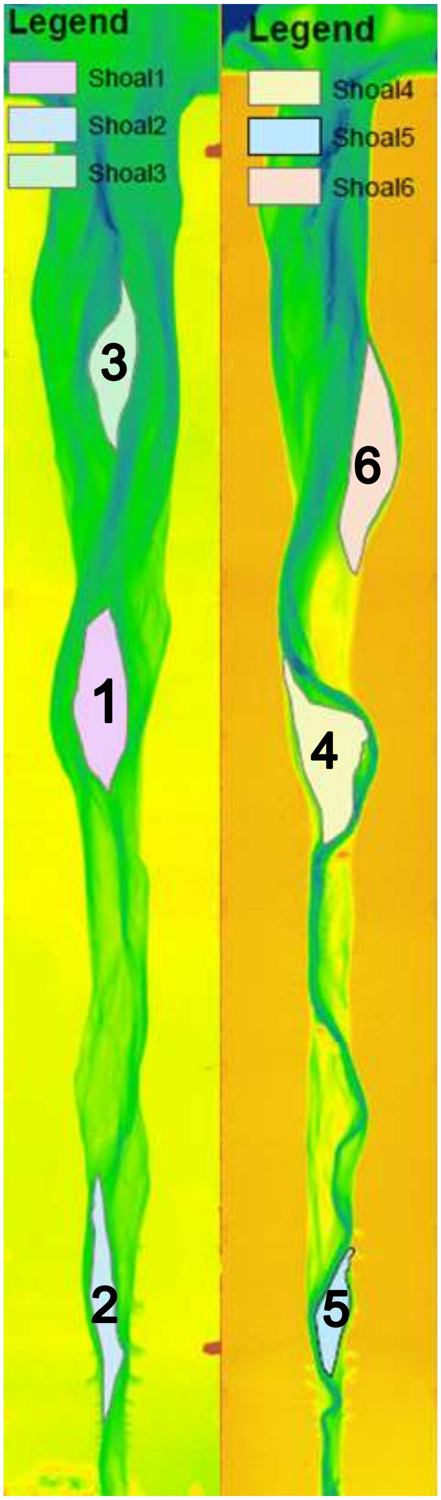


Figure 41: Map showing locations of 6 studied shoals with shoals 1,2,3 being part of the non-dredged experiment and shoals 4,5,6 being part of the dredged experiment.

3.5.1 Response of the shoals

6 shoals were chosen and compared, 3 from this experiment (with dredging and dumping) and 3 from the control experiment (no dredging and dumping). Of these shoals 2 upstream, 2 middle and 2 downstream shoals were compared (Figure 41).Shoals are a key dumping location used in the Western Scheldt and other estuaries worldwide as outlined in chapter 1. However their response to dumping is highly variable and unpredictable. The response of these shoals to dredging and dumping is an important factor when attempting to maintain a multi-channel system. The goal of dumping on these shoals is to allow redistribution of flow and sediment. The following section looks at the response of the shoals to determine how their use as dumping location affects their morphology in particular shoal height and volume.

3.5.2 Average heights of the shoals

For the shoals in the middle of the estuary, the average height of shoal 4 (which had been used as a dumping location) was up to 0.007m higher than shoal 1 (no dredging and dumping). In the case of the upstream shoals during the initial capital dredging and maintenance dredging events (cycles 3100-4000) shoal 5 (used as a dumping location) had a higher average height than shoal 2 (no dredging and dumping). However, for the second capital dredge and maintenance dredges and for the remainder of the experiment shoal 2 (no dredging and dumping) had a higher average height than shoal 5. In the case of the downstream shoals, shoal 6 (experienced dumping) consistently remained higher than shoal 3 (no dredging or dumping) with an average difference of 0.03m.

3.5.3 Cross sections of shoals

Cross sections were purposely taken upstream of dumping locations (and not cross cutting dumping locations) to avoid very high ranges and to analyse any shoaling that took place. Dumping was purposely undertaken on the seaward side of shoals with the goal of inducing shoaling. These cross sections are shown in Figure 44 & Figure 45 (p.51-52).

Shoal 1: Located in the middle of the estuary – non-dredged experiment

The shoal (Figure 44a) was at its highest elevation at the beginning of the experiment (cycle 3279). The shoals increased in elevation towards the end of the experiment (cycles 10915 &13076) but decreased in width leading to a higher narrower shoal towards the end of the experiment. After the initial higher narrower shoal at cycle 3279 the shoal stabilized and remained the same elevation and gradually increased (around 0.05m per 1000 cycles) in width until halfway through the experiment (cycle 7869) after which point there was a stepwise decrease in width (around 0.1m per 1000 cycles) and an increase in shoal height until the termination of the experiment.

Shoal 2: Located upstream – non-dredged experiment

Similar to shoal 1, this shoal (Figure 44b) was at its highest elevation at the beginning of the experiment (cycle 3279). However, unlike shoal 1, this shoal remains at this high elevation for the succeeding cycles until the experiment reaches cycle 6884 at which point the elevation of the shoal and the width of the shoal decreases. The width decreases again in a stepwise fashion from at a rate of 0.7m per 1000 cycles. The exception to this is cycle 8863 which sees a very low elevation shoal (-0.017m versus the average -0.0125m). Towards the end of the experiment the shoals are averagely lower in elevation and at the final stages of the experiment (cycle 13076) the shoal dramatically increases in width again (returning to 0.3m wide).

Shoal 3: Located downstream – non-dredged experiment

Juxtaposed with shoal 1&2 shoal 3 (Figure 44c) has its lowest and narrowest shoal at the beginning of the experiment (cycle 3279). The shoal then increases in both height and width or the succeeding 2000 cycles until cycle 5887 whereby the shoal shows a decreased width (from around 0.9.m to now 0.55m). After this point the width and height of the shoal remain stable until the end of the experiment with the exception of cycle 6884 which sees a wider shoal (0.8m) but a decreased elevation.

Shoal 4: Located in the middle of the estuary – dredged experiment

Shoal 4 (Figure 45a) experienced dumping during 8 out of 10 of the maintenance dredging events that took place on the estuary. Dumping on the shoal lasted from cycles 3150 – 4900. The overall elevation of the shoal is much higher than in the non-dredged experiment with an average height of -0.0025m as compared with -0.001m. The curves are much more uniform with the shoal staying at the same elevation and width for the whole experiment except for cycle 3200 which sees a much lower elevation than all the other cycles (average of -0.01m). This may be due to the lower amount of sediment dumped on the shoal following maintenance dredge 1 (at 3150 cycles), as all succeeding cycles have very large amounts of sediment dumped on the shoal.

Shoal 5: Located upstream – dredged experiment

Shoal 5 (Figure 45b) experienced dumping for 5 out of the 10 maintenance dredging events that took place. Most of the dumping took place in the first 3900 cycles on the narrower estuary formed after the first capital dredging event. Like shoal 4, shoal 5 showed near identical curves for most of the experiment with a uniform width and elevation. This is altered when the estuary becomes wider (immediately prior to the second capital dredging event at 4602 cycles) giving a lower elevation shoal, but one of the same width. When the experiment is allowed to progress without dredging and dumping the shoal decreases in elevation due to erosion and eventually by 13076 cycles is bisected by a side channel and becomes much smaller. The average height of the shoal is -0.0125m which is the same average as the upstream shoal in the non-dredged experiment. However, in the dredged experiment the shoal remained far more stable and showed less lateral variation in elevation than the non-dredged experiment.

Shoal 6: Located downstream – dredged experiment

Shoal 6 (Figure 45c) experienced dumping for 6 out of the 10 maintenance dredging events that occurred. This was spread evenly over the narrower and wider estuary. Unlike shoals 4 & 5, this shoal shows more variation in elevation and width. At 3150 cycles the shoal is wide and low with an average elevation of -0.015m. However, after maintenance dumping occurs on the shoal at 3200 cycles, the shoal becomes higher (-0.01m) and loses some of its width (going from 0.6m to 0.45m). The shoal then erodes back to the same dimensions as cycle 3150 with the absence of maintenance dumping between cycles 3200 and 3300. The shoal stabilizes at this elevation and width until the second capital dredging takes place and the estuary becomes wider. At 4602 cycles (before capital dredge 2 takes place) the shoal becomes elevated above water level in parts with an average elevation of 0m and becomes less wide. This changes however after the second channel is cut and the shoal returns to an elevation of -0.01m but is narrower than in earlier cycles. It retains these dimensions through cycles 4700-5100. However, in the later cycles when the estuary has been allowed to progress without dredging and dumping, the shoal splits and a much narrower higher shoal is formed (0.15m wide and average elevation of -0.075m).

3.5.4 Summary of the morphological response of the shoals & effect of sedimentation

In the dredged experiment the upstream shoals often remained above water level and were eroded much more slowly than those downstream. Shoals become more stable i.e. they retain the same dimensions when they are used as dumping locations. When allowed to progress without dredging or dumping the shoals in the upstream of the estuary naturally erode and lost elevation (reverting back to pre-dredging dimensions), becoming flat and wide quickly after the dredging and dumping stops. Those in the middle of the estuary do not see the same effect, as the shoal becomes so stable that even when dredging and dumping does not occur it maintains its elevation and width. Those downstream react sensitively to changes in dredging and dumping regime.

Cross sections of the shoals showed that some shoals experienced erosion when dumping is temporarily stopped, whilst others experienced sedimentation. When the volume change of the shoals is compared with dumping volumes (Figure 46) it is clear that there is a balance between erosion, sedimentation and dumping. There is no direct correlation with the amount dumped and the volume change of the shoals. Instead there is a complex range of processes occurring which are dependent on location within the estuary. For shoal 4 which is located in the middle of the estuary, the volume of the shoal initially increases and then stabilizes regardless of dumped amount. However, when dumping stops completely, the shoal begins to erode rapidly.

Shoal 5 which is located upstream shows a relatively constant volume over time with slight increases in volume following large dumping events. Again when dumping ceases, the shoal begins to erode rapidly, however it does this at a slower rate than the shoal in the middle of the estuary.

Shoal 6 which is located downstream shows a large increase in volume after the initial dumping events. But then begins to erode regardless of dumping volume. Erosion becomes focused on the shoal whilst dumping occurs. When dumping stops, the shoal stabilizes at the same volume.

Figure 46 depicts the change in shoal volume compared with dumped volume. It is clear that the response of shoals is highly variable. At the seaward end dumping focuses erosion on the shoals, whilst upstream it generally works to encourage sedimentation.

Figure 42: Supratidal shoal elevated above high-water level upstream.

Figure 43: Intertidal shoal located at the seaward end.

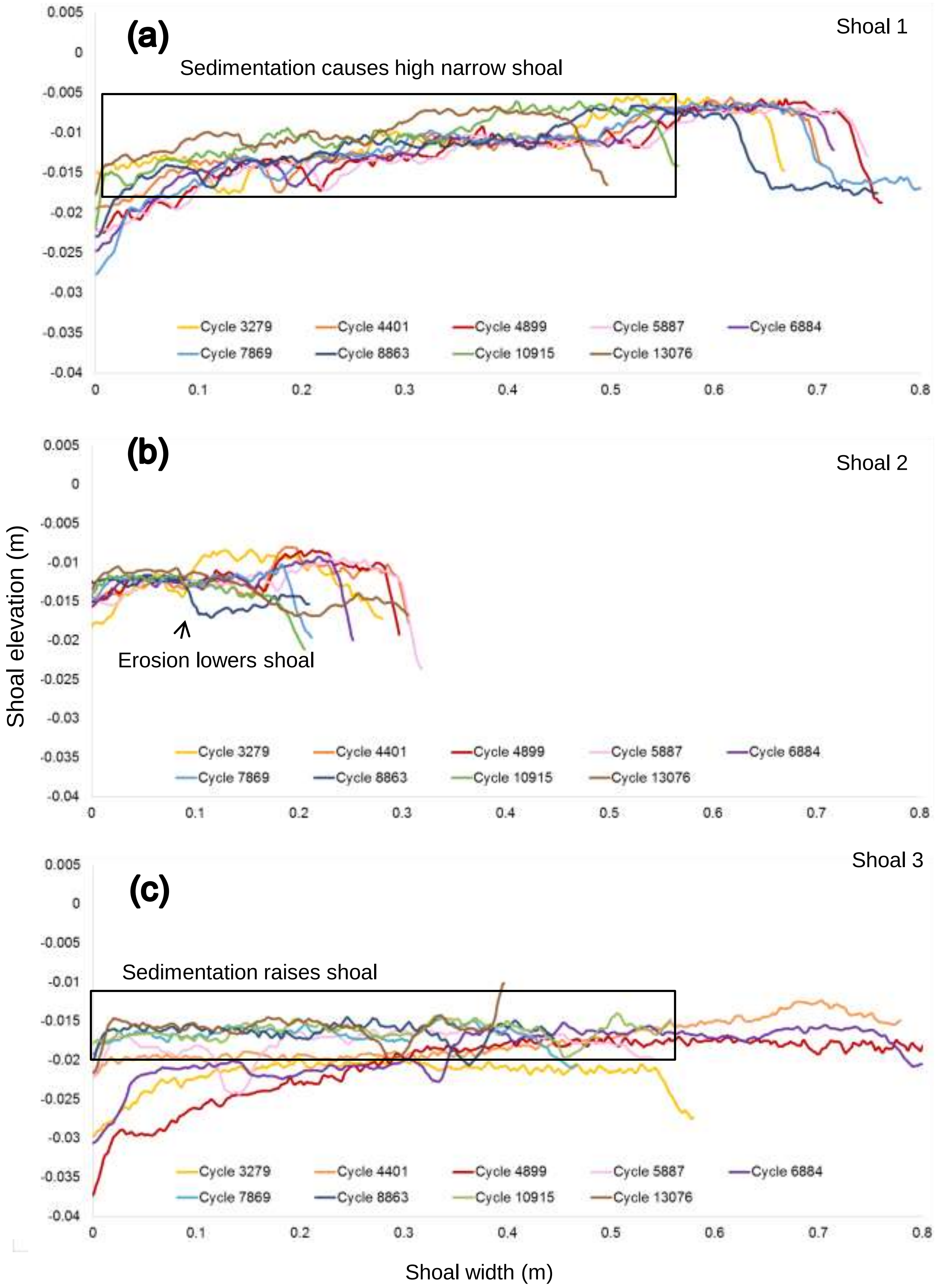


Figure 44: Cross sections of shoals over time for the non- dredged experiment (a) shoal 1, (b) shoal 2 and (c) shoal 3.

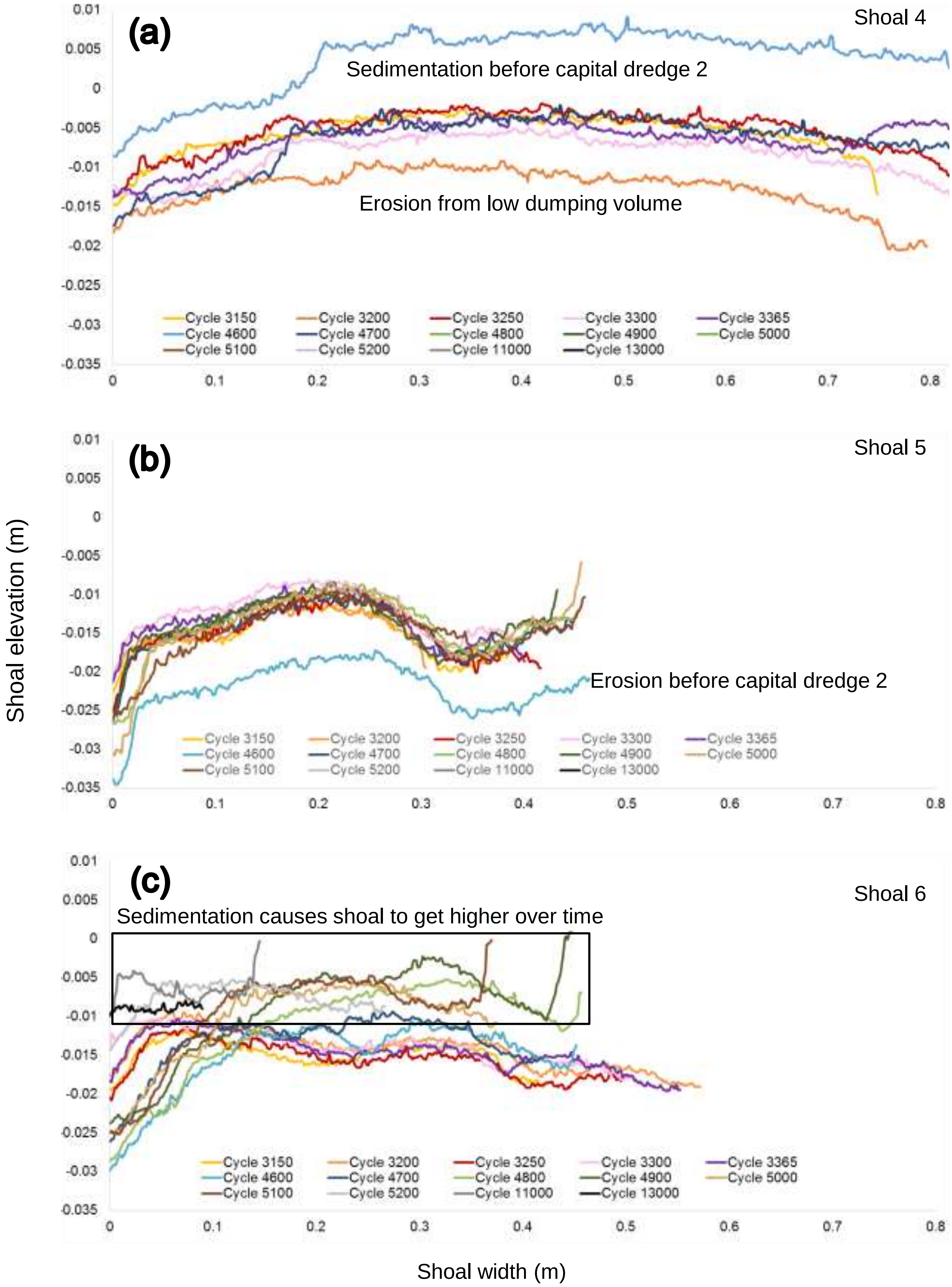


Figure 45: Cross sections of shoals over time for the dredged experiment (a) shoal 4, (b) shoal 5 and (c) shoal 6.

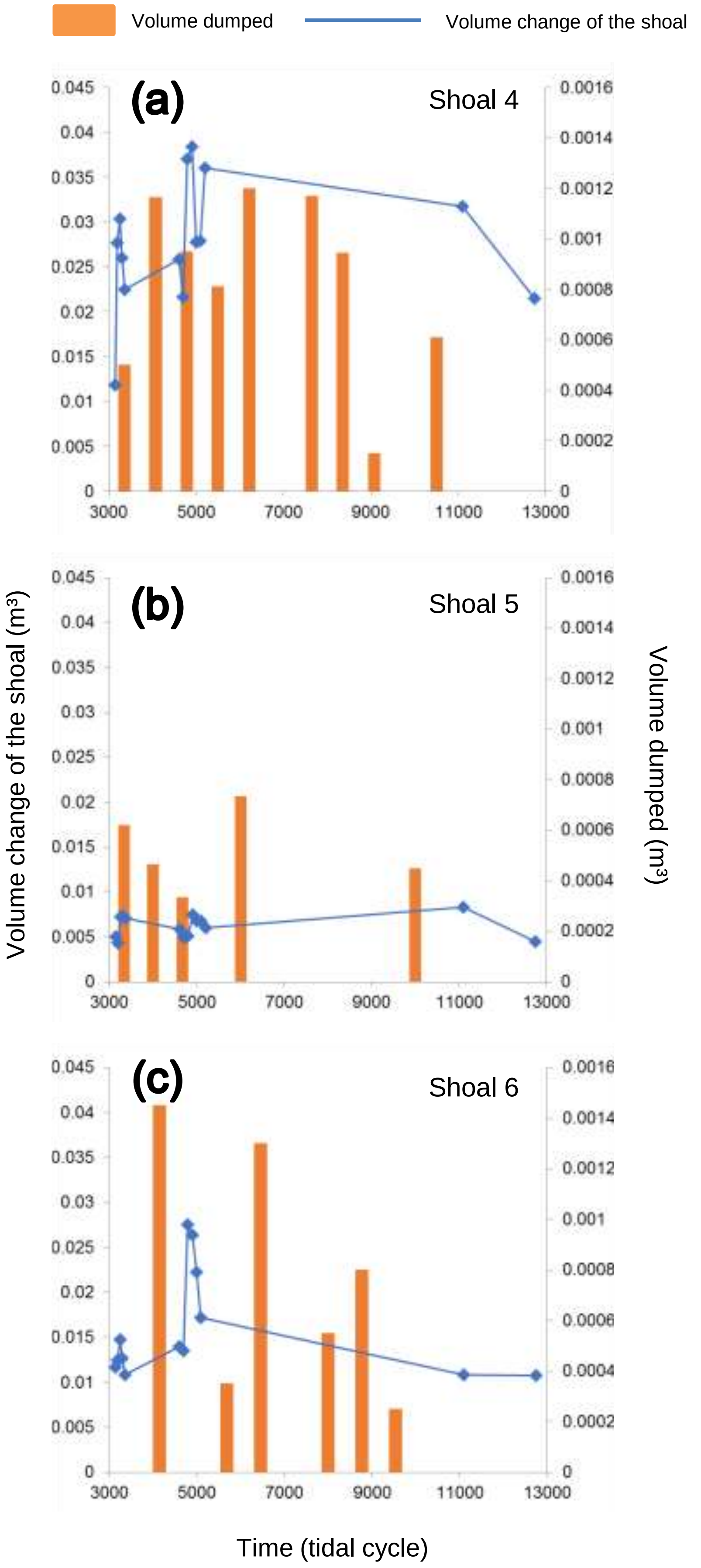


Figure 46: Dumped amount and change in shoal volume over time for the 3 studied shoals from the dredged experiment where (a) shoal 4, (b) shoal 5, (c) shoal 6.

3.5.5 Reaction of the side channels

Figure 47 depicts the different types channels present (main, side and connecting) in both the non-dredged experiment and dredged experiment. In the non-dredged experiment the channel system represents a typical Western Scheldt pattern, as described by Van Veen (1948) with large dominant ebb meanders and short straight flood side channels. The pattern becomes far more erratic and less predictable in the dredged experiment. Side channels are often cut off due to dumping or become blocked.

In the control experiment the number of side channels remains constant over time (Figure 48a) however the percentage area of the estuary occupied by the side channels varies over time with no discernible pattern. The average depth of the side channels remains relatively constant apart from cycle 4489 which sees the averagely deepest side channels.

In the dredged experiment, the initial effect of the dredging of the main channel is to decrease the number and percentage area of the side channels in the estuary (Figure 48b). However, after the second capital dredge (when we move towards a wider estuary) the number and percentage area of the side channels increases again. The average depth of the side channels is much shallower in the narrower estuary situation than in the wider estuary situation which sees deeper side channels.

When both experiments are juxtaposed, the percentage area of the side channels (relative to overall estuary size) in the dredged experiment is considerably lower (range of 6%-16%) than the non-dredged experiment (range of 11%-21%). Despite this, the number of side channels does not vary greatly between the two experiments; in the dredged experiment from cycle 4700 until cycle 13000 in particular the number of side channels are very similar to the non-dredged situation. The average depth of the side channels is greater in the non-dredged situation (range of -0.0175m to -0.028m) whilst dredging and dumping causes averagely shallower side channels with more consistent average depth (range of -0.015m to -0.023m).

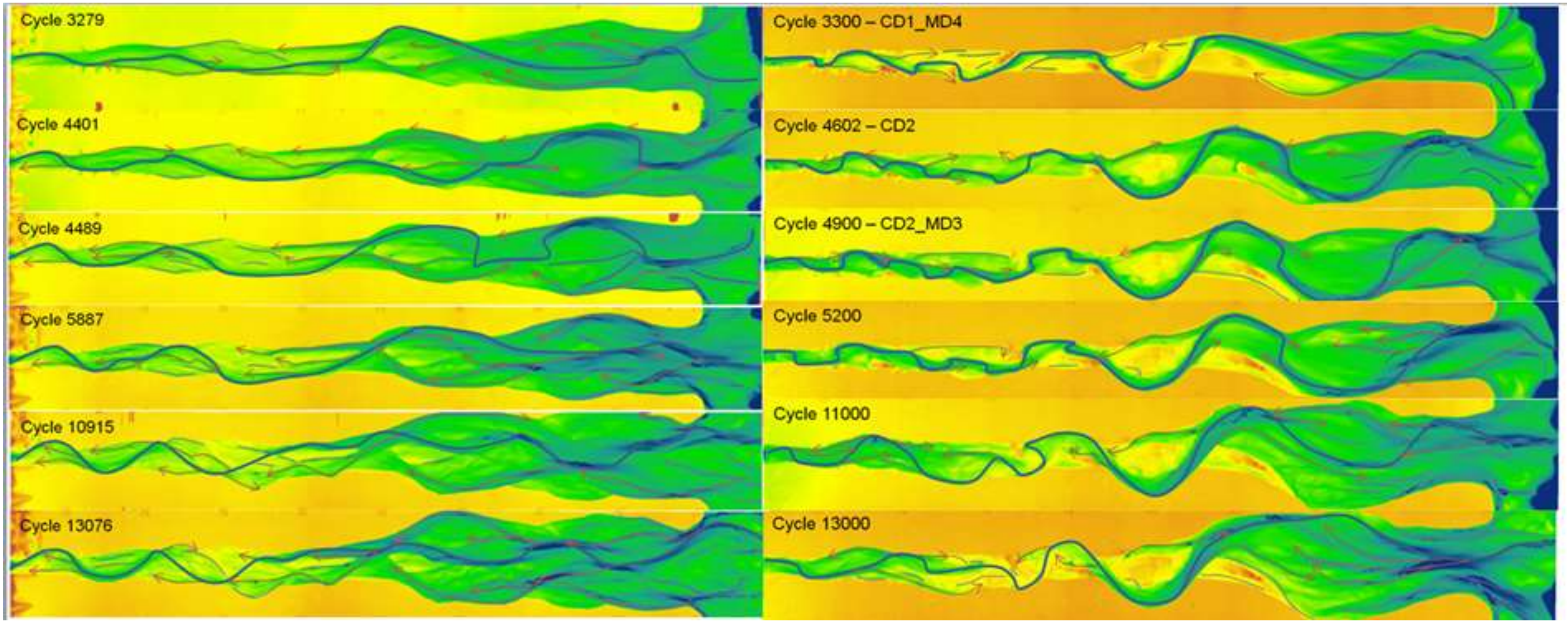


Figure 47: DEMs with marked main channels (blue) and side channels (red) for both the non-dredged experiment (left) and dredged experiment (right).

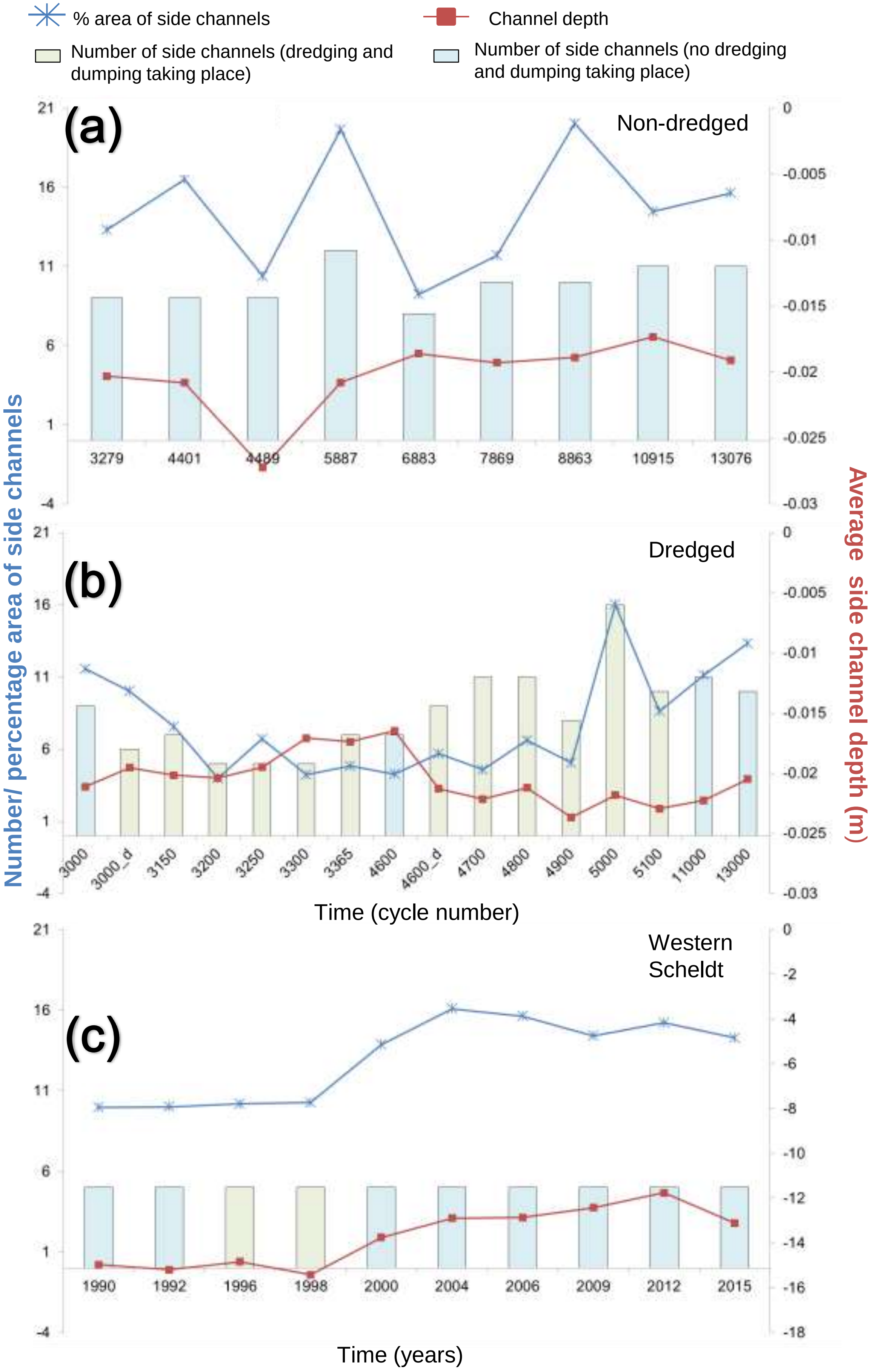


Figure 48: Number of side channels, percentage area of side channels and average depth of side channels over time for (a) the non-dredged experiment (b) the dredged experiment and (c) the Western Scheldt.

3.5.6. Scours and rate of infilling

Scours that were used as dumping locations were analysed to identify how quickly sediment was removed from these locations. The rate of removal of sediment after dumping is shown in Figure 49. The range of rate of removal is -0.13325cm³/s to +0.2305cm³/s meaning that scours both saw sediment removal over time but some of these areas actually acted as sediment traps to increase sediment volume after dumping. More scours gain sediment than remove sediment however, the response is too variable to show a trend in either direction.

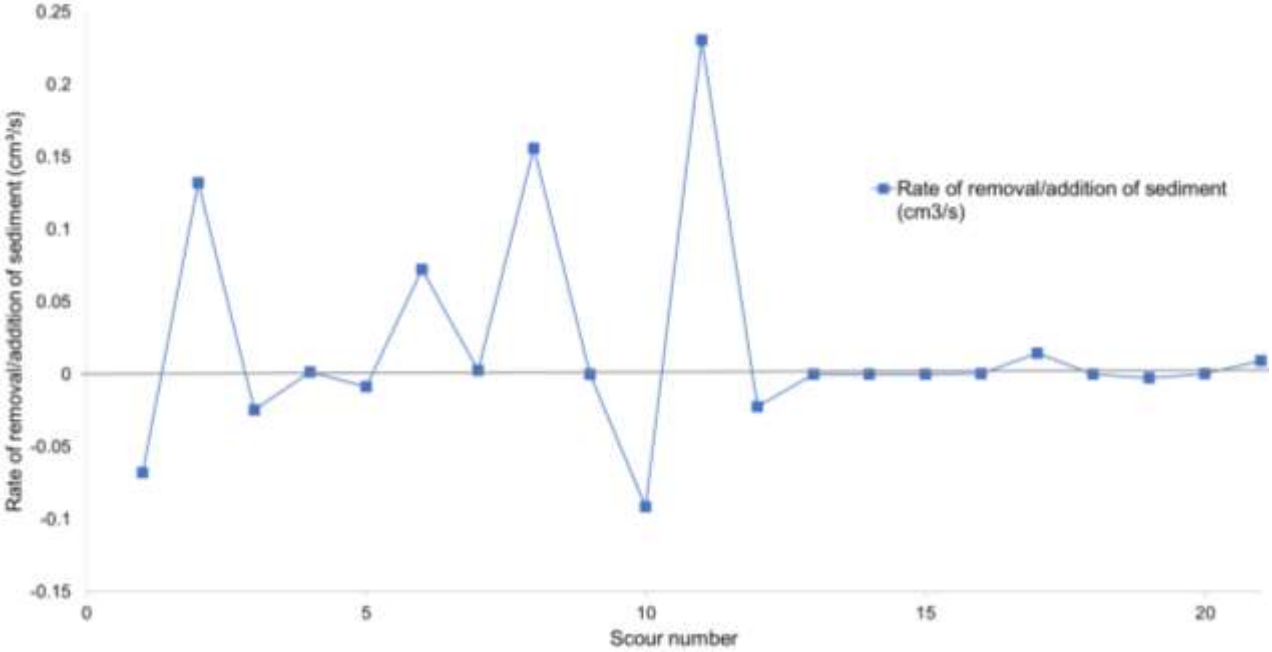


Figure 49: Change in rate of removal/addition of sediment in the scour holes used as dumping locations, each scour is assigned a number scours with earlier scour numbers used as dumping locations earlier in the experiment and later numbers used later in the experiment.

Many factors may influence the unpredictable response of these shoals. Three factors were tested for correlation with the follow hypotheses (Figure 50):

1. The amount of sediment dumped determines whether there is erosion or sedimentation
2. The time during the experiment when the scour was used as a dumping location determines whether there is erosion or sedimentation
3. The area of the scour determines whether there is erosion or sedimentation

Whilst none of these factors show strong correlations (note low R² values) some generalizations can be drawn from the data. Most likely it is the interaction of these processes that determines erosion or sedimentation which is why no one factor shows strong correlation.

The more sediment dumped in the scour the more likely it is to attract sediment and increase in volume. Small dumping volumes allow for the sediment to be removed and eroded. It is likely there is a threshold volume of dumped material however this was not quantifiable for this experiment as there is a lack of information about sediment budgets and sediment transport.

The capacity for the scours to erode also increases with time. Those scours used as dumping locations later in the experiment were more likely to remove sediment than those used as early dumping locations.

Larger scour holes were also more likely to erode than smaller scour holes. This indicates that the “best” scour holes to use as dumping locations were those with a large area, with smaller dumping amounts later in the experiment. Again, there is likely a threshold size to dumped material ratio for these scours. Yet, when looking at Figure 51 which shows the relative percentage of sediment dumped to the total volume of the scour and how this compares with the rate of removal/deposition, there is no discernible pattern to indicate that the amount dumped relative to the size of the scour plays any role in whether the scour fills in or erodes.

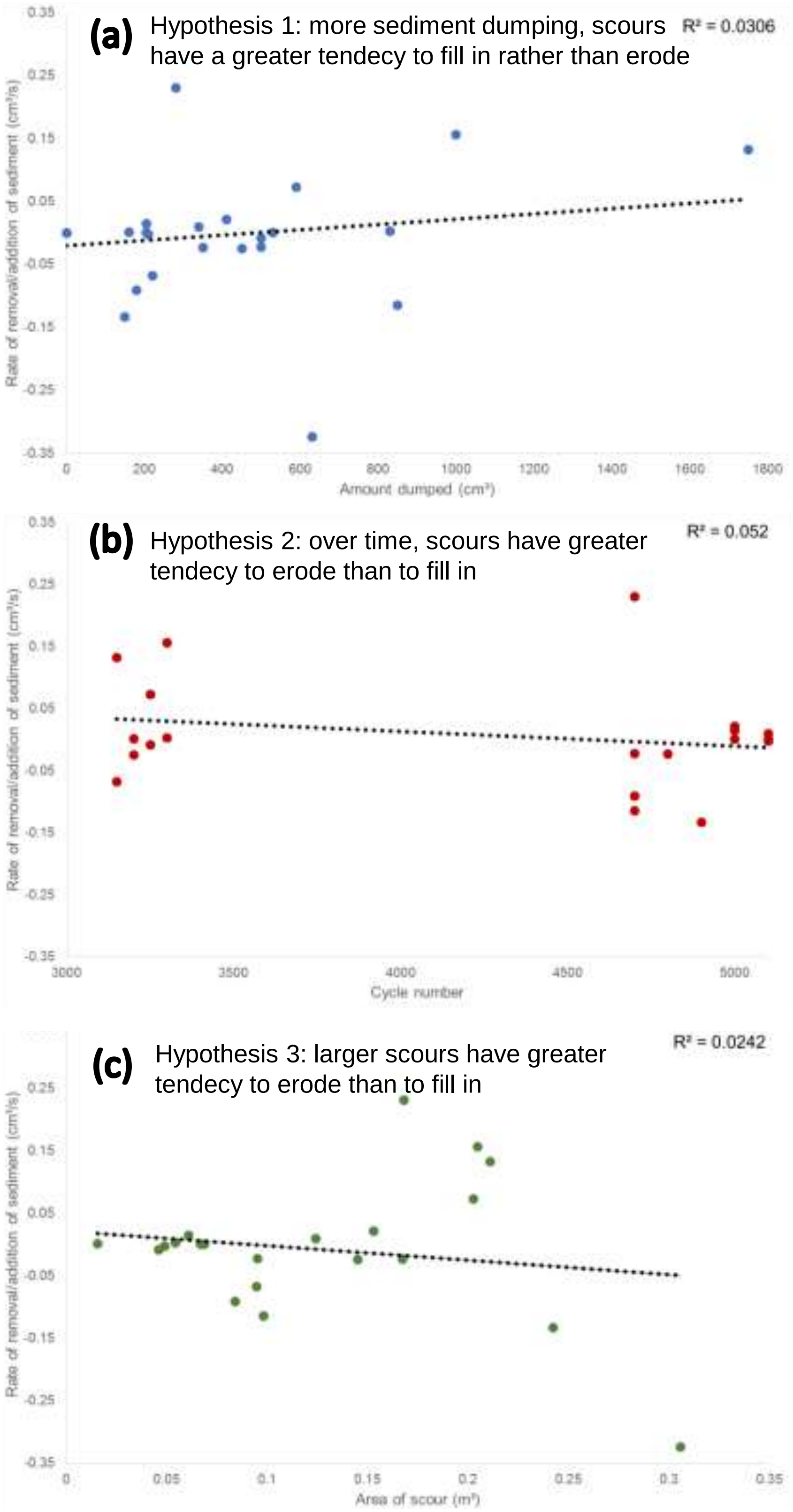


Figure 50: Comparison of correlation of the rate of removal/addition of sediment in scours against (a) amount of sediment dumped, (b) cycle number and (c) area of the scour. Note the low R^2 values in each case.

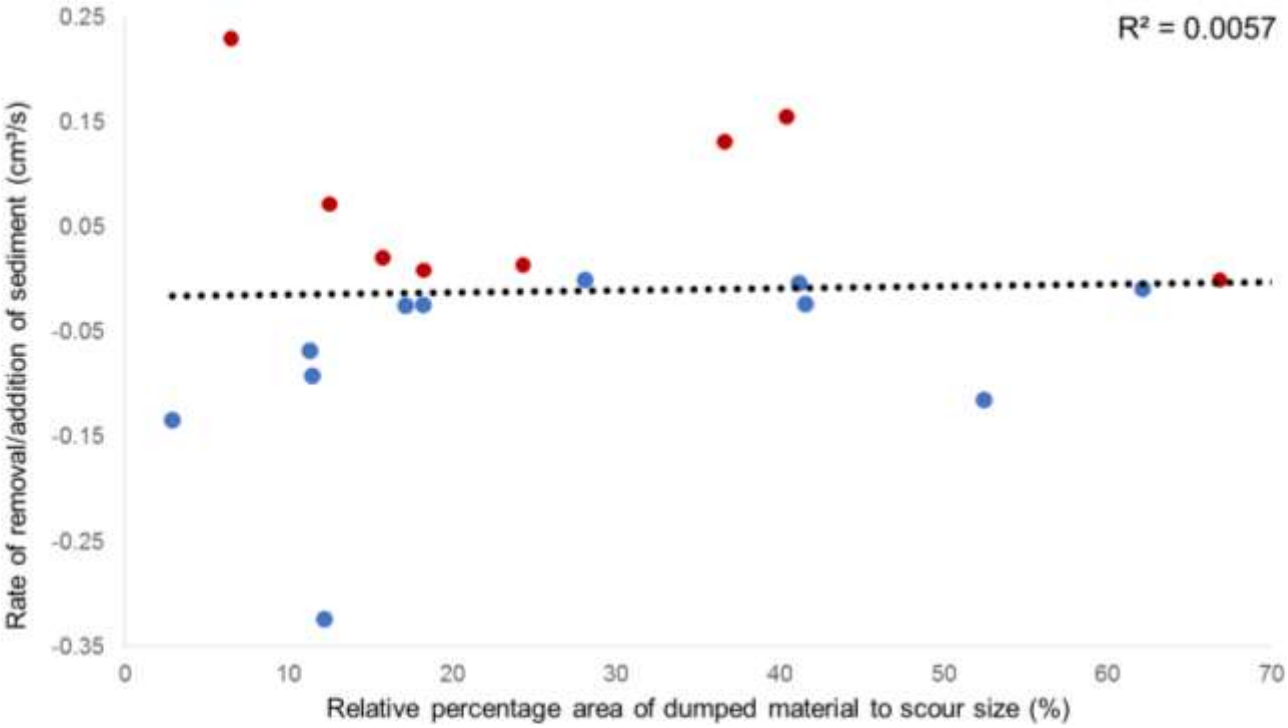


Figure 51: Relative percentage of dumped material to scour size versus the rate of removal/addition of sediment. Red indicated a positive value (addition of sediment). Blue indicates a negative value (removal of sediment).

3.6 A note on experimental issues and drawbacks

In terms of experimental setup, the experiment did not perfectly represent the current situation in the Western Scheldt on several fronts. There was no flora or fauna of any kind used in the experiment, therefore the effect of these on either stabilizing or destabilizing shoal or banks are ignored in this experiment. Likewise, the effects of mud or any non-sandy sediment were ignored as were the presence of hard layers or peat layers which are present in the Western Scheldt as outlined in chapter 1.

The estuary was not constrained by any hard engineering structures such as dikes, harbours etc. which are present in the real Western Scheldt. This meant that the estuary was allowed to expand laterally without any constraint on its width and this meant that channels were free to migrate laterally unlike in the Western Scheldt.

As mentioned in chapter 1, in reality, trailer dredgers enhance suspended sediment concentration in estuaries. However, this effect is not represented in this experiment due to the dredging occurring on a dry bed. This will have altered the sediment transport dynamics in the estuary significantly.

There were several issues encountered in terms of data collection for this experiment. For several cycles sections of overhead imagery (used to create LAB and RGB photos) were missing. Water level readings should have been recorded more frequently to more accurately determine the trends in water levels. The water level readings for cycle 4900 also seem to be an outlier, as the values are very different from the other readings. Several sources of error are present in the used of this equipment as it is very sensitive. For the control experiment the quality of the DEMs was significantly lower than that of the dredged experiment which posed some problems in comparing the two experiments and the validity of the control data.

Comparison of the Metronome’s tidal cycles with real-time is another issue. Whilst each tidal cycle is supposed to be 1000-2000 times faster than real life, the accuracy of the period is yet to be full understood. This makes any form of quantification matching with nature very difficult. So, whilst the features can be described and scaled, comparison of absolute values can be problematic.

Nonetheless, this experiment offers a unique opportunity to compare a completely natural situation with an anthropogenically altered estuary which is not possible in reality. It also can offer information which is lacking from numerical modelling and can allow for more practical analysis.

4. Discussion & implications

The following section discusses the effects seen in the experiment and how they relate to the hypotheses that emerged from Chapter 1. Processes and mechanisms behind these effects are also discussed.

4.1 Typical dredging and dumping volumes and location

The dredging and dumping protocol were designed to closely resemble the practices currently implemented in the Western Scheldt. A comparison of the typically dredged amounts and typically dredged locations in this experiment is compared with that of the Western Scheldt below (Figure 52). The largest difference in the dredging locations were the sills. In the Western Scheldt, sills are the most commonly dredged areas, in the experiment the crosses are. In the Western Scheldt sills typically form at both crosses and bends. There is therefore some discrepancy between the identification of the various features, several of the bars that form in the experiment could equally be called sills, sills form in the crosses etc.

In terms of dumping (Figure 52), the largest variation is in the main channel/scours. Several of the scours used as dumping locations in the Metronome were located in the main channel which may account for the discrepancy in volume. Overall, there was increased dumping on the shoals in the experiment, which was often due to their proximity to dredging locations and lack of options later in the experiment when side channels became clogged or sealed off. Similarly, scours filled in and were no longer available as dumping sites.

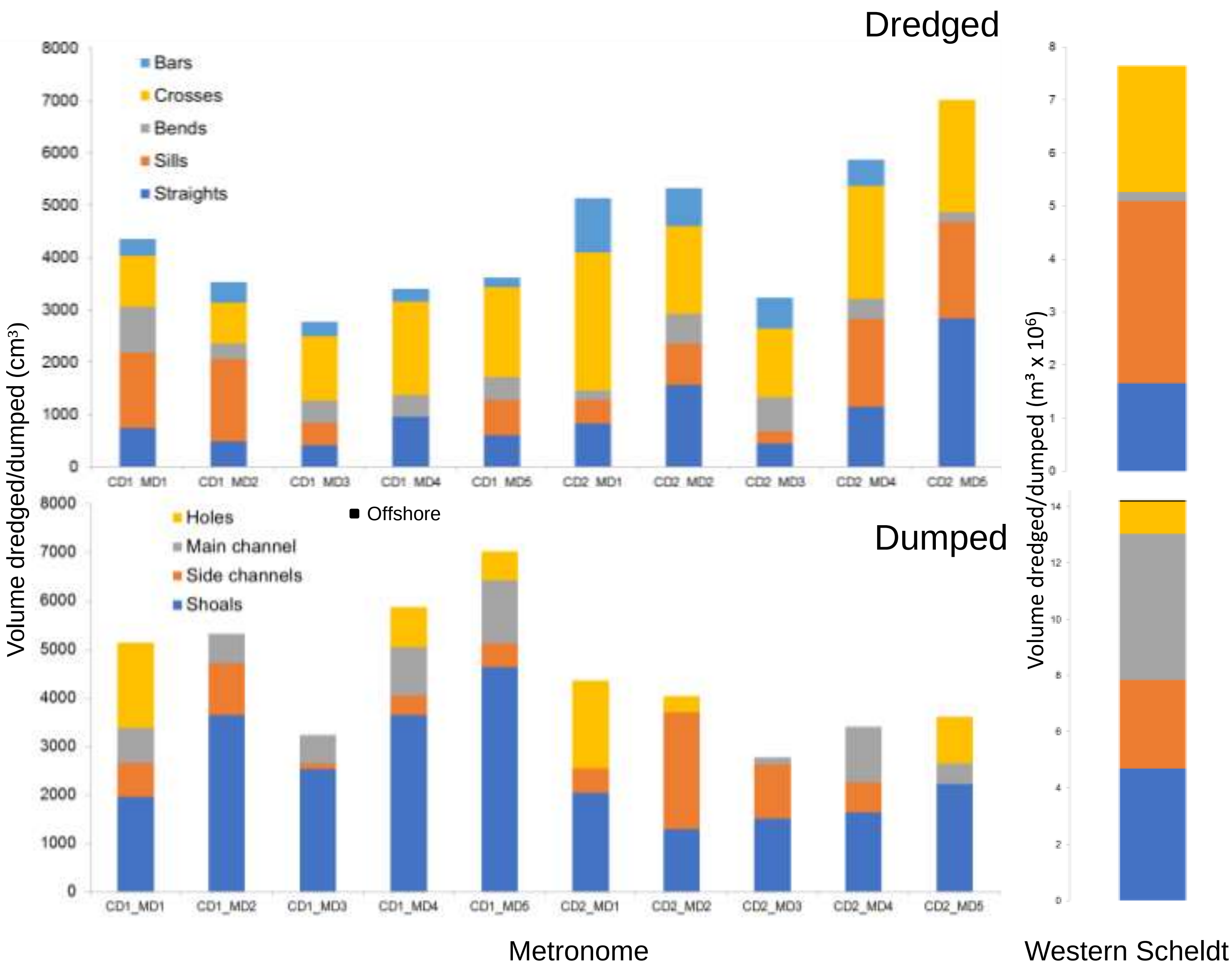


Figure 52: Comparison of maintenance dredging and dumping strategies of this experiment and the Western Scheldt. For the Western Scheldt this data is the average maintenance dredging volume per year since 1980.

4.2 Dredging the crosses

Whilst undertaking the experiment it became clear that one type of area was the most frequently dredged and represented the main navigational issue in the main channel. This was the build-up of sediment in sills at so-called “crosses” (Figure 53). These crosses are naturally shallow sections which must be dredged to allow crossing from one deep section of channel to another as seen in Figure 53.

The method of channel deepening/dredging may be causing this effect. The shortest path was chosen between deep sections of channel but, in reality, the square tight bends seen in the experiment would be an obstruction to ships which would probably have a minimum bend angle/size requirement. Having tight bends alters meander dimensions and therefore changes the dynamics of flow in the bends. Kleinhans et al., (2008) note that sharp bends experience the fastest development of fixed bars and silt up more quickly which concurs with this experiment.

The Western Scheldt represents a typical van Veen structure as aforementioned, and importantly the straight flood channels form in each ebb channel bend (Jeuken, 2000). Alteration of the geometry of these bends will therefore alter the dynamics of where and how many side channels form. In this experiment the presence of tighter bends meant more bifurcations occurred and more straight side channels formed than form in the Western Scheldt.

When bends are sharp, the flow becomes focused in the outer bend bifurcate (the new side channel which forms) (Kleinhans et al., 2008). In this experiment when crosses develop and bars form at the crosses flow becomes redirected into new side channels. Until the bar/sediment is removed from the cross, flow will continue to erode the new side channels.

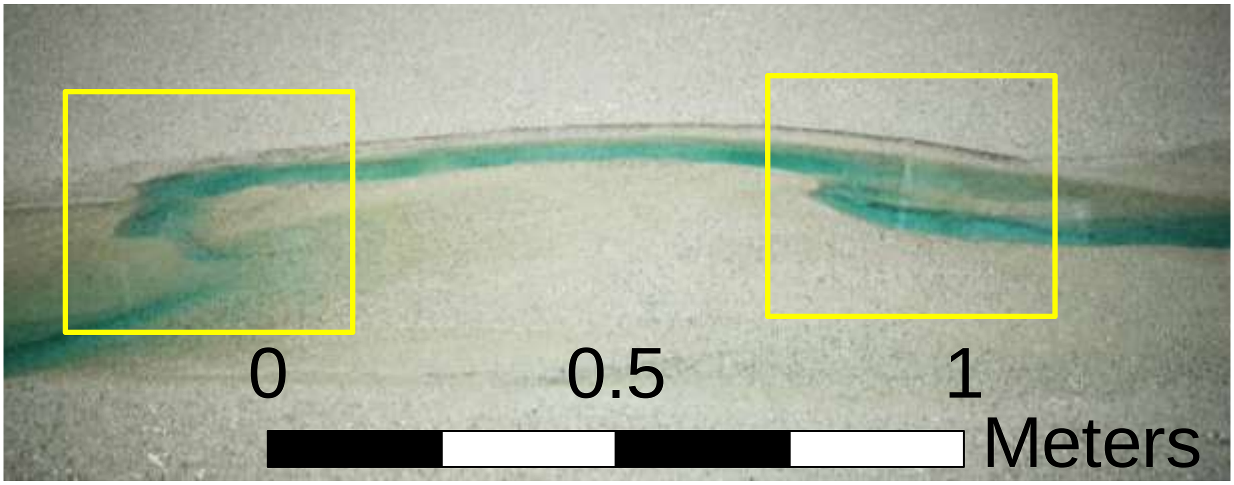


Figure 53: Photograph of the experiment at cycle 3200 showing the build-up of sediment at crosses (yellow boxes).

4.3 Estuary shape and stability

Hypothesis 1: Dredging alters the overall pattern of the estuary by altering the location and extent of channels, bars and shoals

One clear and important factor to emerge from this experiment is the long-term effects of dredging and dumping. Even when dredging and dumping ceased, the system retained its new altered state i.e. it did not revert to a natural multi-channel system (see Figure 32).

This is of particular relevance to ecology as the intertidal area remains at the same percentage area even after dredging and dumping have stopped (Figure 55). Some supratidal areas become intertidal, but simultaneously some intertidal areas become subtidal. The effect is a stasis in the amount of intertidal area.

This indicates that the new equilibrium state created by the deepening, dredging and dumping cannot be reversed without further human interference or action. This is an important factor in future management of estuaries such as the Western Scheldt. As proposed by Bolle et al. (2010) and Jeuken & Wang (2010) when dredging and dumping reach a critical level the naturally stable ebb-flood channel system indeed became unstable and turned into a single channel system.

Both the non-dredged and dredged experiment experience choking (blocking of flow) due to sediment in the upper middle reaches of the estuary (Figure 54). However, this effect is much more extreme in the dredged situation causing the upper and lower sections to become almost completely isolated from each other. This would never occur in the Western Scheldt due to continuous dredging. However it does indicate that this section which includes sharper bends and a narrower estuary is the most prone to silting and therefore is most in need of dredging. In the Western Scheldt the most dredged sill is Drempel van Hansweert (as seen in section 1.5.3) which is in the narrower landward part of the estuary with tighter meander bends. This indicates that wider main channel bends reduce the need for dredging.

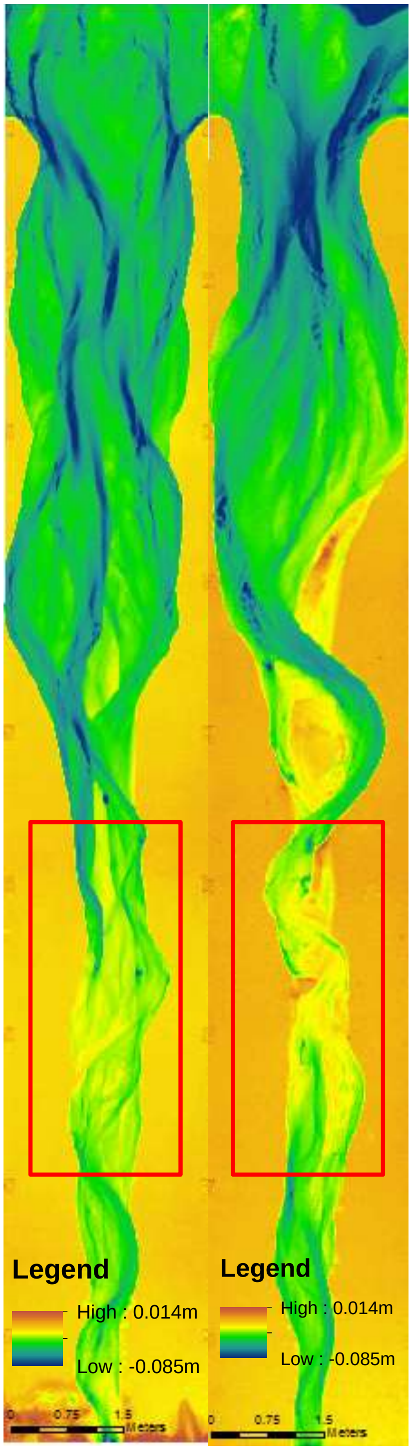


Figure 54: Sediment build-up in the last cycles of the estuary for both the non-dredged (left) and dredged (right) experiments at cycle 13000.

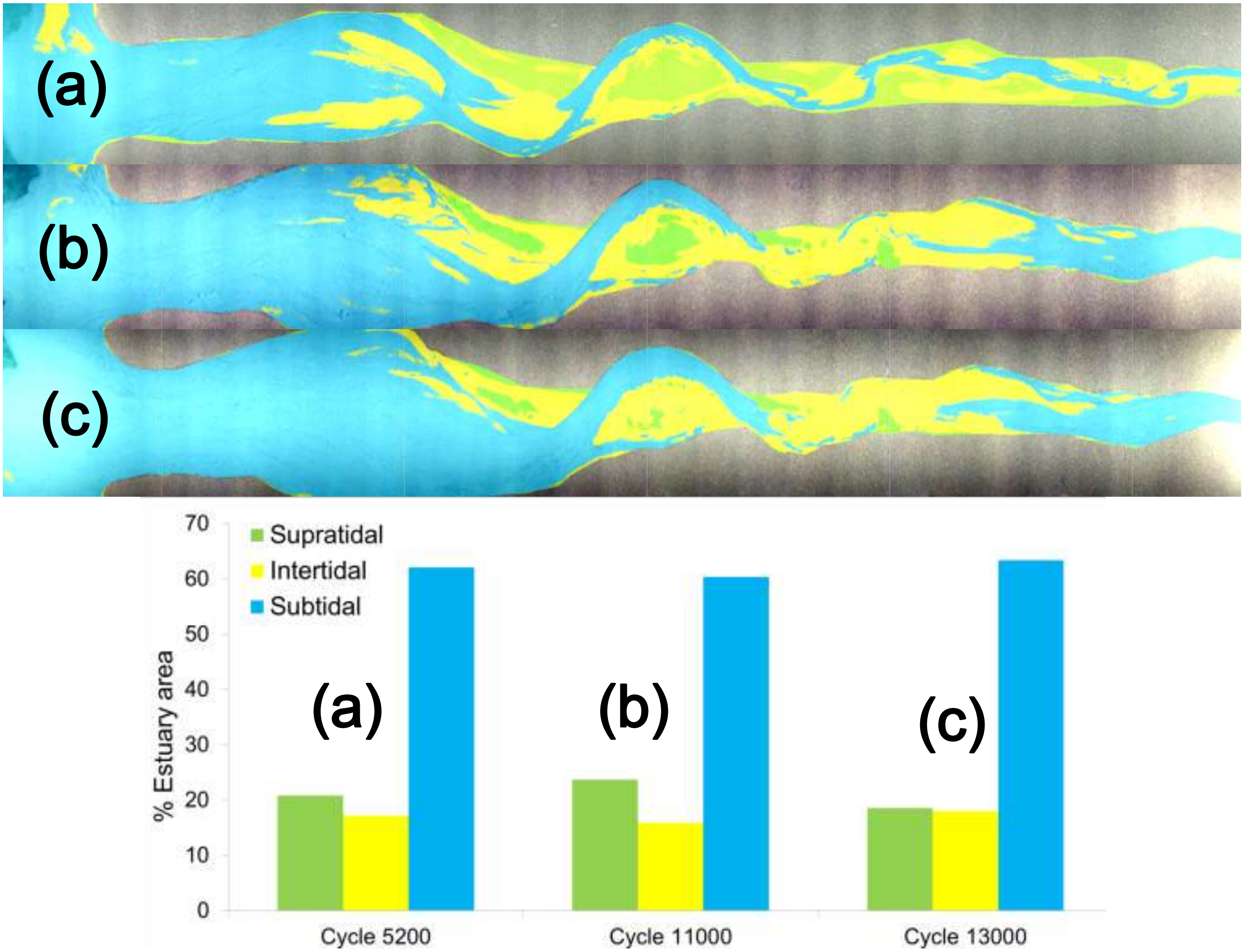


Figure 55: Maps and percentage area of supratidal, intertidal and subtidal area for (a) cycle 5200, (b) cycle 11000 and (c) cycle 13000.

4.4 Response of main channel to dredging and dumping

Hypothesis 2: Dredging changes the natural shape of the main channel

Hypothesis 3: Dredging causes smoothing of the bottom topography of the main channel

Hypothesis 4: Dredging the main channel increases the rate of infill of the main channel

The focus of dredging in both this experiment and in modern estuaries is to deepen the main channel for navigation. This means that any shallow sections of the main channel such as sills are removed. The effect of dredging of the main channel in the experiment was to create a channel with overall lower variability in channel depth, but a channel that infilled quickly, wishing to return to its natural state. Dredging removed shallow sections and dumping in scours worked to smooth the bottom topography of the main channel as proposed by hypothesis 3. By removing shallow and deeper sections there is a less dampening of the tidal wave due to decreased friction and therefore increased tidal propagation velocity and wave height in the main channel. In the Western Scheldt there has been increased high water propagation velocity and higher high water waves in the main channel (VNSC, 2013). Section 4.5 further explores the dynamics of the velocity of the waves in the estuary.

In the Western Scheldt, the effects of dredging and dumping on the main channel bathymetry are not as easily isolated. However, if we look at the average channel depth of the shipping fairway of the Western Scheldt over time (Figure 56) the variation of average channel depth is much lower over time with a strong trend towards deepening. This is because the Western Scheldt is continuously dredged. It does not shallow and then need to be re-deepened like in the experiment. Instead policy dictates to pre-emptively dredge the channel all year round in order to maintain the shipping fairway leading to Antwerp port. This experiment indicates that if the shipping fairway were left undredged, it would silt up quickly as seen in the dredged experiment.

As seen in the Western Scheldt and other estuaries, dredging changes patterns of erosion and deposition for different morphological features within the estuary. In the case of the main channel it smooths bathymetry by eliminating deeper and shallower sections to maintain a minimum channel depth.

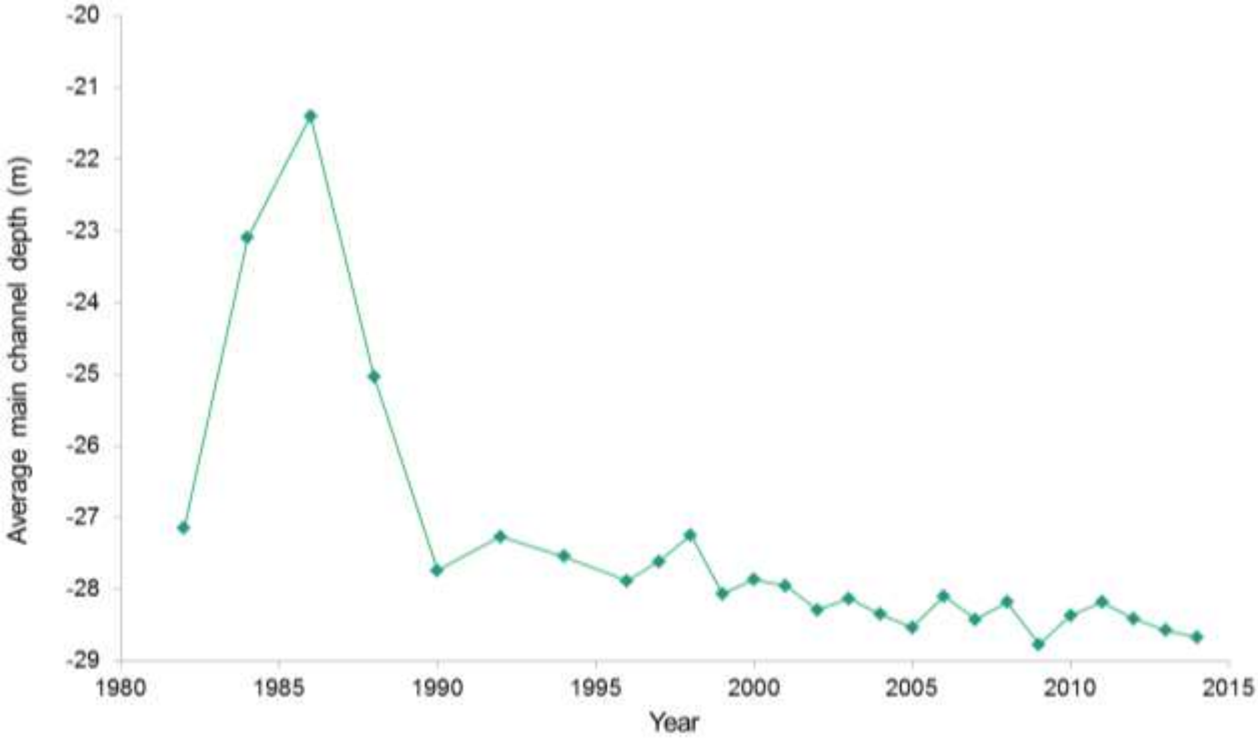


Figure 56: Average main channel depth over time for the Western Scheldt (1982-2014).

4.5 Velocity and tidal propagation

Hypothesis 7: Dredging causes an increase speed of tidal propagation in estuaries

Maps of the difference in both cross channel (u) and along channel (v) velocity between the dredged and non-dredged experiment are shown in Figure 57. The cross channel velocity does not vary much between the two experiments. In both cases, cross channel flow velocity is at its highest magnitude at the crosses (changes from flood to ebb sections of channel).

The along channel velocity is very different for both cases. In the non-dredged case there is high positive (flood) flow in the landward end of the estuary with high negative flow (ebb) in the seaward section of the estuary. Flow velocity is of the greatest magnitude in the middle of the estuary (dominated by ebb flow). In the case of the dredged experiment flow is more uniform over the estuary. It is again ebb dominated but with a lower magnitude than the non-dredged case. The strongest magnitude of flow is immediately upstream of the large shoal in the middle of the estuary.

The dredged experiment has lower velocity in the main channel with a more uniform along channel flow which differs from with the situation in the Western Scheldt. Dredging has in particular increased the velocity in the seaward sections of the Western Scheldt (VNSC, 2013). This does not occur in the experiment. Tidal propagation does increase as the ebb flow is dominant even in the landward sections of the estuary in the dredged experiment.

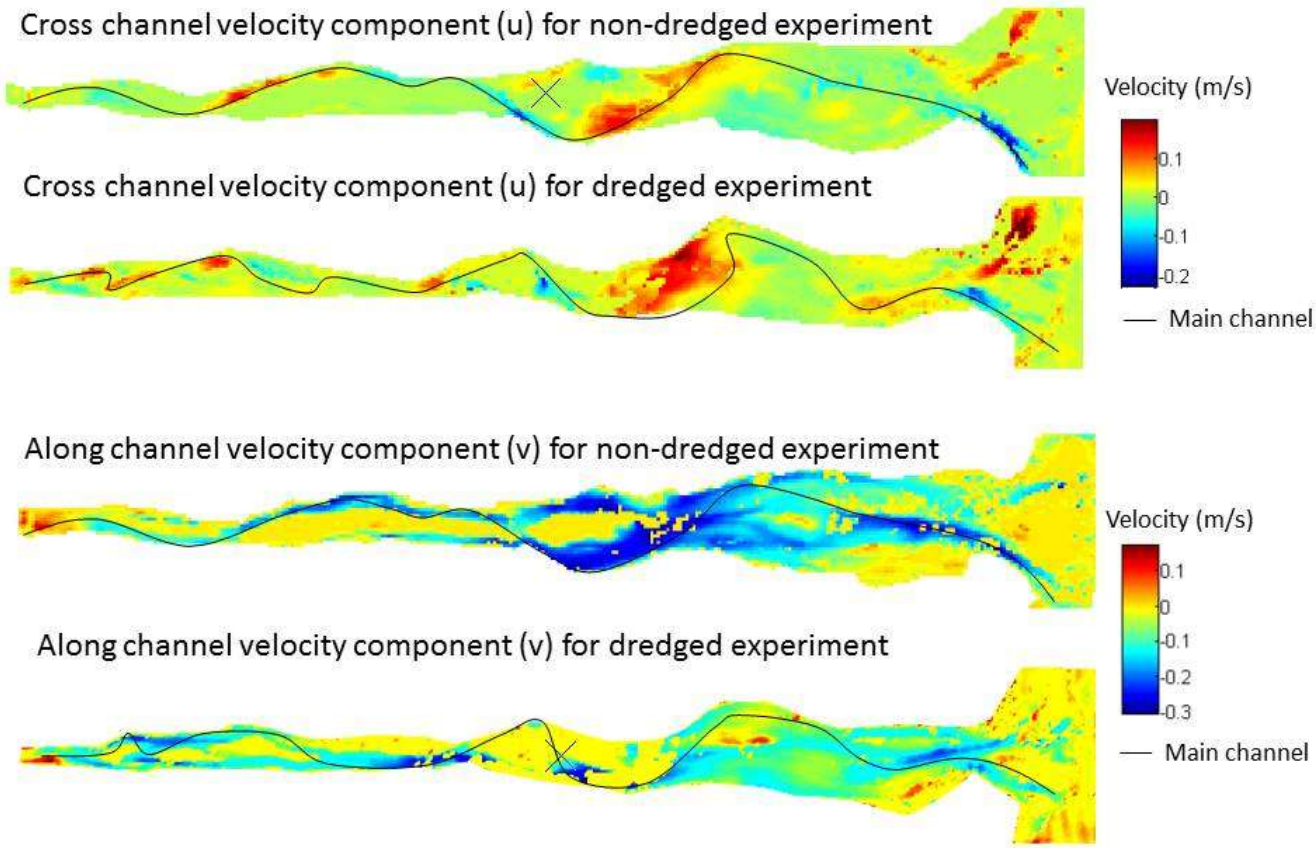


Figure 57: Velocity maps for the non-dredged (cycle 4401) and dredged (cycle 4700) experiments for both the u and v velocity components

4.6 Changing water levels

Hypothesis 9: Dredging alters ebb and flood dynamics in the estuary including asymmetry, duration and peak ebb and flood

The dredged experiment displayed a variation in high water, low water and tidal range when compared with the non-dredged experiment. The shape of the tidal wave is altered with increased frequency and amplitude. Tides become more asymmetric tending towards further ebb dominance due to the dredging of the main channel. Ebb duration is increased in both the main and side channels due to dredging. This agrees with hypothesis 9.

4.6.1 High water and low water

The Western Scheldt has seen a gradual increase in high water levels and a stepwise decrease in low water levels (Figure 58) since channel deepening began (Plancke, 2017, Kuijper & Lescinski, 2013). The dredged estuary in the experiment repeats this pattern with high water increasing in both the main and side channels over time and low water decreasing in both the main and side channels over time. The percentage increase is not quantifiable or comparable due to scaling issues. However, the fact that the trend matches nature is evidence that dredging, and dumping do indeed cause higher high waters and lower low waters. The mechanism behind this is discussed in section 4.6.2.

4.6.2 Tidal range

Hypothesis 6: Dredging alters the tidal prism of estuaries

Hypothesis 8: Dredging increases tidal range in the estuary

In the dredged experiment there was in increase in tidal range in both the main and side channels which matches hypothesis 8. This increase in tidal range is common with dredged estuaries and is well documented in Western Europe, occurring in the Elbe, Ems, Loire, Western Scheldt caused by altering surface of intertidal area, convergence length of the estuary, channel depth and effective hydraulic drag (Winterwerp, 2013).

In the Western Scheldt there has been an increased tidal range over time, partially attributed to natural causes (sea-level rise) and partially attributed to manmade impacts such as poldering and channel deepening/dredging which increase the effect of the funnel shape of the estuary and give a greater cross sectional area (Kuijper & Lescinski, 2013, Plancke, 2017).

In the Western Scheldt, deepening of the channel led to a decreased flood dominance and a tendency towards ebb dominance (Bolle et al., 2010). In the case of the experiment, the estuary was already ebb dominated, however dredging led to increased asymmetry and a stronger relative phase between ebb and flood with a greater tendency towards ebb dominance (see Figure 39).

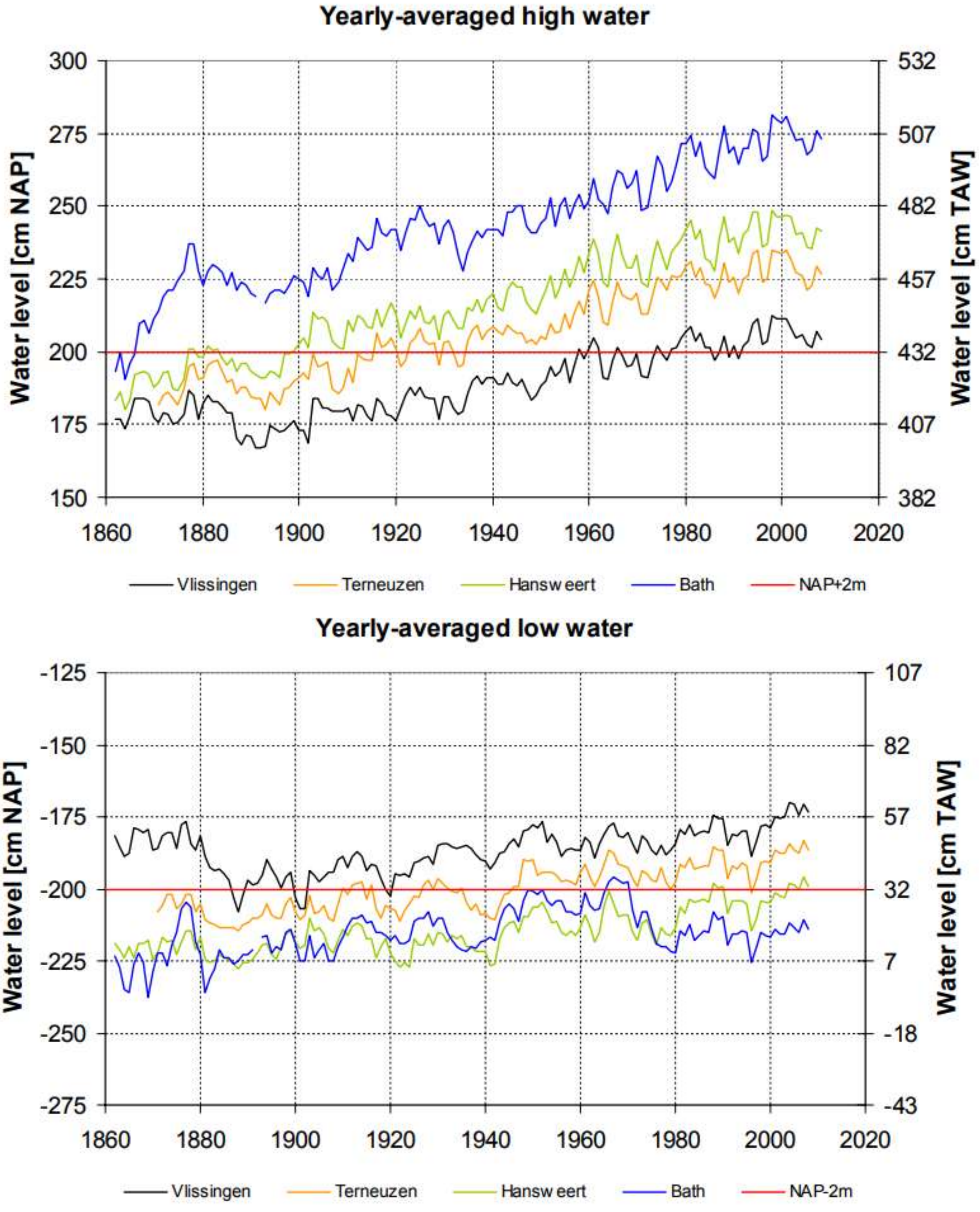


Figure 58: Change in high water and low water levels in the Western Scheldt estuary. Source: VNSC (2012).

4.7 Intertidal area variation due to dredging and dumping

Hypothesis 14: Dredging and dumping leads to decreased intertidal area

This experiment indicates that intertidal areas became raised or were drowned whilst dredging and dumping were active. Several thousand cycles after dredging and dumping were halted the intertidal and supratidal areas remained in relative stasis. Several channels filled in leading to a decreased subtidal area which increased intertidal area. Similarly some supratidal areas reverted back to intertidal areas. But, some intertidal areas also became drowned and became subtidal (see Figure 54 & Figure 55 in section 4.3). Loss of intertidal area not only is a loss of ecological area, but it also leads to increased tidal range and tidal propagation speed. This in turn leads to increased flooding and a need for coastal protection. This implies the need for either increased intertidal area, through Building with Nature (section 1.9.2) or hard engineering structures to deal with the increased flooding.

In the Western Scheldt, dredging and dumping has resulted in the loss of both shallow water areas and intertidal area (Jeuken & Wang, 2010). Historically in the Western Scheldt there has been a large loss of intertidal area, 35% since the 17th century (Ofori, 2009, van der Spek, 1997). The decrease in height, area and volume of the intertidal shoals has slowed in recent years as seen in Figure 59 This suggests that creation of intertidal areas may have to be done artificially as the naturally tendency of the dredged system is to decrease intertidal area and without dredging the intertidal area will be stable (small fluctuations but neither growing or eroding in large volumes).

Dredging has led to loss of intertidal area in the Yangtze estuary in China (Chen, 2016) and Humber estuary in the UK (Aubry & Elliott, 2006). The loss of intertidal area poses a large problem for policy makers particularly in view of the LTV, Working with Nature and protection of ecologically valuable Natura 2000 areas (as seen in section 1.9).

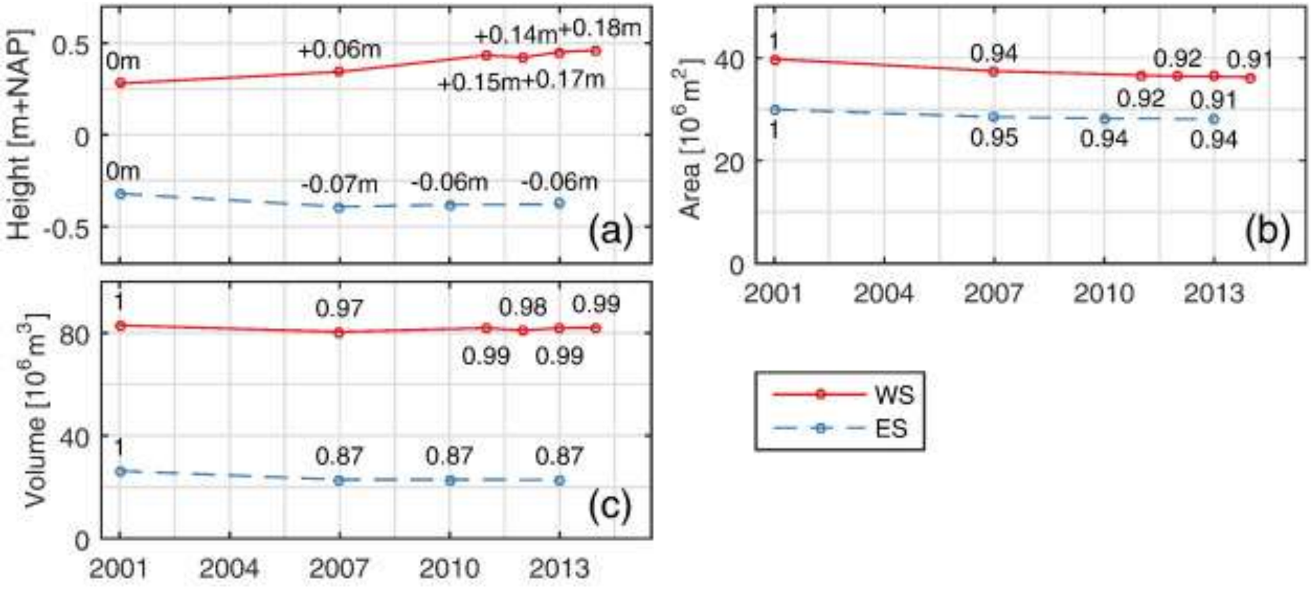


Figure 59: Change in height, area and volume of the intertidal shoals in the Western Scheldt from 2001 to 2015. Source: de Vet, van Prooijen & Wang (2017).

4.8 Response of shoals to dredging and dumping

Hypothesis 11: Dredging leads to the erosion of the sides of shoals

Hypothesis 12: Dumping on shoals leads to increased sedimentation and loss of intertidal area

Hypothesis 13: Dumping on shoals can lead to sediment becoming redistributed into both the main and side channels

The typically intertidal shoals of the Western Scheldt have, due to the dredging and dumping operations begun to increase in height over time (Jeuken & Wang, 2010). The tendency of shoals in the Western Scheldt is to become steeper with a larger average height (de Vet, van Prooijen & Wang, 2017). This is also demonstrated in the dredged experiment as many of the shoals became raised above the high-water level mark (see Figure 42). Some shoals remained intertidal despite dumping measures. Typically, those shoals and bars used as dumping locations in upstream locations became supratidal whilst those closer to the seaward end retained their intertidal status such as the shoal seen in Figure 43. This counteracts the observations of de Vet, van Prooijen & Wang (2017) that the shoals in the eastern Western Scheldt (landward) have been eroding whilst those in the western part of the Western Scheldt have been growing at a rate of 1cm per year. In the experiment larger volumes of sediment were placed on the landward shoals than in the Western Scheldt where dumping in the last 30 years has focused on the seaward shoals. This led to several of the shoals becoming wholly supratidal in the Western Scheldt often only some parts of shoals become supratidal and there can be large spatial variation.

When compared with the empirical prediction from Leuven et al., (2016) which predicts a shoal length of 6.9 times shoal width (Figure 60), the dredged experiment deviates more than the non-dredged experiment. Shoals 1-3 fall in the realm of the prediction with shoal 2 (located upstream) closely matching the prediction. For the dredged experiment shoals 5 and 6 lie in the correct region whilst shoal 4 (located in the middle of the estuary) does not. In the non-dredged situation the landward shoal best matches the prediction whilst in the dredged situation the seaward shoal best matches the prediction.

Leuven et al., (2016) point out that bars are longer in wider estuaries. In the case of both experiments the shoals estuary width scales with location in the estuary, therefore those in the upstream section of the estuary (shoals 2 & 5) are at the narrowest part of the estuary whilst those downstream (shoals 3 & 6) are at the widest part of the estuary. However this does not explain why shoal 4 shows such a large deviation in width. This shoal and shoal 5 (which also shows large deviation from expected ratio) were used as a dumping locations and became very stable as seen in previous sections. This suggests that high volumes of dumping may alter this empirical ratio.

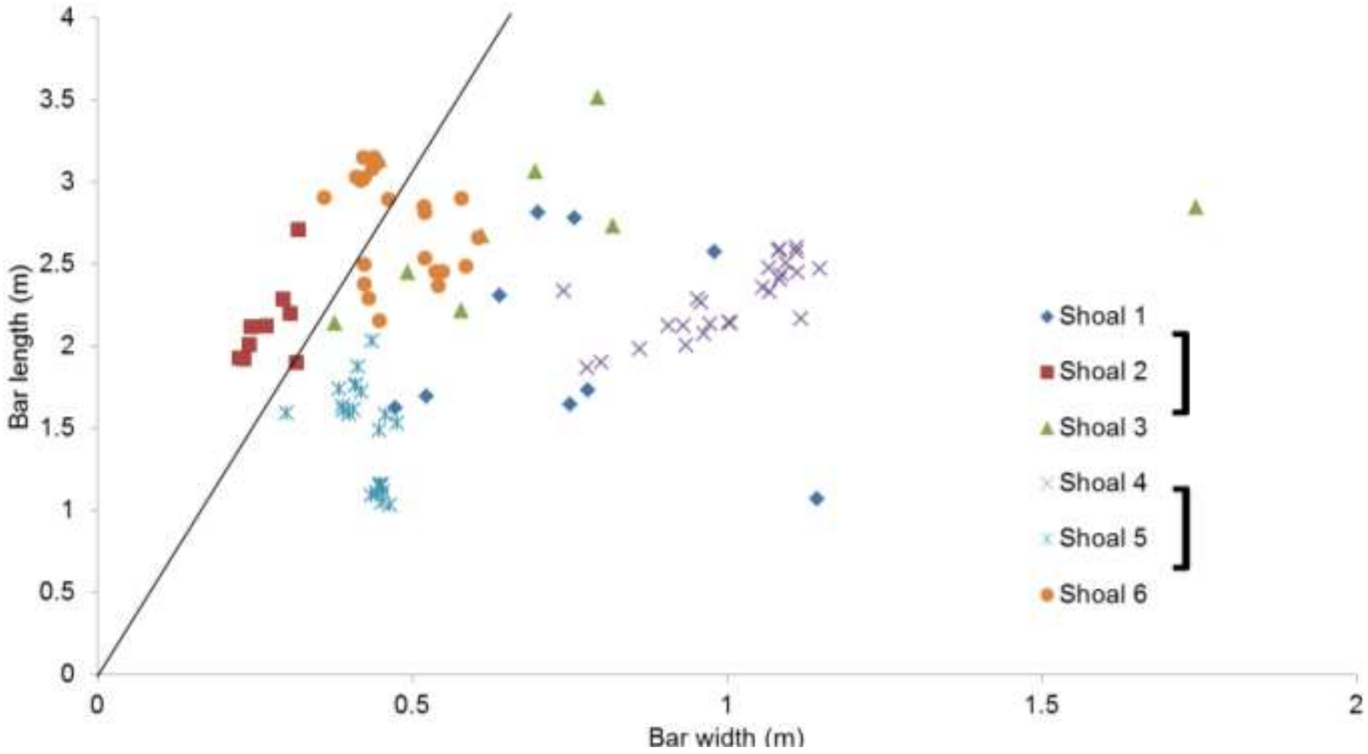


Figure 60: Length to width ratio of all studied shoals from the dredged experiment, black line is the expected length to width ratio of 6.9 as given by Leuven et al. (2016).

4.9 Response of side channels to dredging and dumping

Hypothesis 15: Dumping in the side channels will cause erosion in the main channel whilst dumping in the main channel will lead to erosion in the side channels

Hypothesis 16: Dumping in side channels will cause them to shallow and become less navigable

This experiment could not prove conclusively that hypothesis 15 is correct. Due to the high levels of dumping in side channels and often the remobilization of sediment from shoal dumping in both the side and main channels, too many processes affected erosion and sedimentation patterns to directly attribute channel deepening to this specific process.

In the experiment, side channels were shallower and spanned less percentage area of the estuary than in the non-dredge experiment. The side channels were frequently used as dumping locations and often led to them becoming sealed at one or both ends making them unnavigable (

Figure 61).

The Western Scheldt (see Figure 48) has had the same number of side channels for the last 30 years regardless of dredging and dumping. The general trend is for side channels to shallow over time as they silt up due to dumping. They have become less navigable over time as noted in the DEMs in section 1.8.

The percentage area of the estuary that the side channels encompass has grown over time. The side channels have been eroding shoal edges and increasing in area.

In the Western Scheldt, the effects of dredging and dumping were to enhance long term deepening of the channels, in particular the large ebb channels (Jeuken & Wang, 2010). In the experiment the side channels shallowed and silted up which matches the observations made in the DEMs of the Western Scheldt. One key difference was the absence of any side channel dredging in the experiment which does occur in the Western Scheldt and other estuaries for the purpose of navigation.

As elucidated by Jeuken & Wang (2010), there is a critical level for dumping in the side channels of 5-10% total sediment transport capacity and exceeding this level will cause closure of the channel. In this experiment no channel was ever permanently closed off due to dumping. Several channels became either sealed at one end (see

Figure 61) due to dumping or were closed for several thousand cycles at a time. This was particularly common in the upstream sections of the estuary. Strong ebb flow at the seaward and middle ends ensured the re-opening of side channels in these sections. The effect of dumping in side channels has implications for navigation as these channels are used by smaller (non-commercial) ships. Palaiogianni (2015) outlines that while these locations are chosen to minimise cost they often lead to changing sediment transport and often transfer of sediment along the estuary.

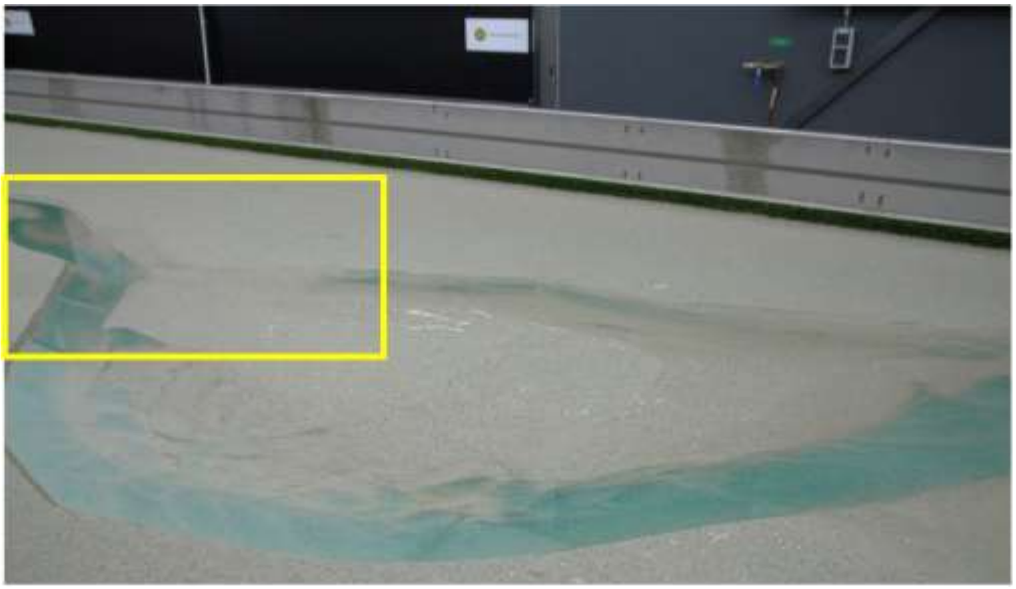


Figure 61: Side channel at location 9-11m length along the estuary at cycle 5000, sealed at one end due to dumping.

4.10 Response of scours/holes to dumping

Hypothesis 17: Dumping in deep scours will cause sediment to be eroded

Hypothesis 18: Dumping in scours will cause overall deepening of these areas

In the experiment, scours used as dumping sites eroded, stabilized and gained sediment. The pattern behind this remains unclear as no statistically significant trends were found relating to the scour size, dumping volume or stage in the experiment. However the trend was for larger scours with low dumped volumes to erode and small scours with large dumped volumes to act as sediment traps. This concurs with Depreiter et al. (2011) who suggest that scour area and depth may be responsible but also could not prove this trend. The DEMs of the Western Scheldt also show that the deep parts of the channel (holes/scours) respond differently spatially with some sections experiencing erosion and others sedimentation and that this also varies on a temporal scale.

The mechanisms behind dumping in deep parts of the channel (scours/holes) represent an interesting area of further research. The rate of removal of the sediment when scaled with nature matches the erosive half-lives of the Western Scheldt which suggest that the processes in the experiment very closely match reality, despite differences in temporal and spatial scale. Therefore a scaled experiment could also be used to test the different mechanisms behind erosion/sedimentation processes in these dumping locations.

4.11 Implications of this experiment for future management of estuaries

This experiment proves it is possible to replicate the same processes happening in dredged estuaries in a tilting tidal flume. The fact that the effects and processes that occur in the Western Scheldt also occur in this experiment make it a useful tool for testing future scenarios and future challenges facing the Western Scheldt. It allows for testing of the effects of different dredging and dumping routines, and sediment management policies. The issue of sediment balance and potential future actions to maintain a healthy sediment balance in the estuary is a key topic for the Western Scheldt and many other estuaries. Various techniques could be implemented in an experiment setting such as this one to test future plans.

Future changes due to climate change and increased urbanization of the Western Scheldt estuary, including the continuous expansion of the market of Antwerp harbour could also be incorporated. The effects of sea-level rise, potential catastrophic events, subsidence and potential further channel deepening would be interesting and important areas of future research.

5. Conclusions

A scaled experiment was devised with a dredging and dumping protocol which was compared with a non-dredged experiment, the dynamics of the Western Scheldt estuary and general effects of dredging and dumping in estuaries. The experiment design and protocol were based on analysis of the past and current dredging and dumping practices in the Western Scheldt. Several proposed effects of dredging and dumping from the literature and analysis of DEMs of the Western Scheldt were analysed. For the most part the same hydrological and sedimentological processes and their associated effects noted in dredged estuaries were also found in the experiment. These effects include:

- Dredging alters the main channel by changing bathymetry and sedimentation/erosion patterns
- The main channel will silt up faster in a dredged setting than a non-dredged setting
- Side channels become shallower due to dredging and dumping
- Dredging and dumping causes a lower overall percentage area of side channel relative to the size of the estuary despite the number of side channels being unchanged
- Shoals become higher and supratidal with a tendency for shoals to become very stable and fixed in both width and height (with continued dumping)
- Scours used as dumping sites can both become sediment traps or be eroded – the explanation for this variation was not found in this study, though it is thought to be linked with scour size and volume of sediment dumping
- Both the main channel and side channels experience higher high-water levels, lower low water levels and an increased tidal range, but when dredging and dumping ceases, the system tries to revert to lower values
- Dredging and dumping cause a more stable estuary in terms of both width and pattern
- The tendency is to move towards a single channel system with offshoot channels rather than a multi-channel system

The scaled experiment was capable of replicating many of the processes associated with dredging and dumping in the Western Scheldt estuary and indeed can be used as springboard for further testing of processes including different dumping locations, effects of sea-level rise and effects of hard engineering.

Acknowledgments

To my supervisors Jasper and Maarten, thank you for your hard work and support, replying tirelessly to emails and queries, you challenged me to do my best and work hard and taught me that university work can also be a lot of fun. Thank you for this opportunity to learn and be challenged.

Thank you to Jelmer and Nathanaël for their guidance and extensive knowledge of dredging and dumping protocols which were invaluable in designing the experiment.

To all who helped me at the Metronome, with setup, monitoring and recording data, Jasper, Ivar, Lisanne, and Lonneke, thank you for shovelling all that sand with me!

To my proof readers, thank you for adding all those commas, removing all of my howevers and alsos and for making sure my work was its absolute best.

To my family (also tireless proof readers) thank you for reading and re-reading something completely outside your comfort zone and for dealing with many angry phone calls when the Metronome cameras inevitably broke down.

To Julien, thank you for supporting me every day through this thesis from beginning to end, listening to every explanation, excited message or exhausted complaint, sorry that I also continuously traipsed lots of sand and blue dye into the house.

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Appendix 1: Note on terminology, definition of terms and abbreviations

Terms used:

Capital dredging event: two such events took place in the dredged experiment, this refers to (re) cutting the channel i.e. both deepening and widening of the channel. This sediment was NOT replaced in the system

Cross: a section of the dredged channel which links two naturally deep parts of the channel which silts in quickly – these are equated to passes or some sills in the Western Scheldt

Cycle: in the case of both the dredged experiment and the control experiment, 1 tidal cycle is 40 seconds in length

Dredged experiment: the experiment conducted which contained both dredging AND dumping, often shortened to dredged experiment for brevity

Maintenance dredging: removal of material in the channel (both in terms of width and depth) to maintain the shipping fairway – this sediment was returned to the system as dry sediment in various dumping locations

Metronome: the name of the tilting tidal flume used for the experiments, Utrecht University

Scours: naturally deep sections of the main channel – these can be equated to pits or wells in the Western Scheldt

Shoal: any given area (intertidal or supratidal) which separates the main channel from the side channels

Abbreviations:

Throughout the results the following abbreviations may be used:

AD = *anno Domini* – Gregorian years

BP = years before present i.e. years before 1950

CD = Capital Dredge

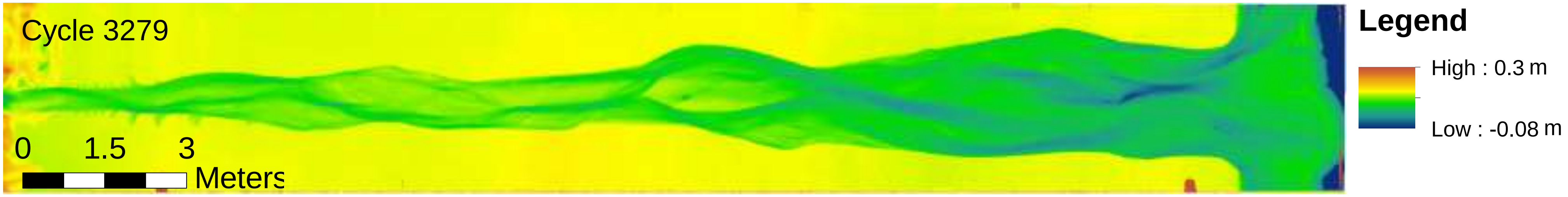
DEM = Digital Elevation Model

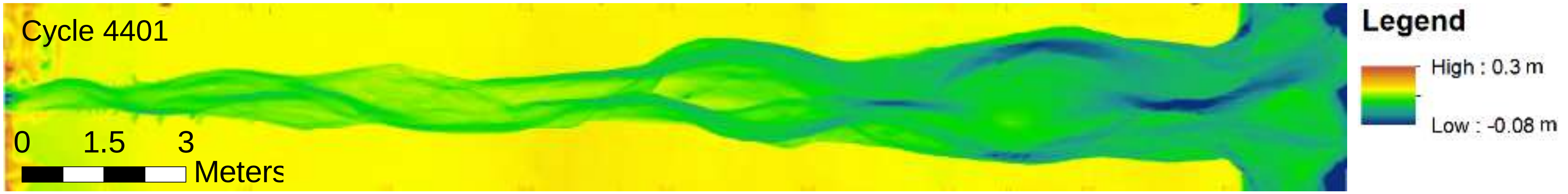
GIS = Geographical Information System (in this case ArcGIS software was used)

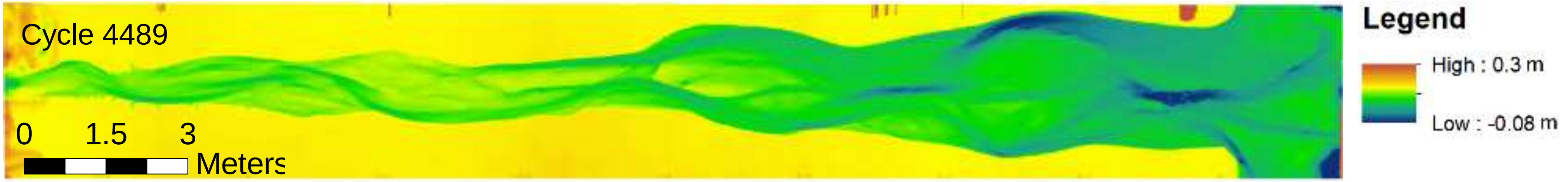
LAB = type of photo in the lab colour space

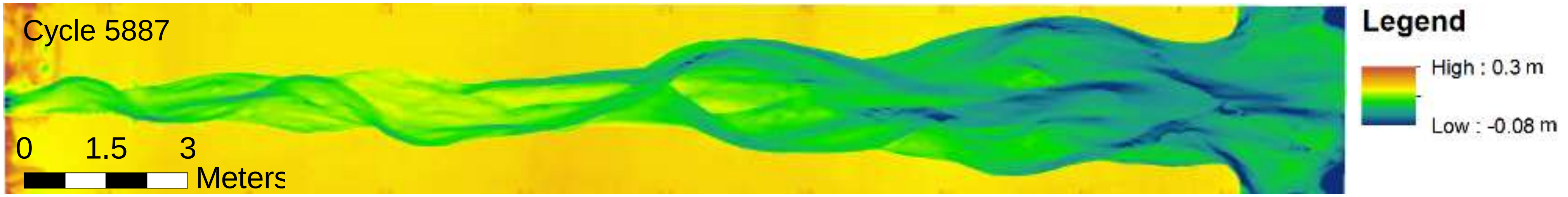
MD = Maintenance Dredge

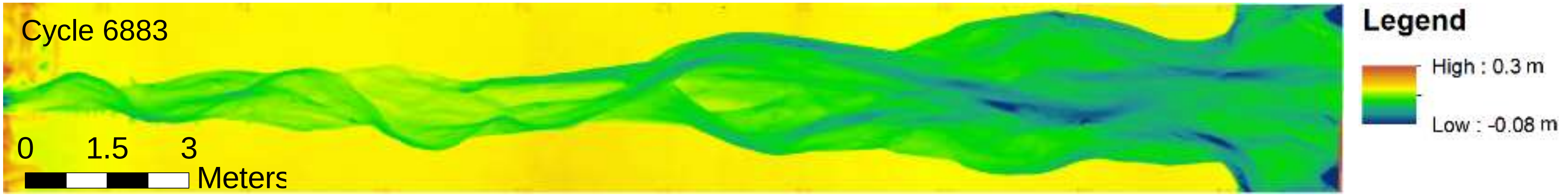
Appendix 2: DEMs of the non-dredged experiment from cycle 3279 until cycle 13076 (end of experiment)

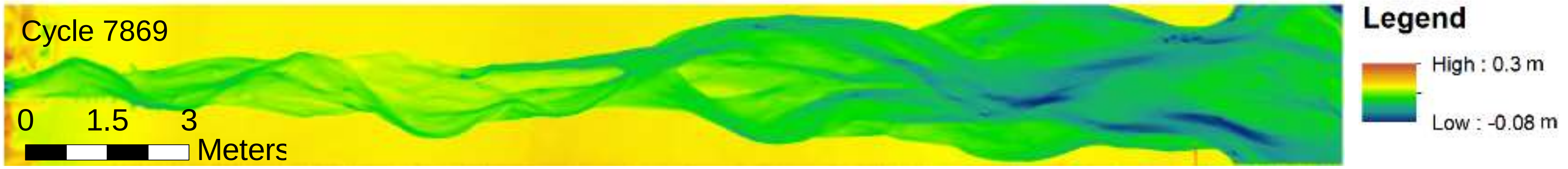


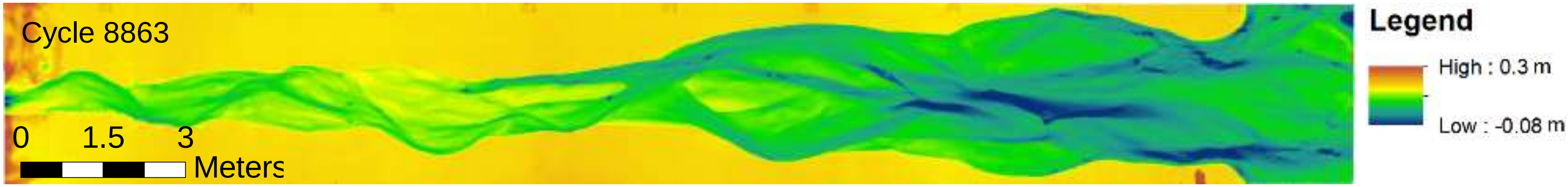


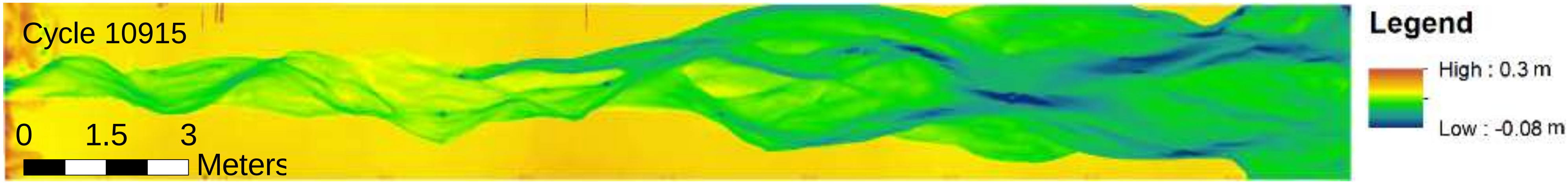


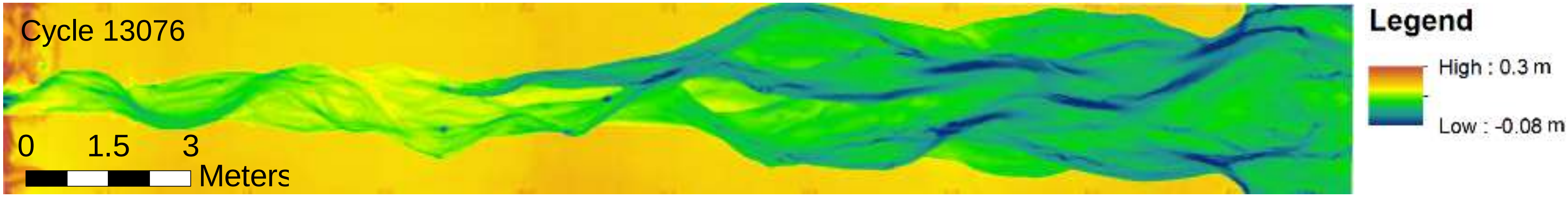




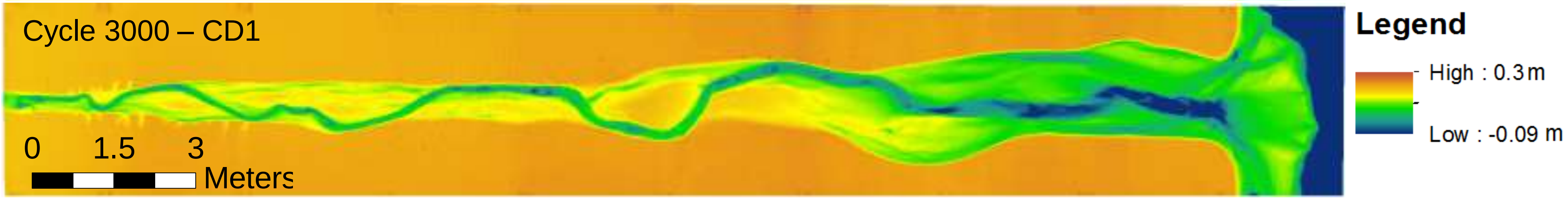


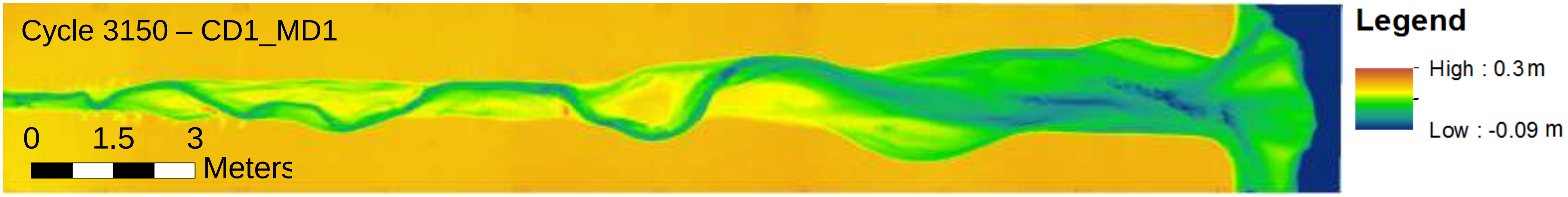

Cycle 8863
0
1.5
3
Meters
Legend
High : 0.3 m
Low : -0.08 m

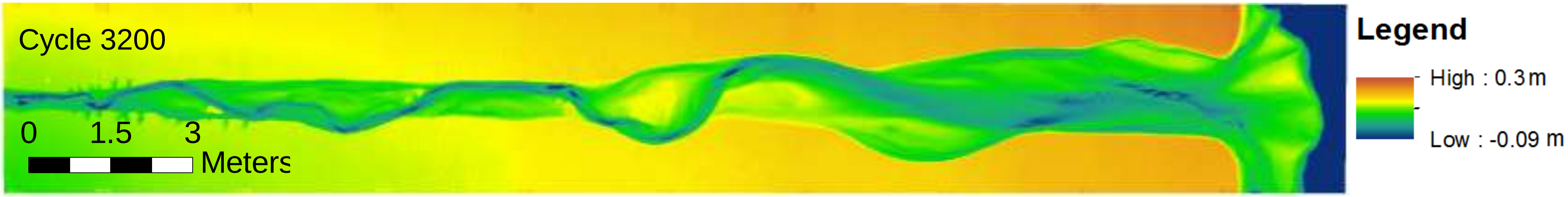

Cycle 10915
0
1.5
3
Meters
Legend
High : 0.3 m
Low : -0.08 m

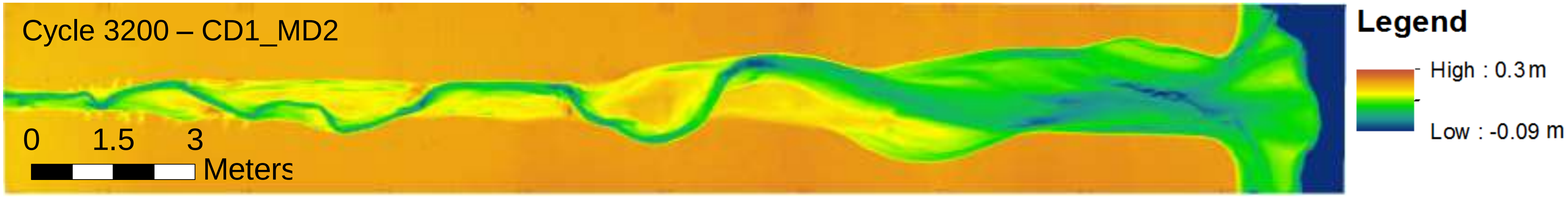

Cycle 13076
0
1.5
3
Meters
Legend
High : 0.3 m
Low : -0.08 m

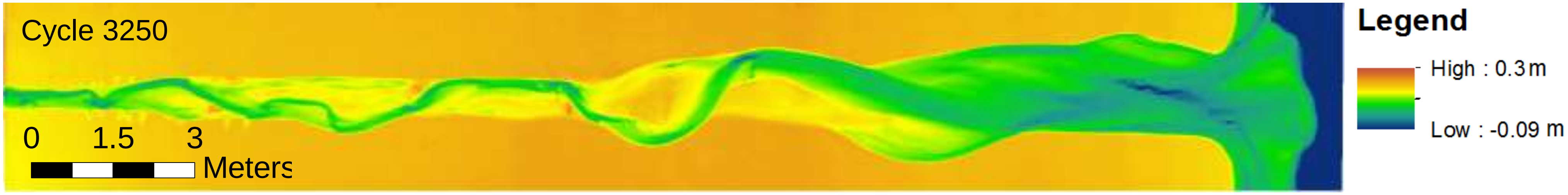
Appendix 3: DEMs of the dredged experiment from cycle 3000 until cycle 13000 (end of experiment)

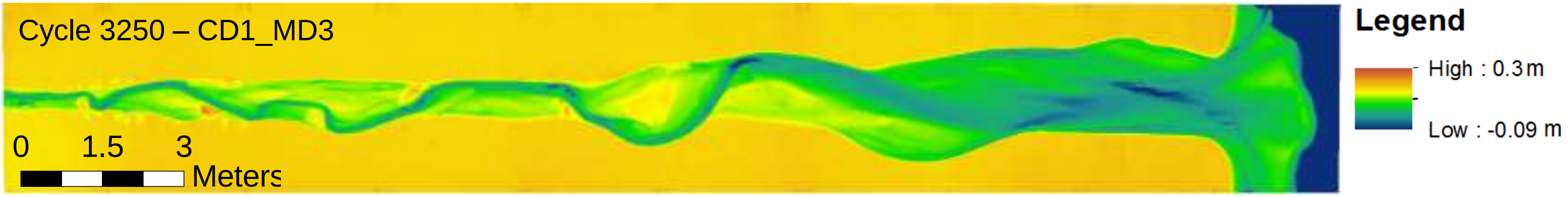


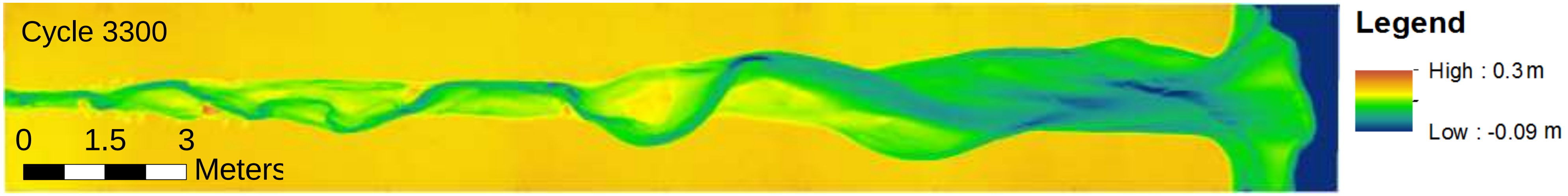


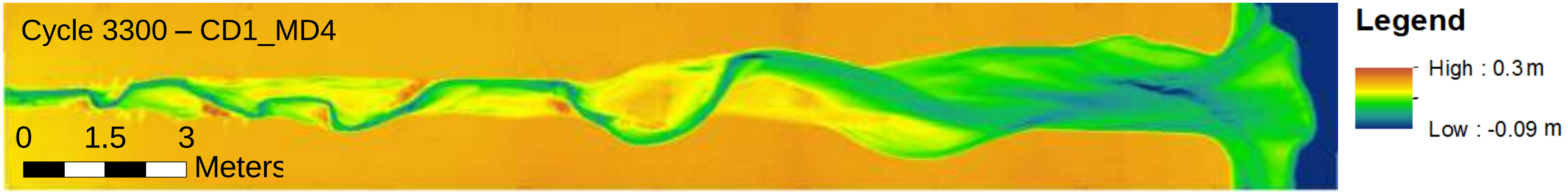


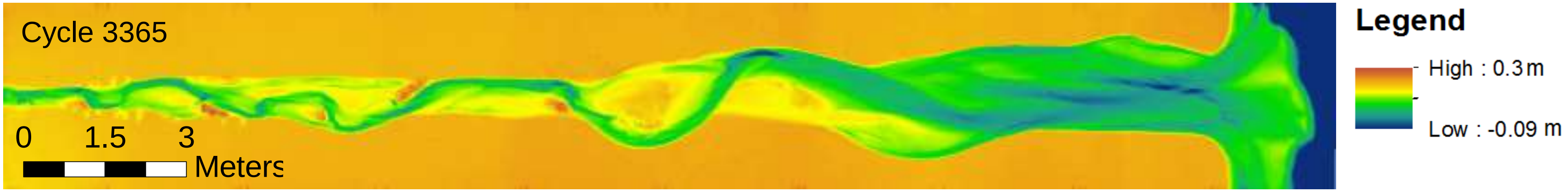


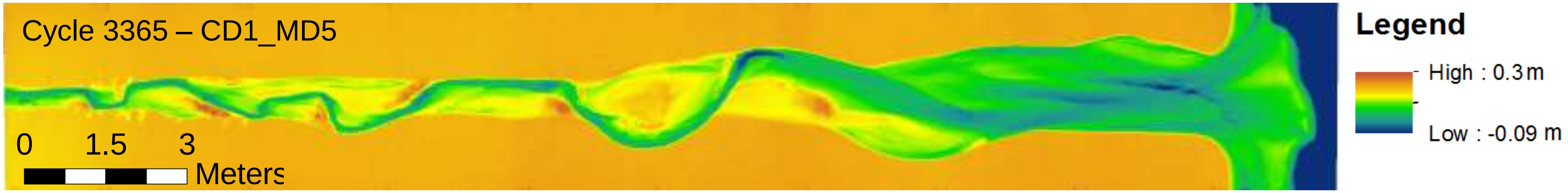


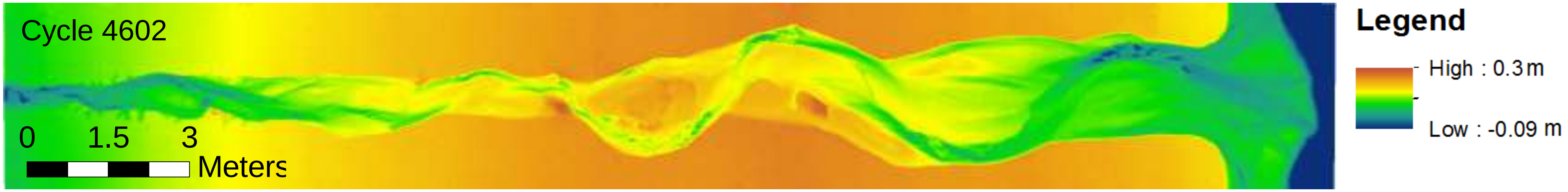

Cycle 3250 – CD1_MD3

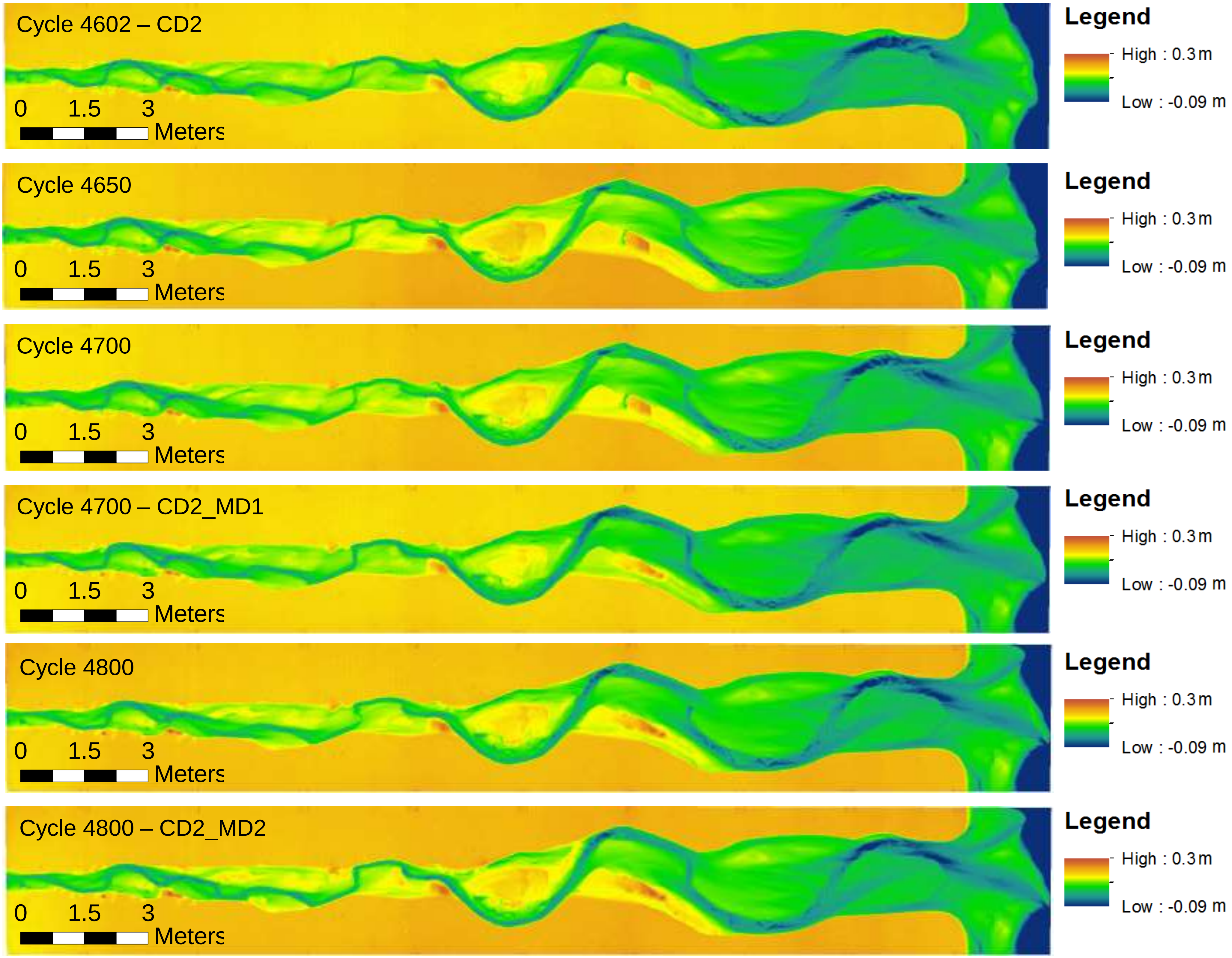

Cycle 3300

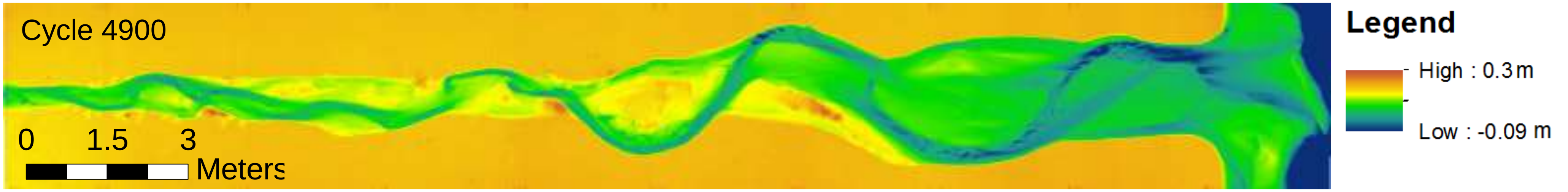

Cycle 3300 – CD1_MD4

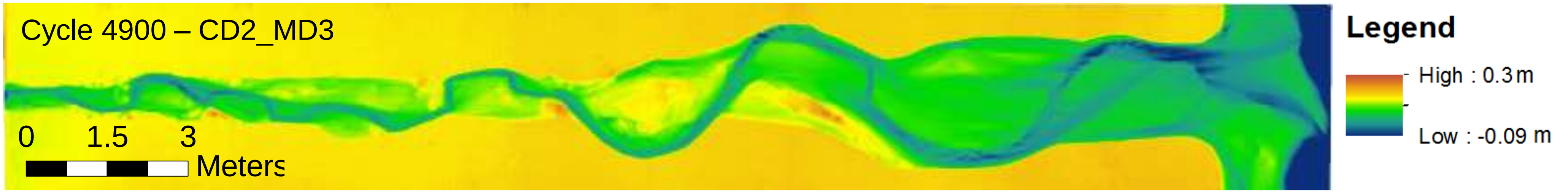

Cycle 3365

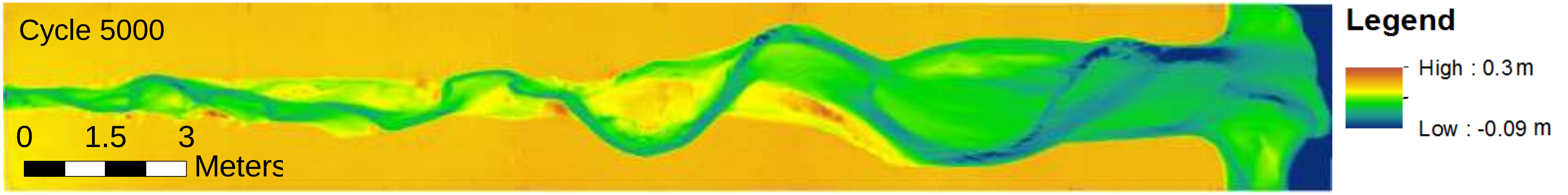

Cycle 3365 – CD1_MD5

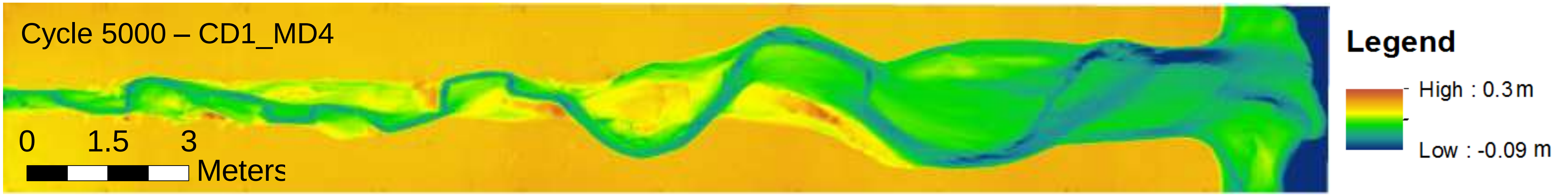

Cycle 4602

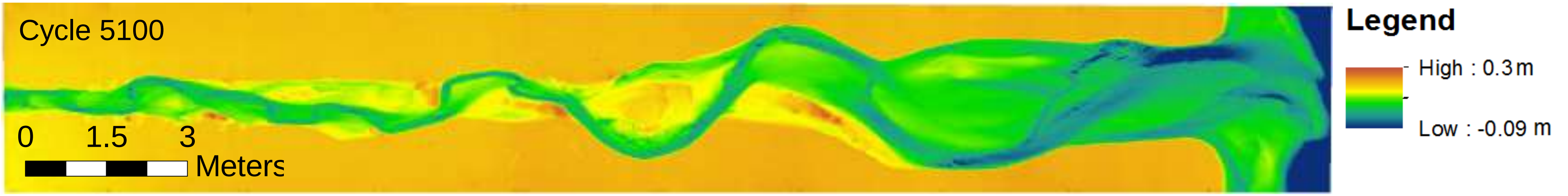

Cycle 4602 – CD2
0 1.5 3
Meters
Legend
High : 0.3 m
Low : -0.09 m
Cycle 4650
0 1.5 3
Meters
Legend
High : 0.3 m
Low : -0.09 m
Cycle 4700
0 1.5 3
Meters
Legend
High : 0.3 m
Low : -0.09 m
Cycle 4700 – CD2_MD1
0 1.5 3
Meters
Legend
High : 0.3 m
Low : -0.09 m
Cycle 4800
0 1.5 3
Meters
Legend
High : 0.3 m
Low : -0.09 m
Cycle 4800 – CD2_MD2
0 1.5 3
Meters
Legend
High : 0.3 m
Low : -0.09 m

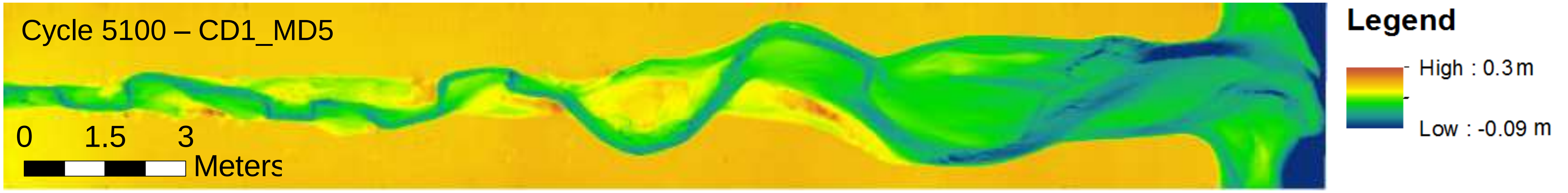

Cycle 4900

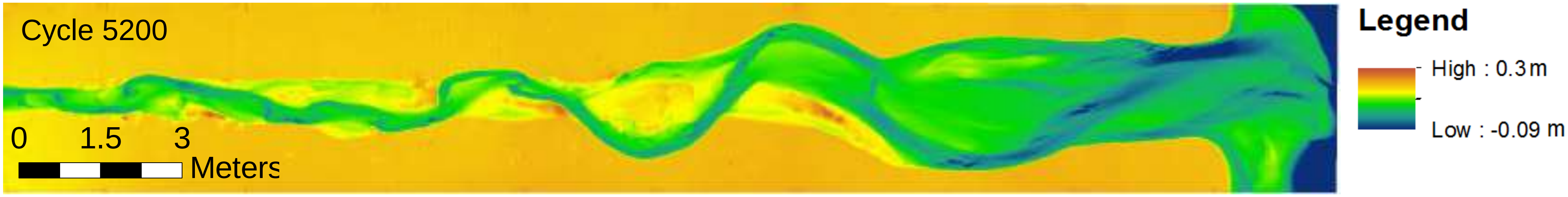

Cycle 4900 – CD2_MD3

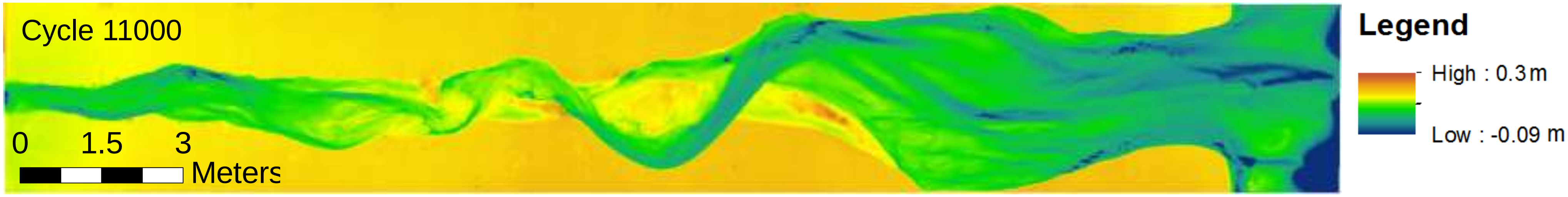

Cycle 5000

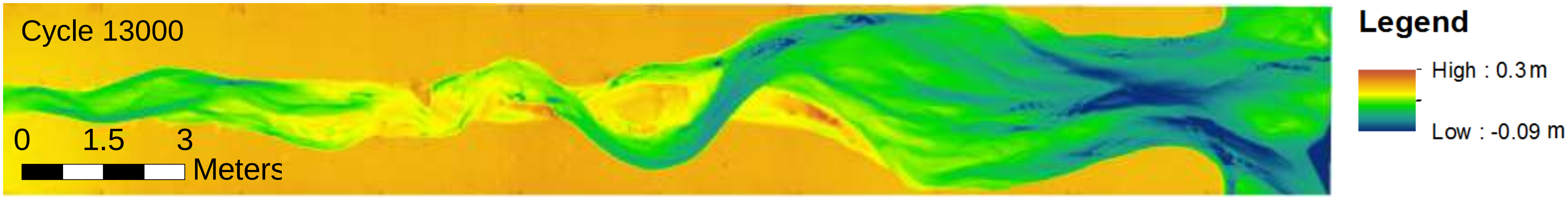

Cycle 5000 – CD1_MD4


Cycle 5100


Cycle 5100 – CD1_MD5


Cycle 5200
0
1.5
3
Meters
Legend
High : 0.3m
Low : -0.09 m


Cycle 11000
0
1.5
3
Meters
Legend
High : 0.3m
Low : -0.09 m


Cycle 13000
0
1.5
3
Meters
Legend
High : 0.3m
Low : -0.09 m