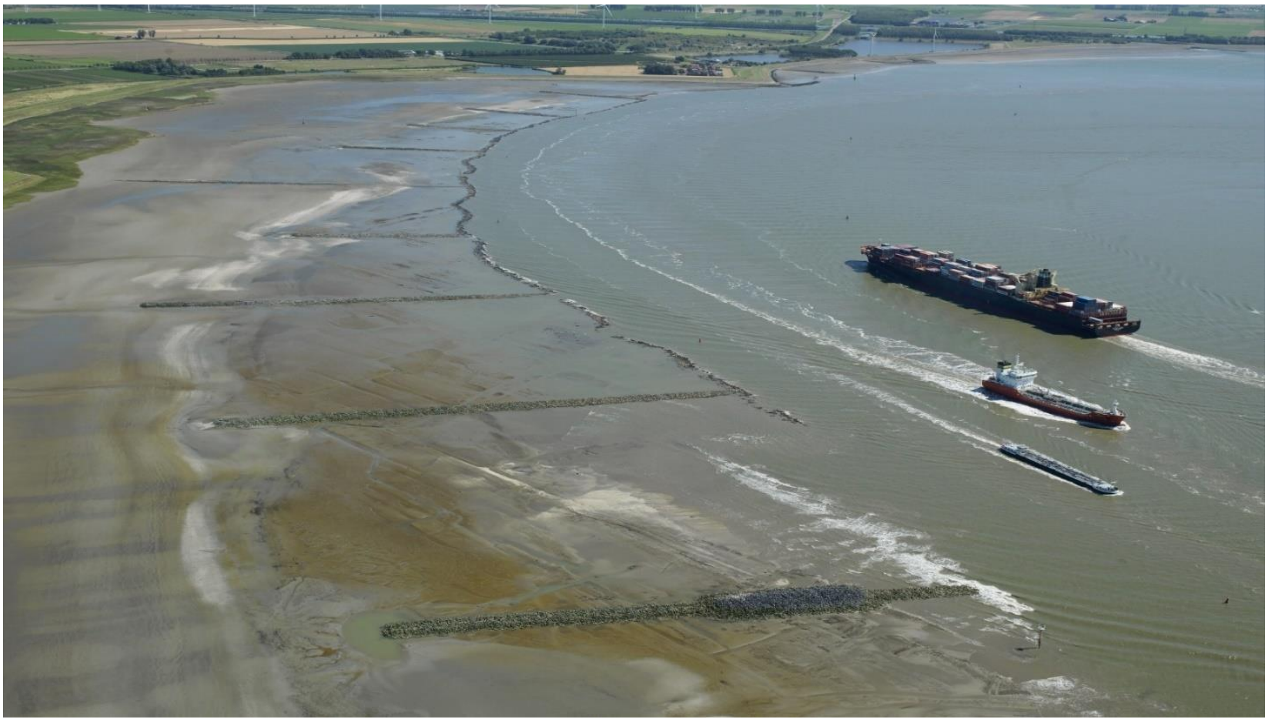
The development of the mean sea level, tidal dynamics and intertidal areas with human interventions in the Western Scheldt estuary, the Netherlands



MSc thesis by Lynn Julia van Wissen van Veen

Hydrology and Quantitative Water Management Group, Wageningen University

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The development of the mean sea level, tidal dynamics and intertidal areas with human interventions in the Western Scheldt estuary, the Netherlands

Master thesis Hydrology and Quantitative Water Management Group in partial fulfilment of the degree of Master of Science in the Climate Studies master programme at Wageningen University, the Netherlands

Lynn Julia van Wissen van Veen

Student number: **1002163**

HWM-80436

Chair group: **Hydrology and Quantitative Water Management Group**

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Supervisors: **prof. dr. ir. Ton Hoitink**

dr. Jasper Leuven

Examiner: **dr. ir. Claudia Brauer**

Abstract

Estuaries are located at the transition from a river to the ocean and serve many different roles. External perturbations such as human interventions can have a large impact on the functioning of the estuarine system. For reasons of data availability, this study uses the Western Scheldt estuary in the Netherlands as an example to investigate impacts of human interventions. The first objective was to investigate if trends in mean sea level, tidal dynamics and the morphological development of the intertidal areas were continuous or that trend breaks occurred. The second objective was to create an overview of the local and large-scale human interventions that occurred in the estuary in between 1950-2020 to simplify linking sudden changes in these trends to human interventions. The trends in tidal dynamics were examined by investigating tidal range, high and low water levels of four measurement stations. Trends in morphological changes of the intertidal areas were examined by investigating changes in surface area, sediment volume, average and maximum height of three intertidal areas that were distributed over the estuary. The Pettitt test was used to detect change points within the trends and a timeline was created to gain an overview of the human interventions. In addition, context and perspectives of other studies were used for verification of the links found by this research. Results of this study show that several change points occurred within the trends of the mean sea level, tidal dynamics and morphology of the intertidal areas. In addition, all change points coincided with the timing of specific human interventions that are related to maintaining and improving navigability. In conclusion, this study gives insights in the continuity of several trends that occurred in the Western Scheldt and proposes a simple and effective method that makes possible links between sudden changes in trends and human interventions visible. This method can be used as starting point of research and can also be applied to case studies of other regions.

Keywords

Intertidal areas, mean sea level, estuary, tidal dynamics, morphology, Western Scheldt, human interventions

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My thanks also goes to my parents who always support me and lent me their car for fieldwork to the Ems and Western Scheldt estuary. Simone and Max were fantastic fellow thesis writers while working in my house and sharing advice and fun. Without them, my thesis experience would have definitely been less joyful as it was very nice working together from the same location and sharing breaks during Corona times. Last but not least, I want to thank my fellow thesis writers from the thesis ring for their much-appreciated feedback.

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Glossary

Intertidal areas	Areas in the estuary that emerge with mean low water and submerge with mean high water level.
Tidal range	The difference between the high and low tide, taking into account spring and neap tides.
Sea level	The average annual water level measured with respect to NAP.
Human interventions	Engineering works like reclamation, dike protection, waterway excavation and sediment supply.

Chapter 1: Introduction

Problem description

Estuaries are located at the transition from a river to the ocean and serve many different roles (Leuven, Pierik, van der Vegt, Bouma, & Kleinhans, 2019). These highly dynamic wetland zones are among the most productive ecosystems in the world by providing valuable ecological habitats and feeding grounds to a large number of marine species (Bouma, de Jong, Twisk, & Wolfstein, 2005). In addition, subtidal channels are often used as shipping fairways to provide access to inland harbours (Bouma et al., 2005; Leuven et al., 2019). Next to this, estuaries provide coastal protection and prevent coastal erosion by attenuating waves and wind (Barbier, 2015).

Intertidal flats are areas within estuaries that emerge with mean low water and submerge with mean high water levels. These areas have an important role, as they inhabit an extensive benthic flora and fauna, provide shoreline stabilisation and storm protection (van Dijk et al., 2019). However, these intertidal flats are under pressure as they are extremely sensitive to external perturbations and climate change (Harley et al., 2006). Several studies showed that human interventions, such as navigation channel deepening, and sea level rise can change the tidal range within the estuary (Arcadis & Technum, 2007; Jiang, Gerkema, Idier, Slangen, & Soetaert, 2020). This affects the sediment transport to the intertidal flats as ebb and flood channels change. Aforementioned can result in changes of the vertical migration of the wetland, the inundation of the low-lying areas and flushing capacity of the estuary (Arbic & Garrett, 2010; Craft et al., 2009; Monsen, Cloern, Lucas, & Monismith, 2002). Next to this, sea level rise and human interventions can cause changes in connecting channels, which affect the spatial extent of intertidal flats and thus important services like food production and coastal protection (de Vet, van Prooijen, & Wang, 2017; Schrijver, 2020; van Dijk et al., 2019).

The Western Scheldt is an estuary in the Netherlands that experiences both anthropogenic interventions and sea level rise (de Vet et al., 2017; Jiang et al., 2020). This has large implications for the intertidal flats within the estuary, as locations, average bed levels, surface areas and volumes of these flats change (de Vet et al., 2017; de Vriend, Wang, Ysebaert, Herman, & Ding, 2011; Schrijver, 2020).

Study area

The Scheldt estuary is located in the southwest of the Netherlands and Belgium. The Western Scheldt is the focus area of this study and the Dutch part of the estuary, see Figure 1. The Western Scheldt experiences a temperature climate with an annual precipitation of about 900 mm and predominantly south-westerly winds (de Vriend et al., 2011). It has a length of about 70 km, a width of about 5km, and is a funnel-shaped estuary (Robke, Elmilady, van der Wegen, & Taal, 2020). Tides are semi-diurnal and the tidal range increases from 3.5 m to 5 m in the upstream direction up to Antwerp (Robke et al., 2020). The river discharge of the Scheldt into the Western Scheldt is a morphologically negligible 120 m^3/s compared to the tidal prism at the mouth of about 1 billion m^3, causing the estuary to be well-mixed (de Vriend et al., 2011; van Dijk et al., 2019). The estuary has a multi-channel system with a regular repetitive pattern, which consists of mutually straight flood channels and evasive meandering ebb channels (de Vriend et al., 2011). These ebb and flood channels are linked by connecting channels and separated by subtidal and intertidal areas. Several anthropogenic measures have been taken in the estuary, such as the construction of breakwaters and deepening of the navigation channel (Robke et al., 2020).

Figure 1 Location of the Western Scheldt estuary in the southwest of the Netherlands.

Justification and objective

The Western Scheldt is a relatively well-researched area. Several studies have focussed on the morphological development of the Western Scheldt. De Vriend et al. (2011) argue that the estuary changed from a sediment importing system to a net exporting system since the 1980s. Van Dijk et al. (2019) state that dredging and disposal strategies are unfavourable to long-term morphology as this causes a further imbalance between the main and secondary channels, and a decrease in surface area of the flats. Schrijver (2020) shows that the main navigation channels have become deeper and that the secondary channels have become shallower since 1955. De Vet et al. (2017) found that the intertidal areas in the Western Scheldt generally increase in height and volume. In addition, they argue that steepening of these flats occurred in recent decades.

Other studies have focussed on the change in tidal dynamics within the estuary. Jiang et al. (2020) state that the tidal dynamics have changed as a result of dredging, sand mining, and modification of shorelines. Kuijper and Lescinski (2013) found that the increase in high waters is higher than the mean sea level rise and that the tidal range increases. Robke et al. (2020) applied several modelling scenarios with different sediment strategies and rates of sea level rise for the period 2020-2100. They argue that in a scenario with a strong increase in sea level rise, a different distribution of deposited sediments or coastal nourishments hardly has any influence on the high and low water levels anymore.

Thus, trends in morphological development of the intertidal flats have been thoroughly researched. This research expresses morphological development in changing surface areas, volumes, average and maximum bed levels of the intertidal areas. In addition, trends in mean sea level and tidal dynamics have been investigated for the Western Scheldt. This research defines tidal dynamics as tidal range, and high and low water levels. However, there is little known about the evolution of the trends as there has been limited attention if these trends are continuous or that sudden changes have occurred within the trends. These change points are important as they could be caused by specific events, like navigation channel deepening. Therefore, trend breaks can show a clear link between external perturbations such as human interventions and changes in tidal dynamics or morphology. This study therefore investigates if change points occurred in the evolution of the mean sea level, tidal range, high and low water levels, surface areas, volumes, average and maximum bed levels of the intertidal flats.

In addition, this study aims to create an overview of the human interventions that occurred within the Western Scheldt in the period 1955-2020. Some studies have already extensively described the navigation channel deepening and deposit strategies that were applied within the estuary (de Vriend et al., 2011; Robke et al., 2020; Schrijver, 2020; van Dijk, W; Leuven, J; Kleinhans, M; Cleveringa, J; Taal, 2020). Others have mentioned coastal protection measures (Bolle, Bing Wang, Amos, & De Ronde, 2010; de Vet et al., 2017). However, there is no clear graphical overview of both the activities related to maintaining navigability and activities related to shoreline management. By combining literature, an overview of the local and large-scale human interventions can be created for the Western Scheldt. In this way, it can be assessed if sudden changes in mean sea level, tidal dynamics or morphology of the intertidal areas can be linked to human interventions in a simple and effective way.

The first objective of this study is therefore to investigate if trends in mean sea level, tidal dynamics and the morphological development of the intertidal were continuous or that trend breaks occurred. The second objective is to create an overview of the local and large-scale human interventions to simplify linking sudden changes in these trends to human interventions.

Research questions

The trends of the mean sea level, tidal dynamics and morphological changes of the intertidal areas and links to human interventions will be researched by answering the following mean research question: how did the mean sea level, tidal dynamics and intertidal areas of the Western Scheldt evolve and is there a link between changes within these trends and human interventions between 1950-2020?

This research question will be answered by investigating the following sub-research questions.

1. *How did the local sea level develop?*
2. *How did the tidal dynamics develop?*
3. *How did the intertidal areas develop?*
4. *Which human interventions took place?*
5. *What is the relation between the human interventions and changes in mean sea level, tidal dynamics, and development of the intertidal areas?*

Reading guide

This document consists of five chapters. Chapter 2 describes the methodology used, i.e. how the research was carried out. Chapter 3 describes the trends of the mean sea level, tidal dynamics and morphology of the intertidal areas in the period 1950-2020. In addition, a graphical overview of the human interventions is shown. Links between sudden changes within trends and human interventions are also described. Chapter 4 compares results to other studies and evaluates if connecting change points of trends to human interventions displayed in a timeline is a valuable starting method to investigate links in an easy and effective way. In addition, this chapter elaborates on the limitations of this research, provides suggestions for further research and describes the wider implications for the application of the method developed by this research. Chapter 5 presents the conclusions of the thesis.

Chapter 2: Methodology

Introduction

This chapter concerns which data was collected, how it was processed and analysed. The period from 1950-2020 was analysed for this research, which was based on data availability. An overview of the parameters that were researched is shown in Table 1 and this will be elaborated on in the following sections. In the first section the data availability, collection, data processing and analysis are explained for mean sea level, in the second section for the tidal dynamics and in the third section for the morphological changes of the intertidal areas. In the fourth section, it is explained how the overview of the local and large-scale human interventions was made. The last section explains how changes in trends of mean sea level, tidal dynamics and morphology were linked to human interventions.

Table 1 Overview of parameters that were researched for this study.

Parameter	Unit	Data since	Source
Mean sea level	Converted with respect to Normal Ordnance Datum (NAP) and expressed in cm.	1880	Permanent Service for Mean Sea Level
High and low water levels	Measured with respect to Normal Ordnance Datum (NAP) and expressed in cm.	1950	Rijkswaterstaat
Average and maximum bed levels	Measured with respect to Normal Ordnance Datum (NAP) and expressed in cm.	1955	Rijkswaterstaat
Surface area intertidal flats	Expressed in m^2.	1955	Rijkswaterstaat
Volumes of the intertidal flats	Expressed in m^3.	1955	Rijkswaterstaat

Mean sea level

Data availability and collection

The local mean sea level, which is defined as the average annual water level measured with respect to Normal Ordnance Datum (NAP), was measured at Vlissingen. Vlissingen is the only sea level measurement station available in the estuary. The local mean sea level data is available for the period 1880-2020 and measured every year by the Permanent Service for Mean Sea Level (PSMSL). The data was expressed in millimetre and defined approximately 7000 millimetre below mean sea level to avoid negative numbers in the annual mean values (PSMSL, 2020).

Data processing and analysis

For this research, the data was converted to centimetre and defined with respect to NAP. A relevelling of NAP in 2005 was also taken into account. Two different methods of analysis were combined to detect trends and trend breaks:

Linear regression

A linear regression method, the parametric t-test method, was conducted to test long-term linear trends for the mean sea level. In addition, the slope of the regression equation was tested for statistical significance, with a p-value less than 0.05 indicating statistical significance.

Pettitt test

The Pettitt test is a generic, widely applied method to test the null hypothesis of no change in a data series when the initial distribution of the data is unknown (Vellinga, Hoitink, van der Vegt, Zhang, & Hoekstra, 2014). The identification of change points in a time series can be statistically confirmed or rejected by the Pettitt test (Pettitt, 1979), with a p-value less than 0.05 indicating statistical significance. That is why the Pettitt test was used to examine the change points in the mean sea level timeseries.

Tidal dynamics

Data availability and collection

Water level data from Rijkswaterstaat, which is in charge of Public Works and Water Management in the Netherlands, were used to analyse the trends of the high and low water levels within the estuary. The high and low water levels were available twice per day for the period 1950-2020 and used to calculate per measurement station the tidal range, average high and low water levels per year.

The selection of water level measurement stations was based on their location and data availability. It was decided to use data from stations that are relatively evenly spread across the estuary to represent different parts of the Western Scheldt. Next to this, the measurement stations had to contain complete and continuous datasets for at least sixty years to ensure statistical validity of the trend and correlation of the results. The stations of Vlissingen, Terneuzen, Hansweert and Bath met the two requirements and were therefore used. For the locations of the measurement stations within the estuary, see Figure 2 and Appendix 1.

Until 1986, the water level data were created by specifically measuring the peaks of the high and low water. For Bath, this was done reading a fixed gauge until 1957. Until that time, the observers used tide predictions and they were trained to wait to make sure that the highest/lowest water level was measured. In addition, short-term fluctuations due to wind and shipping waves were averaged out. From 1957-1986, surveyor sheets were used to determine the high and low water levels for Bath. For Terneuzen, Hansweert and Vlissingen surveyor sheets were used from 1950-1986. Since 1987, the high and low water levels are calculated with a spline approximation from the ten-minute measurement data for all measurement stations.

Data processing and analysis

The annual tidal range was calculated by subtracting the annual average high water level from the annual average low water level for the period 1950-2020. In addition, the following methods were applied to investigate the trends of the tidal range, high and low water levels:

Linear regression

A linear regression method, the parametric t-test method, was conducted to test long-term linear trends. Linear regression graphs were made for the locations Vlissingen, Terneuzen, Hansweert and Bath. In addition, the slope of the regression equations were tested for statistical significance, with a p-value less than 0.05 indicating statistical significance.

Pettitt test

The Pettitt test was used to examine the change points in tidal range, high and low water levels timeseries for the four measurement locations. Change points with a p-value less than 0.05 indicated statistical significance.

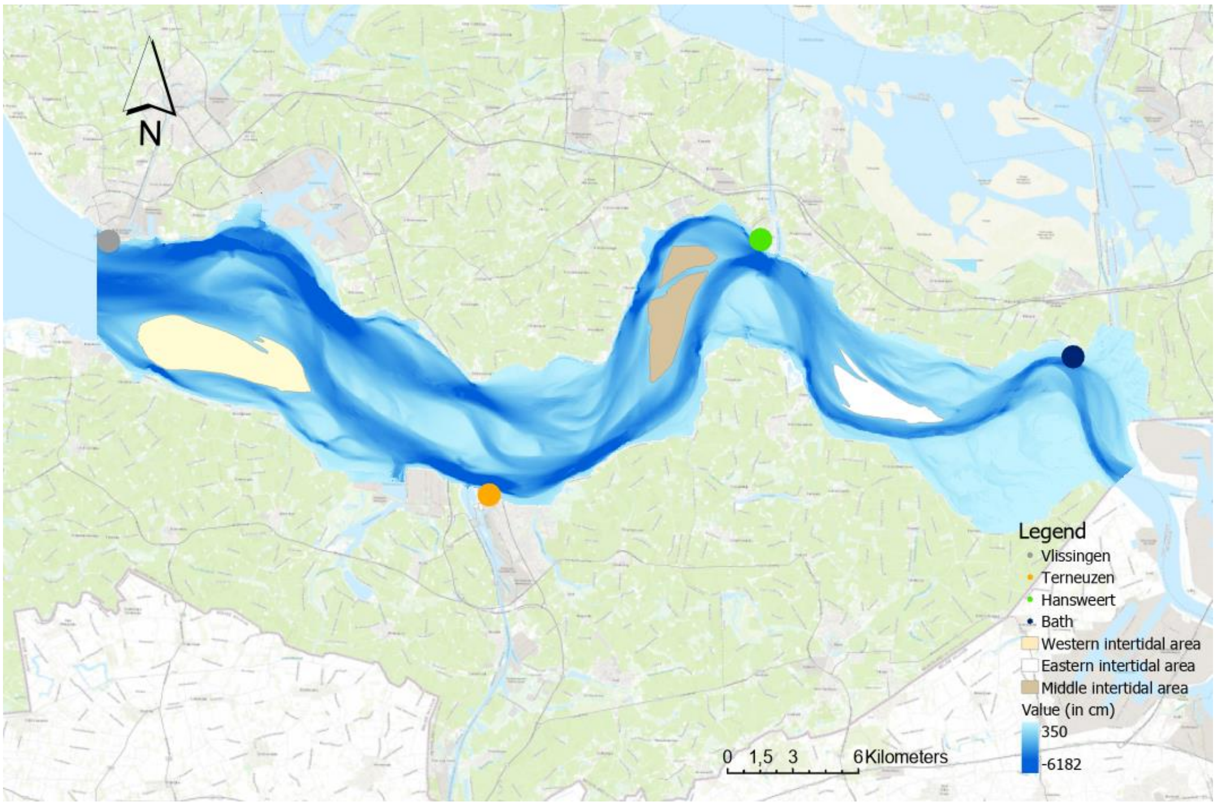

Figure 2 Overview of the water level measurement stations and intertidal areas that were used for this research. Data was retrieved from Rijkswaterstaat and PSMSL.

Intertidal areas

Data availability and collection

Bathymetry data, so called Vaklodingen, from Rijkswaterstaat were used to analyse the trends in morphological changes of the intertidal areas. The data were available for the period 1955-2015 and used to calculate tidal flat surface areas, volumes, average and maximum bed level heights. Until 2001, the bathymetry data were created using single-beam measurements at 100-200 m transects (van Dijk et al., 2019). Since 2001, the bathymetry of the Western Scheldt estuary has been measured with lidar and has therefore a higher resolution of 1 to 5 m.

It was chosen to analyse specific tidal flats that are distributed over the estuary, as this allows examination of local impacts caused by external perturbations. The choice of the intertidal areas was based on their location and minimum bed levels. First, it was decided to select three intertidal areas in total; one in each sub-area of the Western Scheldt. In this way, the western, middle and eastern part of the estuary were represented (see Figure 2).
Second, the intertidal areas had to be surrounded by channels to make sure that they are not attached to the main land as this allowed a robust comparison of the flats. The third requirement with the selection of the intertidal areas was the minimum height of the bed levels. This was chosen to be maximum 225 cm below mean sea level, as this is the maximum low water level. Areas that are

situated lower than this reference level, will not emerge with low water levels. Therefore, they are not defined as intertidal areas as they are permanently under water. Due to large amount of data and the sake of time, this study analysed the morphological change of the flats per decade. By delineating and analysing the three intertidal flats in the same way, the local morphological dynamics were researched in a systematic way.

The approach that was used to delineate the intertidal areas results in areas that change in space and time. This is because the intertidal areas are dynamic and change in location and height throughout the years. Before choosing this approach, this research first investigated both the impact of selecting intertidal areas based on a reference level or a fixed location. The three intertidal areas that were delineated at the start of the timeseries in 1955 were used as fixed location throughout the period of interest. However, by comparing the areas of both fixed and flexible polygons it was decided that the fixed approach was not reliable. This is because minimum, maximum, median and average values of bed levels significantly differed between these two approaches. In addition, it was visible that the fixed polygons did not represent the intertidal areas with a delineation from 2.25 m below mean sea level anymore the further the time proceeded due to the movement of these flats. That is why it was chosen to only implement the approach where intertidal areas where based on their reference level.

A part of the intertidal areas consists of air instead of sediment. However, this was not taken into account in the calculations of the sediment volumes, as it is unknown what the exact air-sediment ratio is for the three flats.

Data processing and analysis

The linear regression and Pettitt test methods were applied to investigate the trends and trend breaks of the morphological changes.

Linear regression

A linear regression method, the parametric t-test method, was conducted to test long-term linear trends for the surface areas, sediment volumes, average and maximum bed levels of the Western, Middle and Eastern intertidal flat. The slope of the regression equations were also tested for statistical significance, with a p-value less than 0.05 indicating statistical significance.

Pettitt test

The Pettitt test was used to examine the change points in the trends of the surface areas, sediment volumes, average and maximum bed levels. Statistical significance was indicated by change points that contained a p-value less than 0.05.

Human interventions

Data availability and collection

Literature review

A literature review was done, which helped to develop a timeline for the anthropogenic measures in the period 1950-2020 for the Western Scheldt. It was chosen to create a timeline for the human interventions, as this allows a clear graphical overview of the timing and duration of the measures. Human interventions that were included had to be engineering works like dredging, sediment supply, the construction of channels or coastal protection measures.

Peer-reviewed journal articles of de Vet et al. (2011), de Vriend et al. (2011) and van Dijk et al. (2019) were used to create an overview of the dredging and disposal activities. Reports from Kuijper and Lescinski (2013), Robke et al. (2020) and Schrijver (2020) were used to gain an overview of the local shoreline management measures, their duration and timing. It was chosen not to include and analyse the effects of the Deltaworks and the closure of the Haringvliet and Grevelingen. This is because Kuijper and Lecinski (2013) already showed that these closures did not result in changes in tidal dynamics or morphology of the Western Scheldt.

Linking changes in trends to human interventions

Data availability and collection

The timeline and change points generated in the previous sections were used to research links between human interventions and sudden changes in trends of the mean sea level, tidal dynamics and morphology of the intertidal areas. In addition, a literature review was done to verify the links established in this research.

Data processing and analysis

The timing of the change points in the trends was compared to the timing of the human interventions in the timeline. In this way, it was investigated if human interventions could be linked to significant changes in mean sea level, tidal dynamics and morphological changes of the intertidal areas.

In addition, a literature review was done to check if other studies established relationships between changes in mean sea level, tidal dynamics or morphology of the flats and human interventions around the trend breaks found by this study. The studies that were used for this verification specifically focussed on investigating the relationships between the anthropogenic measures and changes within the estuary. The studies from Dangendorf et al. (2019), Chen et al. (2017), and Church and White (2006) were used to verify the trend in mean sea level and the explanation for the trend break. The studies from Schrijver (2020) and Kuijper and Lescinski (2013) were used to check if links were found between the human interventions and changes in tidal range, high and low waters around the breakpoints. The studies from Schrijver (2020), van Dijk et al. (2019), de Vet et al. (2017), and de Vriend et al. (2011) were used to verify the links between human interventions and the change in surface areas, volumes and average bed levels of the intertidal areas around the trend breaks found by this study.

Chapter 3: Results and interpretation

This chapter shows the studied trends and gives an overview of the human interventions. The first part shows the trend for the mean sea level. In the second part, the trends in tidal range and high and low water levels are shown. The third part elaborates on the trends in surface area, sediment volume, average and maximum height of the intertidal areas. The fourth part gives an overview of the interventions that have occurred within the estuary. The last part shows links between human interventions and changes in trends of mean sea level, tidal dynamics and morphology of the flats.

Mean sea level

The mean sea level has increased significantly with an average growth rate of 1.5 x 10^{-4} m/year for the period 1950-2019 (see Figure 3). This is about 0.10 m for the period of interest. Based on the Pettitt test, a change point was found in 1980. From 1980 onwards, the mean sea level started to increase with about twice its speed.

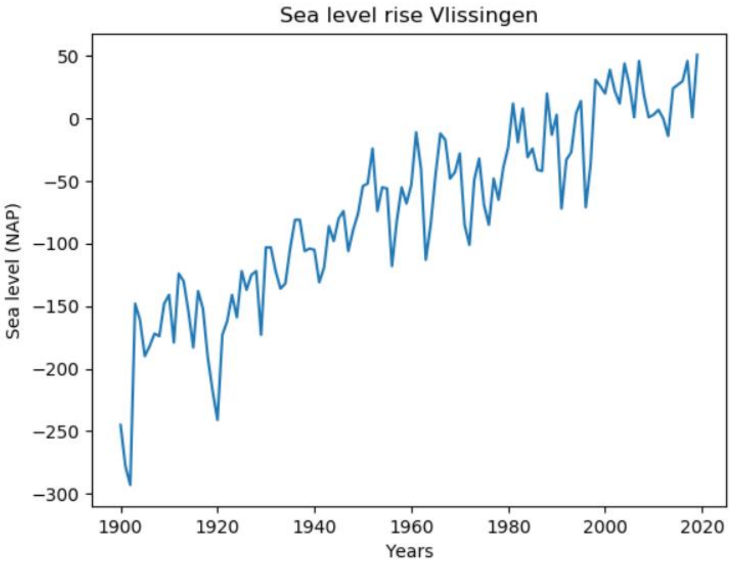

Figure 3 Mean sea level measured at Vlissingen. Measurements have been done by the Permanent Service for Mean Sea Level (PSMSL).

Tidal dynamics

This section explores how the tidal dynamics developed through time. The main focus will be on yearly average values of tidal range, high and low water levels.

Tidal range

There is a long-term cyclic pattern in the tidal range (see Figure 4). The tidal range increases in absolute height from the estuary mouth (Vlissingen) in the landward direction (to Bath). The tidal range not only increases in space, but also over time for all four measurement locations (see Figure 4 and Appendix 2). This means that the difference between the high and low tide becomes larger. The increase of the tidal range in between 1950 and 2020 was the largest for Bath, subsequently followed by Hansweert, Terneuzen and Vlissingen (see Appendix 2).

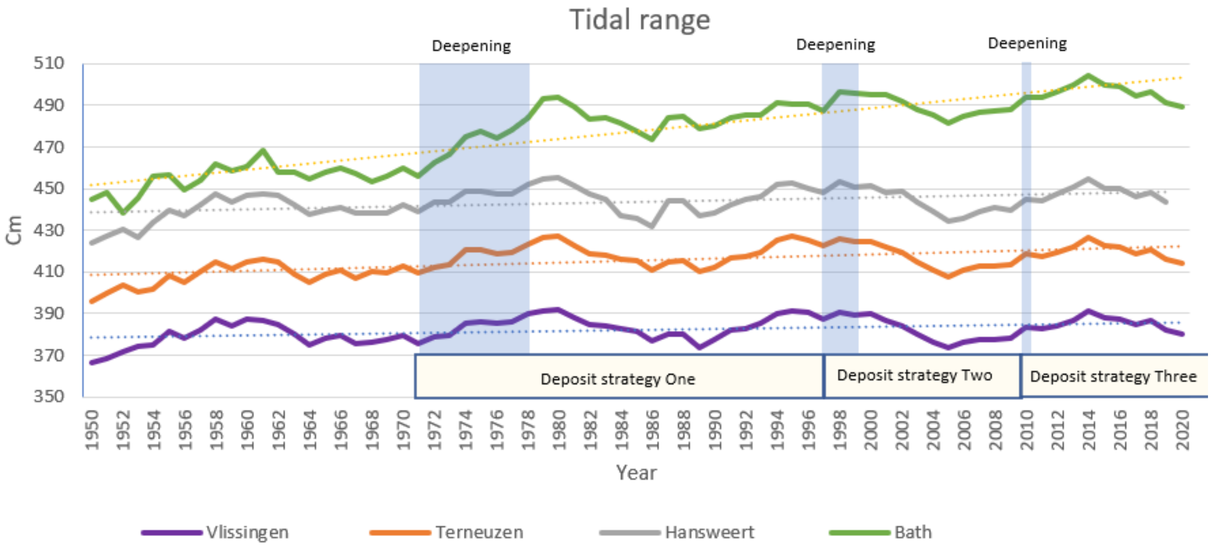

Figure 4 An overview of the tidal range evolvement, displayed per measurement location. In addition, the navigation channel deepening and deposit strategies are displayed in time.

Based on the Pettitt test, several change points within the tidal range timeseries were found. For both Vlissingen and Terneuzen, a change point was found in 1974. For Hansweert no change points in the trend of the tidal range were found. Bath appeared to have a change point in 1978.

High water levels

From estuary mouth in the landward direction the high water levels increase in absolute height (see Figure 5). It was found that for all four measurement locations the high tides increased significantly in time. Bath had the highest increase, followed by Hansweert, Terneuzen, and Vlissingen (see Appendix 2).

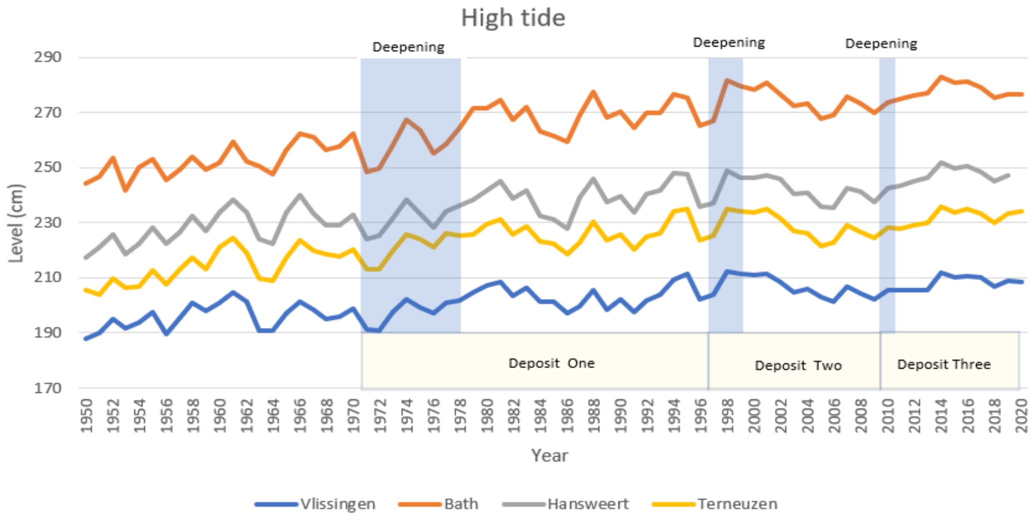

Figure 5 An overview of the high water levels evolvement, displayed per measurement location. In addition, the navigation channel deepening and deposit strategies are displayed in time.

Based on the Pettitt test, several change points within the high water level timeseries were found. For Vlissingen, a change point was found in 1979. For Terneuzen, a trend break was found in 1977, for Hansweert in 1987 and for Bath in 1979.

Low water levels

From the estuary mouth in the landward direction the low tides decrease in absolute height, which means that the tides become lower in space (see Figure 6). The low tides of Vlissingen, Terneuzen and Hansweert increased significantly in height during the research period (see Appendix 2). For Bath, the low tides became significantly lower since 1970 (see Figure 6 and Appendix 2). It was also found that the average increase of the high waters is significantly higher than the average increase of the low waters for all measurement stations during the research period.

Based on the Pettitt test, several change points within the low water level trends were found. For Vlissingen, a change point was found in 1983. For Terneuzen, a change point was found in 1998, for Hansweert in 1983 and for Bath in 1976.

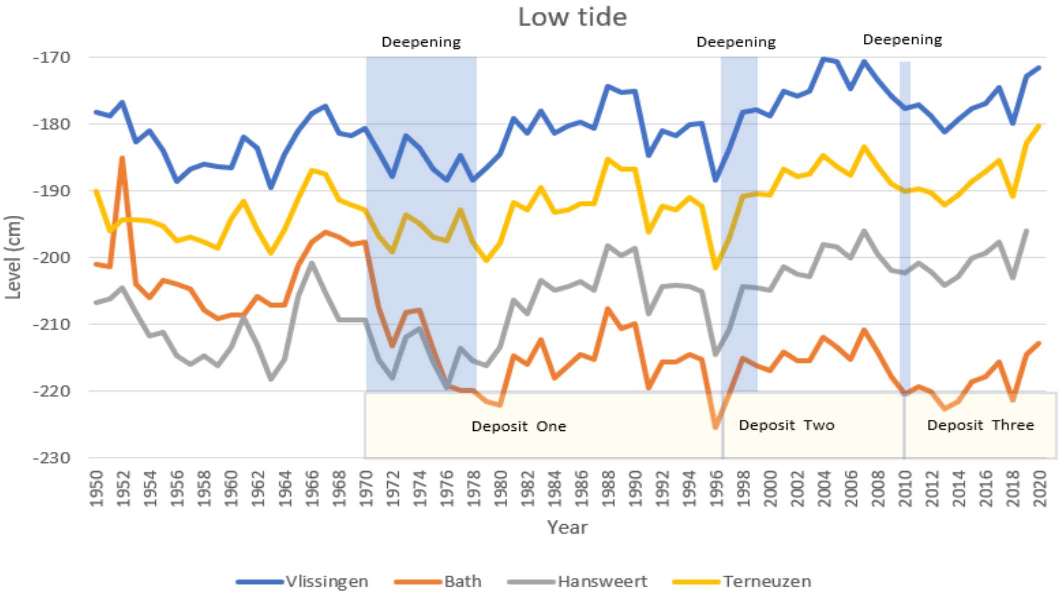

Figure 6 An overview of the low water levels evolvement, displayed per measurement location. In addition, the navigation channel deepening and deposit strategies are displayed in time.

Intertidal areas

This section explores how the intertidal areas have developed through time. The main focus will be on yearly average values of surface area, sediment volume, and average and maximum height.

Surface area

The surface area of both the Middle and Eastern intertidal area decreased, with a downward trend from 1975 onwards (see Figure 7). For the Middle intertidal area a change point in the surface area trend was found in 1975, for the Eastern intertidal area in 1988. The decrease of the Middle intertidal area (from about 41,000 m^2 to 20,000 m^2) was significant and larger than the decrease of the Eastern intertidal area (from 17,000 m^2 to 11,000 m^2). The Western intertidal area has overall increased in area, which is due to a large increase since 2005 (see Figure 7). This change in 2005 for the Western flat coincided with the trend break found in this year with the Pettitt test.

Volume

The sediment volume has significantly increased for all three intertidal areas (see Appendix 3). This increase was the highest for the Western intertidal area (155,000 m^3/year), followed by the Eastern (103,000 m^3/year) and Middle intertidal area (47,000 m^3/year). No change points in the trends of the three intertidal areas were found with the Pettitt test.

Average and maximum height

The average height of all three flats has increased significantly during the period of interest. This increase was the largest for the Eastern intertidal flat, subsequently followed by the Western and Middle flat (see Appendix 3). This means that the average height of the Eastern intertidal area has risen from below to above sea level (from -0.91 m to 0.48 m) from 1988 onwards (see Figure 7). The average height of the Western intertidal area remained above sea level (from 0.06 m to 0.62 m), and for the Middle intertidal area below sea level (from -0.61 m to -0.08 m). Based on the Pettitt test, for both the Western, Middle and Eastern flat a change point in the trend of the average height was found in 1975.

Next to this, the maximum height of all three intertidal areas has also increased (see Figure 7). This increase was significant and the largest for the Eastern intertidal area, subsequently followed by the increase in maximum height of the Western and Middle flat (see Appendix 3). For all three intertidal areas the maximum height is well above mean sea level, as this changed for the Western intertidal area from 2.56 m to 2.83 m above NAP, for the Middle area from 1.40 m to 1.51 m above NAP, and for the Eastern flat from 1.44 m to 2.64 m above NAP. For the Western flat, a change point in the trend was found in 1996, for the Middle flat in 1988 and for the Eastern flat in 1975.

Figure 7 Evolution of the Western, Middle and Eastern intertidal areas. Sea level data was retrieved from the Permanent Service for Mean Sea Level and all other data was retrieved from Rijkswaterstaat.

Human interventions

Anthropogenic measures in the Western Scheldt can be divided into two categories: 1) activities related to shoreline management and 2) activities related to maintaining and improving navigability (de Vriend et al., 2011). An overview of the human interventions that occurred between 1950 and 2020 is displayed in Figure 8. The construction of the Perkpolder nature compensation project, and breakwaters in Knuitershoek and Baalhoek relate to shoreline management. The construction of the Scheldt-Rijn canal, navigation channel deepening and the deposition of sediments relate to maintaining and improving navigability.

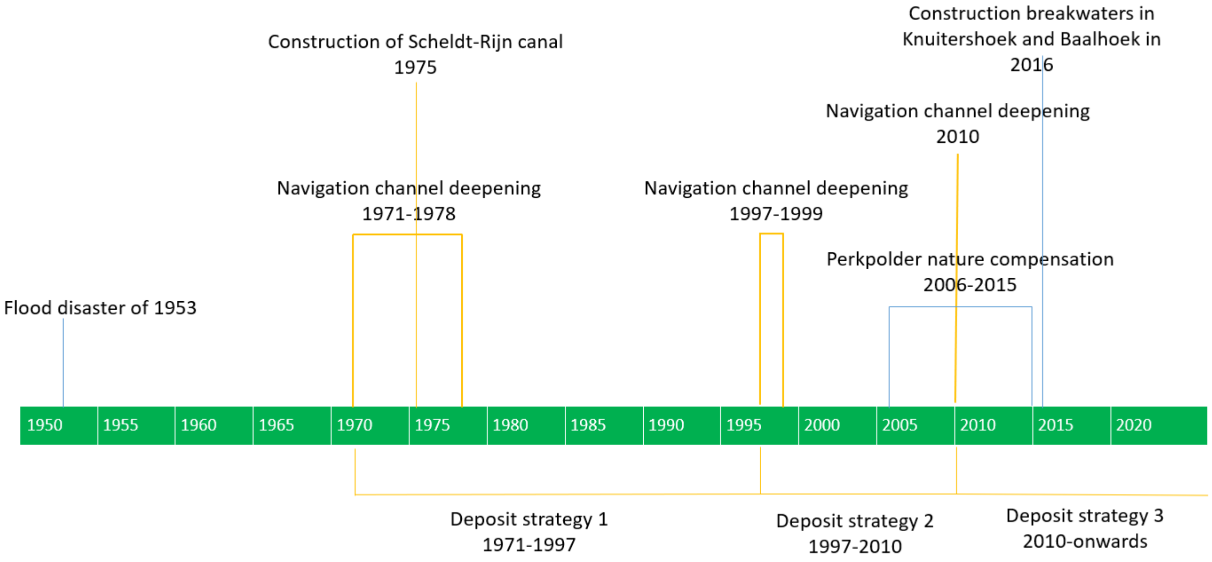

Figure 8 An overview of the human interventions that occurred in the Western Scheldt between 1950 and 2020. The yellow bars indicate measures that are related to maintaining and improving navigability. The blue bars indicate measures that are related to shoreline management.

The navigation channels were deepened three times to keep the ports accessible for cargo vessels of increasing size, see Figure 8 (de Vriend et al., 2011). During the first deepening in the 1970s, the navigation depth was increased from 12 m to 14.5 m. During the second deepening in the 1990s, this was increased by another 1.5 m. In the third deepening, which was carried out in 2010, the navigation depth was increased by another 1.5 m to 17.5 m. Next to this, there were also annual maintenance dredging activities to keep access to the port of Antwerp (van Dijk et al., 2019).

The dredged sediments were moved to other parts in the Western Scheldt, and deposit locations were chosen such that efforts, costs and hindering of the shipping were minimised. Due to optimising the depositing strategy, the locations have shifted.
In Deposit Strategy One from 1971-1987, the dredged materials were deposited as much as possible in the nearest secondary channel (Schrijver, 2020). However, if the dumping rate in the secondary channel exceeds a limit, the two-channel system will develop into a single channel system (Winterwerp; Wang; Stive; Arends; Jeuken; Kuijper; Thoolen, 2001). This can have disadvantages for the ecological value of the multi-channel system, tidal range, flood risks, bank and tidal flat stability, and increases peak velocities in the main channel (van Dijk, W; Leuven, J; Kleinhans, M; Cleveringa, J; Taal, 2020). That is why the deposit strategy was changed from 1997 onwards. During Deposit Strategy Two, sediments from the eastern part of the estuary were deposited in the western part. From 2010 onwards Deposit Strategy Three was implemented. This is the most flexible strategy out of the three strategies, as the approach can be adjusted based on the monitoring of certain quality parameters. In general, sediments are deposited around the same area as where they were dredged, but then on shoal margins.

Links

Change points were found in the trends of the mean sea level rise, tidal range, high and low water levels, average height of the intertidal areas, maximum height, and surface areas (see Table 2). No change points appeared in the trends of the volumes of the intertidal flats. The timing of the change points was compared to the timing of the human interventions in the timeline, see Figure 9. In this way, it was investigated if human interventions could be linked to significant changes in trends of mean sea level, tidal dynamics and morphology of the flats.

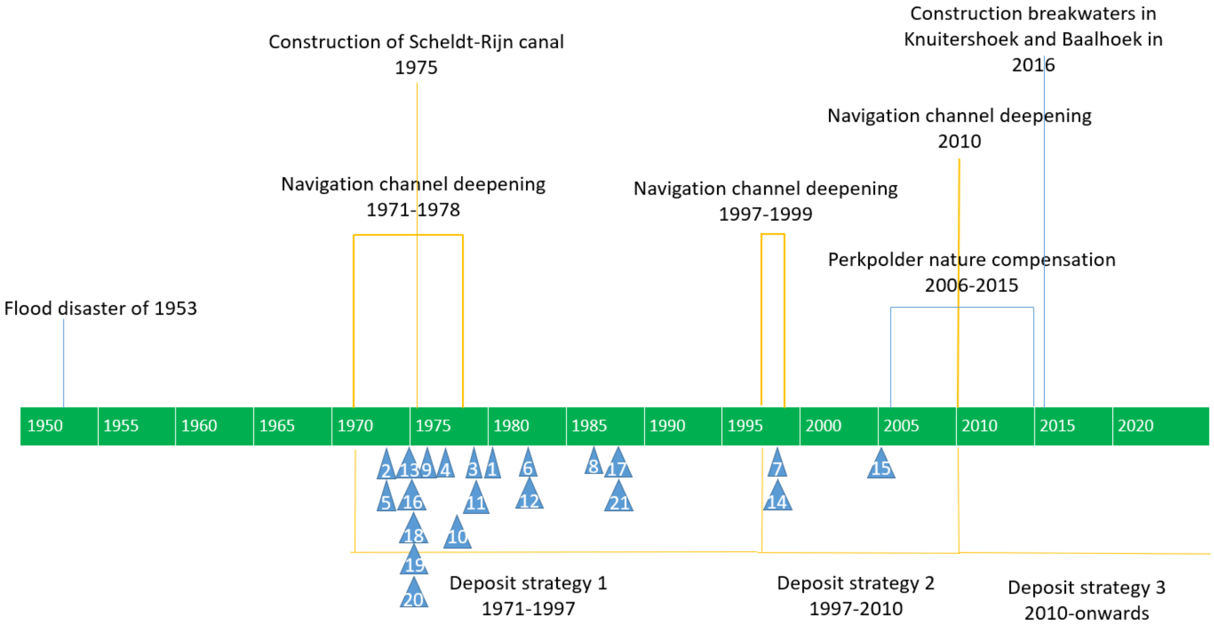

Figure 9 The timing of the change points (blue triangles) compared to the timing of the human interventions. The numbers in the blue triangles indicate the corresponding parameter, which can be found in Table 2.

All change points found, took place during large-scale human interventions related to maintaining and improving navigability in between 1976 and 2005 (see Figure 9). Eighteen out of the twenty one change points occurred during Deposit Strategy One. Out of these eighteen change points, ten occurred also during the first navigation channel deepening. Three out of twenty one change points occurred during Deposit Strategy Two. Out of these three change points, two also occurred during the second navigation channel deepening. Comparisons between specific change points and human interventions will be elaborated on in the Discussion chapter.

Table 2 Overview of the change points, their corresponding number in the graphical overview and applicability.

Location	Parameter	Number in graphical overview	Change point year
Vlissingen	Mean sea level	1	1980
	Tidal range	2	1974
	High water	3	1979
	Low water	4	1983
Terneuzen	Tidal Range	5	1974
	High water	6	1977
	Low water	7	1998
Hansweert	Tidal range	-	-
	High water	8	1987
	Low water	9	1983
Bath	Tidal range	10	1978
	High water	11	1979
	Low water	12	1976
Western flat	Average height	13	1975
	Maximum height	14	1996
	Surface area	15	2005
Middle flat	Average height	16	1975
	Maximum height	17	1988
	Surface area	18	1975
Eastern flat	Average height	19	1975
	Maximum height	20	1975
	Surface area	21	1988

Chapter 4: Discussion

This chapter discusses the timing of specific change points to the timing of the human interventions that are displayed in the timeline. In addition, comparisons are made to other studies to investigate if they established relationships between changes in mean sea level, tidal dynamics or morphology of the flats and human interventions around the trend breaks found by this study. In this way, it is assessed if connecting change points of trends to human interventions displayed in a timeline is a reliable starting method to make possible links visible. In addition, this chapter elaborates on the limitations of this research, provides suggestions for further research and describes the wider implications for the application of the method developed by this research.

Comparisons to other studies

Mean sea level

A trend break was found in 1980 in the mean sea level trend. This change point corresponds to the timing of Deposit Strategy One, see Figure 9. From 1980 onwards, the mean sea level started to increase with about twice its speed, which is in correspondence with the trend of the global mean sea level (Chen et al., 2017; Stocker, T.F.; Qin, G.K; Plattner, M; Tignor, S.K; Allen, J; Boschung, A; Nauels, Y; Xia, 2013). Chen et al. (2017) and Frederikse et al. (2020) investigated the increased rate of global mean sea level rise and stated that is caused by the increased contribution from the Greenland ice sheet and thermal expansion.

The local sea level depends on several factors like air pressure, wind, sea water temperatures, gravitational fields, water depth, friction and flow profiles (Frederikse et al., 2020). Limited attention has been paid to the effects of the human interventions that took place in the estuary on the mean sea level of the Western Scheldt. Deposit Strategy One could have changed the water depth, friction and flow profiles around the measurement station of Vlissingen, causing the trend break. However, other factors like the increased ice-mass loss of Greenland and thermal expansion could also have caused the increased sea level rise. Future research is therefore required that investigates the impact of the human interventions on the local mean sea level. The timeline and change point can be used as starting point to gain an overview of the timing of the trend break relative to the timing of the interventions in the Western Scheldt.

Tidal dynamics

This section compares the timing of the change points found with the Pettitt test for the tidal range, high and low waters to the timing of human interventions. In addition, results are compared to other studies.

Tidal range

Three change points in the trend of the tidal range were found with the Pettitt test. For Vlissingen and Terneuzen the change points occurred both in 1974, for Bath the change point occurred in 1978. These three trend breaks all occurred during Deposit Strategy One and the first navigation channel deepening.

Large-scale dredging occurred in the Western Scheldt, which changed the overall channel depth. This reduced friction for the tidal wave and altered the resonant frequency, which can result in an increased tidal range (de Vriend et al., 2011; Essink, 1999; Talke & Jay, 2020). This is shown in the Western Scheldt estuary, as an increased amplification of the tidal range was observed by this study. It is estimated that the sea level rise explains an increase of the tidal range by 1% in the Western Scheldt (Hollebrandse, 2005; Langendoen, 1987). However, the most prominent observed increase in tidal range relates to the period of the first deepening of the navigation channel from 1971 to 1978 (see Figure 4), which is in accordance with the change points found and findings from Kuijper and Lescinski (2013).

Water levels

Based on the Pettitt test, several change points were found within the low and high water level trends. All change points found, took place during large-scale human interventions related to maintaining and improving navigability in between 1976 and 1998. This study found two change points in high and low water levels, which relate to the period of the first deepening of the navigation channel from 1971 to 1978.

Kuijper and Lescinski (2013) suggest that human interventions such as channel deepening can influence water levels, but that effects could not be retrieved from data records. However, Kuijper and Lescinski (2013) agree that the largest decrease in low tides for Bath was found from 1971 to about 1980, which corresponds to the period of the first deepening of the navigation channel and the change point found in 1976. From 1990 onwards, the downward trend continued for the low water levels of Bath, although at a lower rate. Kuijper & Lescinski (2013) suggest that this can be caused by a change in strategy for maintenance sand mining, dumping and dredging rather than by deepening of the navigation channel only. This research also found minor decreases in low water levels, and no significant change points were indeed detected in the low water levels of Bath after the second and third deepening of the navigation channel.

Schrijver (2020) states that significant changes in water level trends would be the largest in the middle and eastern part of the estuary, as this could be related to the activities of maintaining and improving navigability. This study showed change points for the trends in high and low water levels for both the western, middle and eastern part of the estuary. For example, this research found a change point in the trend in low water levels of Terneuzen in 1998, which is in the western part, during both Deposit Strategy Two and the second navigation channel deepening. During Deposit Strategy Two, sediments from the eastern part of the estuary were deposited in the western part. During the second navigation channel deepening, the channel depth increased with 0.5 m close to Terneuzen. According to Kuijper and Lescinski (2013), tidal volumes have increased significantly in the main channel around Terneuzen after the second deepening. However, no attention has been paid to the effects of this increase in tidal volumes on the local water levels. Further research is therefore needed that investigates and quantifies to what extent the increase in tidal volume and change in deposit strategy both have influenced the change in low water levels around Terneuzen. This knowledge is important, as the comprehension and prediction of low water levels are relevant for ships that want to enter the port of Terneuzen or canal Gent-Terneuzen. The combination of the change points and timeline can be used as a valuable starting point to investigate the links between the timing of the human interventions and the trend break in water levels.

This research did not find change points in the water level trends during small-scale local measures related to coastline management, such as the construction of Perkpolder nature compensation project and the breakwaters in Baalhoek and Knuitershoek. These findings agree with findings from Giardino (2013) and Kuijper and Lescinski (2013), who state that local measures often have a limited impact on the tidal characteristics. Schrijver (2020) specifically stated that the construction of the breakwaters in Knuitershoek and Baalhoek appear to have no effect on changes in the water levels, which is in accordance with findings from this study.

Intertidal areas

This section compares the timing of the change points found with the Pettitt test for the surface areas, average and maximum bed level height of the intertidal areas with the timing of human interventions. In addition, context and perspectives of other studies are used for verification of the links.

Surface area

This research found several change points in the decreasing trends in surface areas of the flats. The change points of the Middle (1975) and Eastern flat (1988) both occurred during Deposit Strategy One, and the change point of the Middle flat also occurred during the first navigation channel deepening. The change point of the Western flat (2005) occurred during Deposit Strategy Two.

The largest change in the decreasing trend of the surface area took place for the Western intertidal area, see Figure 7. Until the change point in 2005, the surface area of the Western flat decreased, but from 2005 onwards a large increase in surface area occurred. This change was also noticed by Schrijver (2020) and de Vriend et al. (2011), who stated that the increase in surface area from 2005 onwards could be related to the second deposit strategy. Sediments from the navigation channel deepening were then deposited in the western part of the estuary and on the ridges of these intertidal areas. In this way, sediments were allowed to slowly move towards the flats, enhancing the Western intertidal area (de Vriend et al., 2011).

Volume

No change points in the trends of the volumes of the intertidal areas were found with the Pettitt test. However, when analysing the trends in sediment volume of the three intertidal areas it was shown that the increase was not continuous through time as there was a sudden decrease in trend from 1988-2015 for the Eastern intertidal area and between 1996-2015 for the Middle intertidal area.

This shows a limitation of the use of the Pettitt test. The ability of the Pettitt test to detect change points depends on the sample size and continuity of the trend (Xie, Li, & Xiong, 2014). It is more difficult for the Pettitt test to detect change points when the sample size is small. In addition, the ability of the Pettitt test to detect change points is reduced when there is a very large variation or a very gradual change in the data series (Xie et al., 2014).

First, because of the sake of time the morphological changes of the intertidal areas were analysed per decade. This resulted in a small sample size and trend breaks that could only be detected per decade. The detection of the change points, and thus the results of this study, for the surface areas, volumes, average and maximum bed levels are impacted because of this. For future research, it is recommended to analyse morphological changes of the flats per year as this provides a closer examination of the trends and allows change points to be assigned to the year in which a sudden change occurs instead of the decade.

Second, the trends in sediment volume show a gradual change as effects occur on a longer timescale due to slower morphological development (de Vriend et al., 2011; van Dijk et al., 2019). This could also explain the lack of detection of change points for the volumes of the flats. Still, effects of the human interventions are visible on the continuity of the trend in sediment volume (van Dijk et al., 2019). From 1976 onwards, dredging volumes increased in the entire Western Scheldt, with most material being dredged in the eastern part (van Dijk et al., 2019). When Deposit Strategy Two started from 1996 onwards, sediments were transported from east to west, which could be linked to the decreasing trends in sediment volumes of the Middle and Eastern intertidal areas (van Dijk et al., 2019). Thus, according to Schrijver (2020) and van Dijk et al. (2019) the sudden decrease in sediment volume from 1988 onwards may be related to the major deepening events and sediment strategies.

It is suggested that future research that investigates trend breaks in gradual trends or trends with a large variation, uses a method based on the two-sample Cramér von Mises test statistic to detect change points (Zhou, van Nooijen, Kolechkina, & Hrachowitz, 2019). The Pettitt test can still be used to detect change points in trends that do not show a large variation or very gradual changes within the timeseries, as the Pettitt test has a high ability to assess the significance of a change (Pettitt, 1979; Xie et al., 2014; Zhou et al., 2019). Thus, it is important to get a clear understanding of the basic characteristics of the studied trend before choosing a change point detection method. In this case, the results of this study are only slightly impacted by this limitation, as most trends analysed did not show very large variation or a very gradual change. That is why the Pettitt test could be applied for all other trends in tidal dynamics and morphology examined.

Average height

This research found for all three intertidal areas a change point in 1975 in the trend of the increasing average heights. After 1975, the increase in average height accelerated for the three flats. The change points occurred during the first navigation channel deepening, Deposit Strategy One and the construction of the Scheldt-Rijn canal.

There has been limited attention to the timing of the human interventions and the accelerated increase in average bed levels of the intertidal areas. However, van Dijk et al. (2019) agree with the increase in average height and state that this increase was not monotonously as the average height of the flats fluctuated substantially. Schrijver (2020) and Kuijper and Lescinski (2013) argue that the increase in average height of the flats in the period 1955-2020 is the result of the different deposit strategies. This is because sand has been distributed in different ways, which resulted in deeper channels and higher intertidal flats (Kuijper & Lescinski, 2013; Schrijver, 2020).

Thus, large-scale anthropogenic measures such as dredging and disposing sediments likely influence the morphological dynamics of the flats. Nonetheless, no studies have quantified yet the impact of the first navigation channel deepening, Deposit Strategy One and the construction of the Scheld-Rijn canal on the accelerated increase of the average bed levels. Establishing quantitative relationships between the human interventions and change points can be complicated as morphological changes often occur on longer timescales and are also influenced by natural factors. Numerical studies are therefore needed to quantify these contributions. This could be done by investigating the impact of isolated parameters that are specified for the Western Scheldt and considered to be relevant (e.g. deepening, depositing, sea level rise, changing water levels) to the change in average bed levels. The timeline can be used as starting point to gain an overview of the timing and duration of the human interventions and to investigate if human interventions could be linked to significant changes in bed levels.

Relevance and implications

This research looked at the trends of the mean sea level, tidal dynamics and morphology of the intertidal areas and several human interventions. Comparisons showed that impacts of human interventions on tidal and morphological dynamics that were investigated by other studies often corresponded with links made in this research between change points in trends and the timing of specific human interventions that were visible in the timeline.

Previous studies that analysed the tidal dynamics and morphology of the intertidal areas of the Western Scheldt can be roughly divided into two categories. The first category of studies mainly investigated the development of the water levels, tidal range and morphology of the flats (Dam, Van Der Wegen, Labeur, & Roelvink, 2016; de Vet et al., 2017; Hollebrandse, 2005; Kuijper & Lescinski, 2013; Schrijver, 2020; Winterwerp; Wang; Stive; Arends; Jeuken; Kuijper; Thoolen, 2001). The second category of studies mainly focussed on the effects of a particular external perturbation, such as dredging or deposition of sediments, on the tidal dynamics or morphology of the intertidal areas (Essink, 1999; Jiang et al., 2020; Nnafie, A; van Oyen, T; de Maerschalck, B; van der Vegt, M; Wegen, 2018; Robke et al., 2020; van Dijk, W; Leuven, J; Kleinhans, M; Cleveringa, J; Taal, 2020; van Rijn, Grasmeijer, & Perk, 2018).

This research showed that a timeline can be used to easily create an overview and compare the timing of the trend breaks to the timing of the specific human interventions. This method complements existing research as it can serve as a quick and simple starting point to investigate sudden changes in trends that were found by the first category of studies that investigated the development of tidal dynamics and morphology. In addition, it can provide an effective and quick tool to subdivide a particular external perturbation that is researched by the second category of studies, such as the deposition of sediments, into the different measures that belong to this and occurred in time (in this case the different deposit strategies). In this way, links between specific measures and changes in trends that occur at the same time are easily visible. This can be helpful for the second category of studies that focusses on investigating impacts. However, combining change points and a timeline is only suggested as starting point to establish and research links between significant changes in trends and human interventions. Correlations need to be further investigated using additional methods such as numerical modelling.

Research about the (local) impacts of human interventions on the tidal dynamics and morphology of intertidal flats is important, as knowledge is obtained about the adaptation capacity of the estuary. In addition, by obtaining knowledge about the impacts of human interventions, effects of planned human interventions can be predicted on the water levels and morphology of the intertidal areas. This is relevant for shipping, coastal and ecosystem management. The method assessed in this study to make possible links visible between sudden changes in trends and the timing of human interventions, can also be applied to case studies of other regions.

Chapter 5: Conclusion

The first objective of this study was to investigate if the trends in mean sea level, tidal dynamics and the morphological development of the intertidal of the Western Scheldt are continuous or that trend breaks occurred. The second objective was to create an overview of the local and large-scale human interventions to simplify linking sudden changes in these trends to human interventions.

The trends in tidal dynamics were examined by investigating tidal range, high and low water levels of four measurement stations. Trends in morphological changes of the intertidal areas were examined by investigating changes in surface area, sediment volume, average and maximum height of three intertidal areas that were distributed over the estuary. The Pettitt test was used to detect change points within the trends and a timeline was created to gain an overview of the human interventions that occurred in between 1950-2020 in the Western Scheldt estuary. In addition, context and perspectives of other studies were used for verification of the links found by this research between sudden changes in the trends and the timing of human interventions.

Trend breaks were detected in almost all trends examined. In addition, all change points coincided with the timing of specific human interventions. The mean sea level started to increase with about twice its speed from the change point in 1980 onwards, which coincided with the timing of Deposit Strategy One. This accelerated increase is also in correspondence with the trend of the global mean sea level. For Vlissingen, Terneuzen and Bath a trend break was detected in the timeseries of the increasing tidal range. Except for the low water levels of Bath, all high and low water levels increased significantly in time. All change points found in the tidal range, high and low water levels took place during large-scale human interventions related to maintaining and improving navigability in between 1976 and 1998.

Change points in the surface area trends were detected for all three intertidal areas, and the Western intertidal area was the only flat that increased in surface area during the period of interest. The sediment volumes of the three intertidal areas increased significantly in size, and these were the only trends where no change points were found. The three intertidal areas all increased significantly in average and maximum height, and after the shared change point of 1975 the increase in average height accelerated for the three flats. The change points in trends of the surface area, average and maximum height occurred during large-scale human interventions related to maintaining and improving navigability in between 1975-2005.

After comparing links established in this and other research, some knowledge gaps were identified. It is therefore recommended that future research will focus on the effect of Deposit Strategy One on the mean sea level. In addition, further investigation and quantification is recommended about the extent to which the navigation channel deepening and deposit strategy both have influenced the low water levels around Terneuzen. Lastly, it is suggested to research and quantify the impact of the human interventions on the accelerated increase in average bed levels of the flats. Research on these topics is relevant, as knowledge is obtained about the adaptation capacity of the estuary. In addition, by obtaining knowledge about the impacts of human interventions, effects of planned human interventions can be predicted on the water levels and morphology of the intertidal areas. This is important for shipping, coastal and ecosystem management.

The method assessed in this study to link sudden changes in trends to the timing of human interventions, was verified with other studies that thoroughly investigated links in the Western Scheldt and showed to be simple and effective. However, combining change points and a timeline is only suggested as starting point to establish and research links between significant changes in trends and human interventions. Correlations need to be further investigated using additional methods such as numerical modelling. It is also important to mention that before the detection of change points in trends is implemented, it is important to get a clear understanding of the basic characteristics of the trend studied. This is because the use of the change point detection method needs to be based on the amount of variation within a trend. In conclusion, this study gives insights in the continuity of several trends that occurred in the Western Scheldt and proposes a simple and effective method that makes possible links between sudden changes in trends and human interventions visible. This method can be used as starting point of research and can also be applied to case studies of other regions.

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Appendix 1- Water level measurement locations

Vlissingen

Figure 10 Location of water level measurement station of Vlissingen, indicated by a black arrow. The water level height of 207 cm above NAP was a real-time measurement at the moment of creating the map.

Terneuzen

Figure 11 Location of water level measurement station of Terneuzen, indicated by a black arrow. The water level height of 228 cm above NAP was a real-time measurement at the moment of creating the map.

Hansweert

Figure 12 Location of water level measurement station of Hansweert. The water level height of 218 cm above NAP was a real-time measurement at the moment of creating the map.

Bath

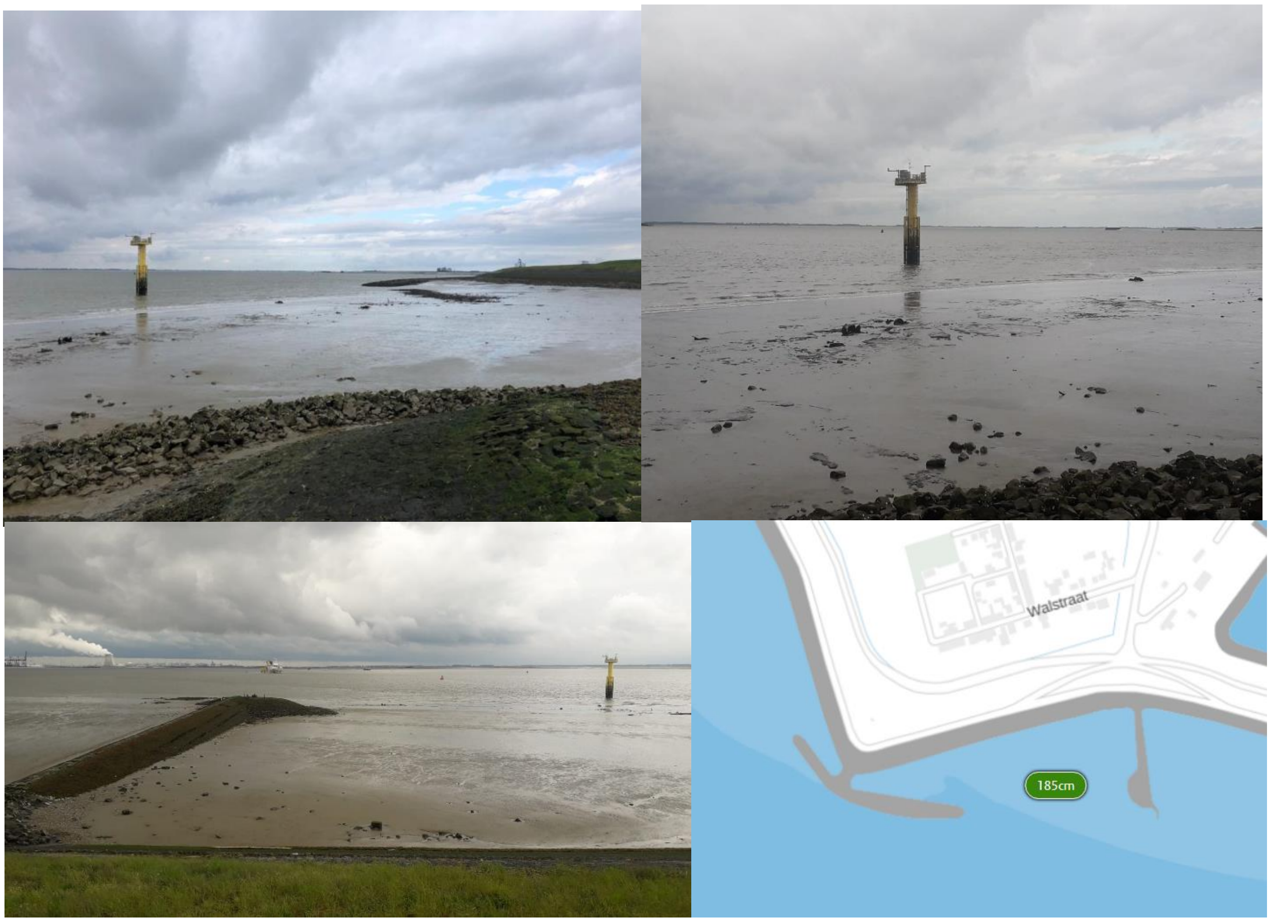

Figure 13 Location of water level measurement station of Bath. The water level height of 185 cm above NAP was a real-time measurement at the moment of creating the map.

Appendix 2- Overview of tidal dynamics

Table 3 Overview of the results per water measurement location.

Location	Parameter	Average change per year	Total change	Significant trend
Vlissingen	Sea level	0.151 cm	10 cm	Yes
	High water	0.234 cm	15 cm	Yes
	Low water	0.131 cm	8 cm	Yes
	Tidal range	0.199 cm	13 cm	Yes
Terneuzen	High water	0.330 cm	22 cm	Yes
	Low water	0.123 cm	8 cm	Yes
	Tidal range	0.267 cm	17 cm	Yes
Hansweert	High water	0.347 cm	22 cm	Yes
	Low water	0.205 cm	13 cm	Yes
	Tidal range	0.282 cm	18 cm	Yes
Bath	High water	0.476 cm	31 cm	Yes
	Low water	-0.262 cm	-17 cm	Yes
	Tidal range	0.631 cm	41 cm	Yes

Appendix 3 Overview of morphological changes of the intertidal areas

Table 4 Overview of the results per intertidal area.

Location	Parameter	Average change per year	Total change	Significant trend
Western intertidal area	Average height	9.4×10^{-4} m	0.55 m	Yes
	Maximum height	4.6×10^{-4} m	0.27 m	No
	Surface area	73.0 m^2	4,307 m^2	No
	Volume	155,000 m^3	9,145,000 m^3	Yes
Middle intertidal area	Average height	7.1×10^{-4} m	0.43 m	Yes
	Maximum height	1.8×10^{-4} m	0.11 m	No
	Surface area	-358.4 m^2	-21,505 m^2	Yes
	Volume	47,000 m^3	2,814,000 m^3	Yes
Eastern intertidal area	Average height	2.3×10^{-2} m	1.39 m	Yes
	Maximum height	2.0×10^{-2} m	1.20 m	Yes
	Surface area	-92.8 m^2	-5,566 m^2	No
	Volume	103,000 m^3	6,164,000 m^3	Yes