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SUB PROJECT 1: DATA ANALYSIS AND HYPOTHESIS - LOWER SEA SCHELDT

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Sub project 1: Data analysis and hypothesis - Lower Sea Scheldt

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2_1	12/01/2012	Internal revision	Peeters, P.
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Abstract

During the past centuries the tidal regime of the Scheldt estuary has seriously changed. This is due to different natural processes and human interventions in the estuary. An important question for the safety management in the Scheldt estuary is how the safety level changes on a long term, taking into account the historical and present human impacts (such as poldering, enlargement, etc.) and natural changes (sea level rise). An important aspect from viewpoint of safety management is the change of the high water levels during the coming decades. The changes in hydrodynamics and morphology of the estuary are related to each other.

Within this report an analysis of both tidal and topo-bathymetric characteristics in the Lower Sea Scheldt since 1900 has been performed. The historical evolution of tidal parameters (high and low water levels, tidal range, duration of rising and falling, celerity of tidal wave) and topo-bathymetric parameters (hypsometric curves, channel volumes, volumes above intertidal areas) was investigated. For these tidal and topo-bathymetric characteristics several relationships were analysed. Long term evolutions show both similar as opposing trends for the investigated geographic sections (i.e. parts of the estuary between water level stations) in the Lower Sea Scheldt.

Preface

This report is part of the research performed in the project “Safety” (In Dutch – Projectgroep Veiligheid) within the scope of the Flemish-Dutch Working group Research & Monitoring (In Dutch – Werkgroep Onderzoek & Monitoring). It was started in 2009 by former collegue Ir. Stefaan Ides. This report combines the work of many people involved within this study, of which we would like to mention Gwendy Vos Msc. (GIS - topo-bathymetry), Yaïr Levy Msc. and the colleagues of the Hydrometry department (tidal characteristics) besides many other people which have made it possible to execute this data analysis.

Contents

List of tables

List of figures

1 Introduction

1.1 General background LTV O&M

The objective of the project "Lange Termijn Visie Onderzoek en Monitoring"1 (LTV O&M) is to realise in the year 2030 a sustainable and multifunctional estuarine water system for the Scheldt estuary. One of the primary goals of the project is to guarantee maximal safety against flooding. Crucial questions for the management of the system are (i) how on the long-term this safety level will develop given natural changes and human interferences and (ii) what measures are needed to safeguard the surrounding areas against flooding. Both questions are addressed within the project by means of two defined sub projects:

1. Evolution of high water levels (sub project 1);
2. Analysis of flood risks (sub project 2).

Both sub projects were identified through a study carried out by Royal Haskoning in commission of Rijkswaterstaat / RIKZ (Van Ledden *et al.*, 2006). The present report describes the activities that have been undertaken as part of sub project 1 (Evolution of high waters). The scope of the work has been wider than to focus only on high waters. Other tidal characteristics such as tidal range, propagation velocity and tidal asymmetry have been addressed as well.

1.2 LTV Veiligheid

During the past centuries the tidal regime of the Scheldt estuary has changed. This is due to different natural processes and human interventions in the estuary, such as poldering, natural evolution of the estuary, enlargement of the navigation channel, continuous maintenance dredging works, permanent withdrawal of sand from the estuary for different purposes, changed tidal conditions in the North Sea, changed upstream discharges etc.

An important question for the safety management in the Scheldt estuary is how the safety level changes on a long term, taking into account the historical and present human impacts (such as poldering, enlargement, etc.) and natural changes (sea level rise). An important aspect from viewpoint of safety management is the change of the high water levels during the coming decades.

The changes in hydrodynamics and morphology of the estuary are related to each other and they should be studied together. The morphology of the Scheldt estuary changes as a result of human impacts and natural changes in the estuary. New morphological conditions can affect hydrodynamics. The change of the hydrodynamics can lead to morphological adaptations of the system, which on their turn can affect hydrodynamics again.

Therefore, analysis of the morphological evolutions in the estuary helps to understand the changes in the tidal regime and vice versa. The objective of this study is twofold: in a first part an analysis of the water level data and topo-bathymetric data of the previous century will be carried out. From this analysis some trends and tendencies will become clear, and the objective is to try to link the observed changes in trends for both parameters to each other and to major events that happened in the estuary (i.e. natural changes as well as human impacts). In a second part, the result of the data analysis will be used to formulate hypotheses, on how and why the tidal penetration in the Scheldt estuary has changed. The validity of these hypotheses will be verified in a later phase of the project using different kind of models.

The results of this study can be found in the two following reports: for the Lower Sea Scheldt area the results are presented in this report, while the analysis for the Western Scheldt is given by [Kuijper *et al.*,2011].

Since the availability of the topo-bathymetric data for the Sea Scheldt is limited from the Dutch-Belgian border to Rupelmonde, only this part of the Sea Scheldt will be studied. The downstream boundary of the study area is set to Bath (in order to connect to the Western Scheldt analysis), the upstream boundary is Rupelmonde.

1.3 Contents of this report

Chapter 2 deals with the water level data, while the topo-bathymetric data is described in chapter 3. In chapter 4 the relation between the water level data and the topo-bathymetric data is investigated. Chapter 5 deals with the human interventions and the changes in tidal characteristics in the Western Scheldt and the Lower Sea Scheldt since 1900. The conclusions and recommendations of this report are given in chapter 6.

2 Water level data

To analyse the evolution of the tidal penetration in the Scheldt estuary, it is necessary to have good historical data. Since the end of the 19th century water level data have been recorded for different locations along the estuary. In this chapter an analysis of the water level data is given.

2.1 Available data

In the Sea Scheldt and its tidal tributaries, water level measurements were carried out since the beginning of the 20th century. However some of these data have never been reported, let alone that one overall report about the water level measurements exists. At Flanders Hydraulics Research an effort is currently going on to gather all these historical water level data and put them in one overall report. At the moment of this study, only a part of the water level stations has already been processed. On Figure 1 the water level stations that are already processed – including the year from which the measurements started – are presented.

Since the study area is limited from Bath to Rupelmonde, only the following water level stations will be used: Bath, Liefkenshoek, Antwerpen and Schelle. An analysis of the other water level stations in the Sea Scheldt and tributaries can be found in the report (Levy *et al.*, 2012 – in preparation).

The data from Bath was delivered by Helpdesk Water. From 1886 until 1971 only the high and low water levels were recorded; for the largest part of this period even only during daytime. From 1971 to 1987 every hour a water level was recorded. From 1987 to present every 10 minutes a water level value is recorded. Since this station is actually located in the Western Scheldt, the water levels are analysed in the report [Kuijper *et al*, 2011].

For the station Antwerpen the water level values before 1971 were taken from the overview of the tidal observations in the Sea Scheldt and tributaries released every 10 years [Van Brabandt, L., 1912; Blockmans, J., 1927; Blockmans, J., 1934; Vekemans, R., 1946; Codde, R. & De Keyser, L., 1954; Codde, R. & De Keyser, L., 1963; Theuns, J. & Coen, I., 1972/1973; Belmans, H & Claessens, J., 1984; Meyvis, L. & Claessens, J., 1994; Taverniers, E. & Mostaert, F., 2009]. After 1971 the water levels were taken from the digitized measurements of the Hydrometry group of Flanders Hydraulics Research. For the stations Liefkenshoek and Schelle the values from the 10 yearly reports of tidal observations in the Sea Scheldt and tributaries were taken until 1981. Only from 1981 on the digitized measurements of the Hydrometry group of Flanders Hydraulics Research were available for these stations.

2.2 Processing

Where the 10 yearly reports of tidal observations in the Sea Scheldt and tributaries, present only yearly averaged values, no information is available of time series of water levels. Therefore only yearly-averaged values were available for the analysis. At this moment, a project is ongoing digitizing high and low water levels at some major tidal stations, starting with Antwerpen.

For the data where time series were available, the mean characteristics were derived using scripts in R and/or Matlab. Where the 10 yearly reports sometimes only publish a limited number of parameters, additional parameters (e.g. duration and delay) could be derived from the available time-series.

2.3 Definition of tidal characteristics

The evolution of the tides in the Sea Scheldt was assessed by means of the following parameters[1]:

- Mean high water (yearly-averaged value and yearly-averaged value for spring and neap tide)
- Mean low water (yearly-averaged value and yearly-averaged value for spring and neap tide)
- Mean half tide (yearly-averaged value and yearly-averaged value for spring and neap tide)
- Mean tidal range (yearly-averaged value and yearly-averaged value for spring and neap tide)
- The highest high water;
- The lowest high water;
- The highest low water;
- The lowest low water.
- Duration of rising water level (*)
- Duration of falling water level (*)
- High water delay relative to Vlissingen (*)
- Low water delay relative to Vlissingen (*)

For the periods in which detailed data are available following additional characteristics were derived, using R-scripts:

- Percentiles of high waters (1% - 5% - 10% - 50% - 90% - 95% - 99%)
- Percentiles of low waters (1% - 5% - 10% - 50% - 90% - 95% - 99%)

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[1] Characteristics marked with an asterix (*) are not continuously available since 1900.

2.4 Evolution of tidal characteristics

2.4.1 Yearly-averaged high and low water and tidal range

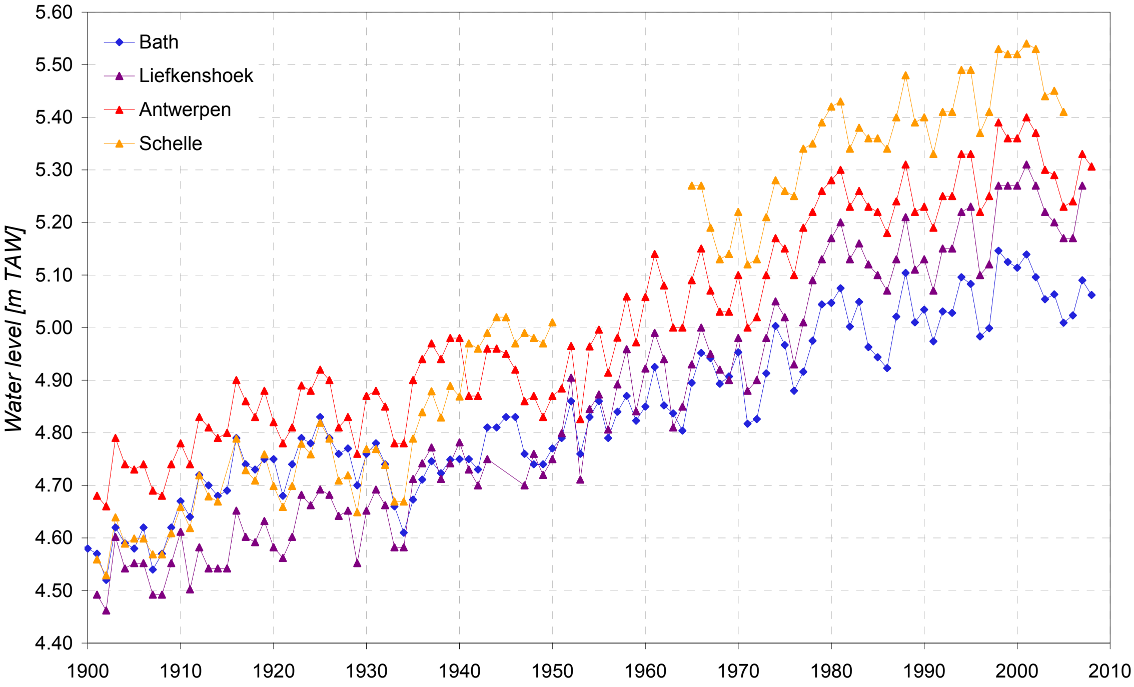

Figure 1 – Yearly-averaged high water in Bath, Liefkenshoek, Antwerpen and Schelle

The yearly-averaged high waters in the lower Sea Scheldt (Figure 1) show an increase with time. During the first 3 decades of the 20th century, the high water levels in Liefkenshoek were lower than the high water levels in Bath. During the 1930's until the 1950's the high water levels of Bath and Liefkenshoek were similar, while since the 1960's the high water levels in Bath were lower than those of Liefkenshoek. Another significant change takes place between Antwerpen and Schelle: before the 1940's high water levels in Antwerpen were higher than high water levels in Schelle. After the 1940's the high water levels in Schelle became higher than in Antwerpen[2]. This corresponds with the deeper penetration of the maximum high water levels up-estuary.

The yearly-averaged low waters in the lower Sea Scheldt (Figure 2) remain at almost the same level during the first decades of the 20th century. The low water levels in Liefkenshoek are ca. 20 cm lower than those at the other stations. From the 1940's until the 1970's the lower water levels of Bath and Liefkenshoek increase, while those in Antwerpen and Schelle remain more or less constant. Since the 1950's the low water levels of Bath are higher than those of the other stations, while before the 1950's these higher low water level were found more up-estuary.

In the 1970's a strong (20 cm) decrease of low water levels can been found for all stations. This decrease can be related to a combination of several infrastructure works: e.g. sand extraction for infrastructural works, construction of guiding walls near Ouden Doel and the Ballastplaat, first deepening campaign of the navigation channel. After the 1970's the low water levels for all stations remain rather constant, except for some yearly variations.

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[2] During the 1940's a slight change in datum level occurred. The correct shift is not known at this moment (order of magnitude of cm).

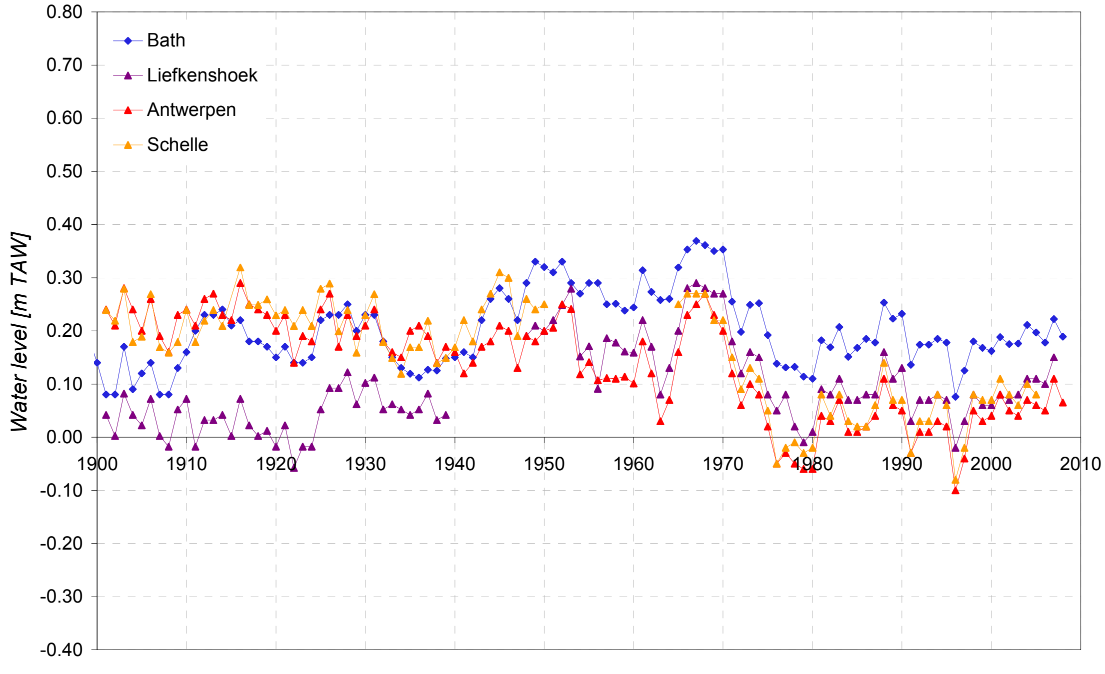

Figure 2 – Yearly-averaged low water in Bath, Liefkenshoek, Antwerpen and Schelle

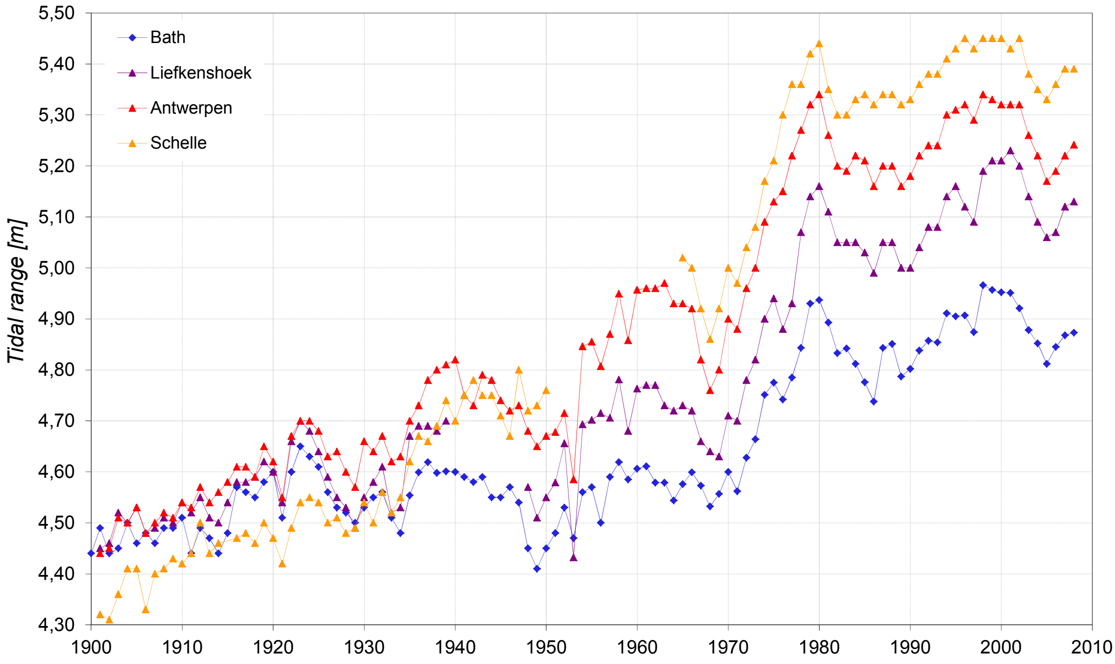

Figure 3 – Yearly-averaged tidal range in Bath, Liefkenshoek, Antwerpen and Schelle

The tidal range in the lower Sea Scheldt (Figure 3) shows a trend that combines the effect of the continuous increase of high water levels and the decrease of the low water levels in the 1970's: the tidal range increases gradually until 1970, has a strong increase during the 1970's, whereafter it increases gradually. This trend is similar for all stations. Since 1980 the tidal range seems to have stabilised.

The ratio of the tidal range, related to Vlissingen (Figure 4), shows a similar trend than the tidal range. Analysing the ratio of the tidal range for different sections (Figure 5), different trends can be found for the considered locations: in the section Hansweert-Bath a strong increase of the ratio of the tidal range takes place in the 1970's. The other sections (Bath-Liefkenshoek, Liefkenshoek-Antwerpen and Antwerpen-Schelle) show in general a rather gradual increase of the tidal range. The section Liefkenshoek-Antwerpen has a decrease of the ratio since the 1980's, while for the section Antwerpen-Schelle an increase occurs during the 1940's.

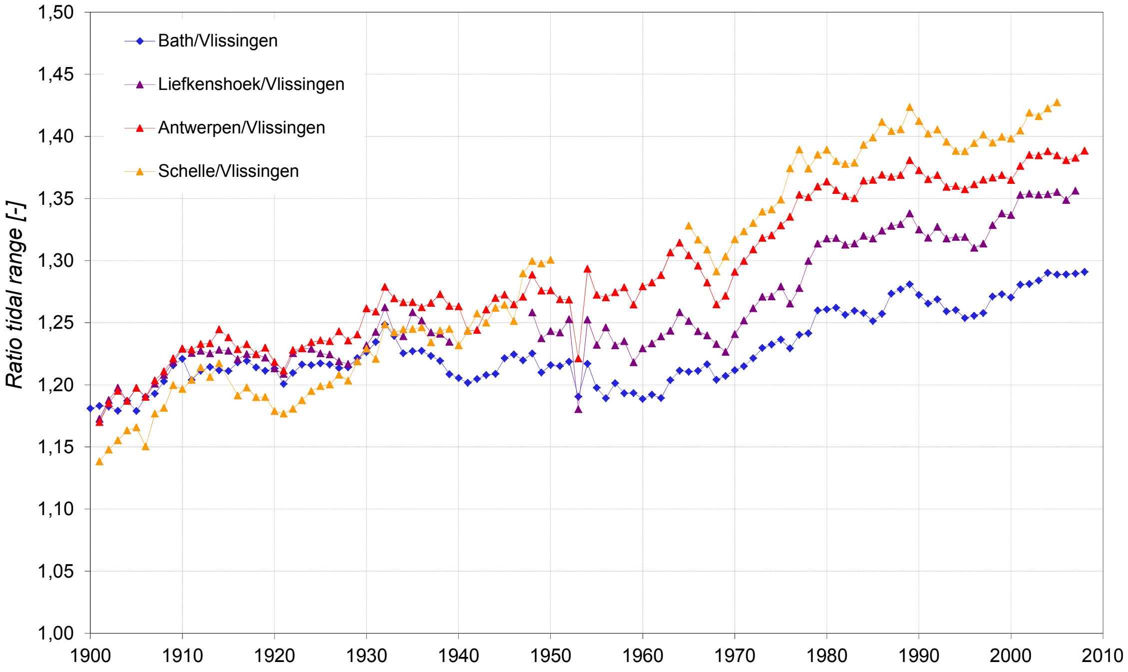

Figure 4 – Yearly-averaged ratio of tidal range in Bath, Liefkenshoek, Antwerpen and Schelle to tidal range in Vlissingen

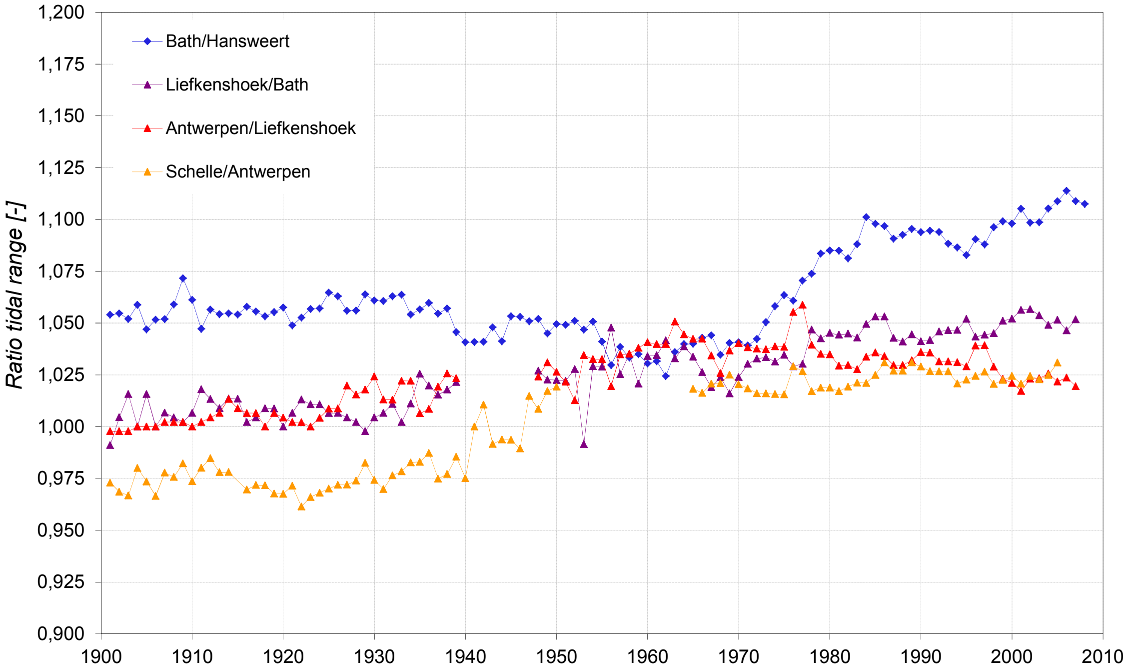

Figure 5 – Yearly-averaged ratio of tidal range in Bath, Liefkenshoek, Antwerpen and Schelle to tidal range in down-estuary station

Table 1 – Indication of sea level rise per station (approximated by linear regression[3] over period 1901 – 2008)

Linear regression [cm/century]	***Bath* *KM 51,8***	***Liefkenshoek* *KM 63,1***	***Antwerpen* *KM 77,6***	***Schelle* *KM 91,2***
Mean high water	46	76	61	98
Mean low water	9	8	-24	-22
Mean tidal amplitude	36	68	85	120

Analysis of the increase of the water levels (Table 1), which can be seen as an indication of sea level rise and is approximated by linear regression over the period 1901 – 2008, indicates that there is an amplification from Vlissingen to Schelle. The high water levels increase stronger up-estuary, with a small fall back for Antwerpen. For the low water levels the trends are less clear, but for the tidal amplitude an increase can found going up-estuary.

2.4.2 Yearly-averaged high and low water and tidal range for spring tide

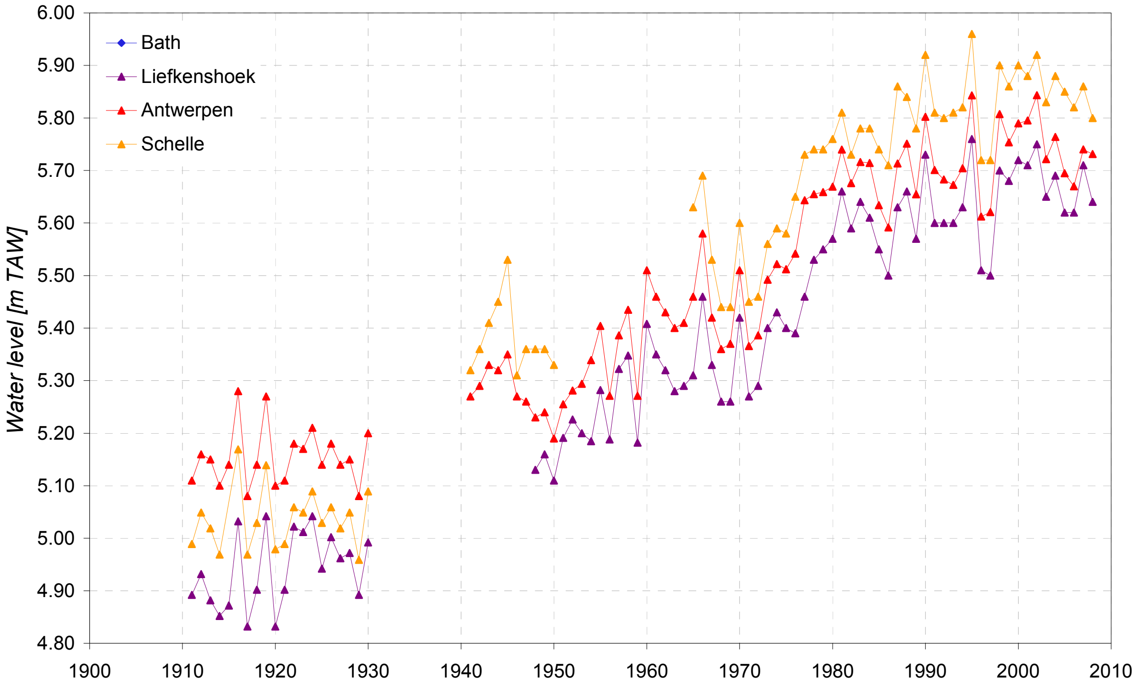

Figure 6 – Yearly-averaged high water for spring tide in Bath, Liefkenshoek, Antwerpen and Schelle

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[3] The assumption of a linear regression is not correct and was chosen to give only a first indication of the linear changes of the different water levels. For the high water level it can be seen from the measurements that a different trend occurs before and after the 1950's. For the low water levels important changes occur in the 1970's, which "disturb" the linear trends. In order to get a full analysis of historical trends, these changes must be taken into account, while also the 18,61 year (nodal) cycle must be taken in consideration!

The trends of the water levels for spring tide conditions are similar to those of the yearly averaged water levels. The high water levels (Figure 6) show a gradual increase, while for the low water levels (Figure 7) the strong decrease during the 1970's stands out. It should be noticed that the increase of the high water levels for spring tide are (slightly ~10cm /100 years) larger than those of the yearly averaged high water levels. The tidal range (Figure 8) combines the effects of the high and low water levels for spring tide conditions. Following Figure 6 to Figure 8, it can be found that since the 1980's, the stabilising trends for HWS, LWS and tidal range spring, are even more pronounced.

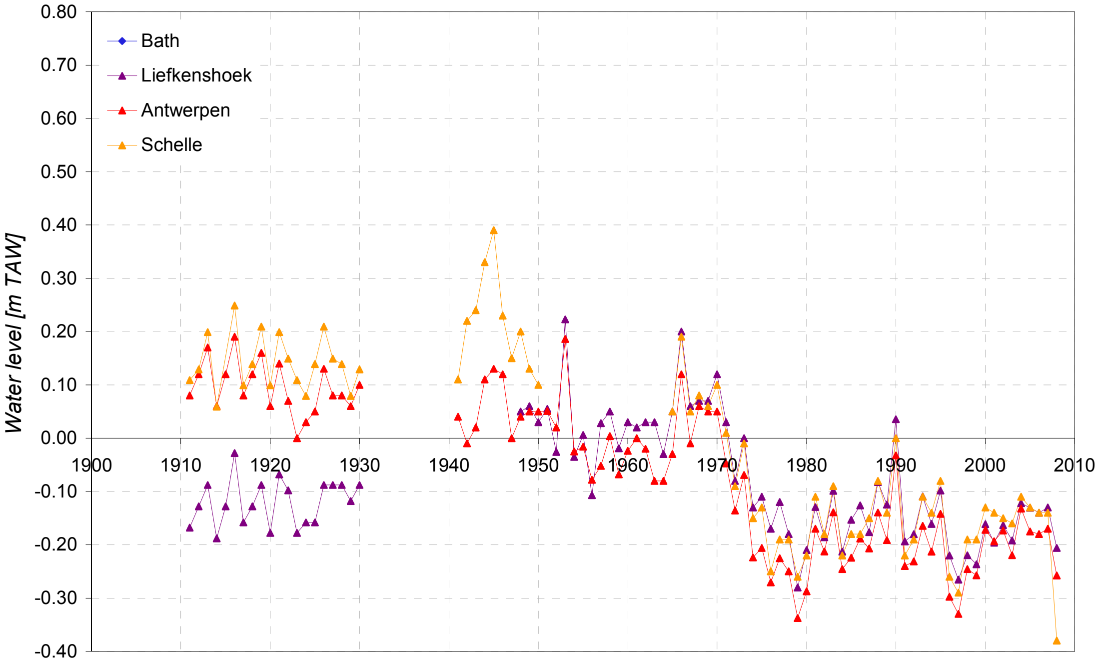

Figure 7 – Yearly-averaged low water for spring tide in Bath, Liefkenshoek, Antwerpen and Schelle

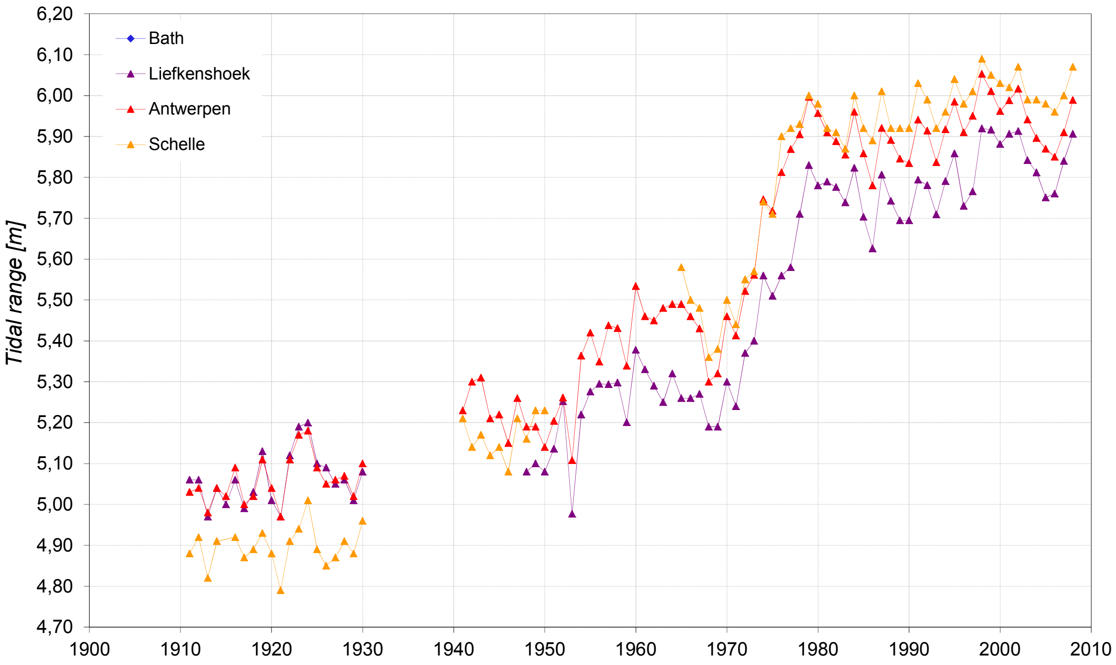

Figure 8 – Yearly-averaged tidal range for spring tide in Bath, Liefkenshoek, Antwerpen and Schelle

2.4.3 Yearly-averaged high and low water and tidal range for neap tide

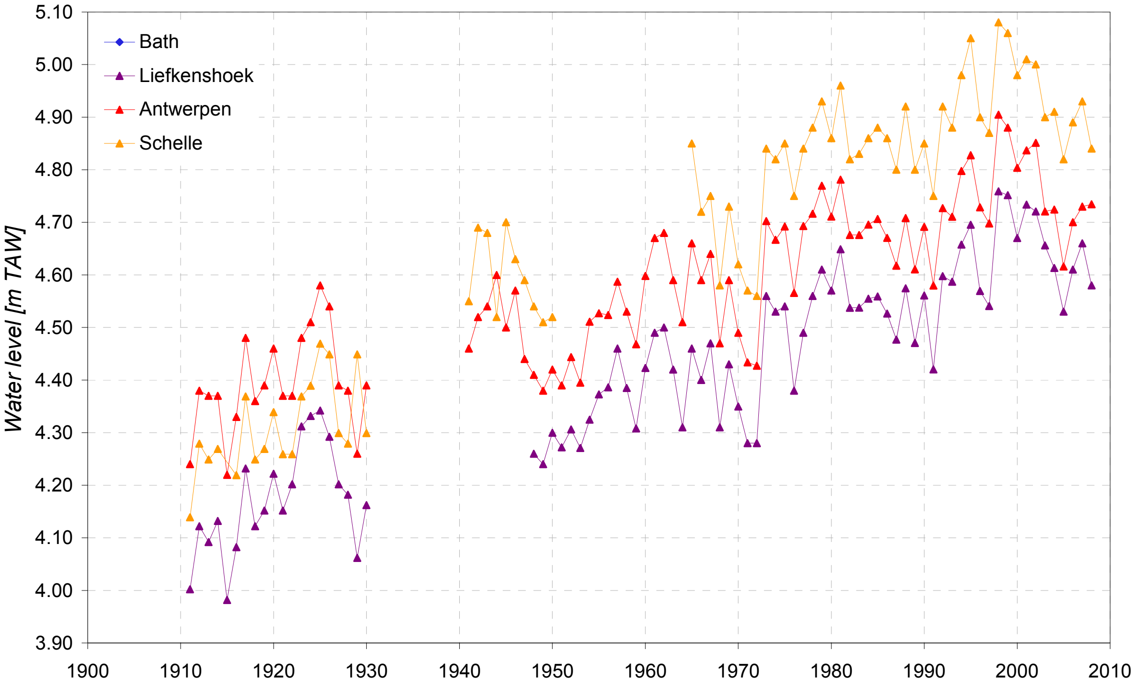

Figure 9 – Yearly-averaged high water for neap tide in Bath, Liefkenshoek, Antwerpen and Schelle

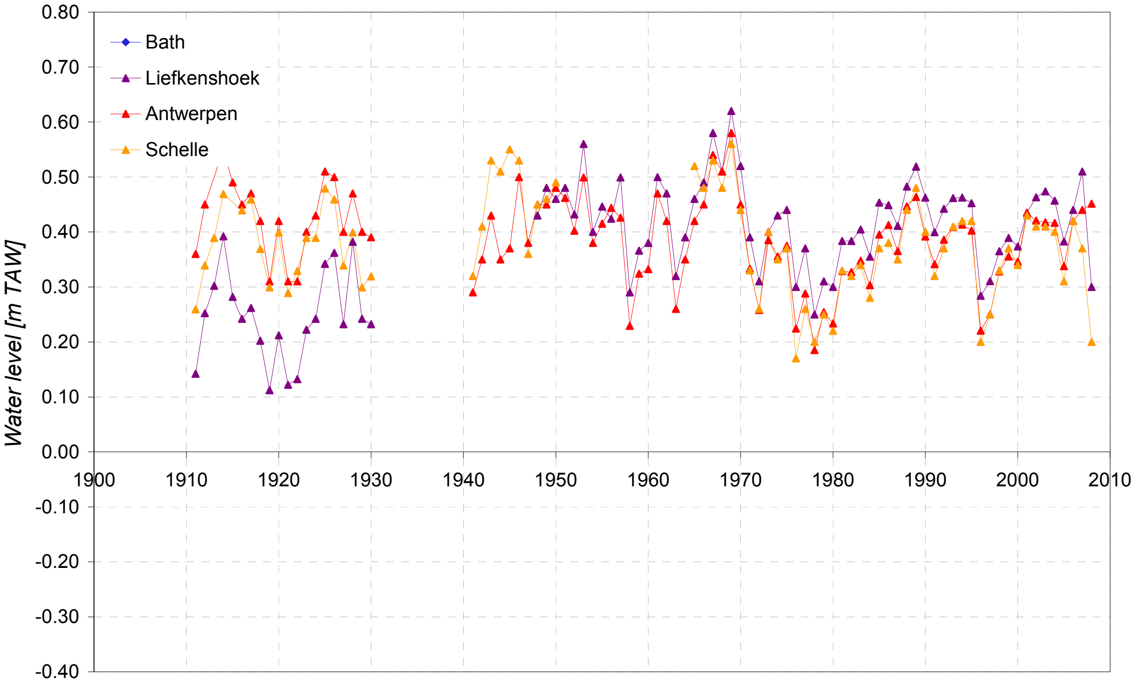

Figure 10 – Yearly-averaged low water for neap tide in Bath, Liefkenshoek, Antwerpen and Schelle

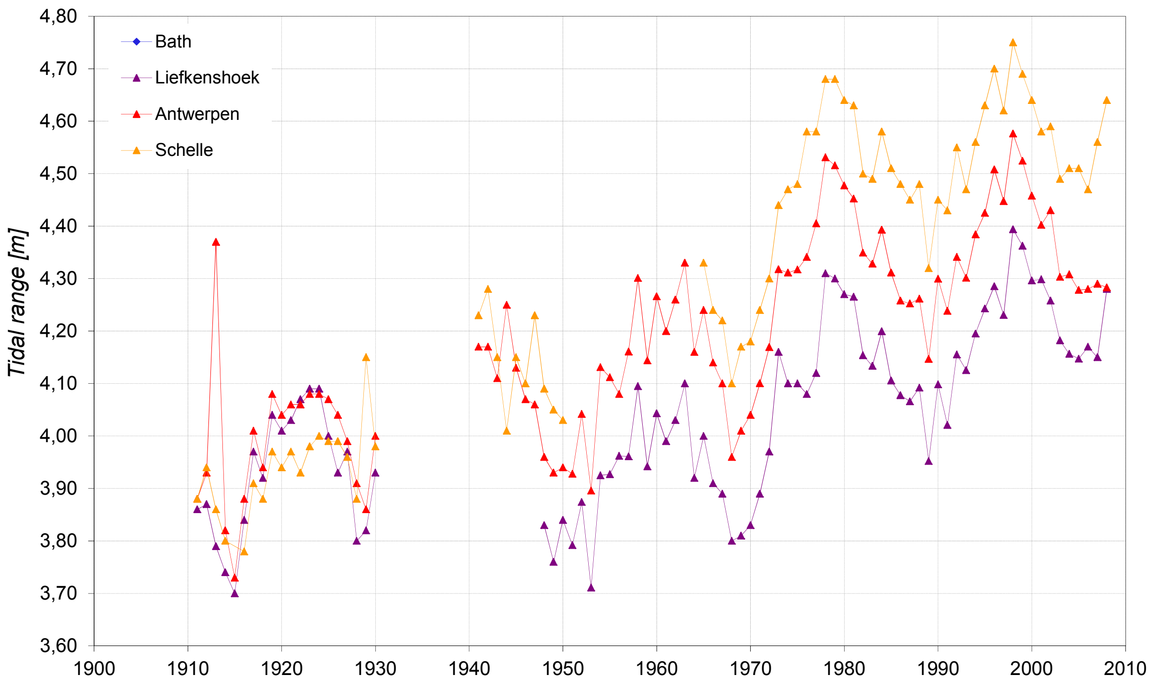

Figure 11 – Yearly-averaged tidal range for neap tide in Bath, Liefkenshoek, Antwerpen and Schelle

The trends of the water levels for neap tide conditions are similar to those of the yearly averaged water levels. The high water levels (Figure 9) show a gradual increase, while for the low water levels (Figure 10) the decrease during the 1970's is present although less pronounced. It should be noticed that the increase of the high water levels for neap tide are (slightly ~10cm /100 years) smaller than those of the yearly averaged high water levels. The tidal range (Figure 11) combines the effects of the high and low water levels for neap tide conditions.

Following Figure 9 to Figure 11, it can be found that since the 1980's, the stabilising trends for HWN, LWN and tidal range neap, are less pronounced.

2.4.4 Yearly-averaged duration of rising and falling

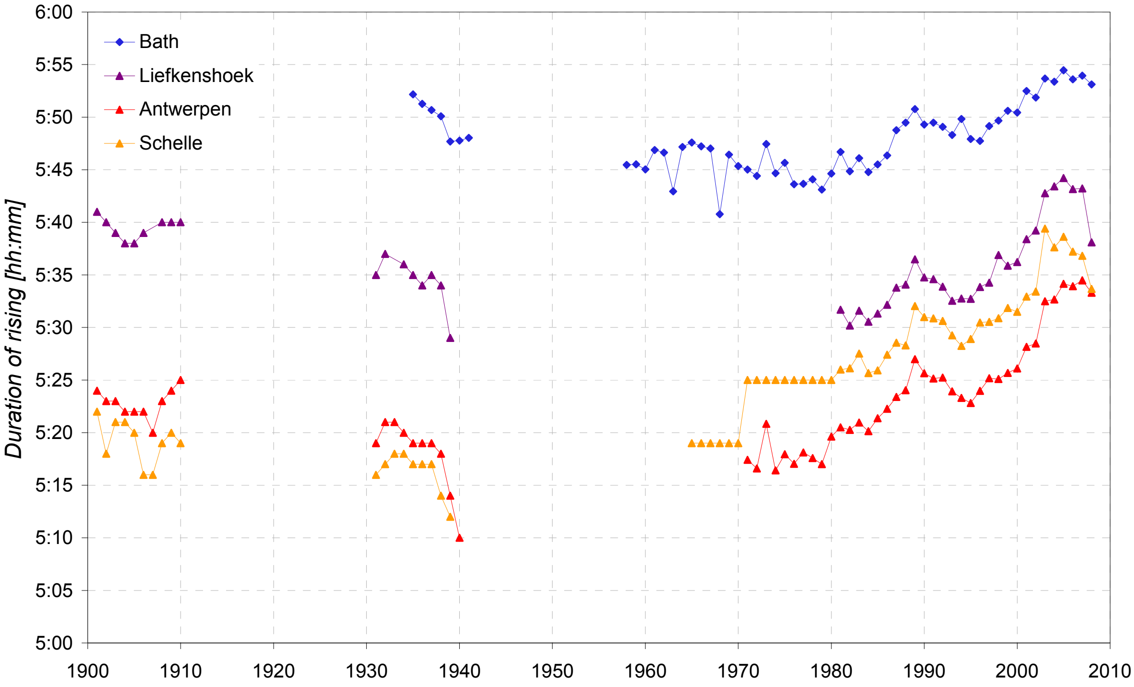

Figure 12 – Yearly-averaged duration of rising in Bath, Liefkenshoek, Antwerpen and Schelle

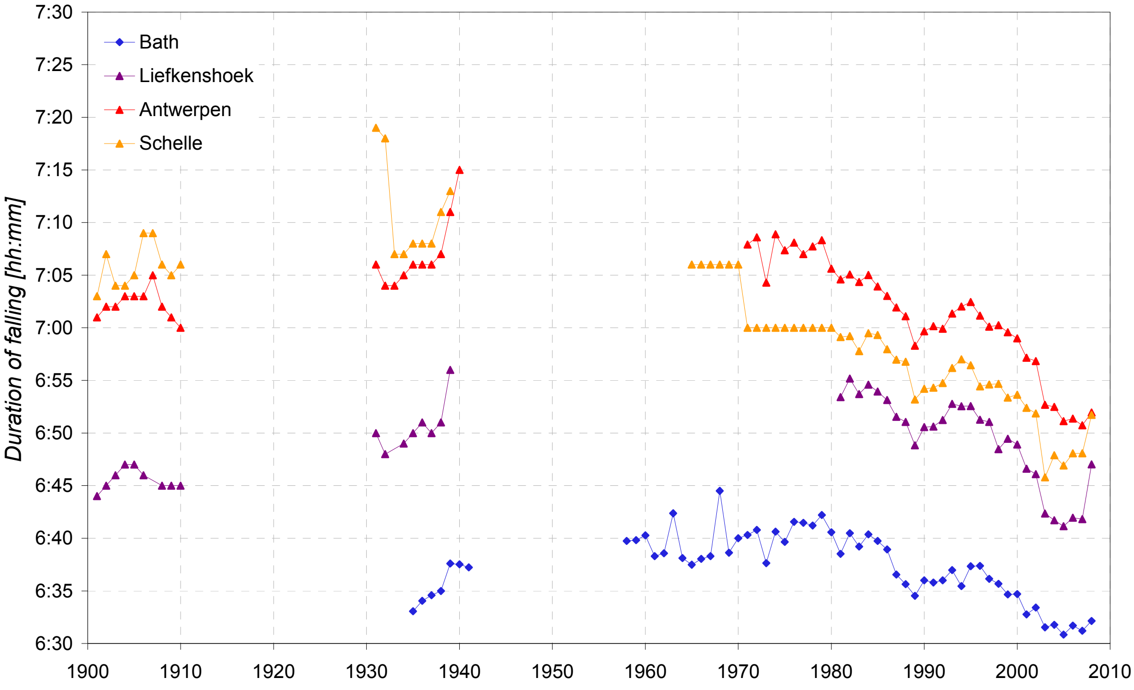

Figure 13 – Yearly-averaged duration of falling in Bath, Liefkenshoek, Antwerpen and Schelle

Time series for the yearly averaged duration of rising (Figure 12) and falling (Figure 13) are only partially available. Only during the last 30 years data is continuously available. An increase in the duration of the rising and consequently a decrease of the duration of the falling can be found. The trend is rather continuous over time. It should be noticed that this trend seems (based on the limited amount of available data) to be contrary to the one of the first half of the 20th century. At this moment, work is ongoing to digitise additional historical data, which will allow a better analysis of this parameter.

2.4.5 Yearly-averaged delay of high and low water to Vlissingen

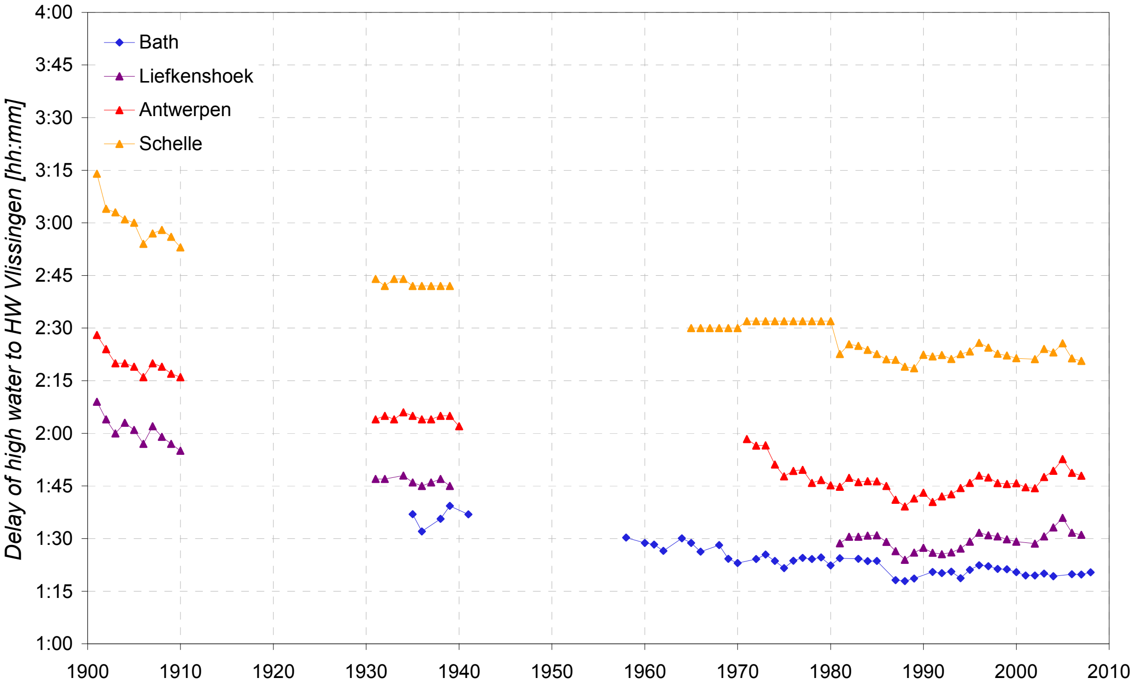

Figure 14 – Yearly-averaged delay of high water in Bath, Liefkenshoek, Antwerpen and Schelle to Vlissingen

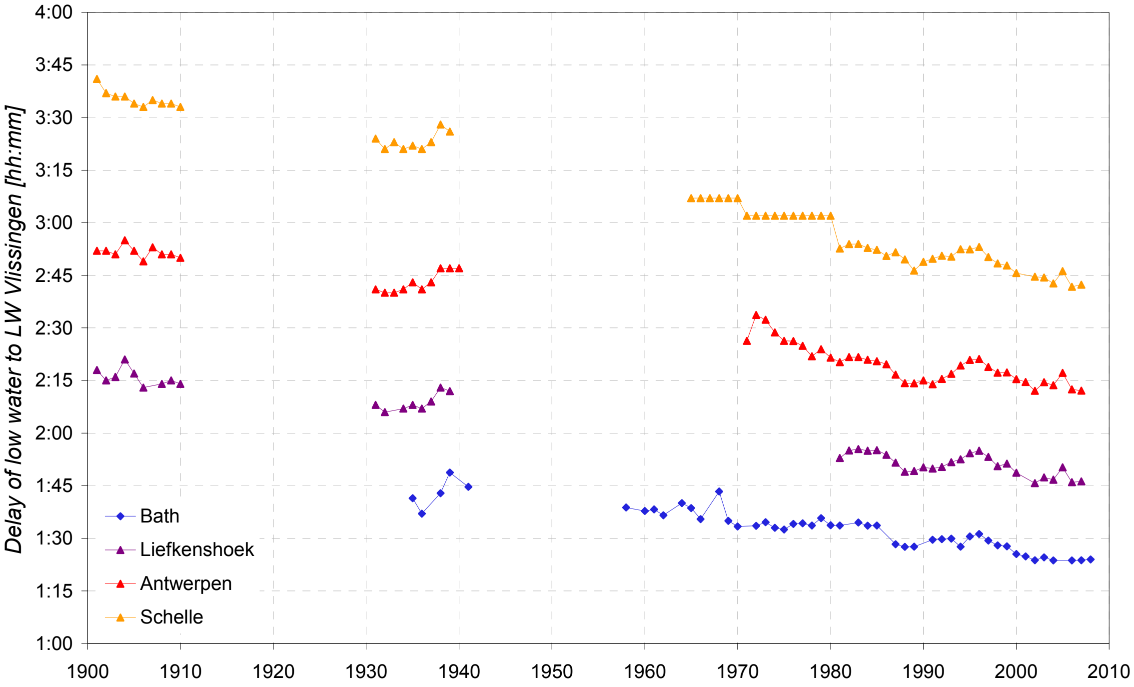

Figure 15 – Yearly-averaged delay of low water in Bath, Liefkenshoek, Antwerpen and Schelle to Vlissingen

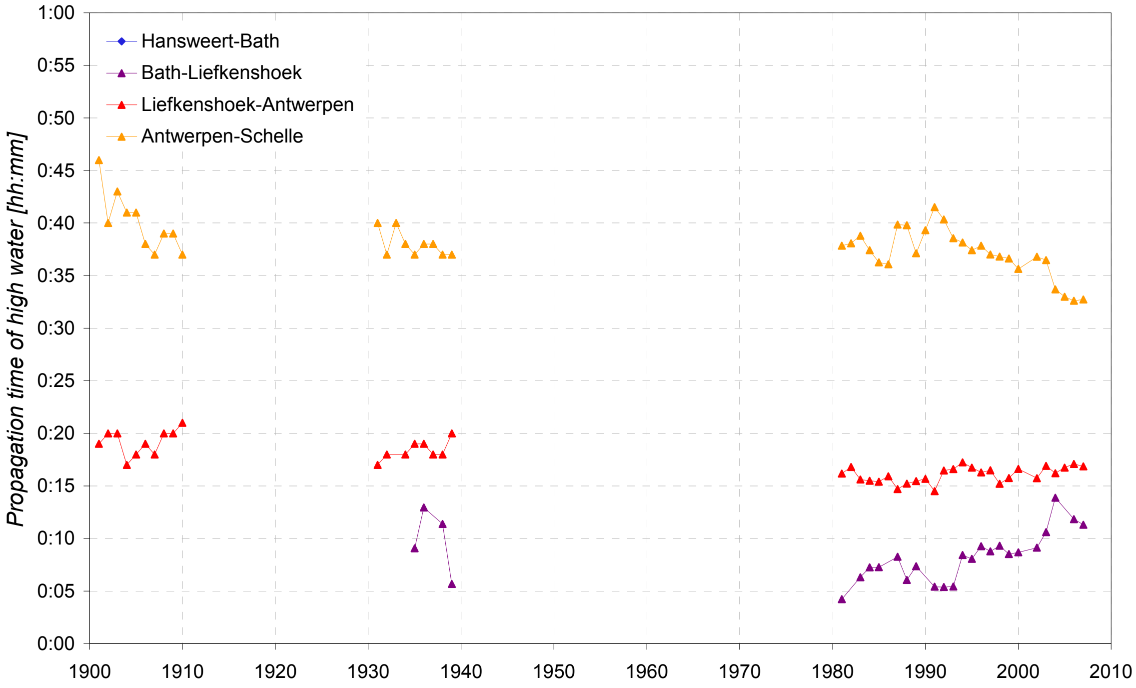

Figure 16 – Yearly-averaged delay of high water per section

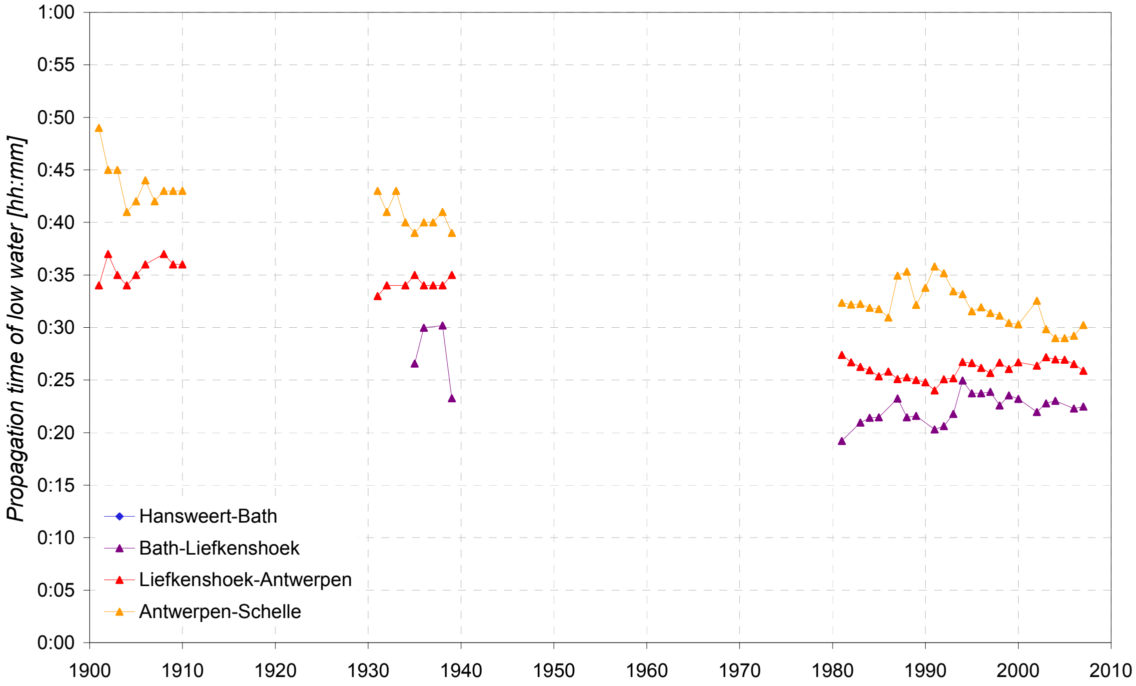

Figure 17 – Yearly-averaged delay of low water per section

Time series for the yearly averaged delay of high and low water to Vlissingen are again only limited available. While interpreting these results, it should be kept in mind that the methodology to determine these temporal parameter have changed during the times. This can lead to an uncertainty on the results of ± 5 minutes, which is of the same order of magnitude than the historical changes.

Only during the last 30 years data is available. During the last 30 years the delay of high water to Vlissingen (Figure 14) remains rather constant for all stations, even a slight increase in time can be seen. This is in contrast with the trend over the first 3 quarters of the 20th century (based on the limited amount of available data) during which the delay decreased gradually. When analysing the delay between 2 consecutive stations (Figure 16) over the last 30 years, different patterns can be found: for Bath-Liefkenshoek the delay increases (propagation speed decreases), for Liefkenshoek- Antwerpen it remains constant, while for Antwerpen-Schelle it decreases (and thus we have increase of propagation speed).

During the last 30 years the delay of low water to Vlissingen (Figure 15) decreases gradually for all stations. This is similar with the trend over the first 3 quarters of the 20th century (based on the limited amount of available data). When analysing the delay between 2 consecutive stations (Figure 17) over the last 30 years, different patterns can be found: for Bath-Liefkenshoek the delay increases (propagation speed decreases), for Liefkenshoek- Antwerpen it remains constant, while for Antwerpen-Schelle it decreases (and thus we have increase of propagation speed). At this moment, work is ongoing to digitise additional historical data, which will allow a better analysis of this parameter.

2.4.6 Yearly-averaged extreme high waters

Time series of high water levels in the Sea Scheldt are only limited available in a digital format. Only during the last 30 years data is available (Figure 18, Figure 19, Figure 20). At this moment, work is ongoing to digitise additional historical data, which will allow a better analysis of this parameter.

The highest high water levels show large fluctuations (up to 100 cm between 2 years), caused by the meteorological conditions during a specific storm event (due to north-western wind) in combination with the tidal conditions (i.e. moment within the spring-neap-cycle) during which the extreme meteorological conditions occur. Therefore additional parameters were derived, allowing a more general analysis of the higher high water levels. The 99% percentile, taking into account the 7 highest high water levels during the year, has for all stations yearly fluctuations up to 40 cm. Over the last 3 decades, there is a slight tendency towards an increase. However, the yearly variations exceed this trend, as percentiles are strongly influenced by the meteorological conditions.

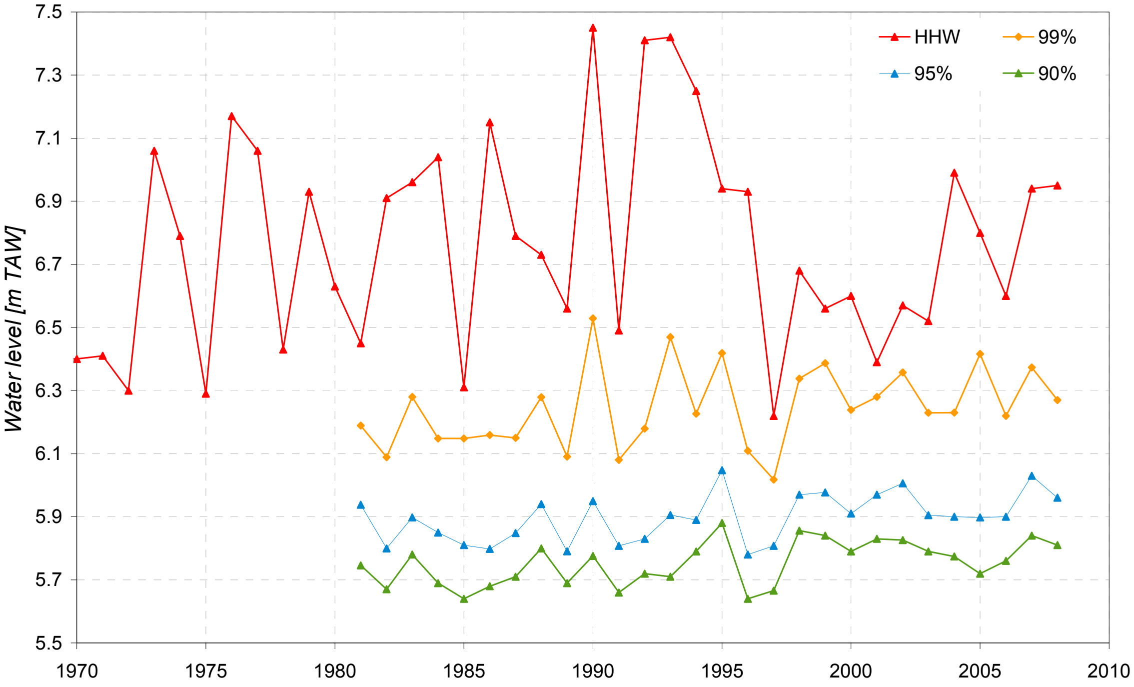

Figure 18 – Extreme high waters (90% - 95% - 99% - highest) in Liefkenshoek

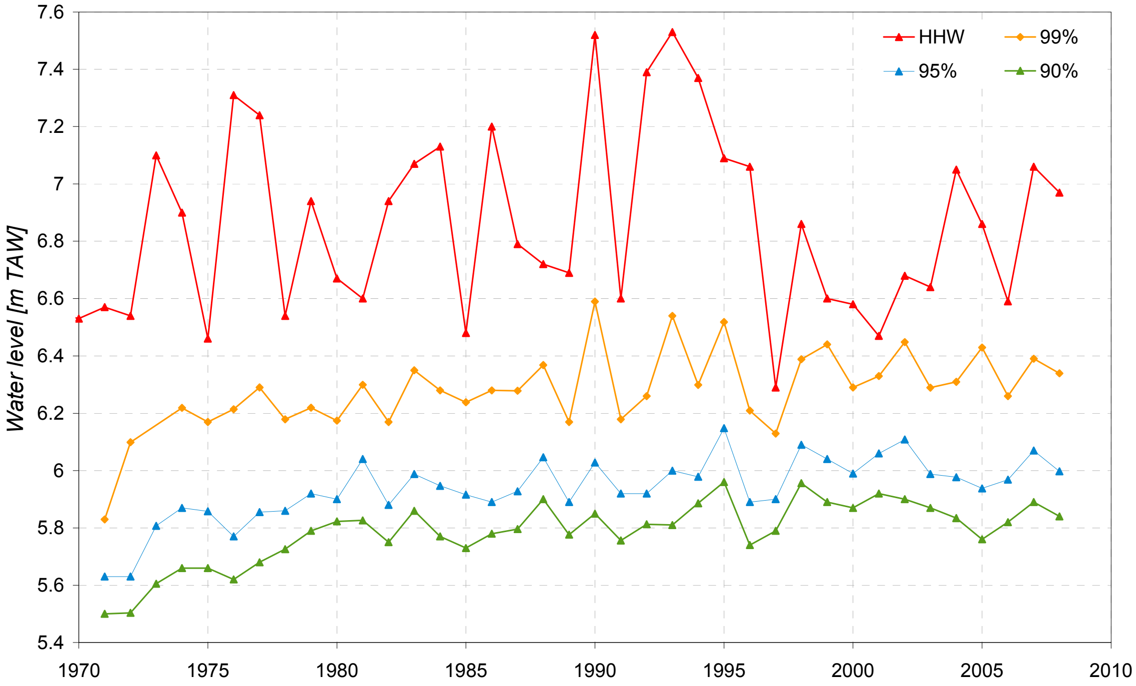

Figure 19 – Extreme high waters (90% - 95% - 99% - highest) in Antwerpen

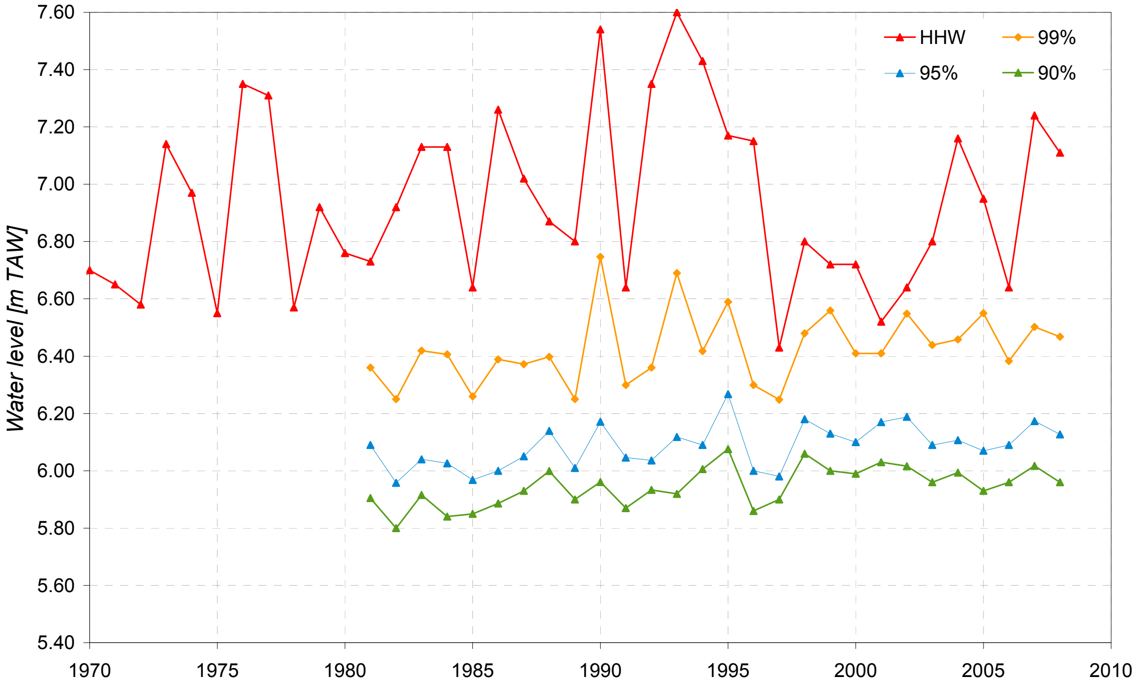

Figure 20 – Extreme high waters (90% - 95% - 99% - highest) in Schelle

Table 2 – Indication of sea level rise per station (approximated by linear regression[4] over period 1981 – 2008)

Linear regression **[cm/century]**	***Liefkenshoek*** ***KM 63,1***	***Antwerpen*** ***KM 77,6***	***Schelle*** ***KM 91,2***
Mean high water	49	59	55
90 % high water	42	72	49
99 % high water	54	68	51

Analysis of the increase of the high water levels (Table 2), which can be seen as an indication of sea level rise and is approximated by linear regression over the period 1981 – 2008, shows for the stations no consistent difference between the rate of increase of the mean high water level and the 90% and 99% highest high water level. For Antwerpen the rate of increase of the 90% and 99% high water levels is higher, while for Liefkenshoek and Schelle it is similar or even lower than the rate of increase of the mean high water level.

2.4.7 Yearly-averaged extreme low waters

Time series of low water levels in the Sea Scheldt are digitally only limited available. Only during the last 30 years data is available (Figure 21, Figure 22, Figure 23). At this moment, work is ongoing to digitise additional historical data, which will allow a better analysis of this parameter.

The lowest low water levels show large fluctuations (up to 60 cm between 2 years), caused by the meteorological conditions during a specific storm event (due to eastern winds) in combination with the tidal conditions (i.e. moment within the spring-neap-cycle) during which the extreme meteorological conditions occur. Therefore additional parameters were derived, allowing a more general analysis of the lower low water levels. The 1% percentile, taking into account the 7 lowest low water levels during the year, has for all stations yearly fluctuations less than 20 cm. Over the last 3 decades almost no changes have occurred for the lower low water levels. Nevertheless both lowest values as the percentiles are strongly influenced by the meteorological conditions.

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[4] The assumption of a linear regression is not necessarily correct and was chosen to give only a first indication of the linear changes of the different higher water levels. Besides this assumption, the trends were determined on a limited data set (28 years) and it should therefore be kept in mind that the results presented in the table are only an first indication!

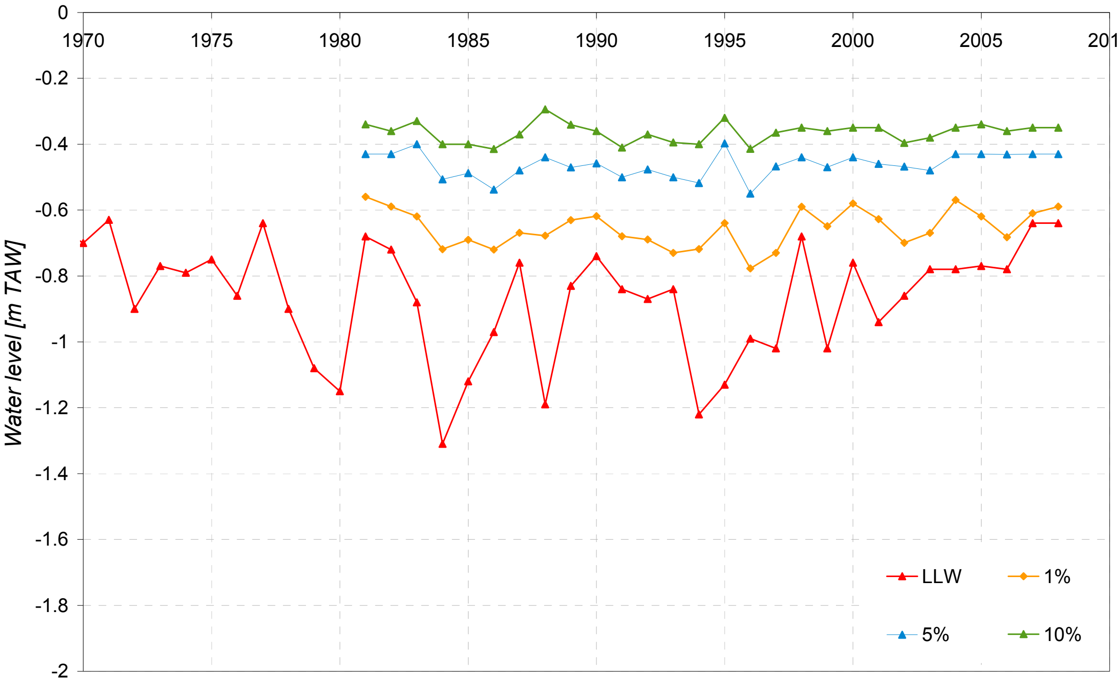

Figure 21 – Extreme low waters (10% - 5% - 1% - lowest) in Liefkenshoek

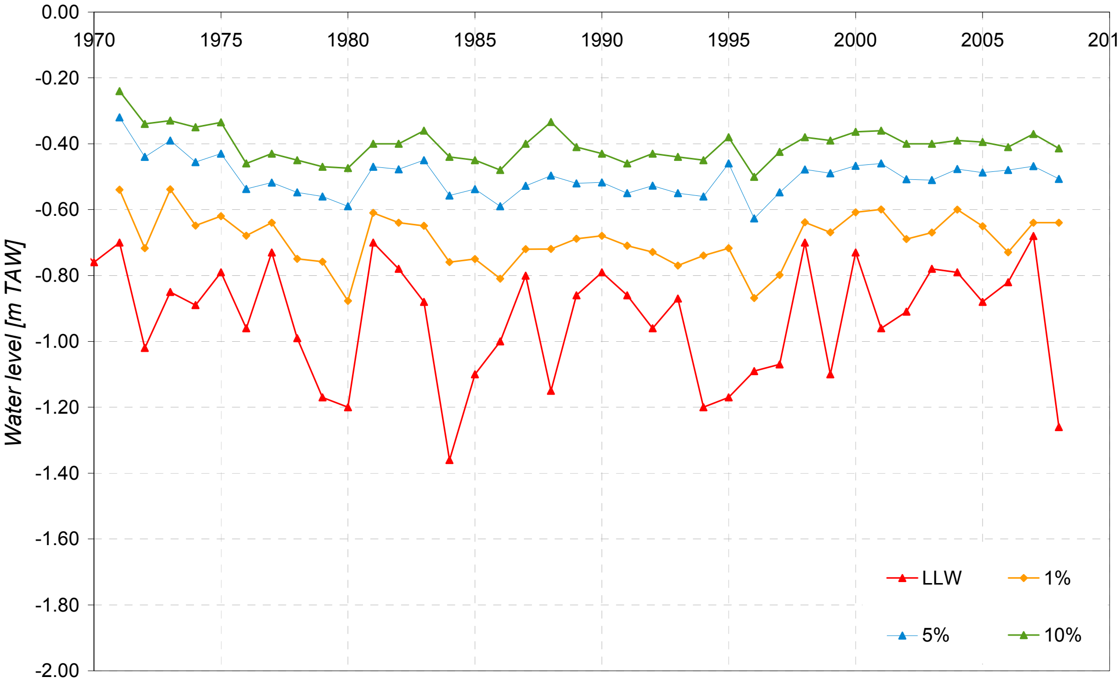

Figure 22 – Extreme low waters (10% - 5% - 1% - lowest) in Antwerpen

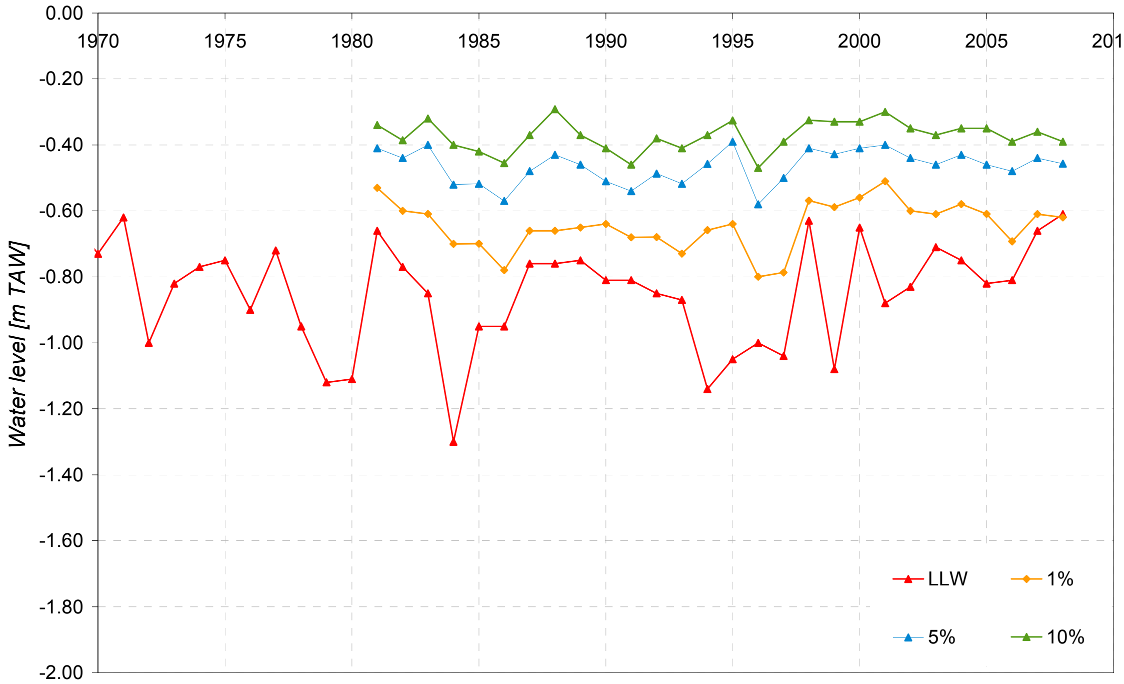

Figure 23 – Extreme low waters (10% - 5% - 1% - lowest) in Schelle

2.5 Summary and discussion of results

Since the start of the measurements in the beginning of the 20th century, significant changes have occurred on all water level parameters. Changes observed for averaged, spring and neap tides are similar, although the absolute magnitude of the changes is different (larger for spring tide, smaller for neap tide). The analysis performed in this chapter focusses on the changes of the validated yearly averaged data. Only a indicative linear trend was determined, which approximates the sea level rise. In order to make a proper analysis of historical trends, changes in the rate of sea level rise (linear trend) must be taken into account, while also the 18,61 year (nodal) cycle must be taken in consideration.

High water level show for all stations an increasing trend since the start of the measurements. Main reason for this evolution is the sea level rise, which can be seen as a boundary condition at the down-estuarine boundary (Vlakte van de Raan, or Vlissingen – Breskens). The local morphology of the estuary causes changes in the magnitude of the sea level rise: in Schelle the mean high water level has increased for almost 100 cm over the past century, while in Bath this was only 50 cm. Another conclusion on the high water level is that the tidal wave propagates further up-estuary: at the beginning of the 20th century the highest high water levels were found in Antwerpen, while at the end of this century high water was highest in Schelle for the considered stations.

Low water levels show a different evolution. Before the 1970’s a minor increase (ca. 20 cm) is found in Bath, while the low water levels for the stations of the lower Sea Scheldt fluctuate around an average value (“status quo”). In the 1970’s an important decrease (ca. 25 cm) of the low water levels can be found for all stations. After the 1970’s, a minor increase of the low water levels seems to occur, while important variations can be seen between two years.

The tidal range combines the effects of both high and low water levels. On the long term a gradual increase of the tidal range takes place. This is mainly caused by the gradual increase of the high water levels at all stations. During the 1970’s a significant increase occurs for all stations, which can be related to the large drop in low water levels. Since 1980, the variation in tidal range seems to have stabilized.

Due to a limited availability of data, long term changes in duration of rising and falling are more difficult to determine. Based on a limited amount of data, a change in trend seems to have occurred in the middle of the 20th century: in the first half a decrease of the duration of rising took place (10 to 15 minutes), while in the second half a gradual increase occurred (ca. 15 minutes). The opposite trend can be found for the duration of the falling. This evolution means that the increase of tidal asymmetry seen in the first half of the 20th century has changed to less asymmetry in the tidal curve, in fact back towards the situation of 1900.

Due to a limited availability of data, long term changes in propagation times (or on the contrary celerities) of high and low water are more difficult to determine. Based on a limited amount of data, an limited increase of celerity can be found for all stations, for both high and low water, in relation to Vlissingen. When the analysis is made (since 1980) by comparing propagation times in different sections between 2 water level stations, it can be found that for the reach Antwerpen-Schelle the propagation time has decreased by ca. 5 minutes, for the reach Liefkenshoek-Antwerpen it has remained quasi constant, while for the reach Bath-Liefkenshoek an increase of ca. 5 minutes has occurred. However, these changes are of the same order of magnitude as the accuracy of the determination of these parameters.

Changes of extreme high and low water levels show good resemblance with the evolution of the mean high and low water levels. The increase of the 99% high water percentile is similar to the increase of the mean high water for all stations.

3 Topo-bathymetric data

3.1 Available data

During the last decade the topo-bathymetry of the Scheldt estuary is regularly measured using following techniques: the intertidal area is measured with the Light Detection and Ranging technique (LIDAR), the subtidal area is measured with the singlebeam and/or multibeam technique. The combination of both techniques provides the topo-bathymetric data covering the entire area. Based on these measurements, an interpolation of the entire area between the Dutch-Belgian border and Rupelmonde is made to a grid with resolution 5m by 5m.

However before 2000 the topo-bathymetry of the Sea Scheldt was not very often measured fully covered. From paper topo-bathymetric maps of the study area, as many as possible points with a known depth value were digitized. These point data were then interpolated to a grid with a resolution of 5m by 5m. For data before 1991 this interpolation was done by the Maritime Access division, after 1991 by Flanders Hydraulics Research. All available data were converted to the UTM31ED50 coordinate system, and the TAW plane was used as the vertical reference plane.

Table 3 gives an overview of the years in which the bathymetric data – covering the study area from the Dutch-Belgian border to Rupelmonde – were available.

Table 3 – Overview of the years with fully covering topo-bathymetric data

Period of measurement for the study area	**Data-availability intertidal areas**	**Year of subtidal measurement for Saeftinge – Doel (Sea Scheldt)**	**Year of subtidal measurement for lodingsvak 1 (Western Scheldt)**
1910	NO		no data
1920	NO		no data
1928 - 1931	NO	1930	1931
1950 - 1951	NO	1950	1951
1958 - 1961	NO	1958	1959
1970 - 1971	NO	1970	1971
1980 - 1981	NO	1980	1980
1990 - 1991	NO	1990	1990
2000 - 2001	YES	2000	2000
2002 - 2003	YES	2002	2002
2004 - 2005	YES	2004	2004
2006 - 2007	YES	2007	2007
2008	NO	2008	2008
2009		2009	2009

In order not to miss an area, it was agreed that the analysis of the Sea Scheldt area would go up to Bath. In the report (referentie Deltares rapport) the analysis stops in Bath. However the bathymetric measurements from the Sea Scheldt area – from Prosperpolder to Bath – are not always available within the Belgian topo-bathymetric data. Therefore the Dutch topo-bathymetric data – provided by the Directie Zeeland – were used to extend the Belgian data up to Bath. In order to do so, the Dutch data from the year closest to the year in which the area Saeftinge-Doel was measured, was used for this. The exact years are also given in Table 3.

The bathymetry for 1928 - 1930 for survey-section 1 of the Western Scheldt is not available. For 2002 - 2003 the Belgian topo-bathymetric data for the area between Prosperpolder and Bath is fully covering. Therefore, the Dutch data for 2002 were not used.

The horizontal accuracy of all bathymetric data does not exceed the cell size (5m x 5m). The estimated accuracy of the vertical bathymetric values varies between the different periods and increases with time. According to the old standards the accuracy was about 30 cm between 1930 and 1950 and about 20 cm for the period from 1960 until 1970. The current bathymetric measurements in the Lower Sea Scheldt have an accuracy of about 10 cm (pers. comm. Flemish Hydrography).

3.2 Extension of topo-bathymetry

The available topo-bathymetric surveys covered large parts of the Scheldt estuary, but for the historical surveys (< 2000) no information was available for the intertidal areas. Where for some situations contour lines were available, defining the border between the subtidal and intertidal area (low water line) on the one hand and the border between the tidal flats (or “slik”) and salt marshes (or “schor”) on the other hand, an extension of the topo-bathymetry was performed. This is further described in paragraph 3.2.1. Besides this extension, the topo-bathymetric data had some large gaps, which could not be filled using traditional interpolation techniques. Therefore an interpolation was performed using expert judgement. This described in paragraph 3.2.2.

3.2.1 Intertidal areas

Based on historical aerial photographs, contour lines, defining the border between the subtidal and intertidal area (low water line) on the one hand and the border between slik and schor on the other hand, were deducted. These contour lines are available for 1930 and 1960 and will used to extend the topo-bathymetry on the intertidal areas. To test the applicability of this technique and also to get an indication of the level that should be assigned to the contour lines, a validation was performed for a known situation.

Determination of level for contour lines

For the topo-bathymetry of 2001, all information above the low water level was erased. This was then reconstructed based on the contour lines derived from aerial photographs. To get an indication of the level that should be allocated to the contour lines, the bottom elevation (negative elevation means below low water level) was plotted along the contour line. This is presented on Figure 24 (border between subtidal and intertidal) and Figure 25 (border between slik and schor).

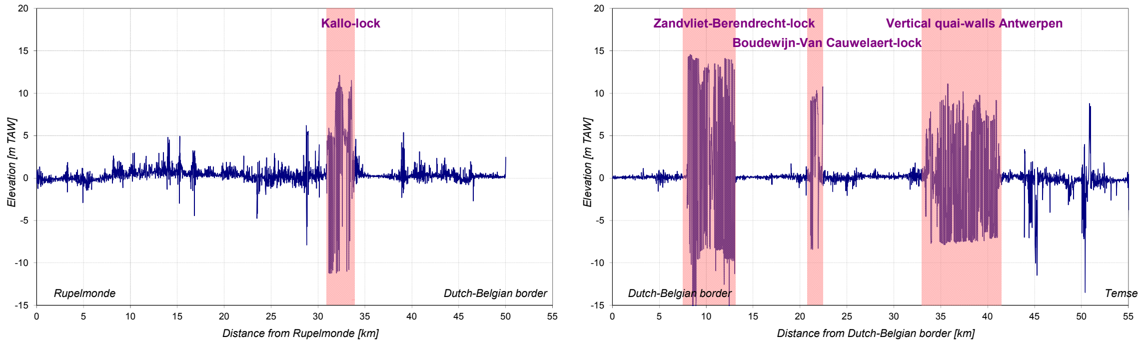

Figure 24 – Bottom elevation along contour line “subtidal – intertidal” for left bank (left) and right (right) bank

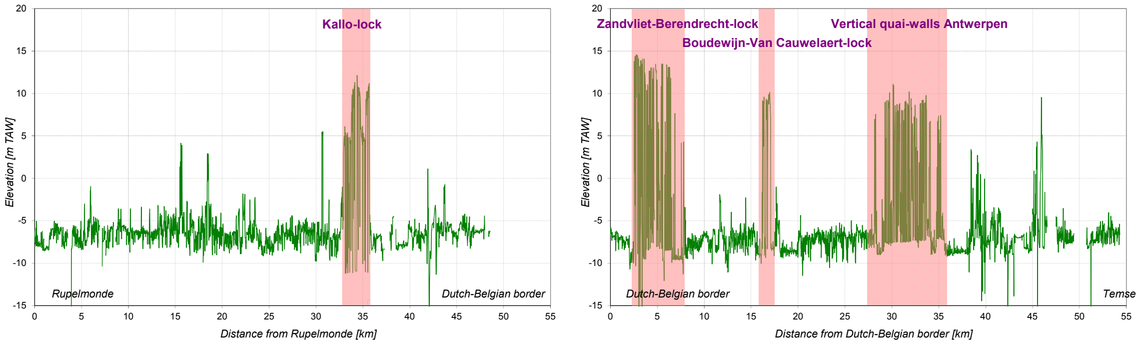

Figure 25 – Bottom depth along contour line “slik – schor” for left bank (left) and right (right) bank[5]

This figures show that the variation along the contour is rather limited, although, in some zones, large variations can occur. These are related to the vertical quay walls near the access channels of the locks and on the right bank in Antwerp. Due to the vertical structures in this zones, the contour lines can be located on top or at the foot of the quay wall, leading to large variations of the bottom depth. These zones are indicated on the figure in pink.

For the contour line “subtidal – intertidal” the average value is 0m TAW with a rather small variation. For the contour line “slik – schor” the average value is +6m TAW with a larger variation. Based on these results, it was opted to use a fixed bottom depth of 0m TAW for the contour line “subtidal – intertidal”, while the bottom depth for the contour line “slik – schor” was chosen on 6m TAW. Because of the larger variation, a sensitivity analysis was performed using a bottom depth of respectively +5m TAW and +7m TAW for the “slik – schor” contour line. Between these contour lines, a linear interpolation was used to reproduce a topo-bathymetry for the intertidal zones.

Validation extension technique

For the validation the hypsometry was calculated for the intertidal zones, aggregated for the Lower Sea Scheldt. The comparison of the calculated volumes was performed for the intertidal areas (blue area on Figure 26, not taking into account the channel volumes (light blue and red area)):

1. From LIDAR-sounding
2. Calculated by linear interpolation between contour lines

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[5] It can be noticed that the distance along the estuary differs for the subtidal – intertidal contour line and the slik – schor contour line. This difference is introduced by the difference in smoothness of both contour lines: the slik-schor contour line is much smoother resulting in a shorter distance along the estuary. E.g. on the right bank the Zandvliet-Berendrecht-locks are situated near KM 5 in de slik-schor contour line, while the same location is located near KM 10 in the subtidal-intertidal contour line. This difference is caused by the existence of the guiding wall of the Ballastplaat, which is present in the subtidal-intertidal contour line and not in the slik-schor contour line.

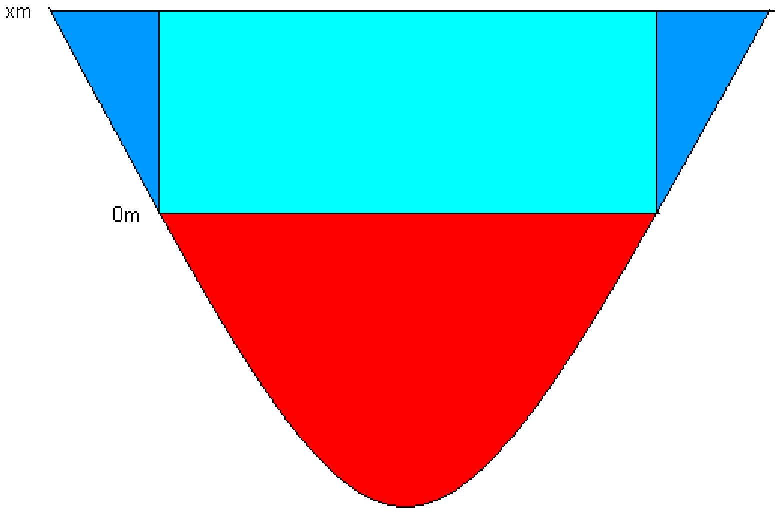

Figure 26 – Schematisation of cross section for validation (in blue volume/area above intertidal area)

Volumes between the reference level and the topo-bathymetry were calculated for this validation for 1m-intervals. The results, including relative differences, can be found in Table 4.

Table 4 – Calculated intertidal volumes for different reference heights

Reference level for calculated volume [m TAW]	***Volume from sounding [Mm³]***	***Calculated volumes by linear interpolation between contour lines Subtidal – intertidal @ 0m TAW – Slik – schor @ Xm TAW***					
		+5m TAW [Mm³]	*Difference [%]*	*+6m TAW [Mm³]*	*Difference [%]*	*+7m TAW [Mm³]*	*Difference [%]*
0	0	0	0,00%	0	0,00%	0	0,00%
+1	0,851	1,028	18,85%	0,957	11,72%	0,908	6,53%
+2	3,328	3,730	11,38%	3,384	1,67%	3,148	-5,55%
+3	7,596	8,048	5,77%	7,170	-5,78%	6,566	-14,54%
+4	13,015	13,944	6,89%	12,242	-6,12%	11,070	-16,15%
+5	19,608	21,901	11,05%	18,641	-5,06%	16,690	-16,08%
+6	27,453			26,923	-1,95%	23,462	-15,67%
+7	37,376					32,039	-15,37%

When the slik – schor contour line is defined at +5m TAW, the water volumes calculated are systematically overestimated. This can be explained by the fact that the extension of the intertidal areas results in a topo-bathymetry that is systematically to low, due to the choice of the contour line at +5m TAW. When the slik – schor contour line is defined at +7m TAW, the water volumes calculated are systematically underestimated. This can be explained by the fact that the extension of the intertidal areas results in a topo-bathymetry that is systematically to high, due to the choice of the contour line at +7m TAW.

From this validation it can be concluded that the definition of the contour line slik – schor at +6m TAW gives the best results. A further improvement can be possible by choosing the spatial varying historical spring low water level for the subtidal – intertidal contour line and the spatial varying historical neap high water level for the slik – schor contour line. Due to the complexity of this method and the good agreement using the simple technique, it was opted not to incorporate the complex methodology.

For the lower reference level a small overestimation of the water volumes can be found, while for the highest reference level a small underestimation of the water volumes can be found. This deviation can be explained due to the linear approximation of the slope of the slik, while in reality a concave and convex form can be found. This is shown in Figure 27.

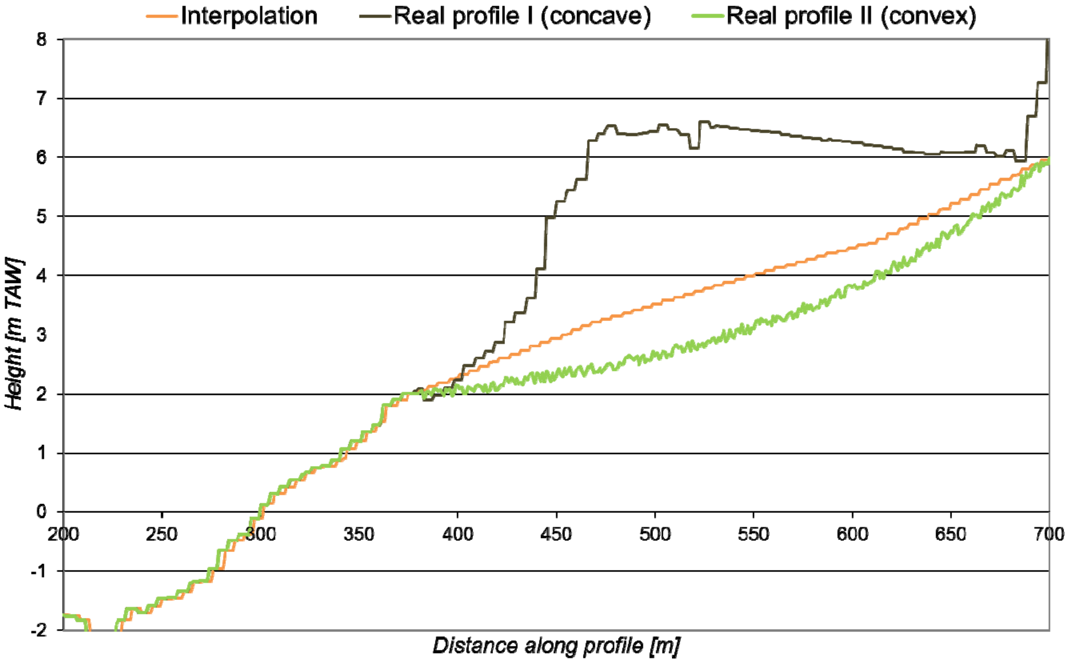

Figure 27 – Linear approximation of concave and convex profile

For the extension of the topo-bathymetry on slik and schor areas for 1930 en 1960, an additional contour line was used with the position of the dikes. This contour line was given a value of 8,35m TAW.

Dutch – Belgian border

For the Bath – Liefkenshoek zone, bathymetric data had to be assimilated from Flemish Hydrography (Belgian part) and from Rijkswaterstaat (Dutch part). For the zone near the border gaps could occur. Therefore an interpolation (Inverse Distance Weighted) was used to fill these gaps, both in the subtidal as the intertidal area.

3.2.2 Gaps in bathymetry

The available bathymetric data for the Lower Sea Scheldt were interpolated to a 5m x 5m grid. However, there were not enough bathymetric data for some areas in order to make a trustworthy interpolation of the bathymetry. Therefore, these so-called gaps in the bathymetric data needed to be interpolated manually. Therefore in a first phase contour lines were manually constructed, while in a second phase an interpolation (Triangular Irregular Network) was conducted. Figure 28 shows an example of an area with a gap before and after manual interpolation.

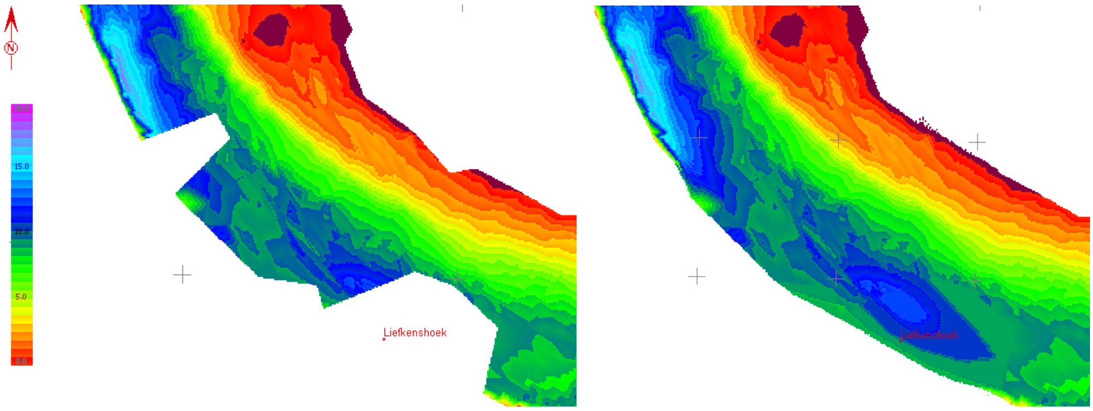

Figure 28 – Gap in bathymetry near Liefkenshoek (1960) before (left) and after (right) manual interpolation

Lock entrances

The lock entrances to the port of Antwerp can store some volume of water. However for most years these areas were not included in the topo-bathymetric measurements. In order to include the lock entrances in the bathymetric analysis, it was chosen to complete the bathymetry for these areas for all years. This is not too difficult, since the lock entrances are maintained at a certain depth by dredging works and the boundary of the lock entrances are vertical quay walls.

By comparing the average depth of the lock entrances to the dredging target depth, it was noticed that there is not always a good correspondence between both. After all the lock entrances are locations where finer sediments can be deposited and there the bathymetry is changes in time (gradual decrease in depth between dredging campaigns and stepwise increase in depth before and after dredging campaign). Besides this, the dredging target depth has increased over the years, as developments in maritime navigation have led to an increase of draft of the vessels.

As a consequence it was chosen to use bathymetric data of the closest year available. In the case that the difference between the imported bathymetry for a missing area and the available bathymetry for a part of the lock entrance is large, some extra adaptations are made in order to get a smooth transition between existing and imported data (for example, the imported bathymetry is made shallower or deeper). An overview of the data used for the locks and the adaptations of these data is presented in Table A1.

For most years the available bathymetry is not complete and has to be extended to the quay walls of the lock entrances. Three boundary files are used to determine the exact boundary of the lock entrances, which of course vary in time:

- the boundary for the present situation;
- the boundary for the area near the Van Cauwelaert lock entrance for the year 1934 (this is before the construction of the Boudewijn lock);
- the boundary for the Zandvliet lock entrance for the year 1967 (before the construction of the Berendrecht lock).

The boundary for the present situation is available in a digital format. The boundaries for the years 1934 and 1967 are digitized from historical section maps. Based on the analysis of the boundary files the bathymetry for some locks is extended on the sides and also towards the lock doors.

For the years in which some of the more recent locks were not built yet, a high level is assigned for the lock entrance areas that did not exist yet (Figure 29). This is done in order to have the same area of the estuary for all analysed years.

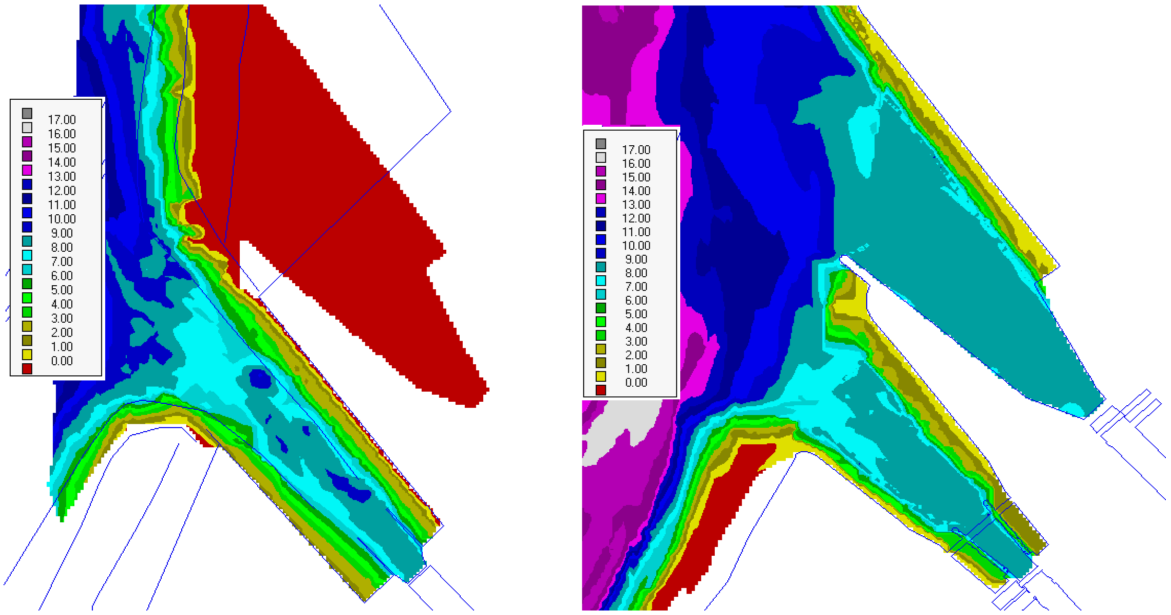

Figure 29 – Bathymetry of Van Cauwelaert and Boudewijn lock entrance before (1950 - left) and after (1980 - right) completion of Boudewijn lock

Deurganckdok

The Deurganckdok was opened in 2005. Since the correspondence between a tidal dock and a lock entrance is big, the bathymetry of the Deurganckdok was processed in the same way as the one of the lock entrances. For all years after construction of the dock, a bathymetric measurement of the dock was carried out. The bathymetry had to be extended for some years in order to be fully covering (until the vertical quay walls).

3.3 Processing

Hypsometric curves were calculated for the extended topo-bathymetries. Therefore the topo-bathymetry for each of the three sections was exported (ASCII - x,y,z) in ArcGIS from a regular grid (5m * 5m). This file was read in Matlab, were a script calculated the volumes below equidistance reference planes. The interval between two planes was 10 cm.

For 1930, 1960, 2001, 2004 and 2007 full (extended) datasets were available. For 1950, 1970, 1980 and 1990 the hypsometric curves could only be calculated below 0m TAW, as no information was available for the intertidal areas. To have an approximation of the hypsometric curves in the intertidal zones for these years, an interpolation was used. This interpolation was based on the available data of the nearest years, calculating the volumes and areas on the intertidal zones as follows:

$$VI_{1m}^{19XX} = V_{1m}^{19XX} - V_{0m}^{19XX} - S_{0m}^{19XX}.1m$$

$$V_{1m}^{1950} = V_{0m}^{1950} + S_{0m}^{1950}.1m + \left[VI_{1m}^{1930} + \frac{1950-1930}{1960-1930}.\left(VI_{1m}^{1960} - VI_{1m}^{1930}\right) \right]$$

with: VI_{ref}^{YYYY} : volume below reference for intertidal zone (without channel) in year YYYY

V_{ref}^{YYYY} : volume below reference (incl. channel) in year YYYY

S_{ref}^{YYYY} : area at reference level in year YYYY

A similar interpolation was used to calculate the intertidal area for the years without data.

3.4 Definition of topo-bathymetric characteristics

Regarding the topo-bathymetry of the Sea Scheldt, the following parameters were deducted:

- Hypsometric curves
- Channel volume: volume below 0m TAW
- Mean channel depth: $D_{mean}^{channel} = \frac{V_{<0mTAW}}{S_{<0mTAW}}$
- Volume of intertidal areas (absolute, relative): $V^{intertidal} = V_{<6mTAW} - V_{<0mTAW} - 6m * S_{0mTAW}$

3.5 Evolution of topo-bathymetric characteristics

Figure 30 to Figure 32 show the hypsometric curves for the 3 sections in the Lower Sea Scheldt. It should be mentioned that the data under 0m TAW are calculated from the available (digitized) depth soundings, while only for 1930, 1960, 2001, 2004 and 2007 data was available for the intertidal zone. For the other years information of the intertidal zone was calculated by interpolation from the available years.

All three sections show a clear pattern in the hypsometric curves: a first group of curves includes the historical situation before the 1960's, while a second group of curves bundles the situation after the 1970's. From the hypsometric curves it can be seen that an important of volumes has occurred during the 1970's. This change can be related to the large amounts of sand that were extracted out of the estuary for infrastructural works in this period.

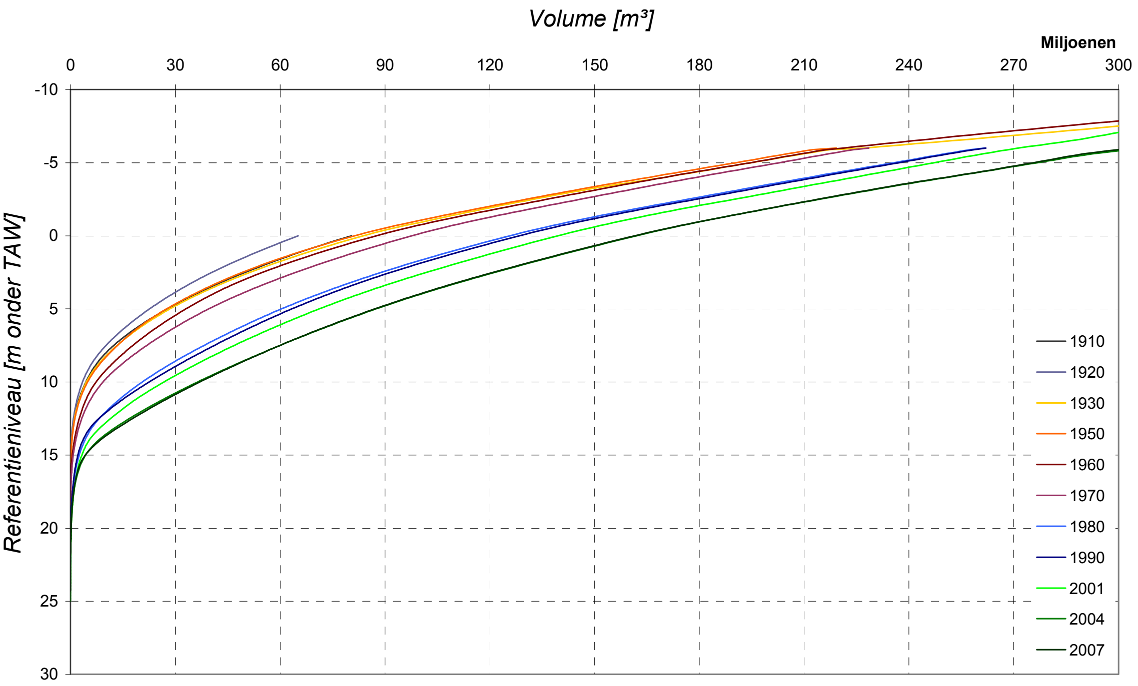

Figure 30 – Hypsometric curve for section Bath - Liefkenshoek

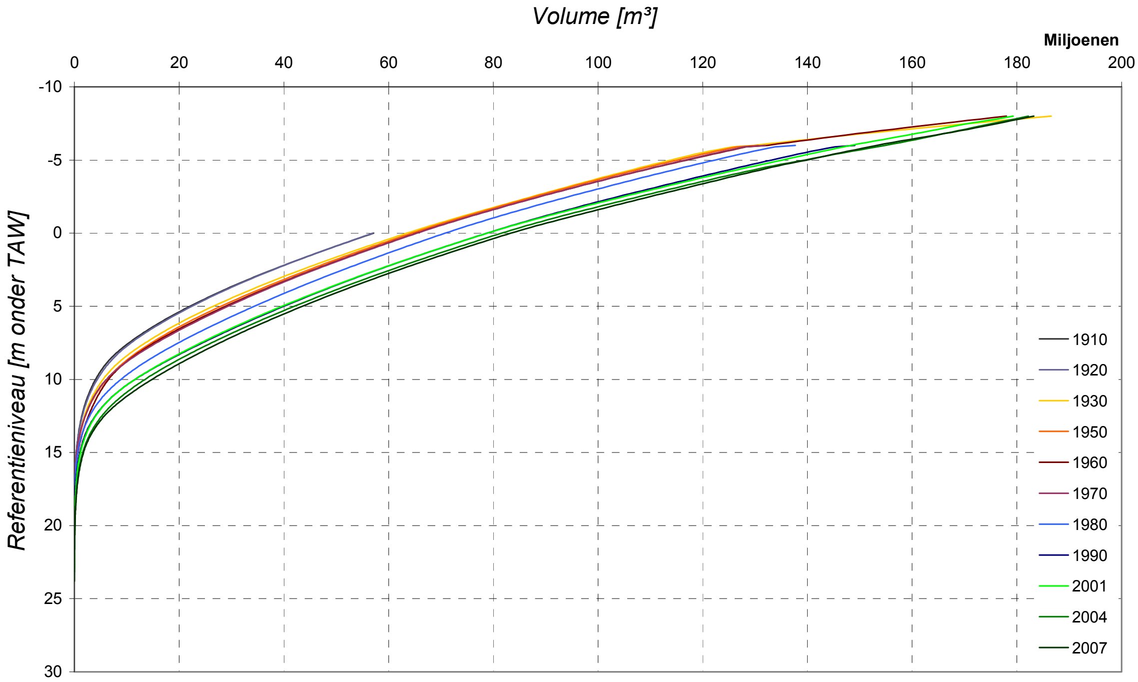

Figure 31 – Hypsometric curve for section Liefkenshoek - Antwerpen

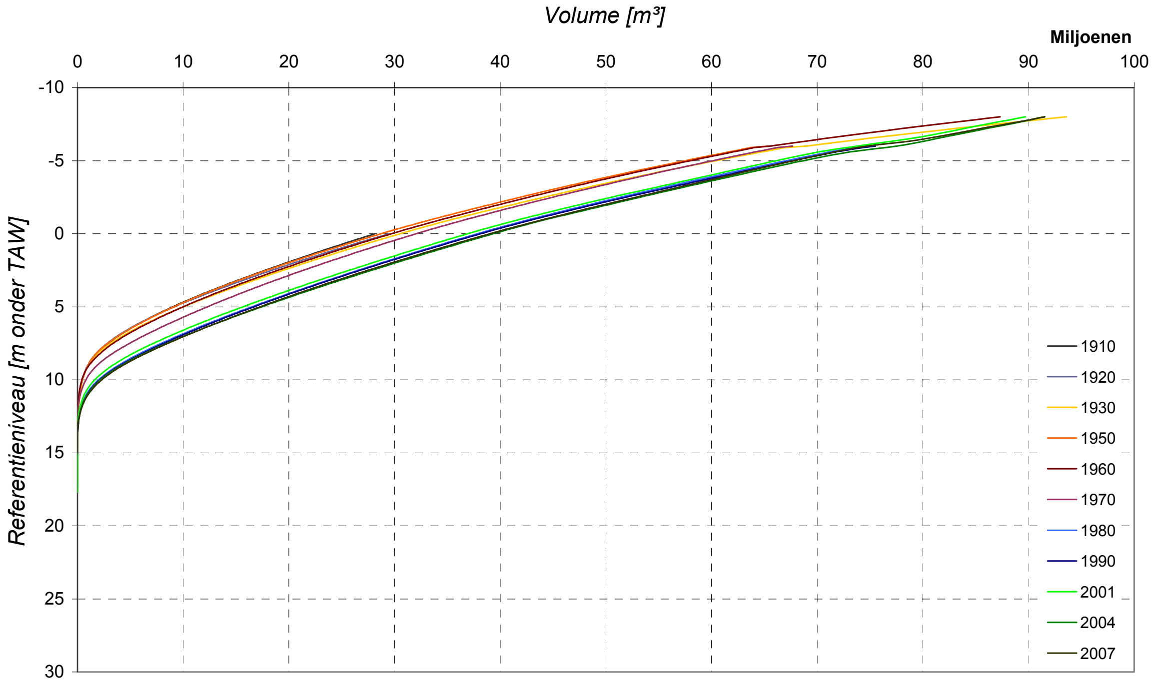

Figure 32 – Hypsometric curve for section Antwerpen - Schelle

While the hypsometric curves include all the information from the topo-bathymetric data, deducted characteristics allow for a better analysis of ongoing trends. Nevertheless, a general conclusion from the hypsometric curves for all three sections can be found: a gradual increase of the volume below certain reference levels (-10m TAW, -5m TAW, 0m TAW) occurs for each sections, most pronounced for the section Bath – Liefkenshoek, indicating an enlargement (deepening and/or widening) of the estuary.

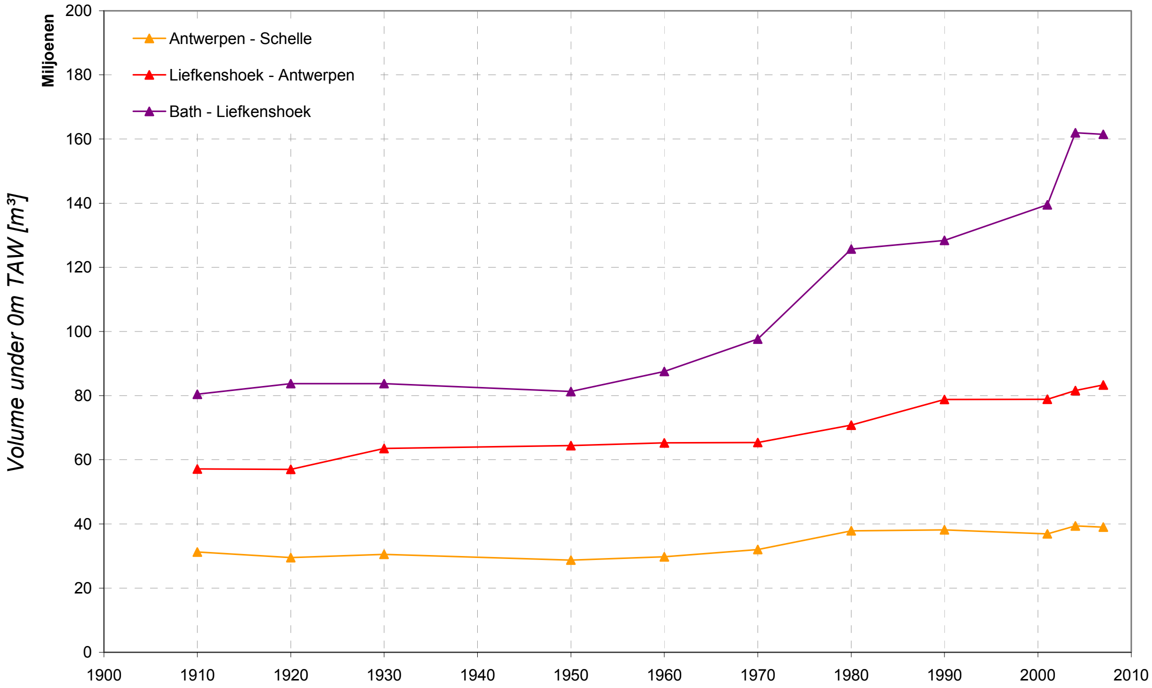

Figure 33 – Water volume of channel (< 0m TAW) for different sections

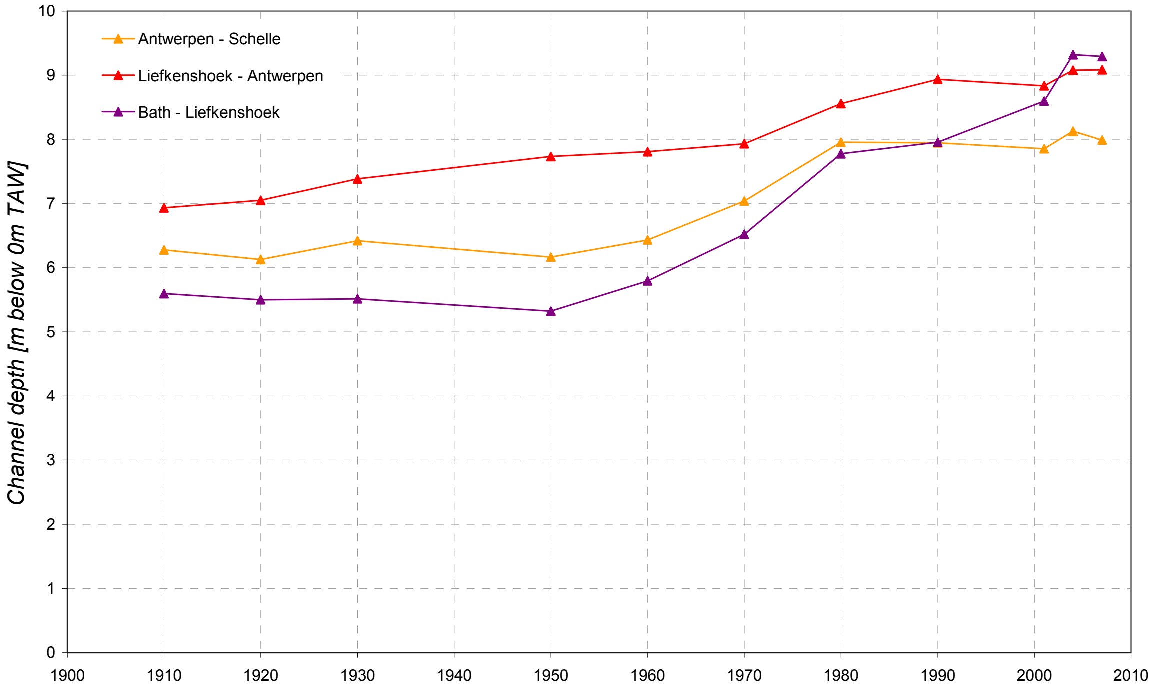

Figure 34 – Channel depth (< 0m TAW) for different sections

The water volume of the channel (Figure 33) for sections Liefkenshoek – Antwerpen and Antwerpen – Schelle remains rather constant until 1970. The channel depth (Figure 34) shows a rather gradual increase. In the 1970's the volume and the depth increase where after they remain at the same level during the 1980's and 1990's. Between 2001 and 2004 a new increase takes place in the section Bath – Liefkenshoek, while this is less pronounced in the other 2 sections.

For the section Bath – Liefkenshoek the volume of the channel(s) remains constant until 1950, with the depth slightly (~ 1 dm) decreasing. From 1950 on a gradual increase in volume (c.q. depth) takes place, which is amplified during the 1970's and at the start of the 2000's. The deepening of the channel is much stronger in the section Bath – Liefkenshoek (~ 38 dm) than in the other sections (~ 19 dm), mainly due to the extraction of sediment for infrastructural works during the 1970's.

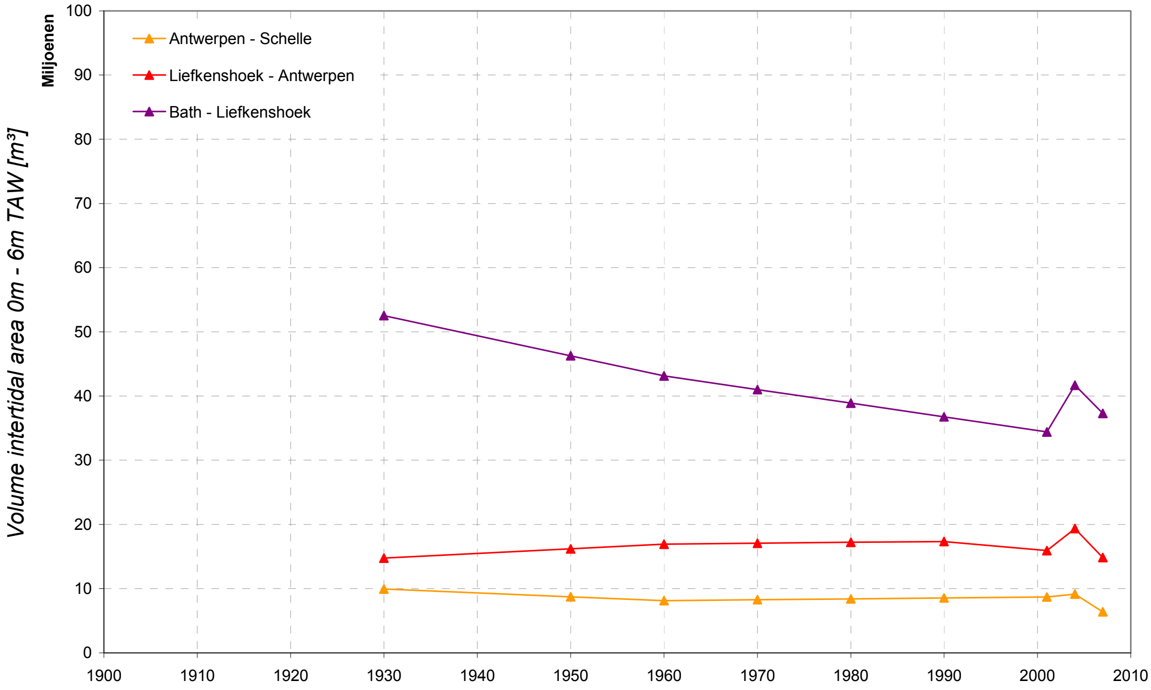

Figure 35 – Water volume above intertidal areas [0m, 6m TAW] for different sections

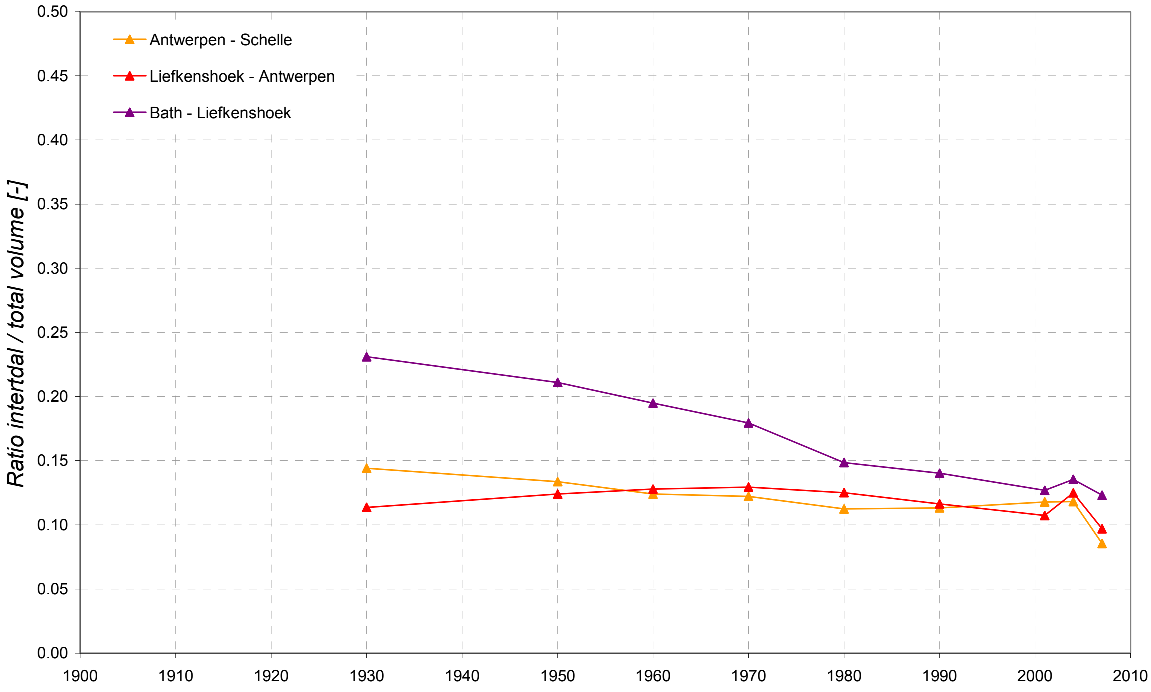

Figure 36 – Ratio of water volume above intertidal areas [0m, 6m TAW] to total volume for different sections

The water volumes above the intertidal areas between 0m and 6m TAW (Figure 35) have a different pattern for all three sections: both section Liefkenshoek – Antwerpen as Antwerpen – Schelle remains rather constant over the total period, although for the section Liefkenshoek – Antwerpen the water volume increases marginally to reach its maximum in 1990, while for the section Antwerpen – Schelle it decreases marginally. The ratio of the volume above the intertidal areas between 0m and 6m TAW to the total volume (Figure 36) has a similar trend and varies between 10% and 15%. The 2004 value deviates from this trend. This could be caused by the different measurement techniques that are used to measure the height of the intertidal areas (discontinuous transects vs. area covering LIDAR).

For the section Bath – Liefkenshoek the water volume above the intertidal areas between 0m and 6m TAW decreases strongly with the ratio of the volume above the intertidal areas between 0m and 6m TAW to the total volume decreasing from 23% to 13%. This trend starts from the first available topo-bathymetry (1930) and continues until the start of the 21st century. This trend can be related to the poldering of intertidal areas that occurred in the past, and the changes in morphology due to this poldering in the past centuries. The effect of more recent human activities (e.g. sand extraction, deepening, infrastructural works) cannot be identified in the trends of these parameters.

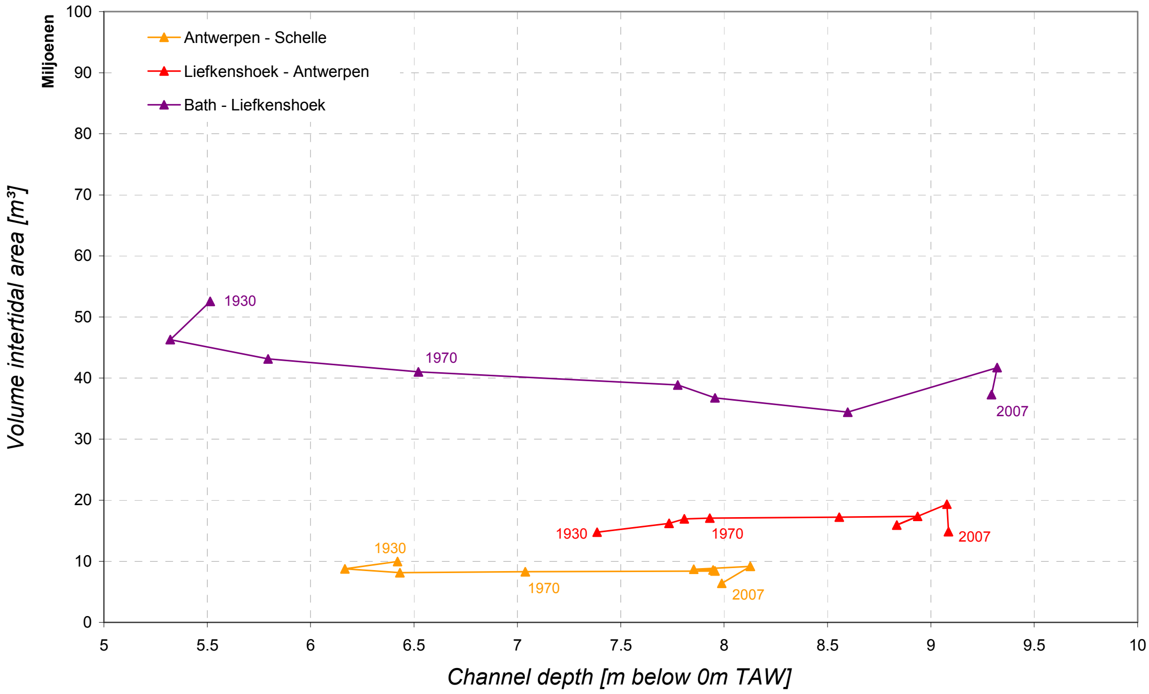

Figure 37 – Channel depth vs. water volume above intertidal areas (0m < X < 6m TAW) for different sections

Figure 37 combines the major changes in volumes of both channel and intertidal areas. For all three sections the channel depth has increased over the last century, while the water volume above the intertidal areas between 0m and 6m TAW remained almost the same. Only for the section Bath – Liefkenshoek a decrease can be seen.

3.6 Summary and discussion of results

The hypsometric curves show for all 3 sections a gradual increase in volumes for different reference levels. For the section Bath – Liefkenshoek, 2 periods have a stronger increase in volume: 1970-1980 and 2001-2004. Over the total period, the channel volume in this section has increased from 80 Mm³ in 1910 to 160 Mm³ in 2007 (+ 100%), while the mean channel depth increased from 5,6 m to 9,3 m. For the section Liefkenshoek – Antwerpen, the most important increase of volume took place between 1970 and 1990. Over the total period, the channel volume in this section has increased from 57 Mm³ in 1910 to 83 Mm³ in 2007 (+ 46%), while the mean channel depth increased from 6,9 m to 9,1 m. For the section Antwerpen – Schelle, the most important increase of volume took place between 1970 and

1980. Over the total period, the channel volume in this section has increased from 31 Mm³ in 1910 to 39 Mm³ in 2007 (+ 25%), while the mean channel depth increased from 6,3 m to 8,0 m.

The water volume above the intertidal areas between 0m and 6m TAW has decreased (ca. -30%) for the section Bath – Liefkenshoek, while for the other sections Liefkenshoek – Antwerpen and Antwerpen – Schelle it remained quasi constant. This evolution relates with the development of the intertidal area in the different sections: for the section in which intertidal volume decreases, a proportional decrease of intertidal area can be found. The direct and indirect impact of past poldering can be related to these developments. Nevertheless it should be mentioned that due to the limited amount of data of the intertidal areas, these conclusions are only indicative and further research is necessary.

4 Relations between tidal and topo-bathymetric data

4.1 Relation between tidal and topo-bathymetric characteristics

Figure 38 to Figure 40 give an overview of the changes in difference of high and low water level between 2 stations and the channel depth in this section for all historical situations. Although different sections show different relations, all can be linearly approximated rather well. Both the section Bath – Liefkenshoek as Antwerpen – Schelle show a stronger increase of the high water level (or increasing difference) for the upstream station compared to the downstream station with an increasing channel depth. The section Liefkenshoek – Antwerpen has an opposite trend. For the low water levels the sections Bath – Liefkenshoek and Liefkenshoek – Antwerpen have a stronger decrease of the low water level for the upstream station compared to the downstream station with an increasing channel depth. For the section Antwerpen – Schelle the difference remains the same with increasing channel depth.

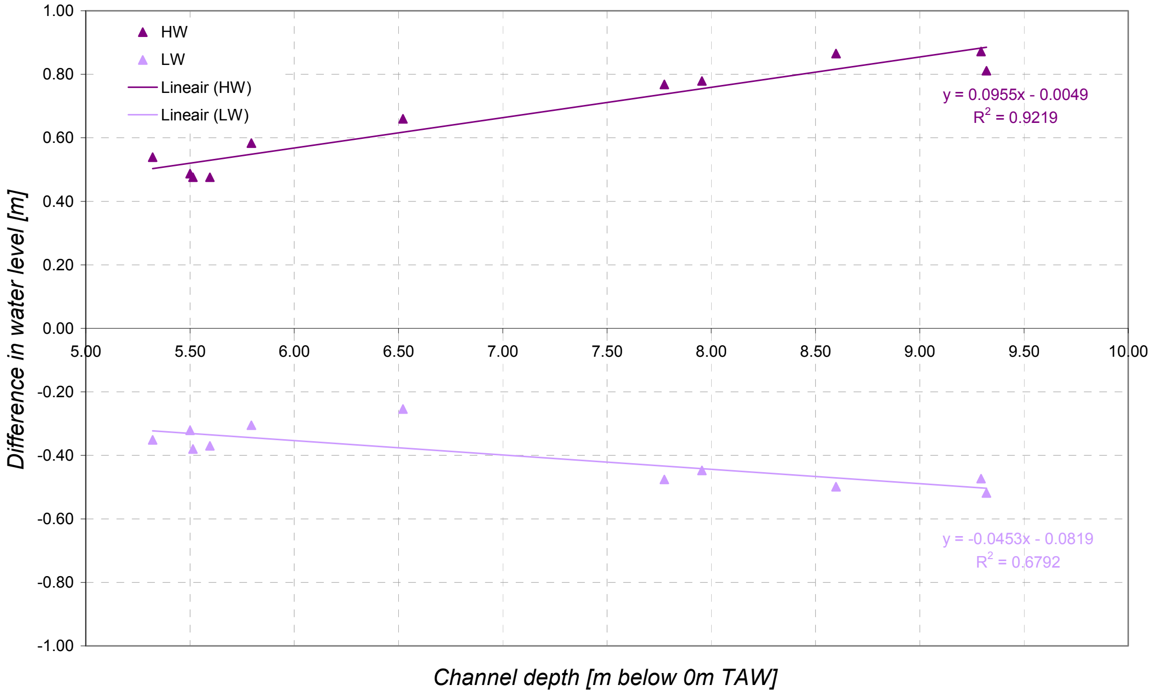

Figure 38 – Channel depth vs. difference in water level (both HW and LW) for section Bath - Liefkenshoek

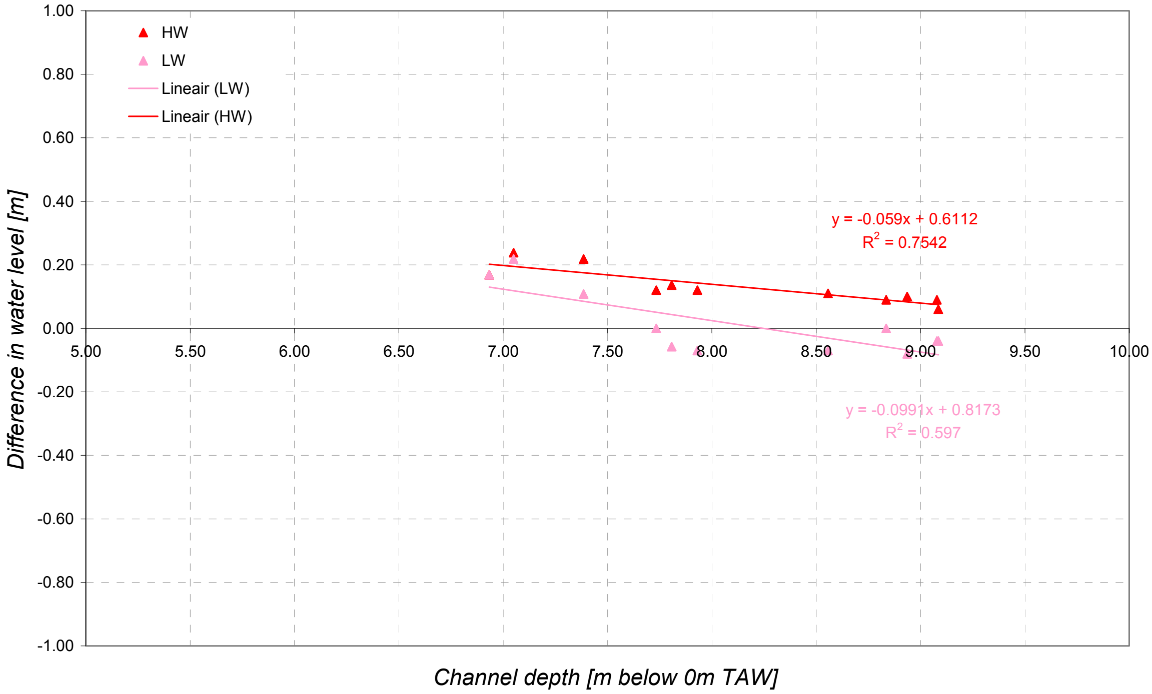

Figure 39 – Channel depth vs. difference in water level (both HW and LW) for section Liefkenshoek – Antwerpen

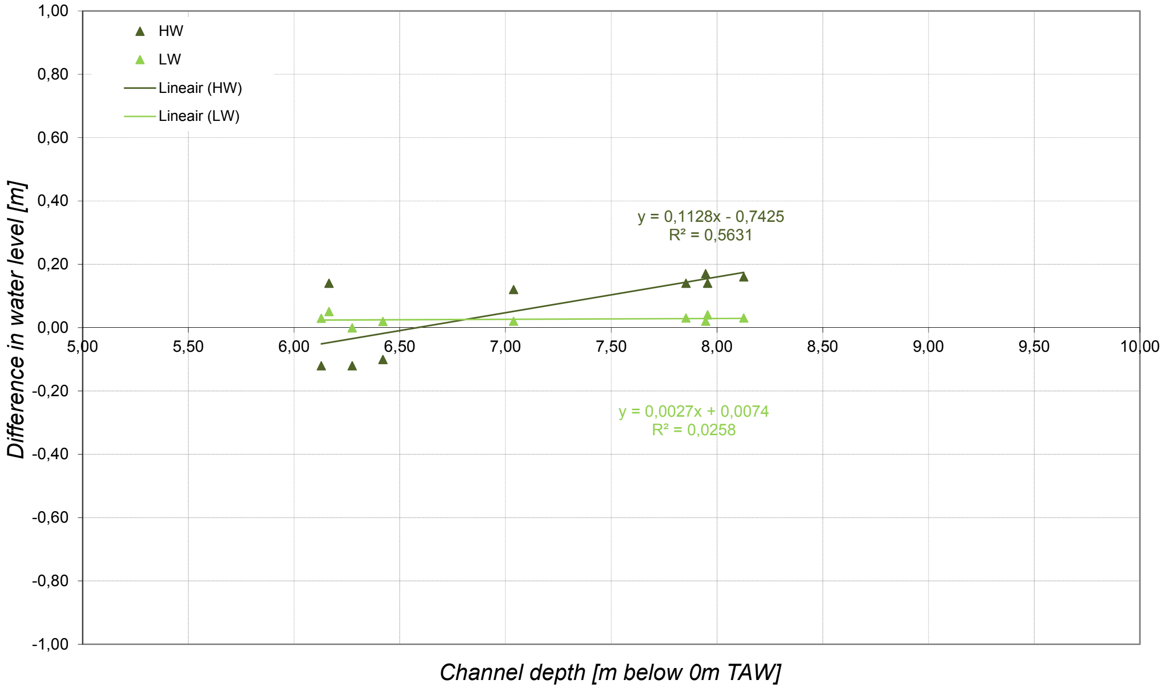

Figure 40 – Channel depth vs. difference in water level (both HW and LW) for section Antwerpen – Schelle

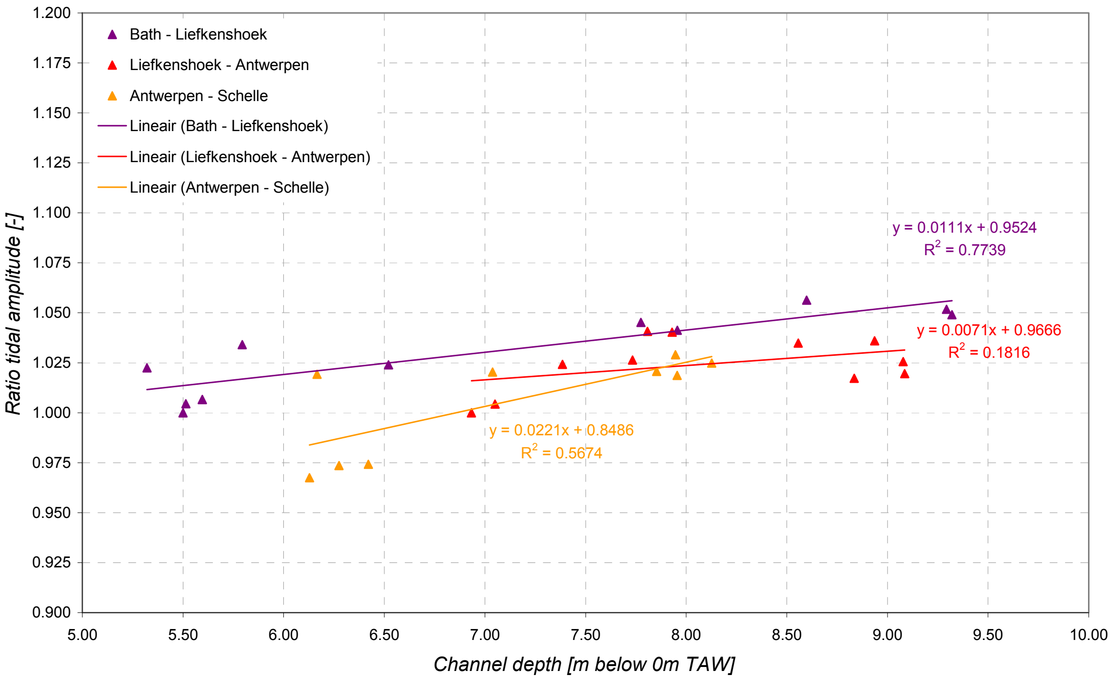

Figure 41 – Channel depth vs. ratio of tidal amplitude for different sections

For all three sections in the Lower Sea Scheldt, the ratio of the tidal amplitude between two consecutive stations increases with increasing channel depth (Figure 41). The rate of increase (slope of regression line) varies for all three sections, with the increase being most pronounced for the Antwerpen – Schelle section. It should be noted that in the first half of the 20th century the tidal amplitude of Antwerpen was larger than Schelle. Since 1950 Schelle has a larger tidal amplitude than Antwerpen. This corresponds with the increased penetration of the tidal wave in the Scheldt estuary (Figure 42).

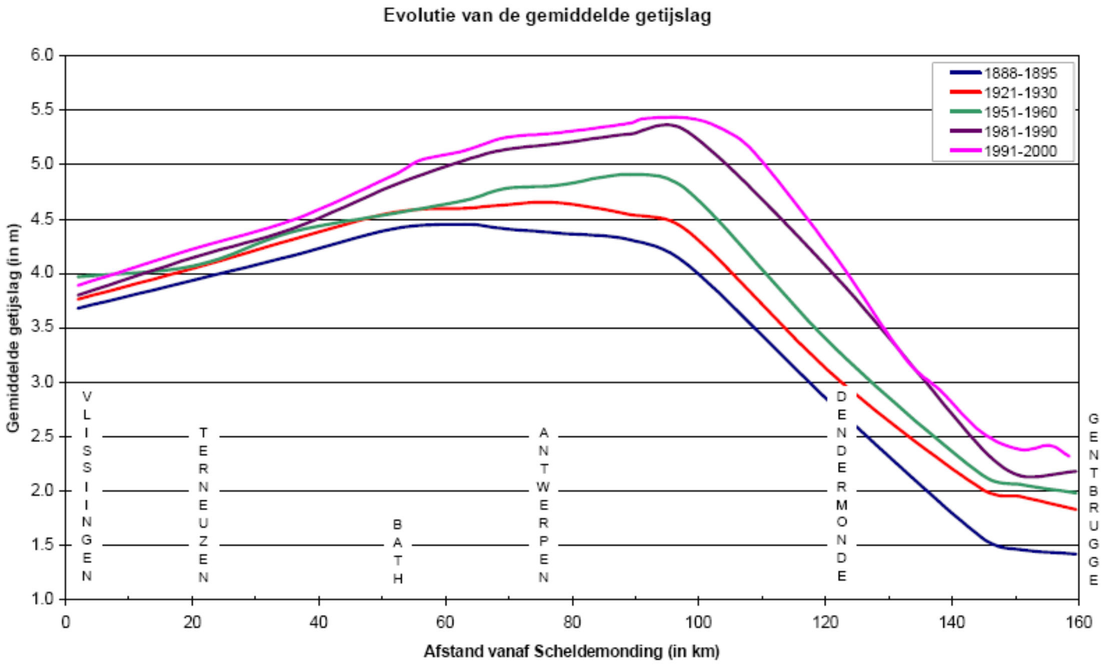

Figure 42 – Tidal amplitude along the longitudinal axis of the Scheldt estuary during the 20th century

(*Source:* after Coen *et al*, 1988)

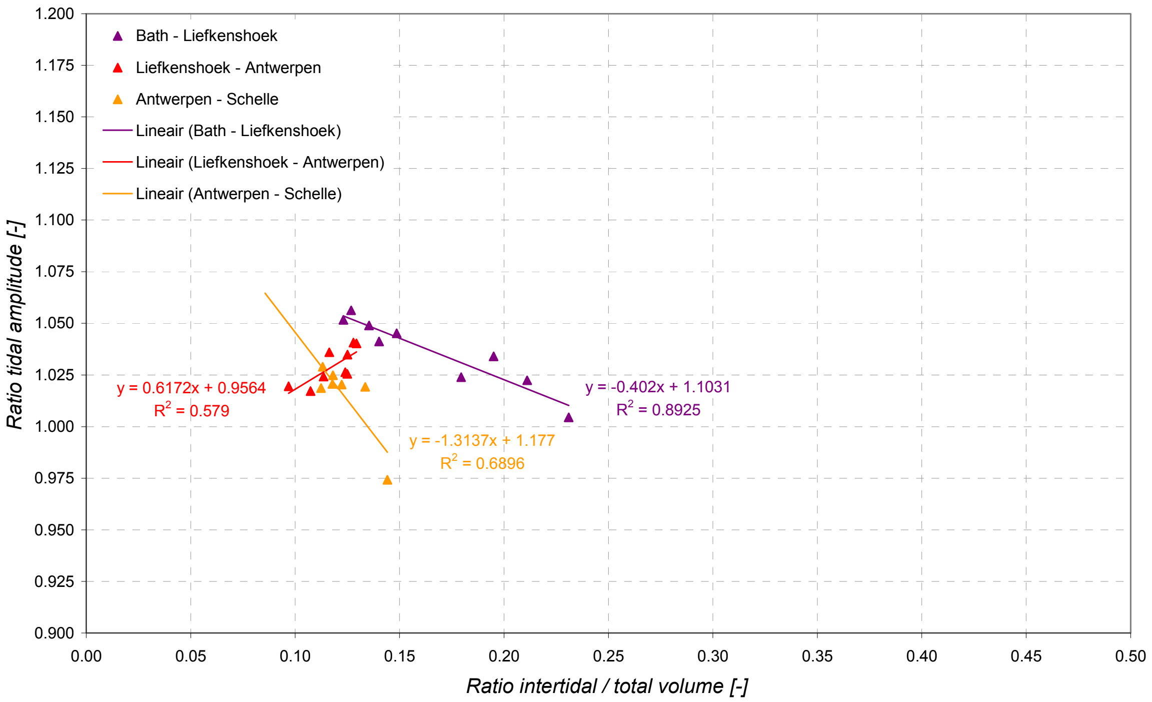

Figure 43 – Ratio of water volume of intertidal areas (0m < X < 6m TAW) to total volume vs. ratio of tidal amplitude for different sections

Comparing the ratio of the tidal amplitude between two consecutive stations increases with the ratio of the intertidal to channel volume (Figure 43) does not give a general trend. For the section Bath – Liefkenshoek a good relation can found: a decrease of the ratio of the intertidal to channel volumes results in an increase of the ratio of tidal amplitude. For the section Antwerpen – Schelle a similar trend can be found, but it is strongly affected by one point (1930) while the variation of the other ratio of volumes is limited. The section Liefkenshoek – Antwerpen gives an opposite trend.

Figure 44 and Figure 45 show the relation between the water volume above the intertidal areas and the high water levels and difference in high water level between the consecutive stations. Only the section Bath – Liefkenshoek shows an obvious relation between the 2 characteristics: a reduction of the water volume above the intertidal area results in an increase of the high water level and difference of high water levels. For the other two sections only the difference in high water level shows some kind of relation with the water volume above the intertidal area, comparable with this one of Bath – Liefkenshoek.

Figure 46 and Figure 47 show the relation between the water volume of the channel and the high water levels and difference in high water level between the consecutive stations. All three sections show in increase of the high water level with the increasing channel volume. For the difference in high water level the sections Bath – Liefkenshoek and Antwerpen – Schelle show an obvious relation between the 2 characteristics: an increase of the water volume of the channel results in an increase of the difference of high water levels. The section Liefkenshoek – Antwerpen shows an opposite trend.

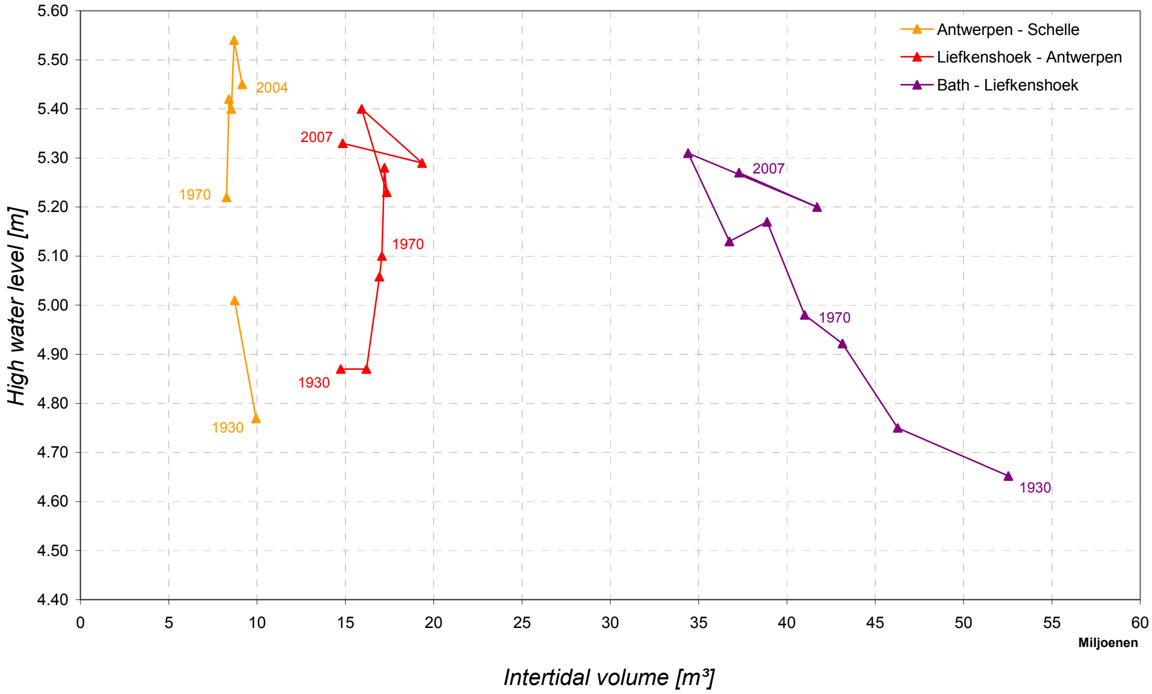

Figure 44 – Water volume of intertidal areas (0m < X < 6m TAW) vs. high water level for different sections

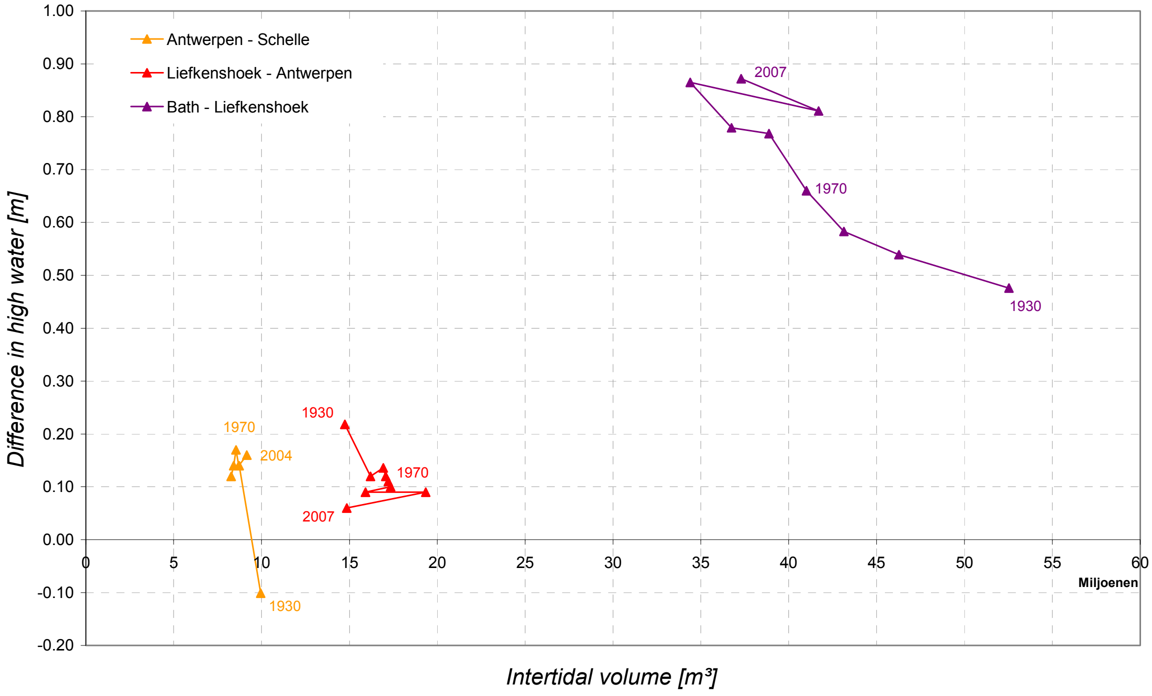

Figure 45 – Water volume of intertidal areas (0m < X < 6m TAW) vs. difference of high water levels for different sections

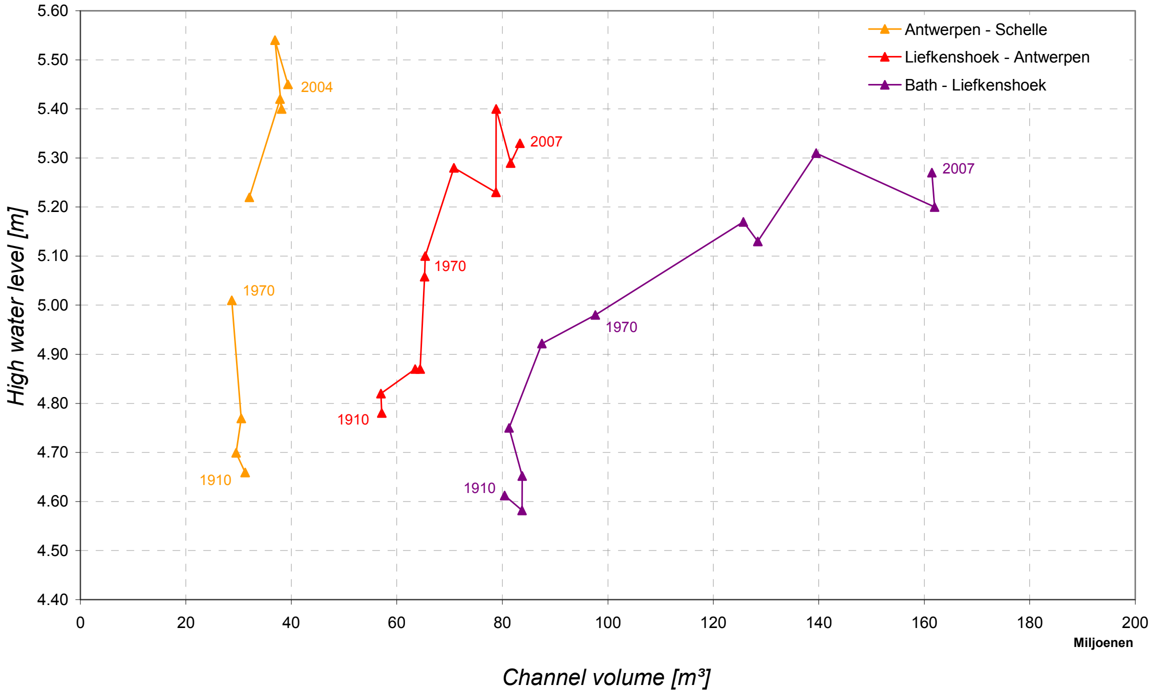

Figure 46 – Water volume of channel (< 0m TAW) vs. high water level for different sections

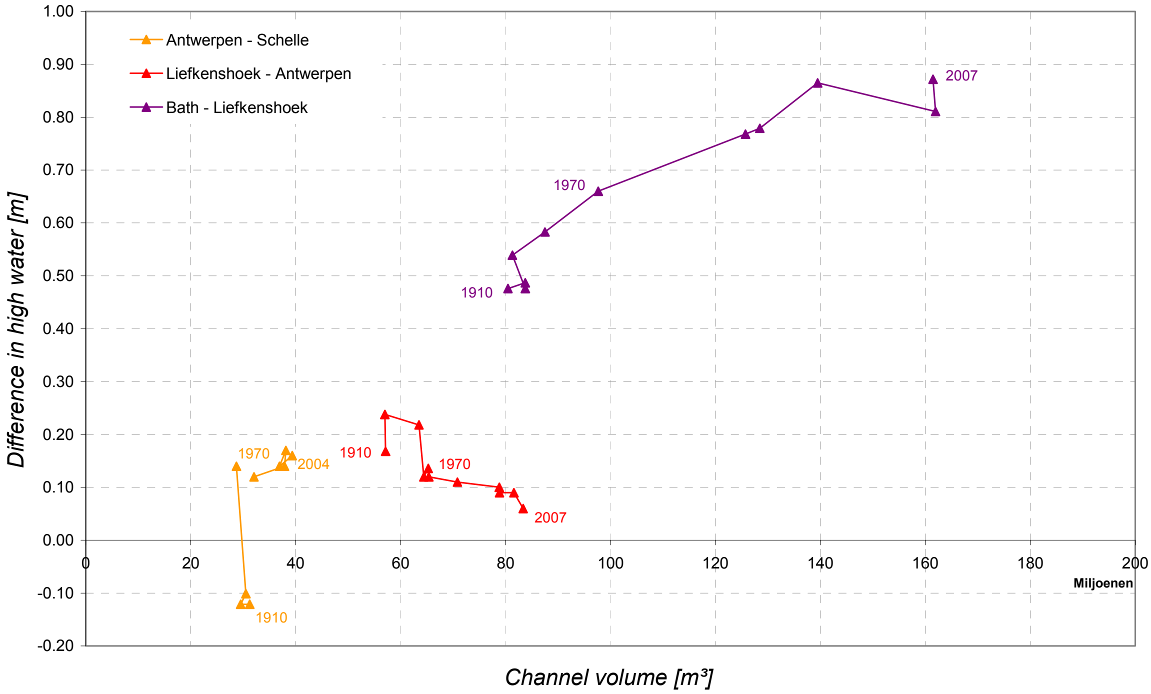

Figure 47 – Water volume of channel (< 0m TAW) vs. difference of high water levels for different sections

Figure 48 and Figure 49 show the relation between the water volume above the intertidal areas and the low water levels and difference in low water level between the consecutive stations. No obvious relation between the 2 characteristics can be found for the sections.

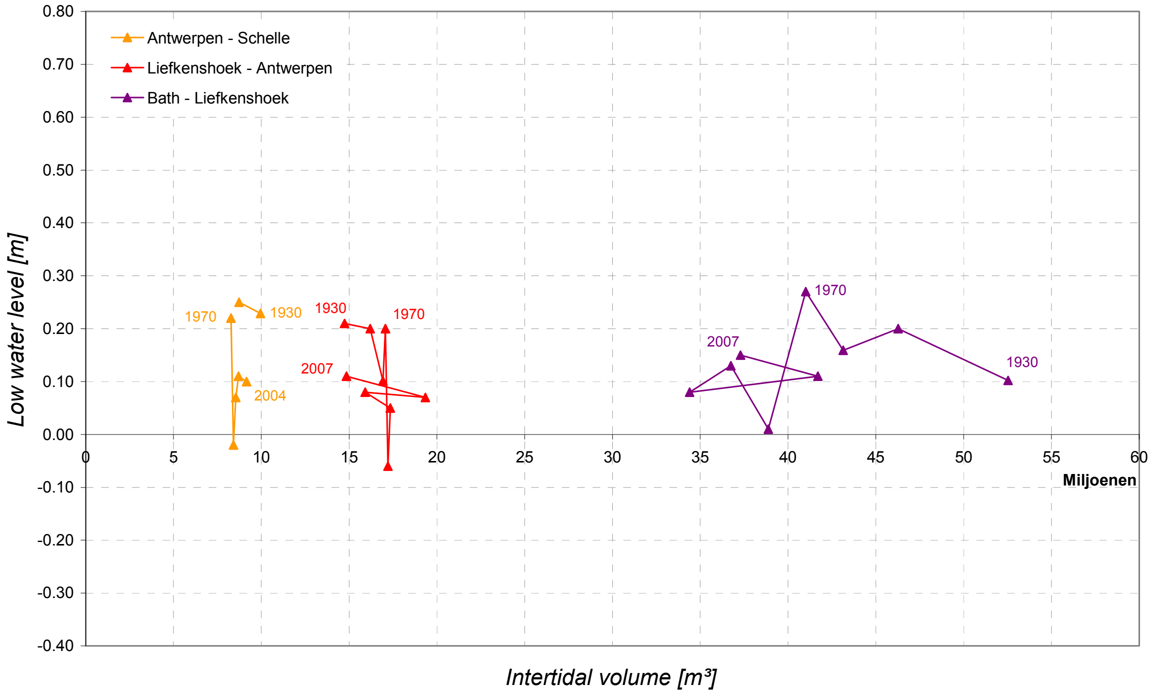

Figure 48 – Water volume of intertidal areas (0m < X < 6m TAW) vs. low water level for different sections

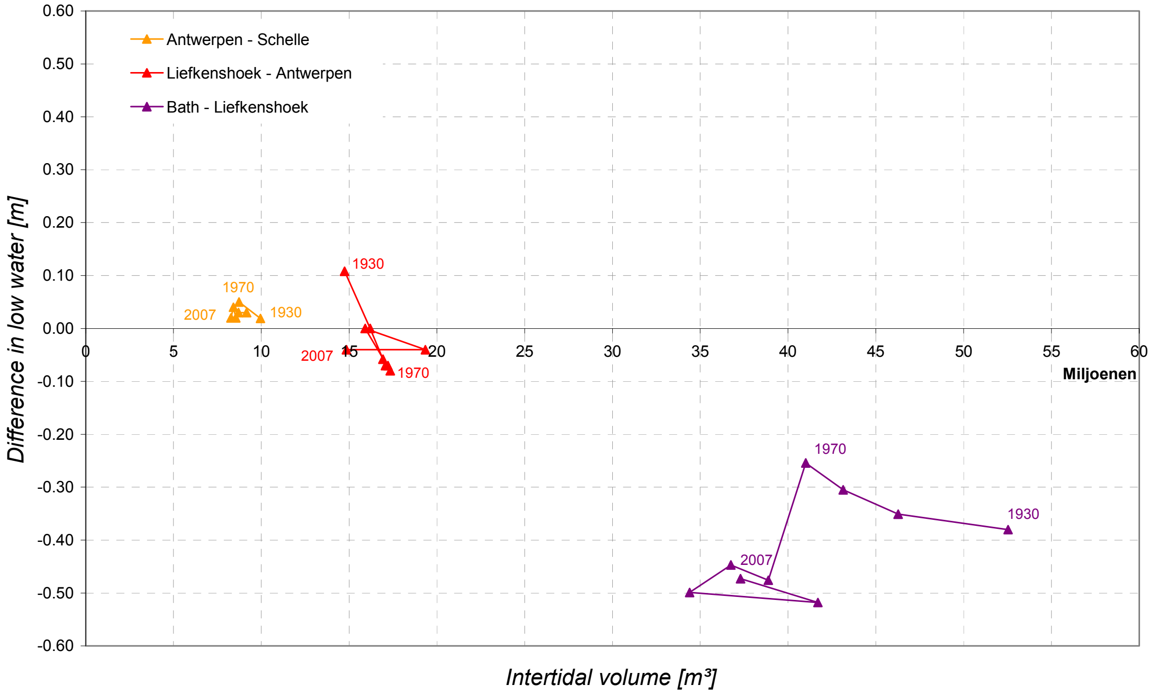

Figure 49 – Water volume of intertidal areas (0m < X < 6m TAW) vs. difference of low water levels for different sections

Figure 50 and Figure 51 show the relation between the water volume of the channel and the low water levels and difference in low water level between the consecutive stations. The sections Liefkenshoek – Antwerpen and Antwerpen – Schelle show a decrease of low water level with an increasing channel volume, while no obvious relation is found for the section Bath – Liefkenshoek. For the sections Bath – Liefkenshoek and Liefkenshoek – Antwerpen also give with an increasing water volume of the channel a lower low water level in the upstream station. The difference in low water level in the section Antwerpen – Schelle remains rather constant.

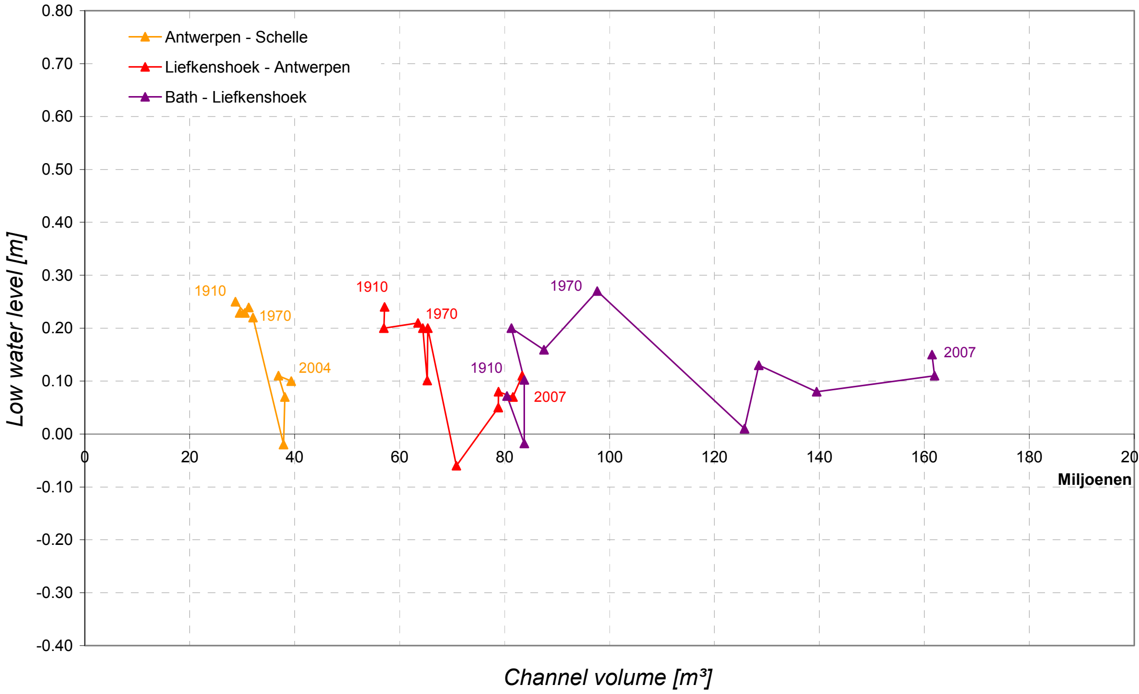

Figure 50 – Water volume of channel (< 0m TAW) vs. low water level for different sections

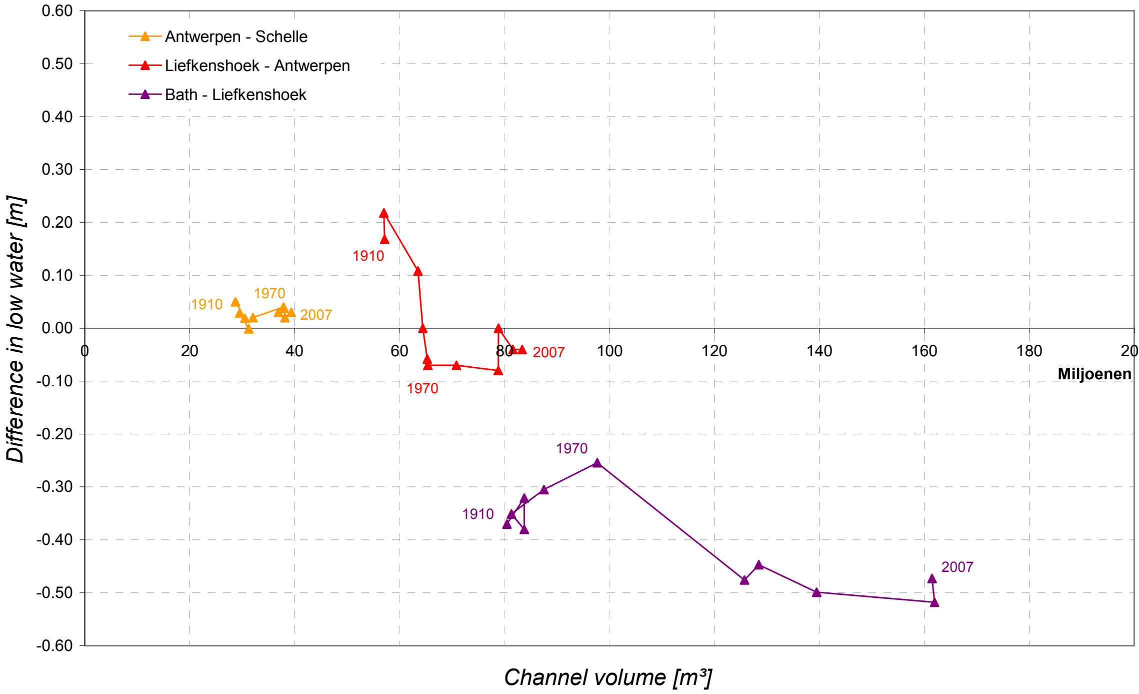

Figure 51 – Water volume of channel (< 0m TAW) vs. difference of low water levels for different sections

4.2 Summary and discussion of results

In this chapter relations between tidal and topo-bathymetric characteristics were investigated. Although some of the investigated relationships show good correlations for some sections, no relations were found resulting in similar trends with good correlations for all sections. The only exception is the relation between the channel depth and the ratio of tidal amplitude (or tidal amplification): an increasing channel depth results in an increase of the ratio of the tidal amplitude. The increase of the tidal amplitude can be caused be an up-estuarine increase of the high water or decrease of the low water. This is different for the 3 sections: for Bath – Liefkenshoek both changes occur, while for Liefkenshoek – Antwerpen the difference in high water decreases but is smaller than the decrease of the low waters; for Antwerpen – Schelle there is only an increase of high waters, while the difference in low water remains quasi constant.

The difference in high water level between 2 consecutive tidal stations increases with increasing channel depth (or volume) in the section for Bath – Liefkenshoek and Antwerpen – Schelle. The section Liefkenshoek – Antwerpen gives an opposing trend. The relation of the difference in low water level between 2 consecutive tidal stations and the channel depth (or volume) is similar for the sections Bath – Liefkenshoek and Liefkenshoek - Antwerpen: an increasing channel depth/volume results in a decreasing low water level in the up-estuarine station. Only in the section Antwerpen – Schelle this decrease was not found.

No clear relation of the volume above the intertidal areas and the low water levels was found, while for the high water levels only the section Bath – Liefkenshoek resulted in a good correlation for these characterisitcs: a decrease of the volume above the intertidal areas results in an increase of the high water levels (amplification of high water level). A similar relation was found for the 2 other section, but less pronounced.

5 Human interventions in the Scheldt estuary since 1900

Jeuken *et al.* (2007) gives an overview of the main human interventions that have taken place in the Scheldt estuary since 1900.

Additionally Figure 52 and Figure 53 give an overview of the relevant human interventions in the Western Scheldt in relation to the high and low water levels. Figure 54 and Figure 55 give an overview of the relevant human interventions in the Sea Scheldt in relation to the high and low water levels.

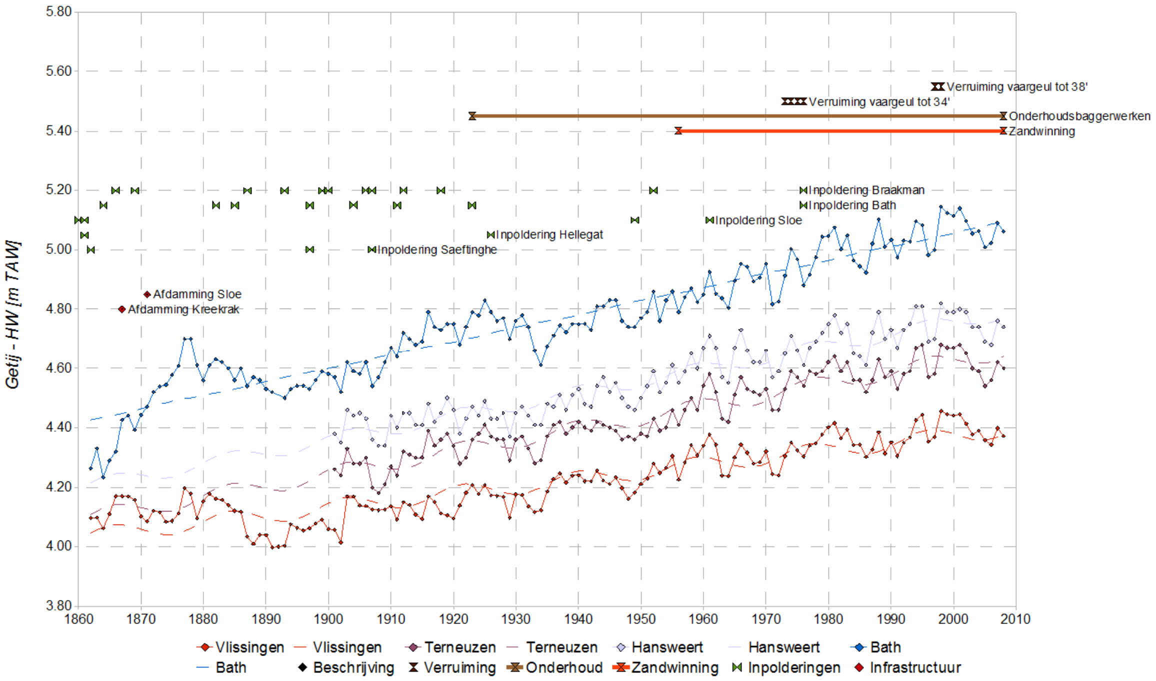

Figure 52 – Overview of human interventions in the Western Scheldt in relation to high water levels

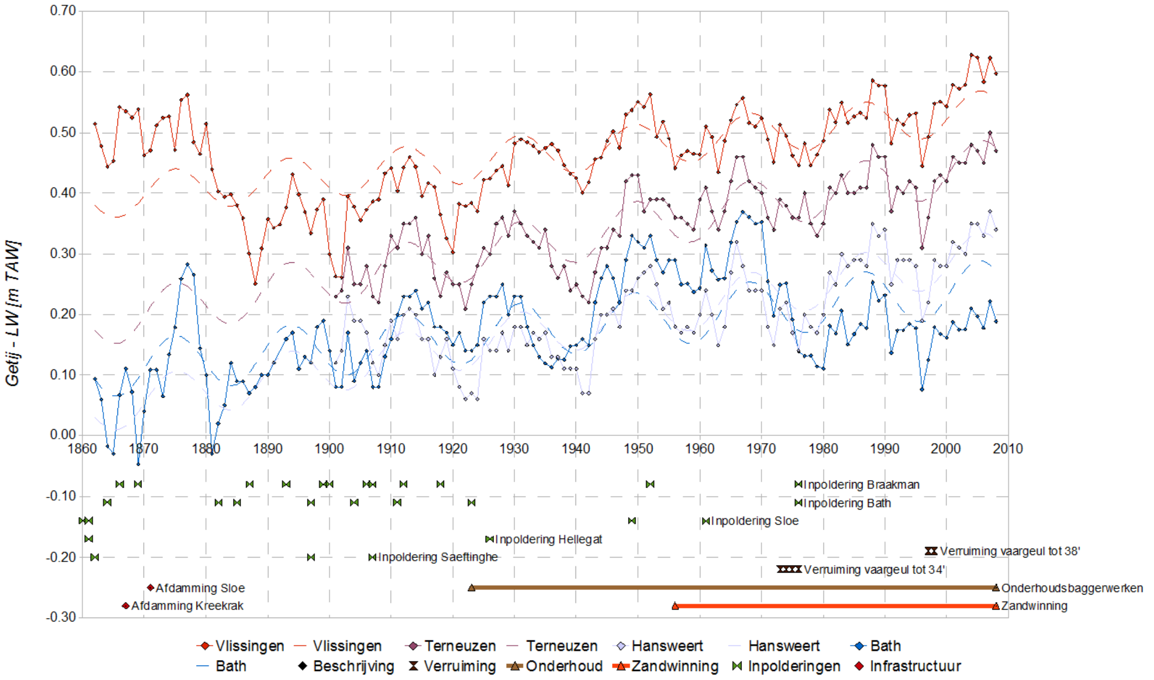

Figure 53 – Overview of human interventions in the Western Scheldt in relation to low water levels

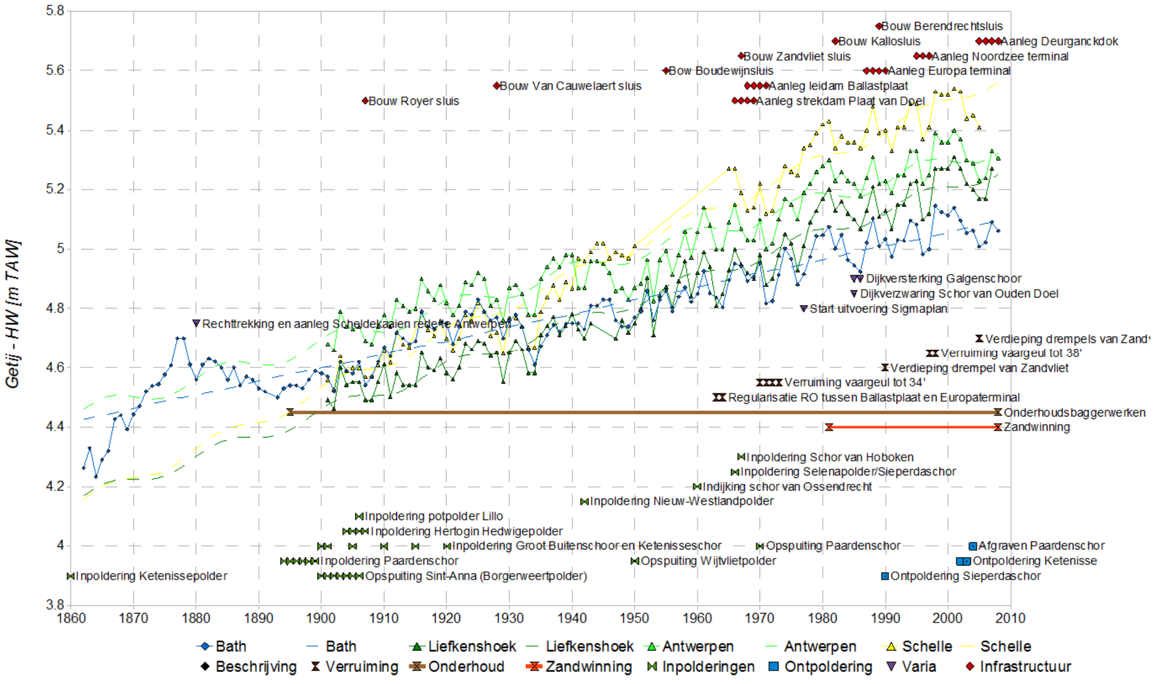

Figure 54 – Overview of human interventions in the Sea Scheldt in relation to high water levels

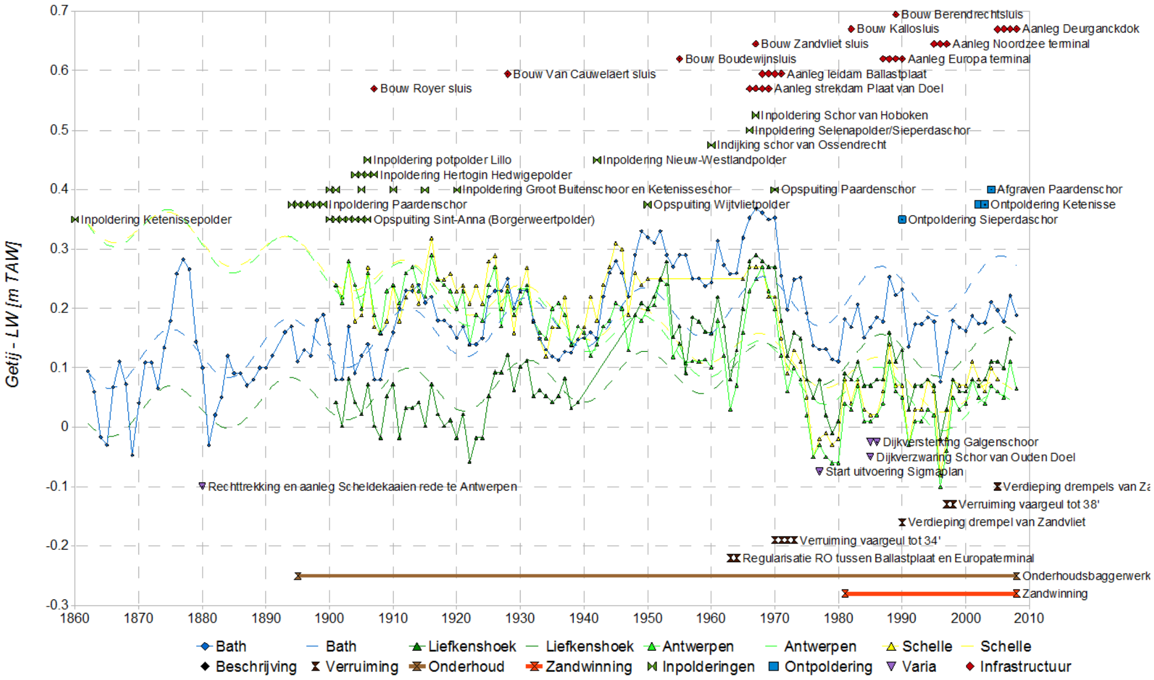

Figure 55 – Overview of human interventions in the Sea Scheldt in relation to low water levels

6 Conclusions and recommendations

6.1 Conclusions

During the past centuries the tidal regime of the Scheldt estuary has seriously changed. This is due to different natural processes and human interventions in the estuary, such as poldering, natural evolution of the estuary, enlargement of the navigation channel, continuous maintenance dredging works, permanent withdrawal of sand from the estuary for different purposes, changed tidal conditions in the North Sea, changed upstream discharges etc.

An important question for the safety management in the Scheldt estuary is how the safety level changes on a long term, taking into account the historical and present human impacts (such as poldering, sand extraction, enlargement, etc.) and natural changes (sea level rise). An important aspect from safety point of view is the change of the high water levels during the coming decades. The changes in hydrodynamics and morphology of the estuary are related to each other. Within this report an analysis of both tidal and topo-bathymetric characteristics in the Lower Sea Scheldt has been performed.

Since the start of the measurements in the beginning of the 20th century, significant changes have occurred on all water level parameters. Changes observed for averaged, spring and neap tides are similar, although the absolute magnitude of the changes is different (larger for spring tide, smaller for neap tide). The analysis performed in this report focusses on the changes of the validated yearly averaged data. Only a indicative linear trend was determined, which approximates the sea level rise. In order to make a proper analysis of historical trends, changes in the rate of sea level rise (linear trend) must be taken into account, while also the 18,61 year (nodal) cycle must be taken in consideration.

High water level show for all stations an increasing trend since the start of the measurements. Main reason for this evolution is the sea level rise, which can be seen as a boundary condition at the down-estuarine boundary (Vlakte van de Raan, or Vlissingen – Breskens). The local morphology of the estuary causes changes in the magnitude of the sea level rise: in Schelle the mean high water level has increased for almost 100 cm over the past century, while in Bath this was only 50 cm. Another conclusion on the high water level is that the tidal wave propagates further up-estuary: at the beginning of the 20th century the highest high water levels were found in Antwerpen, while at the end of this century high water was highest in Schelle for the considered stations.

Low water levels show a different evolution. Before the 1970’s a minor increase (ca. 20 cm) is found in Bath, while the low water levels for the stations of the lower Sea Scheldt fluctuate around an average value (“status quo”). In the 1970’s an important decrease (ca. 25 cm) of the low water levels can be found for all stations. After the 1970’s, a minor increase of the low water levels seems to occur, while important variations can be seen between two years.

The tidal range combines the effects of both high and low water levels. On the long term a gradual increase of the tidal range takes place. This is mainly caused by the gradual increase of the high water levels at all stations. During the 1970’s a significant increase occurs for all stations, which can be related to the large drop in low water levels. Since 1980, the variation in tidal range seems to have stabilized.

Due to a limited availability of data, long term changes in duration of rising and falling are more difficult to determine. Based on a limited amount of data, a change in trend seems to have occurred in the middle of the 20th century: in the first half a decrease of the duration of rising took place (10 to 15 minutes), while in the second half a gradual increase occurred (ca. 15 minutes). The opposite trend can be found for the duration of the falling. This evolution means that the increase of tidal asymmetry seen in the first half of the 20th century has changed to less asymmetry in the tidal curve, in fact back towards the situation of 1900.

Due to a limited availability of data, long term changes in propagation times (or on the contrary celerities) of high and low water are more difficult to determine. Based on a limited amount of data, an limited increase of celerity can be found for all stations, for both high and low water, in relation to Vlissingen. When the analysis is made (since 1980) by comparing propagation times in different sections between 2 water level stations, it can be found that for the reach Antwerpen-Schelle the propagation time has decreased by ca. 5 minutes, for the reach Liefkenshoek-Antwerpen it has remained quasi constant, while for the reach Bath-Liefkenshoek an increase of ca. 5 minutes has occurred. However, these changes are of the same order of magnitude as the accuracy of the determination of these parameters.

Changes of extreme high and low water levels show good resemblance with the evolution of the mean high and low water levels. The increase of the 99% high water percentile is similar to the increase of the mean high water for all stations.

The hypsometric curves show for all 3 sections a gradual increase in volumes for different reference levels. For the section Bath – Liefkenshoek, 2 periods have a stronger increase in volume: 1970-1980 and 2001-2004. Over the total period, the channel volume in this section has increased from 80 Mm³ in 1910 to 160 Mm³ in 2007 (+ 100%), while the mean channel depth increased from 5,6 m to 9,3 m. For the section Liefkenshoek – Antwerpen, the most important increase of volume took place between 1970 and 1990. Over the total period, the channel volume in this section has increased from 57 Mm³ in 1910 to 83 Mm³ in 2007 (+ 46%), while the mean channel depth increased from 6,9 m to 9,1 m. For the section Antwerpen – Schelle, the most important increase of volume took place between 1970 and 1980. Over the total period, the channel volume in this section has increased from 31 Mm³ in 1910 to 39 Mm³ in 2007 (+ 25%), while the mean channel depth increased from 6,3 m to 8,0 m.

The water volume above the intertidal areas between 0m and 6m TAW has decreased (ca. -30%) for the section Bath – Liefkenshoek, while for the other sections Liefkenshoek – Antwerpen and Antwerpen – Schelle it remained quasi constant. This evolution relates with the development of the intertidal area in the different sections: for the section in which intertidal volume decreases, a proportional decrease of intertidal area can be found. The direct and indirect impact of past poldering can be related to these developments. Nevertheless it should be mentioned that due to the limited amount of data of the intertidal areas, these conclusions are only indicative and further research is necessary.

Finally relations between tidal and topo-bathymetric characteristics were investigated. Although some of the investigated relationships show good correlations for some sections, no relations were found resulting in similar trends with good correlations for all sections. The only exception is the relation between the channel depth and the ratio of tidal amplitude (or tidal amplification): an increasing channel depth/volume results in an increase of the ratio of the tidal amplitude. The increase of the tidal amplitude can be caused be an up-estuarine increase of the high water or decrease of the low water. This is different for the 3 sections: for Bath – Liefkenshoek both changes occur, while for Liefkenshoek – Antwerpen the difference in high water decreases but is smaller than the decrease of the low waters; for Antwerpen – Schelle there is only an increase of high waters, while the difference in low water remains quasi constant.

The difference in high water level between 2 consecutive tidal stations increases with increasing channel depth (or volume) in the section for Bath – Liefkenshoek and Antwerpen – Schelle. The section Liefkenshoek – Antwerpen gives an opposing trend. The relation of the difference in low water level between 2 consecutive tidal stations and the channel depth (or volume) is similar for the sections Bath – Liefkenshoek and Liefkenshoek - Antwerpen: an increasing channel depth/volume results in a decreasing low water level in the up-estuarine station. Only in the section Antwerpen – Schelle this decrease was not found.

No clear relation of the volume above the intertidal areas and the low water levels was found, while for the high water levels only the section Bath – Liefkenshoek resulted in a good correlation for these characteristics: a decrease of the volume above the intertidal areas results in an increase of the high water levels (amplification of high water level). A similar relation was found for the 2 other section, but less pronounced.

6.2 Recommendations

Within this report historical development of tidal and topo-bathymetric characteristics was analysed for the Lower Sea Scheldt. While the Western Scheldt is dealt with in [Kuijper *et al.*, 2011], the Upper Sea Scheldt is not investigated yet, although important changes have taken place in this part of the estuary too.

The analysis of possible relations between tidal and topo-bathymetric characteristics was performed based on a limited set of parameters derived from available field measurements. Further analysis could take place on the historical evolution of the important aspects for tidal processes: resistance, inertia, reflection.

Finally this report mentions the different projects that have taken place during the past centuries, but does not investigate the importance of these projects on the changes in tidal and topo-bathymetric characteristics. In [Maximova *et al.*, 2010] and [Coen *et al.*, 2011] numerical scenarios were simulated to get an indication of the direct effect of certain changes (e.g. sea level rise, cutting of meanders, sand mining,…) on the tidal parameters in the Sea Scheldt. Similar scenarios should be defined for the total Scheldt estuary to get an indication of the initial effect of certain changes (both natural as human) of the tidal parameters.

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Tables

Table A1 - Bathymetry for the lock entrances to the port of Antwerp: overview of used bathymetric data

<table>
<tr><th rowspan="2">Lock</th><th colspan="11">Year</th></tr>
<tr><th>1928 - 1930</th><th>1950</th><th>1958 - 1961</th><th>1970</th><th>1980 - 1981</th><th>1990 - 1991</th><th>2000 - 2001</th><th>2002 - 2003</th><th>2004 - 2005</th><th>2007</th><th>2008</th></tr>
<tr><td>Zandvliet</td><td colspan="3">not constructed</td><td>imported from 1980</td><td colspan="6">available samples</td><td rowspan="2">copied from 2007</td></tr>
<tr><td>Berendrecht</td><td colspan="5">not constructed</td><td colspan="5">available samples</td></tr>
<tr><td>Deurganckdok</td><td colspan="8">not constructed</td><td colspan="3">available samples</td></tr>
<tr><td>Boudewijn</td><td colspan="2">not constructed</td><td rowspan="2">copied from 1990</td><td colspan="2" rowspan="2">copied from 1990, 1.5 m shallower</td><td colspan="5">available samples</td><td rowspan="3">copied from 2007</td></tr>
<tr><td>Van Cauwelaert</td><td colspan="2">available samples</td><td colspan="5">available samples</td></tr>
<tr><td>Kallo</td><td colspan="5">not constructed</td><td colspan="5">available samples</td></tr>
<tr><td>Royers</td><td colspan="5">copied from 1990</td><td>available samples</td><td>copied from 2002</td><td>available samples</td><td>copied from 2002, 1.2 m shallower</td><td>copied from 2002, 1.5 m shallower</td><td>copied from 2002, 1.5 m shallower</td></tr>
</table>

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