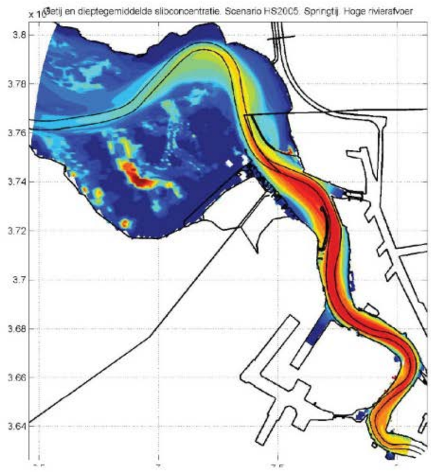
vlaams nederlandse Schelde commissie

departement Mobiliteit en Openbare Werken

Rijkswaterstaat
Ministerie van Infrastructuur en Milieu

# Instandhouding Vaarpassen Schelde
# Milieuvergunningen terugstorten baggerspecie




# LTV – Veiligheid en Toegankelijkheid

## Data-analysis water levels, bathymetry Western Scheldt

**Basisrapport grootschalige ontwikkeling G-5**

**01 oktober 2013**

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## Document Identificatie

| | |
|---|---|
| Titel | Data-analysis water levels, bathymetry Western Scheldt |
| Project | Instandhouding vaarpassen Schelde Milieuvergunningen terugstorten baggerspecie |
| Opdrachtgever | Afdeling Maritieme Toegang - Tavernierkaai 3 - 2000 Antwerpen |
| Bestek nummer | 16EF/2010/14 |
| Documentref | I/RA/11387/12.105/GVH, |
| Documentnaam | K:\PROJECTS\11\11387 - Instandhouding Vaarpassen Schelde\10-Rap\Op te leveren rapporten\Oplevering 2013.10.01\G-5 - Data-analysis water levels, bathymetry Western Scheldt_v2.0.docx |

## Revisies / Goedkeuring

| Versie | Datum | Omschrijving | Auteur | Nazicht | Goedgekeurd |
|---|---|---|---|---|---|
| 1.0 | 23/05/12 | FINAAL | K. Kuijper | J. Lescinski | M. Taal |
| 1.1 | 31/03/13 | Klaar voor revisie | K. Kuijper | J. Lescinski | M. Taal |
| 2.0 | 01/10/13 | FINAAL | K. Kuijper | J. Lescinski | M. Taal |

## Verdeellijst

| | | |
|---|---|---|
| 1 | Analoog | Youri Meersschaut |
| 1 | Digitaal | Youri Meersschaut |

# LTV Veiligheid & Toegankelijkheid

**Data analyses water levels ebb and flood volumes and bathymetries Western Scheldt**

Kees Kuijper, Jamie Lescinski

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# LTV Veiligheid & Toegankelijkheid

**Data analyses water levels ebb and flood volumes and bathymetries Western Scheldt**

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Report

Maart 2013

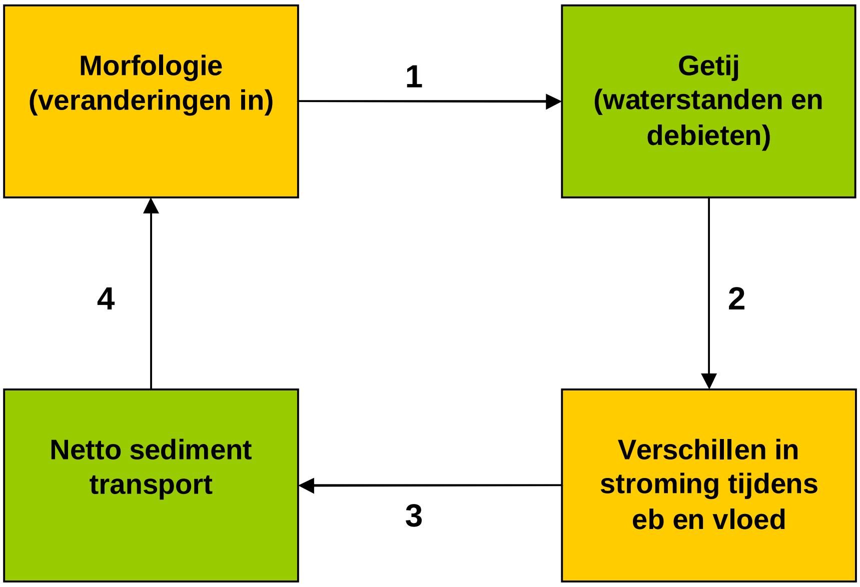
1207720

# Samenvatting

Voor het vervullen van de drie hoofdfuncties van het Schelde-estuarium speelt de waterbeweging een centrale rol. Hoogwaters, en vooral de extreme waarden, zijn van belang voor de veiligheid tegen overstromingen, de laagwaterstanden en de looptijden van hoog- en laagwater bepalen de toegankelijkheid van de havens voor getijgebonden scheepvaart en de getijasymmetrie heeft een relatie met het netto sedimenttransport (incl. slib) en daarmee de morfologie, wat weer relevant is voor o.a. de natuurlijkheid van het gebied. Veranderingen in de waterbeweging kunnen dus van grote betekenis zijn voor het functioneren van het systeem en voor het beheer is kennis hierover essentieel. In dit rapport wordt de evolutie van het getij geanalyseerd op basis van beschikbare meetdata.

**A. Wat is geanalyseerd?**

In dit rapport zijn de waterstanden in de stations Vlissingen, Terneuzen, Hansweert en Bath geanalyseerd (Hoofdstuk 2). Daarbij is gebruik gemaakt van beschikbare gegevens sinds eind 19$^{e}$ eeuw in deze stations. Bij de analyse is het getij gekarakteriseerd met jaargemiddelde waarden voor hoog- en laagwater, getijslag, duren van opgaand en afgaand tij, looptijden van hoog- en laagwater, extreme waterstanden en de M2-, M4- en M6-getijcomponenten (amplitude en fase). Aanvullend hierop zijn ook de eb- en vloedvolumes in de vaste debietmeetraaien beschouwd zoals beschikbaar vanaf 1932. Bij de analyse is gekeken naar langjarige trends en trendbreuken met speciale aandacht voor de verhouding van de getijslag (amplificatie) in twee opvolgende meetstations en veranderingen in getijasymmetrie. De getijbeweging past zich instantaan aan als de geometrie of de morfologie van het estuarium verandert. De bodemligging is per traject tussen twee waterstandstations beschreven met een aantal kentallen zoals de watervolumes van de geulen, watervolumes boven de intergetijdengebieden, arealen van de geulen en intergetijdengebieden, zandvolumes en hoogtes van de intergetijdengebieden (Hoofdstuk 3). Vervolgens is onderzocht in hoeverre bodemveranderingen (Hoofdstuk 4 en 6) en menselijke ingrepen (Hoofdstuk 5) waargenomen veranderingen van de getijkarakteristieken kunnen verklaren. Hiermee wordt stap 1 in navolgend schema geadresseerd. De vervolgstappen waarbij (een verandering in) het getij weer van invloed is op de morfologie vormen geen onderdeel van dit rapport.




Als onderdeel van het programma LTV Veiligheid en Toegankelijkheid wordt ook in andere rapporten van het consortium Deltares-IMDC-Svasek-Arcadis ingegaan op aspecten in het schema:

- Aanvullend onderzoek historische ontwikkeling getij in het Schelde-estuarium. LTV V&T rapport G-8. Hierin wordt de ontwikkeling van de getijslag langs het gehele estuarium geanalyseerd.
- Data-analyse waterstanden Westerschelde. LTV V&T rapport G-1. In dit rapport worden de veranderingen in de waterstanden tussen twee stations geanalyseerd op basis van daggemiddelde waarden.
- Grootschalige sedimentbalans van de Westerschelde en Zeeschelde. LTV V&T rapporten G-2 en G-3.
- Influence morphology on tide and sand transport. Analyse van effecten van ingrepen met speciale aandacht voor getijasymmetrie en de relatie met het netto zandtransport. LTV V&T rapport G-4.
- Data-analyse waterstanden Beneden-Zeeschelde. LTV V&T rapport G-6. In dit rapport wordt de evolutie van de waterstanden langs de Beneden-Zeeschelde geanalyseerd.
- Analytisch model voor respons getij op geometrie. LTV-V&T-rapport G-7
- Effect morfologie monding Westerschelde op getij LTV V&T rapport G-12.
- Synthese en Conceptueel model. LTV V&T rapport G-13. Hierin worden de verbanden tussen de waarnemingen gelegd en een systeembeschrijving voor grootschalige waterbeweging en morfologie gegeven.
- Response of tidal rivers to deepening and narrowing. LTV V&T rapport G-14. Hierin worden de effecten van ingrepen langs de Zeeschelde geanalyseerd met nadruk op veranderingen van getijasymmetrie op slibtransport.
- Ontwikkeling mesoschaal Westerschelde en Zeeschelde (factsheets) LTV V&T rapport K-16, K-17 en K-18.

**B. Waargenomen veranderingen**

In deze samenvatting worden de meest uitgesproken veranderingen genoemd. Voor meer detail wordt verwezen naar de samenvattingen in de afzonderlijke hoofdstukken.

<u>B1: Waterbeweging / getij</u>

- o Sinds einde 19$^{e}$ eeuw is het estuarium dynamischer geworden door een toename van de getijslag en de voortplantingssnelheid. Een deel van de verandering in de getijslag ligt al op zee (een toename bij Vlissingen van 3,5%/100 jaar), maar in het estuarium zijn de veranderingen groter geweest (Terneuzen +5,5%/100 jaar, Hansweert +6%/100 jaar en Bath +10%/100 jaar). Vooral de trendbreuk voor het traject Hansweert-Bath is opvallend, waar een toename van 8% in de periode 1970-1980 plaatsvond.
- o De gemiddelde waterstand is ook toegenomen. Deze veranderingen zijn vooral het gevolg van de zeespiegelstijging.
- o Aangaande eb- en vloeddominantie (op basis van M2- en M4-fase) zijn de verschillen tussen de vier stations in de Westerschelde kleiner geworden, zodat momenteel in alle stations gesproken kan worden van zwakke vloed- of ebdominantie of neutrale condities.
- o Het aantal hoge vloeden en stormvloeden is na 1950 toegenomen vergeleken met de periode ervoor.
- o De getijvolumes van de hoofdgeulen oostelijk van Terneuzen zijn toegenomen ten koste van de nevengeulen. In de monding lijkt sprake van een geringe toename van het getijvolume in de gehele dwarsdoorsnede.

<u>B2: Bathymetrie</u>

*a. Geulen*

- o Het totale doorstroomoppervlak c.q. geulvolume en de gemiddelde diepte van de geulen tussen Vlissingen en Bath zijn toegenomen sinds 1955 (start geanalyseerde bodems). De veranderingen zijn het grootst in het oosten (Hansweert-Bath).
- o Ook in het westen, tussen Vlissingen en Terneuzen, is sprake van verruimde geulen, maar niet zozeer van een verdieping.
- o De meest opvallende verandering in de geulen is de toename van de geuldiepte tussen Hansweert en Bath met 2,5 m tussen 1955 en 2008. Sinds de tweede helft van de ’90-er jaren verdiepen zowel de hoofd- als de nevengeul.
- o Ook opvallend is de functiewisseling van de geulen tussen Terneuzen en Hansweert, maar wel met een gelijk blijvend totaal doorstroomoppervlak van hoofd- en nevengeul.

*b. Intergetijdengebieden*

- o Sinds 1955 zijn de intergetijdengebieden hoger geworden. De laatste 10-20 jaar lijkt een stabilisatie op te treden.
- o Tussen Vlissingen en Bath is het zandvolume van de intergetijdengebieden tussen 1955 en 1980 met 25% toegenomen. Tussen Hansweert en Bath is de toename zelfs 45%.
- o Vanaf 1970 is een grootschalige ‘versteiling’ te zien in de gehele Westerschelde maar vooral in het oosten. De verhouding tussen het watervolume boven de platen en het watervolume van de geulen neemt gestaag af, in ieder geval tot 2002.

De hypothese bij deze waarnemingen is dat het deel oostelijk van Hansweert wordt gedomineerd door verdieping en verruiming als gevolg van baggeren en storten. Dit kan worden onderbouwd door de ingreepgegevens naast de observaties te leggen. Dit is gedaan in andere rapportages van LTV V&T, met als belangrijkste G-13.

**C. Relaties en effecten**

Een deel van de veranderingen in de getijkarakteristieken heeft duidelijk een ‘natuurlijke’ oorzaak (w.o. veranderingen in de forcering van de Noordzee). In hoeverre het andere deel menselijk is, kan meestal niet onweerlegbaar uit de beschreven waarnemingen (grote tijd- en ruimteschaal) gehaald worden. Bovendien zijn er ‘natuurlijke’ veranderingen die (deels) ook weer reacties zijn op menselijke ingrepen uit een verder verleden.

<u>Getij en bodem</u>

De convergentie van een estuarium (afnemende dwarsdoorsnede in opwaartse richting) vormt een kenmerkende typering van de geometrie, die een grootschalige invloed heeft op het getij in de vorm van continue reflecties. De theorie geeft aan (zie LTV-V&T-rapport G-7) dat een versterking van de convergentie tot een toename van de amplificatie (of afname van de demping) en de getijvoortplantingssnelheid leidt. Lokale ingrepen, zoals bestortingen, bedijkingen en kribben hebben slechts een beperkte invloed op het grootschalige gedrag van het getij. Veranderingen in de convergentie komen niet veel voor, aangezien de geometrie vaak is vastgelegd door bedijkingen etc. Wel kunnen (grootschalige) diepteveranderingen van invloed zijn op het getij, waarbij de invloed verloopt via de ruwheid. De berging van water op intergetijdengebieden en in havenbekkens leidt in het algemeen tot een reductie van de getijslag en de getijvoortplantingssnelheid.

Tussen Vlissingen en Hansweert is een beperkte extra amplificatie van de getijslag waarneembaar. Een procentuele toename van de getijslag van 3,5%/100 jaar in Vlissingen wordt nl. 6%/100 jaar in Hansweert. Deze verandering is niet aan een specifieke periode toe te schrijven. De eerste verdieping, welke een lange periode in beslag nam en waarbij flinke veranderingen in de geometrie in het oostelijk deel plaatsvonden, lijkt wel terug te vinden. Tussen Hansweert en Bath kent die periode een toename van de amplificatie, vooral door een verlaging van het laagwater. Een dergelijke toename kan worden verklaard vanuit processen door toegenomen waterdiepte en daardoor een afname van de bodemwrijving. De toegenomen waterdiepte valt samen met de verdiepingsperiode. In hoeverre dit komt door de verdieping alleen, kan niet zonder meer vastgesteld worden op basis van de in dit rapport uitgevoerde data-analyse, maar kan hoogstwaarschijnlijk wel bevestigd worden door ingrepen en morfologische ontwikkelingen in deze periode naast elkaar te zetten. Dit is gedaan in andere rapportages van LTV V&T, met als belangrijkste G-13.
Na de tweede verdiepingsperiode is ook sprake van een verlaging van de laagwaters in Bath (bijv. t.o.v. Vlissingen en Hansweert), al is deze minder groot dan tijdens de eerste verdiepingsperiode. Dit effect is waarschijnlijk niet het gevolg van de verdieping, maar lijkt mede te worden bepaald door een gewijzigde strategie m.b.t. storten en zandwinning. De mate waarin de verdieping en de indirecte effecten ervan, via de morfologische respons, hebben bijgedragen aan de verlaging kan niet worden aangegeven.

De waargenomen toename van de getijvoortplantingssnelheid over bepaalde trajecten kan eveneens worden verklaard uit de toename van de waterdiepte. De relatie tussen veranderingen in getijasymmetrie (2M2-M4) en opgetreden bodemveranderingen moet nog nader worden onderzocht. Dit betreft vooral de grote veranderingen in ebdominantie in Hansweert tussen 1950 en 1985 en de afname van de vloeddominantie in Bath sinds 1971 (d.i. vanaf begin databeschikbaarheid).

Uit de jaarlijkse waterstanddata zijn verder geen duidelijke trendbreuken aan te wijzen, waardoor ook een koppeling met bodemveranderingen lastig wordt. Dit komt onder meer doordat de aanpassing van bodem op getij langzaam verloopt en daarmee de terugkoppeling op het getij. Het is waarschijnlijk dat ingrepen als baggeren, storten en zandwinning invloed hebben op het getij, met een effect dat in principe instantaan is. Het effect is echter lastig statistisch vast te stellen omdat de ingrepen semi-continue activiteiten zijn, die zich niet in een bepaald punt in de tijd concentreren. Wanneer meer zekerheid over het effect ingreep-getij gewenst is kunnen numerieke simulaties de oplossing bieden (waarbij effecten 'losgekoppeld' worden). Hierover is onder meer gerapporteerd in LTV V&T-rapport G-11.

**D. Analyse van waargenomen effecten met analytisch model**

De waargenomen veranderingen in het traject Hansweert-Bath (toename getijslag evenals toename getijvoortplantingssnelheid) kunnen worden verklaard door het analytische model van Van Rijn (Van Rijn, 2010, LTV V&T-rapport G-7). Met de bodemveranderingen als input en een onveranderlijke geometrie (trompetvorm) worden de veranderingen in het getij gereproduceerd. Volgens hetzelfde model zal er, bij een verdere verruiming van de geul in de Westerschelde (lees toename gemiddelde geuldiepte) geen voortdurende verdere toename van de getijslag blijven optreden. Er kan zelfs een afname optreden, zij het pas bij zeer grote gemiddelde geuldiepten van 15-20 m en meer. De geuldiepte is hierbij niet de diepte van alleen de vaargeul maar van het gehele dwarsprofiel. De getijvoortplantingssnelheid zal (volgens hetzelfde model) wel verder toenemen bij doorgaande verruiming, waardoor hoog- en laagwaters eerder landinwaarts gelegen plaatsen zullen bereiken.

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| **Client** | Ministerie van Infrastructuur en Milieu,<br>Vlaamse Gemeenschap, Afdeling maritieme Toegang |
| **Title** | LTV Veiligheid en Toegankelijkheid. Data analysis water levels, ebb and flood volumes and bathymetries Western Scheldt |


**Abstract**

Water level data and bathymetric data of the Western Scheldt have been analysed to study the evolution of high and low waters and their propagation velocity since the end of the 19th century. Analysis of the measured tidal propagation shows that since the end of the 19th century the tide in the Western Scheldt has become more dynamic. This follows from the increase of the tidal range and the larger propagation velocity. In addition the mean water level has risen which is largely due to mean sea level rise. The overall effect is that the high waters and to a lesser extent the low waters have increased in the estuary. The increase of extreme high waters seems to be somewhat larger than that of yearly-average high waters. Differences between ebb- and flood dominance have become smaller converging to almost neutral conditions along the Western Scheldt. With respect to tidal volumes the largest changes have occurred for the individual main and secondary channels east of Terneuzen with the former increasing at the expense of the latter. The tidal volume as sum of both main and secondary channel indicates an increase in the eastern part of the Western Scheldt but less clear trends in the other regions.

Bathymetric changes since 1955 indicate that the channel volume has increased which has resulted in larger channel depths. At the same time the water volume above the intertidal flat area has decreased. Thus tidal flow has increased at the expense of tidal storage. The sand volume of the intertidal flats has become considerably larger while the intertidal area has increased only slightly. As such the intertidal flats have become higher. The overall picture is that since 1955 sand has been redistributed resulting in deeper channels and higher intertidal flats. For the individual sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath the overall characterization of hydrodynamic and bathymetric changes may be somewhat different.

Effects of human interventions such as land reclamations, channel deepening, normalisation works (‘leidammen’) and the Deltaworks could not be retrieved from data records on high and low waters, tidal range and amplification.

The application of an analytical model on tidal propagation showed that the major features as tidal range, amplification and propagation velocity were well represented by the model. The enhanced amplification of tidal range for the section Hansweert-Bath could be explained by the model indicating that changes in overall channel depth played a major role. Furthermore it is predicted that for channel depths larger than 15-20 m the tidal range will reduce. This effect may be (partly) compensated by an increased tidal range of the tidal wave coming from outside the estuary (North Sea) as observed during the past 100 years.


**References**

| Ver | Author | | Date | Remarks | Review | | Approved by | |
|---|---|---|---|---|---|---|---|---|
| 1.0 | Kuijper | | November 2010 | | Jeuken | | | |
| 2.0 | Kuijper/Lescinski | | December 2011 | | Taal | | | |
| 3.0 | Kuijper/Lescinski | | April 2012 | | Taal | | Schilperoort | |
| 3.1 | Kuijper/Lescinski | | March 2013 | | Taal | | Schilperoort | |
| | | | | | | | | |

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|---|---|
| **Project number** | 1207720 |
| **Keywords** | tide, bathymetry, high water, safety, natural changes, human impact, Westerschelde, analytical model |
| **Number of pages** | 188 |
| **Classification** | None |
| **Status** | Final |

# Summary

A primary goal of the project "Lange Termijn Visie Onderzoek en Monitoring (LTV O&M)" is to guaranty maximal safety against flooding in the Scheldt estuary. One of the topics addressed as part of "LTV-Veiligheid" (Safety) is the study of the evolution of the tidal propagation in the estuary in general and of the high waters specifically. Availability of water level data in the stations Vlissingen, Terneuzen, Hansweert and Bath allowed for the assessment of long-term trends in tidal characteristics on the time scale of a century and of short-term fluctuations over a period of one to two decades. Detailed bathymetric data of the Western Scheldt since 1955 were available to analyse changes of morphologic characteristics that may have affected tidal propagation.

## A. Tidal characteristics

The trend-like evolution of a specific tidal characteristic has been assessed by means of a linear regression line from which the slope has been used to compute the average change per century. It should be realised that this is only a first order approximation of the data and that sometimes an approach with piece-wise straight lines (or higher order polynomials) may give better results. The goal of the analysis is to derive long-term average quantities so that linear approximations of the data with single lines have been used. For average tides data for Vlissingen, Terneuzen, Hansweert and Bath are available since 1860-1870 and for spring and neap tides since 1880-1900 (Bath only since 1960).

The rate of increase for the yearly-averaged **high waters** amounts to 0.3-0.4 m/century and for the **low waters** 0.2 m/century between Vlissingen and Hansweert. For spring tides the rate of increase of the high waters has been 0.05-0.1 m/century more and for neap tides 0.05-0.1 m/century less. Changes in low waters for neap tide have been not very much different from the changes for the average tide; for spring tides changes of low waters were somewhat less in Vlissingen and Terneuzen. In Bath the high waters have increased with approximately 0.5 m/century; the low waters have only increased slightly as the increasing trend between 1860 and 1970 was followed by a lowering of the low waters between 1970 and 1980. The changes of high and low waters in Bath for spring and neap tides over a period of more than 100 years could not be determined because data were not available.

**Extreme high waters** were defined as the maximum and 99-, 95- and 90-percentiles per year. The 90$^{th}$-99$^{th}$ percentile trends have an offset of +0.05 m/century from the median (50$^{th}$-percentile) trend which means that per 100 years these extreme high water levels increased 0.05 m more than the average high waters which is about 10%. The 90$^{th}$-99$^{th}$ percentile **low water levels** show approximately the same trend as the median low waters. The number of **high floods and storm surges** (water level >NAP+3.05 m) in Vlissingen has been considerably larger since 1950 as compared with the period before (1880-1950), i.e. 42 versus 10 events per decade. Also the number of events that occurred in pairs or triples has been larger after 1950 (10 versus 1 per decade). However, the average height of the high floods and storm surges has not increased.

The dynamic part of the tide is represented by the **tidal range** which shows a long-term increase of 3.5%/century in Vlissingen. In the more inland located stations the tidal range increases to a larger extent (Terneuzen +5.5%, Hansweert +6% and Bath +10%). The large increase in Bath originates from the lowering of low waters during a relatively short period of time (1970-1980).

The **mean water level** has increased 0.15-0.25 cm/century in the Western Scheldt as derived from data records with lengths of 68 years or longer (i.e. excluding Bath). Since 1971 the increase of the mean water level was largest in Hansweert with 0.4 m/century and smallest in Bath with 0.2 m/century, however the uncertainty is relatively large with a standard deviation of 0.05 m/century.

For average tides the **half tide** (the average of high and low water as an approximation of the mean water level) has increased with 0.25-0.30 m/century in the four water level stations. Changes are larger for spring tides and smaller for neap tides.

The **amplification** of the tidal range of an estuarine section is defined as the ratio of the tidal range in the landward and the seaward location. Between 1970 and 1980 the amplification between Hansweert and Bath has increased with 3-5%. Since 1900, some gradual increase has also been observed for the section Vlissingen-Terneuzen following a downward trend before 1900. For the section Terneuzen-Hansweert the amplification remained relatively constant.

The **propagation velocity** of the high water has increased between Vlissingen and Terneuzen and between Hansweert and Bath. Especially the increase from 9 to 18 m/s between Vlissingen en Terneuzen was substantial. Between Terneuzen and Hansweert the propagation velocity of the high water remained more or less constant. The propagation velocity of the low waters has changed to a lesser extent, i.e. over the past century some increase between Vlissingen and Hansweert and even some decrease between Hansweert and Bath.

The **durations of tidal rise** (from low to high water) **and tidal fall** (from high to low water) in a specific location are related to the propagation velocity of the tidal wave. If for instance over a section the propagation speed of the high water increases in time or the low water decreases the duration of tidal rise becomes shorter. If the duration of tidal rise is different from the duration of tidal fall the tidal curve is asymmetric. In the Western Scheldt the duration of tidal rise is shorter than the duration of tidal fall so that the tide is flood dominant. In Vlissingen this difference amounts 30 min and has not changed much. In Terneuzen the duration of tidal rise has decreased since 1950 with about 5 min thus promoting flood dominance. In Hansweert no major changes have taken place although there were periodic variations over decades of 5-10 min. In Bath the changes were more difficult to assess because of unreliable data before 1960. Since 1980 the duration of tidal rise has gradually decreased so that flood dominance has become less.

The evolution of **M2, M4 and M6 tidal constituents** has been analysed with respect to amplitudes and phases. The M2 and M4 amplitudes exhibit positive linear trends, whereas the M6 amplitude does not show any clear trend. At Bath the M2 amplitude has increased sharply between 1970 and 1980. The linear trends for the M4 amplitude in the four stations are quite different until 1990. The strength of the tidal asymmetry is given by the ratios of the M4 and M2 amplitude and the M6 and M2 amplitude. The M4/M2-amplitude ratio in Vlissingen, Terneuzen and Hansweert shows an increase until 1970 and an approximate constant value after 1970 except in Vlissingen where the asymmetry continues to strengthen. For Bath data are only available since 1971. The M6-M2 ratio does not show clear trends in the four stations. Tidal asymmetry in terms of flood and ebb dominance is given by the phase differences 2M2-M4 and 3M2-M6. The evolution of the phase difference 2M2-M4 shows that Vlissingen has changed from slightly flood-dominated to neutral. Terneuzen has shown an opposite trend from more or less neutral before 1970 to a slightly flood-dominate system between 1970 and 2008. Hansweert has been ebb-dominate since 1940 with large fluctuations between 1960 and 1980. Since then the station is weakly ebb-dominate. Largest changes have occurred in Bath with the M2-to-M4 phase relationship sharply declining since 1970. The station has gone from strongly flood-dominate to almost neutral conditions. In general, differences between the four stations with respect to ebb- and flood dominance have become smaller with all stations with all stations showing weakly flood, weakly ebb or neutral conditions.

The **tidal volumes** in the overall cross-sections suggest an increase in time. This is most apparent in the cross-sections 1 and 2 in the eastern part of the Western Scheldt. For the other cross-sections either erratic variation is large or the observation period is too short to draw definite conclusions. Correlation with the increase in tidal range should be further investigated. The tidal volumes in the main channels east of Terneuzen (Gat van Ossenisse, Zuidergat and Overloop van Hansweert) have significantly increased at the expense of the secondary channels (Middelgat, Schaar van Waarde and Zimmermangeul). Apparently this exchange of tidal volume did not affect much the total tidal volume through the cross-section. West of Terneuzen tidal volumes show less variation in time apart from the Vaarwater langs Hoofdplaat which displays a decreasing tidal volume since 1960-1980. In the central part of the Western Scheldt, macro cells 4 and 5, all channels with the exception of the Zimmermangeul have become more symmetric with respect to ebb and flood volumes. The formerly flood-dominated Zimmermangeul has evolved in an ebb-dominated channel.

**Synthesis evolution tidal characteristics**
From the above the picture emerges that the tide in the Western Scheldt has become more dynamic over the past 100 years (larger tidal range and an increasing propagation velocity). This is accompanied with an increase of the mean water level in the Western Scheldt which is mainly caused by the sea level rise as observed in Vlissingen. For more energetic conditions (spring tide versus average tide and average tide versus neap tide) changes are larger. Variations of the yearly-averaged tidal characteristics may also occur on time scales of one to two decades. These are partly due to variations in the external forcing (18.6 year period of the astronomical tide) and possibly to changes in the bathymetry of sections in the Western Scheldt on this time scale (e.g. Hansweert-Bath). The increased tidal dynamics with respect to water levels is not clearly reflected by an increase of the tidal volume. The most prominent change with respect to tidal volume is the significant increase of tidal volume in the main channels east of Terneuzen at the expense of the tidal volume in the secondary channels.

## B. Bathymetrical characteristics

The bathymetry was analysed using hypsometric curves specifying the water surface area as function of depth. From this curve, and using fixed levels at NAP+2m and NAP-2m for the upper and lower bounds of the intertidal area, the following large-scale bathymetric characteristics have been derived: (i) channel volume, (ii) channel depth, (iii) area of intertidal flats, (iv) water volume above intertidal flats and (v) sand volume and (vi) height of intertidal flats. In this way the morphological changes during the period 1955-2008 for the three sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath were determined.

The total **channel volume** between Vlissingen and Bath has increased between 1955 and 2008 with $7\,10^7$ $m^3$ (+3%). This results from changes between Vlissingen and Terneuzen and between Hansweert and Bath of $5\,10^7$ $m^3$ (+4%) and $6\,10^7$ $m^3$ (+17%).

The channel volume of the section Terneuzen-Hansweert has decreased with 4 $10^7$ $m^3$ (-5%).

The **water volume above the intertidal flats** represents the storage of water during the tidal cycle. This volume has decreased for the sections Vlissingen-Terneuzen and Terneuzen-Hansweert with 1.0 $10^7$ $m^3$ and 0.5 $10^7$ $m^3$ (-15% and -10%) while the section Hansweert-Bath shows no net change between 1955 and 2008. The overall decrease between Vlissingen and Bath has been 1.5 $10^7$ $m^3$ (-10%). The increase of channel volume (see above) and decrease of water volume above the intertidal flats suggest that between Vlissingen and Bath tidal flow has become more dominant over tidal storage although this may be different for individual sections and specific time intervals.

The **channel area** is defined at NAP-2 m. Between Vlissingen and Terneuzen it has first decreased until 1980 and then increased until 2008 resulting in a slight net increase since 1955 (+0.5%). The other two sections show first a decrease in channel area between 1955 and 1970/1980 and a more or less constant value hereafter. The overall change between Vlissingen and Bath has been a decrease of 0.65 $10^7$ $m^2$ (-3%). Between Hansweert and Bath the area of the secondary channel has systematically decreased since 1955 by 30%.

The **channel depth** is computed from the channel volume and the channel area. As such the variation in time of the channel depth may be different from changes of the channel volume alone. Between Vlissingen and Terneuzen the channel depth has increased with about 0.5 m (+4%). The channel depth between Terneuzen and Hansweert has been relatively constant with variations of 0.2 m (2%). The most prominent depth change has taken place for the section Hansweert-Bath where during the period 1955-2008 the channel depth has increased with almost 2.5 m (+27%) of which 1.0 m has occurred between 1970 and 1980 and 1.0 m between 1995 and 2008. Presently (2008) the channel depth for this section is still increasing. Since 1955 the average channel depth between Vlissingen and Bath has increased with 0.8 m (+7%). For the individual main and secondary channels changes have been much larger than for the compound bathymetry of both channels. This especially holds for the section Terneuzen-Hansweert where the secondary channel (Middelgat) has become 3 m shallower whereas the main channel (Gat van Ossenisse-Overloop van Hansweert) has increased in depth with 3 m without having a major impact on the tidal characteristics for this section (amplification of tidal range, tidal propagation velocity). Between Vlissingen and Terneuzen both channels have been in equilibrium since 1970 whereas the section Hansweert-Bath displays on-going erosion with presently both channels contributing to this evolution.

Between 1955 and 2008 the **sand volume of the intertidal flats** has increased for all three sections with a total of 2.7 $10^7$ $m^3$ (+25%) between Vlissingen and Bath. This increase has mainly occurred before 1980/1985. It implies that the decrease of sand volume in the channel (equivalent to the increase of water volume of 7 $10^7$ $m^3$, see above) has been accompanied with an increase of sand volume on the intertidal flats. Or in other words: a redistribution of sand has taken place from the deeper part of the cross-section (channel) to the shallower part (flats).

Between 1955 and 1970/1980 all sections show an increase of the **intertidal area** followed by a decrease during the successive period. Since 1980 the intertidal area has decreased for the section Vlissingen-Terneuzen (-12%) and to a lesser extent for both other sections (Terneuzen-Hansweert: -4%, Hansweert-Bath: -6%). The net change between 1955 and 2008 for the section Vlissingen-Bath has been an increase of 0.35 $10^7$ $m^2$ (+5%).

The height of the intertidal flat follows from the sand volume and the tidal flat area. The combined changes of sand volume and tidal flat area have resulted in an increase of the **intertidal flat height** of 0.25 m for Vlissingen-Terneuzen, 0.45 m for Terneuzen-Hansweert and 0.4 m for Hansweert-Bath relative to the level NAP-2 m. For the section Vlissingen-Bath the height of the intertidal flats increased on average with 0.35 m. The deepening of the channels and heightening of the intertidal flats reflect the large-scale steepening of the bathymetry of the Western Scheldt.

**Synthesis evolution bathymetrical characteristics**
The description given above with respect to the observed morphological changes for the whole Western Scheldt between Vlissingen and Bath is summarised as follows. Since 1955 the water volume of the channel (i.e. the volume below NAP-2 m plus the volume between NAP-2 m and NAP in the channel) has increased with 7 $10^7$ $m^3$ (+3%). At the same time the channel area has decreased with 0.65 $10^7$ $m^2$ (-3%). These changes resulted in an increase of the mean channel depth (relative to NAP) of 0.8 m (+7%). The water volume above the intertidal flats (i.e. between NAP-2 m and NAP+ 2 m) has decreased with 1.5 $10^7$ $m^3$ (-10%) although the tidal flat area has increased with 0.35 $10^7$ $m^2$ (+5%). As such, the decrease of the water volume above the flats results from the increased height of the tidal flats with 0.35 m. Most significant changes in the Western Scheldt have been (i) the increase of the channel depth of 2.5 m since 1970 between Hansweert and Bath, (ii) the increase of the sand volume of the intertidal areas between 1955 and 1980 in all sections (+25%) and the resulting heightening of the tidal flats with 0.35 m. For the individual main and secondary channels the most pronounced changes have occurred between Terneuzen and Hansweert where the main channel depth has increased with 3 m while the depth of the secondary channel has decreased with the same magnitude without a major effect on the tidal range and tidal propagation velocity. The main channel between Hansweert and Bath displays on-going erosion since 1955 with a similar trend for the secondary channel from approximately 1985 onward.

## C. Effects of human interventions

Histories of yearly-average high and low waters, tidal range and amplification of tidal range in water level stations were used to investigate if *sudden* effects of human interventions on tidal characteristics could be derived from the records. In general, no clear responses could be isolated from the inter-annual variation. The most prominent observed change relates to the increase of the tidal range in Bath relative to that in Hansweert between 1970 and 1980. This increase of tidal amplification coincides with the period of the first deepening of the navigation channel however to what extent this deepening has induced or contributed to the observed changes cannot yet be decided upon as natural morphological evolution may have played a role as well. Effects of land reclamation on tidal characteristics could neither be derived from the data despite the relatively large reduction of the reclaimed area. This may be explained by the fact that at the time of reclamation areas were well above local low water so that tidal storage was already reduced to a large extent. The construction of the guiding walls (‘leidammen’) near the Dutch-Belgian border appears to have no effects on tidal properties that can be discerned from inter-annual variation. Similarly, the construction of the major primary dams as part of the Delta works did not influence water levels in Vlissingen. Indirect effects of man-made changes resulting from morphological adaptation have not been studied as part of the present work.

Possible effects of dredging and dumping resulting from maintenance of the navigation channel and sand mining were not addressed since these interventions are continuous activities that do not produce sudden changes of the tidal characteristics.

## D. Analysis with analytical model

Changes in tidal and bathymetric characteristics were first analysed with scatter plots showing for the section Hansweert-Bath a clear relationship. An analytical model for tidal propagation in a convergent estuary was used to explain the increase of M2-amplitude with channel depth. The model was also able to reproduce the increase of the M2-phase velocity which is the propagation velocity of the M2-tidal constituent. Application of the model to the sections Vlissingen-Terneuzen and Terneuzen-Hansweert also showed good agreement between observed and predicted M2-amplitude and M2-phase velocity. It is concluded that an increase in channel depth results in an increase of M2-amplitude up to a channel depth of 15-20 m. For larger channel depths the M2-amplitude will decrease with increasing channel depth. At these channel depths the apparent M2-phase velocity will have become very large. However the tidal wave coming from the North Sea may display an on-going increase of the M2-amplitude as a continuation of the observed trend during the past 100 years.

# Contents

**Appendices**

# 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 passed centuries the tidal regime of the Scheldt estuary has changed. This is due to natural processes as well as human interventions in the estuary, such as reclamation works, deepening of the navigation channel, maintenance dredging, of sand mining and changed forcing (tidal conditions in the North Sea and upstream river discharges).

An important question for the safety management in the Scheldt estuary is how the safety level will vary on the long term, taking into account the historical and present human impacts and natural changes such as sea level rise. An important aspect from the viewpoint of safety management is the possible increase of high water levels.

The changes in hydrodynamics and morphodynamics of the river are inter-related and should be studied together. The morphology of the Scheldt estuary varies as a result of natural evolution and human impacts. This affects hydrodynamics which in turn can lead to morphological adaptation of the system.

Therefore, analysis of the morphological evolution of the estuary will help to understand the changes that have occurred with respect to the tidal regime and vice versa. An analysis of water level and topo-bathymetric data of the previous century is carried out. The objective is then to link the observed changes of water levels as output to the observed changes of topography and bathymetry as input. It is hereby considered that the tidal propagation instantaneously adapts to changes in geometry and/or bed levels.

*1. Long-term Vision Research and Monitoring.*

The results of this study can be found in two reports. For the Western Scheldt area the results are presented in this report. The analysis for the Lower Sea Scheldt is given in LTV V&T-report G-6.

### 1.3 Contents of this report

Chapter 2 presents and discusses data on water levels and discharges. Topo-bathymetric data are described in Chapter 3. In Chapter 4 some relationships between water level data and topo-bathymetric data are investigated. The major human interventions in the Western Scheldt are discussed in Chapter 5 and it is investigated if possible impacts of these interventions can be deduced from the observations. An analytical model on tidal propagations is used in Chapter 6 to analyse observed changes in tidal amplification and propagation velocity of the tidal wave.

Some additional figures are included in Appendix A without further text. A description of the water level data in the stations Cadzand, Westkapelle, Vlissingen, Terneuzen, Hansweert and Bath is given in Appendix B. Appendix C compares the evolution of the tidal range at Vlissingen with other stations along the Dutch and German coast.

# 2 Tidal data

In this chapter data are presented on water levels as well as tidal volumes. Water levels have been measured in the Western Scheldt since the end of the 19$^{th}$ century. Methods have changed over the years and an overview is given in Section 2.1. Discharge measurements have been carried since 1932 in a number of transects along the estuary with irregular time intervals, see also Section 2.1. Processing of the data is briefly described in Section 2.2. The measurements are analysed in terms of certain characteristics which are defined in Section 2.3. Evolution of the water level and discharge characteristics are successively is analysed in successively Section 2.4 and 2.5. The findings are summarised in Section 2.6.

## 2.1 Available data

### 2.1.1 Water levels

In the Western Scheldt water levels are measured in six stations: Westkapelle, Cadzand, Vlissingen, Terneuzen, Hansweert and Bath. Of these, Westkapelle and Cadzand are located along the coast while the other four stations are situated within the estuary at approximately equal intervals of 20 km. Water levels are being recorded since the end of the 19$^{th}$ century; however methods and frequency have changed in the course of time. For instance manual reading of tide gauges of only high and/or low water levels in the past has developed into full automatic data acquisition every 10 minutes at present.

The Helpdesk Water of Rijkswaterstaat (Waterdienst – Mr. Koos Doekes) delivered data of the aforementioned stations on the following aspects:

- Time series on water levels;
- All high and low water levels as well as times of occurrences for each year;
- Average high and low water level per year;
- Average high and low water level during spring tide as well as neap tide;
- Propagation time between Vlissingen and the other stations in the Western Scheldt;
- Tidal constituents.

The data are described in detail in Appendix B; a summary is given in Table 2.1a.

*Table 2.1a: Available water level data in stations along the Western Scheldt. dt is the time step for data acquisition.*

| | | HW+LW | Yearly-averaged HW+LW | |
|---|---|---|---|---|
| Station | Time series<br>dt in [min] | For all tides in a year | Average tide | Spring and neap tide |
| Cadzand | 1971-1987: dt=60<br>1987-2008: dt=10 | 1877-2008 | 1880-2008 | HW: 1901-2000<br>LW: 1908-2000 |
| Westkapelle | 1971-1987: dt=60<br>1987-2008: dt=10 | 1884-2008 | 1880-2008 | 1955-2000 |
| Vlissingen | 1911-1971: dt=180<br>1971-1987: dt=60<br>1987-2008: dt=10 | 1877-2008 | 1862-2008 | 1882-2000 |

| | | | | |
|---|---|---|---|---|
| Terneuzen | 1940-1971: dt=180<br>1971-1987: dt=60<br>1987-2008: dt=10 | 1878-2008 | 1871-2008 | 1901-2000 |
| Hansweert | 1939-1971: dt=180<br>1971-1987: dt=60<br>1987-2008: dt=10 | 1880-2008 | 1862-2008 | 1881-2000 |
| Bath | 1971-1987: dt=60<br>1987-2008: dt=10 | 1886-2008 | 1862-2008 | 1958-2000 |

From Table 2.1a it follows that earliest data on water levels relate to high and low waters only. All high and low waters in a specific year are available since 1877/1886. Time series have been acquired since 1911 in Vlissingen but in the other stations much later. Initially the time step (dt) was 180 min; since 1987 water levels are being acquired with a time step of 10 min in all stations. Data processing by Rijkswaterstaat regarding average spring and neap high and low waters has yet only proceeded until 2000. Occasionally there are gaps in the (older) data (e.g. periods with only high waters or only high and low waters during the daytime); see Appendix B for more information.

### 2.1.2 Discharges

Data on derived quantities from discharge measurements in transects along the Western Scheldt are supplied by the Meetadviesdienst Zeeland of Rijkswaterstaat. Measurements have been carried out since around 1930 with irregular intervals varying between 20 and 30 years for the oldest measurements and 10 years or less in the 2$^{nd}$ half of the 20$^{th}$ century. Nowadays, in some transects measurements are repeated every year if necessary. Until 1995 flow velocities were measured with Ott-mills whereas since 1995 ADCP's are being used. Data availability in the used transects in this report is summarized in Table 2.1b[2]. From these measurements flood, ebb and tidal volume have been derived (Rijkswaterstaat, 2011) for the total cross-section as well as for the individual main and secondary channels.

*Table 2.1b: Available data on discharges in transects along the Western Scheldt.*

| Transect | Main channel | Secondary channel | Years of measurements |
|---|---|---|---|
| 1 | | | 1971, 1975, 1982, 1991, 1996, 2000, 2006, 2010 |
| 2 | Nauw van Bath | Schaar v.d. Noord | 1972, 1982, 1989, 1994, 1998, 2004, 2009 |
| 3 | Overloop van Valkenisse | Zimmermangeul | 1933, 1963, 1980, 1988, 1990, 1995, 1996, 2001, 2007 |
| 5 | Zuidergat | Schaar van Waarde | 1937, 1957, 1964, 1970, 1975, 1981, 1988 |
| 5A | Zuidergat | Schaar van Waarde | 1990, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2005, 2010 |
| 6 | Gat van Ossenisse | Middelgat | 1932, 1957, 1968, 1972, 1978, 1983, 1988, 1989, 1994, 2001, 2004, 2009 |
| 7 | Put van Terneuzen | Everingen | 1961, 1974, 1982, 1989, 1996, 1997, 1998, 1999, |

*[2] Transects 4, Zuid-Everingen and 8 have not been considered because of limited data availability.*

| | | | |
|---|---|---|---|
| | | | 2000, 2001, 2002, 2003, 2008 |
| 9 | Honte/Schaar v.d. Spijkerplaat | Vaarwater langs Hoofdplaat | 1960, 1979, 1991, 1996, 2001, 2006, 2010 |
| 10 | Honte | Vaarwater langs Hoofdplaat | 1958, 1971, 1982, 1989, 1997, 2002, 2007 |
| 11 | Wielingen | Sardijngeul | 1932, 1966, 1985, 1995, 1997, 2000, 2006, 2009 |
| 12 | Wielingen | Oostgat + Deurloo | 1991, 1997, 1999, 2000, 2002, 2007 |
| 14 | Scheur | Oostgat + Vlakte v.d. Raan | 1992, 1998, 2003, 2008 |

## 2.2 Processing

Data were obtained from Rijkswaterstaat as ASCII-files. The data on high and low waters were imported in Excel and supplementary tidal characteristics such as tidal range (difference between high and low water) and half tide (average of high and low water) were determined. Matlab scripts were written to compute the tidal propagation time for high and low waters between two stations as well as the duration of tidal rise and tidal fall in all stations except Cadzand and Westkapelle. The latter two stations were omitted because attention will focus on the effect of bathymetry on tidal characteristics in the Western Scheldt eastwards of Vlissingen[3]. Finally, for each year extreme high waters were derived from the computed cumulative frequency distribution. This was also done with Matlab scripts.

Ebb-, flood and tidal volumes were computed from the discharge measurements by Rijkswaterstaat (2011). This was done for the total transects and for the individual channels if present. Volumes were normalized by Rijkswaterstaat to year-averaged values taking into account the actual tidal conditions during the measurements and the year-averaged tide in the most nearby water level station.

## 2.3 Definition of tidal characteristics

The evolution of the water levels in the Western Scheldt was assessed by means of the following parameters:

In each station or transect:
- Yearly-averaged high and low water;
- Yearly-averaged tidal range;
- Yearly-averaged half tide;
- Yearly-averaged high and low water for spring and neap tides;
- Yearly-averaged tidal range for spring and neap tides;
- Yearly-averaged half tide for spring and neap tides;
- Yearly-averaged duration of tidal rise and tidal fall;
- Extreme high and low water;
- Amplitude of the mean tide (A0);
- Amplitude analysis of the M2, M4, and M6 tides;
- Phase analysis of the M2, M4, and M6 tides;
- Ebb-, flood and tidal volume.

3. *Bathymetries of the ebb tidal delta are less frequently measured, see Chapter 3.*

<u>Between two stations:</u>
- Ratio of tidal range (amplification);
- Yearly-averaged propagation time and propagation velocity;
- M4/M2 and M6/M2 amplitude ratio (ebb-flood dominance);
- 2M2-M4 and 3M2-M6 phase difference (ebb-flood dominance).

Results are presented and discussed in the following sub sections. The locations of the water level stations and the three regions in between are given in Figure 2.1. Figure 2.2 – Figure 2.6 give in detail the locations of the six water level stations.

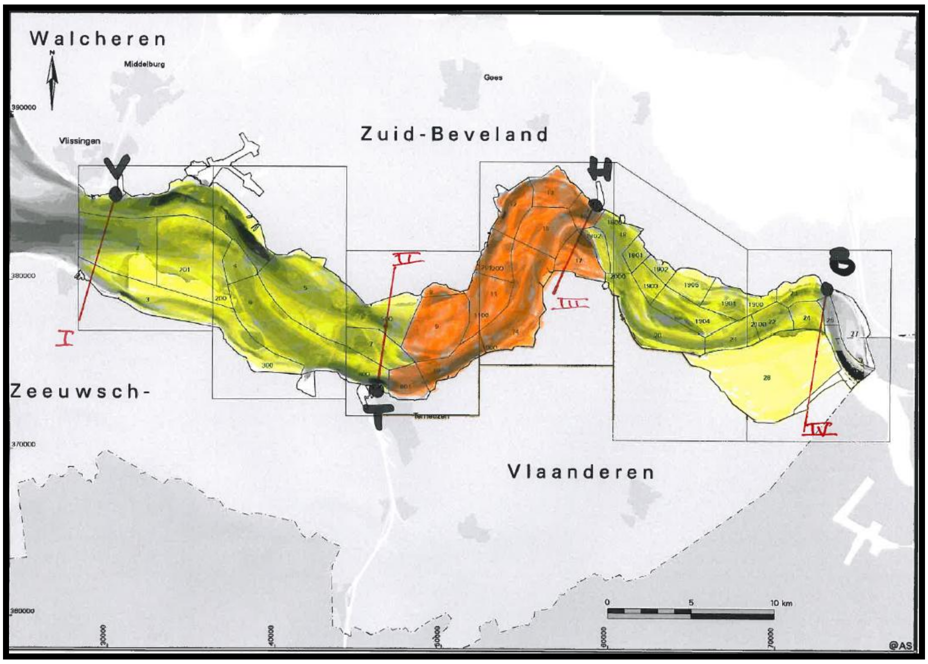



*Figure 2.1: Locations of water level stations and intermediate regions. V = Vlissingen, T = Terneuzen, H = Hansweert, B = Bath. Intermediate regions are: V-T ≈ macro cell 1 and 3 and meso cell 2; T-H ≈ macro cell 4; H-B ≈ macro cell 5 and 6.*


*Figure 2.2: Locations of water level stations Westkapelle and Cadzand.*


*Figure 2.3: Location of water level station Vlissingen.*


*Figure 2.4: Location of water level station Terneuzen.*

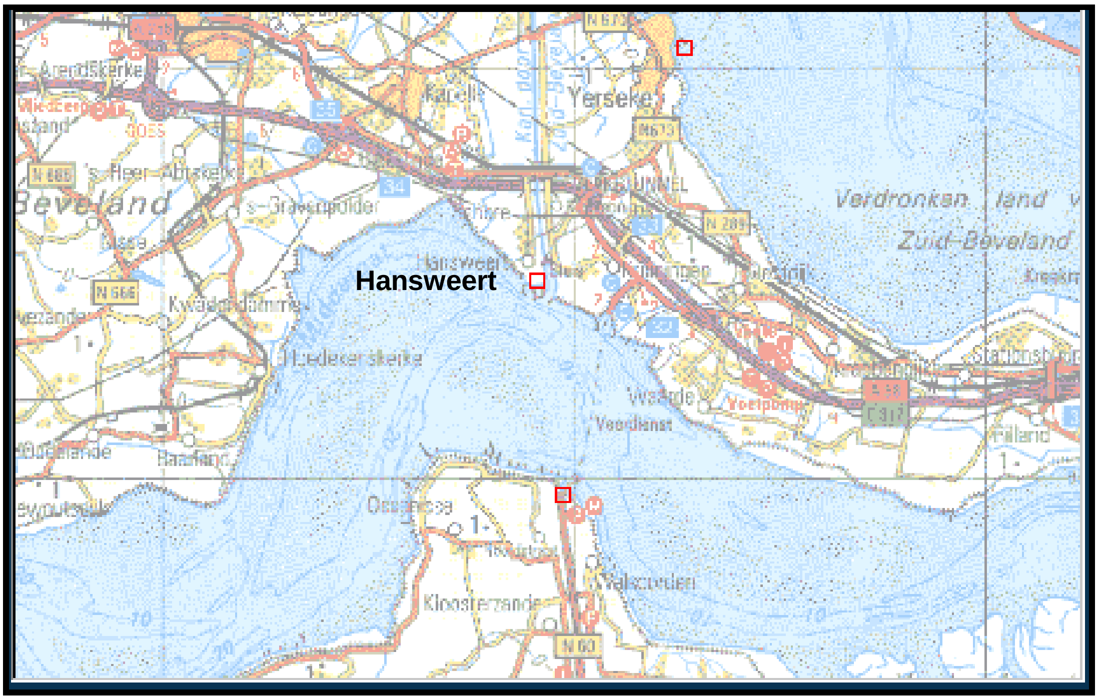



*Figure 2.5: Location of water level station Hansweert.*

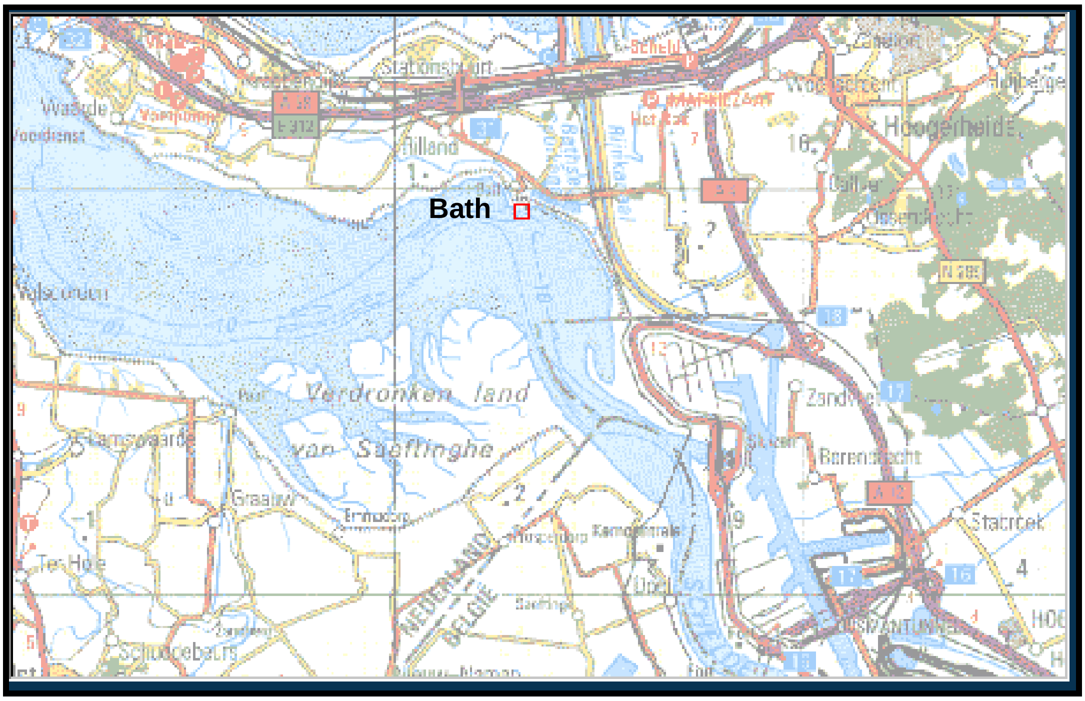



*Figure 2.6: Location of water level station Bath.*

Transects in which discharge measurements have been carried out are given in Figure 2.7.

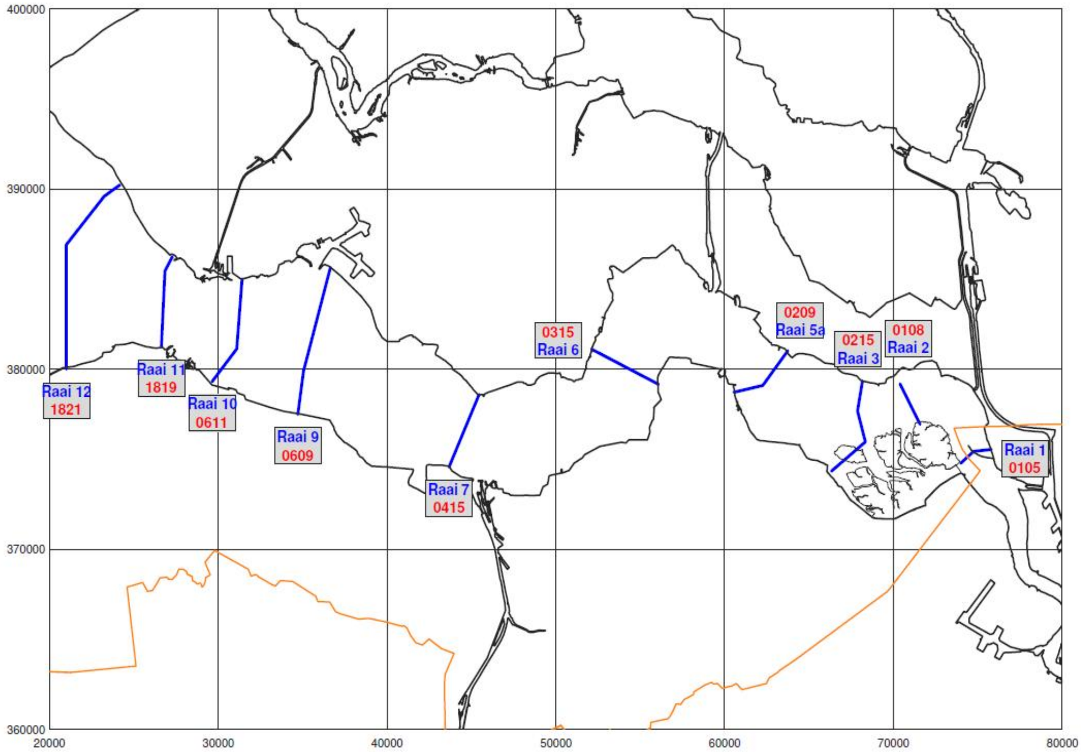
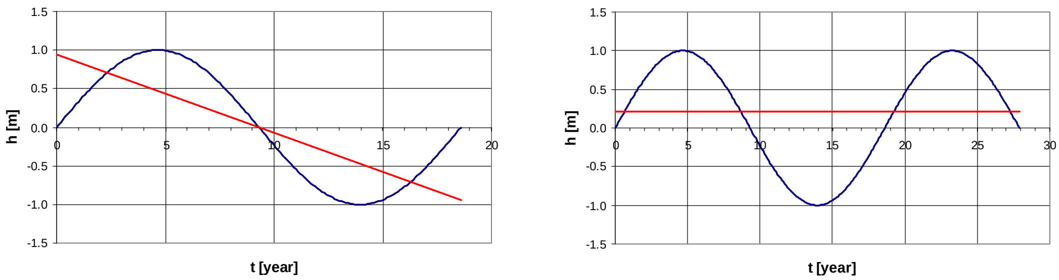



*Figure 2.7: Transects for discharge measurements along the Western Scheldt (Rijkswaterstaat, 2011). Transect 14 is in the ebb tidal delta.*

## 2.4 Evolution of water levels

Firstly, the tidal characteristics for each individual water level station will be examined, see Sections 2.4.1 – 2.4.14. Secondly, the properties for a section will be presented, such as the ratio of the tidal range (amplification), propagation time and velocity and changes in tidal asymmetry parameters, see Sections 2.4.15 – 2.4.18. Trends will be estimated with linear regression of tidal characteristics that are based on yearly-averaged values. Data records include the 18.6 year variation. Best estimates are then obtained if the period for the regression analysis is 1.5, 2.5, 3.5 etc. times the lunar nodal period of 18.6 year, otherwise the linear trend is biased by this oscillation. As an example, see below, a linear fit is determined for a simple sine function, showing a slope of the regression line. If the regression is done for 1.5 times the period of the sine function the regression line is almost horizontal although with an offset. For a recent discussion on this see Baart et al. (2011).



For the average tides the period 1887-2008 is selected to estimate trends of the tidal characteristics. The duration of this period is 122 years (including 2008) which is 6.56 times the 18.6 year variation. For spring and neap tides data records are shorter. For these tides the period 1901-1999 (including 1999) is selected which is 5.32 times the 18.6 year variation.

### 2.4.1 Yearly-averaged high and low water

The yearly-averaged high waters have steadily increased since the start of the observations in 1862, see Figure 2.8. The only exception is the period between approximately 1880 en 1890 when all four stations show a decrease of the high waters. Also the high waters in Vlissingen before approximately 1885 seem to be relatively high as compared to those in the other stations (see also Appendix A). In Vlissingen only one high water and one low water during daytime were taken from tidal gauges for the periods 1 January - 26 July 1877, 1 December 1877 - 7 February 1878 and 14 May 1879 - 31 March 1881 but this does not seem to be the explanation for the observed variations. Finally, the high waters in Bath show a distinct increase of almost 0.5 m between 1864 and 1877 (13 years) which is about the same as the total increase during the 20th century.

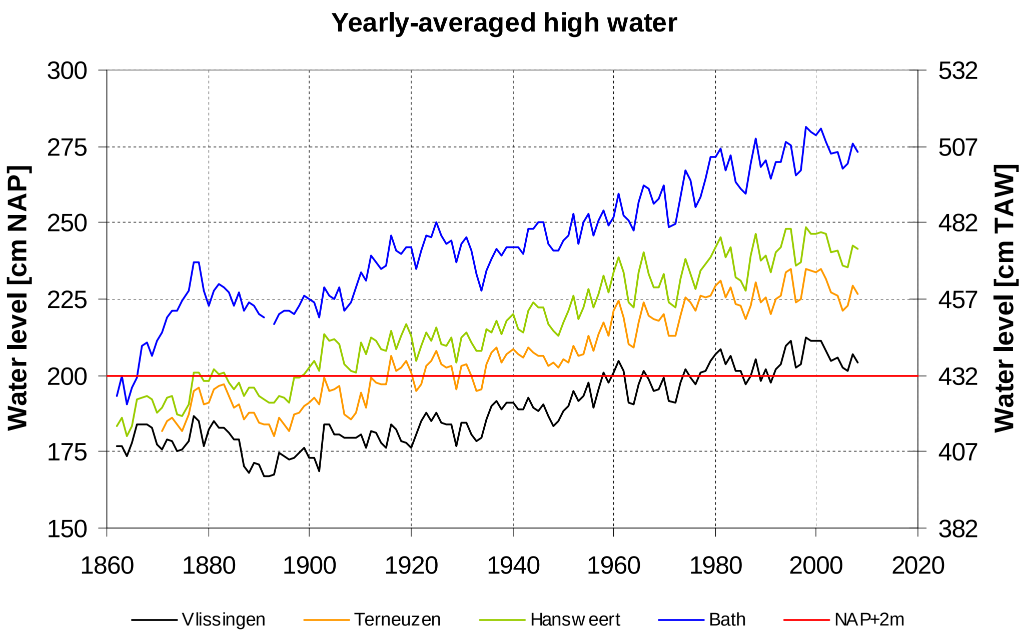



*Figure 2.8: Yearly-averaged high water in Vlissingen, Terneuzen, Hansweert and Bath.*

The variations in time of the low waters are less than the variations of the high waters, see Figure 2.9. Since approximately 1890 all stations show an increase (i.e. higher low waters). As noted before for the high waters also the low waters in Vlissingen before 1890 seem to be relatively high in comparison with the low waters in the other stations. In Bath the steadily increase of low water before 1970 is abruptly changed in a decrease (lower low water levels) between 1970 and 1980. The magnitude of this change is however not exceptionally large as compared to variations in the past (e.g. around 1880). Since 1980 the low waters in this station have remained unaltered.

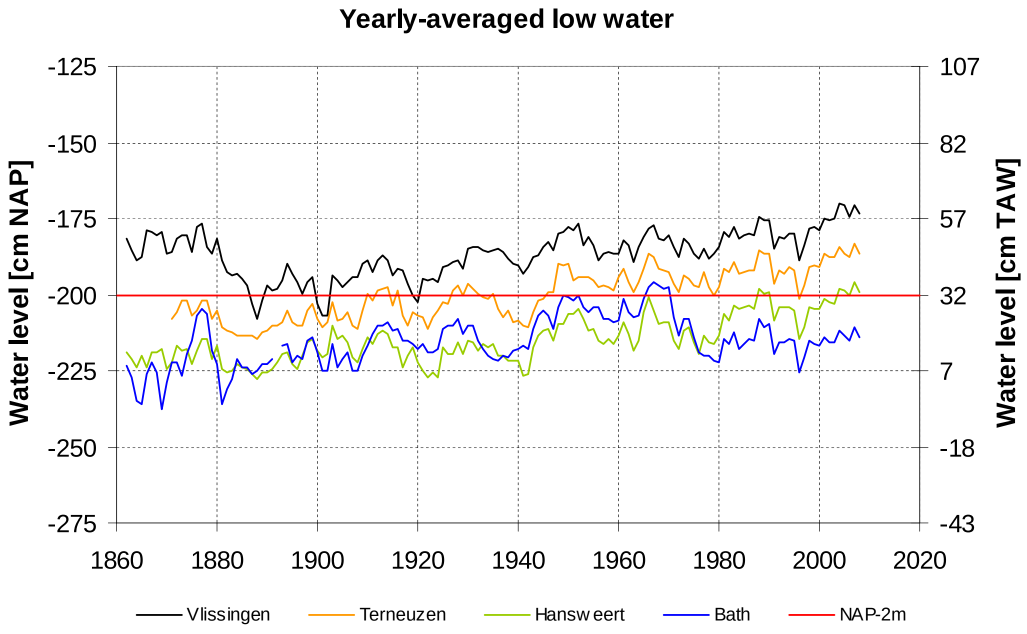



*Figure 2.9: Yearly-averaged low water in Vlissingen, Terneuzen, Hansweert and Bath.*

To investigate the increase of high and low waters alongside the Western Scheldt the time series as shown in Figure 2.8 and Figure 2.9 were approximated with linear trends for the period 1887-2008. The slopes of these linear trends are given in Table 2.1c in terms of change per 100 years. The low waters in Bath could not be represented well with a linear fit due to the sudden decrease between 1970 and 1980 ($r^2$ = 0.1).

*Table 2.1c: Increase of high and low waters in the Western Scheldt as approximated with linear regression for the period 1887-2008.*

| | | **Average change [cm/century]** | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| High water | Average | 32 | 40 | 42 | 47 |
| Low water | Average | 19 | 18 | 17 | (6) |

*[1]) $r^2$ = 0.1.*

The data presented in Table 2.1c are shown as a function of the longitudinal coordinate *x* in Figure 2.10. From Table 2.1c and Figure 2.10 it follows that for the period 1887-2008:

- The increase of high waters amounts 30 to 40 cm/century, which is more than the mean sea level rise of 15 to 20 cm/century.
- The increase of high waters in Terneuzen, Hansweert and Bath is 25-50% larger than in Vlissingen.
- The increase of low waters is 20 cm/century between Vlissingen and Hansweert. In Bath the increase is only 6 cm/century which is caused by the sudden drop of the low water between 1970 and 1980.

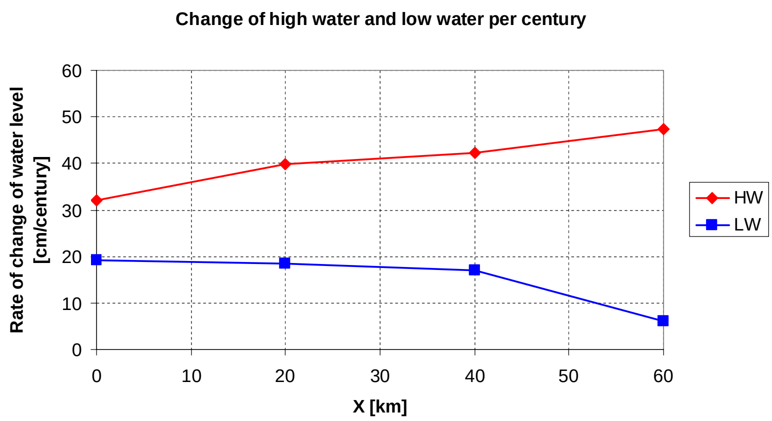



*Figure 2.10: Change of high and low water per century along the Western Scheldt following from the slopes of the regression lines for the period 1887-2008 (see Table 2.1c).*

### 2.4.2 Yearly-averaged tidal range

Figure 2.11 presents the change of the yearly-averaged tidal range (= HW-LW) since 1862 (Vlissingen, Hansweert and Bath) and since 1871 (Terneuzen). There is a long-term trend for all four stations indicating an increase of this parameter. The tidal range also shows a periodic component with duration of 18.6 year and a fluctuation of about ± 7 cm in Vlissingen (± 2%). In Bath the tidal range increases between 1970 and 1980 with approximately 35 cm which is equal to the total increase during the preceding 100 years. Similar to the high and low waters the evolution of the tidal range in the four stations between 1887 and 2008 is approximated with a linear regression resulting in average changes per century as given in Table 2.1d.

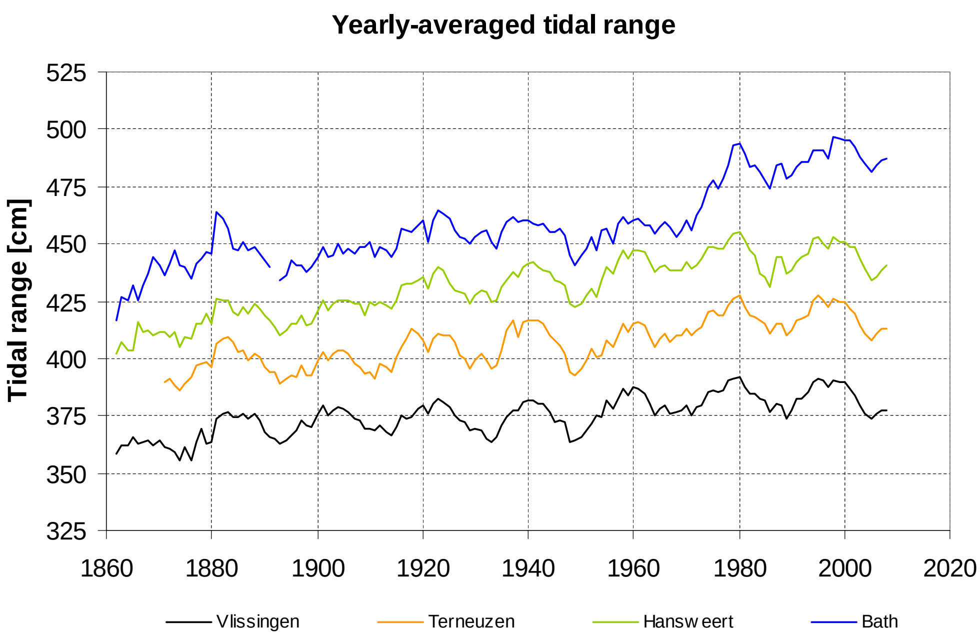



*Figure 2.11: Yearly-averaged tidal range in Vlissingen, Terneuzen, Hansweert and Bath.*

*Table 2.1d: Increase of tidal range in the Western Scheldt as approximated with linear regression for the period 1887-2008.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| Tidal range | Average | 13 | 21 | 25 | 41 |

The data presented in Table 2.1d are shown as a function of the longitudinal coordinate *x* in Figure 2.12. From Table 2.1d and Figure 2.12 it follows that for the period 1887-2008:

- The tidal range has increased on average over a period of 100 years with 13 cm in the mouth of the Westerschelde (Vlissingen). The relative increase is 3.5%/century.
- The increase of the tidal range becomes larger going in upstream direction resulting in an increase of 41cm/century in Bath (+10%).

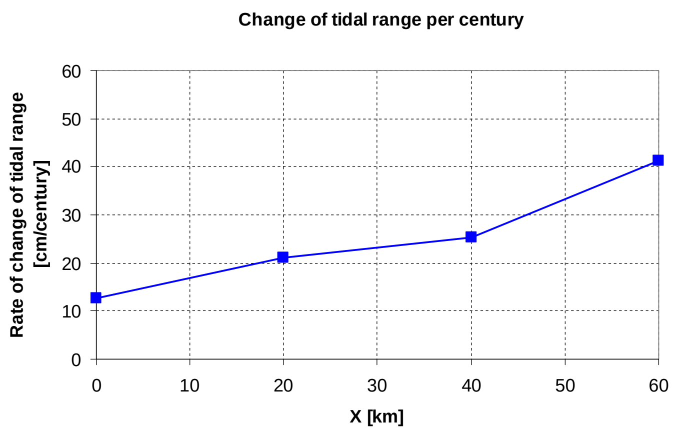



*Figure 2.12: Change of tidal range per century along the Western Scheldt following from the slopes of the regression lines for the period 1887-2008 (see Table 2.1d).*

In Section 2.4.15 the amplification of the tidal range between two water level stations will be discussed. It is defined as the ratio of the tidal range in the landward station and the tidal range in the seaward station. For instance the amplification $ampl_{VT}$ of the tidal range between Vlissingen ($H_V$) and Terneuzen ($H_T$) is defined as:

$$H_T = ampl_{VT}\, H_V$$

If first is assumed that the amplification $ampl_{VT}$ is 1 and constant in time an increase of 13 cm/100 year in Vlissingen would result in the same rate of increase in Terneuzen:

$$\frac{H_T}{dt} = ampl_{VT} \frac{H_V}{dt} = \frac{H_V}{dt} \quad (ampl_{VT} = 1)$$

Because the amplification between both stations is in the order of 1.07 (see Section 2.4.15) an increase in Terneuzen of 1.07*13 = 14 cm/100 year would be expected if the amplification is still assumed to be constant in time. According to Table 2.1d the tidal range in Terneuzen has increased with 21 cm/100 year, which implies that amplification between Vlissingen and Terneuzen has increased. Similarly, amplification between Terneuzen and Hansweert has increased but to a lesser extent. The largest increase of tidal amplification has occurred between Hansweert and Bath.

### 2.4.3 Yearly-averaged half tide

The yearly-average half tide (= (HW+LW)/2) is a measure for the mean water level. Figure 2.13 shows that since 1890 this parameter has increased. It is remarked that the half tide is not an exact measure of the mean water level as it is influenced by the shape of the tidal curve. The time series of Figure 2.13 are approximated with linear functions and the slopes of the lines are given in Table 2.2 in terms of cm/century.

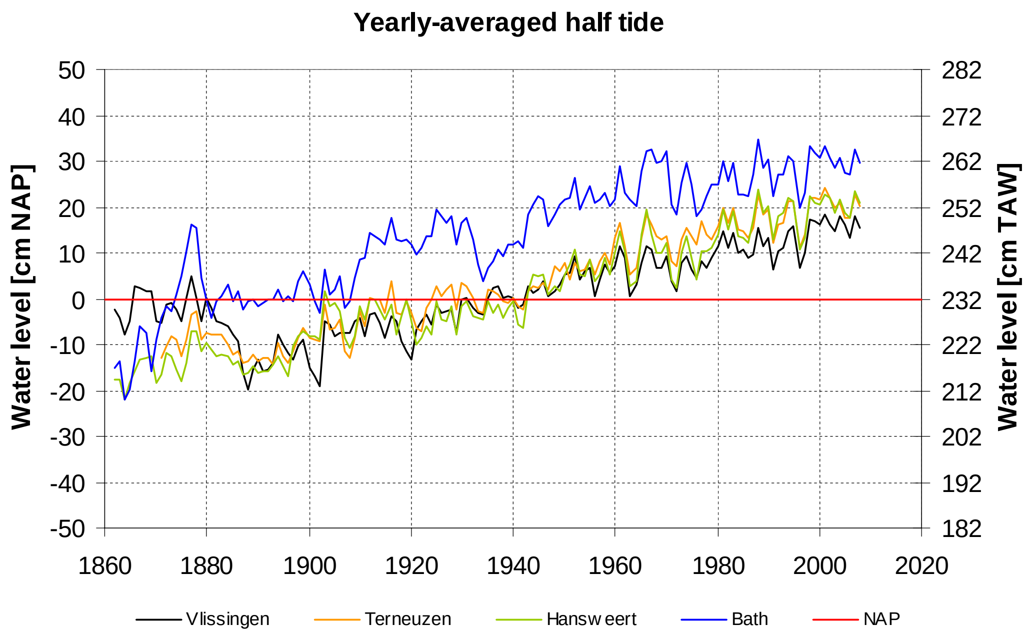



*Figure 2.13: Yearly-averaged half tide in Vlissingen, Terneuzen, Hansweert and Bath.*

*Table 2.2: Increase of half tide in the Western Scheldt as approximated with linear regression for the period 1887-2008.*

| | | **Average change [cm/century]** | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| Half tide | Average | 26 | 29 | 30 | 27 |

The data presented in Table 2.2 are shown as a function of the longitudinal coordinate *x* in Figure 2.14. From Table 2.2 and Figure 2.14 it follows that for the period 1887-2008:

- The half tide in the Western Scheldt has increased with approximately 28 cm over a period of 100 years. In Vlissingen, Terneuzen en Hansweert this is from 10-15 cm below NAP to 15-20 cm above NAP.
- The mean water level in Vlissingen following from tidal analysis (see Section 2.4.12) has increased with 19.6 cm/100 year if determined for the period 1911-2007 for which these data are available. For comparison: the increase of the half tide in Vlissingen for the same period amounts to 24.5 cm/100 year.

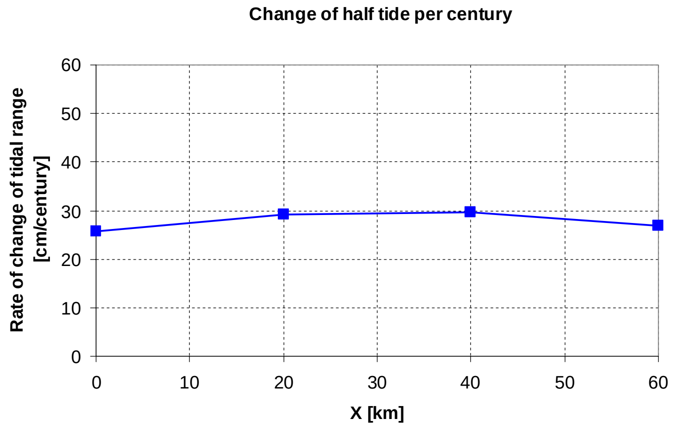



*Figure 2.14: Change of half tide per century along the Western Scheldt following from the slopes of the regression lines tides as shown in Table 2.2.*

## 2.4.4 Yearly-averaged high and low water for spring tides

The yearly-averaged high and low waters for spring tides are given in Figure 2.15 and Figure 2.16. Also for spring tides the slopes of the time series are determined with linear regression. This is done for the period 1901-1999 (stations Vlissingen, Terneuzen and Hansweert) as well as for the period 1958-1999 (all stations). In the latter case the period is relatively short and regression coefficients are lower than for the longer period. The slopes of the regression lines in terms of cm/century are given in Figure 2.17, Table 2.3, and Table 2.4.

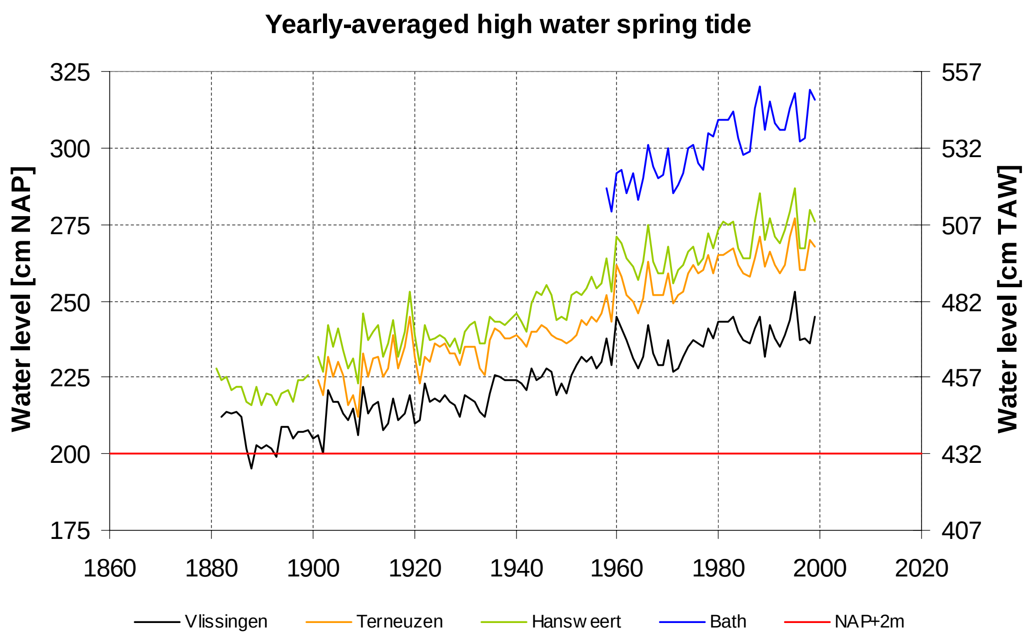



*Figure 2.15: Yearly-averaged high water during spring tide in Vlissingen, Terneuzen, Hansweert and Bath.*

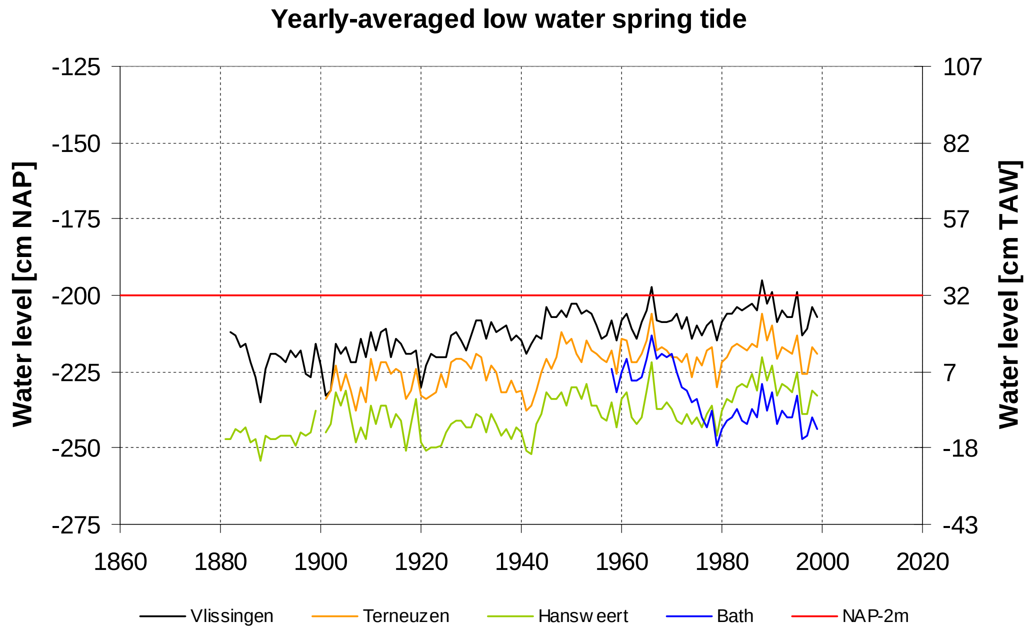



*Figure 2.16: Yearly-averaged low water during spring tide in Vlissingen, Terneuzen, Hansweert and Bath.*

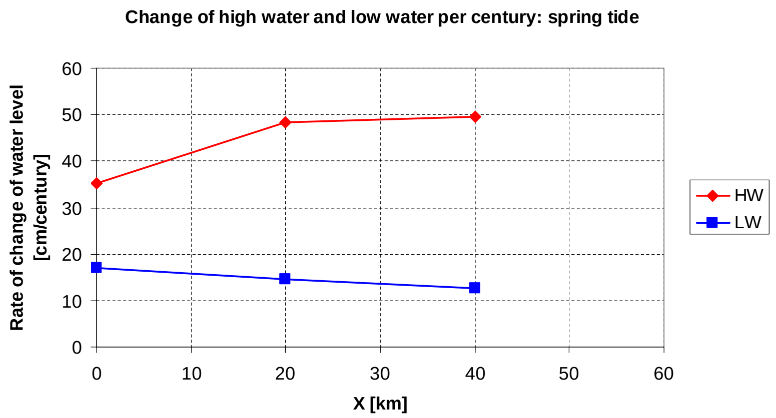



*Figure 2.17: Change of high and low waters per century along the Western Scheldt for spring tides as derived from water level data for the period 1901-1999.*

*Table 2.3: Increase of high and low waters in the Western Scheldt for spring tides as approximated with linear regression for the period 1901-1999.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| High water | Spring tide | 35 | 48 | 50 | - |
| Low water | Spring tide | 17 | 15 | 13 | - |

*Table 2.4: Increase of high and low waters in the Western Scheldt for spring tides as approximated with linear regression for the period 1958-1999.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| High water | Spring tide | 21 | 43 | 39 | 71 |
| Low water | Spring tide | 12 | 2 | 21 | -54 |

From Figure 2.17 and Table 2.3 it follows that for stations Vlissingen, Terneuzen and Hansweert:

- The increase of high waters for spring tides during a period of 100 years is 35-50 cm, which is 5-10 cm more than for average tides;
- The increase of low waters for spring tides during 100 years is approximately 15 cm, which is 3 cm less than for average tides.

Since 1958 the increase of high waters in Bath has been significantly more than in the other stations, i.e. 71 cm/century in Bath and 20-40 cm/century in the other stations. However, the period is relatively short and the variation is large resulting in a regression coefficient $r^2$ of 0.68 for Bath and less than 0.2 for the other stations. The low waters during spring tide in Bath show on average a decrease since 1958 which is opposite to the increase in the other stations for the same period. The observed decrease in Bath mainly occurs between 1970 and 1980.

### 2.4.5 Yearly-averaged tidal range for spring tides

The evolution of the yearly-averaged tidal range for spring tides is presented in Figure 2.18. The slopes of the regression lines are given in Figure 2.19 and Table 2.5 for the period 1901-1999 (Vlissingen, Terneuzen and Hansweert) and in Table 2.6 for the period 1958-1999 (all stations).

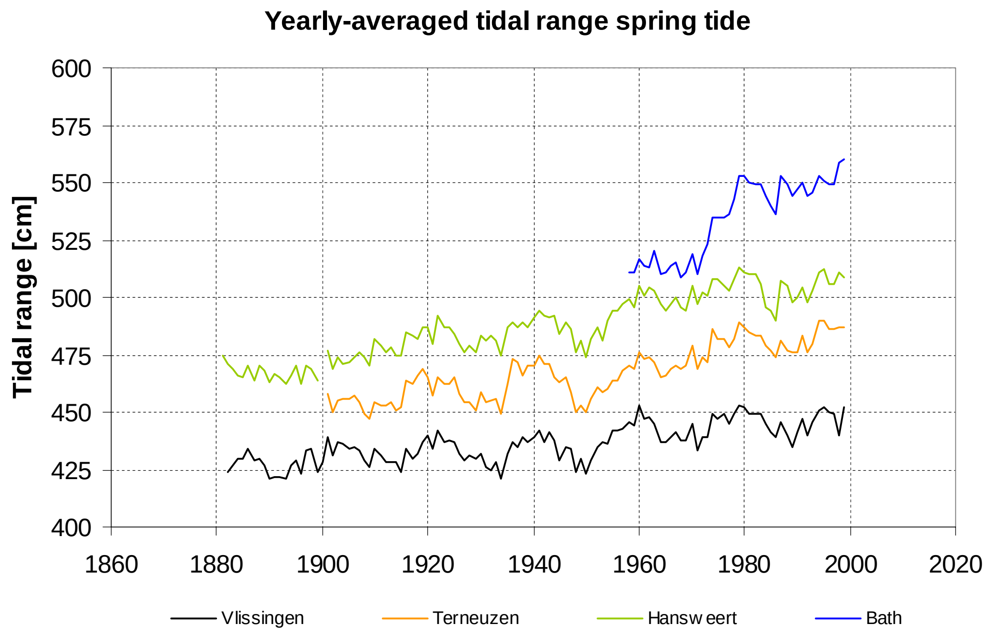



*Figure 2.18: Yearly-averaged tidal range during spring tide in Vlissingen, Terneuzen, Hansweert and Bath.*

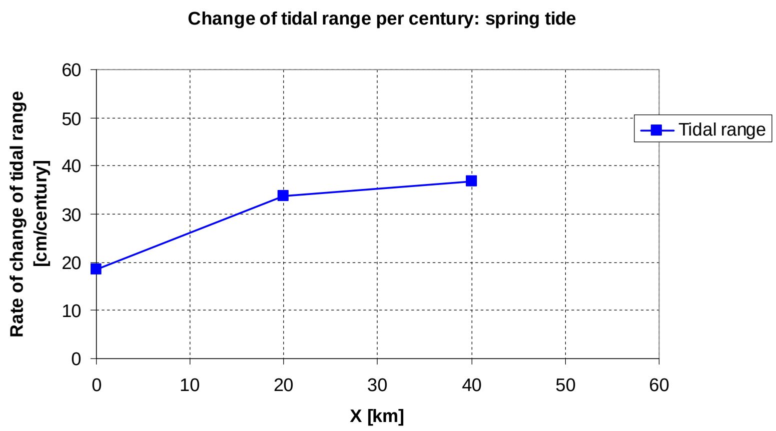



*Figure 2.19: Change of tidal range per century along the Western Scheldt for spring tides as derived from water level data for the period 1901-1999.*

*Table 2.5: Increase of tidal range in the Western Scheldt for spring tides as approximated with linear regression for the period 1901-1999.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| Tidal range | Spring tide | 18 | 34 | 37 | - |

*Table 2.6: Increase of tidal range in the Western Scheldt for spring tides as approximated with linear regression for the period 1958-1999.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| Tidal range | Spring tide | 9 | 41 | 18 | 125 |

It follows that for the stations Vlissingen, Terneuzen and Hansweert:

- the increase of the yearly-averaged tidal range for spring tides during 100 years is 20-40 cm, which is 5-15 cm larger than for average tides;
- the increase becomes larger going in upstream direction.

Since 1958 the tidal range in Bath has increased with a rate of 125 cm/century ($r^2$ = 0.81), which is considerably more than the rate of change in the other stations during the same period (10-40 cm/century).

### 2.4.6 Yearly-averaged half tide for spring tides

Figure 2.20 shows the evolution of the half tide between 1872/1901 and 2000. The slopes of the time series, as determined by linear regression, is given in Figure 2.21 and Table 2.7 for the period 1872/1901-2000 (Vlissingen, Terneuzen and Hansweert) and in Table 2.8 for the period 1958-2000 (all stations).

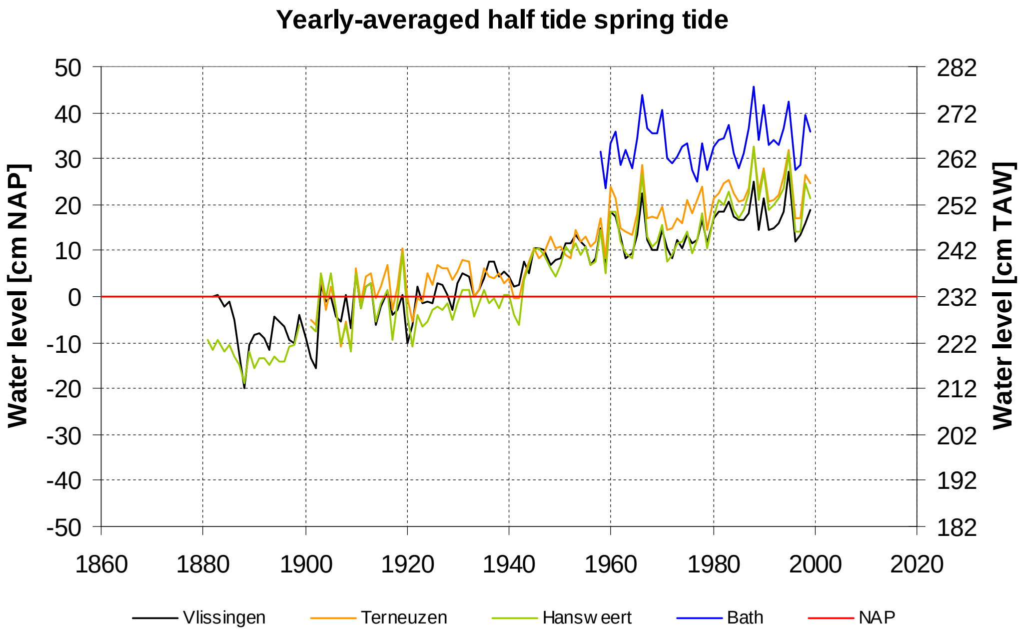



*Figure 2.20: Yearly-averaged half tide during spring tide in Vlissingen, Terneuzen, Hansweert and Bath.*

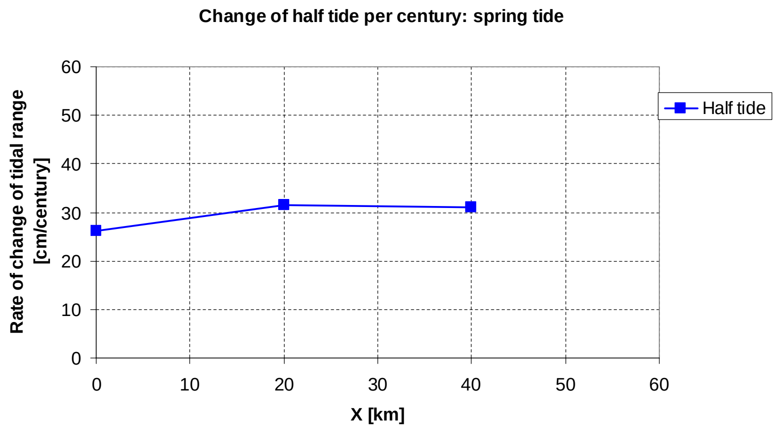



*Figure 2.21: Change of half tide per century along the Western Scheldt for spring tides as derived from water level data for the period 1901-1999.*

*Table 2.7: Increase of half tide in the Western Scheldt for spring tides as approximated with linear regression for the period 1901-1999.*

| | | **Average change [cm/century]** | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| Half tide | Spring tide | 26 | 31 | 31 | - |

*Table 2.8: Increase of half tide in the Western Scheldt for spring tides as approximated with linear regression for the period 1958-2000.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| Half tide | Spring tide | 16 | 22 | 30 | 9 |

From Figure 2.21 and Table 2.7 it follows that:

- The rate of increase of the half tide for spring tide is 30 cm/century in Vlissingen, Terneuzen and Hansweert, which is not very different from the rate of change for average tides.

### 2.4.7 Yearly-averaged high and low water for neap tides

The yearly-averaged high and low waters for neap tides are given in Figure 2.22 and Figure 2.23. The slopes of the time series are determined with linear regression for the period 1901-1999 (stations Vlissingen, Terneuzen and Hansweert) as well as for the period 1958-1999 (all stations). In the latter case the period is relatively short and regression coefficients are smaller than for the longer period. The slopes of the regression lines in terms of cm/century are given in Figure 2.24, Table 2.9 and Table 2.10.

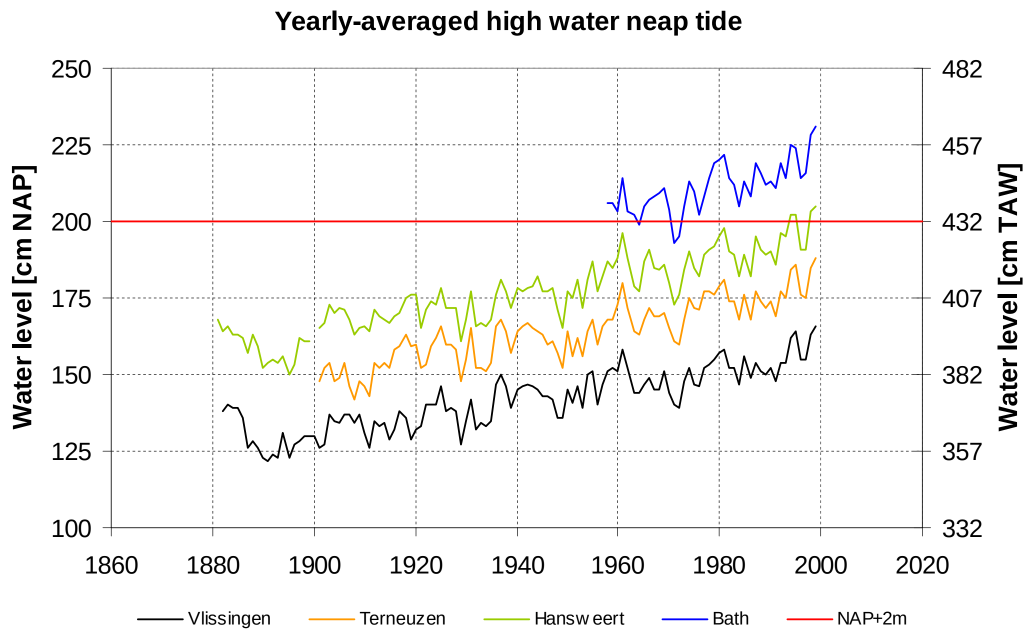



*Figure 2.22: Yearly-averaged high water during neap tide in Vlissingen, Terneuzen, Hansweert and Bath.*

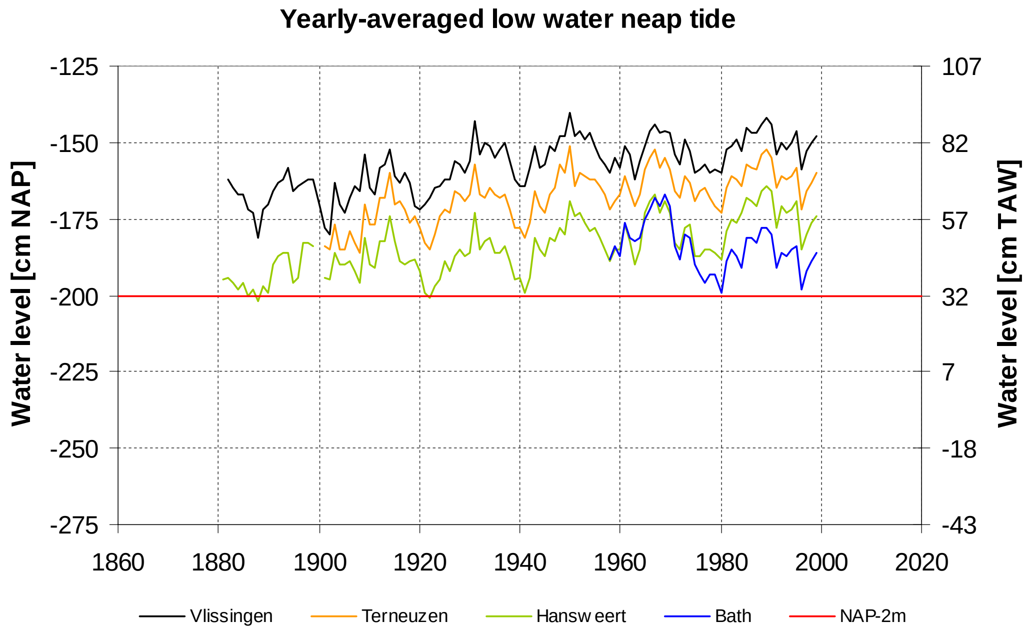



*Figure 2.23: Yearly-averaged low water during neap tide in Vlissingen, Terneuzen, Hansweert and Bath.*

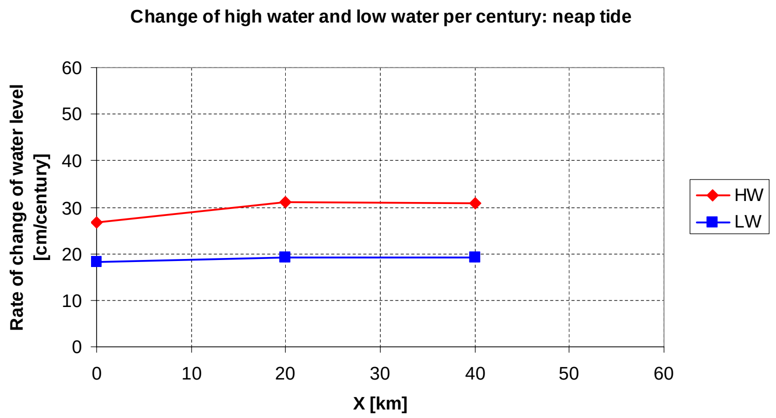



*Figure 2.24: Change of high and low waters per century along the Western Scheldt for neap tides as derived from water level data for the period 1901-1999.*

*Table 2.9: Increase of high and low waters in the Western Scheldt for neap tides as approximated with linear regression for the period 1901-1999.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| High water | Neap tide | 27 | 31 | 31 | - |
| Low water | Neap tide | 18 | 19 | 19 | - |

*Table 2.10: Increase of high and low waters in the Western Scheldt for neap tides as approximated with linear regression for the period 1958-1999.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| High water | Neap tide | 27 | 31 | 34 | 47 |
| Low water | Neap tide | 13 | 9 | 24 | -25 |

From Figure 2.24 and Table 2.9 it follows for stations Vlissingen, Terneuzen and Hansweert that:

- The increase of high waters for neap tides during a period of 100 years is 30 cm, which is 5-10 cm less than for average tides;
- The increase of low waters for neap tides during 100 years is not very different from average tides.

Since 1958 the increase of high waters in Bath has been more than in the other stations, i.e. 47 cm/century in Bath and 25-35 cm/century in the other stations. However, the period is relatively short and the variation is large resulting in a regression coefficient $r^2$ of 0.49 for Bath. The low waters during neap tide in Bath show a decrease since 1958 which is opposite to the increase in the other stations for the same period. The observed decrease in Bath mainly occurs between 1970 and 1980.

### 2.4.8 Yearly-averaged tidal range for neap tides

The evolution of the yearly-averaged tidal range for neap tides is presented in Figure 2.25. The slopes of the regression lines are given in Figure 2.26 and Table 2.11 for the period 901-1999 (Vlissingen, Terneuzen and Hansweert) and in Table 2.12 for the period 1958-1999 (all stations).

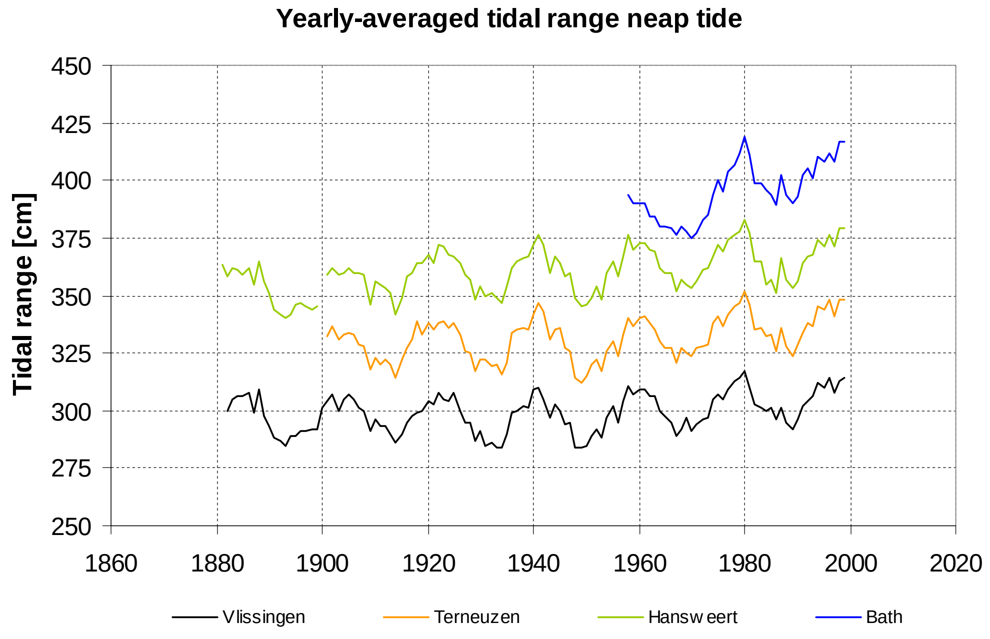



*Figure 2.25: Yearly-averaged tidal range during neap tide in Vlissingen, Terneuzen, Hansweert and Bath.*

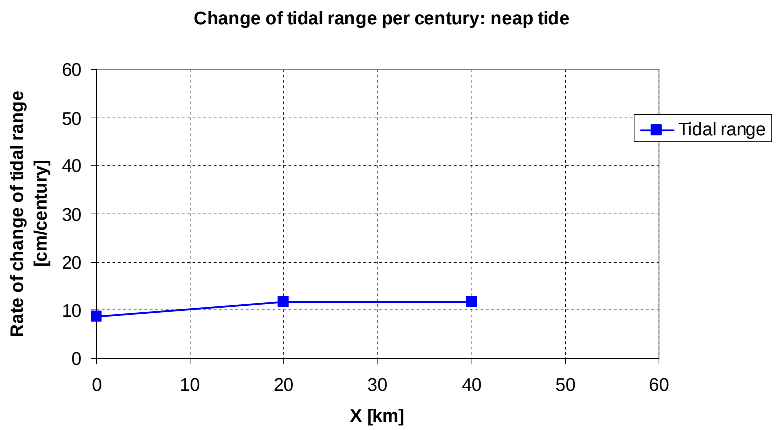



*Figure 2.26: Change of tidal range per century along the Western Scheldt for neap tides as derived from water level data for the period 1901-1999.*

*Table 2.11: Increase of tidal range in the Western Scheldt for neap tides as approximated with linear regression for the period 1901-1999.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| Tidal range | Neap tide | 9 | 12 | 12 | - |

*Table 2.12: Increase of tidal range in the Western Scheldt for neap tides as approximated with linear regression for the period 1958-1999.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| Tidal range | Neap tide | 14 | 22 | 10 | 72 |

It follows that in the stations Vlissingen, Terneuzen and Hansweert:

- the increase of the yearly-averaged tidal range for neap tides during 100 years is about 10 cm, which is 5-15 cm less than for average tides;
- the increase somewhat larger in upstream direction.

Since 1958 the tidal range in Bath has increased with a rate of 72 cm/century ($r^2$ = 0.50), which is considerably more than the rate of change in the other stations during the same period (10-20 cm/century).

### 2.4.9 Yearly-averaged half tide for neap tides

Figure 2.27 shows the evolution of the half tide between 1872/1901 and 2000. The slopes of the time series, as determined by linear regression, is given in Figure 2.28 and Table 2.13 for the period 1901-1999 (Vlissingen, Terneuzen and Hansweert) and in Table 2.14 for the period 1958-1999 (all stations).

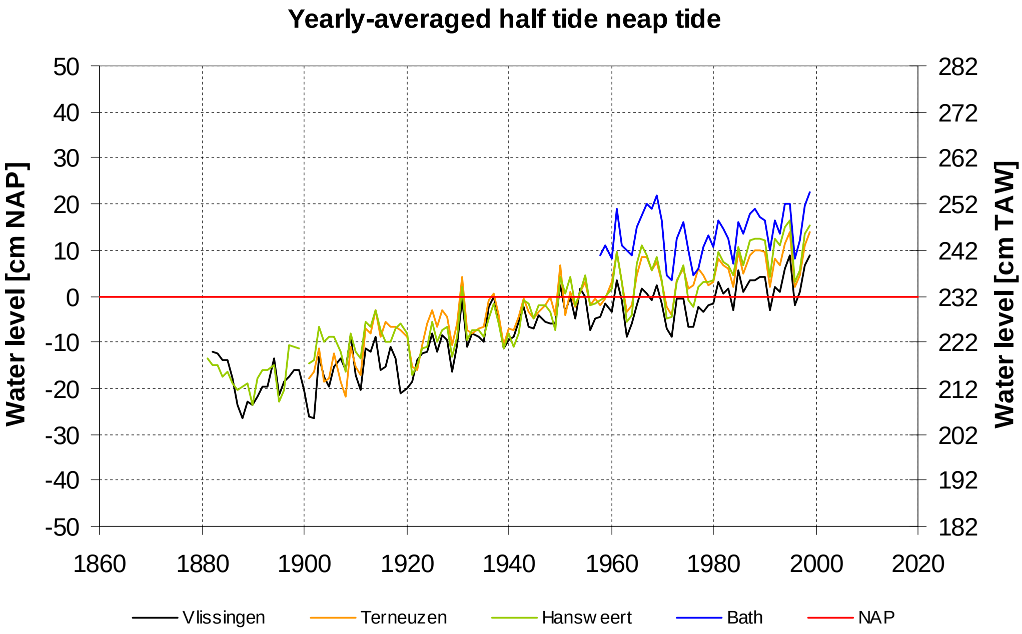



*Figure 2.27: Yearly-averaged half tide during neap tide in Vlissingen, Terneuzen, Hansweert and Bath.*

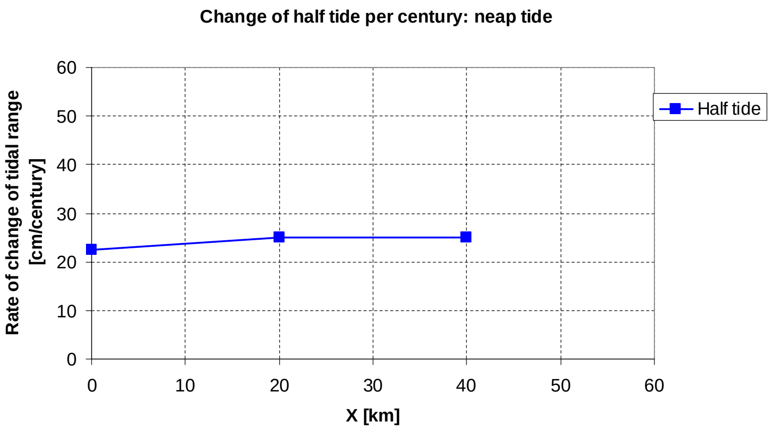



*Figure 2.28: Change of half tide per century along the Western Scheldt for neap tides as derived from water level data for the period 1901-1999*

*Table 2.13: Increase of half tide in the Western Scheldt for neap tides as approximated with linear regression for the period 1901-1999.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| Half tide | Neap tide | 22 | 25 | 25 | - |

*Table 2.14: Increase of half tide in the Western Scheldt for neap tides as approximated with linear regression for the period 19581999.*

| | | Average change [cm/century] | | | |
|---|---|---|---|---|---|
| **Parameter** | **Tide** | **Vlissingen x = 0 km** | **Terneuzen x = 20 km** | **Hansweert x = 40 km** | **Bath x = 60 km** |
| Half tide | Neap tide | 20 | 20 | 29 | 11 |

From Figure 2.28 and Table 2.13 it follows that:

- The rate of increase of the half tide for neap tide is 25 cm/century, which is approximately 5 cm/century less as compared to the rate of change for average tides.

2.4.10 Yearly-averaged duration of tidal rise and tidal fall

Parameters related to the shape of the tidal curve in a specific location are defined as (i) the duration of tidal rise, i.e. from low water to high water, and (ii) the duration of tidal fall, i.e. from high to low water. Both parameters describe the asymmetry of the (vertical) tide. If the duration of tidal rise is shorter than the duration of tidal fall peak velocities during flood may be larger than peak velocities during ebb. As the transport of sand (*s*) is proportional to the power of the flow velocity (*u*), i.e. $s \sim u^n$ this may give rise to a net sand transport in flood direction which in turn will affect the morphology of the estuary. It is remarked that this is a first order approximation and that the asymmetry of the horizontal tide rather than that of the vertical tide governs the residual sediment transport. The former indicator however is much more difficult to derive from measurements. The parameters in this sub section are not of primary importance with respect to issues on safety. However, they are given here for completeness and possibly for later use.

Figures 2.29-2.32 show the durations of tidal rise and tidal fall in the stations Vlissingen, Terneuzen, Hansweert and Bath. It follows that:

- The duration of tidal rise (flood period) is generally shorter than the duration of tidal fall (ebb period);
- The difference in duration of tidal rise and tidal fall is smallest in Hansweert (~ 20 min) and largest in Bath (~ 50 min);
- In Vlissingen the asymmetry of the vertical tide has not much changed since the start of the observations;
- In Terneuzen the duration of tidal rise has decreased since 1950 with approximately 5 min and thus the duration of tidal fall has increased by the same amount.
- In Hansweert the durations of tidal rise and tidal fall have not changed much although there are variations of 5-10 min especially between 1960 and 1980. The increase of duration of tidal rise between 1960 and 1970 showing a decrease of flood dominance is consistent with the decrease of the phase difference 2M2-M4 during this period (see upper window in Figure 2.45) indicating an increase of ebb dominance. Also the decrease of the duration of tidal rise between 1970 and 1980 (more flood dominance) is consistent with the increase of the phase difference 2M2-M4 (less ebb dominance).
- Between 1901 and 1934 and between 1942 and 1957 the sum of the durations of tidal rise and tidal fall in Bath appears to be 10-15 min less than the tidal period of 745 min. Therefore these data have been removed from Figure 2.32. Since 1980

the duration of tidal rise had gradually increased (~ 10 min) and consequently the duration of tidal fall has decreased.

With respect to water levels the tide is asymmetric with a flood dominance in all stations in the Western Scheldt (duration of tidal rise is shorter than the duration of tidal fall). The asymmetry is smallest in Hansweert and largest in Bath. The asymmetry has increased in Terneuzen since about 1950 and has decreased since 1980 in Bath.

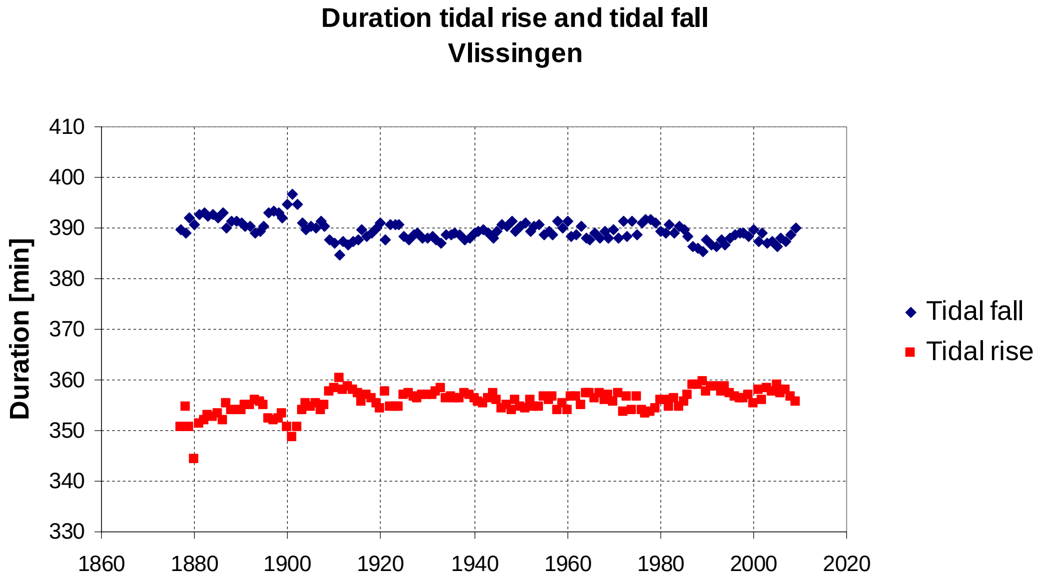



*Figure 2.29: Yearly-averaged duration of tidal rise and tidal fall in Vlissingen.*

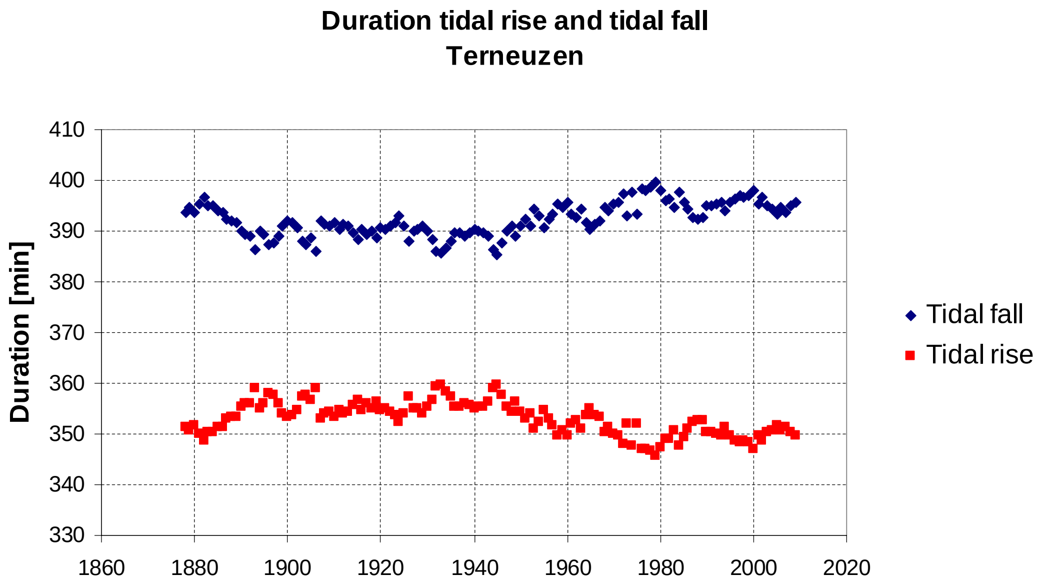



*Figure 2.30: Yearly-averaged duration of tidal rise and tidal fall in Terneuzen.*

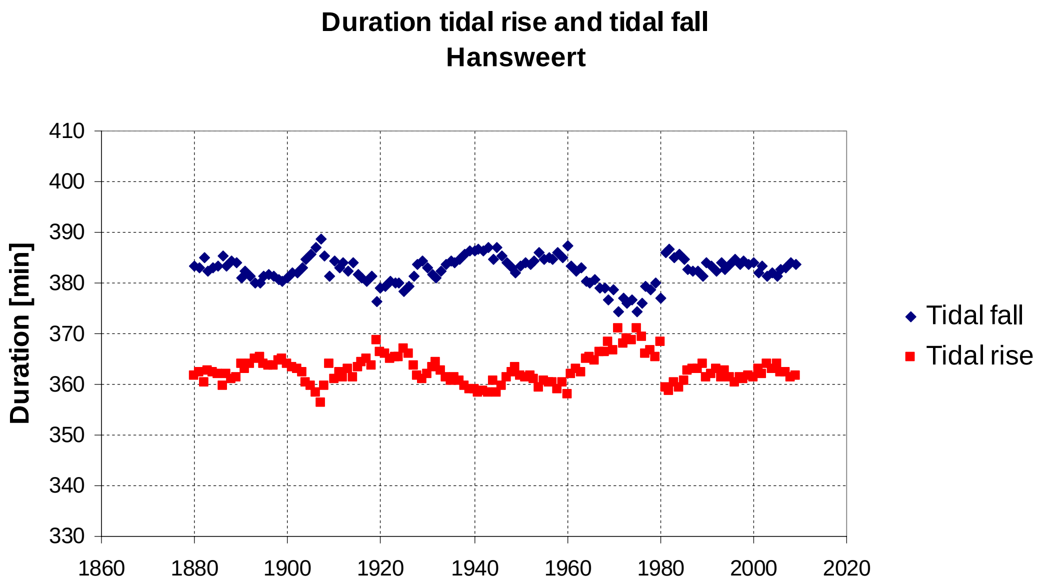



*Figure 2.31: Yearly-averaged duration of tidal rise and tidal fall in Hansweert.*

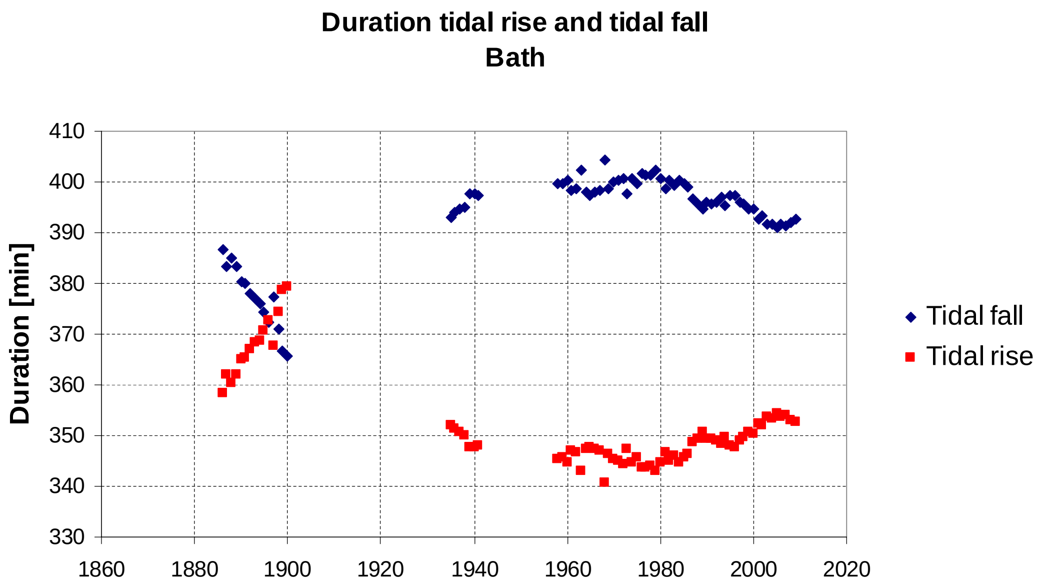



*Figure 2.32: Yearly-averaged duration of tidal rise and tidal fall in Bath.*

### 2.4.11 Extreme high and low water

Figure 2.33 shows the frequency of occurrence distribution for all high water levels measured at Vlissingen, between 1877 and 2008, with respect to NAP. This figure illustrates that there is a gradual increase in the high water level between the 20$^{th}$ and 90$^{th}$ percentiles, with less than a meter range. In contrast, the two edges, less than the 3$^{rd}$, and greater than the 97$^{th}$ percentiles, there is a large range in observed water levels.

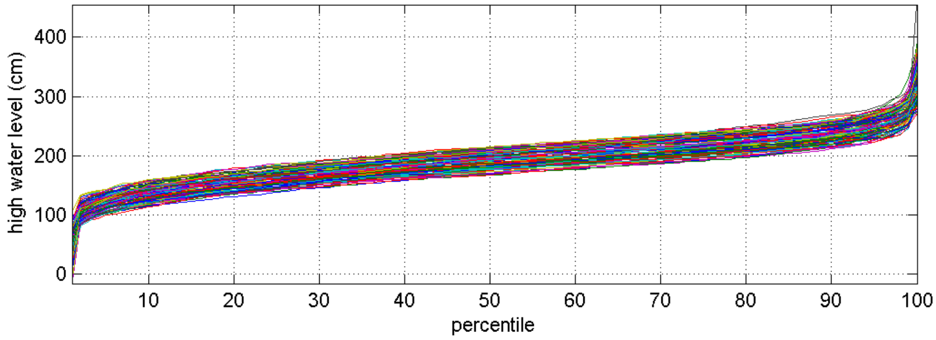



*Figure 2.33: Frequency distribution of all high water levels measured between 1877 and 2008 at Vlissingen*

From these frequency distributions, a series of plots have been made to describe the temporal evolution of the 50th (the median), 90th, 95th, 99th, and 100th (the maximum) percentile water levels for each station (Figure 2.34). A few common trends exist for all stations:

- High variability in the 100th percentile water levels
- Rapidly decreasing water level variability with decrease in the significant percentile values
- From 1900 onwards, the water level per significant percentile value is increasing in time (positive slope of each trend line)

Additionally, it can also be seen in Figure 2.34 that the high water level per significant percentile value increases when moving upstream (i.e. the maximum high water level is observed at Bath, which is nearly one meter larger than the maximum observed at Vlissingen).

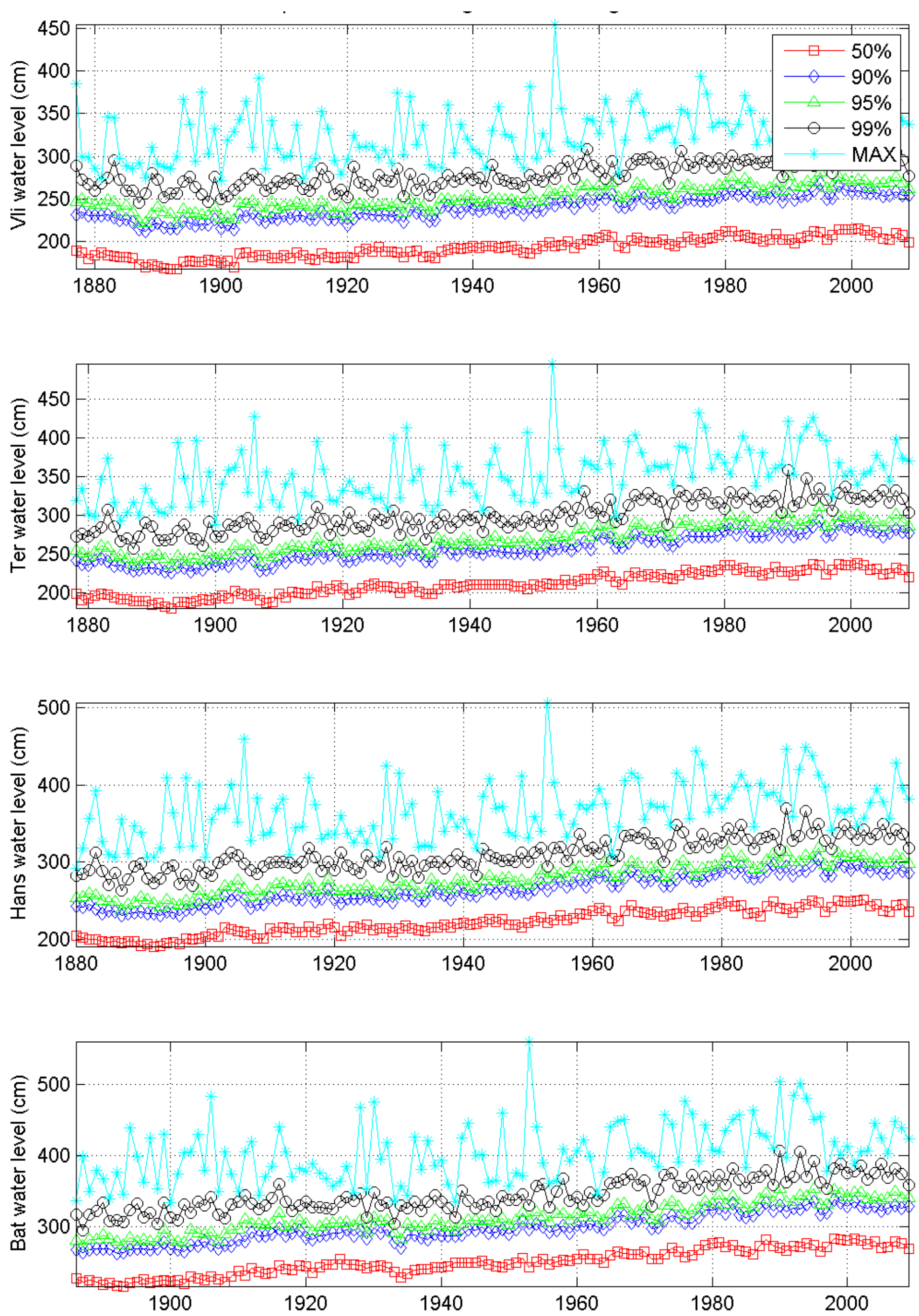



*Figure 2.34: 50th, 90th, 95th, 99th, and 100th percentile time series of the high water levels observed at Vlissingen (top panel), Hansweert (upper central panel), Terneuzen (lower central panel), and Bath (bottom panel) for the period 1877-2008.*

Similarly to the high water level analysis, a low water analysis was also performed. Similar patterns are found in the low water level frequency distributions, compared to the high water level distributions. Figure 2.35 illustrates the time series of low high water level per significant percentile value, per station. Again, there appears to be an increase in the low water levels starting from roughly 1900 and the most variability is found in the 100th percentile low water levels. In contrast to the high water level analysis, there is a smaller range in observed low water levels (i.e. roughly 300cm range for high water and 200cm range for low water). Additionally, the 18.6-cycle is visible in most of the low water level time series, whereas it was not in the high water level significant percentile time series. The 18.6-cycle is the most visible in the median low water level time series, and becomes weaker with increasing significant percentile time series.

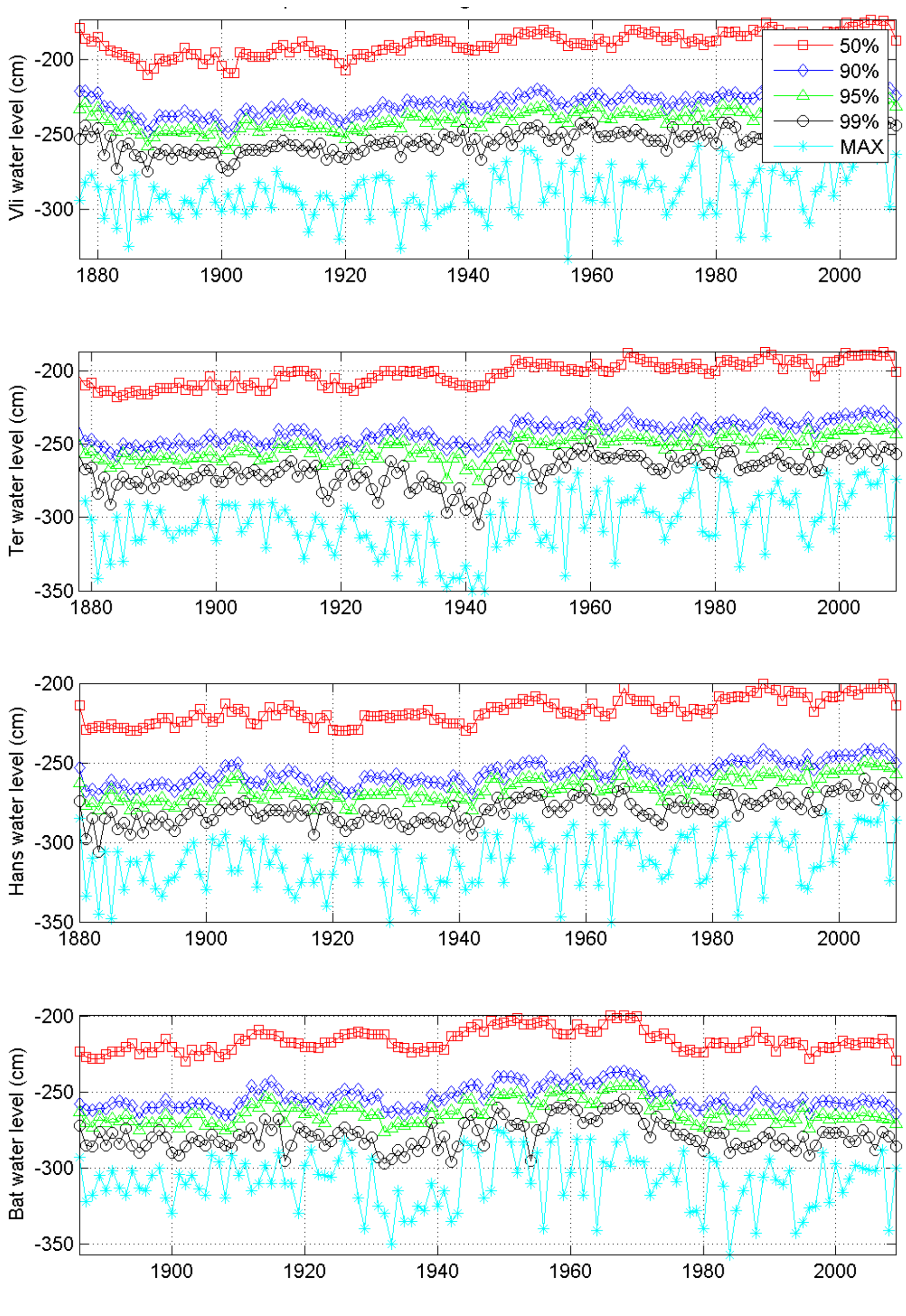



*Figure 2.35: 50th, 90th, 95th, 99th, and 100th percentile time series of the low water levels observed at Vlissingen (top panel), Hansweert (upper central panel), Terneuzen (lower central panel), and Bath (bottom panel) for the period 1877-2008.*

The slopes of the linear regressions of each of the significant percentile time series, for both high and low water levels, at each station, are shown in Figure 2.36. This figure highlights the positive trends observed in each of the time series, with the exception of the Bath maximum observed low water level signal, which has a slightly negative linear trend. It is interesting to observe that the maximum high water level slope is similar to that of the 90$^{th}$, 95$^{th}$, and 99$^{th}$ percentiles at Vlissingen (0km) and Terneuzen (20km), but deviates from these other trends farther upstream. The median high water level trend has a relatively constant offset of roughly -0.05cm/year from the 90$^{th}$-99$^{th}$ significant percentile trends. In contrast, the median low water level trend has a smaller offset from the 90$^{th}$ – 99$^{th}$ percentile trends (roughly 0.02cm/year) until Bath, where these percentile trends are approximately the same. The maximum low water level trend also differs from the high water level pattern in that it is roughly the same as the median low water level trend in Vlissingen, Terneuzen and Hansweert and strongly deviates at Bath, Overall, Figure 2.36 illustrates a maximum positive slope of the high water level time series of nearly 0.55cm/year and a maximum positive slope of the low water level time series of less than 0.2cm/year, indicating an increase in the overall tidal range, particularly when moving upstream from Vlissingen. Finally it is noted that for the extreme high waters (90$^{th}$ – 99$^{th}$ percentile) the increase relative to mean sea level rise of 0.2cm/year (see Section 2.4.12) amounts to 0.1cm/year in Vlissingen up to 0.35cm/year in the landward stations along the Western Scheldt. For the low waters a decrease of 0.05cm/year or less is observed relative to mean sea level rise except in Bath where the extreme low waters (90$^{th}$ – 99$^{th}$ percentile) show a decrease of 0.15cm/year.

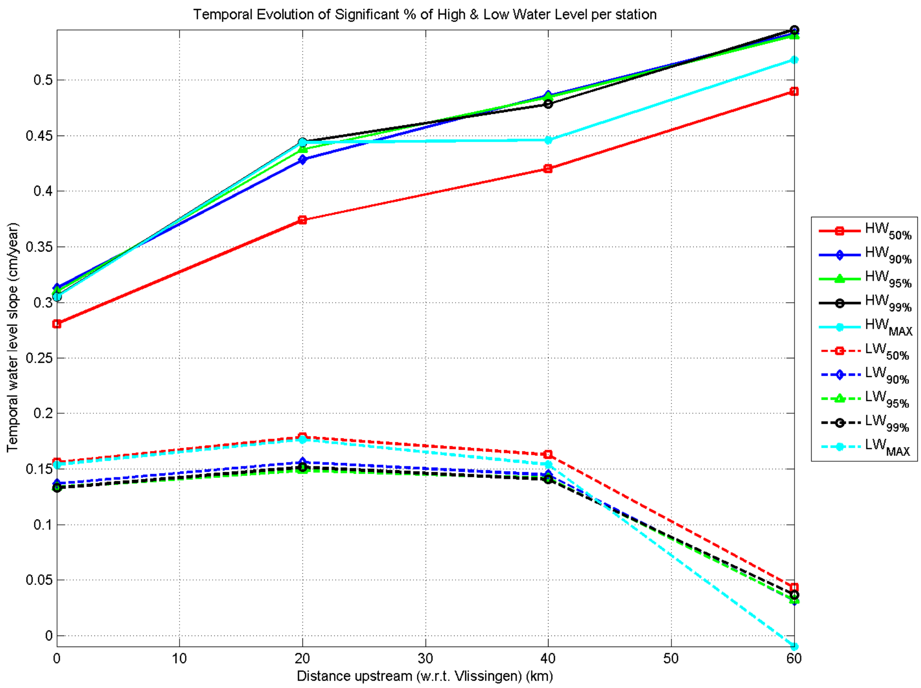



*Figure 2.36: Slope of the linear trend of each significant water level over time.*

The number of ‘high floods’ (‘hoge vloeden’), low, moderate and high storm surges per decade is given in Figure 2.37. The figure shows that the number of high floods and storm surges per decade has significantly increased since 1950: between 1880 and 1950 on average 10 floods and surges per decade and from 1950 until 2010 42 of these events per decade, which is a remarkably large difference. However, the average height of the high floods and storm surges has not changed much as shown by Figure 2.38.

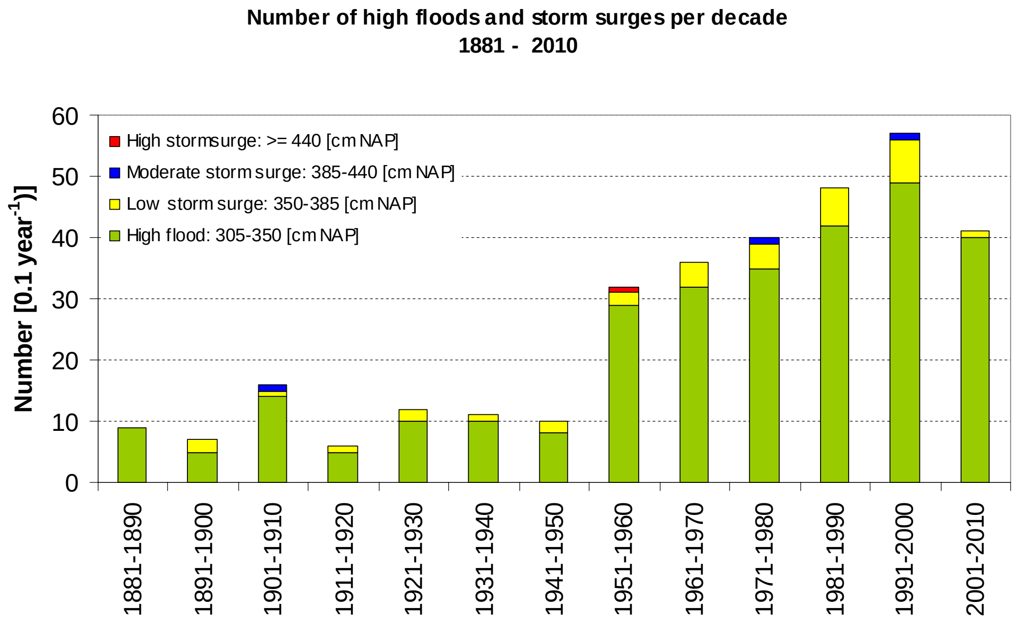



*Figure 2.37: Number of high floods, lower, moderate and high storm surges per decade in Vlissingen.*

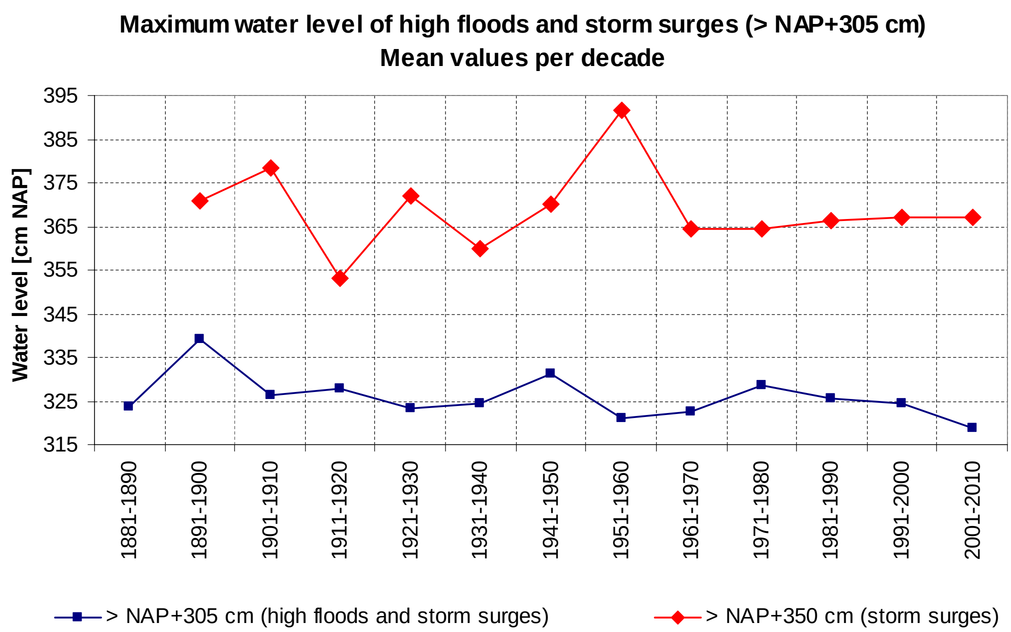



*Figure 2.38: Maximum water level of high floods and storm surges (> NAP+305 cm). Mean values per decade.*

An observation made in the second half of the last century was that high floods and storm surges occurred more in pairs than during the previous decades. Consequently, the duration of storms was relatively longer. In Figure 2.39 high floods and storm surges have been counted as one when they lasted for two or more successive tides. Between 1880 and 1950 on average 9 floods and storm surges per decade occurred (apparently only one event that lasted longer than a single tidal period) and between 1950 and 2010 approximately 32 floods and storm surges per decade (10 events with a duration longer than one tidal period). Thus also from this perspective the number of high floods and storm surges has increased since 1950.

**Number of high floods and storm surges per decade (pairs counted as 1).**
**1881 - 2010**

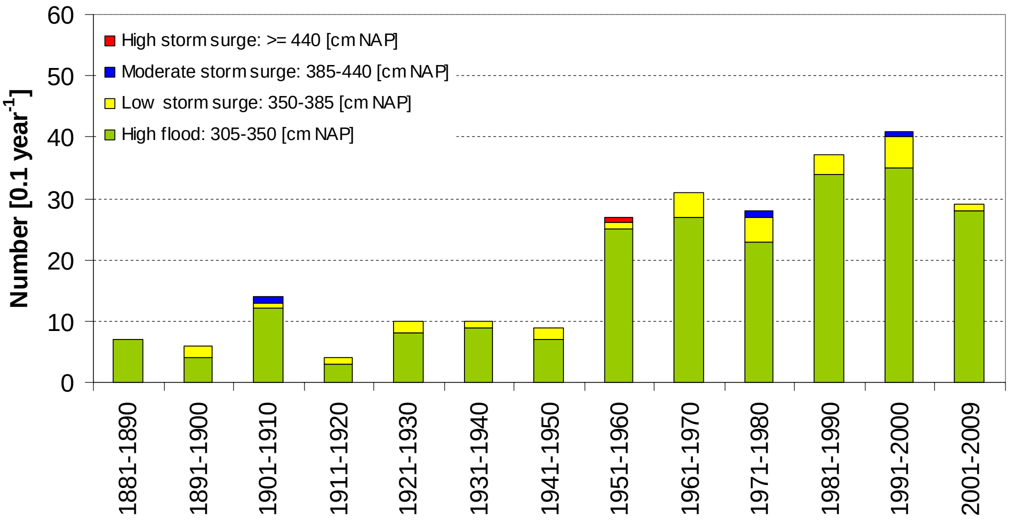



*Figure 2.39: Number of high floods, lower, moderate and high storm surges per decade in Vlissingen. Pairs of storms counted as one.*

It is concluded that since 1950 the number of extreme events in Vlissingen with maximum water levels above NAP+305 cm has increased significantly. The duration of the floods and storm surges has become larger. The more frequent occurrences of events with longer durations were not accompanied with higher surge levels.

### 2.4.12 Amplitude of the mean tide (A0)

The yearly mean tidal amplitude, per station, is shown in Figure 2.40. There is a clear positive trend in time for all stations, with the lowest and highest mean water levels being observed at Vlissingen and Bath, respectively. Over the course of approximately 100 years, the mean water level has risen roughly 20 cm at Vlissingen, which has the longest measurement record. The other three stations exhibit similar trends in time to Vlissingen. This change could indicate a rise in sea level, amongst other things such as bathymetric changes.

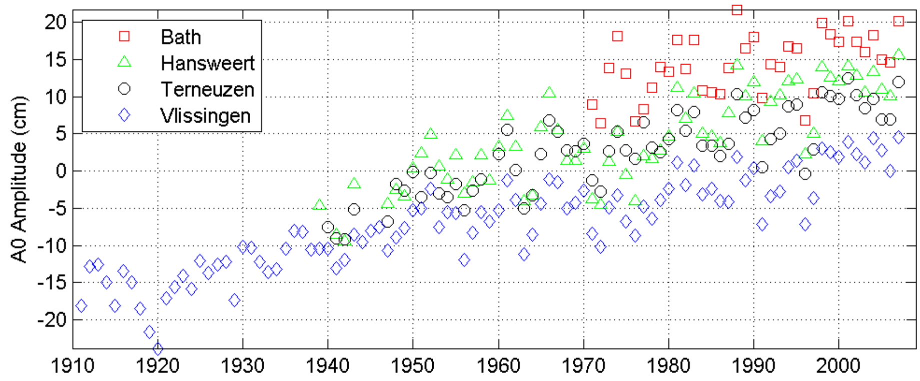



*Figure 2.40: Yearly mean tidal amplitude at Vlissingen, Terneuzen, Hansweert, and Bath*

In Figure 2.41 the slopes of the linear regression lines of the four stations are given. Also the standard deviation is indicated. Three periods are distinguished: for each station the period from start, the period 1943-2007 which is 3.5 times the 18.6 year oscillation and the period 1971-2007 (2.0 times 18.6 year) for which the length of the data record is equal for all four stations.

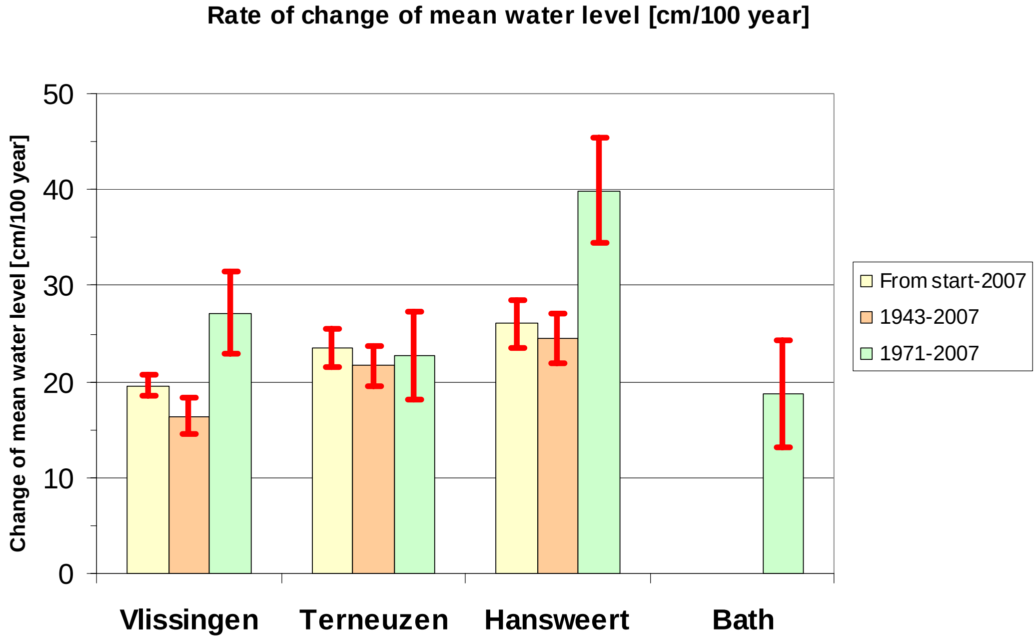



*Figure 2.41: Slopes of linear regression lines and standard deviations for yearly-averaged mean water level in cm per 100 year. Note that the analysis periods for the four stations are different for the 'From start-2007' bars (depending on data availability).*

The rate of increase of the mean water level in Vlissingen amounts 19.6 cm/100 years for the period 1911-2007, 16.4 cm/100 year for the period 1943-2007 and 27.1 cm/100 year for the period 1971-2007. Note that the standard deviation is largest for the latter period.

The rate of increase of the mean water level in Terneuzen en Hansweert for the period 'From start-2007' is somewhat larger than in Vlissingen. Differences however are small and uncertainties are large. Longitudinal variation of the mean water level is influenced by the geometry and bathymetry through the Stokes drift. Thus the evolution of the bathymetry may have affected the mean water level in the inland stations.

### 2.4.13 Amplitude analysis of the M2, M4, and M6 tides

Figure 2.42 illustrates the yearly amplitude of the M2, M4, and M6 tidal constituents at Vlissingen, Terneuzen, Hansweert, and Bath. The M2 and M4 tides exhibit positive linear trends over time, whereas the M6 tide does not exhibit any clear trend at the four stations. The M2 tidal amplitude appears to have a similar trend in time between the three downstream stations (Vlissingen to Hansweert), whereas at Bath there is a sharp increase in the M2 tidal amplitude between 1970 and 1980. This is likely due to morphological changes between Hansweert and Bath during this time frame (see section 3.4). From 1980 to present day, Bath exhibits a positive linear trend for the M2 amplitude that is similar to the three downstream stations, with the tidal amplitude increasing by roughly 0.15cm with each station, when moving upstream.

The M4 tidal amplitude exhibits an increasing linear trend until roughly 1990 for the three downstream stations. However, these linear trends differ quite dramatically between the various stations and in time. The M4 amplitude at:

- Vlissingen maintains a relatively smooth, small increase over time (~0.0003cm/year), with one slight negative deviation in the 1960's.
- Terneuzen (relatively) sharply increases between 1940 and 1970, and then oscillates around 0.12cm until approximately 1995 when the amplitude begins to decrease.
- Hansweert, which is similar to Terneuzen in that it sharply increases between 1940 and the late 1980's, but with a dip in the early 1970's, before decreasing again after 1990.
- Bath decreases between 1970 and 1980, and then oscillates around 0.12cm till present day.

Unlike the M2, and somewhat the M6 amplitudes, the M4 amplitudes at the four stations, after 1970, tend to have similar magnitudes with only the M4 at Vlissingen demonstrating any consistent pattern (increasing trend). The M6 amplitudes increase moving upstream, as does the M2 amplitudes. However, the M6 amplitudes for the three downstream stations differ by roughly 0.005cm, whereas the difference between the M6 amplitudes at Hansweert and Bath is roughly 0.03cm.

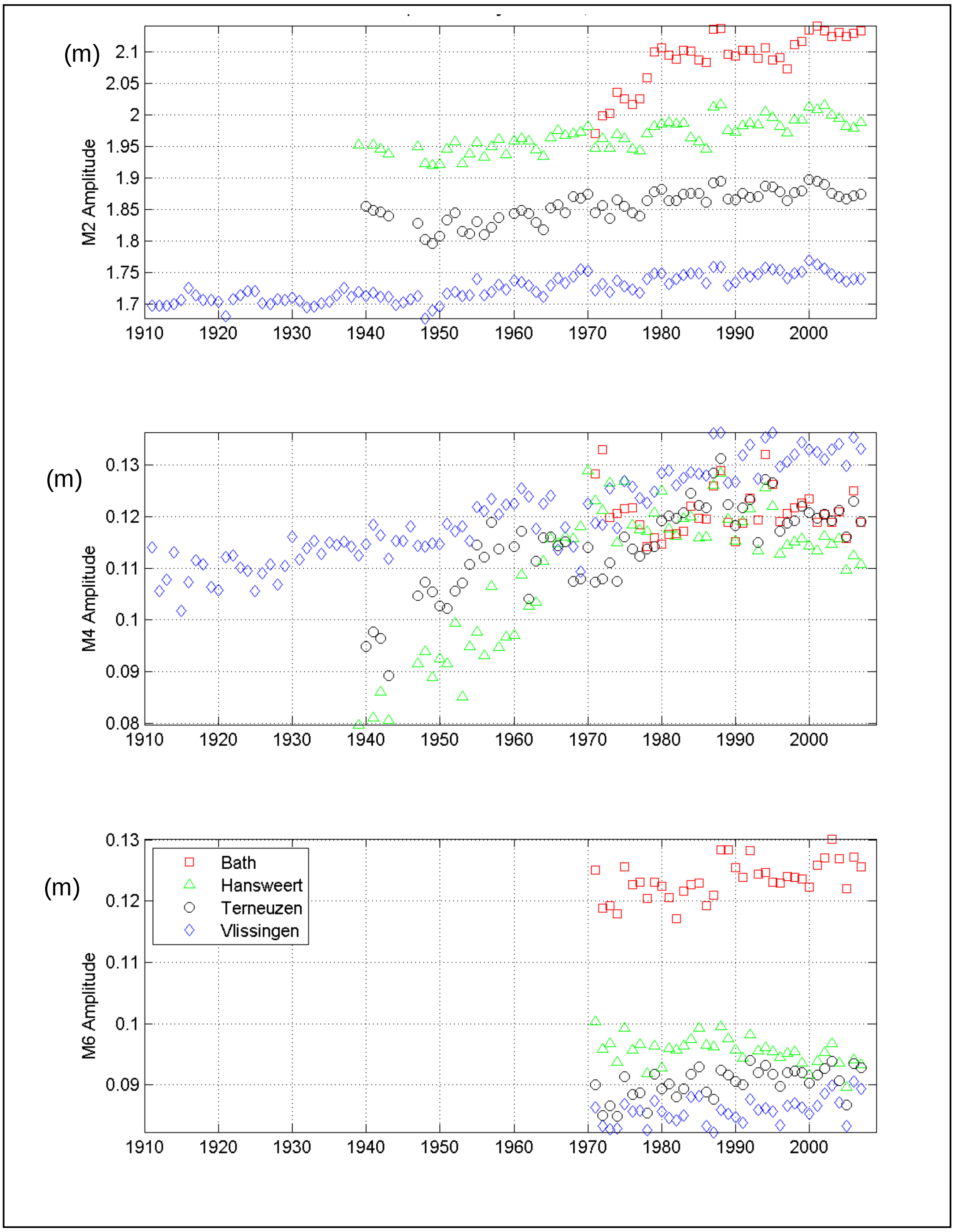



*Figure 2.42: Yearly M2, M4 and M6 tidal amplitudes at Vlissingen, Terneuzen, Hansweert, and Bath*

The vertical tide asymmetry typically refers to the distortion of the predominate semidiurnal tide, as a result of the overtides (Wang et al., 2002). A direct measure of the vertical tide asymmetry is the ratio of the M4 tidal amplitude to the M2 tidal amplitude. This measure is shown in Figure 2.43, along with the ratio of the M6 to the M2 tidal amplitudes, for each of the four stations, in time.

Up until 1970, all stations showed a M4-M2 ratio increasing in time, implying the vertical tide asymmetry was increasing. After 1970, only at Vlissingen did the vertical tide asymmetry continue to strengthen. At Terneuzen, Hansweert and Bath, the M4-M2 ratio begin to oscillate around 0.06 beginning in the 1970's, with a slight strengthening of the vertical tide asymmetry at Terneuzen in the 1980's. For the two upstream stations, there is a slight, overall decrease in the strength of the M4-M2 ratio after 1970. The M6-M2 ratio exhibits a similar pattern to the M6 tidal amplitude, in that the ratios of the three downstream stations are all similar (~0.46-0.50), where as at Bath, the ratio is much higher (~0.56-0.62). This indicates the vertical tide asymmetry is stronger at Bath, than at the three downstream stations. In time, there is:

- A slight decrease at Bath and Hansweert, and
- A slight increase at Vlissingen and Terneuzen.

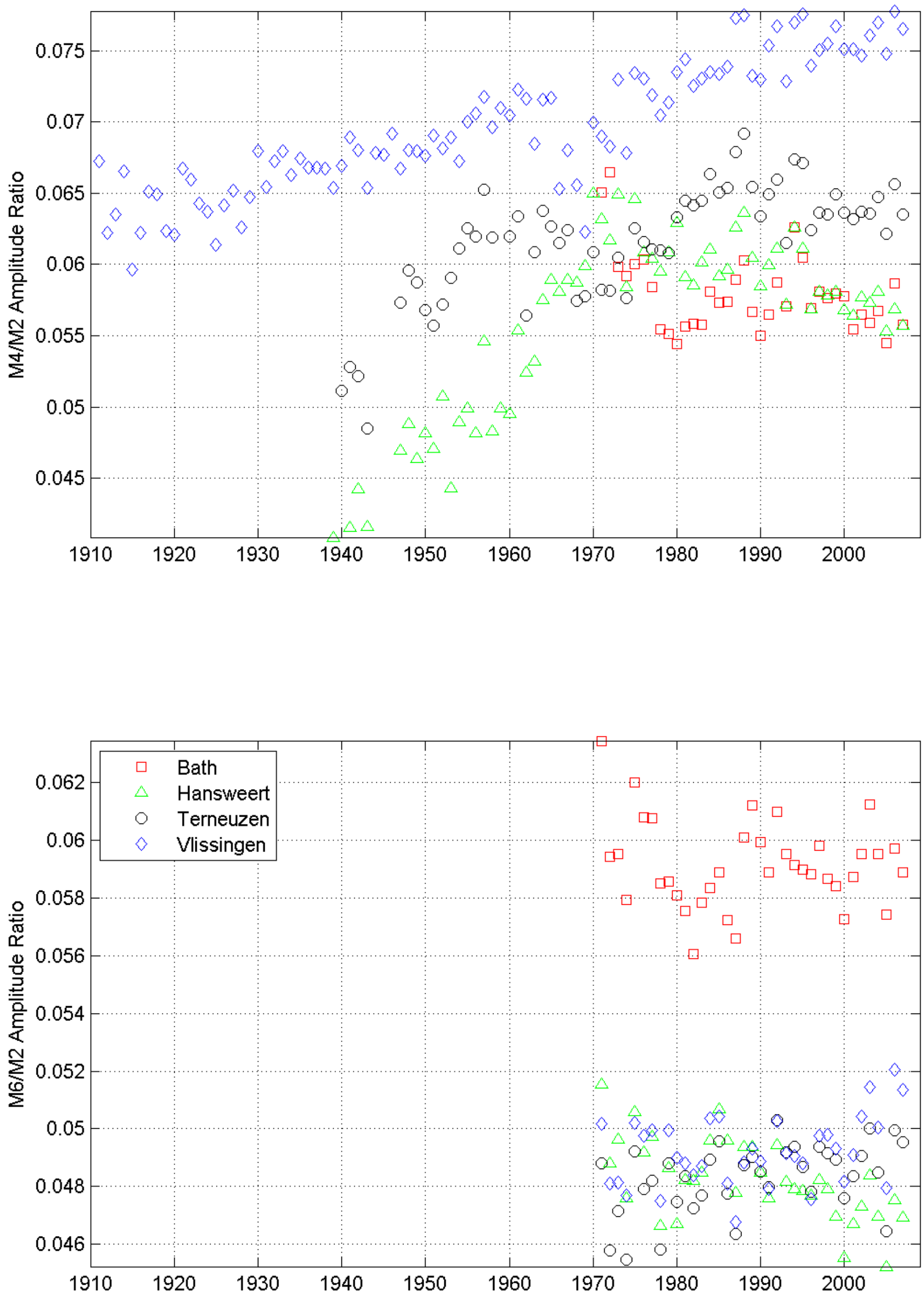



*Figure 2.43: Yearly M4/M2 and M6/M2 tidal amplitude ratios at Vlissingen, Terneuzen, Hansweert, and Bath*

### 2.4.14 Phase analysis of the M2, M4, and M6 tides

The temporal evolution of the M2, M4, and M6 phases at the four stations are shown in Figure 2.44. The M2 phases range between 60° and 95°, whereas the M4 and M6 phases range between 110°-185° and 110°-260°, respectively. For all three tidal constituents, the phases at Vlissingen and Terneuzen are the smallest, and maintain a roughly uniform separation from each other in time. For the M2 and M6 tidal constituents, the phases observed at Hansweert and Bath also maintain roughly uniform degree of separation in time. However, beginning around 1970 the phase of the M4 tide decreases at the Hansweert station and increases at Bath. Therefore, in the 1980's, the phase of the M4 tide was roughly the same at both the Hansweert and Bath stations.

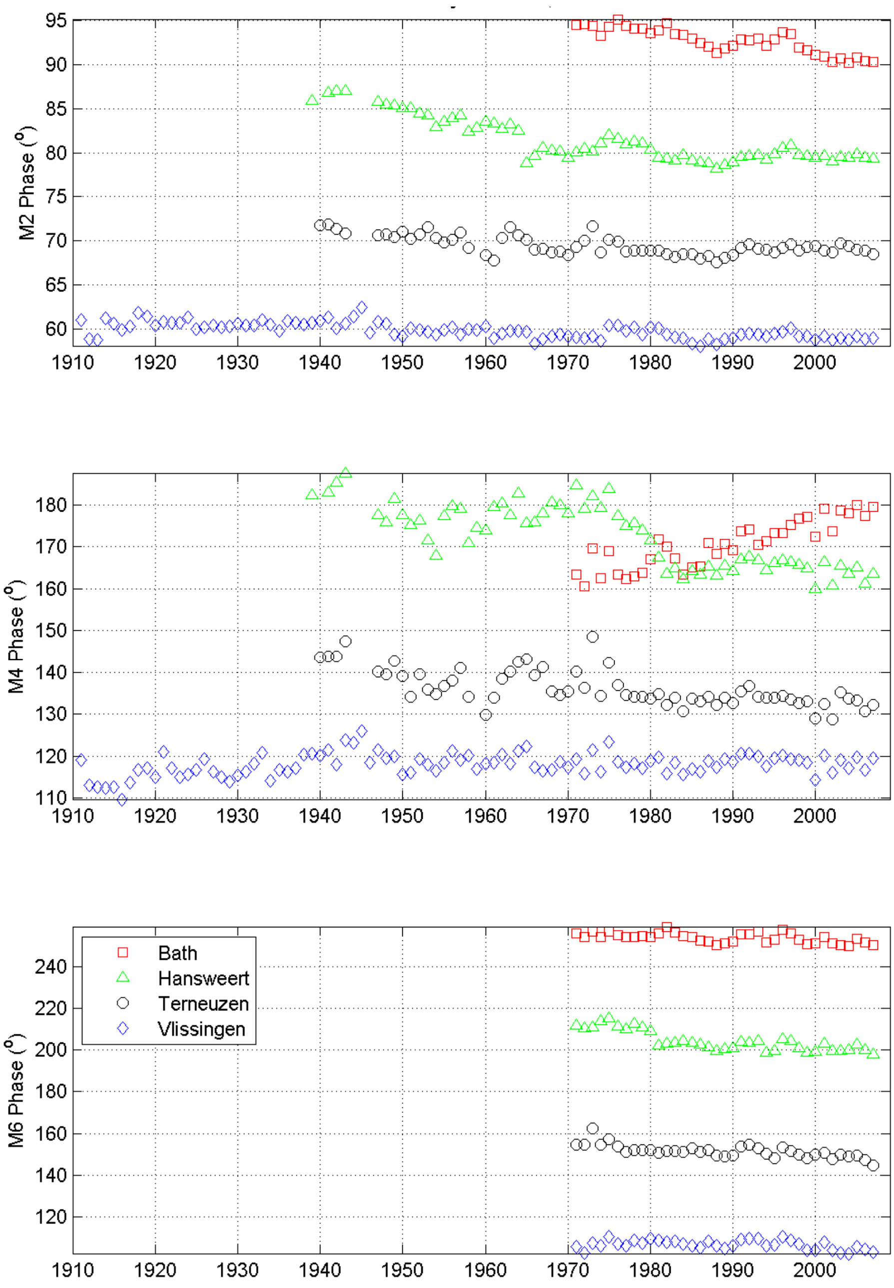
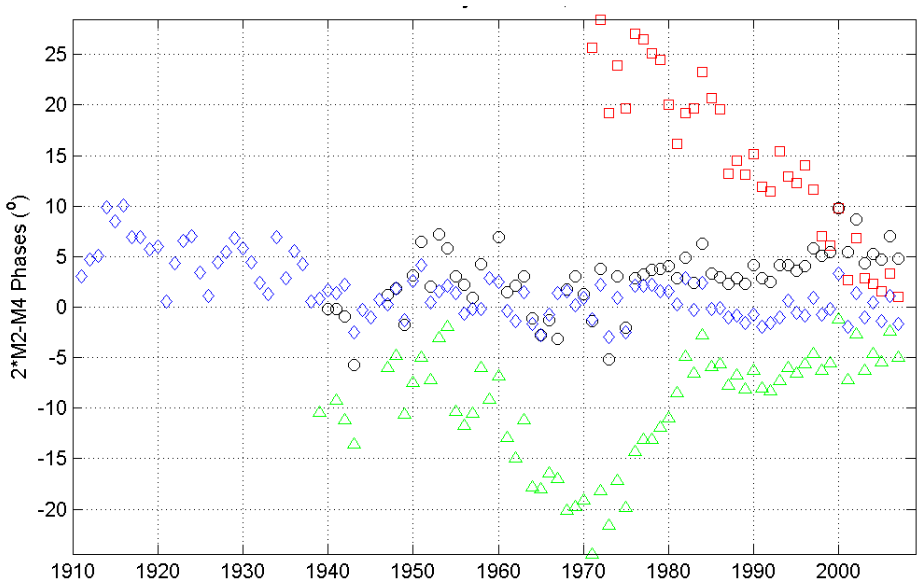



*Figure 2.44: Yearly M2, M4 and M6 tidal phases at Vlissingen, Terneuzen, Hansweert and Bath*

The nature of the vertical tide asymmetry can be defined by 2*M2-M4 phases. If this parameter is between 0°-180°, this indicates that the duration of the fall of the water level exceeds the duration of the rise, therefore that area is flood-dominate (Wang et al., 2002). If the parameter is between -180°-0°, then that area is ebb-dominate. Figure 2.45 illustrates the temporal evolution of this phase relationship, as well as 3*M2-M6 phases, at the four stations.



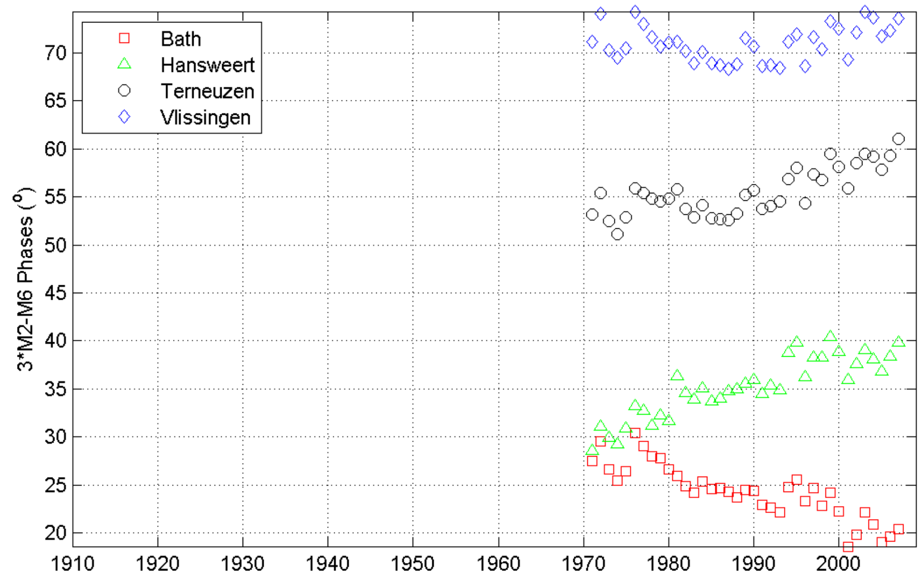




*Figure 2.45: Yearly tidal phase relationships (2*M2-M4 and 3*M2-M6) at Vlissingen, Terneuzen, Hansweert and Bath*

Since 1910, Vlissingen has gone from a flood-dominate station to a neutral station. If this trend continues, the station will become ebb-dominate. This is in contrast to Terneuzen, which has been a somewhat neutral station, oscillating back and forth between flood- and ebb-dominate, until the early 1970's. Since the 1970's, this station has exhibited a positive linear trend, indicating an increasingly flood-dominate system. The M2-to-M4 phase relationship at Bath has sharply declined since the 1970's, going from a strongly flood dominate system to a neutral state. Hansweert was weakly ebb-dominate from 1940 to 1960, and then became more strongly ebb-dominate until the mid-1970's. This shift in ebb-dominance between 1960 and 1970 at Hansweert is likely due to the large bathymetric changes occur in the central reaches of the Western Scheldt during this time period (Wang et al., 2002). From the mid-1970's to 1990, Hansweert quickly returned to weakly ebb-dominate. Since 1990, Hansweert has remained a weakly ebb-dominate system, moving towards a neutral system.

#### 2.4.15 Amplification of tidal range

The amplification is defined as the ratio of the tidal range in station 2 and the tidal range in station 1, where station 1 (e.g. Vlissingen) is at the seaward side and station 2 (e.g. Terneuzen) is at the landward side of an estuarine section. Figures 2.46–2.48 show the amplification factors for the sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath for average tides (Figure 2.46), spring tides (Figure 2.47) and neap tides (Figure 2.48). From the figures it follows that:

- Amplification for the section Vlissingen-Terneuzen varies between 1.06 and 1.10. Since about 1890 a gradual increase between Vlissingen and Terneuzen can be observed (also following from a linear regression line), however variation is large and the amplification in 2008 is not very much different from its value at the beginning of the data record. Alternatively, one could state that amplification has not much changed since 1920.
- Amplification for the section Terneuzen-Hansweert is slightly less compared with the section Vlissingen-Terneuzen varying between 1.04 and 1.08. No clear trend is present since 1900.
- For the section Hansweert-Bath amplification has gradually decreased from 1.08 around 1880 to 1.03 in 1960. This is followed by an increase up to 1.10 at present.
- For spring tide conditions the amplification is approximately 0.02 smaller (not for Hansweert-Bath) than for yearly-averaged tides whereas for neap tides the amplification is approximately 0.02 larger. This may be explained by the larger and smaller tidal velocities for respectively spring and neap tides and thus the greater and less damping due to bed friction.

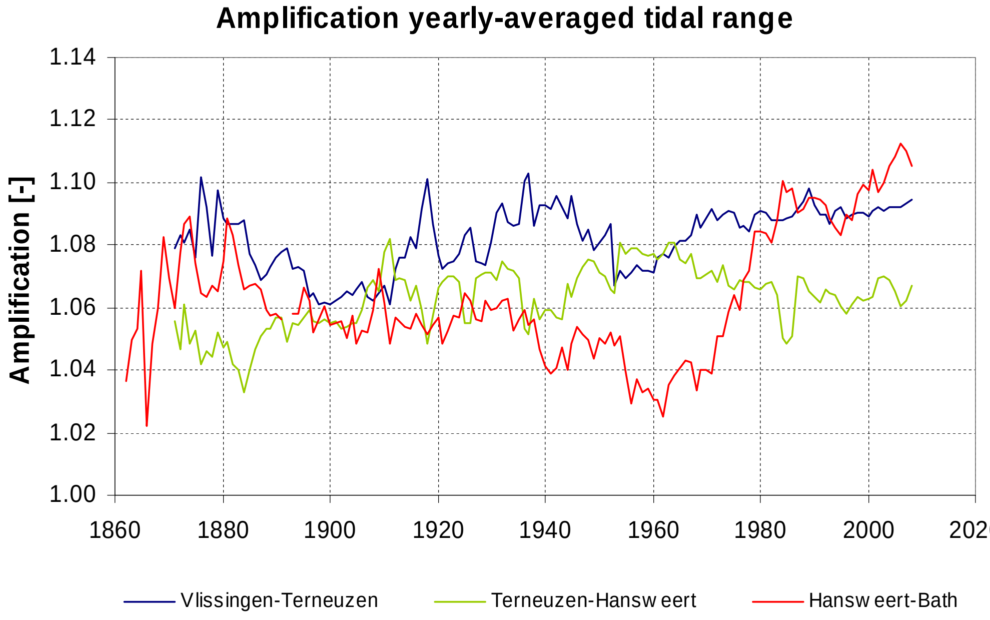



*Figure 2.46: Amplification of the tidal range for Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath for average tides.*

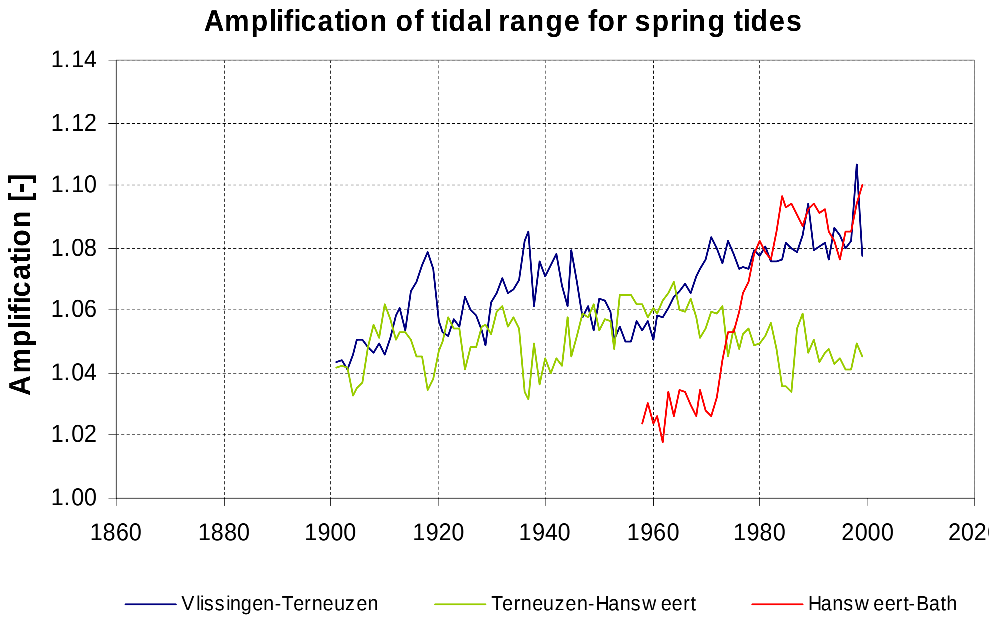



*Figure 2.47 Amplification of the tidal range for Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath for spring tides.*

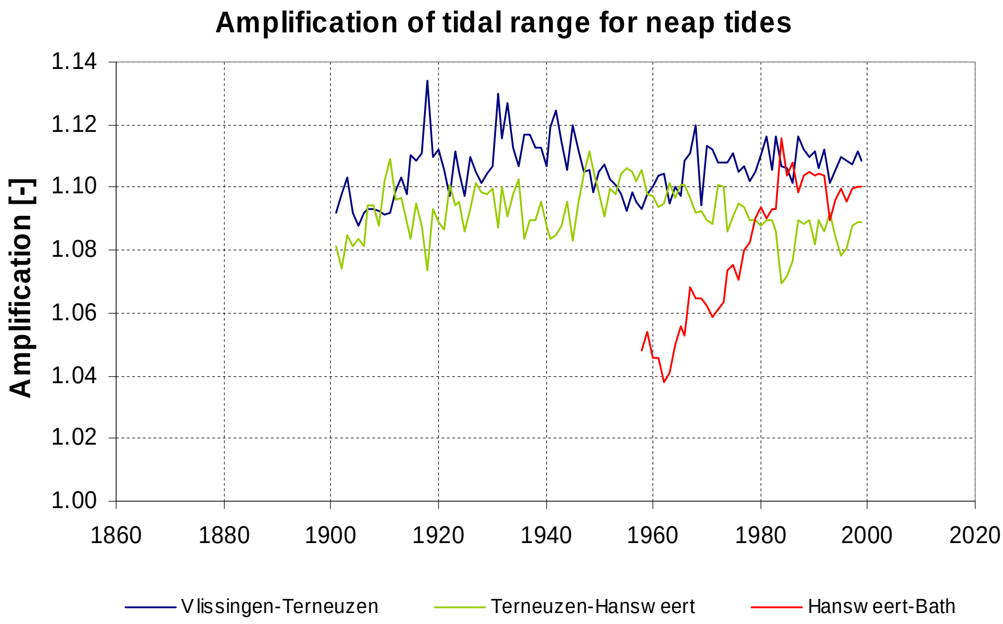



*Figure 2.48: Amplification of the tidal range for Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath for neap tides.*

The amplification of the tide is also determined for the M2-amplitude. Data on tidal components are available since 1911 for Vlissingen, since 1939/1940 for Terneuzen and Hansweert and only since 1971 for Bath. Results are similar as those presented above for the tidal range, i.e. for the sections Vlissingen-Terneuzen and Terneuzen-Hansweert no large changes and for the section Hansweert-Bath an increase between 1970 and 1985 followed by a period with first a decrease and then an increase again, Values for the amplification factor are in this case generally somewhat lower than for the tidal range, see Figure 2.49.

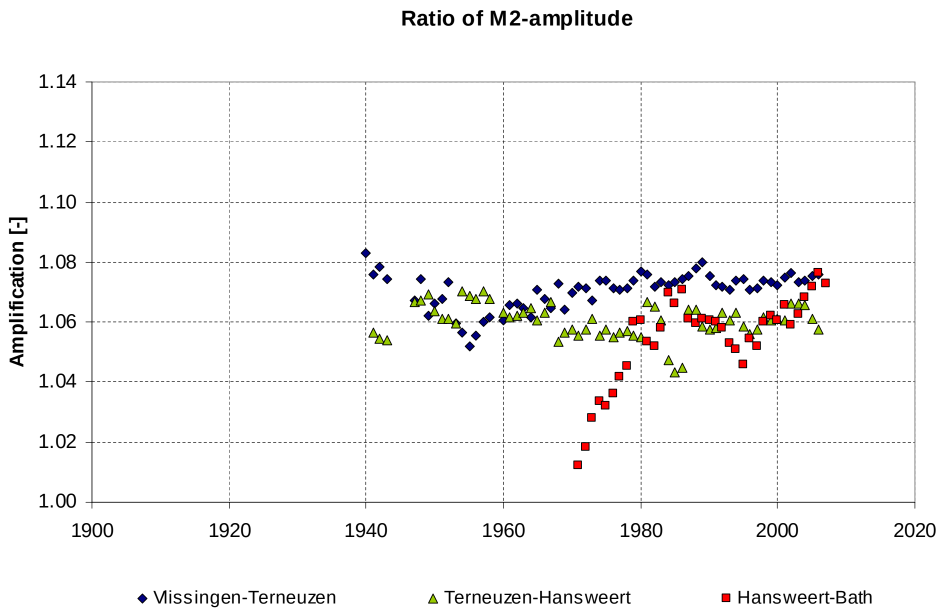



*Figure 2.49: Amplification of the M2-amplitude for Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath.*

### 2.4.16 Yearly-averaged tidal propagation time and velocity

The difference in time of high and low water in two stations is defined as the propagation time. Figures 2.50 and 2.51 present the propagation time of the tidal wave in the stations Terneuzen, Hansweert and Bath relative to Vlissingen for high and low water. From Figure 2.50 it follows that between 1900 and 1980 the propagation time of high water between Vlissingen and Terneuzen has decreased from approximately 40 min to 20 min. It implies that the propagation velocity has increased with a factor two (see hereafter). Since 1980 the propagation time seems to be constant. The same can be observed for the propagation time between Vlissingen and Hansweert and between Vlissingen and Bath, i.e. a decrease of 20 min between 1900 and 1980/1985 followed by a period until present with a constant propagation time. This indicates that the changes have mainly occurred between Vlissingen and Terneuzen. Similarly for low water the propagation time has decreased since the start of the measurements, although the changes are somewhat smaller than for high water.

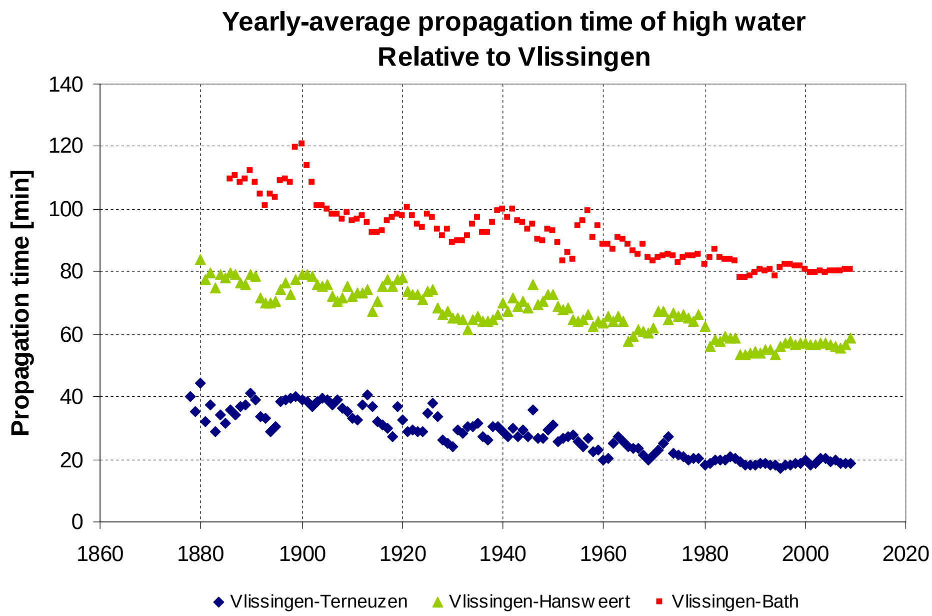



*Figure 2.50: Yearly-averaged propagation time of high water in Terneuzen, Hansweert and Bath relative to Vlissingen.*

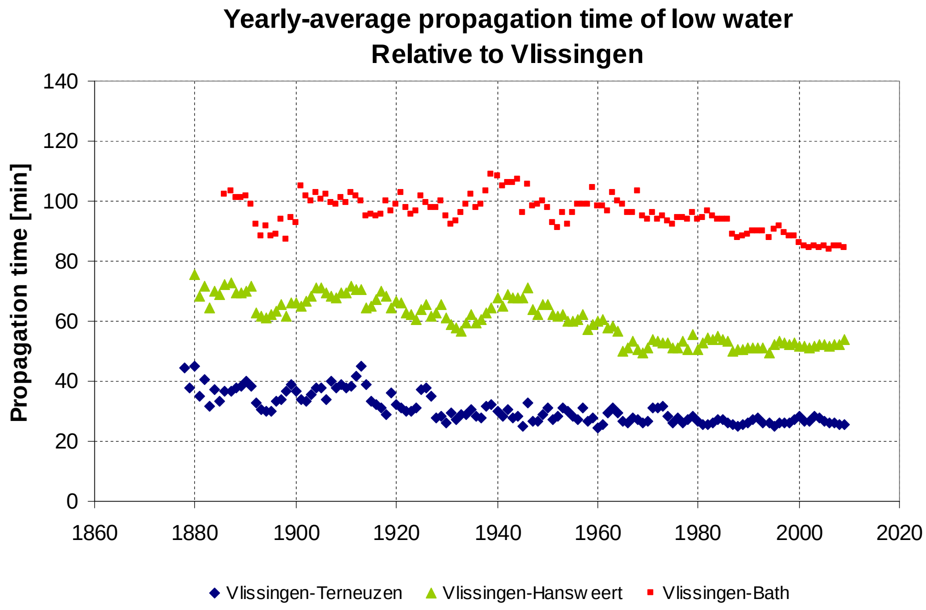



*Figure 2.51: Yearly-averaged propagation time of low water in Terneuzen, Hansweert and Bath relative to Vlissingen.*

Figure 2.52 and Table 2.15 present the changes in propagation times in Terneuzen, Hansweert and Bath relative to Vlissingen as determined by means of linear regression (in terms of minutes per century). It is remarked that the use of linear regression to indicate linear trends is not always obvious.

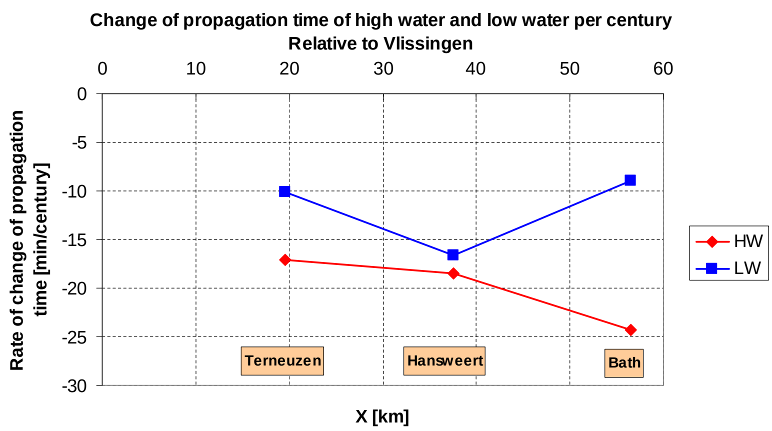



*Figure 2.52: Change of yearly-averaged propagation time per century of high and low water in Terneuzen, Hansweert and Bath relative to Vlissingen.*

*Table 2.15: Decrease of yearly-averaged propagation time of high and low water for the sections Vlissingen-Terneuzen, Vlissingen-Hansweert and Vlissingen-Bath as approximated with linear regression for the period 1878/1886-2008.*

| | | **Average change [min/century]** | | |
|---|---|---|---|---|
| **Parameter** Propagation time of: | **Tide** | **Vlissingen-Terneuzen (x = 19.5 km)** | **Vlissingen-Hansweert (x = 37.5 km)** | **Vlissingen-Bath (x = 56.5 km)** |
| high water | Average tide | -17 | -18 | -24 |
| low water | Average tide | -10 | -17 | -9 |

The actual value of the propagation time between two stations is a parameter that depends on the mutual distance between both stations. The propagation velocity is more physically related to the characteristics of the tidal wave. It is here determined from the propagation time and the distance between the stations and the value may be different for high and low water[4]. Figure 2.53 gives the yearly-averaged propagation velocity for high water as derived for the sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath. Data for Hansweert-Bath between 1901 en 1934 and between 1942 and 1957 were not considered as they were unreliable (the sum of the duration of rising and falling tide is less than 745 min). Similarly, the propagation velocity for low water is presented in Figure 2.54. From the figures it follows that:

- The propagation velocity of high water between Vlissingen and Terneuzen has increased from about 10 m/s to 18 m/s;
- Between Terneuzen and Hansweert the propagation velocity has remained constant over more than 100 years;
- Between Hansweert and Bath the propagation velocity shows large variations over the years with a tendency of an increase of 10 m/s to approximately 15 m/s.
- The propagation velocity of the low waters has changed less over the past century as compared with the high waters.
- Between Vlissingen and Terneuzen the propagation velocity of low water has increased from about 9 m/s to 12.5 m/s and between Terneuzen and Hansweert from 10 m/s to 13 m/s.
- Between Hansweert and Bath the propagation velocity of low water has decreased from about 12 m/s to 7 m/s around 1970 followed by an increase to 10 m/s at present.

4. *This definition is not straightforward as for a standing wave for instance high waters occur simultaneously within the estuary. This would result in a propagation velocity that is infinitely large. Actually there are two propagating waves in opposite direction each with a finite propagation velocity. Interference of both waves results in the aforementioned standing wave.*

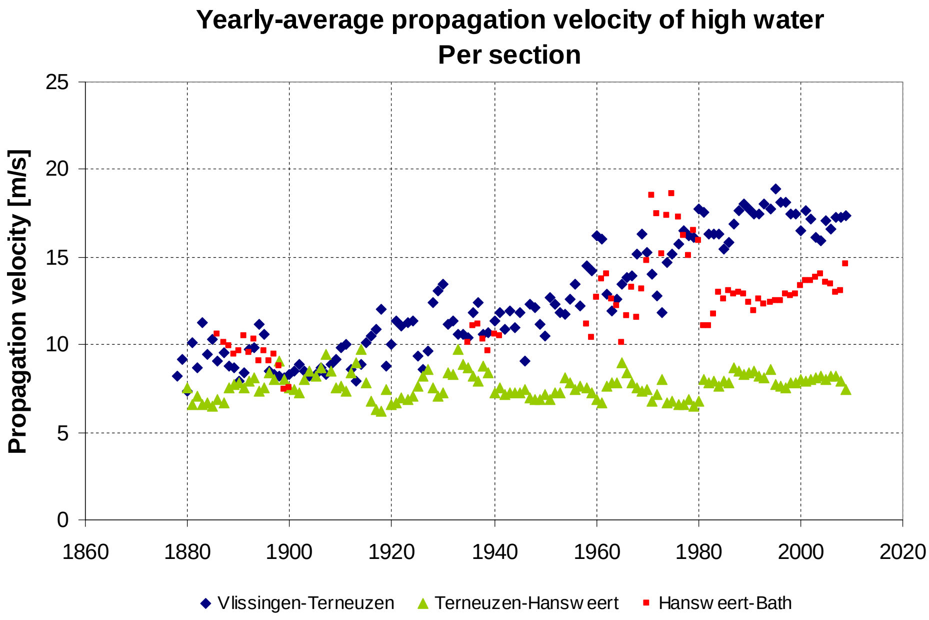



*Figure 2.53: Yearly-averaged propagation velocity of high water for the sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath.*

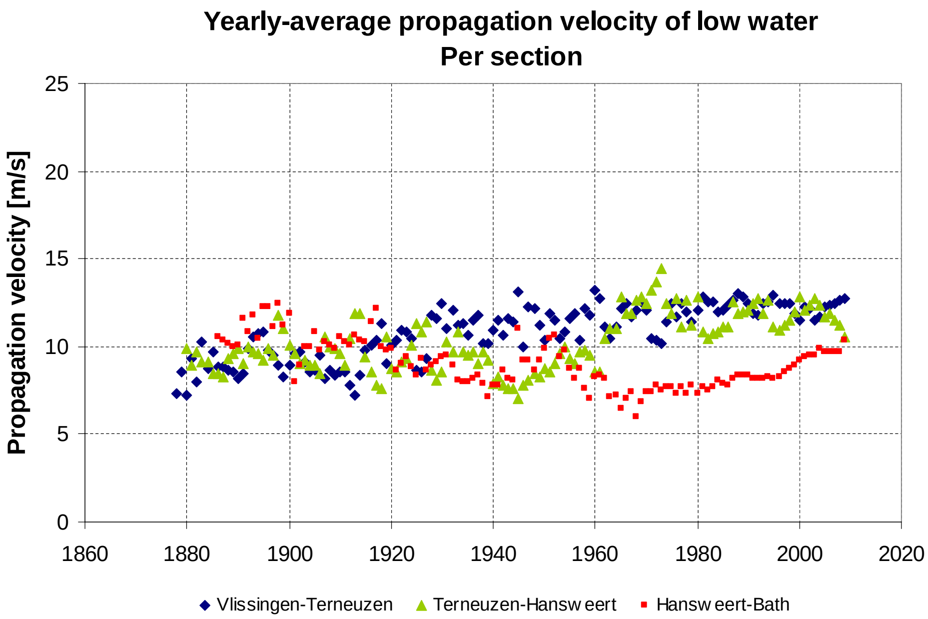



*Figure 2.54: Yearly-averaged propagation velocity of low water for the sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath.*

Figure 2.55 and Table 2.16 summarise the changes in propagation velocities for the sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath as determined by means of linear regression (in terms of m/s per century).

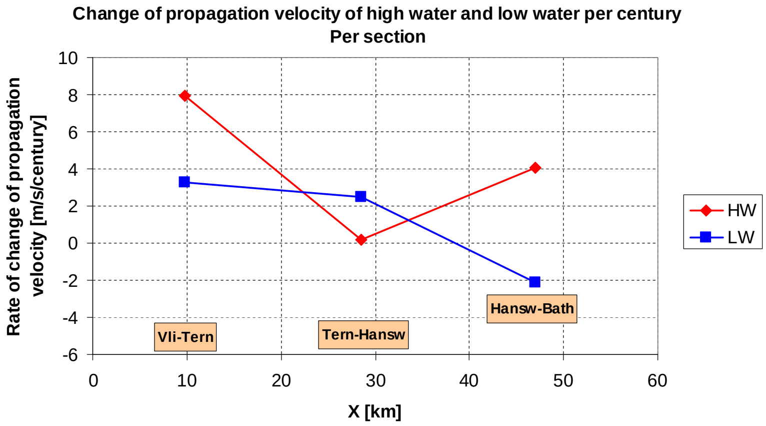



*Figure 2.55: Change of yearly-averaged propagation velocity per century of high and low water for the sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath.*

*Table 2.16: Change of yearly-averaged propagation velocity of high and low water for the sections Vlissingen-Terneuzen, Vlissingen-Hansweert and Vlissingen-Bath as approximated with linear regression for the period 1878/1886-2008.*

| | | **Average change [m/s/century]** | | |
|---|---|---|---|---|
| **Parameter** Propagation velocity of: | **Tide** | **Vlissingen-Terneuzen (x = 9.75 km) [1])** | **Terneuzen-Hansweert (x = 28.5 km) [1])** | **Hansweert-Bath (x = 47 km) [1])** |
| high water | Average tide | +8.1 | +0.2 | +2.6 |
| low water | Average tide | +3.4 | +2.8 | -2.3 |

*[1]) indicates the centre location of each section.*

Propagation velocities of the tidal wave ($c$) for the three sections are also derived from the M2-phase ($\varphi$) and the distances between the successive stations ($L$):

$$c = \frac{360\,L}{(\varphi_2 - \varphi_1)T_{M2}}$$

where $\varphi_2$ is the M2-phase in the landward station of a section, $\varphi_1$ the M2-phase in the seaward station [degrees] and T is the period of the M2 tidal constituent [s] and equivalent to 12 hr 25 min. The so-called phase velocity can be considered as some average of the propagation velocities for the high and low water as presented before. The section lengths have been based on the distances between the stations along the main channel (taken from Google Earth). This results in lengths of 19.5 km for Vlissingen-Terneuzen, 18.0 km for Terneuzen-Hansweert and 19.0 km for Hansweert-Bath. Results are given in Figure 2.56.

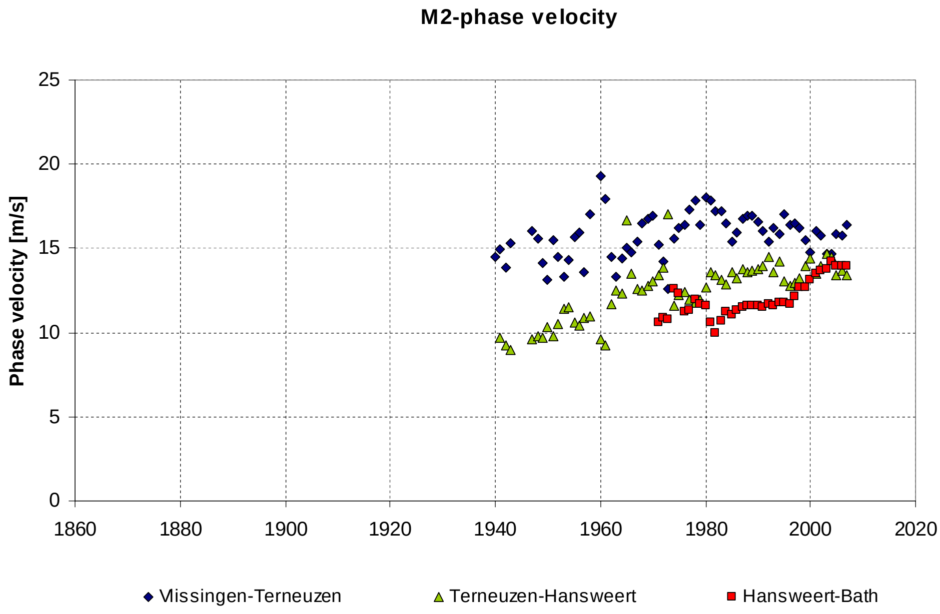



*Figure 2.56: Yearly-averaged M2 phase velocity for the sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath.*

The phase velocity for the section Vlissingen-Terneuzen has been approximately constant. There might have been a slight increase between 1940 and 1980 although scatter is large. Since 1980 the phase velocity has slightly reduced to 16 m/s in 2007, which is about the average of the propagation velocities of the high and low water. Before 1970 the scatter is relatively large which may be caused by the low sampling frequency at that time (once per 3 hour). The phase velocity for the section Terneuzen-Hansweert shows an increasing trend between 1940 and 1970 from 10 m/s to 14 m/s. Since then the phase velocity has been approximately constant and equal to the average of the high and low water propagation velocities. The increase between 1940 and 1970 mainly reflects the increase of the low water propagation velocity. Between Hansweert and Bath the phase velocity has increased from 11-12 m/s before 1995 to 14 m/s in 2007. As such the phase velocities for the three sections have become almost the same varying between 14 and 16 m/s.

### 2.4.17 M4/M2 and M6/M2 amplitude ratio (ebb-flood dominance)

Figure 2.57 illustrates that prior to 1965 the downstream vertical tidal asymmetry was stronger than upstream. From roughly 1965 to 1975, there was a switch in this dominance to the upstream station between Bath and Hansweert, as well as between Hansweert and Terneuzen. From 1975 until the mid-1990's Bath had a smaller vertical tidal asymmetry than Hansweert. Post the mid-1990's, Bath and Hansweert have roughly the same vertical tidal asymmetry. In contrast, after 1975, the vertical asymmetry at Terneuzen continues to strengthen compared to that at Hansweert resulting in the negative linear trend in Figure 2.57.

Between 1940 and 2008, Vlissingen has a larger vertical tidal asymmetry than Terneuzen, but the degree of this ratio oscillates in time between roughly 0.75 and 0.95. For the last 20 years, there is a negative linear trend, indicating the vertical tidal asymmetry at Vlissingen is strengthening compared to that at Terneuzen.

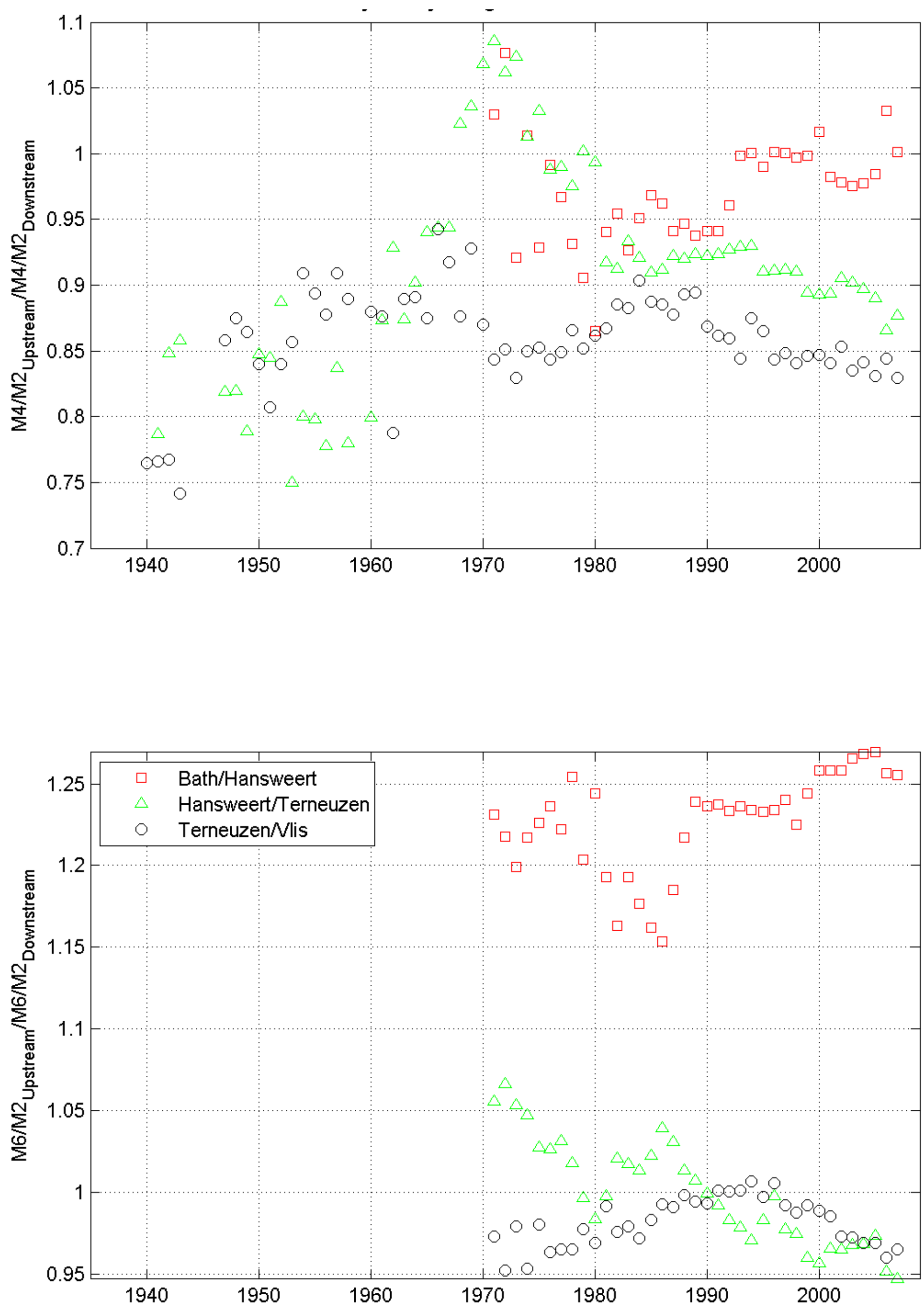



*Figure 2.57: Yearly M4/M2 and M6/M2 tidal amplitude ratios between upstream and downstream stations (i.e. Hansweert and Bath)*

### 2.4.18 2M2-M4 and 3M2-M6 phase difference (ebb-flood dominance)

Figure 2.58 illustrates the relationship of the tidal dominance between two stations. In the upper panel, it can be seen that the difference in vertical tide dominance is quickly decreasing between Bath and Hansweert, to point that they are nearly equal in 2008. Comparatively, the vertical tidal dominance between Terneuzen and Vlissingen was roughly equal between 1940 and 1975, and since has continued to steadily increase. From 1940 to 1950, the vertical tide dominance between Hansweert and Terneuzen remained around -10°. From 1950 to 1970, this difference increased by an additional 10°. From 1970 to roughly 1980, this difference returns to only 10° in total, and since remained around this level. These changes in the vertical tide dominance between Hansweert and Terneuzen are mainly forced by the changes observed in the M4 and M2 components at Hansweert.

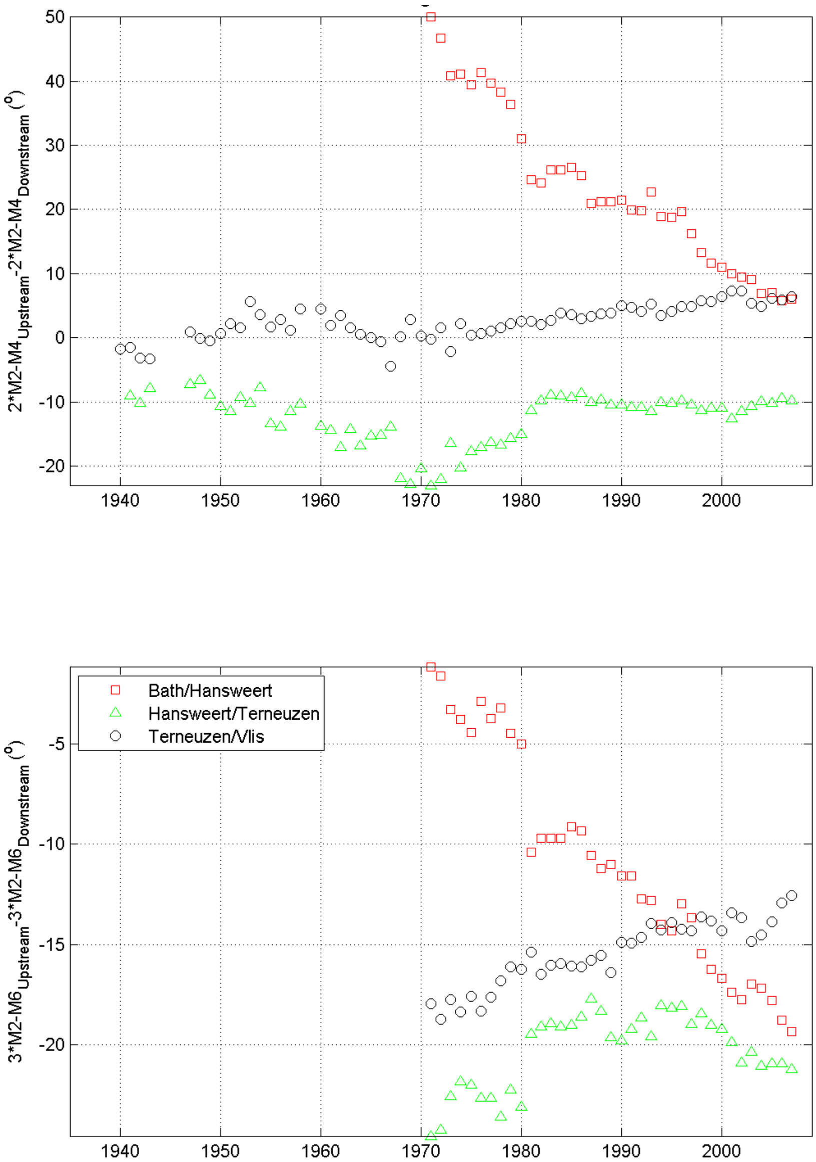



*Figure 2.58: Yearly M2, M4 and M6 tidal phase relationship (2*M2-M4 and 3*M2-M6) differences between upstream stations and downstream station (i.e. Bath and Hansweert)*

Based upon the M2 phase information for each of the stations, in time, the propagation time of this wave can be determined between stations. Figure 2.59 shows the temporal evolution of the propagation time of the M2 wave between successive stations, as well as relative to Vlissingen. Between all stations, with the exception of Vlissingen to Terneuzen, there is a negative linear trend in time, indicating a decrease in the propagation time, and thus, an increase in the propagation speed of the M2 wave.

There is approximately 20km between each successive station. However, the propagation time between these stations varies by more than 5 minutes prior to the mid-1990's. This figure implies that the channels lengths between the successive stations are becoming more uniform, resulting in the convergence of the propagation time between each river stretch. The decrease in the propagation speeds is likely linked to the channel deepening and reduction of the intertidal regions.

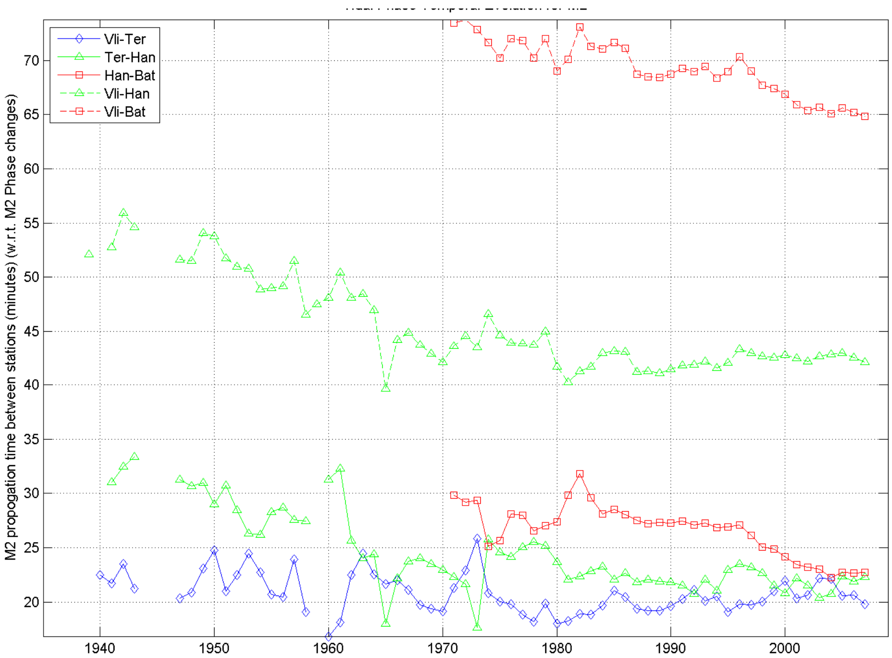



*Figure 2.59: Yearly M2 propagation time between successive stations, as well as upstream stations and Vlissingen*

## 2.5 Evolution of tidal discharges

This section presents the tidal volumes derived from the discharge measurements for the total cross-sections (Figure 2.60) as well as for the individual main and secondary channels (Figure 2.62). Results are given on a full scale of the vertical axes. For convenience Figure 2.7 of Section 2.3, showing the transects, is repeated hereafter.

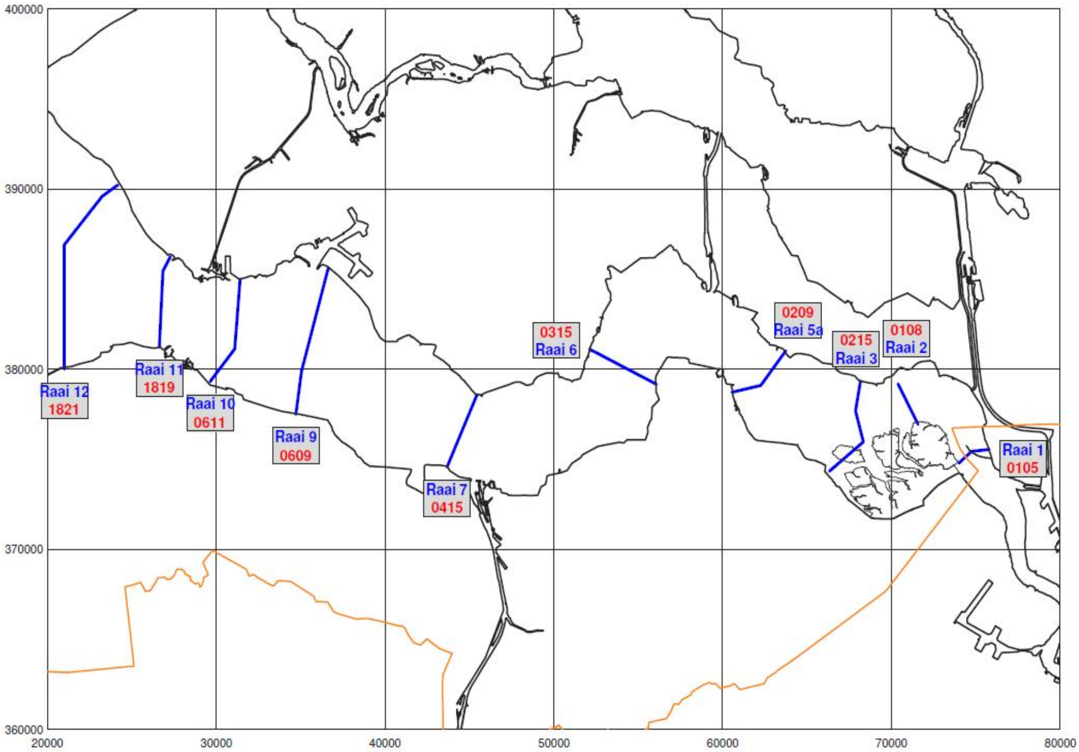
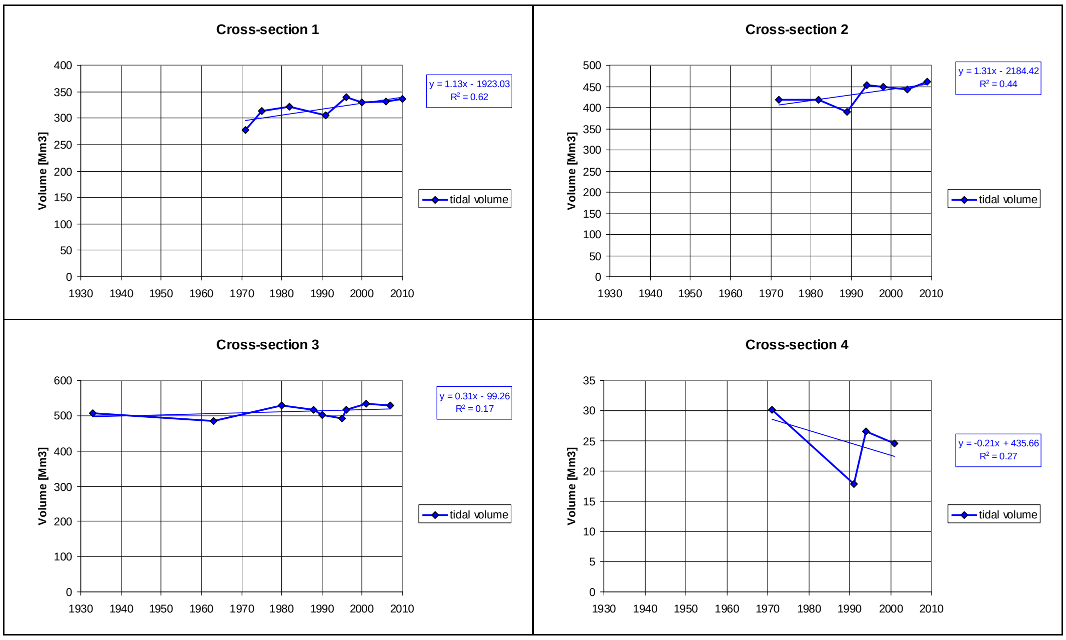



*Figure 2.7: Transects for discharge measurements along the Western Scheldt (Rijkswaterstaat, 2011). Transect 14 is in the ebb tidal delta.*



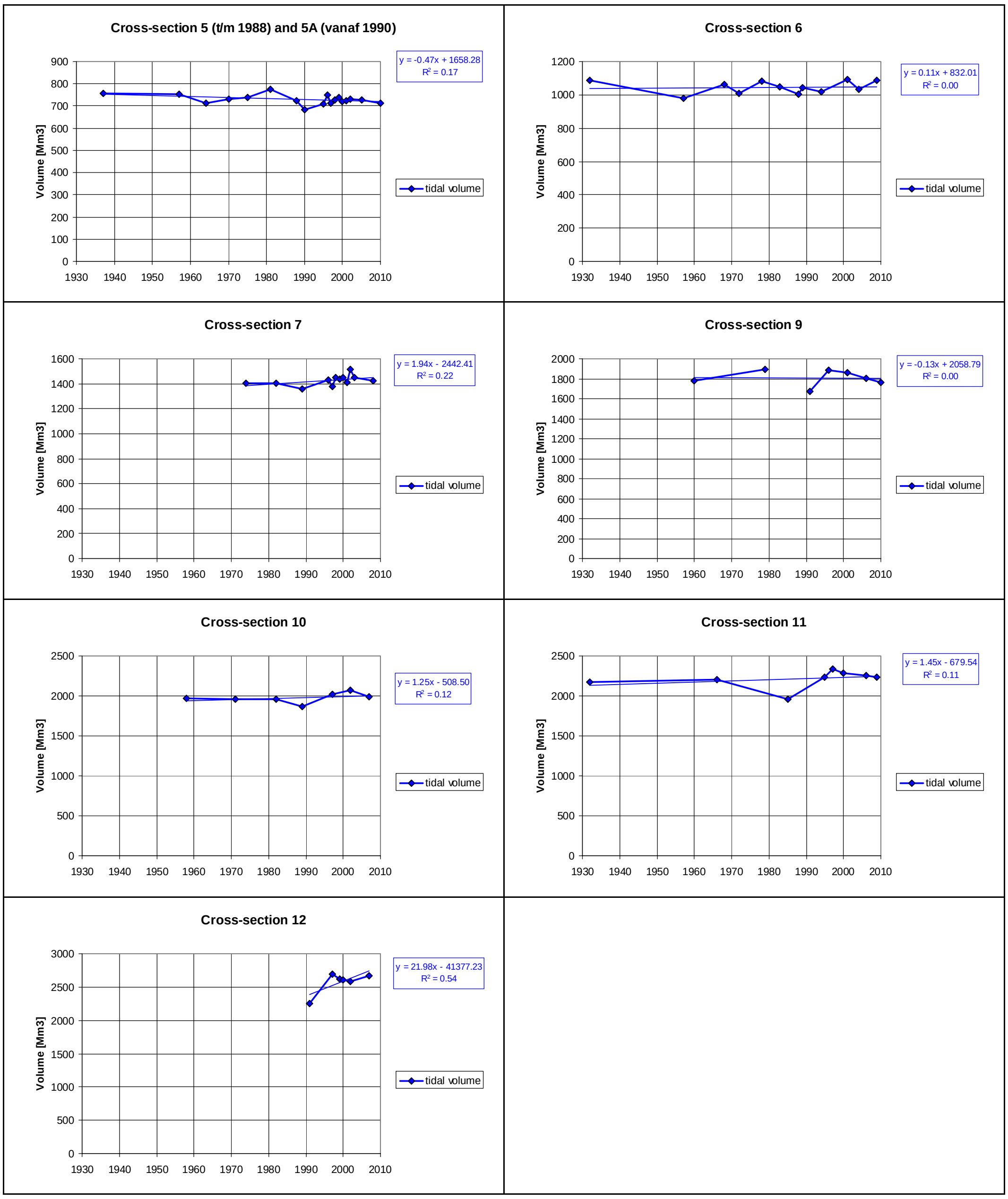



*Figure 2.60: Tidal volumes for the total cross-sections.*

In all cross-sections, except 5/5A and 9, the tidal volume shows a positive slope indicating an increase in time[5]. However, scatter is relatively large compared to the linear trend as indicated by the low regression coefficients. In cross-sections 1 and 2 the increase of the tidal volume with 10-15% over 40 years has been most pronounced. Also the tidal volumes in cross-sections 12 and 14 increase but definite conclusions are hampered by the (still) short observation period. Figure 2.61 presents the relative changes of the tidal volume in cross-sections 1 and 2 versus the relative change of the tidal range in the nearby water level station Bath. Changes are computed relative to 1971 and 1972 being the first year in the records of both cross-sections.

[5] *In 1990 cross-section 5 was relocated to cross-section 5A slightly eastward of the former section.*

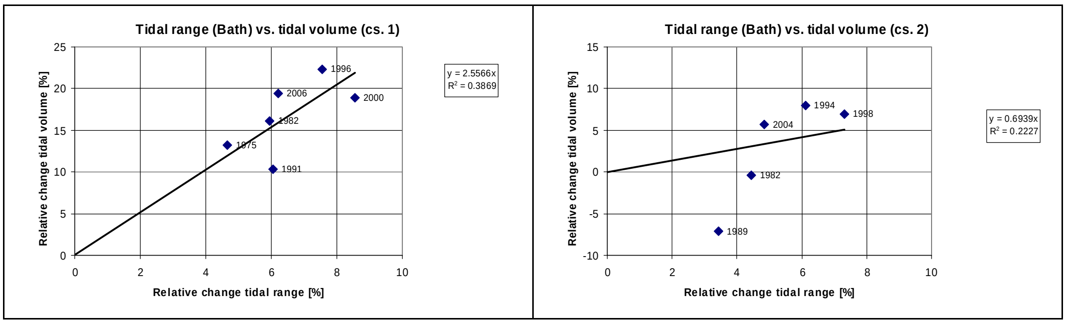
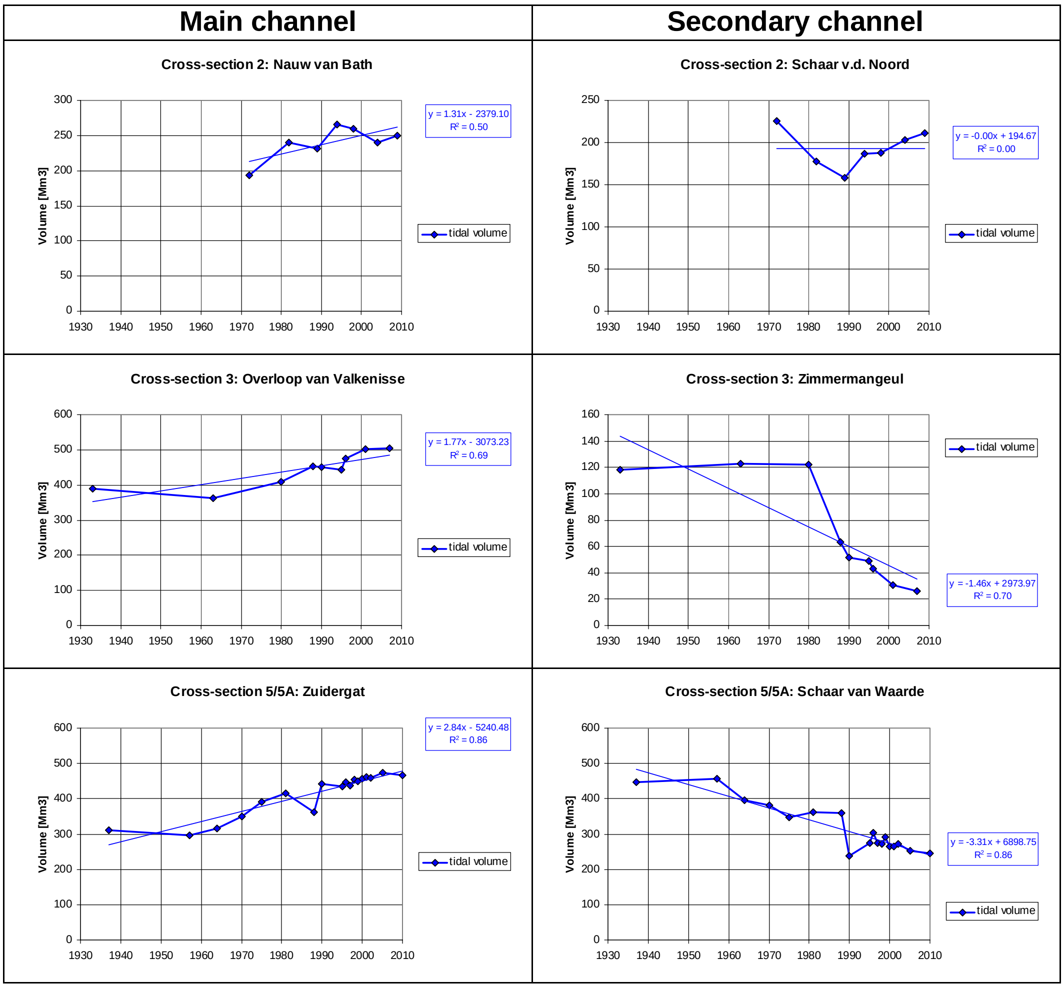


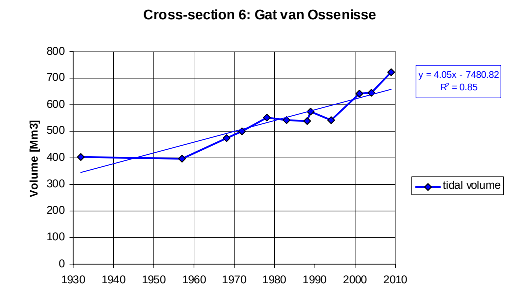

*Figure 2.61: Relative change tidal volume in cross-sections 1 (left) and 2 (right) versus relative change tidal range in Bath.*

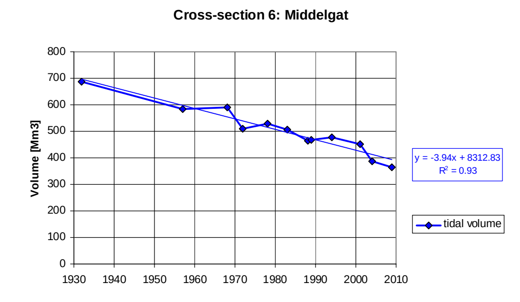
Figure 2.61 indicates that there is no clear correlation between both quantities although this would be expected. Neither in the other cross-sections there is a clear agreement between changes of tidal range and tidal volume. Further analysis is needed.

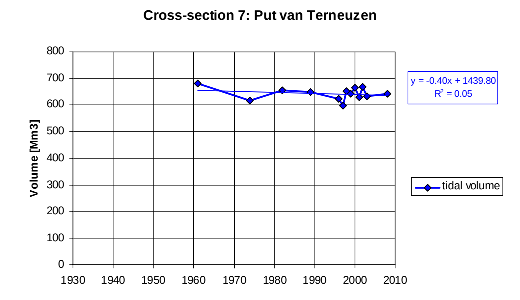
Figure 2.62 gives the tidal volumes for the main and secondary channels separately.

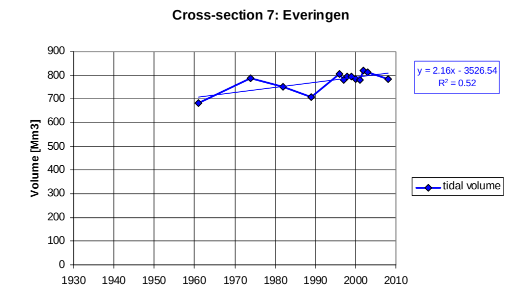


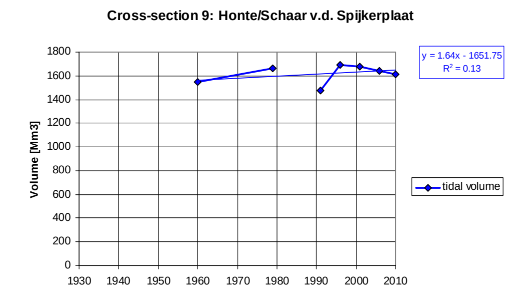
| Main channel | Secondary channel |
|---|---|

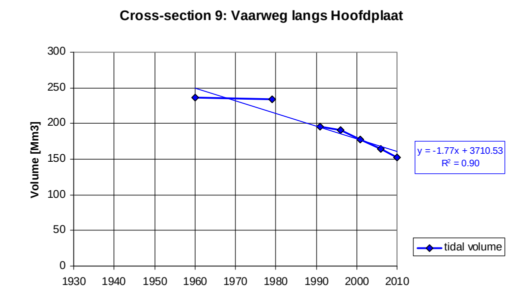


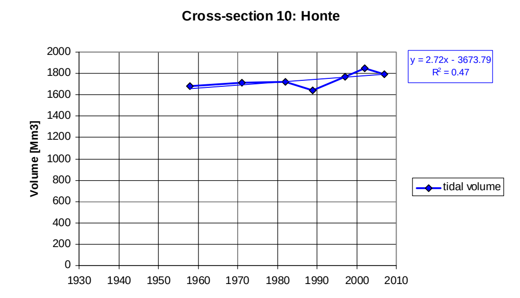



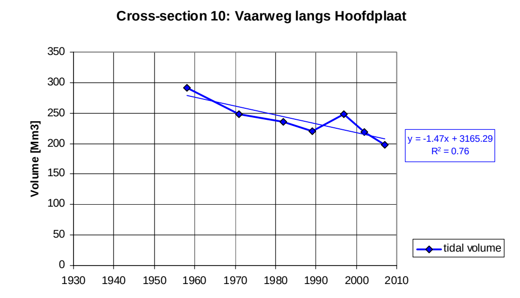



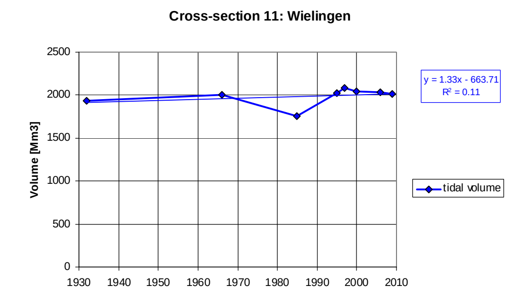



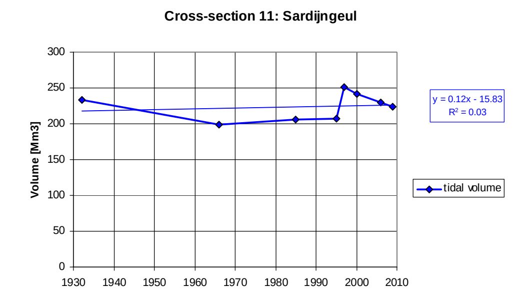



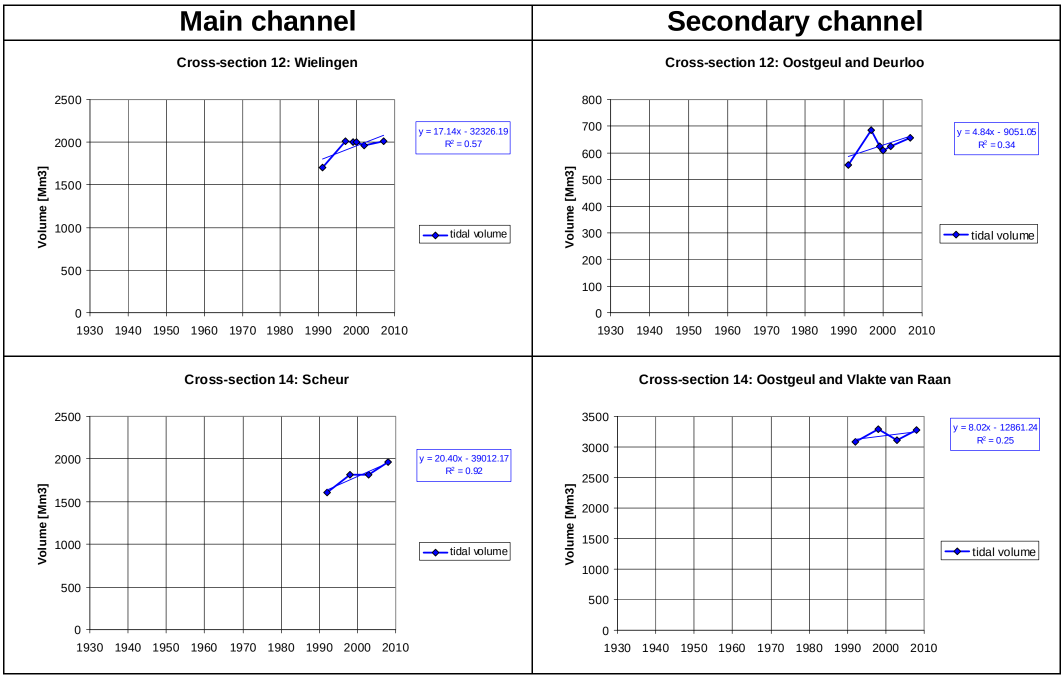



*Figure 2.62: Tidal volumes for the main channel (left) and secondary channel (right) in the transects along the Western Scheldt.*

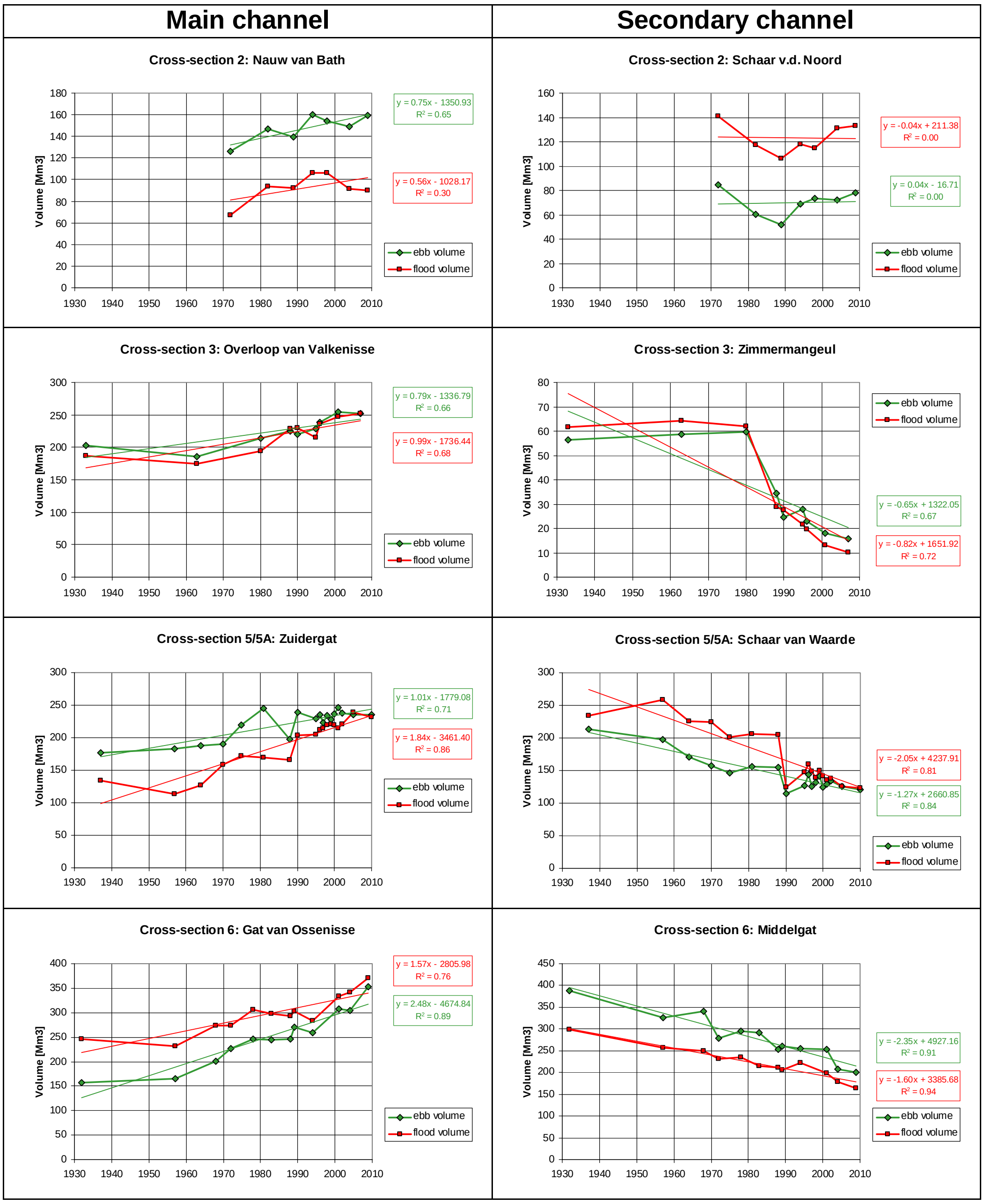
The tidal volume in the main channel Nauw van Bath has increased since 1970, whereas the tidal volume in the secondary channel Schaar v.d. Noord has been more or less constant with large variations. Similarly, in the Overloop van Valkenisse the tidal volume has increased since 1960. From 1980 onwards the secondary channel Zimmermangeul shows a sharp decline in tidal volume. In cross-section 5/5A both channels show an opposite behaviour with since 1960 an increase of the tidal volume in the main channel (Zuidergat) at the expense of the tidal volume in the secondary channel (Schaar van Waarde). The absolute changes in both channels are of the same order of magnitude. A similar behaviour is displayed by the channels in cross-section 6. The tidal volume in the main channel (Gat van Ossenisse) has increased since 1960 and the tidal volume in the Middelgat has decreased with the same magnitude. In cross-section 7 changes in tidal volume are minor. In cross-section 9 the channel Honte/Schaar v.d. Spijkerplaat is stable with respect to tidal volume whereas the tidal volume Vaarweg langs Hoofdplaat has sharply decreased since 1980. The latter also holds for cross-section 10 where the main channel Honte shows a gradual increase. No clear trends are found in cross-section 11 (Wielingen and Sardijngeul). In transects 12 (Wielingen/Oostgeul-Deurloo) and 14 (Scheur/Oostgat-Vlakte van de Raan) records are short but an increase in tidal volume seems to be present since 1990.

The results on tidal volumes presented above can be summarized as follows:

- The tidal volumes in the overall cross-sections suggest an increase in time. This is most apparent in the cross-sections 1 and 2 in the east of the Western Scheldt. For the other cross-sections erratic variation is large compared with a trend like increase or the observation period is too short to draw conclusions. Correlation with the increase in tidal range should be further investigated.
- The tidal volumes in the main channels east of Terneuzen (Gat van Ossenisse, Zuidergat and Overloop van Hansweert) have significantly increased at the expense of the secondary channels (Middelgat, Schaar van Waarde and Zimmermangeul). Apparently this exchange of tidal volume did not affect much the total tidal volume through the cross-section.

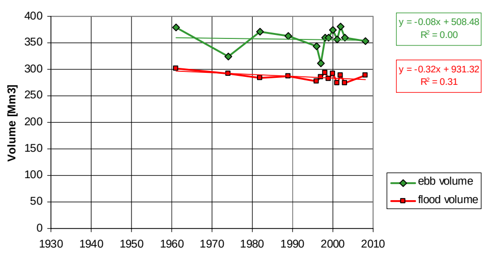
- West of Terneuzen tidal volumes show less variation in time apart from the Vaarwater langs Hoofdplaat which captures a decreasing tidal volume since 1960-1980.

Figure 2.63 shows the ebb and flood volumes for the main channels as well as for the secondary channels.

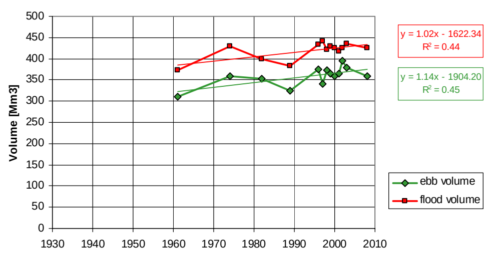


| Main channel | Secondary channel |
|---|---|

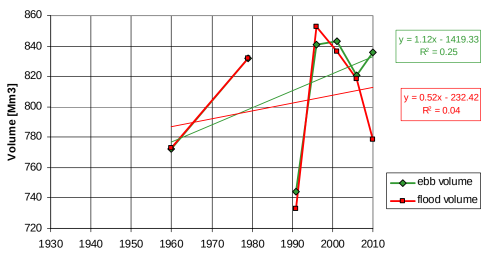
Cross-section 7: Put van Terneuzen



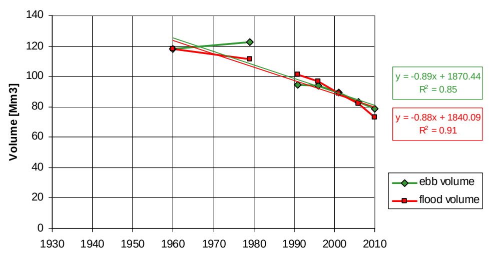

Cross-section 7: Everingen



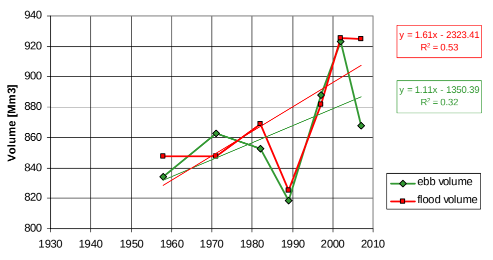

Cross-section 9: Honte/Schaar v.d. Spijkerplaat



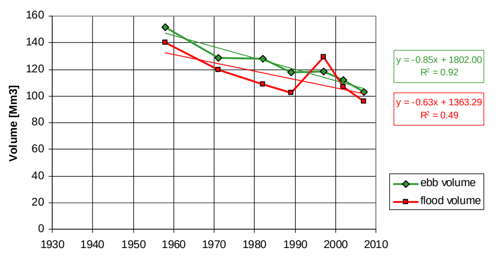

Cross-section 9: Vaarweg langs Hoofdplaat



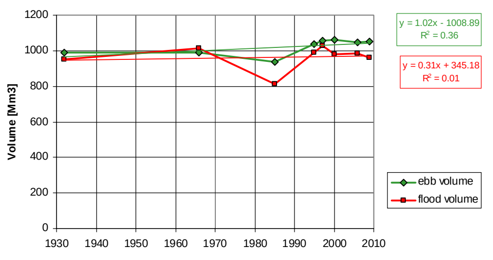

Cross-section 10: Honte



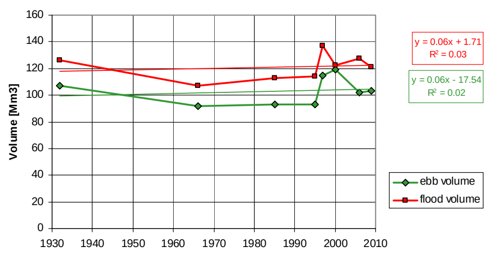

Cross-section 10: Vaarweg langs Hoofdplaat



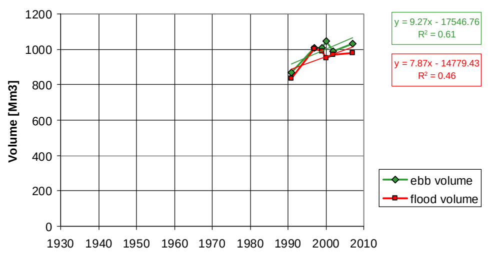

Cross-section 11: Wielingen



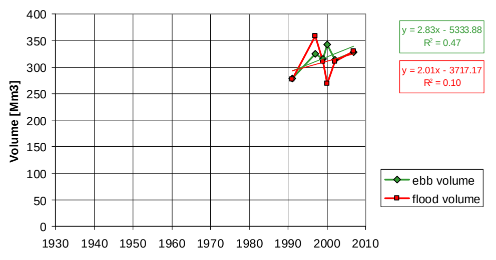

Cross-section 11: Sardijngeul




Cross-section 12: Wielingen




Cross-section 12: Oostgeul and Deurloo



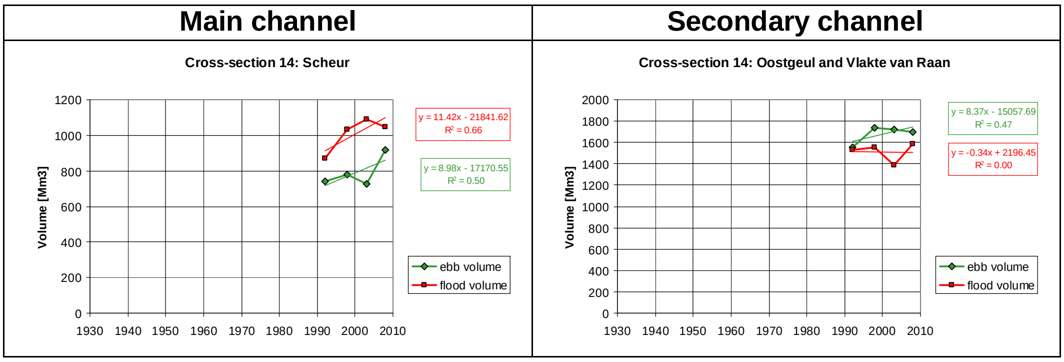
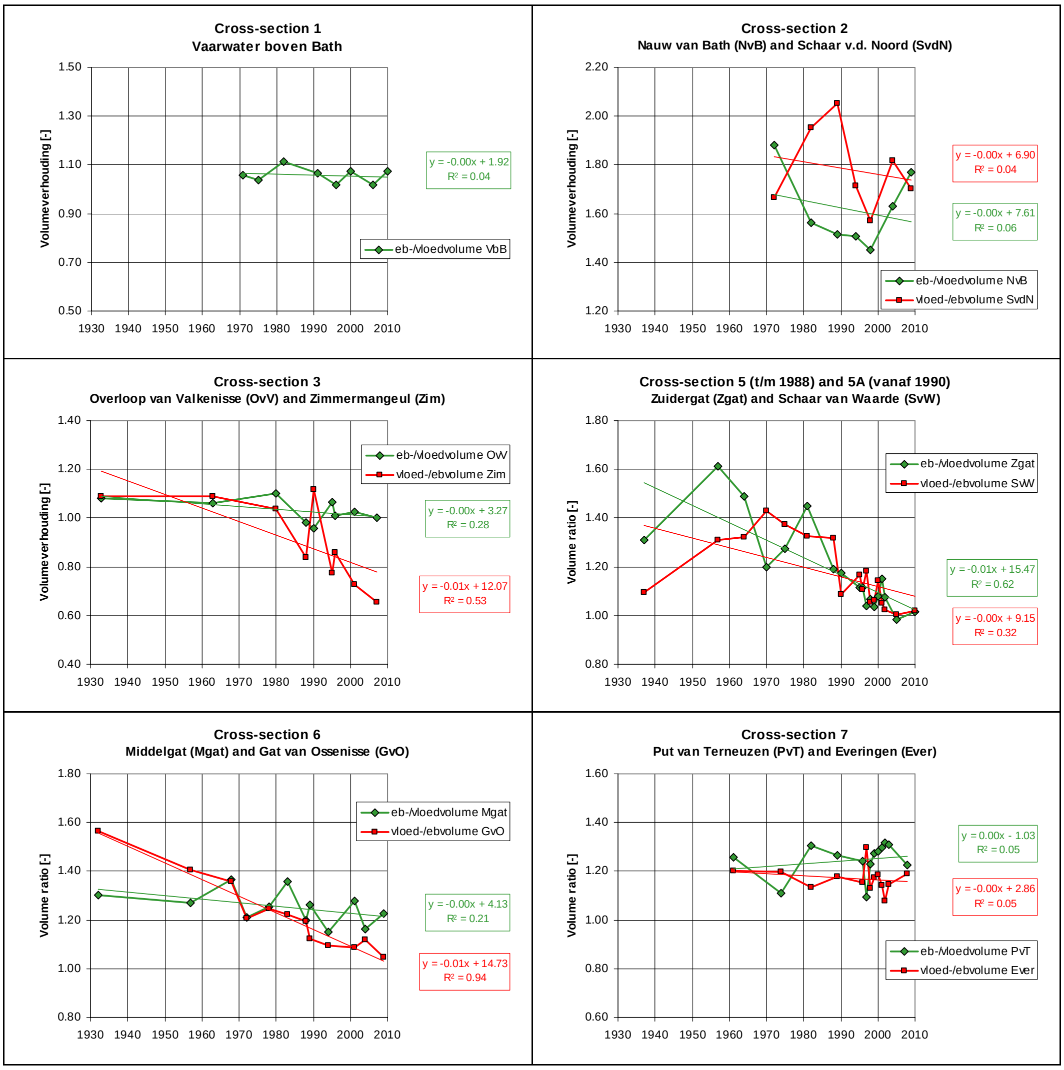



*Figure 2.63: Ebb and flood volumes for the main channel (left) and secondary channel (right) in the transects along the Western Scheldt.*

Figure 2.64 shows the ratio of the ebb and flood volume for the main channels, which are mostly ebb-dominated, and the ratio of the flood and ebb volume for the secondary channels.



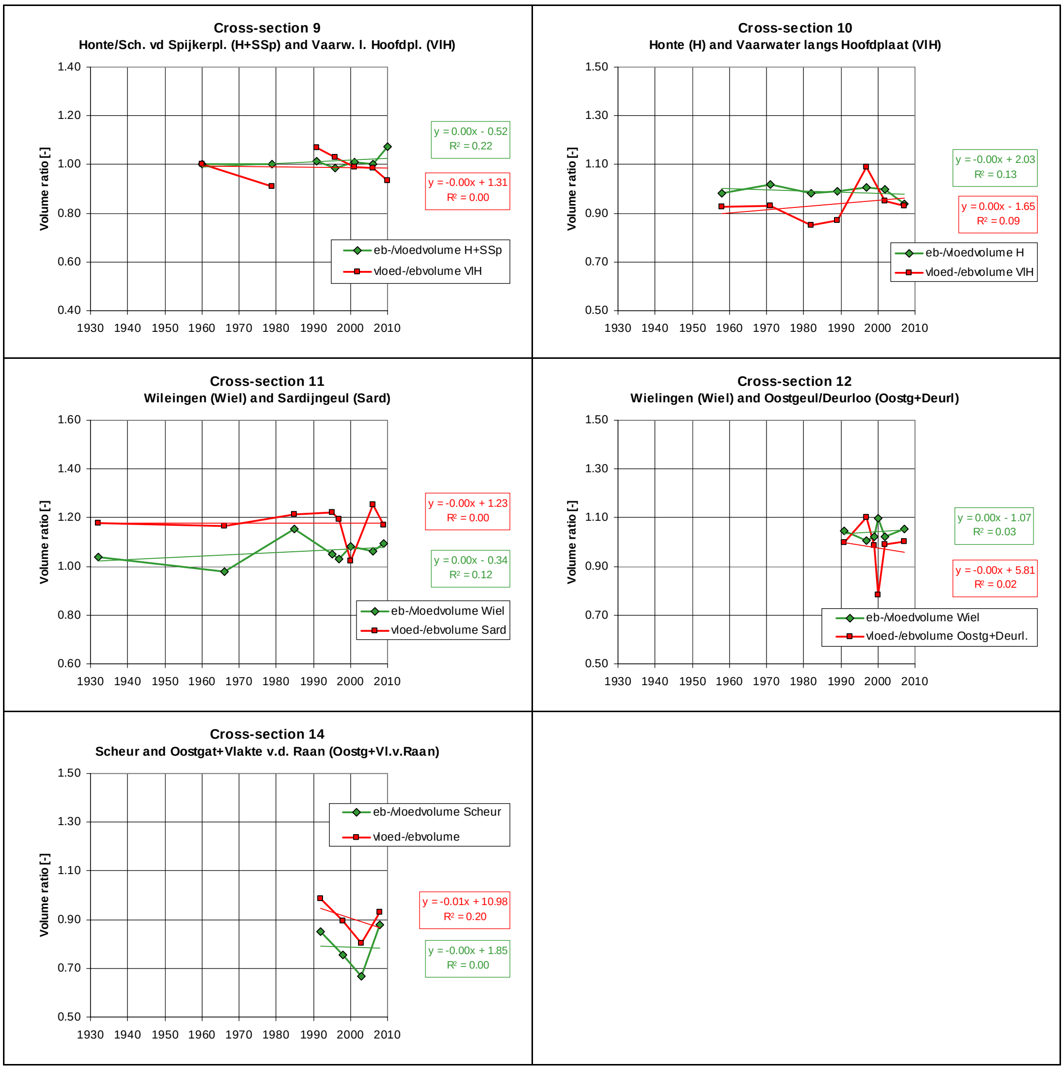



*Figure 2.64: Ratio of ebb and flood volume for the main channel (green lines) and ratio of flood and ebb volume for the secondary channel (red lines) in the transects along the Western Scheldt.*

The most significant trends from these graphs are as follows:

- o In cross-section 3 the flood/ebb volume ratio for the secondary channel Zimmermangeul is showing a downward trend. After 1990 this ratio has become less than one so that the ebb volume has become larger than the flood volume. The ebb/flood ratio of the main channel Overloop van Valkenisse has decreased to some extent with presently a value of approximately one.
- o In cross-section 5 both channels show a downward trend indicating that the main channel Zuidergat has become less ebb-dominated, with presently a ratio of one, and the secondary channel Schaar van Waarde has become less flood-dominated also resulting in a ratio of one.
- o Similarly, in cross-section 6 the ebb/flood ratio for the main channel Gat van Ossenisse and the flood/ebb ratio for the Middelgat show a persistent downward trend. Thus the Middelgat is becoming less ebb dominant whereas the Gat van Ossenisse is becoming less flood dominant. For the latter the ratio has become almost one nowadays.

The results indicate that in the central part of the Western Scheldt, i.e. cross-sections 3 and 5 in macro cell 5 and cross-section 6 in macro cell 4, all channels with the exception of the Zimmermangeul have become more symmetric with respect to ebb and flood volumes. The formerly flood-dominated Zimmermangeul has evolved in an ebb-dominated channel.

## 2.6 Summary and discussion of results

All water level stations in the Western Scheldt indicate a gradual increase of the mean water level over the last 100 years. In Vlissingen the increase is 15-20 cm/100 y, which represents the effect of sea level rise.

Observations of water levels in the stations Vlissingen, Terneuzen, Hansweert and Bath show that the **yearly-averaged high waters** have increased since about 1890. The average rate amounts +32 cm/century in Vlissingen gradually increasing in landward direction to +40 cm/century in Terneuzen, +42 cm/century in Hansweert and +41 cm/century in Bath. On the other hand the rate of increase of the **yearly-averaged low waters** in the four stations has been approximately the same during the past 100 years, i.e. varying between 17 and 22 cm/century and on average 19 cm/century. This implies that the **yearly-averaged tidal range** has increased from 13 cm/century in Vlissingen to 22 cm/century in Terneuzen, 25 cm/century in Hansweert and 41 cm/century in Bath. At the same time the **yearly-averaged mean water level** as approximated with the half tide has increased 26-32 cm/century, slightly becoming larger in landward direction.

For **spring tides** the rate of increase of the high waters is 5-10 cm/century greater than for yearly-averaged tides whereas for **neap tides** the rate of increase is 5-10 cm/century smaller. For spring tides as well as neap tides the rate of increase of low waters (13-18 cm/century for spring and 19 cm/century for neap) is not very much different from that of yearly-averaged tides (17-19 cm/century). The aforementioned figures are based on the observations in the stations Vlissingen, Terneuzen and Hansweert as data for spring and neap tidal conditions in Bath are only available since 1958. The observed changes in high and low water result in changes of the tidal range in the three stations that are approximately 50% larger for spring tides than for yearly-averaged tides. For neap tides the tidal range has increased 20-40% less than for yearly-averaged tides. Finally, the rate of increase of the half tide is for spring tide 1-3 cm/century larger and for neap tide 3-4 cm/century smaller than for the yearly-averaged tide.

The **amplitudes of the M2 and M4 tides** exhibit positive linear trends, whereas the **amplitude of the M6 tide** does not. The strength of the tidal asymmetry as given by the **M4-M2 amplitude ratio** has increased up until 1970. After 1970 this trend has persisted in Vlissingen while in the other stations the ratio has remained more or less constant. The **M6-M2 amplitude ratio** in the four stations (only available since 1970) does not show a clear trend and is more or less the same in the three seaward locations. In Bath the ratio and thus the asymmetry of the tide is larger. The **phase difference 2M2-M4** has decreased from slightly positive (flood-dominate) to almost neutral. Terneuzen has changed from neutral, however with oscillations, to slightly flood-dominate. Hansweert has always been ebb-dominate however with large variations between 1960 and 1980. The most significant changes have occurred in Bath where the tide has changed from strongly flood-dominate to almost neutral at present.

The **amplification of the tidal range** is related to estuary shape, depth and bed friction. Since 1900 the amplification between Vlissingen and Terneuzen and Terneuzen and Hansweert has not changed very much in a systematic way but has varied between 1.06 and 1.10. Some increase of tidal amplification between Vlissingen and Terneuzen may be derived from the data but scatter is large. Between Hansweert and Bath the amplification has gradually decreased from 1900 until 1960 followed by a distinct increase from 1.03 to 1.10 between 1960/1970 and 1980/1985. For spring tide conditions the amplification for subsequent sections in the Western Scheldt is approximately 0.02 smaller than for yearly-averaged tides (not for Hansweert-Bath) whereas for neap tides the amplification is approximately 0.02 larger. The reason for these differences is that for stronger tides (spring versus average and average versus neap) tidal velocities are larger and thus energy dissipation due to be bed friction is also larger reducing tidal amplification. The evolution of the amplification of the M2-amplitude is similar to that of the tidal ranges although magnitudes are somewhat smaller.

In addition to the tidal range the **propagation time** (or equivalent the propagation velocity) characterises the tidal propagation in an estuary. The observations show that since the end of the $19^{th}$ century the propagation time of the high water between Vlissingen and Terneuzen and between Vlissingen and Hansweert has decreased with 18 min. This seems small but is in effect 50% of the actual propagation time between these two stations around 1900. Between Vlissingen and Bath the reduction has been 24 min/century. The implication is that the propagation velocity between Vlissingen and Terneuzen has almost doubled during 100 years (from 10 to 18 m/s) while it has remained on average constant between Terneuzen and Hansweert (but varying between 7 and 10 m/s). Between Hansweert and Bath the yearly-averaged propagation velocity shows large fluctuations but presently it is larger (15 m/s) than at the end of the $19^{th}$ century (10 m/s). The propagation velocity for the section Vlissingen-Terneuzen is nowadays much larger than what can be derived from conventional expressions for frictionless progressive waves (= $\sqrt{(gh)}$ with $h$ the water depth). The propagation velocity of the low waters has changed to a lesser extent over the past century.

The **phase difference of the M2 tide** between two successive stations also shows an increase of the tidal propagation velocity. This increase is most pronounced between Terneuzen and Hansweert (since 1940) and between Hansweert and Bath (since 1995). Presently (2007), the phase velocity is not very much different for the three sections with values between 14 and 16 m/s. These values are significantly larger than for a purely progressive frictionless wave in a prismatic channel ($c = \sqrt{(gh)}$).

The **duration of tidal rise** in the Western Scheldt is smaller than the **duration of tidal fall** indicating flood dominance. Defined in this way it appears that since 1900 tidal asymmetry has not changed much in Vlissingen. In Terneuzen flood-dominance of the vertical tide has increased since 1950. In Hansweert there have been changes up and down but no clear trend is apparent. Finally, in Bath flood dominance has decreased since 1980. To find correlations with bathymetric changes of a section the variation of tidal asymmetry between the two successive stations should be addressed (Wang et al., 2002).

East of Terneuzen the main channels appear to convey a significant increasing portion of the total **tidal volume** through the cross-section. Consequently, the tidal volumes in the secondary channels show a decreasing trend. The total tidal volume through a cross-section seems to increase in the two most eastward transects, however for the other cross-sections this cannot definitely concluded. A clear correlation between changes in tidal range and tidal volume cannot be deduced from the measurements. In the central part of the Western Scheldt (macro cell 4 and 5) the channels Overloop van Valkenisse, Zuidergat and Middelgat have become less ebb-dominated while the flood-dominated channels Zimmermangeul, Schaar van Waarde and Gat van Ossenisse have become less flood-dominated. With the exception of the Zimmermangeul the tide has become more symmetric with respect to the **ratio of ebb and flood volume**.

**Summarising**, since the end of the 19th century the tidal range in the Western Scheldt has increased and thus the estuary has become more dynamic due to an increased tidal forcing (increase of 3.5-10%/century). At the same time the mean water level in the estuary has increased, predominantly due to the mean sea level rise. The consequence of both effects is that high waters as well as low waters have increased during the past 100 years but that the resulting changes of the low waters have been smaller than the changes of the high waters. The increase of the tidal dynamics has been more pronounced for spring tides than for neap tides. The increase of the tidal range is accompanied with a larger propagation velocity of the tidal wave which also reflects an increase of the tidal dynamics since the end of the 19th century. In the central part of the Western Scheldt the main channels Gat van Ossenisse, Zuidergat and Overloop van Valkenisse capture a significant increasing portion of the total tidal volume through the cross-section. In these channels and in Middelgat and Schaar van Waarde the tide has become more symmetric with respect to the ratio of flood and ebb volume.

# 3 Topo-bathymetric data

## 3.1 Available data

Until 1985 bathymetries in the eastern part of the Western Scheldt (compartments 1 to 3, see Figure 3.1) were measured about every two years[6]. Since 1985 soundings are being carried out every year. In the western part of the Western Scheldt (compartments 4 to 6) bathymetries were measured every two years until 1996 and since then every year. Thus only since 1996 echo soundings for the entire Western Scheldt (i.e. compartments 1 to 6) are carried out on a yearly basis. In the ebb tidal delta ('Voordelta') the number of compartments is 10 and the bed levels have only been measured on a regular basis since 1969 with intervals of 0 to 3 years.

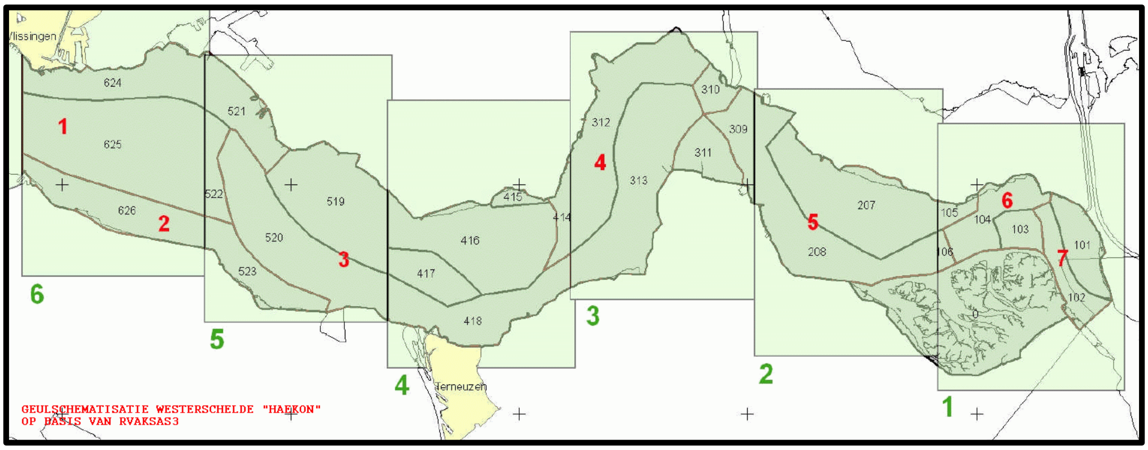



*Figure 3.1: Echo sounding sections 1-6 ('vaklodingen') of the Western Scheldt as indicated by the green numbers. Red numbers relate to macro cells and meso cell (these cells are not shown in the figure). Sub sections are being used for setting-up sand balances.*

Bathymetries of the Western Scheldt and the ebb tidal delta ('Voordelta') were obtained from the *Meetadviesdienst RWS Zeeland* on 20x20 $m^2$ ArcInfo grids. They were provided as separate files containing the echo sounding in the individual compartments in a specific year. Also merged bathymetries were obtained from Rijkswaterstaat containing all echo sounding data of all compartments in a specific year, see Table 3.1. The latter files have been used by Rijkswaterstaat for setting-up sand balances of the areas. The merging consisted of a quality check and data were excluded by Rijkswaterstaat if they were considered erroneous. The merged files include the bed levels of the intertidal areas. Since the (early) 90's of the 20th century these intertidal areas have been measured every year by means of (manual) levelling and in the years 2001, 2004, 2006, 2007 en 2008 also with laser-altimetry. Before the 90's intertidal areas were not measured annually and missing data for a specific year were copied from preceding years.

6. *Known as 'vaklodingen'.*

*Table 3.1: Years with merged bathymetries of the Western Scheldt and the Voordelta.*

| Estuarine section | Year | Total |
|---|---|---|
| Western Scheldt | 1955,<br>1957-1980,<br>1982,<br>1984-2008. | 51 |
| Voordelta | 1969,<br>1971-2004. | 35 |

For the present the attention will focus on the bathymetries of the Western Scheldt. In a later stage of the project the data processing and analysis can be extended to the Voordelta.

The merged files of the Western Scheldt have been used for further processing, see section 3.2.

## 3.2 Processing

An example of a merged ArcInfo GIS file is given in Figure 3.2 representing the bathymetry of the Western Scheldt for the year 1982. The file contains the available data in the echo sounding compartments 1, 2, 3, 5 and 6. Data in echo sounding compartments 3 are not available for 1982 and should be used from the preceding year or, in this case, even the year before (1980). In this way for each year a compound bathymetry is obtained that completely covers the Western Scheldt from the Belgian-Dutch border to the cross-section between Vlissingen and Breskens. Table 3.2 gives for all years an overview of these compound bathymetries indicating the years of measurement in the six echo sounding compartments. It is noted that in this way a bathymetry for each year becomes available but that there is some mutual dependency between the bathymetries of successive years.

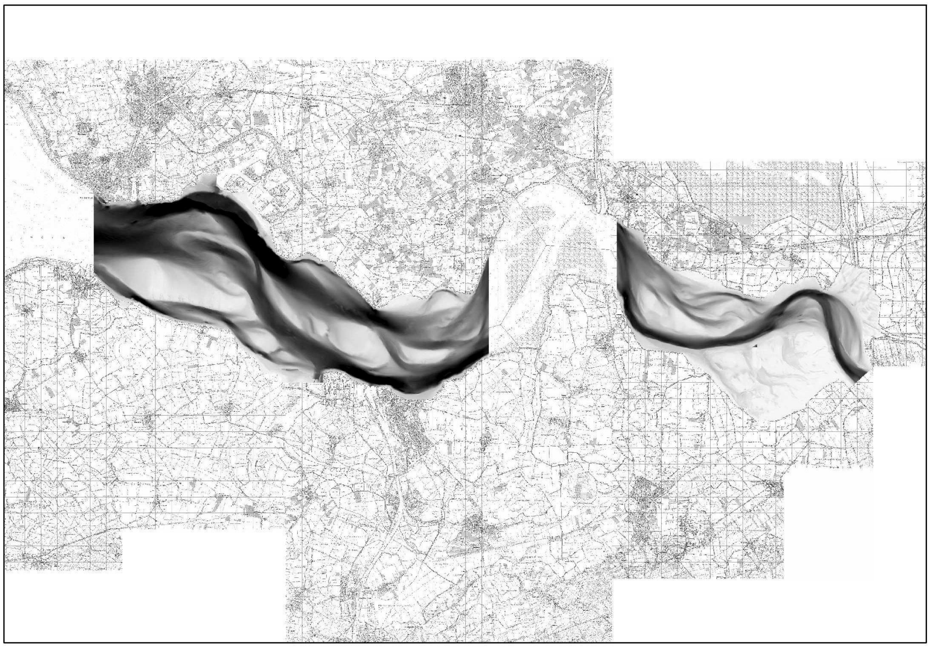


*Figure 3.2: Bathymetric data (ArcInfo) of the Western Scheldt for the year 1982.*

*Table 3.2: Compound bathymetries of the Western Scheldt. Indicated are years of echo soundings in compartments. Underlined numbers relate to previous years.*

| | Echo sounding compartment | | | | | | | Echo sounding compartment | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year of bath.** | **1** | **2** | **3** | **4** | **5** | **6** | **Year of bath.** | **1** | **2** | **3** | **4** | **5** | **6** |
| 1955 | 1955 | 1955 | 1955 | 1955 | 1955 | 1955 | 1982 | 1982 | 1982 | 1980 | 1982 | 1982 | 1982 |
| 1956 | 1955 | 1955 | 1955 | 1955 | 1955 | 1955 | 1983 | 1982 | 1982 | 1980 | 1982 | 1982 | 1982 |
| 1957 | 1957 | 1957 | 1957 | 1955 | 1955 | 1955 | 1984 | 1982 | 1984 | 1984 | 1982 | 1982 | 1984 |
| 1958 | 1957 | 1957 | 1957 | 1958 | 1958 | 1958 | 1985 | 1985 | 1984 | 1985 | 1982 | 1982 | 1984 |
| 1959 | 1959 | 1959 | 1959 | 1958 | 1958 | 1958 | 1986 | 1986 | 1986 | 1986 | 1986 | 1982 | 1984 |
| 1960 | 1959 | 1959 | 1959 | 1960 | 1960 | 1960 | 1987 | 1987 | 1987 | 1987 | 1986 | 1982 | 1984 |
| 1961 | 1961 | 1961 | 1961 | 1960 | 1960 | 1960 | 1988 | 1988 | 1988 | 1988 | 1988 | 1982 | 1988 |
| 1962 | 1961 | 1961 | 1961 | 1962 | 1962 | 1962 | 1989 | 1989 | 1989 | 1989 | 1988 | 1982 | 1988 |
| 1963 | 1963 | 1963 | 1961 | 1962 | 1962 | 1962 | 1990 | 1990 | 1990 | 1990 | 1990 | 1990 | 1990 |
| 1964 | 1963 | 1963 | 1961 | 1964 | 1964 | 1964 | 1991 | 1991 | 1991 | 1991 | 1990 | 1990 | 1990 |
| 1965 | 1965 | 1965 | 1965 | 1964 | 1964 | 1964 | 1992 | 1992 | 1992 | 1992 | 1992 | 1992 | 1992 |
| 1966 | 1965 | 1965 | 1965 | 1966 | 1966 | 1966 | 1993 | 1993 | 1993 | 1993 | 1992 | 1992 | 1992 |
| 1967 | 1967 | 1967 | 1965 | 1966 | 1966 | 1966 | 1994 | 1994 | 1994 | 1994 | 1994 | 1994 | 1994 |
| 1968 | 1967 | 1967 | 1965 | 1968 | 1968 | 1968 | 1995 | 1995 | 1995 | 1995 | 1994 | 1994 | 1994 |
| 1969 | 1969 | 1969 | 1969 | 1968 | 1968 | 1968 | 1996 | 1996 | 1996 | 1996 | 1996 | 1996 | 1996 |
| 1970 | 1969 | 1969 | 1969 | 1970 | 1970 | 1970 | 1997 | 1997 | 1997 | 1997 | 1997 | 1997 | 1997 |
| 1971 | 1971 | 1971 | 1971 | 1970 | 1970 | 1970 | 1998 | 1998 | 1998 | 1998 | 1998 | 1998 | 1998 |
| 1972 | 1971 | 1971 | 1971 | 1972 | 1972 | 1972 | 1999 | 1999 | 1999 | 1999 | 1999 | 1999 | 1999 |
| 1973 | 1973 | 1973 | 1973 | 1972 | 1972 | 1972 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 |
| 1974 | 1973 | 1974 | 1974 | 1974 | 1974 | 1974 | 2001 | 2001 | 2001 | 2001 | 2001 | 2001 | 2001 |
| 1975 | 1975 | 1975 | 1975 | 1974 | 1974 | 1974 | 2002 | 2002 | 2002 | 2002 | 2002 | 2002 | 2002 |
| 1976 | 1975 | 1975 | 1975 | 1976 | 1976 | 1976 | 2003 | 2003 | 2003 | 2003 | 2003 | 2003 | 2003 |
| 1977 | 1977 | 1977 | 1977 | 1976 | 1976 | 1976 | 2004 | 2004 | 2004 | 2004 | 2004 | 2004 | 2004 |
| 1978 | 1977 | 1977 | 1977 | 1976 | 1978 | 1978 | 2005 | 2005 | 2005 | 2005 | 2005 | 2005 | 2005 |
| 1979 | 1979 | 1979 | 1979 | 1976 | 1978 | 1978 | 2006 | 2006 | 2006 | 2006 | 2006 | 2006 | 2006 |
| 1980 | 1980 | 1980 | 1980 | 1980 | 1980 | 1980 | 2007 | 2007 | 2007 | 2007 | 2007 | 2007 | 2007 |
| 1981 | 1980 | 1980 | 1980 | 1980 | 1980 | 1980 | 2008 | 2008 | 2008 | 2008 | 2008 | 2008 | 2008 |

The merging of separate files into one data set, representing the bathymetry for a specific year, is done with UCIT[7]. UCIT is the acronym for Universal Coastal Intelligence Toolkit and consists of a data base and a Matlab toolbox with a great number of analysis routines. A screen dump of UCIT is given in Figure 3.3 showing the fixed map grids along the Dutch coast (lower left window), the selected bathymetry (upper left window), date of the used echo sounding data (upper right window) and an interactive window to select Matlab tools (lower right window) for data processing. With Figure 3.4 another example is given showing that the bathymetry of 1986 consists of echo sounding data of 1986 (compartments 1 to 4), 1984 (compartment 6) and 1982 (compartment 5), see also Table 3.2.

*7. Developed by Deltares.*

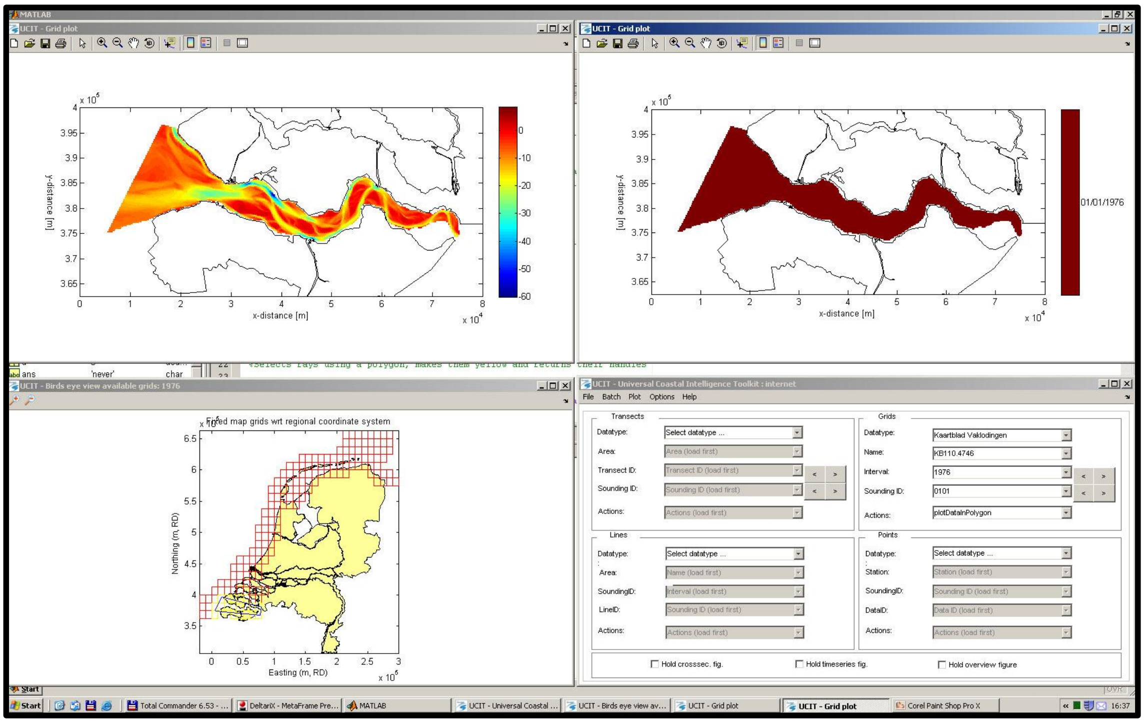


Figure 3.3: Screen dump of UCIT interface.

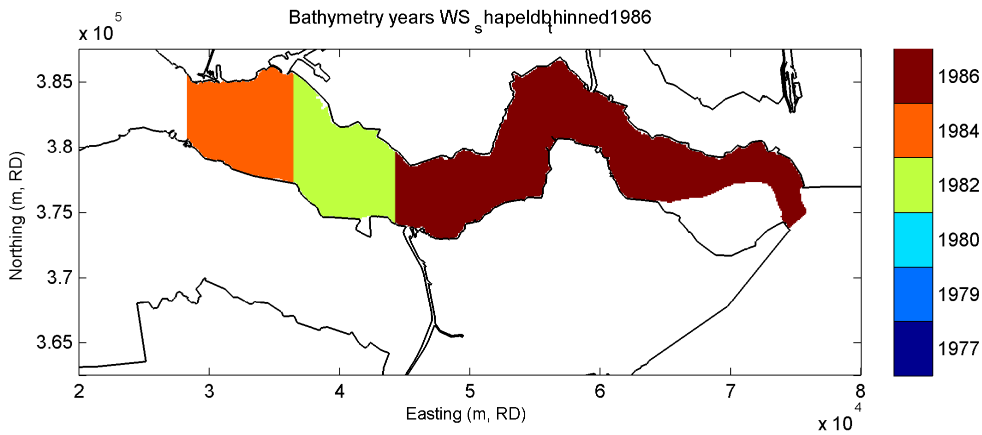



Figure 3.4: Compound bathymetry of the Western Scheldt for 1986 indicating years of echo sounding measurements.

After the construction of the compound bathymetries Matlab scripts are used to compute the yearly hypsometric curves. A hypsometric curve specifies the horizontal area as enclosed by a polygon for successive depths and as such resembles a two-dimensional cross-section[8]. As an example Figure 3.5 presents for 1955 and 2008 the hypsometric curves of the Western Scheldt between Vlissingen-Breskens and the Belgian-Dutch border. From these curves various morphologic parameters are derived such as the volume of water in the channels, the volume of water above the intertidal flats, the sand volume of the intertidal flats etc. This is further discussed in Section 3.3.

8. Sometimes the hypsometric curve is defined as the volume below a certain depth as a function of the depth.

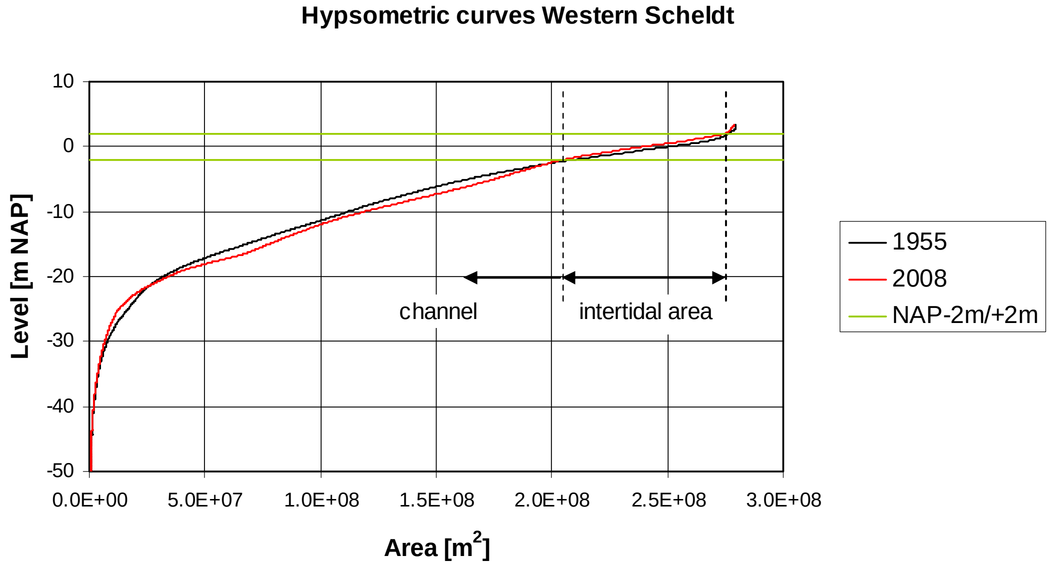



*Figure 3.5: Hypsometric curves in 1955 and 2008 for the Western Scheldt between Vlissingen and the Belgian-Dutch border.*

A quality check was done by comparing some morphological parameters derived by Rijkswaterstaat for their sand balance studies with the parameters as derived within the present project using UCIT. All parameters are derived for the entire Western Scheldt using the polygon as obtained from Rijkswaterstaat (the number of points has been reduced by a factor 3). Results are given for the:

- area of the Western Scheldt at levels of NAP-2,0 m (Figure 3.6) and NAP-5,0 m (Figure 3.7);
- volume below levels NAP+3,5 m (Figure 3.8), NAP-2,0 m (Figure 3.9) and NAP-5,0 m (Figure 3.10).

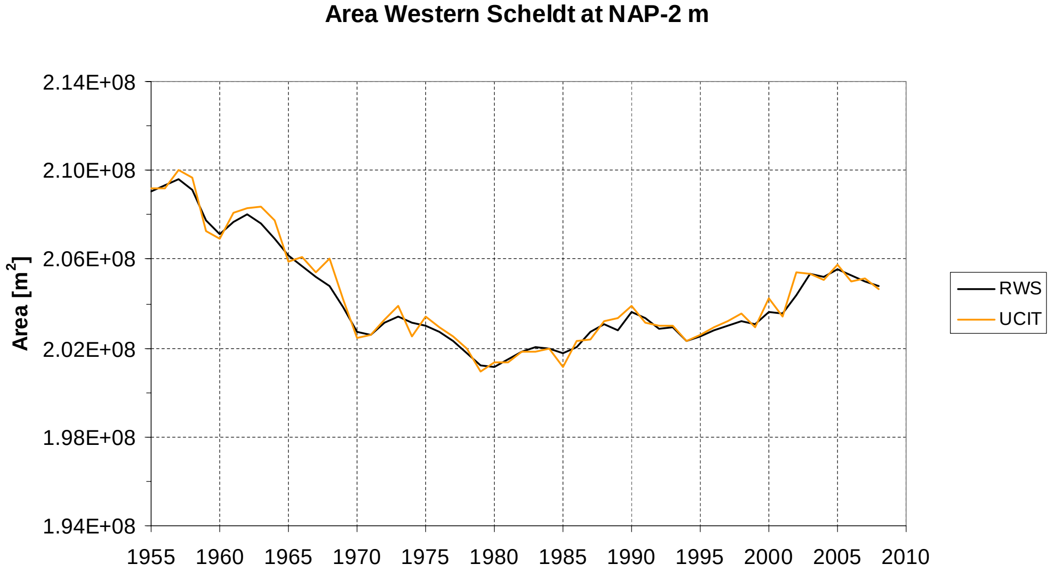



*Figure 3.6: Area Western Scheldt at NAP-2.0 m between 1955 and 2008..*

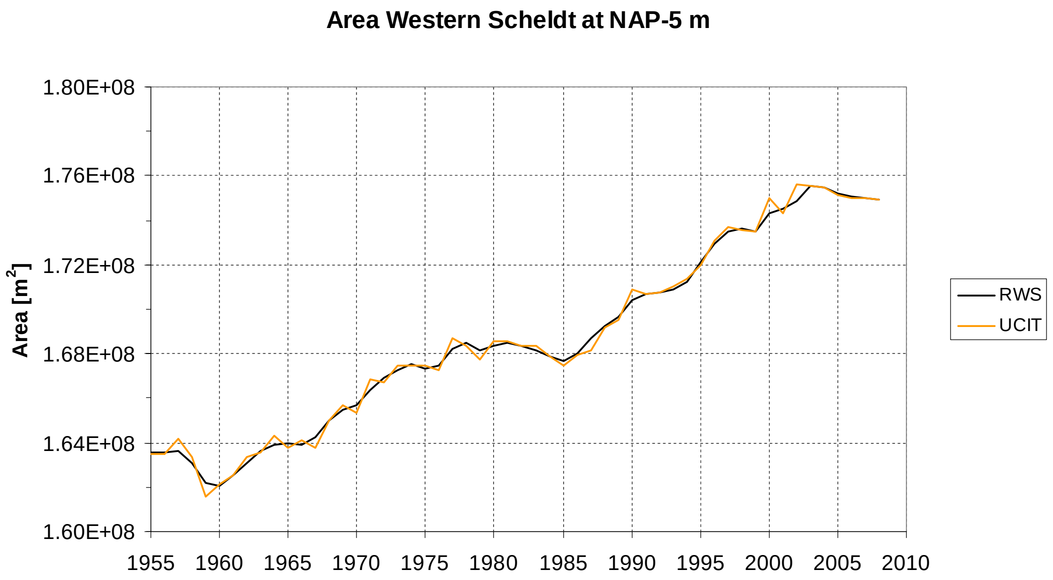



*Figure 3.7: Area Western Scheldt at NAP-5.0 m between 1955 and 2008.*

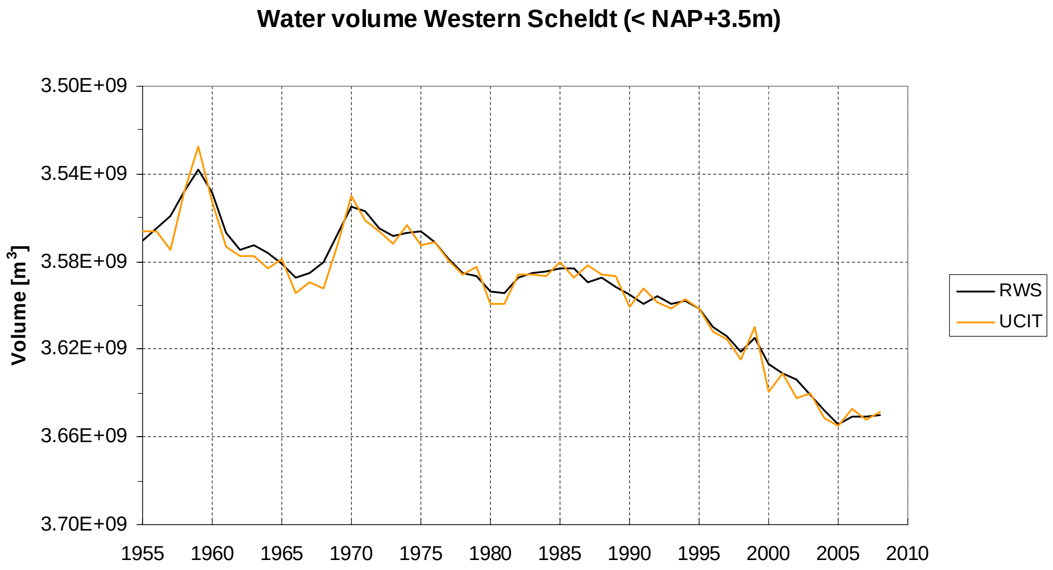



*Figure 3.8: Volume Western Scheldt below NAP+3.5 m between 1955 and 2008.*

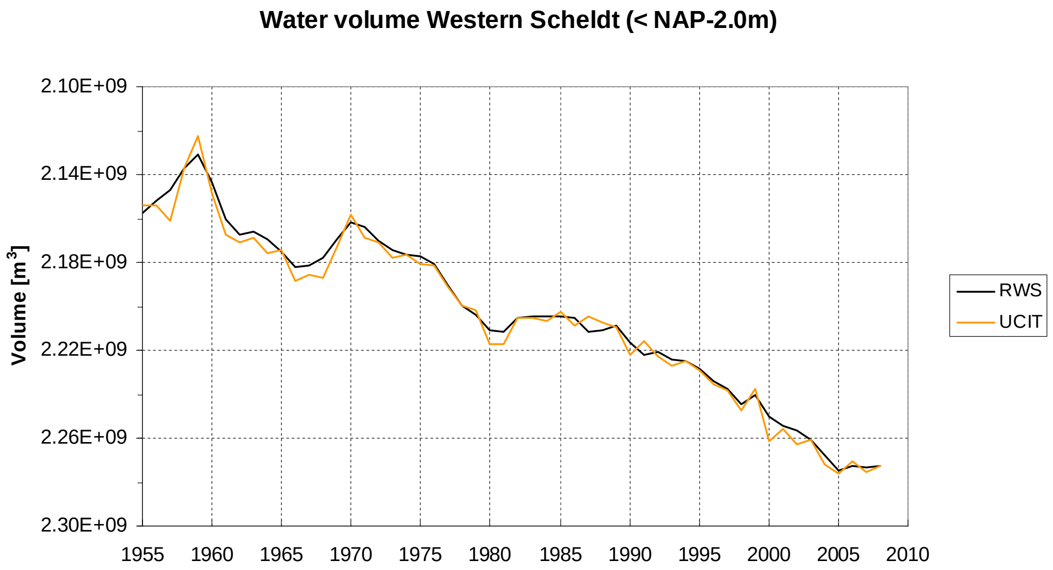



*Figure 3.9: Volume Western Scheldt below NAP-2.0 m between 1955 and 2008.*

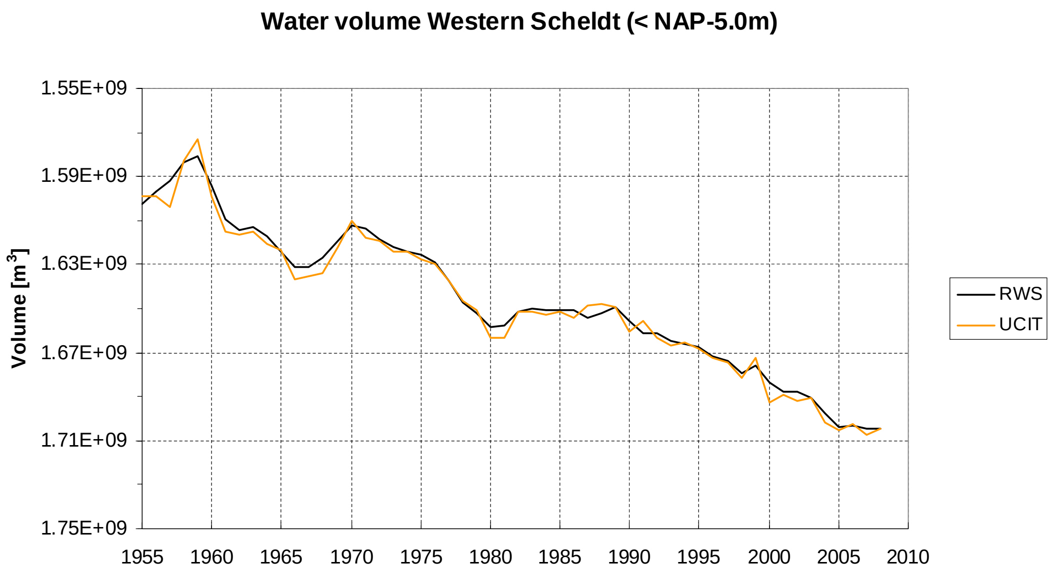



*Figure 3.10: Volume Western Scheldt below NAP-5.0 m between 1955 and 2008.*

From Figure 3.6 and Figure 3.7, and Figure 3.8 - Figure 3.10, it follows that the results obtained by Rijkswaterstaat[9] are reproduced by the methodology as described above.

9. *Data were provided by Rijkswaterstaat Zeeland.*

## 3.3 Definition of morphologic characteristics

Morphologic parameters are derived from the hypsometric curves computed with UCIT for each year. This is done for three sections in the Western Scheldt: Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath. Thus each section is bounded with the water level stations at the upstream and downstream side, see Figure 3.11.

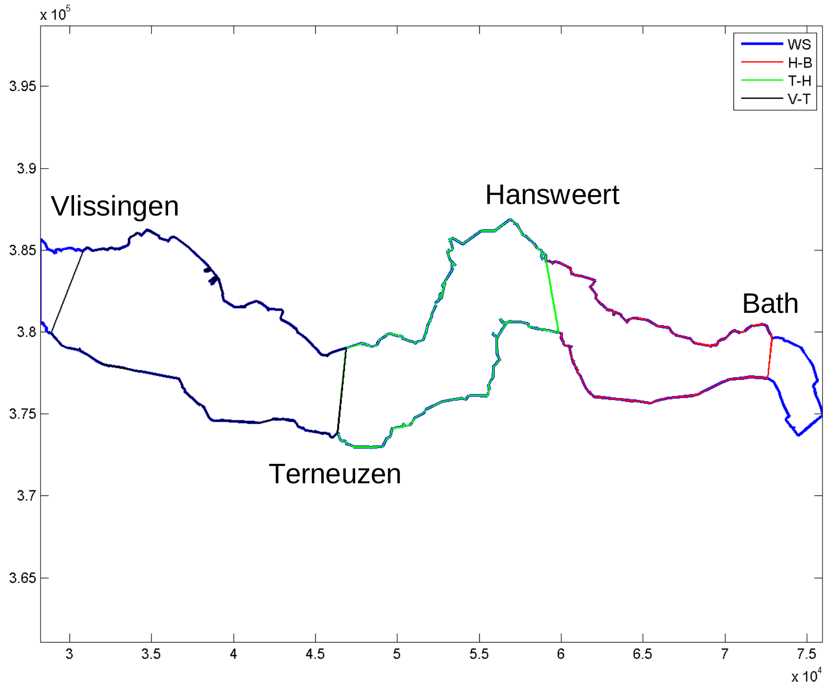
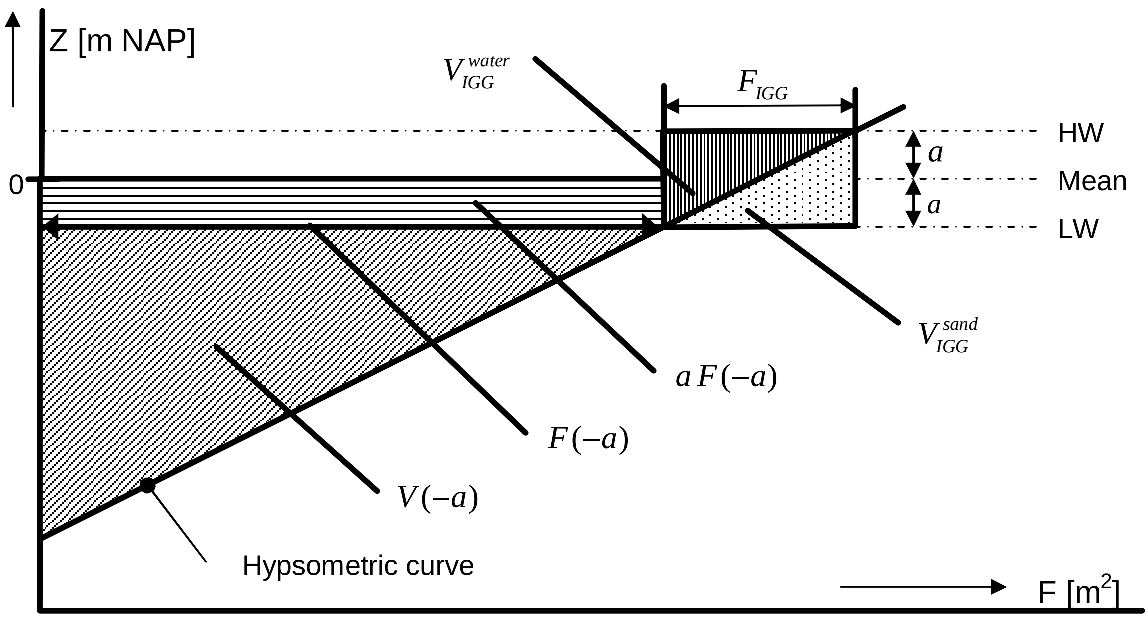



*Figure 3.11: Sections of the Western Scheldt between Vlissingen and Terneuzen, Terneuzen and Hansweert and Hansweert and Bath.*

The sketch hereafter gives schematically the hypsometric curve and some quantities associated with this. A sinusoidal tide is assumed with an amplitude *a* and it is assumed that the mean water level is at *z* = 0 m NAP.

- $V(-a)$ :water volume below LW;
- $F(-a)$ :area of water surface at LW;
- $F_{IGG}$ :area of intertidal flats;
- $V_{IGG}^{water}$ :volume of water above the intertidal flats;
- $V_{IGG}^{sand}$ :volume of sand of the intertidal flats.

These characteristics are derived in the following way (Wang et al., 2002):




*Definition sketch hypsometric curve and morphologic characteristics*
*a = tidal amplitude [m]; F = area [m$^2$]; V = volume [m$^3$]*
*HW = high water; LW = low water; IGG = intertidal flats (shoals and salt marshes)*

The following morphologic characteristics are derived from the hypsometric curve:

<u>a. Volume of the channel ($V_{ch}$):</u>

The volume of the channel ($V_{ch}$) is defined as the sum of the volume below low water ($V(-a)$) and the tidal amplitude ($a$) times the water surface area at low water ($F(-a)$):

$$V_{ch} = V(-a) + a\,F(-a) \tag{3.1}$$

<u>b. Channel depth ($h_{ch}$):</u>

The channel depth ($h_{ch}$) is defined as the volume of the channel ($V_{ch}$) divided by the surface water area at low water ($F(-a)$):

$$h_{ch} = \frac{V_{ch}}{F(-a)} = \frac{V(-a)}{F(-a)} + a \tag{3.2}$$

Note that in Move (Peters et al., 2003)) the depth of the channel is defined as the depth below NAP-2.0 m ($h_{MOVE}$):

$$h_{MOVE} = \frac{V(-a)}{F(-a)} \quad with \quad a = 2\,m$$

Thus it follows that $h_{ch} = h_{MOVE} + a = h_{MOVE} + 2$ [m].

c. Area of intertidal flats ( $F_{IGG}$ ):

The intertidal area ($F_{IGG}$) is defined as the difference between the water surface area at high water ($F(a)$) minus the water surface area at low water ($F(-a)$).

$$F_{IGG} = F(a) - (F - a) \quad (3.3)$$

d. Water volume above intertidal flats ( $V_{IGG}^{water}$ )

The water volume above the intertidal flats ( $V_{IGG}^{water}$ , see sketch) is defined as:

$$V_{IGG}^{water} = V(a) - V(-a) - 2a\,F(-a) \quad (3.4)$$

e. Sand volume of intertidal flats ( $V_{IGG}^{sand}$ )

The sand volume of the intertidal flats ( $V_{IGG}^{sand}$ , see sketch) is defined as:

$$V_{IGG}^{sand} = 2a\,F(a) - \left[V(a) - V(-a)\right] \quad (3.5)$$

An increase of the sand volume of the intertidal flats is not necessarily equal to a decrease of the water volume above the intertidal flats. For instance, if the area of the intertidal flats increases the sand volume of the flats as well as the water volume above the flats may increase.

f. Height of intertidal flats ( $h_{IGG}$ )

The height of the intertidal flats ($h_{IGG}$) is defined as the sand volume of the intertidal flats ( $V_{IGG}^{sand}$ ) divided by the area of the flats ( $F_{IGG}$ ):

$$h_{IGG} = \frac{V_{IGG}^{sand}}{F_{IGG}} = \frac{2a\,F(a) - \left[V(a) - V(-a)\right]}{F(a) - (F - a)} \quad (3.6)$$

The height of the intertidal flats is given relative to low water.

The hypsometric curve gives the areas at depths relative to NAP. It is noted here that the mean water level ($z_{mean}$) is not necessarily at $z$ = 0 m NAP although in the Western Scheldt this is a fair approximation. In that case the volume $V(a)$ represents the volume below $z = z_{mean} + a$ and the area $F(-a)$ is the area at $z = z_{mean} - a$. Similar arguments hold for the other quantities. Furthermore, the difference between high and mean water level is not equal to the difference between mean water level and low water (both have been assumed equal to $a$ in the equations (3.1) – (3.6)). Finally it is noted that the high and low waters as well as the mean water level may vary on a long time scale (decades). To avoid too much complexities at the same time (see Intermezzo) it will be assumed in the next section that the mean water level is at NAP in all stations in the Western Scheldt and that the tide is symmetrical with an amplitude of 2 m. In this way bathymetric properties of the Western Scheldt are characterised with fixed reference levels: $z$ = -2 m NAP, $z$ = 0 m NAP and $z$ = +2 m NAP. Further relaxation of this schematisation will be investigated in a later stage, e.g. *a* varying per section and in time and also with different values for high and low waters.

**Intermezzo**

If the tidal amplitude increases with time resulting in higher high waters and lower low waters then by definition the area of the intertidal flats becomes larger even if the bathymetry remains unchanged. If this quantity is plotted as a time series one might conclude that the bathymetry changes while this is not necessarily the case. Therefore it is more transparent to use fixed reference levels to characterise parts of the hypsometric curve that resemble morphologic quantities such as channel depth and water volume on the intertidal area. However to explain the tidal propagation on the basis of bathymetric characteristics it may be necessary to use the actual properties.

## 3.4 Evolution of bathymetric characteristics

In this section a description is given of the evolution of the morphologic parameters of the Western Scheldt for the period 1955-2008. The overall bathymetry is considered, i.e. no distinction is made between main channel and secondary channel. In Section 5 the evolution of the latter channels is presented.

As indicated in Section 3.3 the following morphologic characteristics are considered:

- Water volume of the channel;
- Water volume above the intertidal flats;
- Area of the channel at low water;
- Water depth of the channel;
- Area of the intertidal flats;
- Sand volume of the intertidal flats.
- Height of the intertidal flats (relative to low water = NAP-2m);

The morphologic characteristics per section are computed for each year using reference levels at NAP-2.0 m, NAP and NAP+2.0 m.

### 3.4.1 Channel volume

The channel volumes in the three sections are shown in Figure 3.12 - Figure 3.14 (red lines; right vertical axis). During the period 1955-2008 the channel volume between Vlissingen and Terneuzen has increased with 5 $10^7$ $m^3$ (+4%). Since approximately 1980 this increase seems systematic with possibly slowing down the last few years. Between Terneuzen and Hansweert the channel volume has decreased with 4 $10^7$ $m^3$ (-5%) although the channel has become stable since 1990. The channel volume between Hansweert and Bath has increased with 6 $10^7$ $m^3$ (+17%) attaining a constant volume since 2002. The channel in this section has particularly expanded between 1970 and 1980 and between 1995 and 2002. Both periods coincide with the periods when the navigation channel was deepened and widened. The total volume increase of the channels between 1955 and 2008 for the section Vlissingen-Bath has been +7 $10^7$ $m^3$ (+3%).

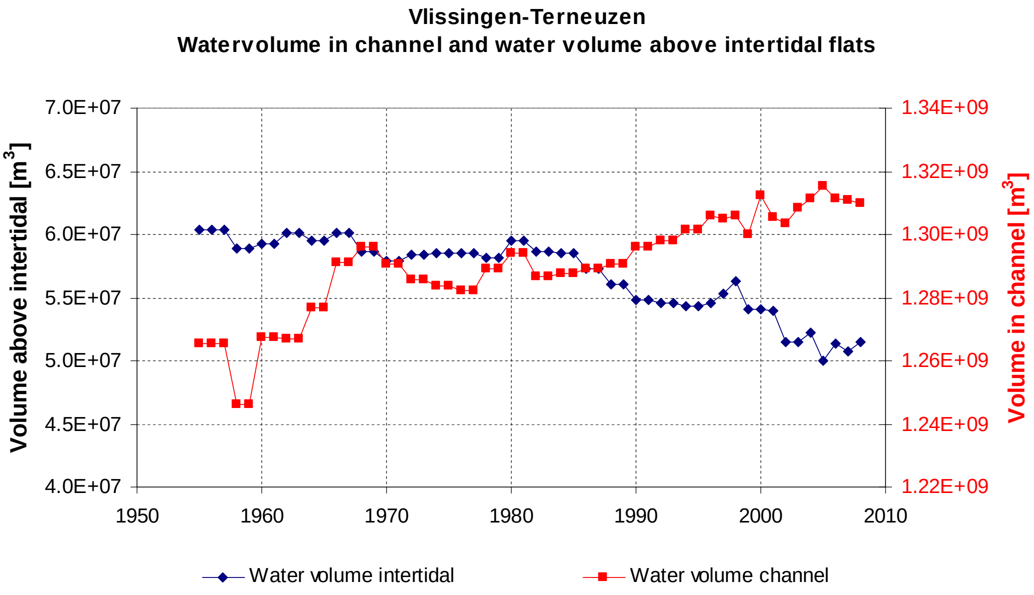



*Figure 3.12: Water volume of the channel (right axis) and above intertidal flats (left axis) for the section Vlissingen-Terneuzen.*

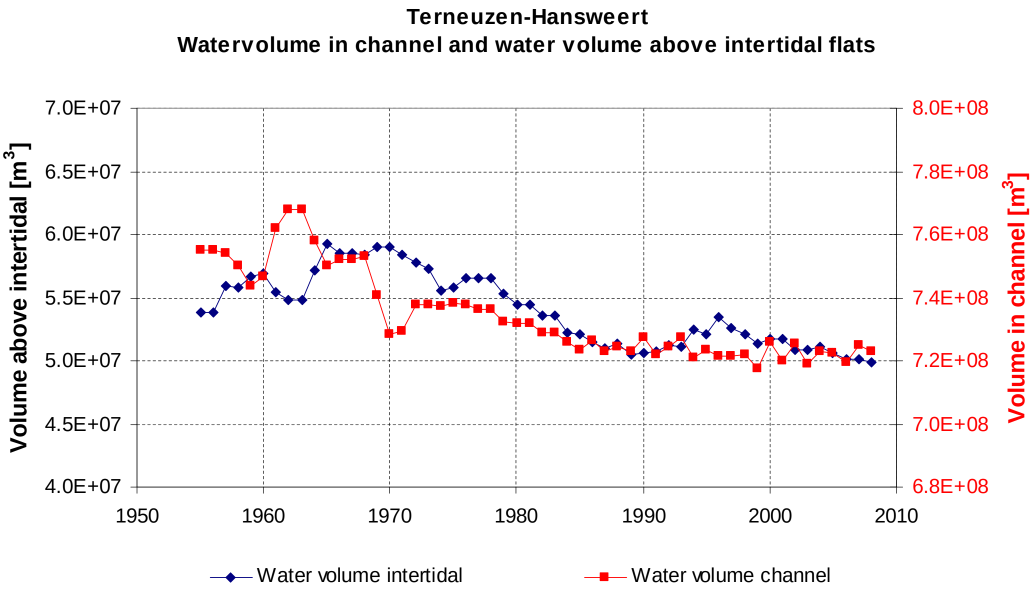



*Figure 3.13: Water volume of the channel (right axis) and above intertidal flats (left axis) for the section Terneuzen-Hansweert.*

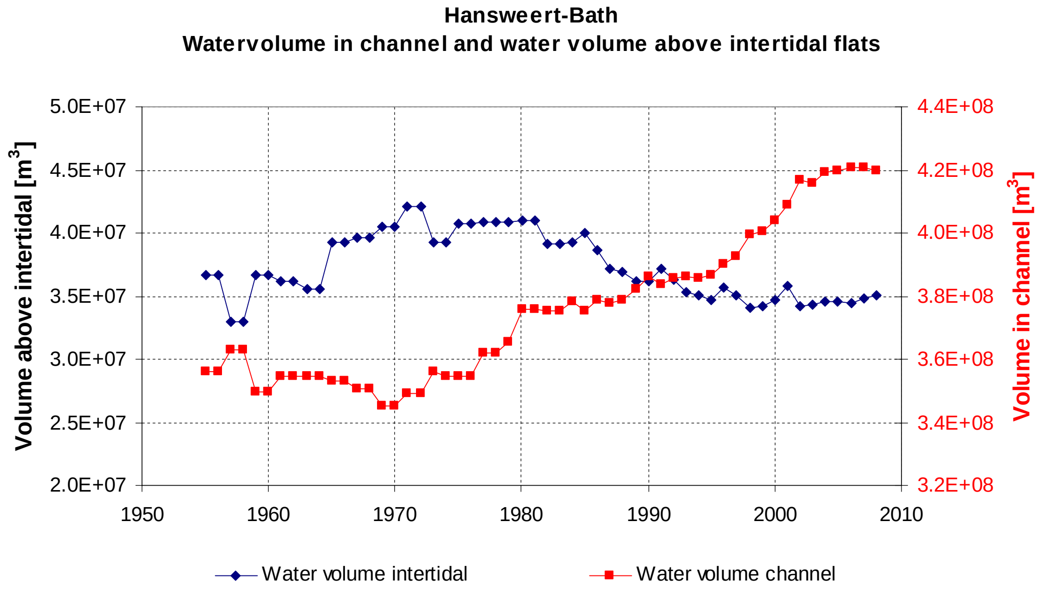



*Figure 3.14: Water volume of the channel (right axis) and above intertidal flats (left axis) for the section Hansweert-Bath.*

### 3.4.2 Water volume above intertidal flats

The water volume above the intertidal flats is also shown in Figure 3.12 - Figure 3.14 (blue lines, left axis). Since 1955 the water volume of the sections Vlissingen-Terneuzen and Terneuzen-Hansweert has decreased with 1 $10^7$ $m^3$ (-15%) and 0.5 $10^7$ $m^3$ (-10%) respectively. This reduction has mainly taken place since about 1980. The latter also holds for the section Hansweert-Bath where until 1970 an increase of the water volume above the intertidal flats of +0.5 $10^7$ $m^3$ (+15%) is observed, followed by a decrease since 1980 of the same amount. The net change during the period 1955-2008 for the total section Vlissingen-Bath has been a decrease of -1.5 $10^7$ $m^3$ (-10%).

### 3.4.3 Ratio of water volume above intertidal flats and channel volume

The ratio of the water volume above the intertidal flats and the channel volume is shown in Figure 3.15 - Figure 3.17. For the section Vlissingen-Terneuzen this ratio decreases systematically from 0.05 to 0.04 (-20%). It means that the flow part of the section (the channel) increases at the expense of the storage part (above the flats). For the section Terneuzen-Hansweert first an increase of the ratio is observed (from 0.07 to 0.08 i.e. +15%) and since 1970 a decrease from 0.08 to 0.07 (-12%). The latter holds also for the section Hansweert-Bath but here the (absolute) variation has been larger. Between 1955 and 1970 an increase from 0.10 to 0.12 (+20%) followed by a systematic decrease from 0.12 to 0.08 (-30%).

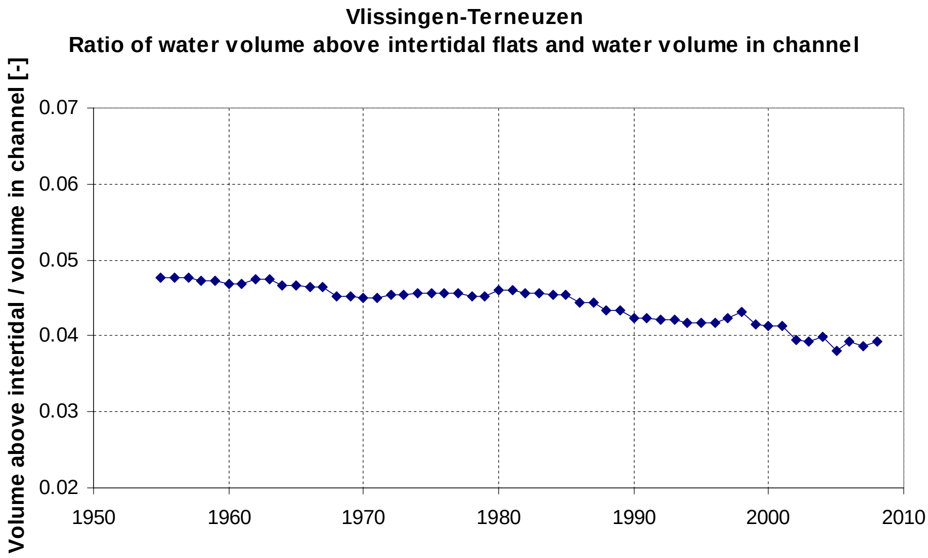



*Figure 3.15: Ratio of the water volume above the intertidal flats and the channel volume for the section Vlissingen-Terneuzen.*

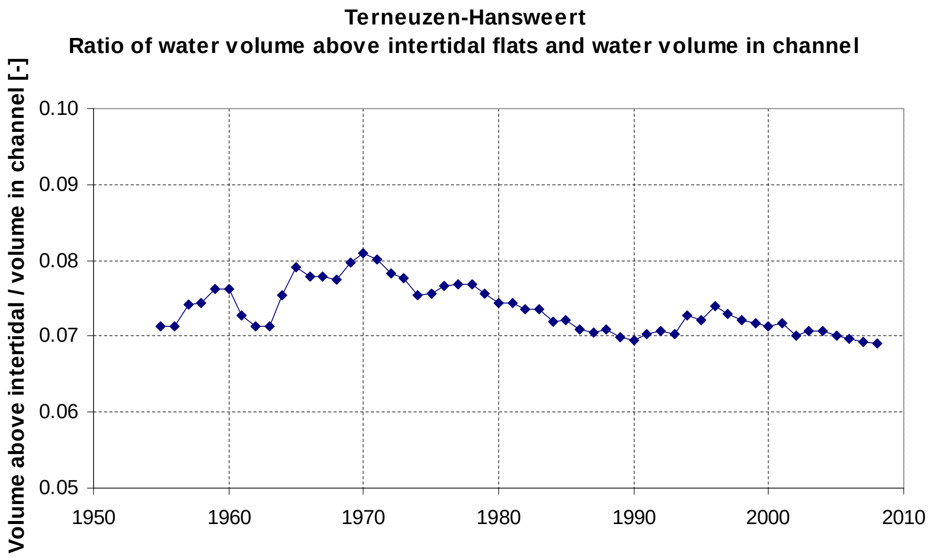



*Figure 3.16: Ratio of the water volume above the intertidal flats and the channel volume for the section Terneuzen-Hansweert.*

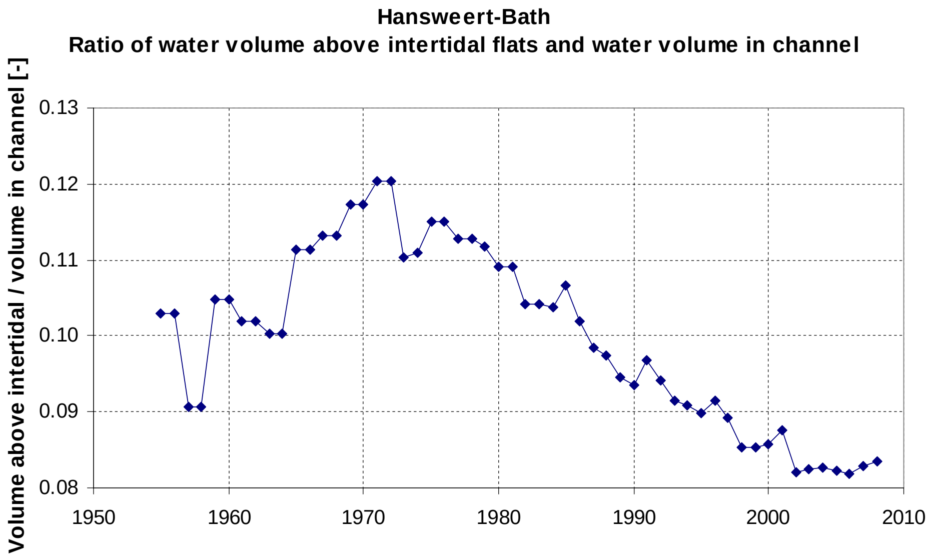



*Figure 3.17: Ratio of the water volume above the intertidal flats and the channel volume for the section Hansweert-Bath.*

### 3.4.4 Channel area at low water

The surface water area at NAP-2 m is given for the three sections in Figure 3.18 - Figure 3.20. This parameter is of interest as it is used to compute the water depth in association with the water volume below NAP-2 m. For the section Vlissingen-Terneuzen the channel area decreases between 1955 and 1980 with 0.2 $10^7$ $m^2$ (-2%) and then increases until present with 0.3 $10^7$ $m^2$ (+3%). For the section Terneuzen-Hansweert the channel area decreases between 1955 and 1970 with 0.4 $10^7$ $m^2$ (-6%) and then remains constant. Between Hansweert and Bath the variation of the channel area is similar to that of section Terneuzen-Hansweert. First the channel area decreases between 1955 and 1980 with 0.4 $10^7$ $m^2$ (-10%) and then remains constant. Between Vlissingen and Bath the channel area has decreased with 0.65 $10^7$ $m^2$ (-3%).

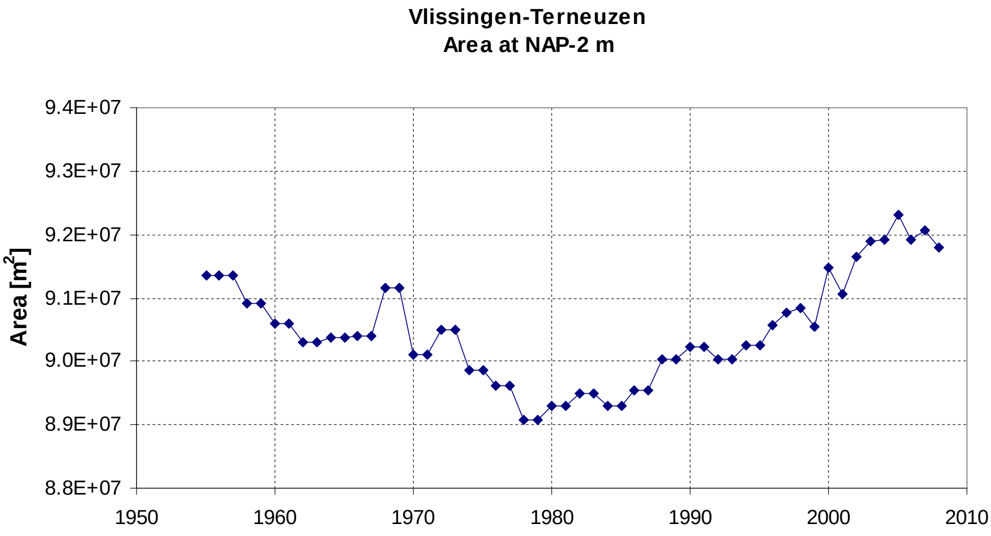



*Figure 3.18: Area of the channel at NAP-2 m for the section Vlissingen-Terneuzen.*

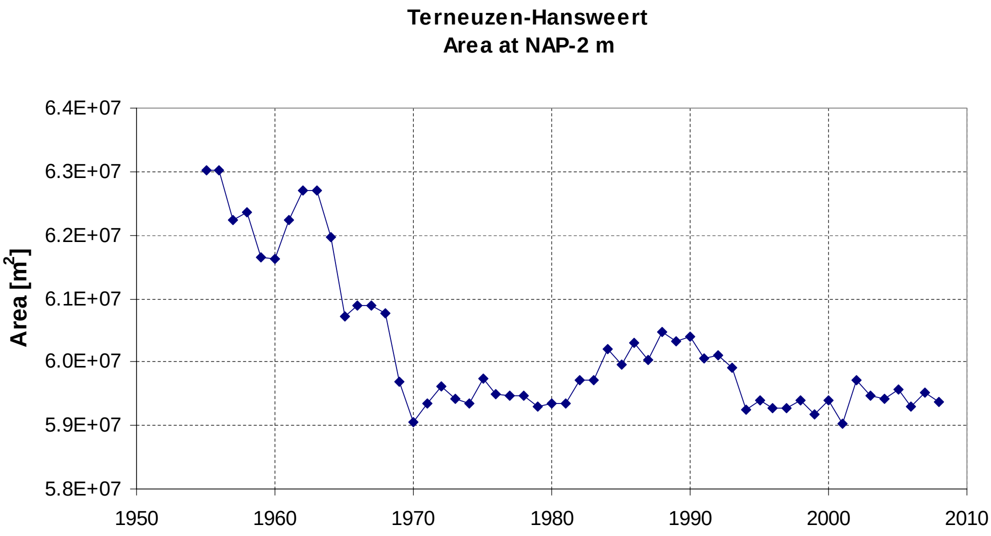



*Figure 3.19: Area of the channel at NAP-2 m for the section Terneuzen-Hansweert.*

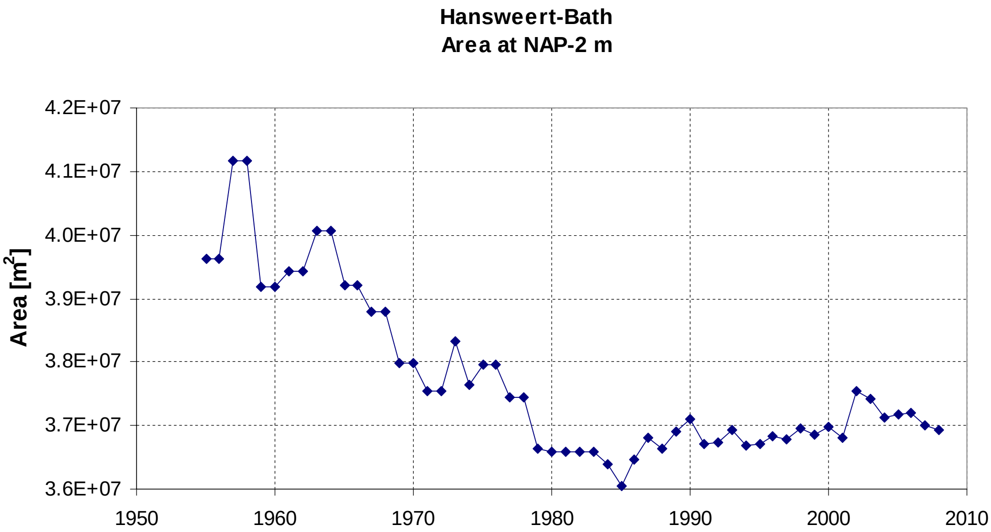



*Figure 3.20: Area of the channel at NAP-2 m for the section Hansweert-Bath.*

### 3.4.5 Channel depth

The change of the channel depth in the sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath is given in Figure 3.21 - Figure 3.23. The channel depth in the section Vlissingen-Terneuzen has increased during the period 1955-2008 by approximately 0.5 m (+3.5%). Between 1955 and 1980 there was an increase of 0.75 m followed by a slight decrease of 0.25 m during the successive period. As such the data do not show a persistent trend. Also for the section Terneuzen-Hansweert no systematic increase or decrease of channel depth can be distinguished. Variations in channel depth between 12 and 12.5 m occur (±1.5%). Since the early 90's of the 20$^{th}$ century an equilibrium seems to be established. The largest change has occurred in the section Hansweert-Bath where an increase in channel depth from 9.0 m to 11.4 m has taken place (+27%). A sharp increase of 1.0 m can be distinguished for the relatively short period of 1976-1980. This period was followed by approximately 10 years with only minor changes of the channel depth. Since the early 90's of the 20$^{th}$ century the channel depth increases again with no clear signs that equilibrium is being reached. The average channel depth between Vlissingen and Bath (not shown) has increased with 0.8 m.

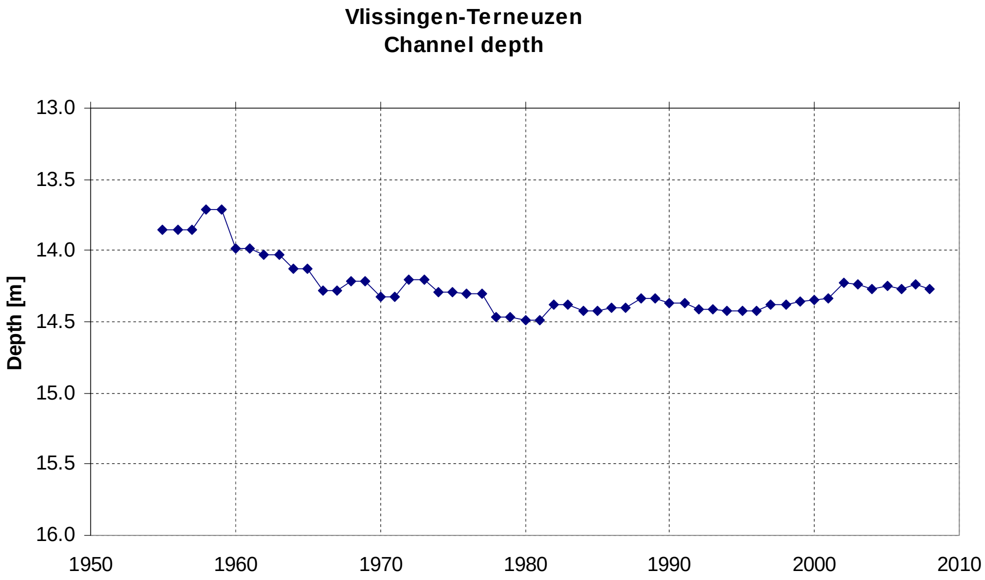



*Figure 3.21: Channel depth for the section Vlissingen-Terneuzen.*

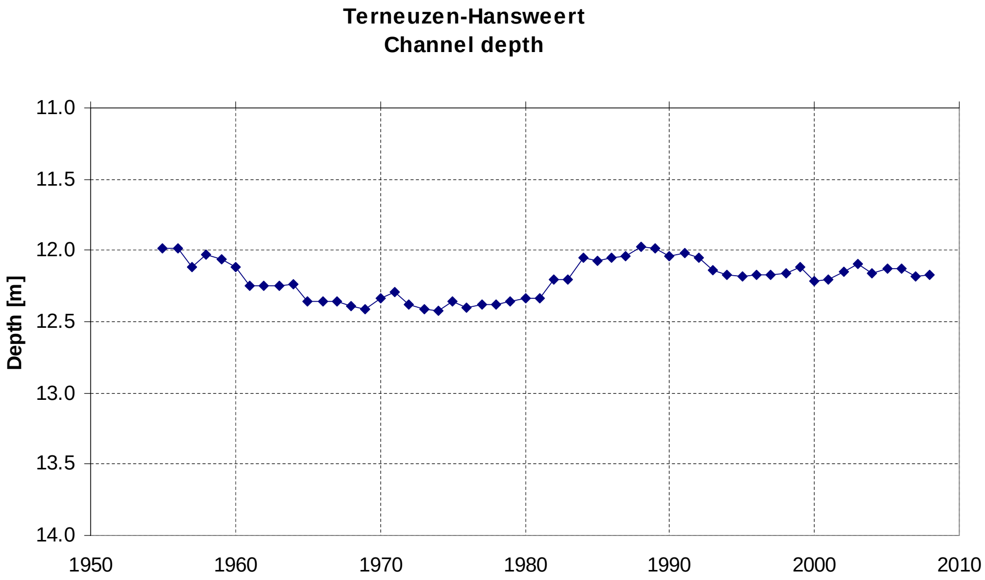



*Figure 3.22: Channel depth for the section Terneuzen-Hansweert.*

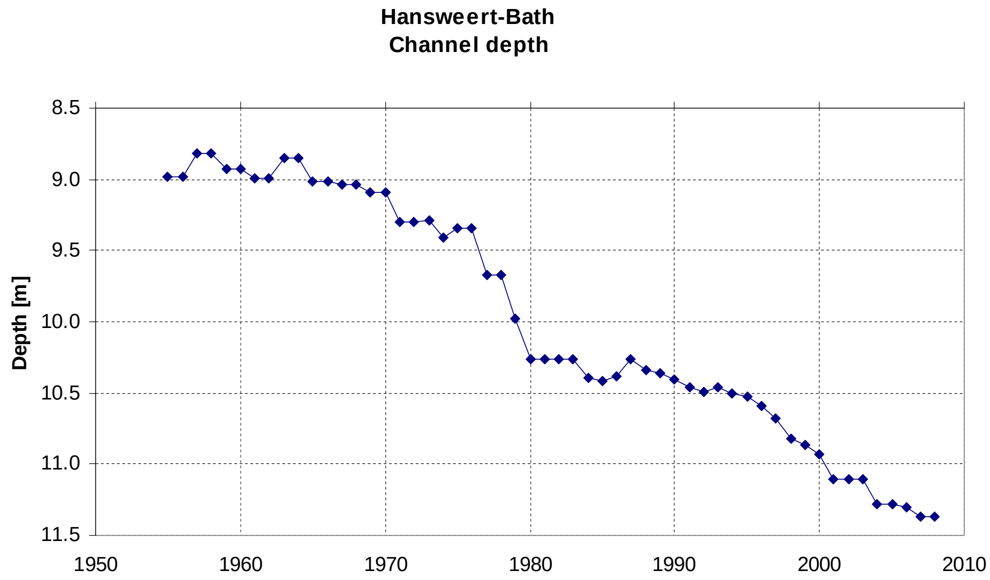



*Figure 3.23: Channel depth for the section Hansweert-Bath.*

### 3.4.6 Area intertidal flats

The area of the intertidal flats during the period 1955-2008 is given for the three sections in Figure 3.24 - Figure 3.26. For all sections the area varies within a range of 0.5 $10^7$ $m^2$ which is approximately ±8% of the long-term averaged value for the sections Vlissingen-Terneuzen and Terneuzen-Hansweert and ±15% for the section Hansweert Bath. For all sections there is an increase of the intertidal area between 1955 and 1970/1980 and a decrease during the period hereafter. The decrease of intertidal area since 1980 is most pronounced for sections Vlissingen-Terneuzen and Hansweert-Bath. Whether this decrease has come to an end since 2002 cannot be concluded from the data given the fluctuations of the intertidal area.

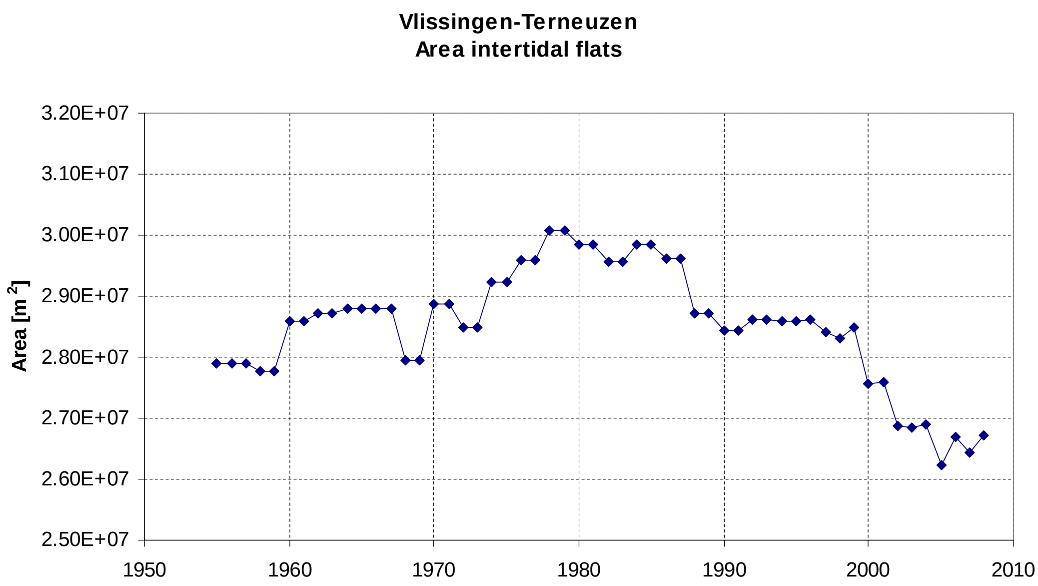



*Figure 3.24: Area intertidal flats for the section Vlissingen-Terneuzen.*

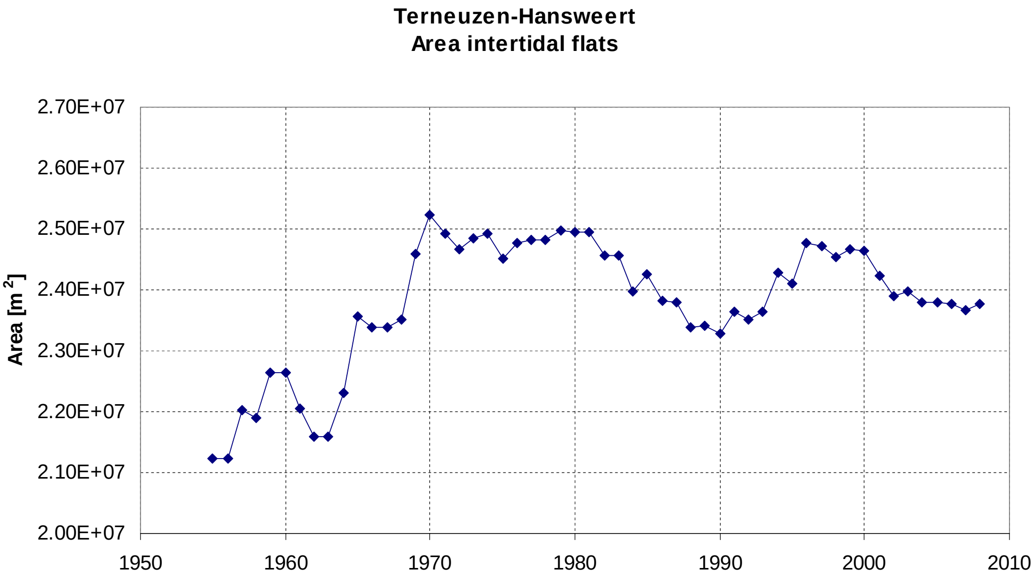



*Figure 3.25: Area intertidal flats for the section Terneuzen-Hansweert.*

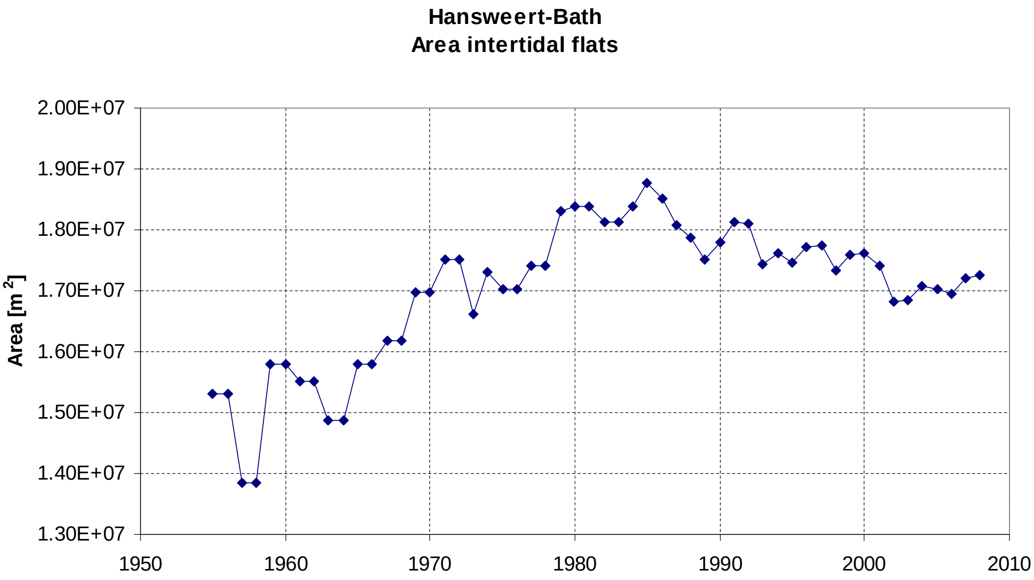



*Figure 3.26: Area intertidal flats for the section Hansweert-Bath.*

### 3.4.7 Sand volume intertidal flats

Between 1955 and 1980/1985 the sand volume of the intertidal flats, see Figure 3.27 - Figure 3.29 has changed in a similar way for all three sections, i.e. an increase of 1.0-1.5 $10^7$ $m^3$ (Vlissingen-Terneuzen: +20%; Terneuzen-Hansweert: +45%; Hansweert-Bath: +45%), see Figure 3.21 - Figure 3.23. Following this period the sand volume of the intertidal flats for the section Vlissingen-Terneuzen has decreased with 0.5 $10^7$ $m^3$ whereas the sand volume remained constant for the other two sections. For the whole period, between 1955 and 2008, the sand volume of the intertidal flats has increased for all three sections with a total of 2.7 $10^7$ $m^3$ (+25%). Thus the decrease of sand volume in the channels (which is equivalent to the increase of the water volume, see Section 3.4.1) has been accompanied with an increase of the sand volume on the intertidal flats.

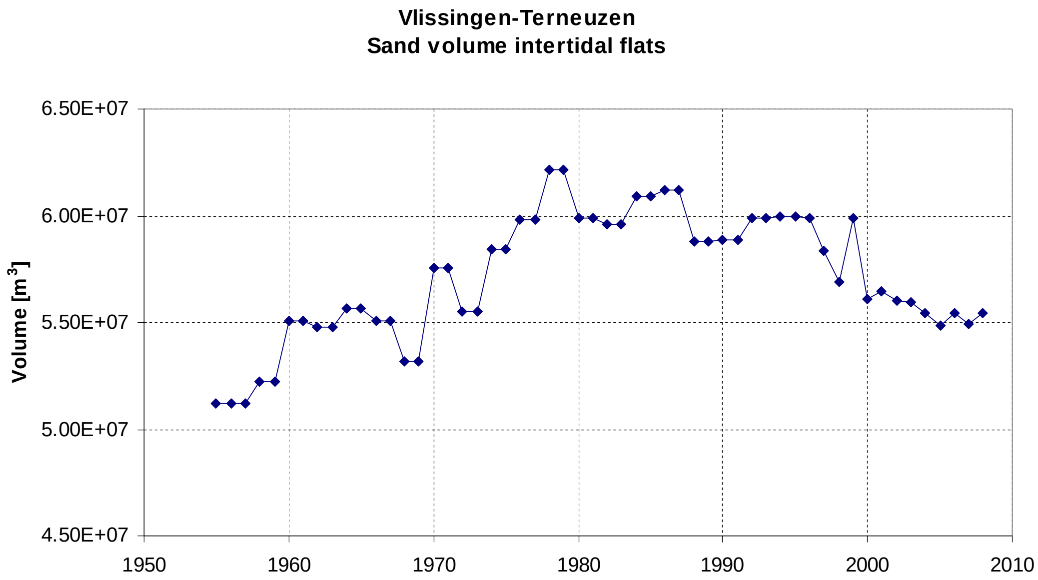



*Figure 3.27: Sand volume of intertidal flats for the section Vlissingen-Terneuzen.*

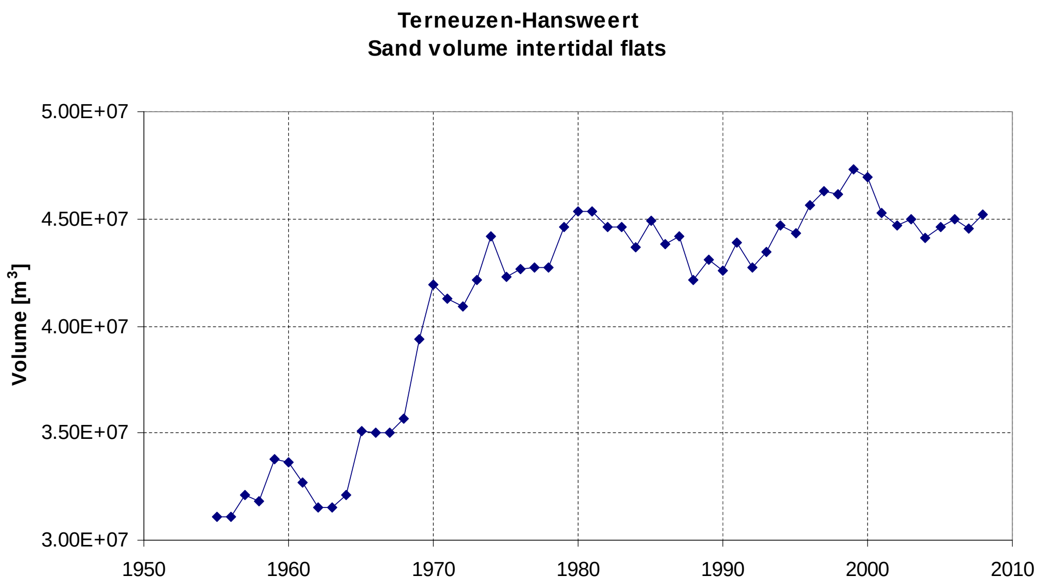



*Figure 3.28: Sand volume of intertidal flats for the section Terneuzen-Hansweert.*

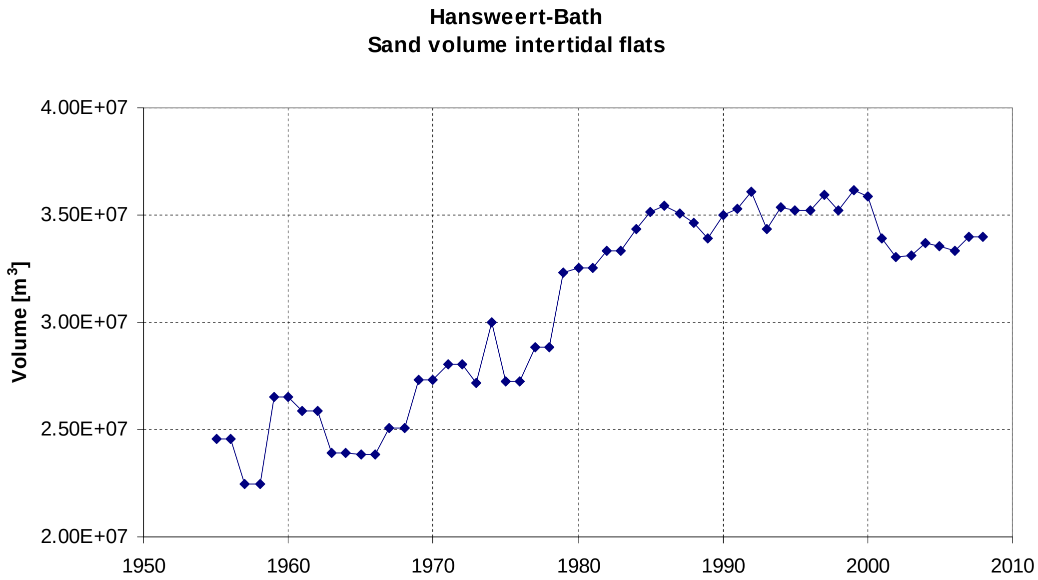



*Figure 3.29: Sand volume of intertidal flats for the section Hansweert-Bath.*

### 3.4.8 Height of intertidal flats

Changes in the sand volume and area of the intertidal flats result in an increase or decrease of the average height of the flats. The tidal flat height *relative to the lower level of the intertidal flats*, which is defined here as NAP-2.0 m, is given for the sections in Figure 3.30 - Figure 3.32. In all sections the average height of the tidal flat has increased since 1955. Between Terneuzen and Bath this increase amounted approximately 0.4 m in both sections (+25%). For the section Vlissingen-Terneuzen the height increased with 0.2 m (+10%). In the latter case the average elevation of the tidal flats is presently slightly above NAP while for the sections Terneuzen-Hansweert and Hansweert-Bath the elevation is now slightly below or around NAP. The data suggest that the average elevation of the intertidal flats cannot be much higher than the average water level (presently ≈ NAP).

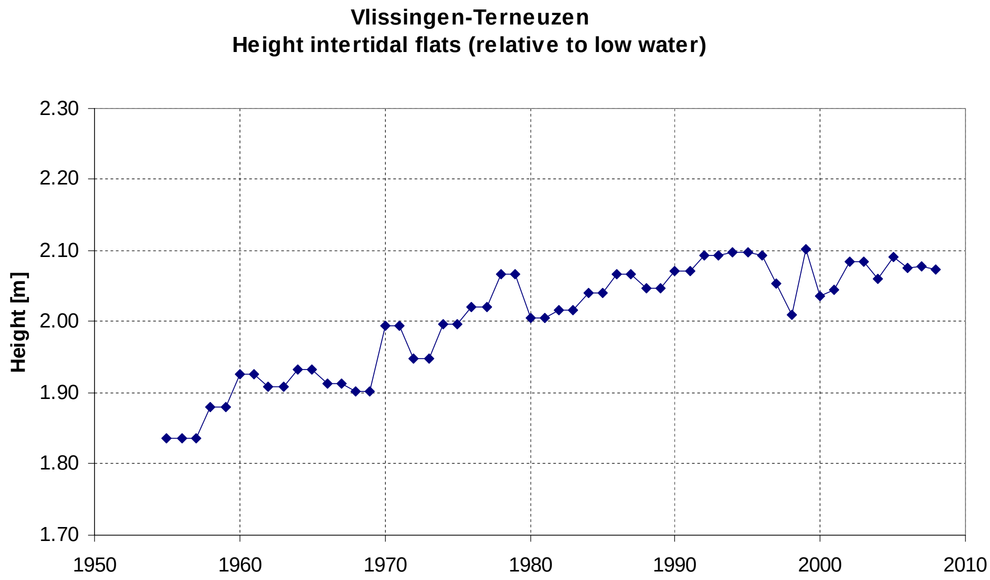



*Figure 3.30: Height of intertidal flats relative to low water (defined at NAP-2m) for the section Vlissingen-Terneuzen.*

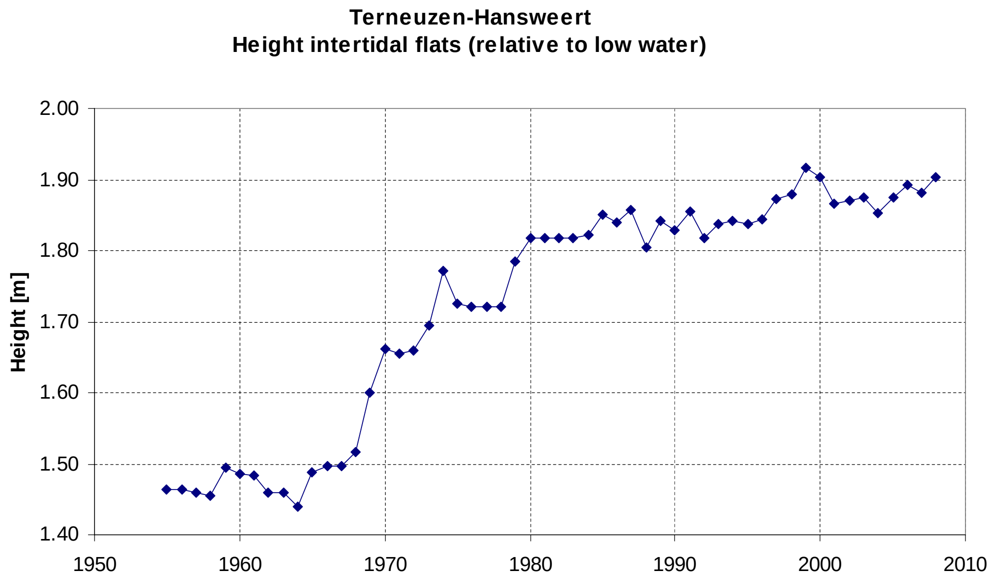



*Figure 3.31: Height of intertidal flats relative to low water (defined at NAP-2m) for the section Terneuzen-Hansweert.*

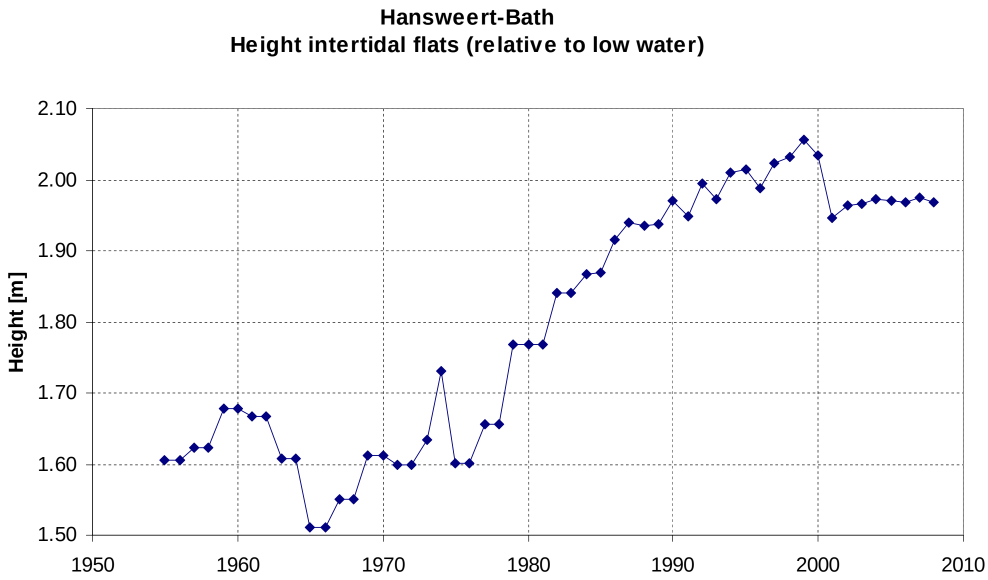



*Figure 3.32: Height of intertidal flats relative to low water (defined at NAP-2m) for the section Hansweert-Bath.*

## 3.5 Evolution of main and secondary channels

The evolution of the individual main and secondary channels for the sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath are analysed with respect to channel area at NAP-2m and channel depth relative to NAP, see Section 3.3. By definition, the water volume of the channel is equal to the channel area multiplied with the mean water depth. The schematisation is given in Figure 3.33 and resembles that of the macro cells intersected with straight lines at the locations of the water level stations. It was decided to omit the Middelplaat near Terneuzen and the Platen van Ossenisse (east) near Hansweert from the schematisation as they are difficult to assign to one of the channels. However, this may also hold for some other areas thus making this choice somewhat arbitrarily.

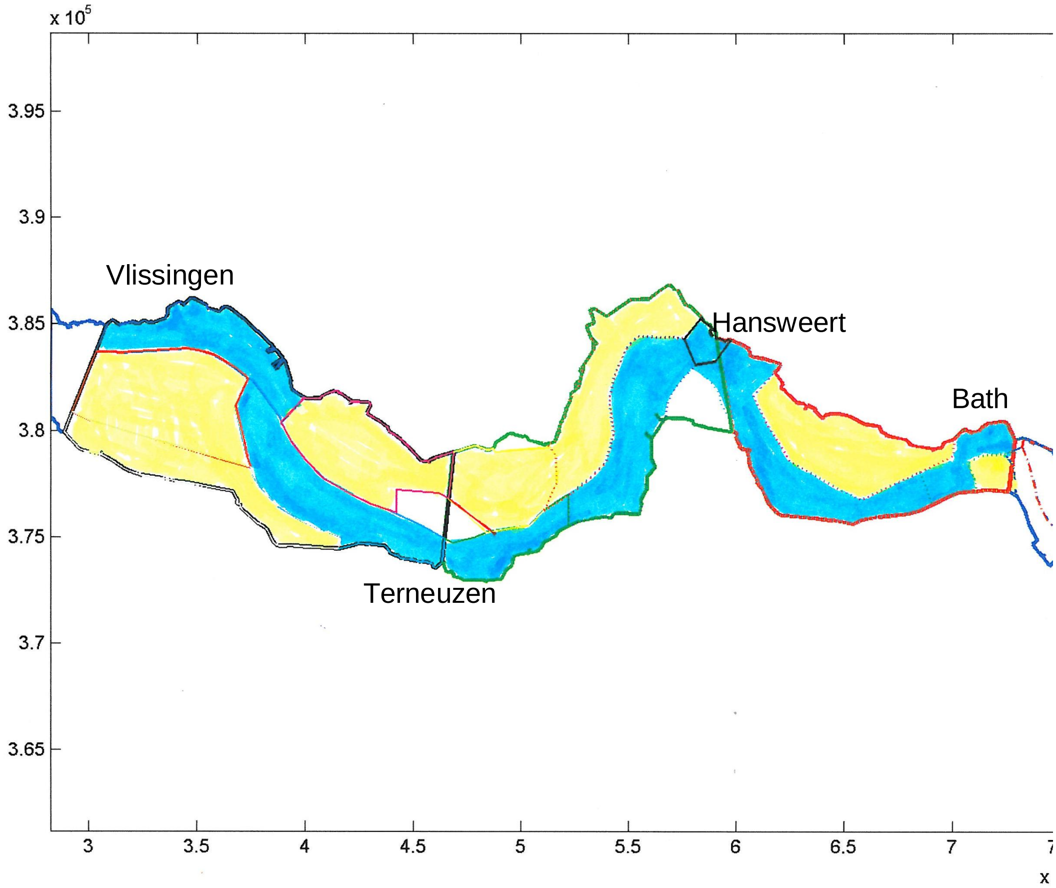



*Figure 3.33: Main channels (blue) and secondary channels (yellow).*

### 3.5.1 Channel area

Figure 3.34 gives the channel area of the main and secondary channels for each of the three sections in the Western Scheldt. Minimum and maximum values of the vertical axes are different but the ranges are equal.

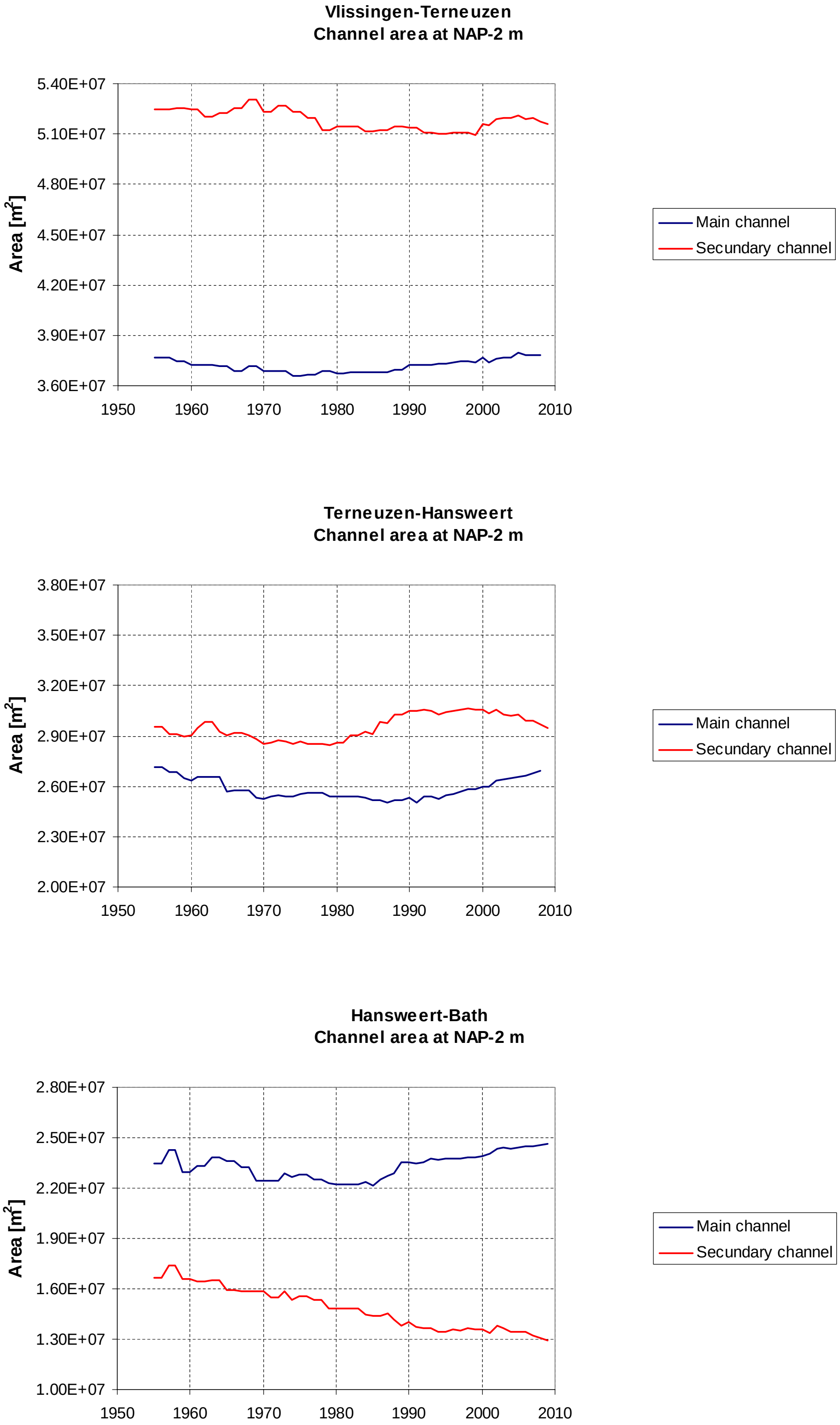



*Figure 3.34: Channel area at NAP-2m of the main channels (blue line–left axis) and secondary channels (red line–right axis) in the sections Vlissingen-Terneuzen (top), Terneuzen-Hansweert (middle) and Hansweert-Bath (bottom). Note that vertical axes have different minimum and maximum values but same range.*

The area of the main channel between Vlissingen and Terneuzen does not show a clear trend but varies a few percent over a time span of 50 years. Since 1980 the area of the main channel tends to increase whereas the area of the secondary channel has remained more or less stable. In the section Terneuzen-Hansweert the main channel area exhibits somewhat larger variations than in the previous section. It has first decreased until 1990 with 7% followed by an increase with the same magnitude until present. Between 1955 and 2008 the secondary channel has remained more or less stable showing fluctuations of a few percent and since 2000 decreasing in channel area. The main channel of the section Hansweert-Bath displays a downward trend (decreasing area) between 1955 and 1985 (~8%) followed by an upward trend (~10%) since then. Of all sections the change of the area of the secondary channel is most pronounced showing a persistent downward trend since 1955 (~30%).

In general, the areas occupied by the main channels have decreased by a few percent between 1955 and 1980/1990 and since then increased with approximately the same magnitude. The secondary channels in the sections Vlissingen-Terneuzen and Terneuzen-Hansweert are more or less dynamically stable with variations of about 5%. The secondary channel between Hansweert and Bath displays a significant and persistent downward trend indicating that the area occupied by the channel has decreased with 30%.

### 3.5.2 Channel depth

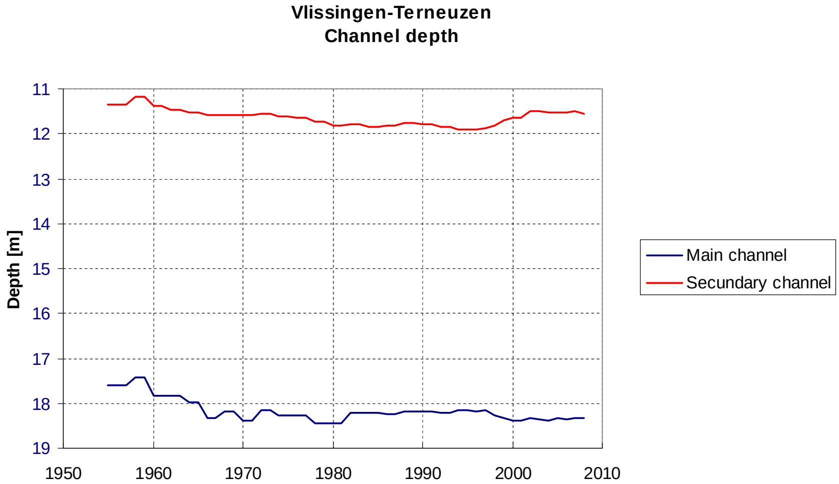
Figure 3.35 gives the channel depth of the main and secondary channels for each of the three sections in the Western Scheldt. Minimum and maximum values of the vertical axes are different but the ranges are equal for the three sections.

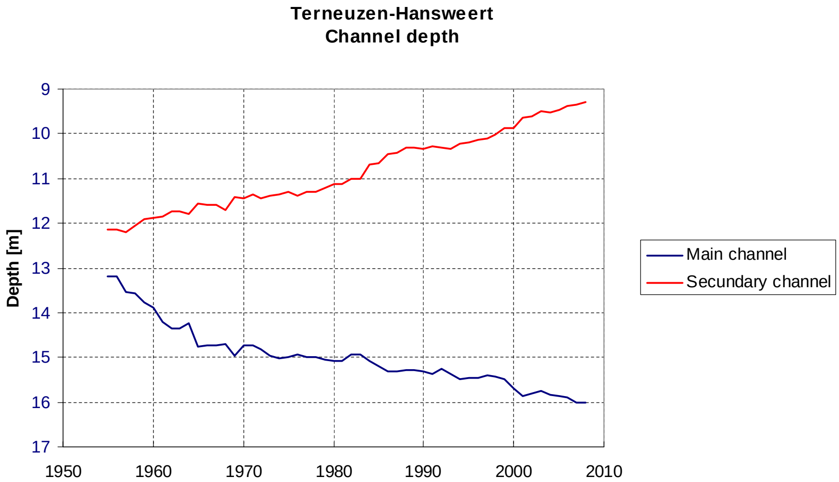
Before 1970 the depth of the main channel between Vlissingen and Terneuzen has slightly increased (~1 m) but since then remained stable. The secondary channel displays a minor trend with the channel depth increasing by about 0.5 m until 1995. Since then the depth has decreased to some extent so that the overall change is almost nil. Between Terneuzen and Hansweert changes of channel depth for both the main and the secondary channel have been significant. The main channel (Gat van Ossenisse and Overloop van Hansweert) has deepened since 1955 by 3 m at the expense of the secondary channel (Middelgat) showing an opposite trend with the same magnitude. Initially, the channel depths only differed 1 m but this difference has increased to almost 7 m at present. There are no signs that this development approaches equilibrium. Similarly, the main channel depth between Hansweert and Bath has increased with 3 m since 1955. Between 1980 and 1995 this evolution has temporarily stopped but since then seems to regain its former behaviour. The secondary channel displays less fluctuation in water depth although there seems to be a trend with increasing depth since 1980.

In general all main channels exhibit an increasing water depth with major changes between Terneuzen and Bath that are still continuing. The secondary channel between Terneuzen and Hansweert is the only channel which is shoaling without signs of reaching equilibrium. The other two secondary channels are either in equilibrium (Vlissingen-Terneuzen) or eroding since 1980 (Hansweert-Bath).

Finally, the evolution of the individual channels for each section is compared with the evolution of the overall bathymetry, i.e. without making distinction between the two channels. Between Vlissingen and Terneuzen the initial (slight) erosion of both channels followed by a period with equilibrium is reflected by what has been shown in

Figure 3.21 for the overall bathymetry of this section. This is contrary to what is shown in Figure 3.22 for the overall bathymetry between Terneuzen and Hansweert. Merging both channels into one completely masks the major changes of the individual channels. Apparently, the evolution of the individual channels did not have a major impact on tidal propagation given the unchanged amplification and tidal propagation velocity between both stations. For the section Hansweert-Bath the increasing depth of the overall bathymetry between 1970 and 1980 is mainly caused by the deepening of the main channel. The overall deepening since 1990 firstly results from net erosion of the secondary channel (until 2000) and since then from erosion of both channels.



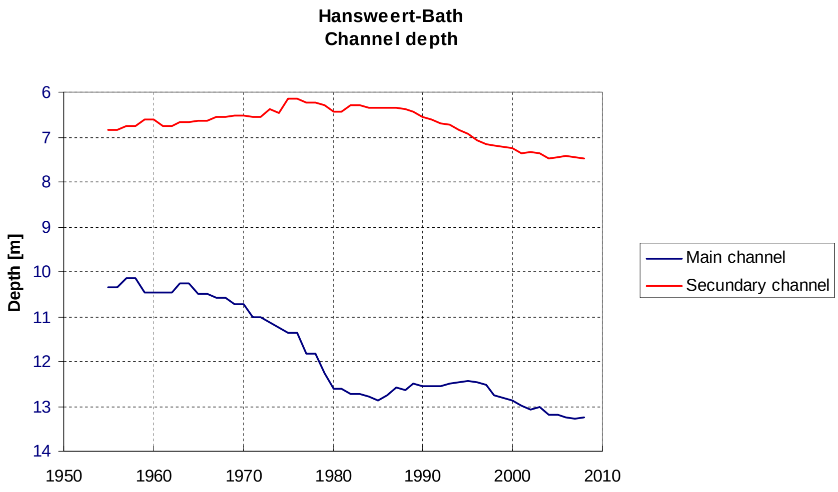



*Figure 3.35: Channel depth relative to NAP of the main channels (blue line–left axis) and secondary channels (red line–right axis) in the sections Vlissingen-Terneuzen (top), Terneuzen-Hansweert (middle) and Hansweert-Bath (bottom). Note that vertical axes have different minimum and maximum values but same range.*

## 3.6 Summary

Seaward of Hansweert the channel depth varies within a range of approximately 0.5 m. Between Hansweert and Bath the channel depth has increased considerably since 1955 without showing signs that an equilibrium is approached. The question here is to what extent the deepening of the channel has been affected by means of net dredging (= dredging minus dumping) and sand mining.

The area of the intertidal flats shows largest fluctuations on a time scale of decades and minor fluctuations from year to year. Since 1980 there seems to be a decreasing trend in intertidal area which is most apparent for the section Vlissingen-Terneuzen. The data suggest that since 1980 the channel area in this section has increased.

Since 1980 there is a negative trend for all three sections with respect to the water volume above the intertidal flats. This may have resulted in a larger tidal propagation velocity (because of less storage) and a change in tidal asymmetry. Although the changes are not large it is noted that they have occurred for the whole Western Scheldt between Vlissingen and Bath.

During the period 1955-2008 the sand volume of the intertidal area has increased for all three sections of the Western Scheldt. The major changes have taken place before 1980. Since 1980 the sand volume has remained constant between Terneuzen and Bath while the volume has decreased between Vlissingen and Terneuzen.

For the main and secondary channels of each section the decrease of channel area of the secondary channel between Hansweert and Bath is most pronounced (-30%). For all other channels variations of a few percent are on time scales of decades without any clear trends.

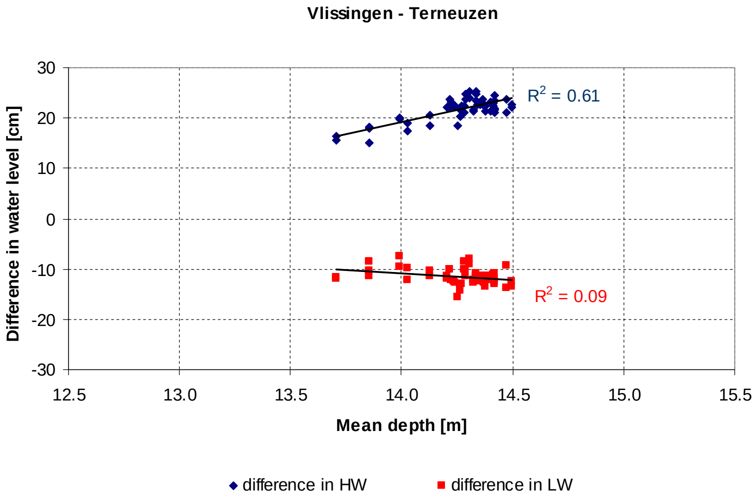
Between Terneuzen and Hansweert significant changes have occurred regarding channel depths of main and secondary channel. Since 1955 the main channel (Gat van Ossenisse-Overloop van Hansweert) has deepened with 3 m while the secondary channel (Middelgat) has become shallower with the same magnitude. Apparently the opposite trend of both channels has not affected tidal propagation as the tidal amplification and propagation velocity has remained more or less constant during this period. Also the main channel between Hansweert and Bath shows since 1955 an increasing trend with respect to channel depth although the channel has remained stable between 1980 and 1995. Since then, channel depth increases again. The secondary channel for this section shows smaller variations although the channel depth seems to increase1985. The main and secondary channels between Vlissingen and Terneuzen are rather stable.

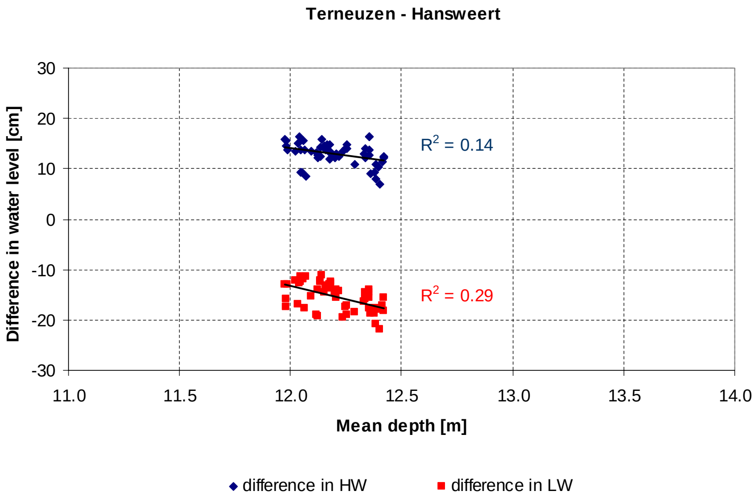
# 4 Relations between tidal and topo-bathymetric data

The previous chapters have dealt with the evolution of tidal characteristics (Chapter 2) and bathymetric characteristics (Chapter 3). In this chapter relationships between both will be investigated between both using scatter plots.

## 4.1 High and low waters versus water depth

Figure 4.1 shows the differences between the yearly-averaged high water in the landward and seaward station of the sections Vlissingen-Terneuzen, Terneuzen-Hansweert and Hansweert-Bath as a function of channel depth. Similarly, the differences for the yearly-averaged low waters are presented. The same ranges for the horizontal and vertical axis have been used for the three sections.



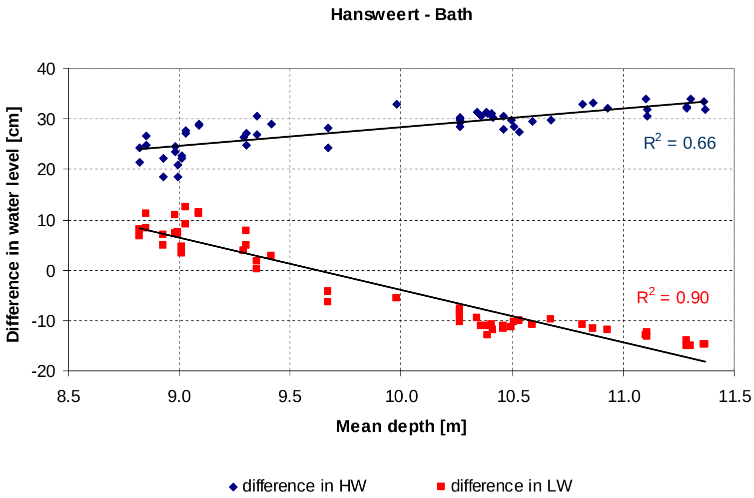



*Figure 4.1: Difference in high water and low water (landward minus seaward station) versus channel depth for the sections Vlissingen-Terneuzen (upper), Terneuzen-Hansweert (middle) and Hansweert-Bath (bottom).*

From Figure 4.1 it follows that:

- Between Vlissingen and Terneuzen high waters increase with increasing channel depth and low waters decrease slightly (lower low waters) although the latter has low significance.
- Between Terneuzen and Hansweert both high and low waters seem to decrease with increasing channel depth although significance is low because of the minor changes in channel depth.
- Between Hansweert and Bath high waters increase and to a larger extent low waters decrease (lower low waters) with increasing channel depth. It is noted that for relatively small depth changes of 0.5 m the effect on high and low waters may not be significantly derived from the observations.

For the section Hansweert-Bath low waters appear to be more sensitive to depth changes than high waters. This is because the effect on roughness and energy dissipation is larger at smaller water depths during low water in comparison with larger water depths at high water. It is not clear why the response of high and low waters to depth changes is opposite for the section Vlissingen-Terneuzen. Possibly, effects of the hypsometry (including storage on intertidal flats) and tidal asymmetry play a role in this.

## 4.2 Amplification of tidal range versus water depth

The amplification of the tidal range (*Ampl*) is related to the difference in tidal range between two successive stations 1 and 2 ($TR_2$-$TR_1$) as follows:

$$\frac{TR_2 - TR_1}{TR_1} = \frac{TR_2}{TR_1} - 1 = Ampl - 1$$

with

$$Ampl = \frac{TR_2}{TR_1}$$

Hereafter, the amplification rather than ($TR_2$-$TR_1$) is shown as it is used by analytical models on tidal propagation. The amplification for the three sections is given in Figure 4.2.

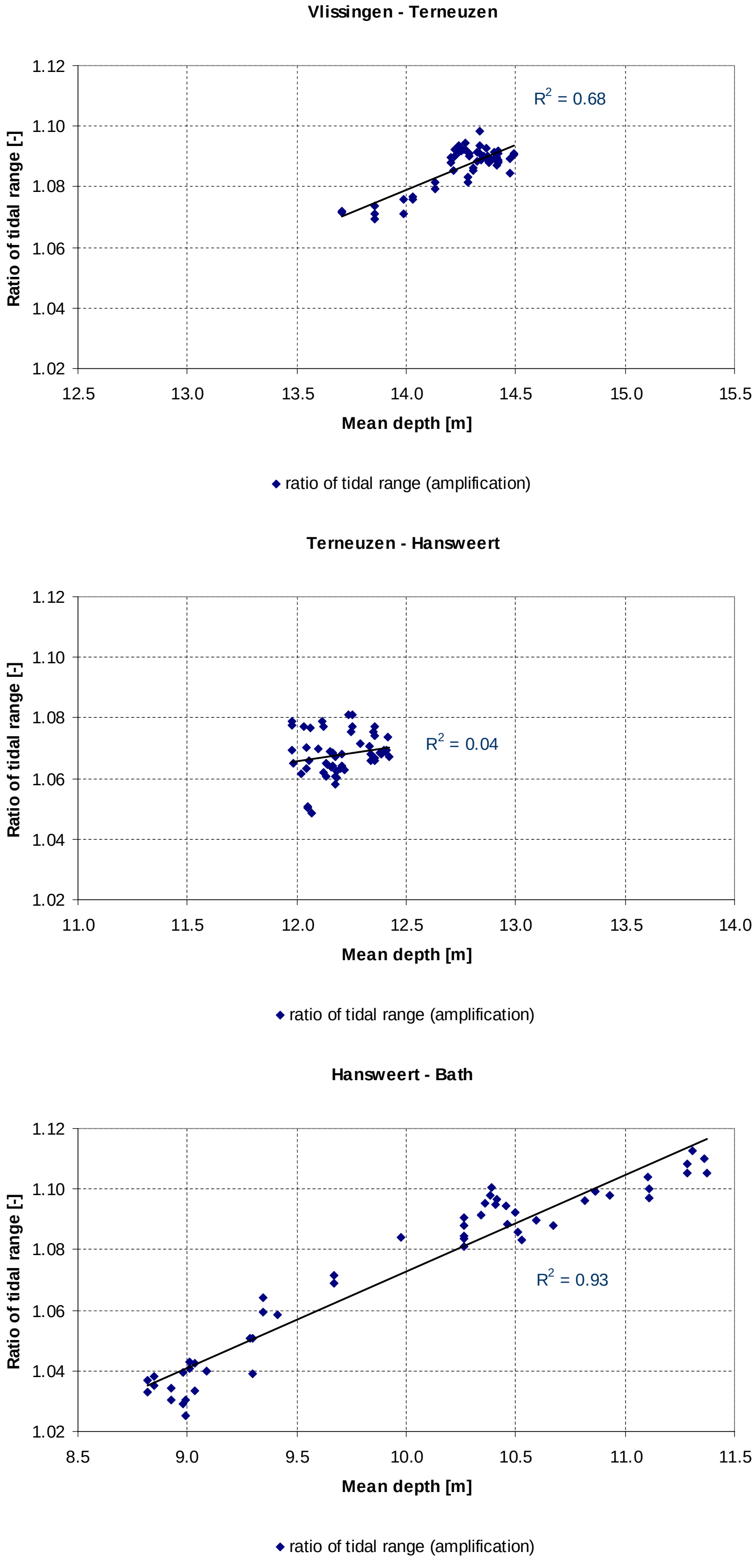



*Figure 4.2: Ratio of tidal range (landward over seaward station) versus mean water depth for the sections Vlissingen-Terneuzen (upper), Terneuzen-Hansweert (middle) and Hansweert-Bath (lower).*

The data in Figure 4.2 has been approximated with linear regression lines, which is in fact an arbitrarily choice not supported by physical reasoning. This also holds for the second order polynomial as used in Figure 4.3 for the section Hansweert-Bath. However this approximation of the data seems to indicate that at larger depths the rate of increase of amplification decreases with depth.

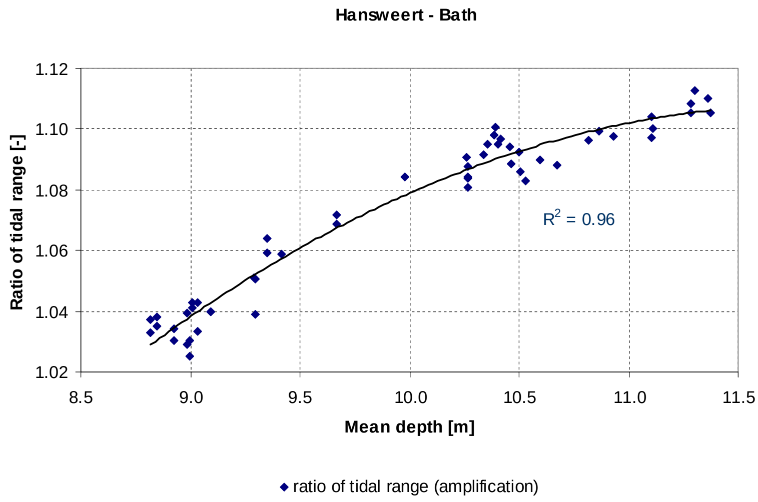
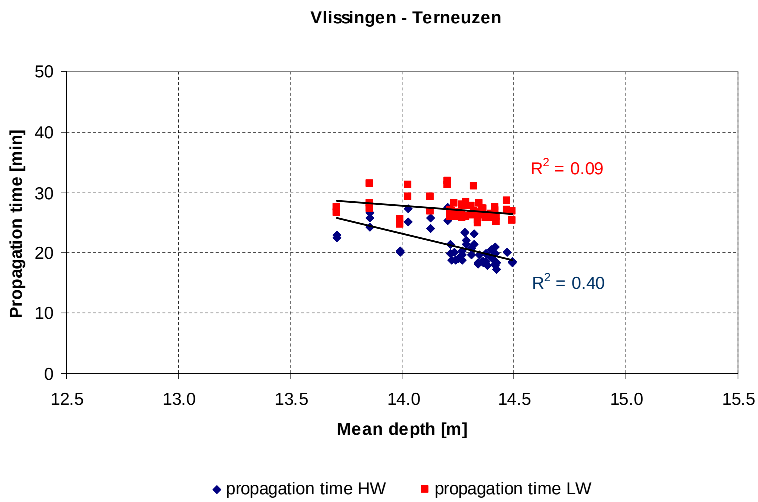



*Figure 4.3: Ratio of tidal range (landward over seaward station) versus mean water depth for the section Hansweert-Bath approximated with a 2nd order polynomial.*

## 4.3 Propagation time versus water depth

The propagation time of the high and low waters between two successive stations are given in Figure 4.4 as a function of channel depth.



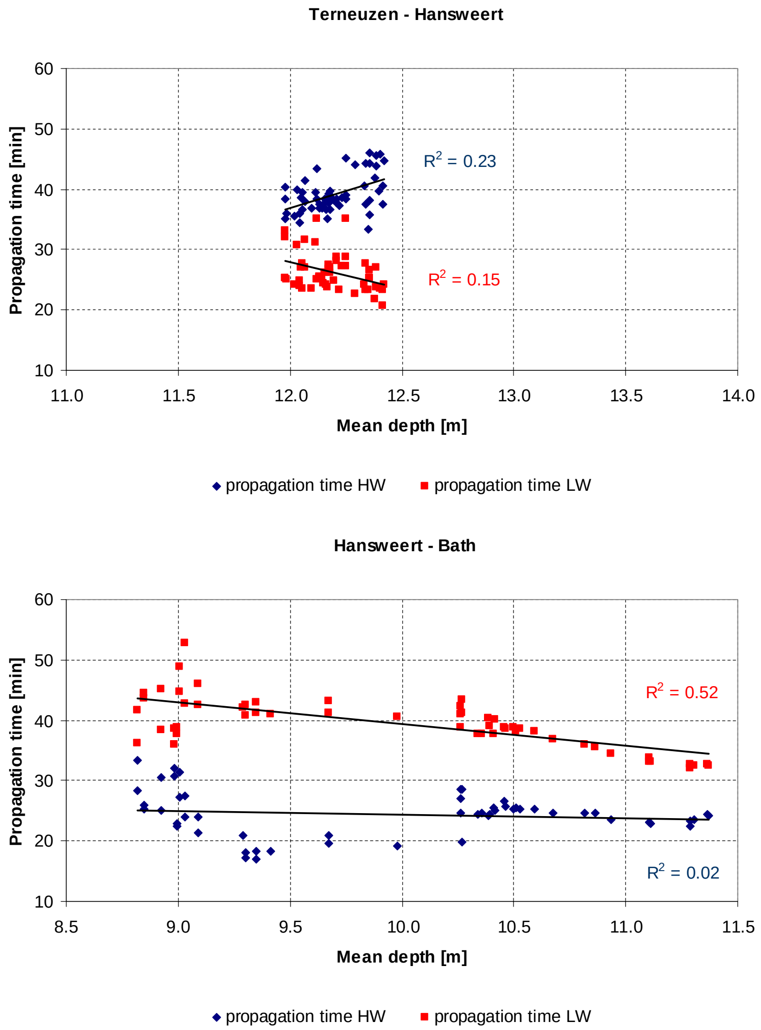



*Figure 4.4 Propagation time versus mean water depth for the sections Vlissingen-Terneuzen (upper), Terneuzen-Hansweert (middle) and Hansweert-Bath (lower).*

- From Figure 4.4 it follows that there is no clear relation between propagation time and channel depth, although the propagation time of the low waters seems to decrease with increasing channel depth (i.e. the propagation velocity increases). This dependency can also be observed for the propagation time of the high waters between Vlissingen and Terneuzen.
- the propagation time of the high water between Hansweert and Bath is not very much affected by the large depth changes within this section.

It seems that the relatively large scatter of the data (sometimes in the order of 5-10 min[10]) masks a possible dependency of propagation time on channel depth. These variations are relatively large compared with the actual values which are in the order of 20-40 min.

[10] *This may be caused by the low sampling frequency of 1-3 hrs before 1987.*

# 5 Human interventions in the Western Scheldt since 1860

This chapter explores whether human interventions in the Western Scheldt may have affected tidal characteristics in the estuary. Distinction can be made between effects that occur immediately after an intervention and effects that occur on a longer time scale due to morphological adaptation. The latter will not be addressed hereafter as it is difficult to isolate effects of man-made changes from effects that have a natural cause (through morphologic development of the system). Attention will focus on yearly-average values of high and low waters and tidal range. Conclusions on possible effects of interventions are only based on visual inspection of the graphs without statistical analysis or such[11]. Sand mining and dredging and dumping within the estuary will not be considered as these are on-going activities for which it is not easy to separate possible effects from other causes.

A more detailed analysis has been carried out as part of LTV V&T to relate large-scale sediment processes to changes in propagation and distortion of the tide (LTV V&T-report G-4). For this purpose Fourier analyses have been performed for successive periods of 25 hr (1971-1986) and 24 hr 50 min (1986-present) to derive amplitudes and phases of the semi-diurnal, quarter-diurnal and M6 components. Attention focuses on amplification of the amplitudes of the semi-diurnal component and the phase difference between the semi-diurnal and quarter-diurnal component. The latter is believed to be of special importance for the net sediment transport in longitudinal direction and thus for the morphological processes and sediment budgets in the Western Scheldt.

## 5.1 Effect of land reclamation in the 20th century

Mol (1995) gives an overview of land reclamation works in the Western Scheldt since 1800. Given the availability of water level data only the works since 1862 have been considered hereafter. Total reclaimed areas of Zwin, Braakman, Hellegat, Saeftinge, Sloe en Bath e.o. are shown in Figure 5.2; for locations see Figure 5.1.

*[11] The effect of the second deepening of the navigation channel (1997-1998) on the low waters at Bath is discussed in somewhat more detail as this was found to be statistically significant as part of the monitoring project MOVE (van Eck, Holzhauer, 2006). See Section 5.3.*

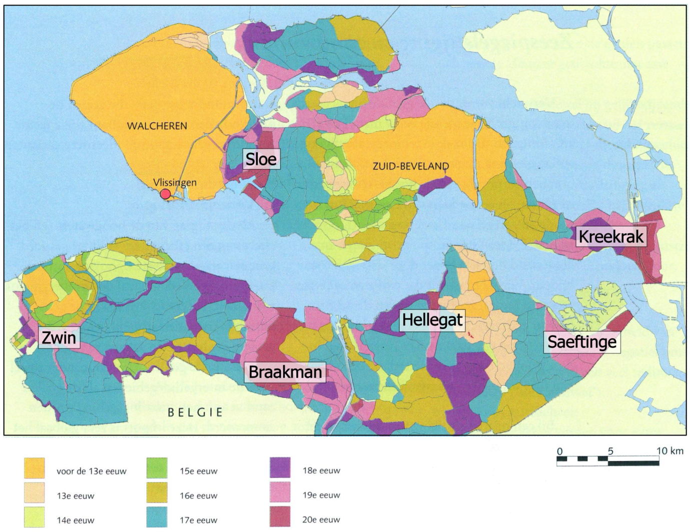



*Figure 5.1: Land reclamation works along the Western Scheldt (Vroon, 1997).*

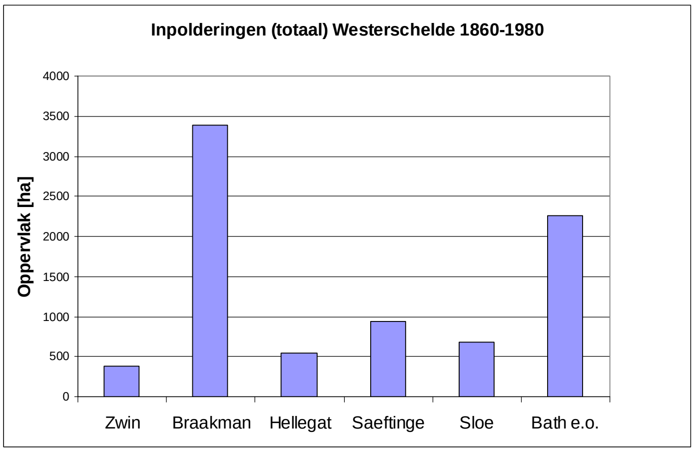



*Figure 5.2: Total reclaimed area between 1860 and 1980 in the Western Scheldt (data from Mol, 1995).*

Figure 5.3 presents the reclaimed areas per decade for each of the locations.

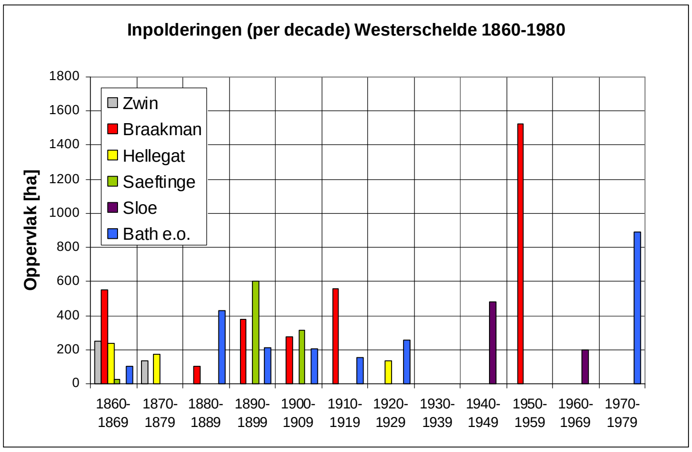
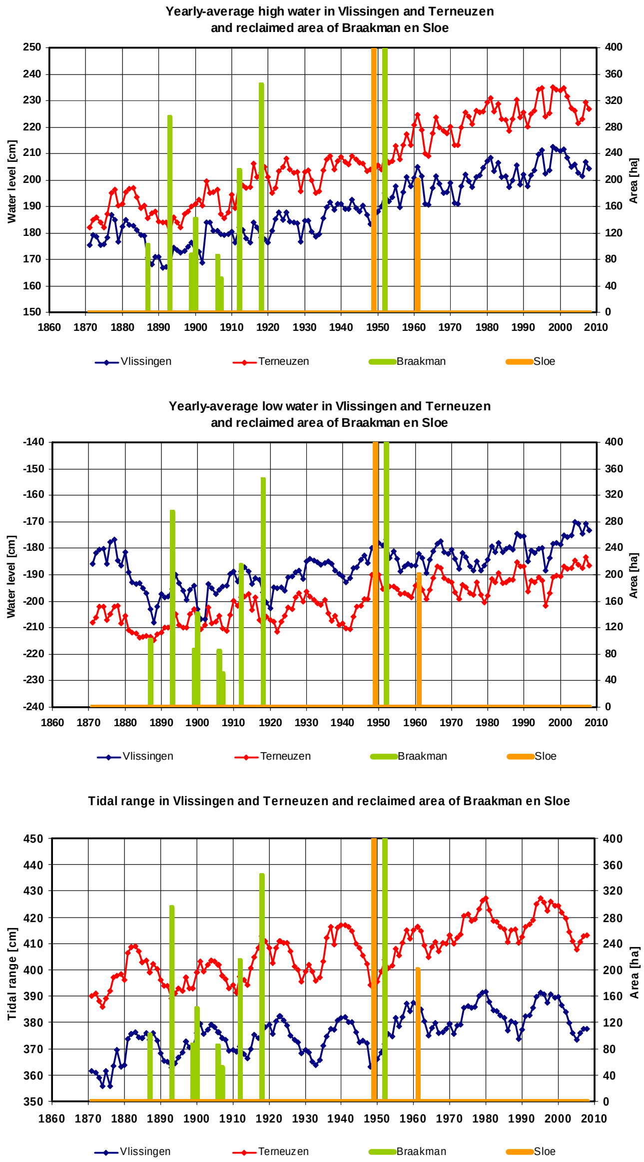



*Figure 5.3: Reclaimed areas per decade between 1860 and 1980 in the Western Scheldt (data from Mol, 1995).*

Figures 5.2 and 5.3 indicate that the major reclamation works since 1860 relate to the Braakman (~3400 ha) and to a lesser extent Bath (2250 ha). Since 1860 the total of 7800 ha of all reclaimed areas excluding Zwin[12] is approximately 33% of the present-day Western Scheldt area at NAP between Vlissingen and the Dutch-Belgium border (240 $km^2$). Effects on the tidal volume were probably less because areas may have been above low water level during reclamation. However, no precise data on this are available.

Figure 5.4 presents the yearly-average high and low waters and the tidal range in Vlissingen and Terneuzen, the amplification of the tidal range between both stations (all left axes) and the reclaimed areas of Sloe and Braakman (right axes). Similarly, Figure 5.5 presents the yearly-average high and low waters and the tidal range in Hansweert and Bath, the amplification of the tidal range between both stations and the reclaimed areas of Saeftinge and Bath.




[12] *Connected with the outer delta and not with the Western Scheldt.*

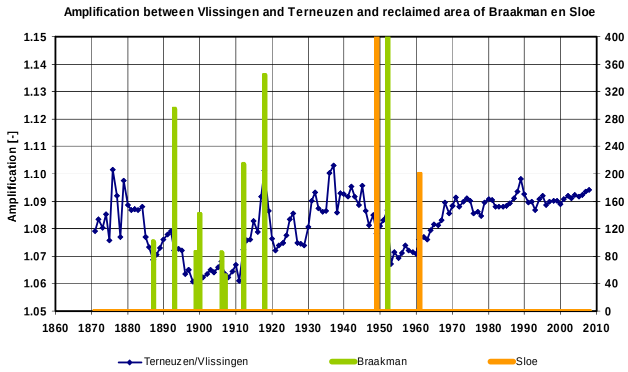
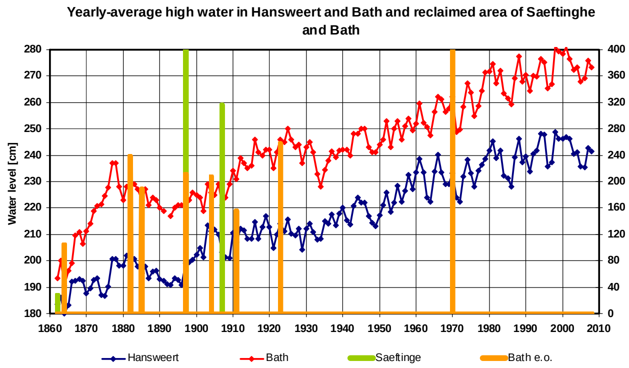
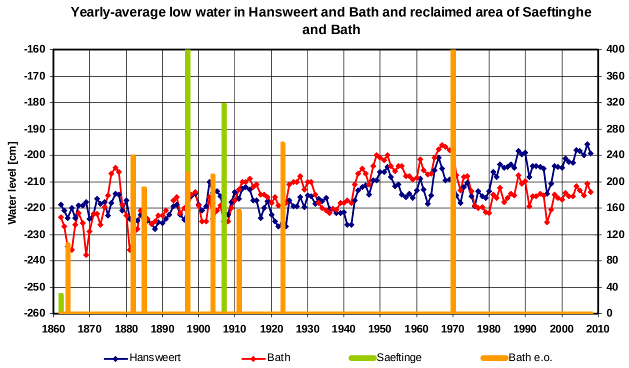
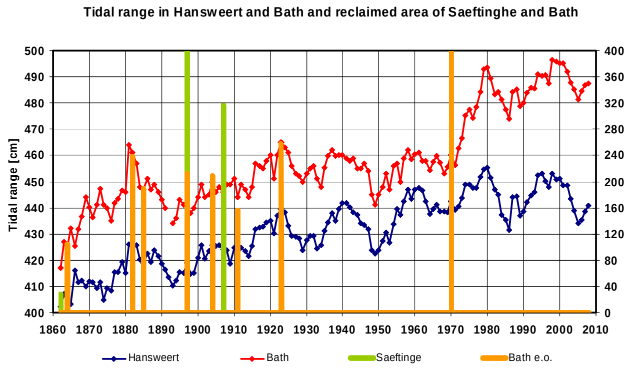



*Figure 5.4: Yearly-average high water, yearly-average low water, yearly-average tidal range and amplification between Vlissingen and Terneuzen with area of land reclamation of Braakman and Sloe.*



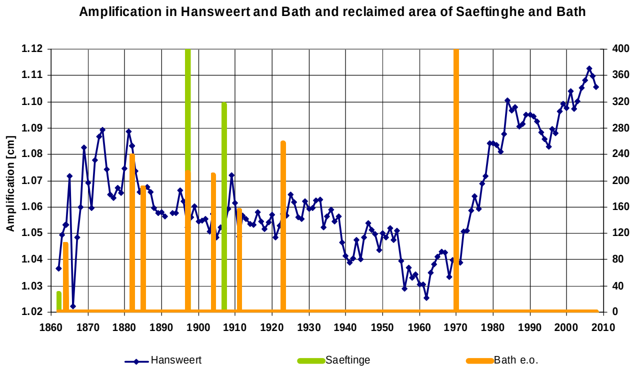



*Figure 5.5: Yearly-average high water, yearly-average low water, yearly-average tidal range and amplification between Hansweert and Bath with area of land reclamation of Saeftinge and Bath.*

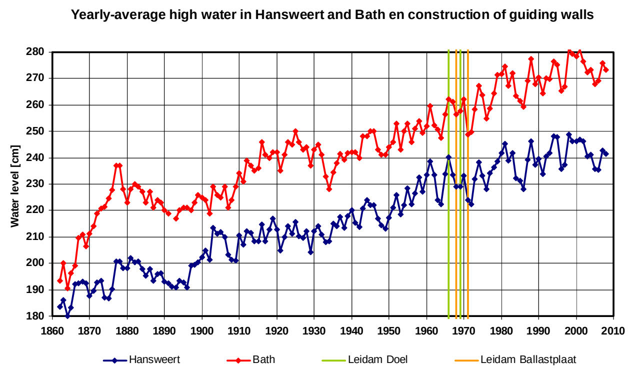
From the figures it can be derived that no effects of land reclamation works on the tidal characteristics follow. In fact, inter-annual variability masks effects if present.

## 5.2 Structures (guiding walls)

Between 1966 and 1969 the guiding wall ('leidam') at Plaat van Doel was constructed. The length is 2 km and its height at the connection with the dike at NAP+3.6 m (TAW+5.9 m) rapidly decreasing to NAP-1.4 m (TAW+0.9 m). Between 1968 and 1971 a 2nd guiding wall was constructed at the Ballastplaat. The length is 3 km and its height at the connection with the dike at NAP+5.3 m (TAW+7.6 m) decreasing to NAP-2.4 m (TAW-0.1 m).

Figure 5.6 presents the yearly-average high and low waters and the tidal range in Vlissingen and Terneuzen, the amplification of the tidal range between both stations and the periods during which both guiding walls were constructed.

No immediate effects of the guiding walls on the tidal characteristics, larger than the inter-annual variability, follow from Figure 5.6.



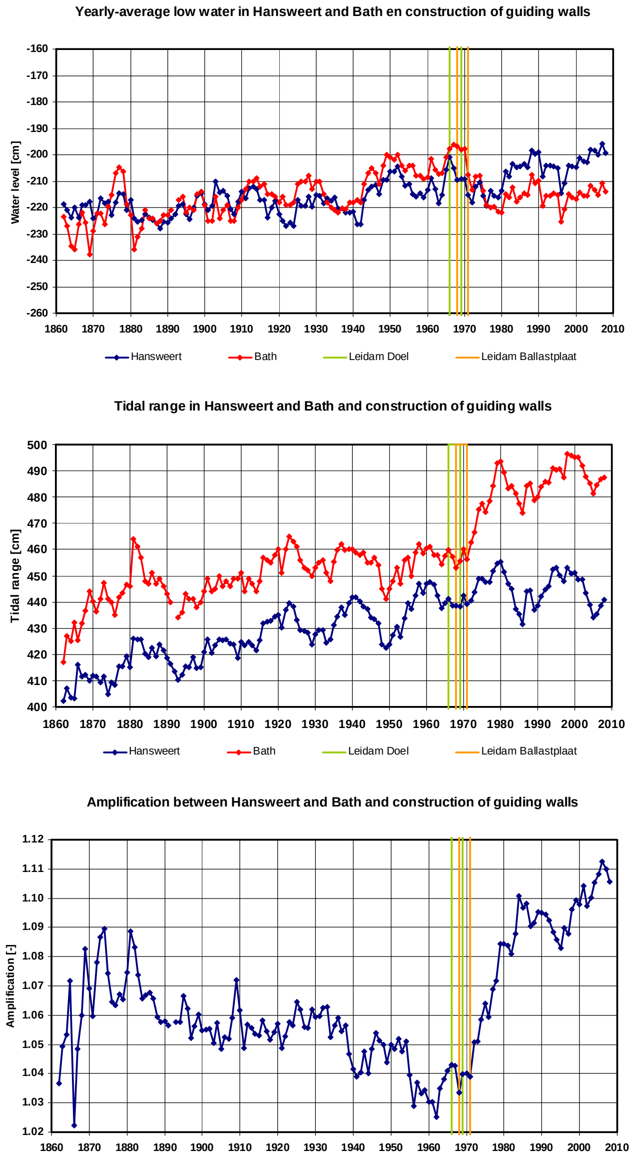



*Figure 5.6: Yearly-average high water, yearly-average low water, yearly-average tidal range and amplification between Hansweert and Bath with construction periods of guiding walls (leidammen Plaat van Doel and Ballastplaat).*

## 5.3 Deepening of the navigation channel

Before 2008 there have been two periods during which the navigation channel was deepened[13]. The first period started with the lowering of the sill at Bath at the end of the 60's of the last century, and ended in 1979 with the deepening of the sill at Hansweert. However, the exact dates of this first deepening are not exactly known. During these works the sills were lowered with 2.5-3 m until a depth of 12 m below mean lowest low water spring (ÑAP-14.7 m). The second deepening was between July 1997 and July 1998, however the sill at Vlissingen was deepened in 1999 and the channels in the mouth of the Western Scheldt in 2000. Furthermore, dredging was done in 2000 and 2001 to increase the width of the navigation channel in certain locations. The lowering

*[13] Maintenance dredging works at the sills already started in the beginning of the $20^{th}$ century: 1905 at Bath, 1907 at Valkenisse, 1927 at Hansweert and 1932 at Platen van Walsoorden (Mol, 1995).*

of the sills during the second deepening was 1-1.5 m. The third deepening is not considered in this report.

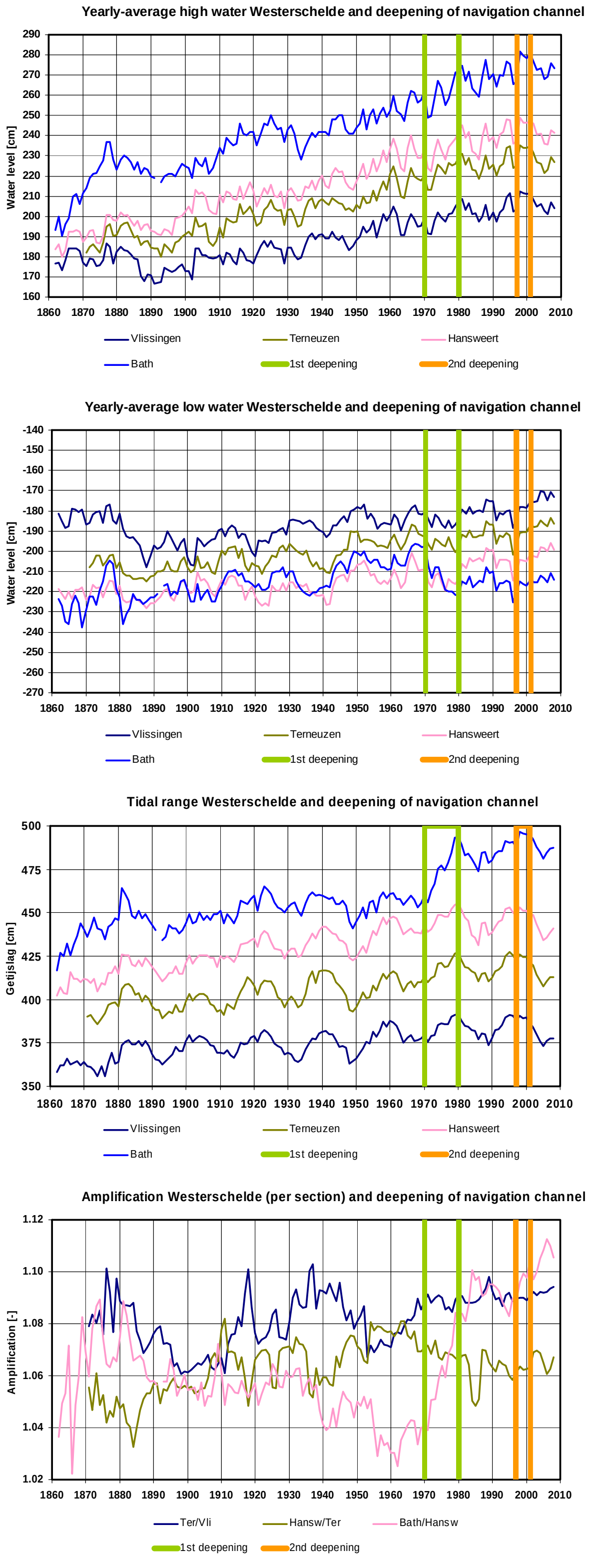



*Figure 5.7: Yearly-average high water, yearly-average low water, yearly-average tidal range and amplification in the Western Scheldt with deepening periods of the navigation channel.*

Figure 5.7 presents the yearly-average high and low waters and the tidal range in Vlissingen and Terneuzen, the amplification of the tidal range between both stations and the periods during which the navigation depth was increased.

During the first deepening high waters have increased but this is not very much different from previous trends. Low waters decreased in this period but only in Bath this seems to deviate from the increasing trend as observed prior to the deepening works. Between 1970 and 1980 the tidal range increased in all stations which was primarily caused by the 18.6 year cycle. Between Hansweert and Bath the ratio of the tidal range in Bath and Hansweert increased during this period indicating that the tidal range in Bath evolved more rapidly than the tidal range in Hansweert. As discussed in the previous chapters the channel depth (the portion of the cross-section below NAP-2m) increased in the same period, however whether this reflects the natural evolution of this section or is the result of the deepening of the *navigation* channel is not clear yet. During the second deepening, no increase of mean high and low waters and tidal range larger than the inter-annual variation is observed. As the project MOVE (van Eck and Holzhauer, 2006) found that the evolution of the low waters in Hansweert and Bath following the deepening statistically deviated from the 10 year trend preceding the deepening this aspect will be addressed in more detail hereafter.

Figure 5.8 shows the difference of the yearly-averaged low waters in Bath and Vlissingen similar to the results presented by van Eck and Holzhauer (2006) but now with data until 2010 instead of 2005. The blue line with symbols represents the difference in low water level for the reference period as used for the analysis in MOVE (1986-1996). The red line with symbols gives the differences for the period during the deepening (1997-1998) and following this period (1999-2010).

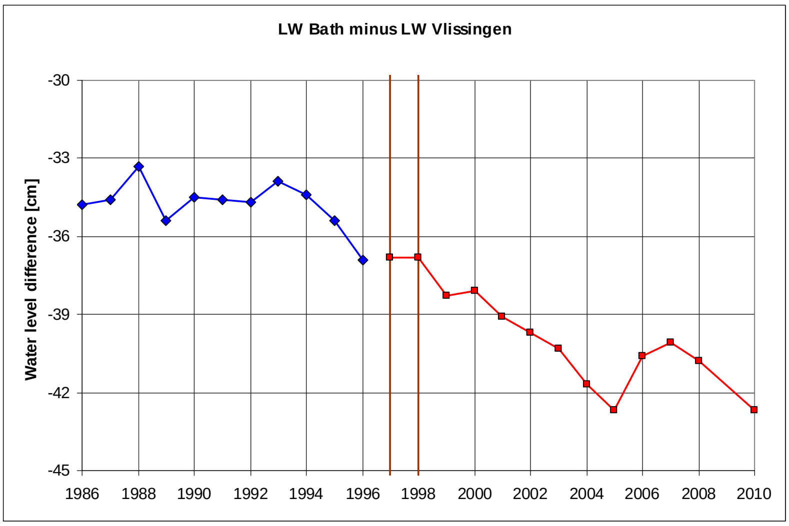



*Figure 5.8: Difference of low waters between Bath and Vlissingen prior the second deepening (blue line) and during and following the deepening of the navigation channel (red line).*

Figure 5.8 shows that after the deepening the difference between the low waters in Bath and those in Vlissingen has increased compared to the difference during the period preceding the deepening of the navigation channel (with the low waters in Bath lower than the low waters in Vlissingen). However, there appears to be no *direct* effect *during* the deepening (1997 and 1998) which is the objective of the present analysis. Moreover, a decrease of the low waters in Bath compared to those in Vlissingen already appears to be present in 1995 and possibly earlier. The downward trend of the low water difference between Bath and Vlissingen after 1998 may be an indirect effect of the channel deepening (morphological response) or caused by other processes.

For further analysis the section Hansweert-Bath is considered. Figure 5.9 shows the difference of the low waters between Bath and Hansweert (left axis) and the net cumulative sediment volume due to dredging, dumping and sand mining (right axis) in macro cell 5 between Hansweert and Bath.

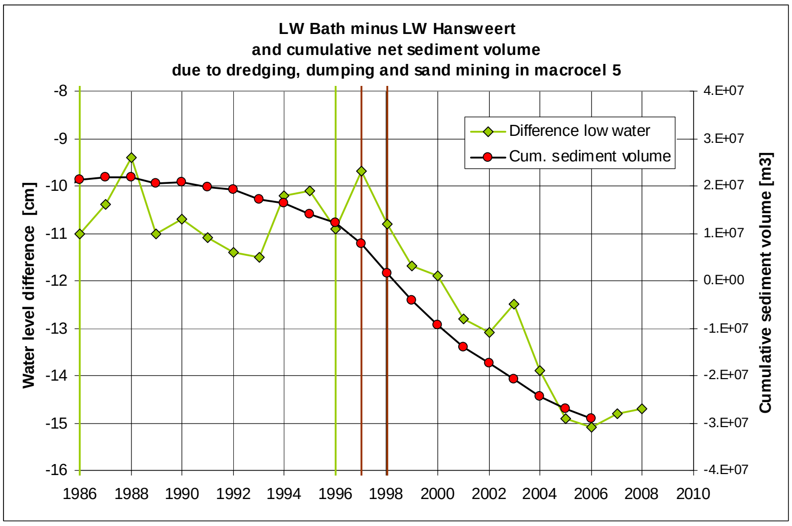



*Figure 5.9: Difference of low waters between Bath and Hansweert between 1986 and 2010 (green line) and cumulative net sediment volume due to dredging, dumping and sand mining in macro cell 5 (black line with red symbols).*

Figure 5.9 suggests that the lowering of the low waters in Bath relative to Hansweert is governed by the net extraction of sediment resulting from dredging, dumping and sand mining activities. The latter appears to start in the early 90's of the last century and may be associated with a different strategy for dredging, dumping and sand mining. Figure 5.10 finally presents the same results for the low water differences between Bath and Hansweert in relation to the *water* volume of macro cell 5 (below NAP+3.5m). The figure indicates that the volume of this section of the Western Scheldt has become larger since 1994 and that low waters in Bath have become lower in accordance with these water volume changes.

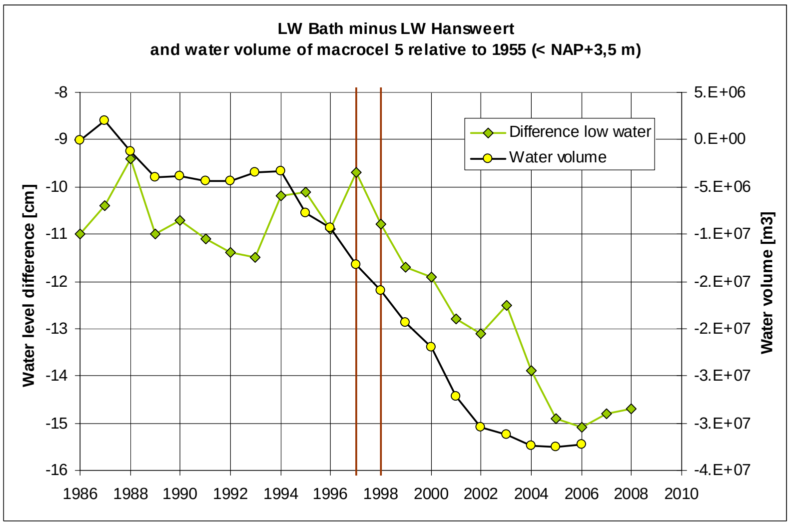


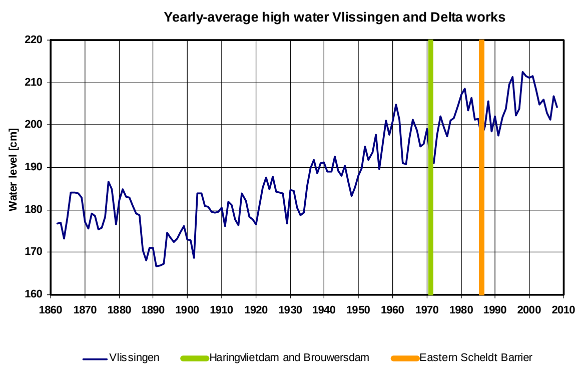

*Figure 5.10: Difference of low waters between Bath and Hansweert between 1986 and 2010 (green line) and water volume of macro cell 5 (black line with yellow symbols).*

The conclusion is thus that the trend-like change of the low waters in Bath relative to Hansweert appears to be affected by maintenance dredging and dumping and sand mining rather than by the deepening of the navigation channel only.

## 5.4 Delta works

The closure of the tidal basins as part of the Deltaworks can be considered as large-scale reclamations. For the tidal wave travelling along the coast the reduction of storage area may have resulted in an increase of the tidal range. The closures mainly took place between 1960 and 1970 followed by a partial closure of the Eastern Scheldt in 1986. Largest effects on water levels in Vlissingen may be expected from the construction of the primary dams of the Haringvliet and Grevelingen (Brouwersdam) and to a lesser extent of the Eastern Scheldt Barrier.

Figure 5.11 presents the yearly-average high and low waters and the tidal range in Vlissingen and the years of completion of the closure dams.



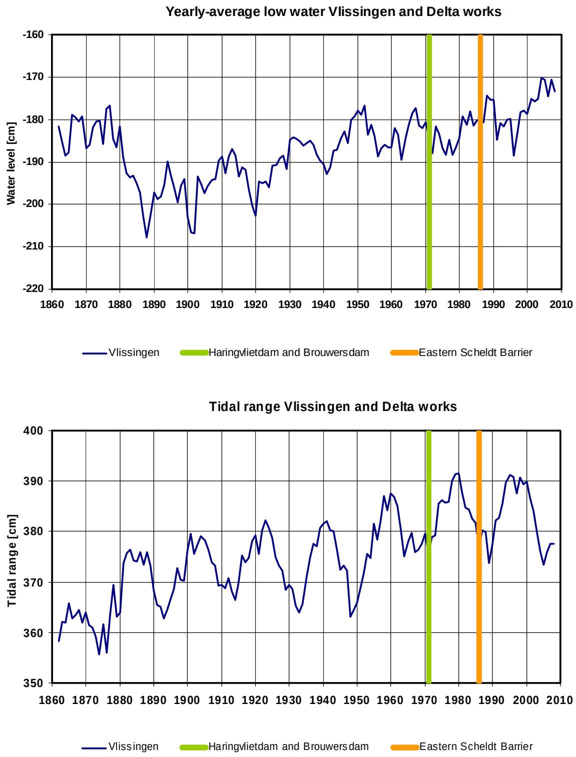



*Figure 5.11: Yearly-average high water, yearly-average low water, yearly-average tidal range in Vlissingen with construction periods of the (partial) closure dams as part of the Delta works.*

Figure 5.11 shows that the closures of Haringvliet and Grevelingen not have resulted in a sudden change of high and low waters and tidal range. In the years preceding the complete closure, i.e. during construction, the tidal range seems to reduce less than expected from the 18.6 year oscillation, however possible effects are masked by the natural variation. The partial closure of the Eastern Scheldt appears to have no noticeable effects on the tidal characteristics in Vlissingen.

Langendoen (1987) and Hollebrandse (2005) performed numerical simulations on the closure of an estuary comparable in size with those in the southwestern delta (tidal prism of 1 $10^9$ $m^3$). An increase of tidal range was reported to be in the order of 1.5-2% which is equivalent to 5-10 cm for Vlissingen.

## 5.5 Summary

Major human interventions in the Western Scheldt and its mouth and their possible effects on tidal characteristics have been discussed. Attention has focused on reclamation works since 1860, normalization of the channel (construction of guiding walls), deepening of the navigation channel and the closures of tidal basins as part of the Deltaworks. Histories of yearly-average high and low waters, tidal range and amplification of tidal range in water level stations were used to investigate if instantaneous effects of interventions on these tidal characteristics could be derived from the records.

In general, no clear responses of these man-made changes could be isolated from the inter-annual variation. The most prominent observed change relates to the increase of the tidal range in Bath relative to that in Hansweert between 1970 and 1980. This increase of tidal amplification coincides with the period of the first deepening of the navigation channel however to what extent this deepening has induced or contributed to the observed changes cannot yet be decided upon as natural morphological evolution may have played a role as well. Effects of land reclamation on tidal characteristics could neither be derived from the data. This may be explained by the fact that at the time of reclamation areas are well above local low water so that tidal storage was already reduced to a large extent. The construction of the guiding walls ('leidammen') near the Dutch-Belgian border appears to have no noticeable instantaneous effects on tidal properties. Similarly, the construction of the major primary dams as part of the Delta works did not have effects on water levels in Vlissingen although in literature possible effects on tidal range of 5-10 cm have been predicted for a schematized estuary comparable with those in the southwestern delta.

Possible effects of dredging and dumping resulting from maintenance of the navigation channel and sand mining were addressed for the section Hansweert-Bath. The conclusion is that the trend-like change of the low waters in Bath relative to Hansweert appears to be affected by maintenance dredging and dumping and sand mining rather than by the deepening of the navigation channel only.

It is stressed that human interventions may have effects on the longer term due to morphological adaptation. The analysis of these possible indirect effects is out of the scope of the present work.

# 6 Analysis of tidal propagation with analytical model

In Chapter 4 data on tidal characteristics have been related to data on bathymetric characteristics. In this chapter the relationships will be analysed using an analytical model on tidal propagation.

## 6.1 Schematisation of bathymetry in 1D

The major difficulty in applying a one-dimensional model is the schematisation of a two-dimensional bathymetry in one-dimension, i.e. how to make a distinction between the channel that conveys the water and the tidal flats that act as storage areas. This is of importance as both the channel depth as the storage area affects tidal propagation.

Figure 6.1 shows for the year 2008 the area $F(z)$ at successive depths $z$ (hypsometric curve) for the section Hansweert-Bath. In Figure 6.1 levels at NAP-2 m, NAP and NAP+2 m are indicated as approximations for the high, mean and low water in this section. The sub area of the cross-section marked with yellow are above the intertidal flats where during tidal rise water is stored. The sub-area indicated with blue represents the channel.

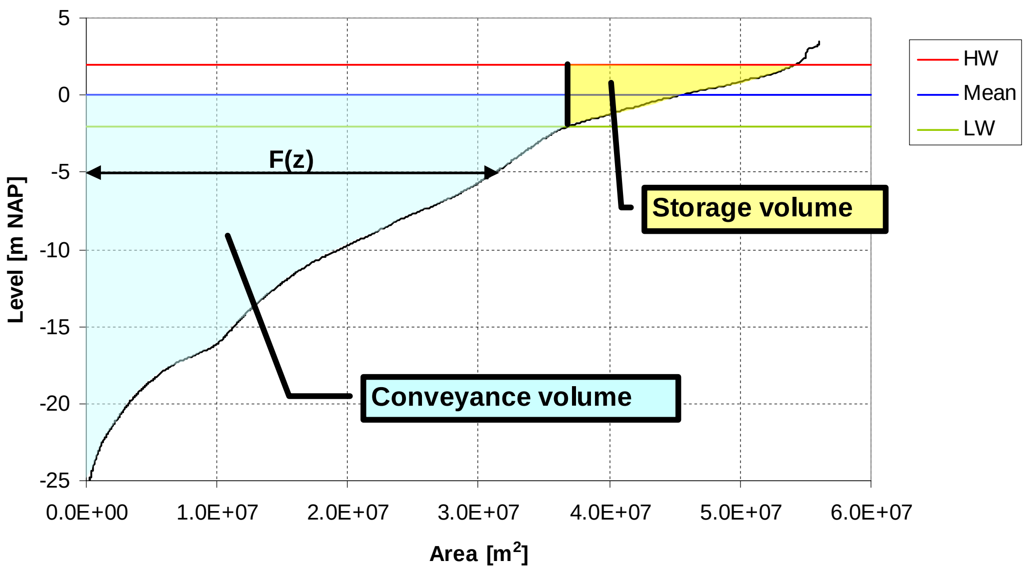



*Figure 6.1: Hypsometric curve for the section Hansweert-Bath in 2008.*

The channel depth $h_{ch}$ [m] thus follows from the water volume of the channel $V_{ch}$ [m$^3$] and the water surface area at low water $F_{LW}$ [m$^2$], see Figure 6.1:

$$h_{ch} = \frac{V_{ch}}{F_{LW}} = \frac{V_{<LW} + aF_{LW}}{F_{LW}} = \frac{V_{<LW}}{F_{LW}} + a \qquad (6.1)$$

where $a$ [m] is the difference between mean water level and low water.

The storage width $b_s$ [m] follows from the water volume above the tidal flats $V_s$ [$m^3$], the tidal range $R$ [m] and the section length $L$ [m] between, in this case, Hansweert and Bath:

$$b_s = \frac{V_s}{R\,L} \tag{6.2}$$

The channel width $b_{ch}$ [m] is given by the ratio of the surface area at low water $F_{LW}$ and the section length L:

$$b_{ch} = \frac{F_{LW}}{L} \tag{6.3}$$

The hypsometric curve of Figure 6.1 is thus represented by the schematized cross-section given in Figure 6.2 over a length $L$.

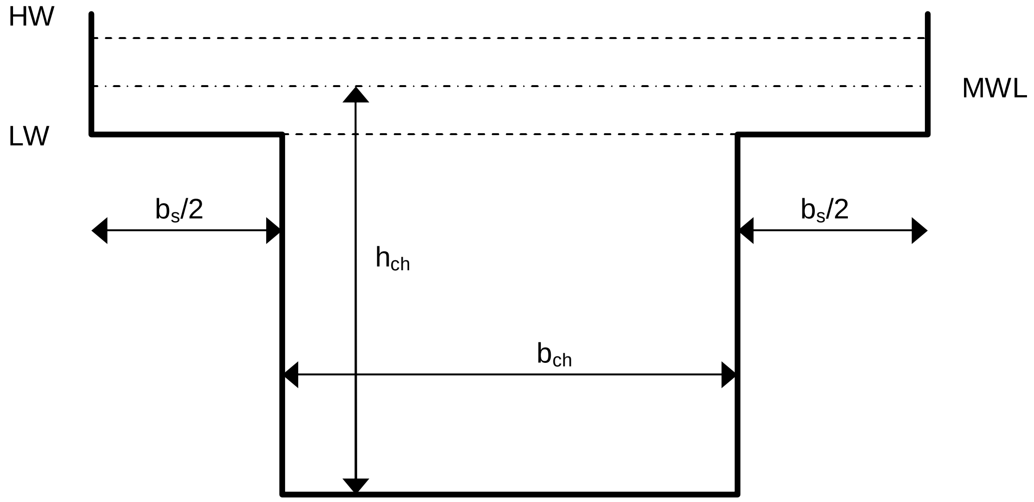



*Figure 6.2: Schematized cross-section.*

## 6.2 Analytical model

The analytical model for tidal propagation in a convergent estuary like the Scheldt is given by Van Rijn (2010, LTV V&T-report G-7). The model assumes an exponential relationship for the cross-sectional area and a horizontal bed. The equations for continuity and momentum have been linearised assuming linear friction and neglecting convective acceleration. It can be shown that the equations are also applicable if storage is present along the channel, see LTV V&T-report G-7 and LTV V&T-report G-14. In that case the channel depth $h_{ch}$ should be replaced with an effective channel depth $h_{eff}$ [m] according to:

$$h_{eff} = \frac{A_{ch}}{b_s} = \frac{b_{ch}\,h_{ch}}{b_s} \tag{6.4}$$

with $A_{ch}$ the channel area [$m^2$] and $b_{ch}$, $h_{ch}$ and $b_s$ as defined in Section 6.1.

## 6.3 Results of the analytical model

**Hansweert-Bath**
The analytical model is used to compute the amplification of the tidal range and the propagation speed of the tidal wave. This is first done for the section Hansweert-Bath for the period 1955 to 2008 because for this section changes in channel depth have been significant. The model requires input of the channel depth and the ratio of storage width $b_s$ and channel width $b_{ch}$ for each year. As such $h_{ch}$ and $b_s/b_{ch}$ are derived from the measured bathymetries for each year, see Figure 6.3. To compute $h_{ch}$ and $b_s/b_{ch}$ from the hypsometry (with a resolution of 0.05 m for the vertical coordinate), the evolution of the M2-amplitude and mean water level during this period have been taken into account. However, comparison with a computation with constant values for both quantities during this period indicates only minor differences between both approaches.

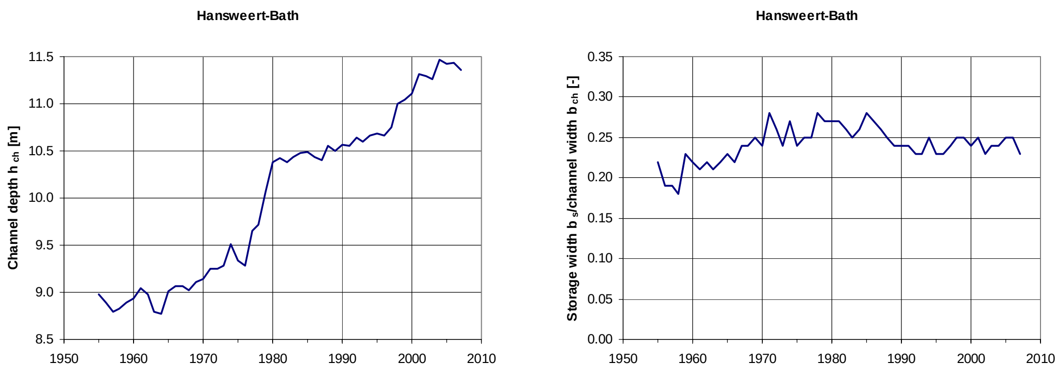



*Figure 6.3: Channel depth (left) and ratio of storage and channel width (right) for the section Hansweert-Bath.*

The equations are solved iteratively as first the tidal velocity amplitude is estimated to determine the friction term. An improved estimate for the tidal velocity amplitude then follows from the model. The tidal velocity amplitude for friction is assessed in the seaward location of the section. Calibration parameters are the Nikuradse roughness $k_s$ and the convergent length scale $L_a$ for the cross-sectional area $A$ given by:

$$A(x) = A_0 e^{-x/L_b} \qquad (6.5)$$

with $A_0$ [m$^2$] the cross-sectional area at the seaward station of the section (Hansweert) and $x$ the longitudinal distance along the section (positive up-estuary).

The convergent length scale $L_a$ is assessed from the bathymetry of 1998 as derived from Delft3D, see Figure 6.4:

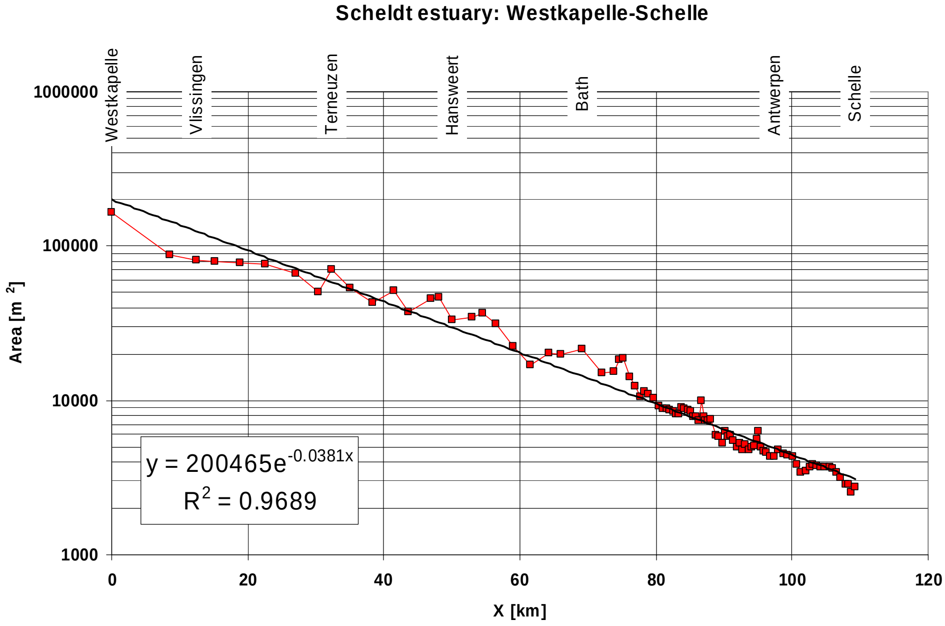



*Figure 6.4: Cross-sectional area of the Scheldt estuary between Westkapelle and Schelle.*

The overall convergent length scale of the estuary between Westkapelle and Schelle is 1/0.0381 = 26 km, however it may differ to some extent for specific sections along the estuary. Other quantities used as input for the model are given in Table 6.1. The quantity 2M2-amplitude rather than the M2-amplitude itself is used hereafter as a measure for the tidal range.

*Table 6.1: Input for the analytical model for the section Hansweert-Bath.*

| **Input for the model** | | |
|---|---|---|
| Tidal period | T | 45000 s |
| Nikuradse roughness | $k_s$ | 0.08 m |
| Converging length for the width | $L_a$ | 27000 m |
| Section length Hansweert-Bath | L | 19000 m |
| | | |
| **Derived quantities** | | |
| Chézy roughness | C | 57 $m^{0.5}/s$ ($h_{ch}$ = 10 m) |
| Manning roughness | n | 0.026 $s/m^{1/3}$ |

The Nikuradse roughness $k_s$, the Chézy roughness $C$ and the Manning roughness $n$ are related as follows:

$$C = 18\log\left(\frac{12h}{k_s}\right)$$

$$n = \frac{(k_s)^{1/6}}{25}$$

The yearly-average 2M2-amplitude in Hansweert has been used as downstream boundary and input for the model. From this the 2M2-amplitude in Bath is computed by the model, see Figure 6.5 (upper left window).

Observed and computed values show good agreement, see the regression between both quantities (upper right window; $r^2$ = 0.93). Observed and computed amplification of the M2-amplitude is given in the lower left window of Figure 6.5. In the lower right window the M2-phase velocity according to observations and model computations are presented. Magnitude and increase after 1980 are reproduced by the model (red line). For comparison the phase-velocity of a frictionless tidal wave in a prismatic channel is shown (blue line) indicating much lower values and only minor evolution in time. In Bath the M2-amplitude and M2-phase before 1970 are not available. These values have been derived as follows: firstly from regression, linear relationships between the observed tidal range and M2-amplitude and between the low water propagation velocity and phase velocity have been established for the period 1971-2007 and secondly these relationships have been applied for the period 1955-1970 to derive the M2-aplitude from the tidal range and the M2-phase velocity of the low water propagation velocity for this period.

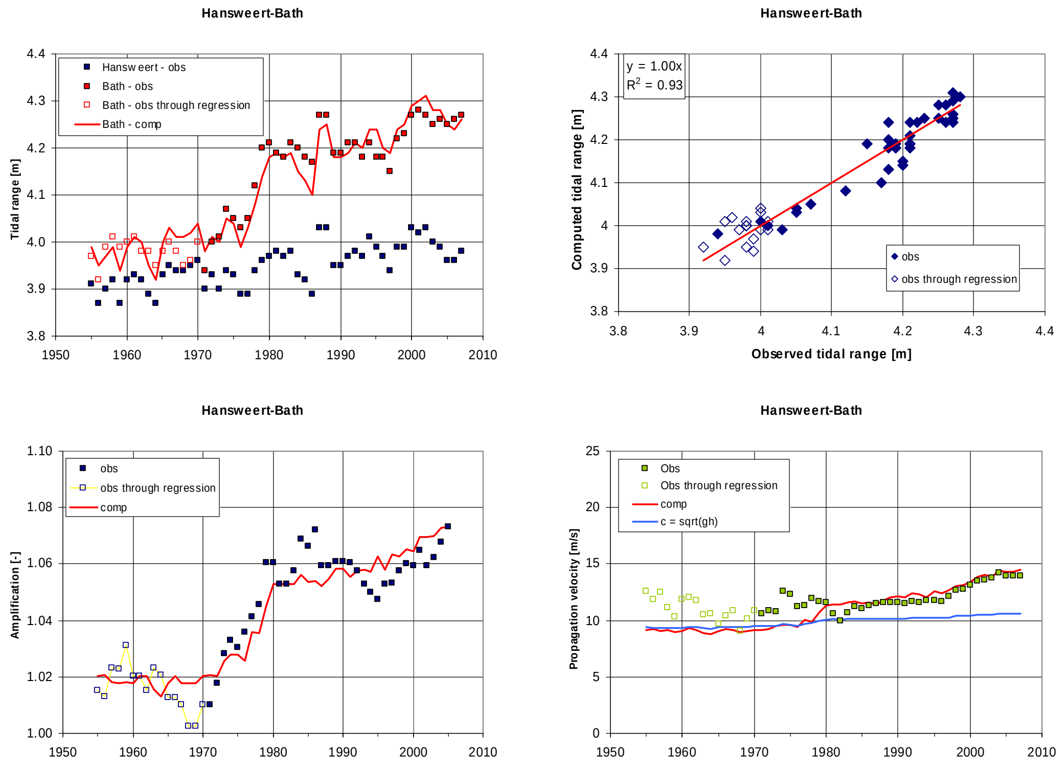



*Figure 6.5: Observed 2*M2-amplitude in Hansweert and observed and computed 2*M2-amplitude in Bath (upper left), regression observed and computed 2*M2-amplitude in Bath (upper right), amplification of M2-amplitude in Bath (lower left) and observed and computed M2-phase velocity for the section Hansweert-Bath (Ber 18)*

**Vlissingen-Terneuzen and Terneuzen-Hansweert**

The analytical model has also been applied to the sections Vlissingen-Terneuzen and Terneuzen-Hansweert. For these sections changes in channel depth and the ratio $b_s/b_{ch}$ have been minor, see Figure 6.6. Similar to the section Hansweert-Bath, $h_{ch}$ and $b_s/b_{ch}$

have been computed taking into account the evolution of the M2-amplitude and mean water level during the period 1955-2008.

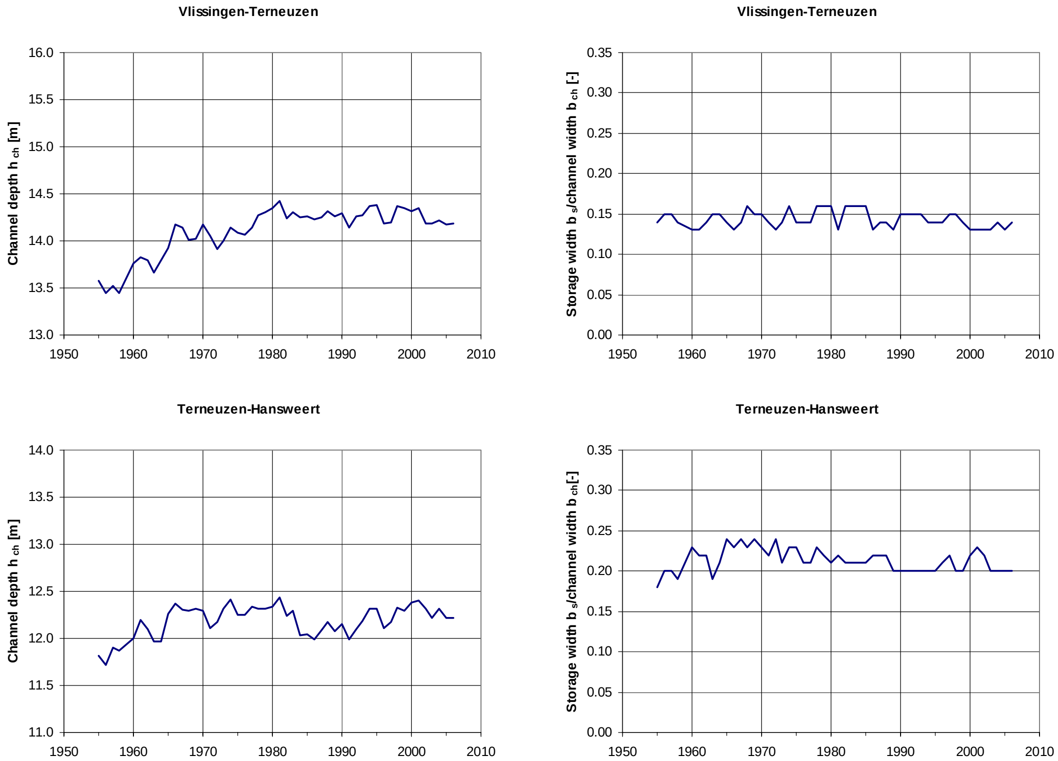



*Figure 6.6: Channel depth (upper left) and ratio of storage and channel width (upper right) for the section Vlissingen-Terneuzen and channel depth (lower left) and ratio of storage and channel width (lower right) for the section Terneuzen-Hansweert.*

Model input for both sections is given in Table 6.2 and Table 6.3. For the section Vlissingen-Terneuzen the roughness $k_s$ is chosen slightly larger than for the section Hansweert-Bath (0.10 m vs. 0.08 m) and the convergence length is 39 km (see hereafter).

*Table 6.2: Input for the analytical model for the section Vlissingen-Terneuzen.*

| **Input for the model** | | |
|---|---|---|
| Tidal period | T | 45000 s |
| Nikuradse roughness | $k_s$ | 0.10 m |
| Converging length for the width | $L_a$ | 39000 m |
| Section length Vlissingen-Terneuzen | L | 19500 m |
| | | |
| **Derived quantities** | | |
| Chézy roughness | C | 58 $m^{0.5}/s$ ($h_{ch}$ = 14 m) |
| Manning roughness | n | 0.027 $s/m^{1/3}$ |

For the section Terneuzen-Hansweert the roughness $k_s$ is equal to the value for the section Hansweert-Bath (0.08 m) and the convergence length is 33 km (see hereafter).

*Table 6.3: Input for the analytical model for the section Terneuzen-Hansweert.*

| **Input for the model** | | |
|---|---|---|
| Tidal period | T | 45000 s |
| Nikuradse roughness | $k_s$ | 0.08 m |
| Converging length for the width | $L_a$ | 33000 m |
| Section length Terneuzen-Hansweert | L | 18000 m |
| | | |
| **Derived quantities** | | |
| Chézy roughness | C | 59 $m^{0.5}/s$ ($h_{ch}$ = 12 m) |
| Manning roughness | n | 0.026 $s/m^{1/3}$ |

Comparison of the model results with observations is done in Figure 6.7 for the section Vlissingen-Terneuzen and in Figure 6.8 for the section Terneuzen-Hansweert.

For section Vlissingen-Terneuzen the amplification of the M2-amplitude has increased to some extent before 1970 reflecting the increase of channel depth during this period. The magnitude of amplification is reproduced by the model with realistic values of the calibration parameters $k_s$ and $L_a$. Observed and computed 2*M2-amplitude in Terneuzen are in agreement with $r^2$ = 0.84. Also the magnitude of the phase velocity is reproduced with values larger than the propagation velocity of a frictionless tidal wave in a prismatic channel.

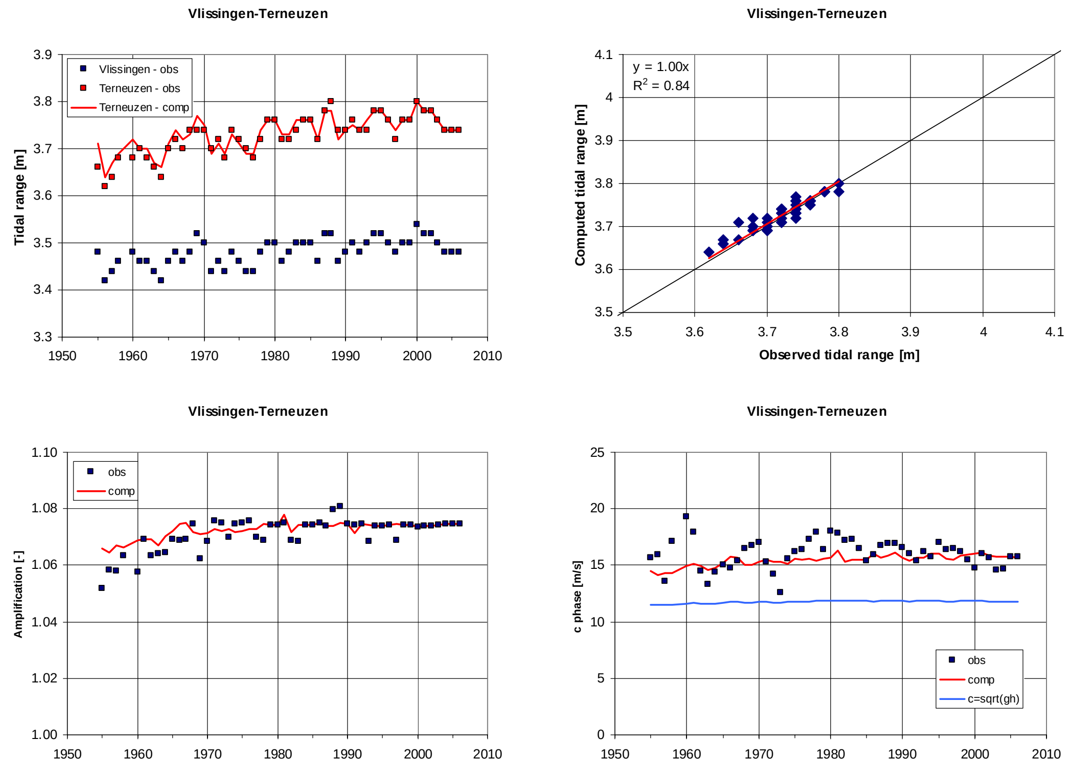



*Figure 6.7: Observed 2*M2-amplitude in Vlissingen and observed and computed 2*M2-amplitude in Terneuzen (upper left), regression observed and computed 2*M2-amplitude in Terneuzen (upper right), amplification of M2-amplitude in Terneuzen (lower left) and observed and computed M2-phase velocity for the section Vlissingen-Terneuzen (Ber15).*

For section Terneuzen-Hansweert changes of the overall channel depth $h_{ch}$, i.e. without making distinction between main and secondary channel, and the ratio $b_s/b_{ch}$ have been negligible. Observed and computed amplification thus show a constant amplification of 1.06 between 1955 and 2008 although there is some scatter in the observed data. Observed and computed 2*M2-amplitudes are in agreement with $r^2$ = 0.73. Apparently the large changes of the main and secondary channels for this section, see Chapter 3, did not have effect on the amplification along this section. The M2-phase velocity is in agreement with the observed values and larger than that of a frictionless tidal wave in a prismatic channel.

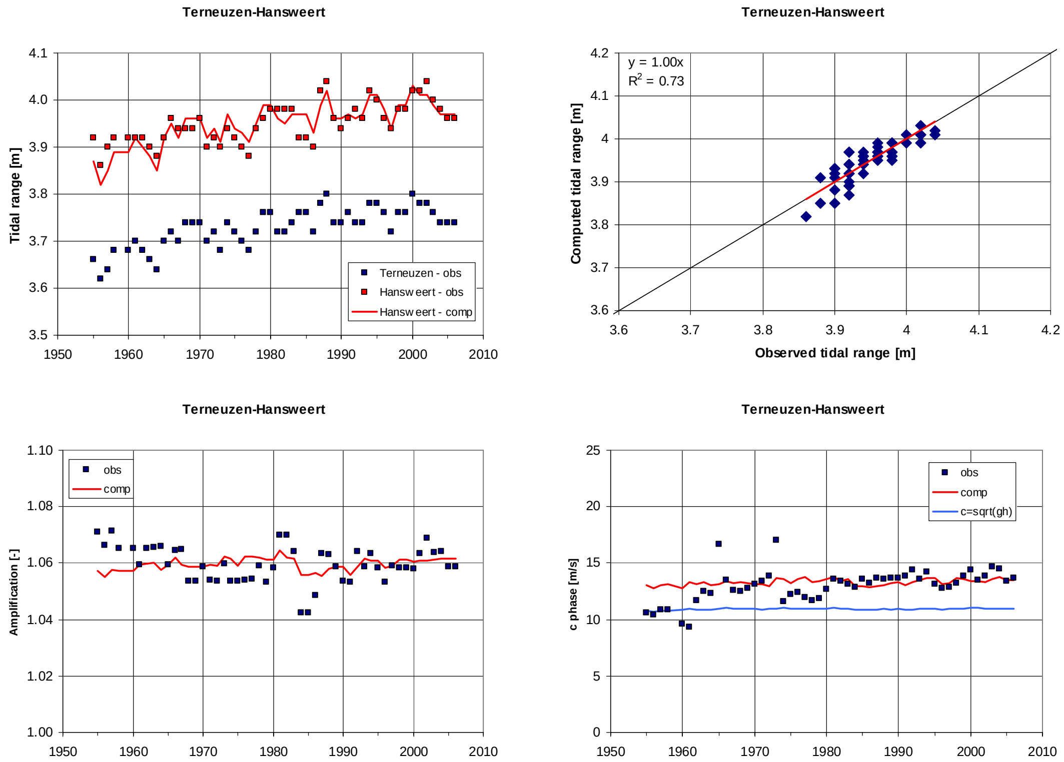



*Figure 6.8: Observed 2*M2-amplitude in Terneuzen and observed and computed 2*M2-amplitude in Hansweert (upper left), regression observed and computed 2*M2-amplitude in Hansweert (upper right), amplification of M2-amplitude in Hansweert (lower left) and observed and computed M2-phase velocity for the section Terneuzen-Hansweert (Ber9).*

## 6.4 Discussion of model results

The analytical model according to Van Rijn (2010, LTV V&T-report G-7) has been applied to three sections of the Western Scheldt. The purpose was to analyze observed quantities related to tidal propagation such as the longitudinal variation of the M2-amplitude (amplification) and the phase velocity (propagation velocity). The mere value of this approach is that physical knowledge is used to explore cause-effect relationships between bathymetric properties and tidal characteristics. However, some assumptions have been made to allow for this approach:

- The equations have been linearized using linear friction, neglecting convective acceleration, assuming a horizontal bed and schematizing the variation of the cross-sectional area along the estuary with a simple exponential function.

- The water level amplitude should be small compared with the water depth which limits the application of the model to the Western Scheldt to, say, water depths larger than 5 m.
- The application of the model to individual sections with different values for water depth and convergence length is strictly speaking not allowed as changes in geometric properties result in reflection at the boundaries between two successive sections.

Despite these assumptions the model is capable in reproducing the tidal characteristics in the Western Scheldt using realistic values for the calibration parameters (roughness and convergence length). The applied Nikuradse roughness equivalent to a Manning value of 0.026-0.027 s/m$^{1/3}$ is in good agreement with values applied in numerical models. For instance, the calibrated NEVLA-model makes use of a space-varying roughness field with Manning values between 0.018 and 0.030 s/m$^{1/3}$ while a uniform roughness for the Western Scheldt of 0.025 s/m$^{1/3}$ also resulted in an adequate reproduction of the water levels downstream Schelle (Maximova et al., 2009). The convergence length $L_a$ was firstly based on the overall value of 26 km for the estuary between Westkapelle and Schelle. However, modification to values of 27, 33 and 39 km was necessary to arrive at the calibration results described in this chapter. Figure 6.9 compares the cross-sectional area along the estuary computed according to these convergence lengths with the longitudinal variation as derived from the Delft3D schematisation which is based on the observed bathymetry of 1998.

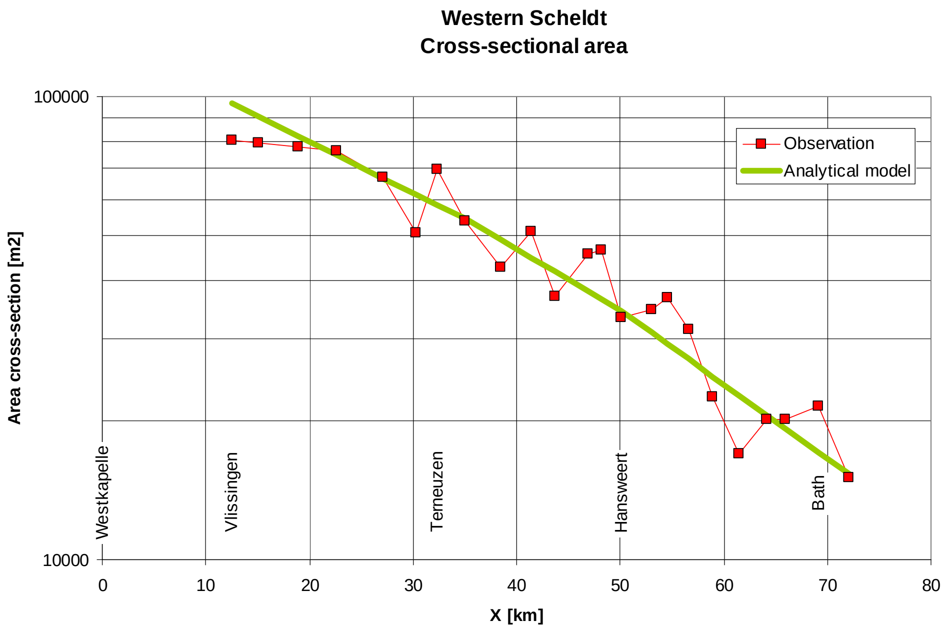
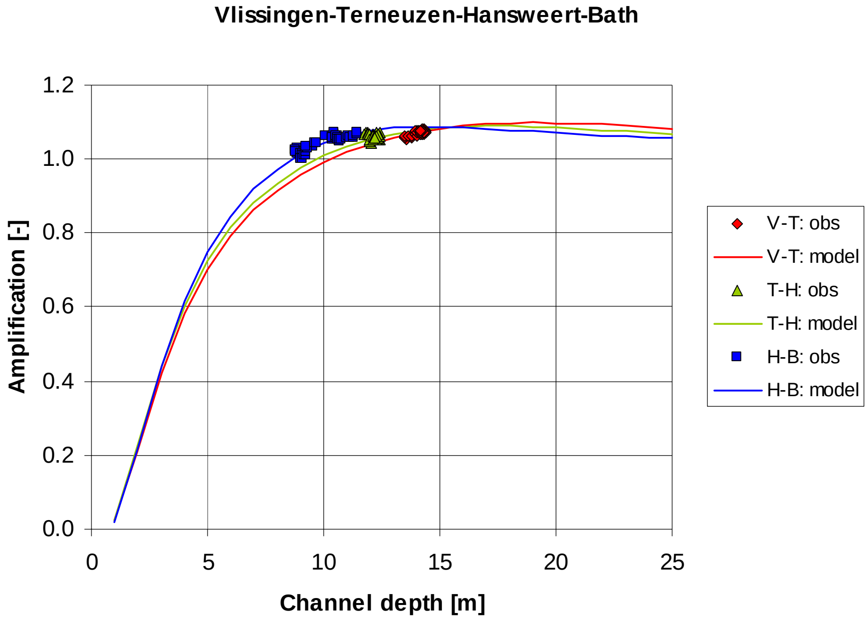



*Figure 6.9: Cross-sectional area between Westkapelle and Bath according to Delft3D bathymetry of 1998 (red squares) and as applied to the analytical model (green line) with convergence lengths of 39 km (Vlissingen-Terneuzen), 33 km (Terneuzen-Hansweert) and 27 km (Hansweert-Bath).*

The convergence length may be time-dependent if the cross-sectional area varies in time but this has not been investigated. The schematisation of the cross-section into a flow and storage area was described in Section 6.1. If the total cross-section is considered to represent the flow area (thus no storage), the channel depth follows from the ratio of the water volume below mean water level (~NAP) and the water surface area at mean water level. Because the water surface area at mean water level is larger than that at low water the computed channel depth is less than according to Eq. (6.1) (the additional water volume on the intertidal flats between mean and low water level is relatively small). The tidal characteristics computed in this way for the section Hansweert-Bath show less agreement with the observed values: the M2-phase velocity is too large if the amplification of the M2-amplitude is correctly reproduced. However, this should be further investigated with calibration and application to the other sections.

The usefulness of the model was already shown by Van Rijn (2010) but presently it is established that the observed evolution of the M2-amplitude and M2-phase velocity could be described by the model as well using input on the observed channel depth and ratio of storage to channel width. The model results indicate that the increase of the M2-amplification between Hansweert and Bath can be explained by the deepening of the channel (not necessarily the navigation channel). Similarly, the increase of the phase velocity resulting from channel deepening is reproduced by the model.

Given these results it is analyzed what the effect will be of a further deepening of the channel. Figure 6.10 shows the observed and computed amplification as a function of the channel depth for all three sections. This is shown for the ratios $b_s/b_{ch}$ = 0.15 (Vlissingen-Terneuzen) and $b_s/b_{ch}$ = 0.25 (Terneuzen-Hansweert-Bath). As noted above the model results are not valid for channel depths less than, say, 5 m as the ratio of the tidal amplitude and mean channel depth is then not sufficiently small.



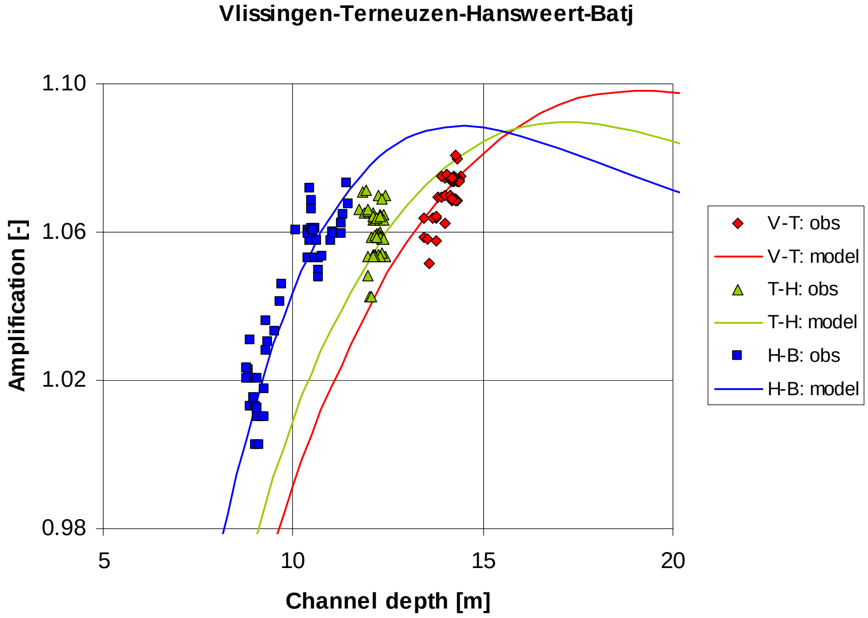




*Figure 6.10: Amplification of the M2-amplitude as function of the channel depth for the sections Vlissingen-Terneuzen (red), Terneuzen-Hansweert (green) and Hansweert-Bath (blue). Upper window: vertical axis full scale; lower window: vertical axis 0.98-1.10. Symbols: observations; lines model.*

Figure 6.10 shows that the ratio of the M2-amplitude of he landward and seaward station of each section is larger than 1 (amplification) and that a further increase with increasing channel depth will be limited to approximately 0.02 for each section. As such the M2-amplitude in Bath will increase with maximal 6% (~0.1 m) if the channel depth of each section will increase with 3-5 m to 15-20 m. The M2-phase velocity may substantially increase with further deepening of the channels, see Figure 6.11.

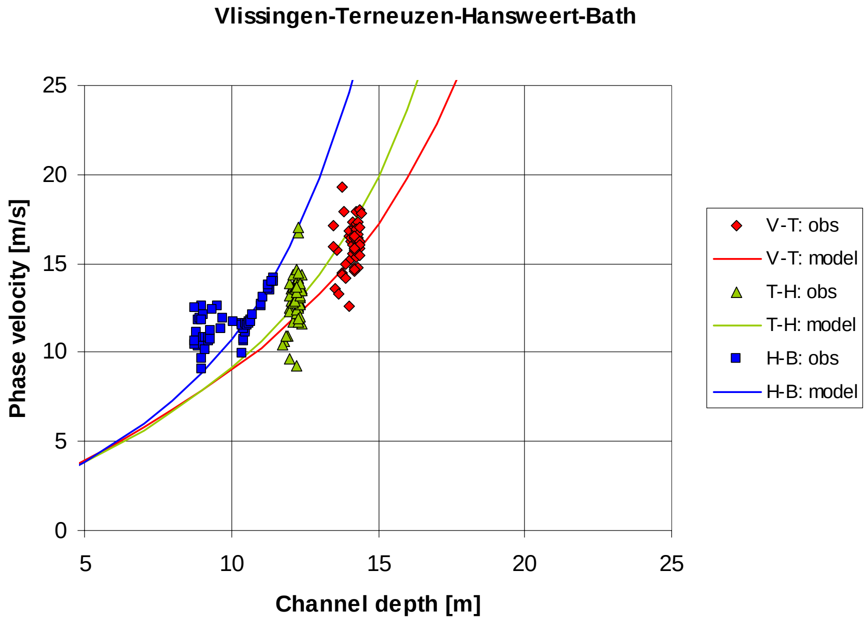



*Figure 6.11: M2-phase velocity as function of the channel depth for the sections Vlissingen-Terneuzen (red), Terneuzen-Hansweert (green) and Hansweert-Bath (blue). Symbols: observations; lines model.*

# 7 References

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- Tidal phenomena in the Scheldt Estuary, part 2. LTV V&T-rapport G-7.
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# A Additional Figures

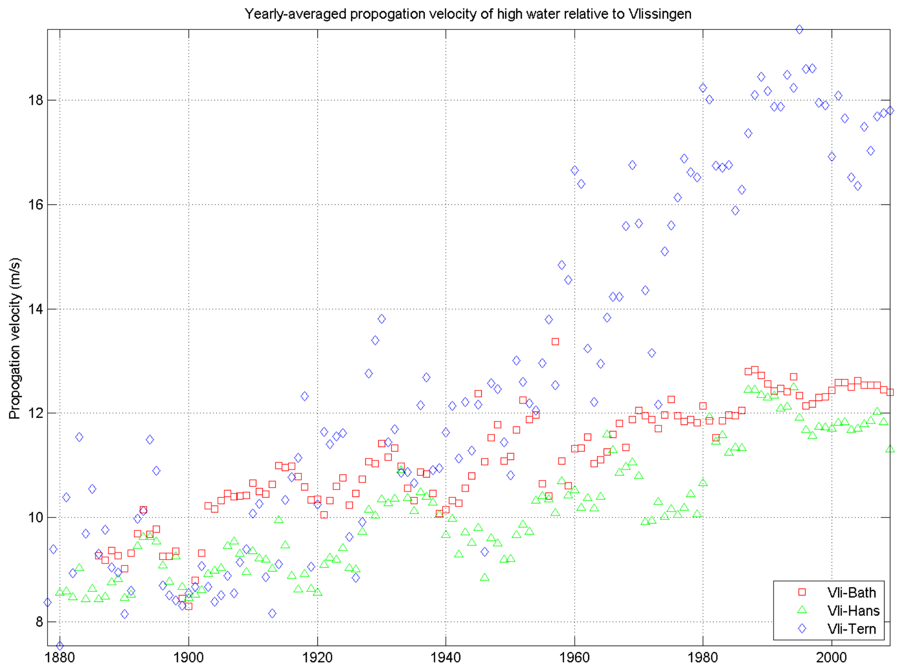



*Figure A.1: Yearly-averaged propagation velocity of high water for the sections Vlissingen-Terneuzen, Vlissingen-Hansweert and Vlissingen-Bath.*

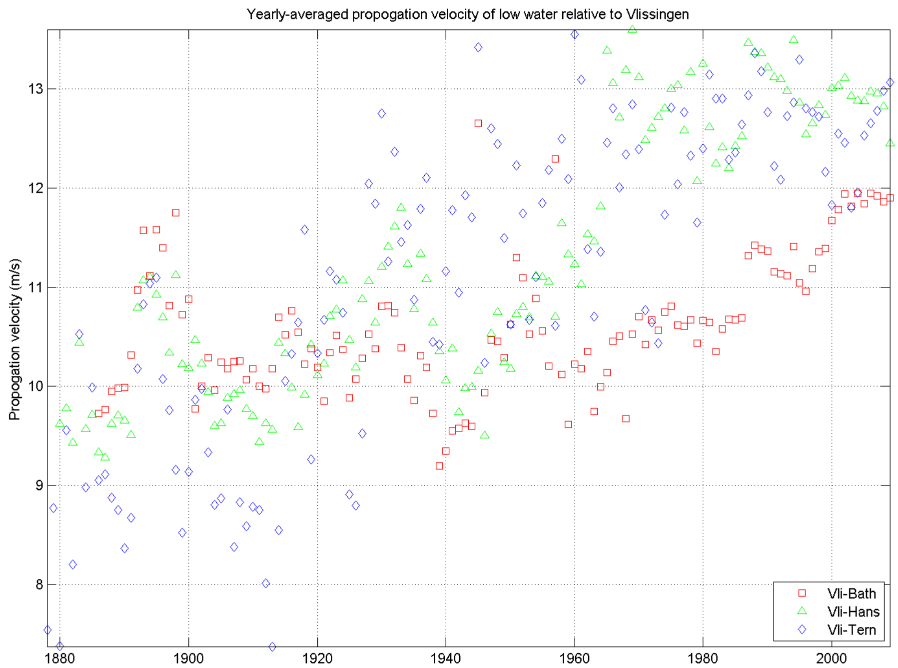



*Figure A.2: Yearly-averaged propagation velocity of low water for the sections Vlissingen-Terneuzen, Vlissingen-Hansweert and Vlissingen-Bath.*

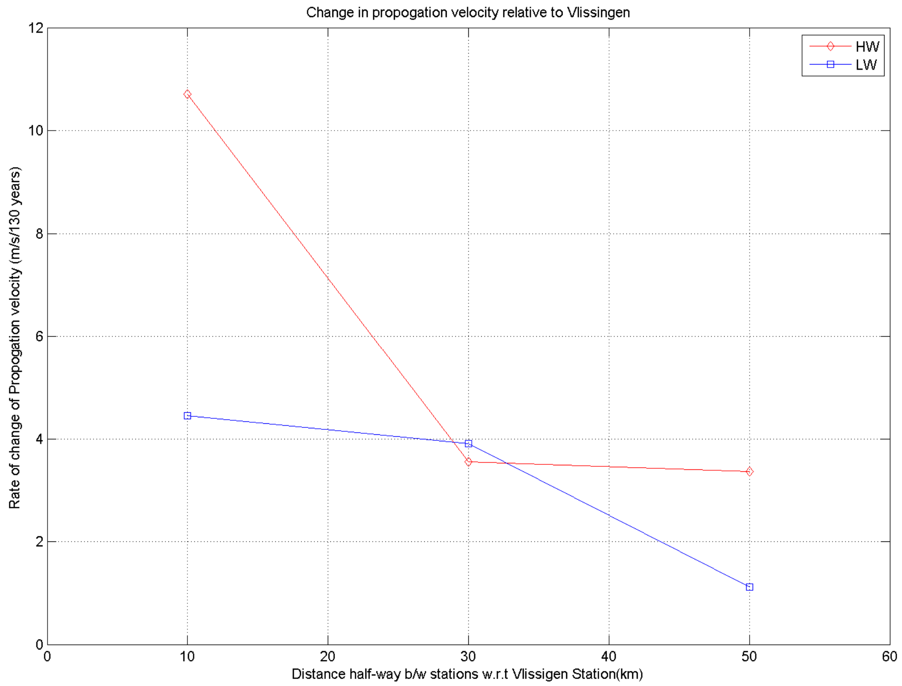



*Figure A.3: Change of yearly-averaged propagation velocity per century of high and low water for the sections Vlissingen-Terneuzen, Vlissingen-Hansweert and Vlissingen-Bath.*

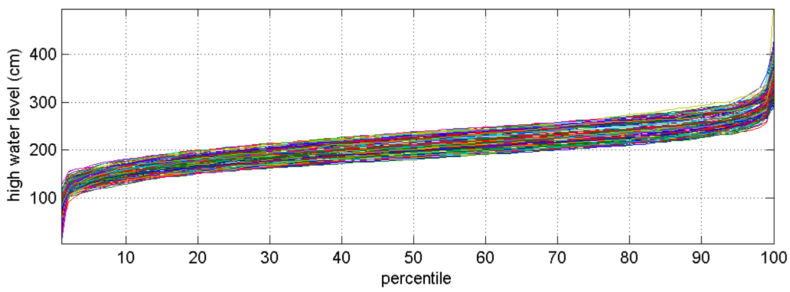



*Figure A.4: Frequency distribution of all high water levels measured between 1878 and 2008 at Terneuzen*

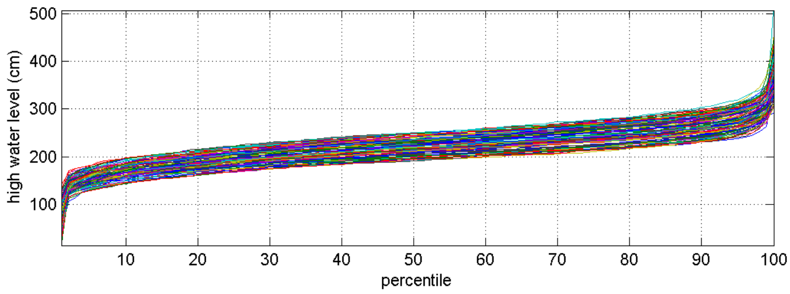



*Figure A.5: Frequency distribution of all high water levels measured between 1880 and 2008 at Hansweert*

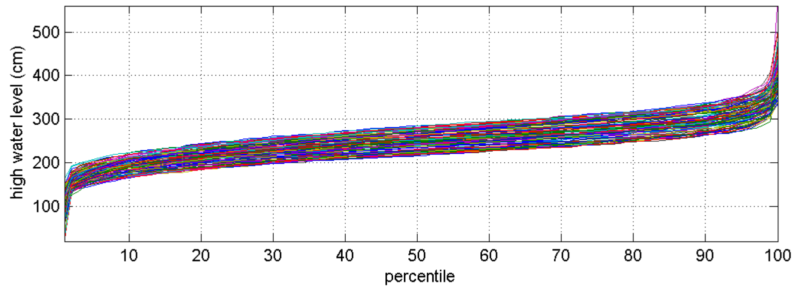



*Figure A.6: Frequency distribution of all high water levels measured between 1886 and 2008 at Bath*

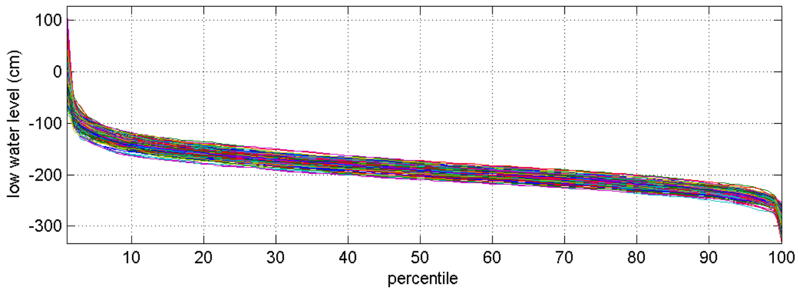



*Figure A.7: Frequency distribution of all low water levels measured between 1877 and 2008 at Vlissingen*

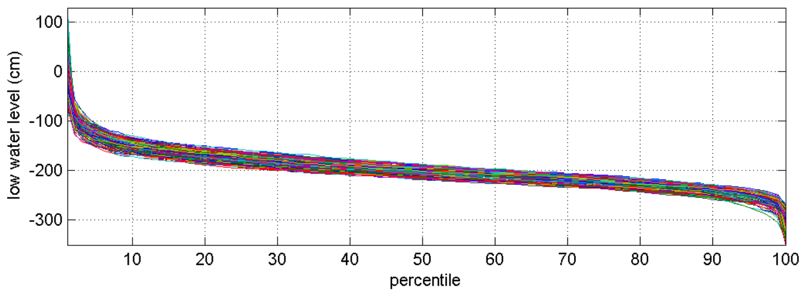



*Figure A.8: Frequency distribution of all low water levels measured between 1878 and 2008 at Terneuzen*

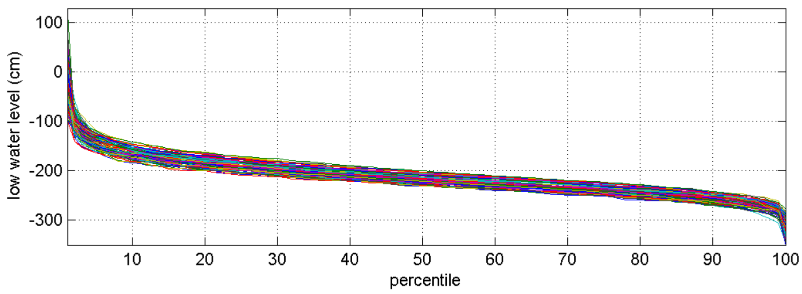



*Figure A.9: Frequency distribution of all low water levels measured between 1880 and 2008 at Hansweert*

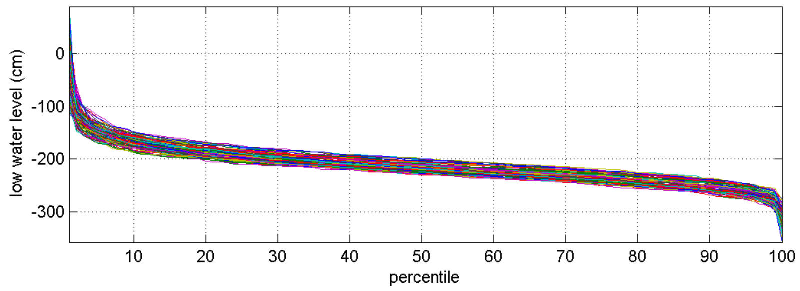



*Figure A.10: Frequency distribution of all low water levels measured between 1886 and 2008 at Bath*

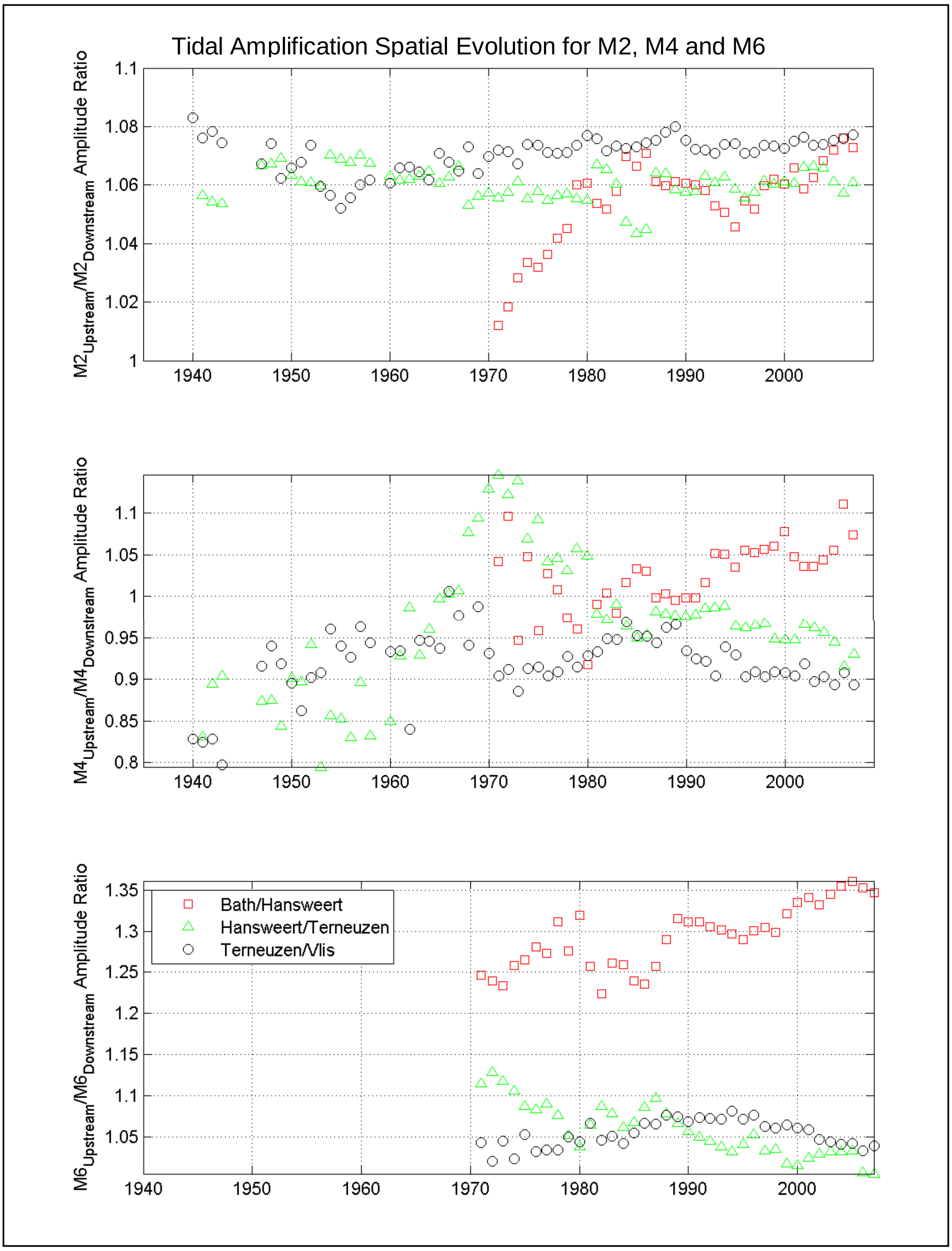



*Figure A.11: Yearly M2, M4 and M6 tidal amplitude ratios between upstream stations and downstream station.*

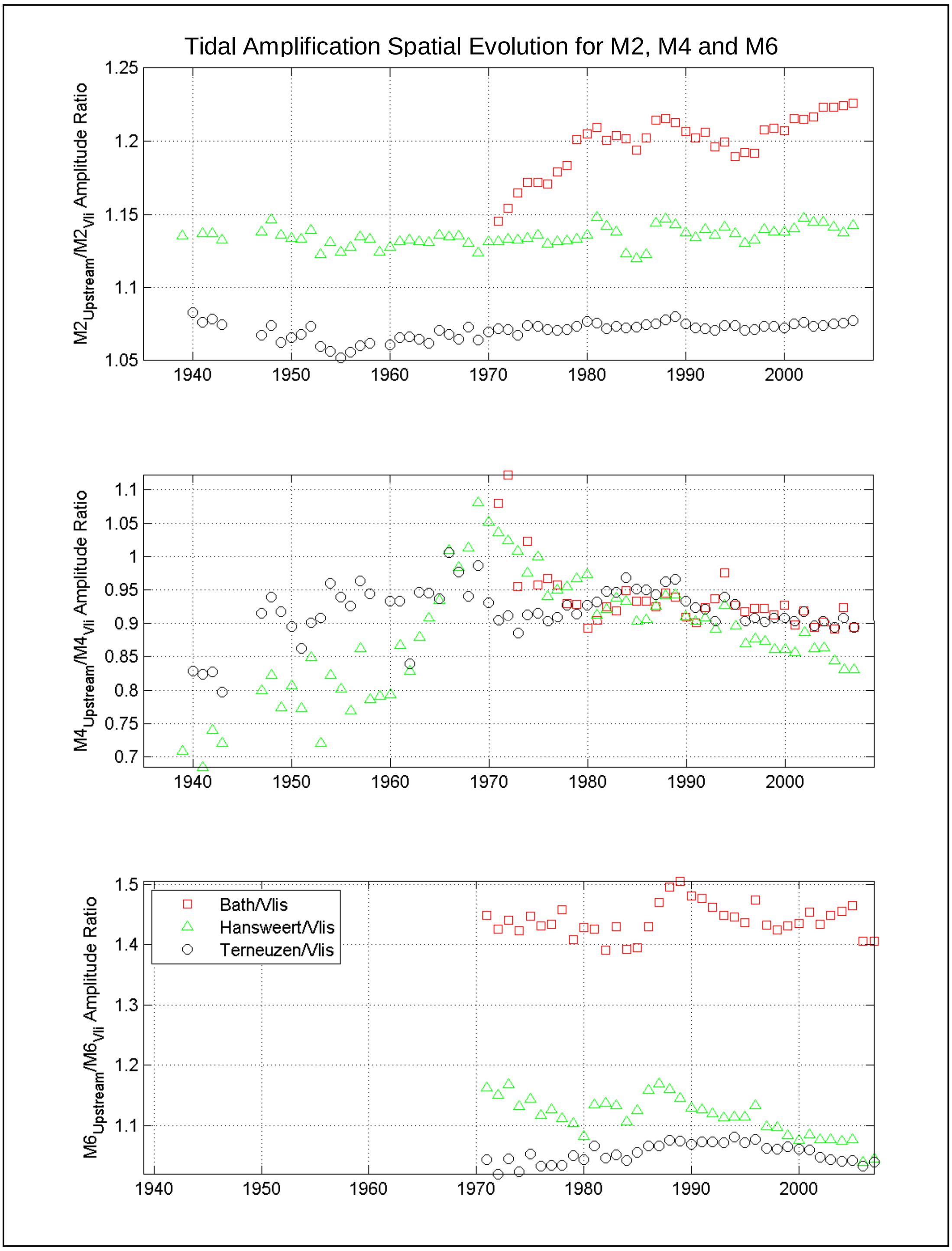



*Figure A.12: Yearly M2, M4 and M6 tidal amplitude ratios between upstream stations and Vlissingen*

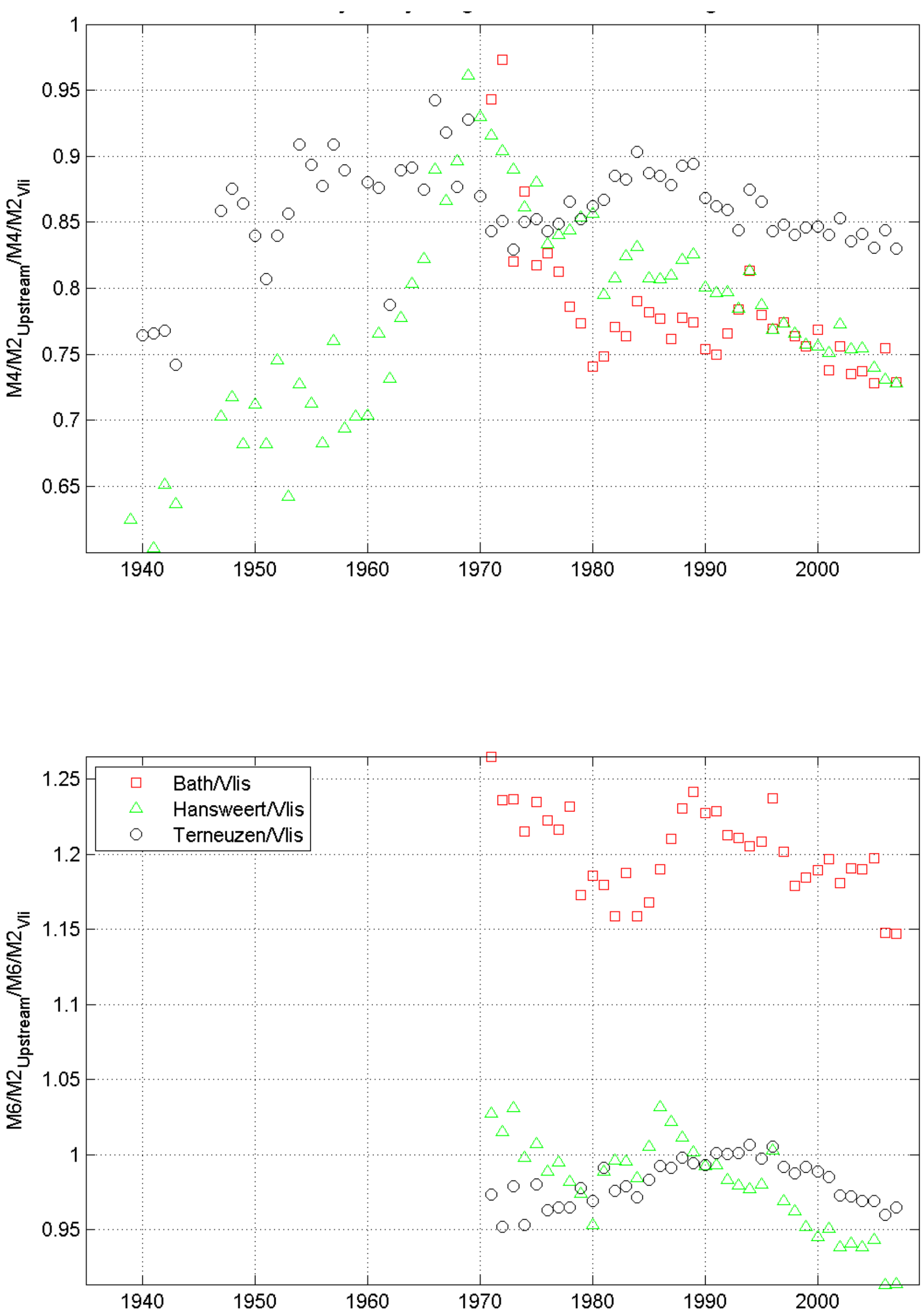



*Figure A.13: Yearly M4/M2 and M6/M2 tidal amplitude ratios between upstream stations and Vlissingen*

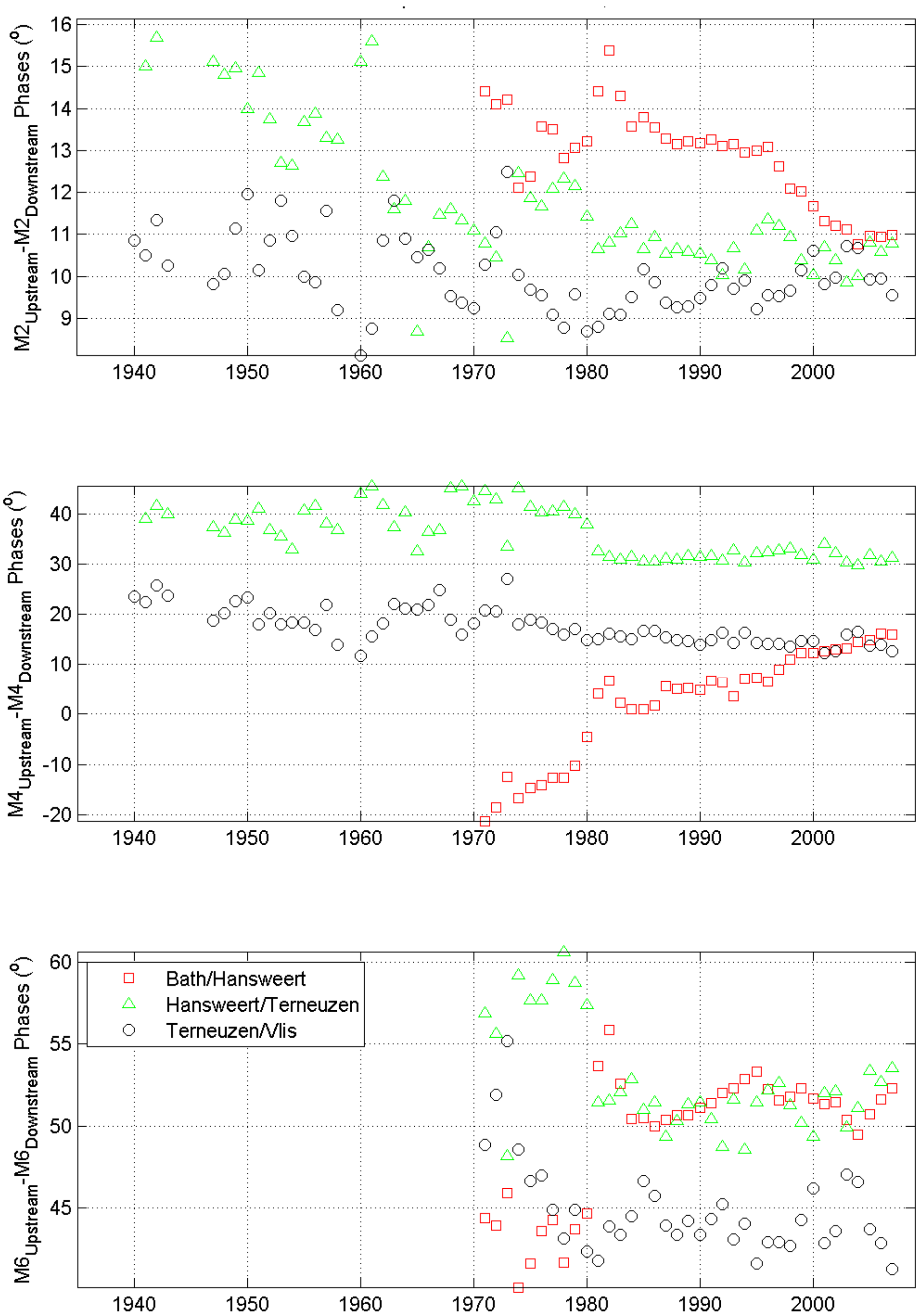



*Figure A.14: Yearly M2, M4 and M6 tidal phase differences between upstream stations and downstream station (i.e. Bath and Hansweert)*

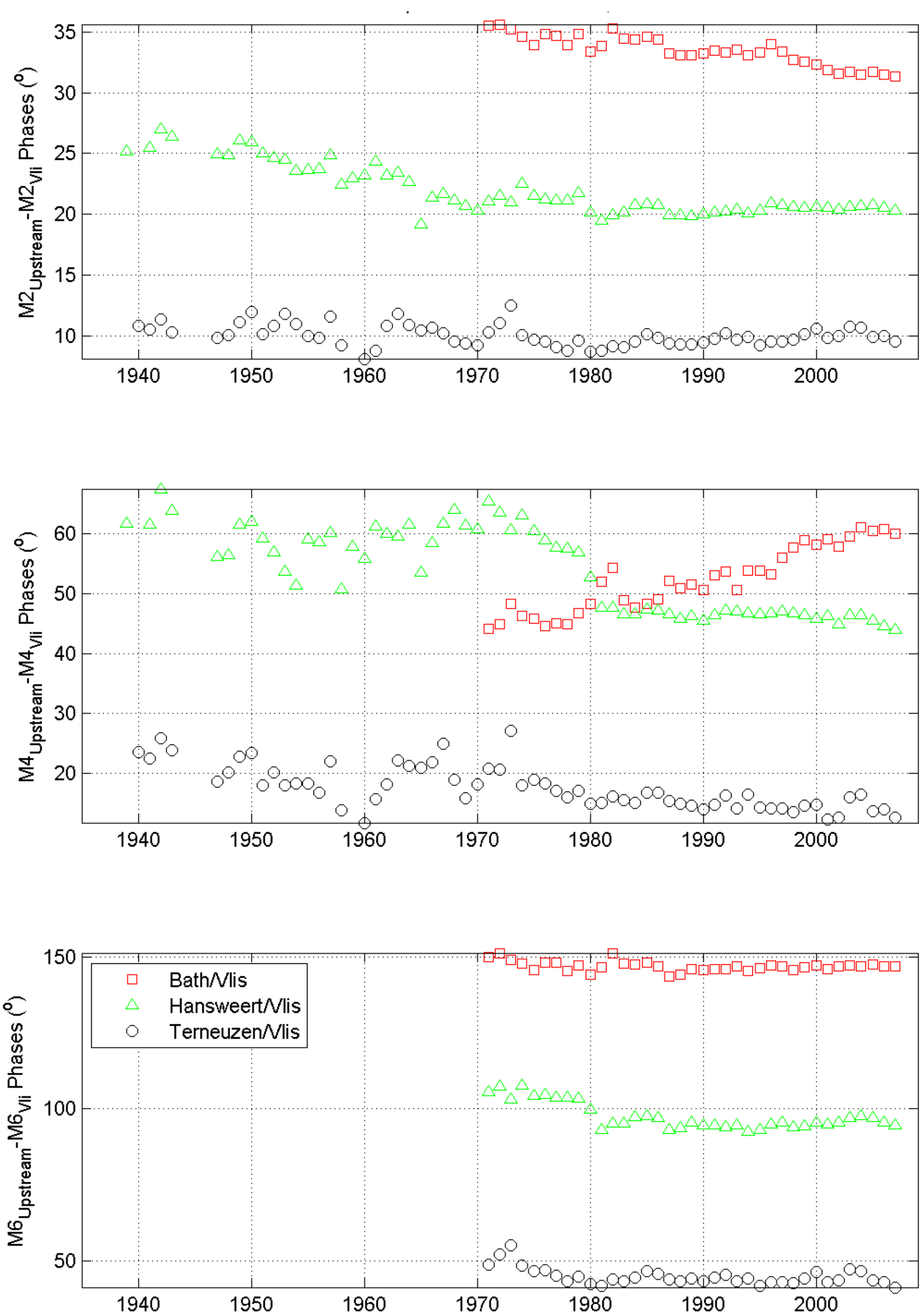



*Figure A.15: Yearly M2, M4 and M6 tidal phase differences between upstream stations and Vlissingen*

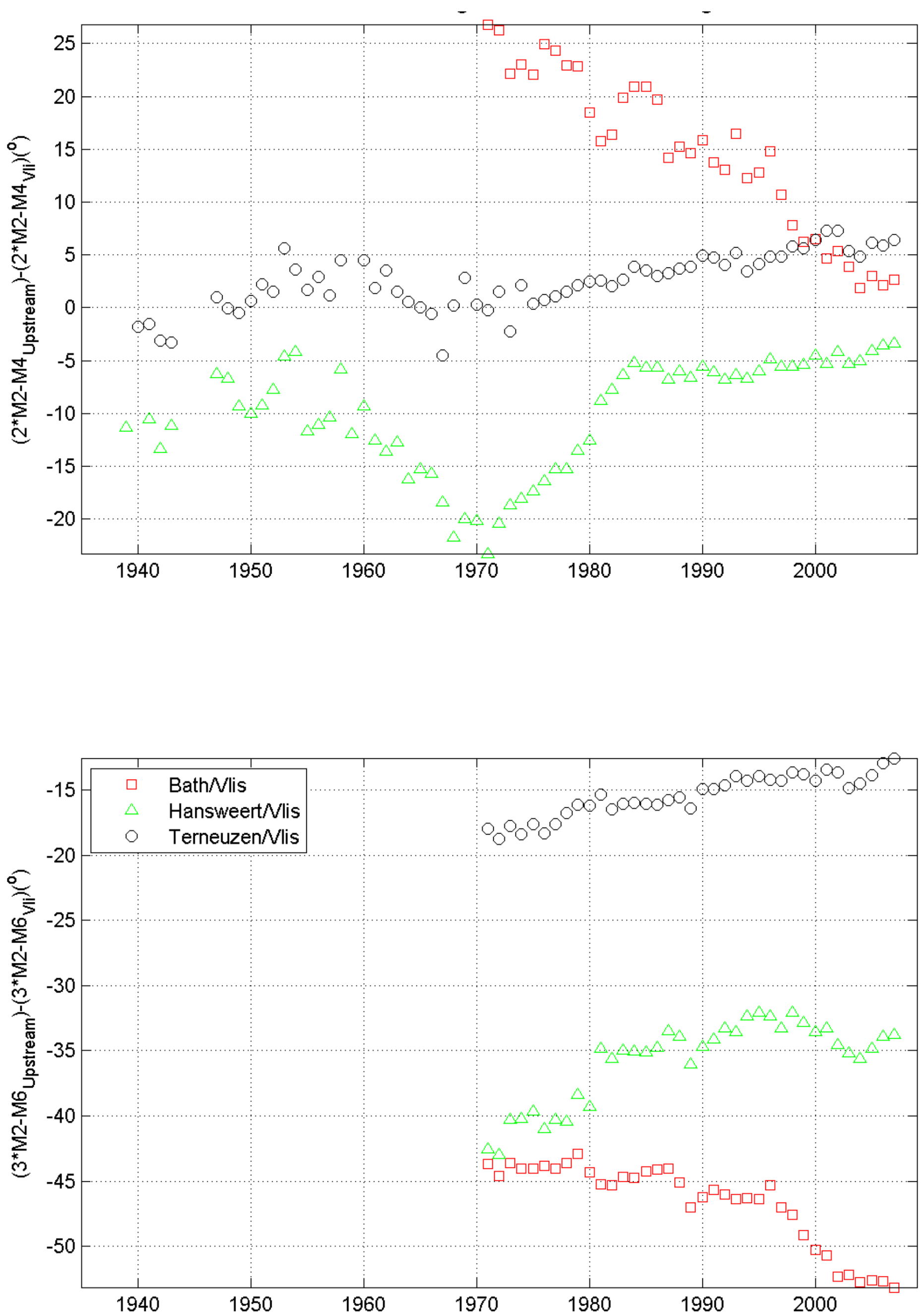



*Figure A.16: Yearly M2, M4 and M6 tidal phase relationship (2*M2-M4 and 3*M2-M6) differences between upstream stations and Vlissingen*

# B Available data on water levels

Data on water levels have been obtained from the Helpdesk Water of Rijkswaterstaat.

**1. Time frame**

Time is given in MET which is current winter time.

**2. Definition of spring and neap tides**

Tidal characteristics for spring and neap tides have been derived as follows (Helpdesk Water):

De waarden van gemiddeld hoogwater en laagwater per jaar bij springtij en doodtij volgen uit de havengetalberekening, die per jaar apart is uitgevoerd. De havengetalberekening is eigenlijk een vereenvoudigde vorm van de vroeger in Nederland gebruikte getijanalysemethode (culminatieanalyse). Er wordt een verband bepaald tussen het tijdstip van maansculminatie en de aan de culminatie gekoppelde elementen:

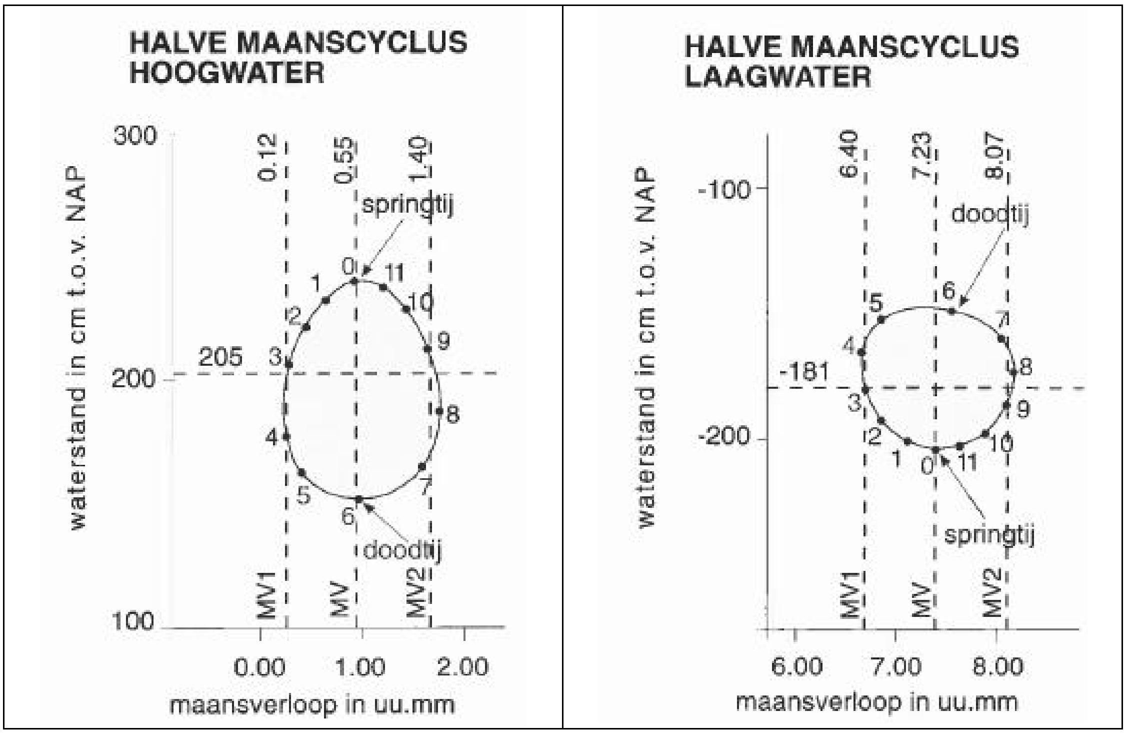
- tijd hoogwater (i.e. maansverloop t.o.v. culminatietijdstip)
- stand hoogwater
- tijd laagwater
- stand laagwater

Hierbij worden de culminatietijdstippen 0-12 uur en 12-24 uur op een hoop gegooid, en wordt ook geen onderscheid gemaakt tussen boven- en onderculminaties. Het resultaat zijn twee verbanden, voor hoogwater en laagwater, tussen culminatietijdstip en zowel tijd (maansverloop) als stand. De grafieken die deze verbanden weergeven staan bekend als 'aardappelgrafieken'. De gemiddelde standen voor springtij zijn nu per definitie de standen op de aardappelgrafieken behorend bij een culminatietijdstip 0 uur, en de standen bij doodtij die behoren bij een tijdstip van 6 uur.

Een veel gedetailleerdere beschrijving is te vinden in de Begrippenlijst voorin "Gemiddelde getijkromme 1991.0" (RIKZ, 1994) met dien verstande dat het daar gaat over de bepaling van de standaardwaarden (slotgemiddelden 1991.0), waarvoor de havengetalberekening over een grotere periode is uitgevoerd, en waarbij de standen voor springtij en doodtij achteraf nog zijn gecorrigeerd met het verschil tussen de standaardwaarde voor gemiddeld tij (op andere wijze berekend) en het overall gemiddelde dat uit de havengetalberekening volgde.

*Referentie:*

Rijksinstituut voor Kust en Zee/RIKZ, 1994, Gemiddelde Getijkromme 1991.0. Afdeling Informatiesystemen.




*Verbanden tussen standen van hoog- en laagwater per culminatie-uur (volgens de halve maancyclus) voor Vlissingen. Ontleend aan [RIKZ, 1994].*

### 3. Descriptions of water level data

The pages hereafter describe the available water level data in Cadzand, Westkapelle, Vlissingen, Terneuzen, Hansweert and Bath on the following aspects:

A. Time histories (Tijdreeksen)
B. High and low waters and times of occurrences for each year (HW-LW; alle hoog- en laagwaters in een jaar)
C. Time differences for high and low waters relative to Vlissingen (Tijdsverschil hoog- en laagwaters t.o.v. Vlissingen)
D. Spring tide - mean tide - neap tide; average high and low water per year (Springtij - gemiddeld tij - doodtij; gemiddelde hoog- en laagwaters per jaar)
E. Tidal constituents per year (Getijcomponenten per jaar)

## Cadzand

### A. Tijdreeks

Beschikbare equidistante waterstanden van Cadzand in twee tekstbestanden:

wca060.txt 1971 t/m 1986, dt = 1 uur, 11688 dataregels
wca010.txt 1987 t/m 31 mei 2009, dt = 10 min., 98244 dataregels

De tekstbestanden bevatten elk 3 tekstregels, gevolgd door dataregels met 12 data per regel, in vaste breedte ( 12i6 ).
Begin- en eindtijd zoals vermeld in de derde tekstregels zijn in MET.

Deze bestanden bevatten geen hiaten.

Van Cadzand zijn in de tijd dat de waterstanden handmatig werden afgelezen van de peilregistraties (d.w.z. t/m 1970) nooit equidistante waterstanden getabelleerd. Er bestond al lang een peilschrijver bij de sluis, maar deze registreerde rond laagwater niet goed, zodat de data niet bruikbaar waren voor toepassingen als berekening van gemiddelde zeestanden en harmonische analyse.

De 10-minuut gemiddelden van 1 januari 1987 t/m 6 september 1993 zijn bepaald als het gemiddelde van de VOORGAANDE 10 minuten, zodat ze eigenlijk 5 minuten achterlopen. Dit geldt voor alle zes waterstandsmeetpunten.

### B. HW-LW (alle hoog- en laagwaters in een jaar)

Tijden en standen van hoog- en laagwaters (HW/LW-data), in één tekstbestand:

hlcad.txt Cadzand 6 januari 1877 t/m mei 2009,
met alleen HW's van 1 september 1900 t/m 1907 en
peilschaalwaarnemingen met meestal alleen 1 HW en 1 LW overdag van 1928 t/m 31 augustus 1966;
alle wel beschikbare LW-data van eind 19e eeuw t/m augustus 1966 zijn onbetrouwbaar.

Het tekstbestand bevat 14 tekstregels, gevolgd door dataregels met datum, tijd in MET (tegenwoordige wintertijd), soort ( 1 = HW, 2 = LW ) en stand in cm + NAP, in vaste breedte.

**C. Tijdsverschil hoog- en laagwaters t.o.v. Vlissingen**

De gemiddelde tijdsverschillen van hoog- en laagwater met Vlissingen per jaar, in 2 tekstbestanden geheten

<soort><cad>.txt

met

<soort> :
dth = tijdsverschil hoogwater
dtl = tijdsverschil laagwater

De tekstbestanden bevatten elk 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde in minuten, in vaste breedte.
Hiaten zijn aangegeven als -999.

De berekening is alleen uitgevoerd op dag- en nachtwaarnemingen van peilschrijvers en DNM's.

De gegevens voor laagwater te Cadzand van voor 1908 zijn te onbetrouwbaar, maar uit de berekening blijkt dat dit ook geldt voor de periode 1908 t/m 1927.

**D. Springtij-gemiddeld tij-doodtij (gemiddelde hoog- en laagwaters per jaar)**

Gemiddelde HW- en LW-standen per jaar in 6 tekstbestanden geheten:

<soort><cad>.txt

met:

<soort> :
gh = gemiddeld hoogwater
gl = gemiddeld laagwater
sh = hoogwater springtij
sl = laagwater springtij
dh = hoogwater doodtij
dl = laagwater doodtij

Deze bestanden bevatten steeds 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde waarde in cm + NAP, in vaste breedte.

Hiaten (o.a. een aantal LW-data bij Cadzand) zijn aangegeven als -999.9.

De springtij- en doodtijreeksen lopen slechts t/m 1999. Er is helaas nog geen gelegenheid geweest de hiervoor benodigde zg. havengetalberekening opnieuw te operationaliseren.

De reeksen voor gemiddeld HW en LW daarentegen gaan verder terug dan de complete HW/LW-datasets.
Het oudste deel is berekend uit reeksen met 1 HW resp. 1 LW overdag per dag, afgelezen van vaste peilschalen.

**E. Getijcomponenten per jaar**

Getijcomponenten per jaar, in 38 tekstbestanden geheten

hc<jaar><cad>.txt

met

<jaar> in 4 cijfers

De tekstbestanden voor de jaren t/m 1970 ( alleen locaties han, ter en vli ) bevatten 9 tekstregels, gevolgd door 47 dataregels ( analyse uit 3-uurlijkse standen, alleen viermaaldaagse en langzamere componenten ); die voor de jaren 1971 t/m 2001 9 tekstregels, gevolgd door 94 dataregels ( analyse uit uurlijkse standen, huidige standaardset ); en die voor de periode v.a. 2002 8 tekstregels, gevolgd door 94 dataregels ( idem, maar standaarduitvoer van programma was gewijzigd ).

De dataregels bevatten het HATYAN-codenummer, hoeksnelheid in graden per uur, amplitude in cm, fase ( g ) in graden t.o.v. MET en naam component, in vaste breedte.

De tekstregels beginnend met MIDD bevatten de middenstand in cm + NAP.

Zoals eerder vermeld lopen de equidistante waterstanden van 1 januari 1987 t/m 6 september 1993 zoals opgeslagen in DONAR feitelijk 5 minuten achter, maar bij de harmonische analyses is hiervoor gecorrigeerd.

Alle analyses zijn uitgevoerd met de al sinds lang ook voor de reguliere getijanalyse en -voorspelling gebruikelijke aanpassingen van de theoretische waarden van de knoopfactorcorrectie voor de amplitude ( f ). Deze data zijn ook in een groot aantal eerdere onderzoeken zo gebruikt.

De bestanden voor Cadzand lopen vanaf 1971.

## Westkapelle

### A. Tijdreeks

Beschikbare equidistante waterstanden van Westkapelle in twee tekstbestanden :

wwk060.txt 1971 t/m 1986, dt = 1 uur, 11688 dataregels
wwk010.txt 1987 t/m 31 mei 2009, dt = 10 min., 98244 dataregels

De tekstbestanden bevatten elk 3 tekstregels, gevolgd door dataregels met 12 data per regel, in vaste breedte ( 12i6 ).
Begin- en eindtijd zoals vermeld in de derde tekstregels zijn in MET.

Deze bestanden bevatten geen hiaten.

Ook van Westkapelle zijn tot 1971 nooit equidistante waterstanden getabelleerd. Een eerste peilschrijver, geïnstalleerd in 1884, was al rond 1900 buiten werking geraakt; een tweede, geïnstalleerd in 1934, werd in 1943 vernield, waarna opnieuw werd overgeschakeld op peilschaalwaarnemingen overdag. Pas vanaf medio 1954 waren er weer peilschrijverwaarnemingen.

De 10-minuut gemiddelden van 1 januari 1987 t/m 6 september 1993 zijn bepaald als het gemiddelde van de VOORGAANDE 10 minuten, zodat ze eigenlijk 5 minuten achterlopen. Dit geldt voor alle zes waterstandsmeetpunten.

### B. HW-LW (alle hoog- en laagwaters in een jaar)

Tijden en standen van hoog- en laagwaters ( HW/LW-data ) in één tekstbestand:

hlwka.txt Westkapelle september 1884 t/m mei 2009,
echter geen gegevens van april 1890 t/m augustus 1899 en van juli 1943 tot 20 augustus 1946, en
twee grote perioden met peilschaalwaarnemingen met (meestal) alleen 1 HW en 1 LW overdag, zoals aangegeven in de kop van het bestand.

Het tekstbestand bevat 14 tekstregels, gevolgd door dataregels met datum, tijd in MET ( tegenwoordige wintertijd ), soort ( 1 = HW, 2 = LW ) en stand in cm + NAP, in vaste breedte.

**C. Tijdsverschil hoog- en laagwaters t.o.v. Vlissingen**

De gemiddelde tijdsverschillen van hoog- en laagwater met Vlissingen per jaar, in 2 tekstbestanden geheten

<soort><wka>.txt

met

<soort> :
dth = tijdsverschil hoogwater
dtl = tijdsverschil laagwater

De tekstbestanden bevatten elk 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde in minuten, in vaste breedte.
Hiaten zijn aangegeven als -999.

De berekening is alleen uitgevoerd op dag- en nachtwaarnemingen van peilschrijvers en DNM's.

**D. Springtij-gemiddeld tij-doodtij (gemiddelde hoog- en laagwaters per jaar)**

Gemiddelde HW- en LW-standen per jaar, in 6 tekstbestanden geheten:

<soort><wka>.txt

met

<soort> :
gh = gemiddeld hoogwater
gl = gemiddeld laagwater
sh = hoogwater springtij
sl = laagwater springtij
dh = hoogwater doodtij
dl = laagwater doodtij

Deze bestanden bevatten steeds 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde waarde in cm + NAP, in vaste breedte.

Hiaten zijn aangegeven als -999.9.

De springtij- en doodtijreeksen lopen slechts t/m 1999. Er is helaas nog geen gelegenheid geweest de hiervoor benodigde zg. havengetalberekening opnieuw te operationaliseren.

De reeksen voor gemiddeld HW en LW daarentegen gaan verder terug dan de complete HW/LW-datasets.
Het oudste deel is berekend uit reeksen met 1 HW resp. 1 LW overdag per dag, afgelezen van vaste peilschalen.

**E. Getijcomponenten per jaar**

Getijcomponenten per jaar, in 38 tekstbestanden geheten

hc<jaar><wka>.txt

met

<jaar> in 4 cijfers

De tekstbestanden voor de jaren t/m 1970 ( alleen locaties han, ter en vli ) bevatten 9 tekstregels, gevolgd door 47 dataregels ( analyse uit 3-uurlijkse standen, alleen viermaaldaagse en langzamere componenten ); die voor de jaren 1971 t/m 2001 9 tekstregels, gevolgd door 94 dataregels ( analyse uit uurlijkse standen, huidige standaardset ); en die voor de periode v.a. 2002 8 tekstregels, gevolgd door 94 dataregels ( idem, maar standaarduitvoer van programma was gewijzigd ).

De dataregels bevatten het HATYAN-codenummer, hoeksnelheid in graden per uur, amplitude in cm, fase ( g ) in graden t.o.v. MET en naam component, in vaste breedte.

De tekstregels beginnend met MIDD bevatten de middenstand in cm + NAP.

Zoals eerder vermeld lopen de equidistante waterstanden van 1 januari 1987 t/m 6 september 1993 zoals opgeslagen in DONAR feitelijk 5 minuten achter, maar bij de harmonische analyses is hiervoor gecorrigeerd.

Alle analyses zijn uitgevoerd met de al sinds lang ook voor de reguliere getijanalyse en -voorspelling gebruikelijke aanpassingen van de theoretische waarden van de knoopfactorcorrectie voor de amplitude ( f ). Deze data zijn ook in een groot aantal eerdere onderzoeken zo gebruikt.

De bestanden voor Westkapelle lopen vanaf 1971.

## Vlissingen

### A. Tijdreeks

Beschikbare equidistante waterstanden van Vlissingen, in vier tekstbestanden :

| | |
|---|---|
| wvl180a.txt | 1911 t/m 1960, dt = 3 uur, 12176 dataregels |
| wvl180b.txt | 1961 t/m 1970, dt = 3 uur, 2435 dataregels |
| wvl060.txt | 1971 t/m 1986, dt = 1 uur, 11688 dataregels |
| wvl010.txt | 1987 t/m 31 mei 2009, dt = 10 min., 98244 dataregels |

De tekstbestanden bevatten elk 3 tekstregels, gevolgd door dataregels met 12 data per regel, in vaste breedte ( 12i6 ).
Begin- en eindtijd zoals vermeld in de derde tekstregels zijn in MET.

Deze bestanden bevatten geen hiaten.

De 10 minuutgemiddelden van 1 januari 1987 t/m 6 september 1993 zijn bepaald als het gemiddelde van de VOORGAANDE 10 minuten, zodat ze eigenlijk 5 minuten achterlopen. Dit geldt voor alle zes waterstandsmeetpunten.

### B. HW-LW (alle hoog- en laagwaters in een jaar)

Tijden en standen van hoog- en laagwaters ( HW/LW-data ) in één tekstbestand:

hlvli.txt Vlissingen januari 1877 t/m mei 2009,
echter met in het begin enkele perioden met peilschaalwaarnemingen met (meestal) alleen 1 HW en 1 LW overdag; deze zijn aangegeven in de kop van het bestand.

Het tekstbestand bevat 14 tekstregels, gevolgd door dataregels met datum, tijd in MET (tegenwoordige wintertijd), soort ( 1 = HW, 2 = LW ) en stand in cm + NAP, in vaste breedte.

### C. Tijdsverschil hoog- en laagwaters t.o.v. Vlissingen

Niet van toepassing.

**D. Springtij-gemiddeld tij-doodtij (gemiddelde hoog- en laagwaters per jaar)**

Gemiddelde HW- en LW-standen per jaar in 6 tekstbestanden geheten:

<soort><vli>.txt

met

<soort> :
gh = gemiddeld hoogwater
gl = gemiddeld laagwater
sh = hoogwater springtij
sl = laagwater springtij
dh = hoogwater doodtij
dl = laagwater doodtij

Deze bestanden bevatten steeds 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde waarde in cm + NAP, in vaste breedte.

Hiaten zijn aangegeven als -999.9.

De springtij- en doodtijreeksen lopen slechts t/m 1999. Er is helaas nog geen gelegenheid geweest de hiervoor benodigde zg. havengetalberekening opnieuw te operationaliseren.

De reeksen voor gemiddeld HW en LW daarentegen gaan verder terug dan de complete HW/LW-datasets.
Het oudste deel is berekend uit reeksen met 1 HW resp. 1 LW overdag per dag, afgelezen van vaste peilschalen.

De standen van Vlissingen van voor ca. 1885 lijken nogal hoog, ook in vergelijking met zeer naburige meetpunten. Dit was al bijna honderd jaar geleden opgevallen, maar aangezien er nooit een duidelijke fout kon worden getraceerd zijn de standen ongewijzigd gelaten.

**E. Getijcomponenten per jaar**

Getijcomponenten per jaar, in 98 tekstbestanden geheten

hc<jaar><vli>.txt

met

<jaar> in 4 cijfers

De tekstbestanden voor de jaren t/m 1970 ( alleen locaties han, ter en vli ) bevatten 9 tekstregels, gevolgd door 47 dataregels ( analyse uit 3-uurlijkse standen, alleen viermaaldaagse en langzamere componenten ); die voor de jaren 1971 t/m 2001 9 tekstregels, gevolgd door 94 dataregels ( analyse uit uurlijkse standen, huidige standaardset ); en die voor de periode v.a. 2002 8 tekstregels, gevolgd door 94 dataregels ( idem, maar standaarduitvoer van programma was gewijzigd ).

De dataregels bevatten het HATYAN-codenummer, hoeksnelheid in graden per uur, amplitude in cm, fase ( g ) in graden t.o.v. MET en naam component, in vaste breedte.

De tekstregels beginnend met MIDD bevatten de middenstand in cm + NAP.

Zoals eerder vermeld lopen de equidistante waterstanden van 1 januari 1987 t/m 6 september 1993 zoals opgeslagen in DONAR feitelijk 5 minuten achter, maar bij de harmonische analyses is hiervoor gecorrigeerd.

Alle analyses zijn uitgevoerd met de al sinds lang ook voor de reguliere getijanalyse en -voorspelling gebruikelijke aanpassingen van de theoretische waarden van de knoopfactorcorrectie voor de amplitude ( f ). Deze data zijn ook in een groot aantal eerdere onderzoeken zo gebruikt.

De bestanden voor Vlissingen lopen vanaf 1911.

## Terneuzen

### A. Tijdreeks

Beschikbare equidistante waterstanden van Terneuzen in vier tekstbestanden :

| | |
|---|---|
| wte180a.txt | 1940 t/m 1960, dt = 3 uur, 5358 dataregels |
| wte180b.txt | 1961 t/m 1970, dt = 3 uur, 2435 dataregels |
| wte060.txt | 1971 t/m 1986, dt = 1 uur, 11688 dataregels |
| wte010.txt | 1987 t/m 31 mei 2009, dt = 10 min., 98244 dataregels |

De tekstbestanden bevatten elk 3 tekstregels, gevolgd door dataregels met 12 data per regel, in vaste breedte ( 12i6 ).
Begin- en eindtijd zoals vermeld in de derde tekstregels zijn in MET.

Het eerste bestand bevat hiaten; deze zijn aangegeven als -999.

De 10-minuut gemiddelden van 1 januari 1987 t/m 6 september 1993 zijn bepaald als het gemiddelde van de VOORGAANDE 10 minuten, zodat ze eigenlijk 5 minuten achterlopen. Dit geldt voor alle zes waterstandsmeetpunten.

### B. HW-LW (alle hoog- en laagwaters in een jaar)

Tijden en standen van hoog- en laagwaters ( HW/LW-data ) in één tekstbestand:

hlter.txt Terneuzen maart 1878 t/m mei 2009, geheel compleet.

Het tekstbestand bevat 14 tekstregels, gevolgd door dataregels met datum, tijd in MET (tegenwoordige wintertijd), soort ( 1 = HW, 2 = LW ) en stand in cm + NAP, in vaste breedte.

**C. Tijdsverschil hoog- en laagwaters t.o.v. Vlissingen**

De gemiddelde tijdsverschillen van hoog- en laagwater met Vlissingen per jaar, in 2 tekstbestanden geheten

<soort><ter>.txt

met

<soort> :
dth = tijdsverschil hoogwater
dtl = tijdsverschil laagwater

De tekstbestanden bevatten elk 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde in minuten, in vaste breedte.
Hiaten zijn aangegeven als -999.

De berekening is alleen uitgevoerd op dag- en nachtwaarnemingen van peilschrijvers en DNM's.

**D. Springtij-gemiddeld tij-doodtij (gemiddelde hoog- en laagwaters per jaar)**

Gemiddelde HW- en LW-standen per jaar, in 6 tekstbestanden geheten:

<soort><ter>.txt

met

<soort> :
gh = gemiddeld hoogwater
gl = gemiddeld laagwater
sh = hoogwater springtij
sl = laagwater springtij
dh = hoogwater doodtij
dl = laagwater doodtij

Deze bestanden bevatten steeds 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde waarde in cm + NAP, in vaste breedte.

Hiaten zijn aangegeven als -999.9.

De springtij- en doodtijreeksen lopen slechts t/m 1999. Er is helaas nog geen gelegenheid geweest de hiervoor benodigde zg. havengetalberekening opnieuw te operationaliseren.

De reeksen voor gemiddeld HW en LW daarentegen gaan verder terug dan de complete HW/LW-datasets.
Het oudste deel is berekend uit reeksen met 1 HW resp. 1 LW overdag per dag, afgelezen van vaste peilschalen.

## E. Getijcomponenten per jaar

Getijcomponenten per jaar, in 65 tekstbestanden geheten

hc<jaar><ter>.txt

met

<jaar> in 4 cijfers

De tekstbestanden voor de jaren t/m 1970 ( alleen locaties han, ter en vli ) bevatten 9 tekstregels, gevolgd door 47 dataregels ( analyse uit 3-uurlijkse standen, alleen viermaaldaagse en langzamere componenten ); die voor de jaren 1971 t/m 2001 9 tekstregels, gevolgd door 94 dataregels ( analyse uit uurlijkse standen, huidige standaardset ); en die voor de periode v.a. 2002 8 tekstregels, gevolgd door 94 dataregels ( idem, maar standaarduitvoer van programma was gewijzigd ).

De dataregels bevatten het HATYAN-codenummer, hoeksnelheid in graden per uur, amplitude in cm, fase ( g ) in graden t.o.v. MET en naam component, in vaste breedte.

De tekstregels beginnend met MIDD bevatten de middenstand in cm + NAP.

Zoals eerder vermeld lopen de equidistante waterstanden van 1 januari 1987 t/m 6 september 1993 zoals opgeslagen in DONAR feitelijk 5 minuten achter, maar bij de harmonische analyses is hiervoor gecorrigeerd.

Alle analyses zijn uitgevoerd met de al sinds lang ook voor de reguliere getijanalyse en -voorspelling gebruikelijke aanpassingen van de theoretische waarden van de knoopfactorcorrectie voor de amplitude ( f ). Deze data zijn ook in een groot aantal eerdere onderzoeken zo gebruikt.

De bestanden voor Terneuzen lopen vanaf 1940, waarbij ontbreken : 1944, '45, '46 en '59.

## Hansweert

### A. Tijdreeks

Beschikbare equidistante waterstanden van Hansweert in vier tekstbestanden:

| | |
|---|---|
| wha180a.txt | 1939 t/m 1960, dt = 3 uur, 5358 dataregels |
| wha180b.txt | 1961 t/m 1970, dt = 3 uur, 2429 dataregels |
| wha060.txt | 1971 t/m 1986, dt = 1 uur, 11688 dataregels |
| wha010.txt | 1987 t/m 31 mei 2009, dt = 10 min., 98244 dataregels |

De tekstbestanden bevatten elk 3 tekstregels, gevolgd door dataregels met 12 data per regel, in vaste breedte ( 12i6 ).
Begin- en eindtijd zoals vermeld in de derde tekstregels zijn in MET.

Het eerste bestand bevat hiaten; deze zijn aangegeven als -999.

Voor de Tweede Wereldoorlog werd in Nederland de zg. Amsterdamse Tijd ( GMT + 20 min. ) aangehouden. Bij de bewerking van waterstanden is deze nog t/m 1960 gebruikt. Ten tijde van de handmatige verwerking van waterstanden, t/m 1970, werden van een aantal meetpunten in het getijgebied naast de tijden en standen van hoog- en laagwaters ook standen om de 3 uur, te weten om 2, 5, 8, ... , 23 uur, afgelezen. De oorspronkelijke tijden t.o.v. Amsterdamse Tijd zijn in DONAR omgerekend naar MET, dus 2:40, 5:40 uur enz. Dit is de reden dat er twee bestanden met waterstanden om de 3 uur zijn.

De 10-minuut gemiddelden van 1 januari 1987 t/m 6 september 1993 zijn bepaald als het gemiddelde van de VOORGAANDE 10 minuten, zodat ze eigenlijk 5 minuten achterlopen. Dit geldt voor alle zes waterstandsmeetpunten.

### B. HW-LW (alle hoog- en laagwaters in een jaar)

Tijden en standen van hoog- en laagwaters (HW/LW-data), in één tekstbestand:

hlhan.txt Hansweert juli 1880 t/m mei 2009, geheel compleet.

Dit tekstbestand bevat 14 tekstregels, gevolgd door dataregels met datum, tijd in MET ( tegenwoordige wintertijd ), soort ( 1 = HW, 2 = LW ) en stand in cm + NAP, in vaste breedte.

De HW/LW-data van 1987 t/m 6 september 1993 zijn berekend uit de 10 min. gemiddelden die zijn bepaald als gemiddelde over de voorgaande 10 min. ( zie 1e e-mail ) en niet achteraf gecorrigeerd, en lopen dus feitelijk ook alle 5 min. achter.

De HW/LW-data vanaf 2007 staan nog niet in DONAR, en zijn nu ad hoc berekend. Voor 2007 zijn de equidistante waterstanden overigens wel al definitief.

**C. Tijdsverschil hoog- en laagwaters t.o.v. Vlissingen**

De gemiddelde tijdsverschillen van hoog- en laagwater met Vlissingen per jaar, in 2 tekstbestanden geheten

<soort><han>.txt

met

<soort> :
dth = tijdsverschil hoogwater
dtl = tijdsverschil laagwater

De tekstbestanden bevatten elk 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde in minuten, in vaste breedte.
Hiaten zijn aangegeven als -999.

De berekening is alleen uitgevoerd op dag- en nachtwaarnemingen van peilschrijvers en DNM's.

**D. Springtij-gemiddeld tij-doodtij (gemiddelde hoog- en laagwaters per jaar)**

Bijgaande files bevatten de gemiddelde HW- en LW-standen per jaar, in 6 tekstbestanden geheten:

<soort><han>.txt

met

<soort> :
gh = gemiddeld hoogwater
gl = gemiddeld laagwater
sh = hoogwater springtij
sl = laagwater springtij
dh = hoogwater doodtij
dl = laagwater doodtij

Deze bestanden bevatten steeds 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde waarde in cm + NAP, in vaste breedte.

Hiaten zijn aangegeven als -999.9.

De springtij- en doodtijreeksen lopen slechts t/m 1999. Er is helaas nog geen gelegenheid geweest de hiervoor benodigde zg. havengetalberekening opnieuw te operationaliseren.

De reeksen voor gemiddeld HW en LW daarentegen gaan verder terug dan de complete HW/LW-datasets.
Het oudste deel is berekend uit reeksen met 1 HW resp. 1 LW overdag per dag, afgelezen van vaste peilschalen.

**E. Getijcomponenten per jaar**

Getijcomponenten per jaar, in 66 tekstbestanden geheten

hc<jaar><han>.txt

met

<jaar> in 4 cijfers

De tekstbestanden voor de jaren t/m 1970 ( alleen locaties han, ter en vli ) bevatten 9 tekstregels, gevolgd door 47 dataregels ( analyse uit 3-uurlijkse standen, alleen viermaaldaagse en langzamere componenten ); die voor de jaren 1971 t/m 2001 9 tekstregels, gevolgd door 94 dataregels ( analyse uit uurlijkse standen, huidige standaardset ); en die voor de periode v.a. 2002 8 tekstregels, gevolgd door 94 dataregels ( idem, maar standaarduitvoer van programma was gewijzigd ).

De dataregels bevatten het HATYAN-codenummer, hoeksnelheid in graden per uur, amplitude in cm, fase ( g ) in graden t.o.v. MET en naam component, in vaste breedte.

De tekstregels beginnend met MIDD bevatten de middenstand in cm + NAP.

Zoals eerder vermeld lopen de equidistante waterstanden van 1 januari 1987 t/m 6 september 1993 zoals opgeslagen in DONAR feitelijk 5 minuten achter, maar bij de harmonische analyses is hiervoor gecorrigeerd.

Alle analyses zijn uitgevoerd met de al sinds lang ook voor de reguliere getijanalyse en -voorspelling gebruikelijke aanpassingen van de theoretische waarden van de knoopfactorcorrectie voor de amplitude ( f ). Deze data zijn ook in een groot aantal eerdere onderzoeken zo gebruikt.

De bestanden voor Hansweert lopen vanaf 1939, waarbij ontbreken : 1940, '44, '45 en '46.

**Bath**

**A. Tijdreeks**

Beschikbare equidistante waterstanden van Bath in twee tekstbestanden :

wba060.txt 1971 t/m 1986, dt = 1 uur, 11688 dataregels
wba010.txt 1987 t/m 31 mei 2009, dt = 10 min., 98244 dataregels

De tekstbestanden bevatten elk 3 tekstregels, gevolgd door dataregels met 12 data per regel, in vaste breedte ( 12i6 ).
Begin- en eindtijd zoals vermeld in de derde tekstregels zijn in MET.

De 10-minuut gemiddelden van 1 januari 1987 t/m 6 september 1993 zijn bepaald als het gemiddelde van de VOORGAANDE 10 minuten, zodat ze eigenlijk 5 minuten achterlopen. Dit geldt voor alle zes waterstandsmeetpunten.

**B. HW-LW (alle hoog- en laagwaters in een jaar)**

Tijden en standen van hoog- en laagwaters ( HW/LW-data ) in één tekstbestand:

hlbat.txt Bath mei 1886 t/m mei 2009,
echter met grote perioden met peilschaalwaarnemingen met (meestal) alleen 1 HW en 1 LW overdag; deze zijn aangegeven in de kop van het bestand.

Dit tekstbestand bevat 14 tekstregels, gevolgd door dataregels met datum, tijd in MET (tegenwoordige wintertijd), soort ( 1 = HW, 2 = LW ) en stand in cm + NAP, in vaste breedte.

De HW/LW-data van 1987 t/m 6 september 1993 zijn berekend uit de 10 min. gemiddelden die zijn bepaald als gemiddelde over de voorgaande 10 min. en niet achteraf gecorrigeerd. Zij lopen dus feitelijk ook alle 5 min. achter.

De HW/LW-data vanaf 2007 staan nog niet in DONAR, en zijn nu ad hoc berekend. Voor 2007 zijn de equidistante waterstanden overigens wel al definitief.

**C. Tijdsverschil hoog- en laagwaters t.o.v. Vlissingen**

De gemiddelde tijdsverschillen van hoog- en laagwater met Vlissingen per jaar, in 2 tekstbestanden geheten

<soort><bat>.txt

met

<soort> :
dth = tijdsverschil hoogwater
dtl = tijdsverschil laagwater

De tekstbestanden bevatten elk 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde in minuten, in vaste breedte.
Hiaten zijn aangegeven als -999.

De berekening is alleen uitgevoerd op dag- en nachtwaarnemingen van peilschrijvers en DNM's.

**D. Springtij-gemiddeld tij-doodtij (gemiddelde hoog- en laagwaters per jaar)**

Gemiddelde HW- en LW-standen per jaar, in 6 tekstbestanden geheten:

<soort><bat>.txt

met

<soort> :
gh = gemiddeld hoogwater
gl = gemiddeld laagwater
sh = hoogwater springtij
sl = laagwater springtij
dh = hoogwater doodtij
dl = laagwater doodtij

Deze bestanden bevatten steeds 1 tekstregel, gevolgd door dataregels met jaar en gemiddelde waarde in cm + NAP, in vaste breedte.

Hiaten zijn aangegeven als -999.9.

De springtij- en doodtijreeksen lopen slechts t/m 1999. Er is helaas nog geen gelegenheid geweest de hiervoor benodigde zg. havengetalberekening opnieuw te operationaliseren.

De reeksen voor gemiddeld HW en LW daarentegen gaan verder terug dan de complete HW/LW-datasets.
Het oudste deel is berekend uit reeksen met 1 HW resp. 1 LW overdag per dag, afgelezen van vaste peilschalen.

Er bestaat wel enige gerede twijfel over de kwaliteit van de oudere LW-data van Bath.

**E. Getijcomponenten per jaar**

Getijcomponenten per jaar, in 38 tekstbestanden geheten

hc<jaar><bat>.txt

met

<jaar> in 4 cijfers

De tekstbestanden voor de jaren t/m 1970 ( alleen locaties han, ter en vli ) bevatten 9 tekstregels, gevolgd door 47 dataregels ( analyse uit 3-uurlijkse standen, alleen viermaaldaagse en langzamere componenten ); die voor de jaren 1971 t/m 2001 9 tekstregels, gevolgd door 94 dataregels ( analyse uit uurlijkse standen, huidige standaardset ); en die voor de periode v.a. 2002 8 tekstregels, gevolgd door 94 dataregels ( idem, maar standaarduitvoer van programma was gewijzigd ).

De dataregels bevatten het HATYAN-codenummer, hoeksnelheid in graden per uur, amplitude in cm, fase ( g ) in graden t.o.v. MET en naam component, in vaste breedte.

De tekstregels beginnend met MIDD bevatten de middenstand in cm + NAP.

Zoals eerder vermeld lopen de equidistante waterstanden van 1 januari 1987 t/m 6 september 1993 zoals opgeslagen in DONAR feitelijk 5 minuten achter, maar bij de harmonische analyses is hiervoor gecorrigeerd.

Alle analyses zijn uitgevoerd met de al sinds lang ook voor de reguliere getijanalyse en -voorspelling gebruikelijke aanpassingen van de theoretische waarden van de knoopfactorcorrectie voor de amplitude ( f ). Deze data zijn ook in een groot aantal eerdere onderzoeken zo gebruikt.

De bestanden voor Bath lopen vanaf 1971.

# C Increase of tidal range at Vlissingen and in the North Sea

Changes of the tidal range in the Scheldt-estuary are the combined effect of changes of the tidal forcing originating in the North Sea (and even farther in the Atlantic Ocean) and changes in the tidal propagation within the estuary. For the present project the seaward boundary of the estuary is chosen at Vlissingen. However, for predictions on the evolution of the tide in the Scheldt-estuary also expected changes of tidal characteristics in the North Sea are of importance.

Hollebrandse (2005) compared changes in the tidal range in stations along the Dutch coast (from Vlissingen to Delfzijl) and in the Wadden Sea with stations along the German North Sea islands (from Borkum to List), one station in the North Sea (Euro Platform) and one station to the south-west of England. Various statistical techniques were applied to analyze the data. One of the results is given in Figure C.1, where the evolution of the tidal range along the Dutch and German coast is compared. It was obtained by (i) computing the record-averaged tidal range and subtracting it from the original data set and subtracting the nodal tide effect (which is the tidal oscillation with a period of 18.6 years).

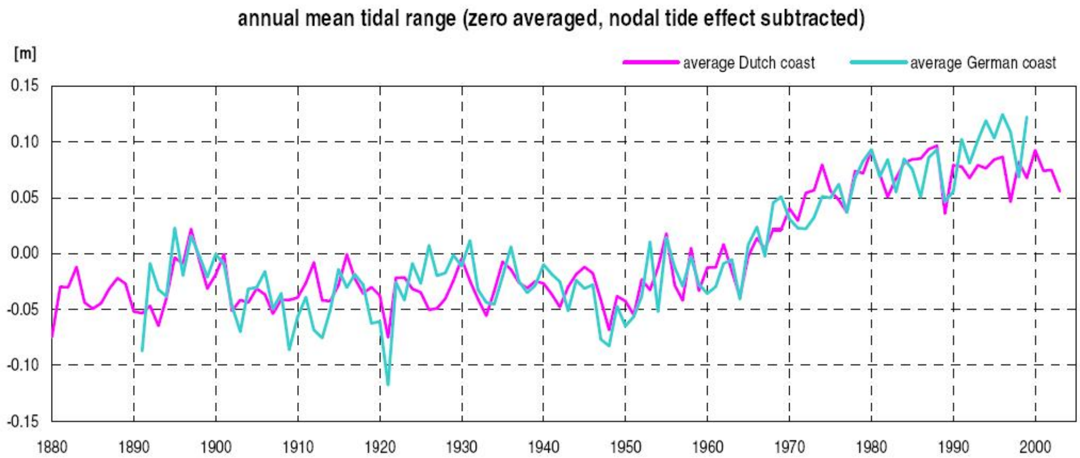



*Figure C.1: Tidal range development along the Dutch and German coast. The average of the Dutch stations Vlissingen, Burghsluis, Hoek van Holland, Scheveningen and IJmuiden and the average of the German stations Borkum, Norderney, Lighthouse Alte Weser, Helgoland, Wittdün and List are shown (Hollebrandse, 2005).*

Figure C.1 shows that the residual tidal range has remained constant before 1950. Between 1950 and 1980 the tidal range increased with approximately 10 cm and since then the tidal range has remained constant again although the tidal range in the German stations seem to increase further after 1990. A satisfactory explanation of this trend could not be given but it was suggested that it resulted from “complex changes in the oceanic and the shelf sea system due to meteorological and astronomic changes”. The hypothesis that the coastal engineering works in the River Rhine delta (inlet closures in the Zeeland area) could have been be the common cause was rejected on the basis of model simulations. Furthermore one would expect that the “sudden” closures of tidal inlets, most of them between 1960 and 1970, do not result in a gradual trend although the effect of a morphological response is possible. Hollebrandse (2005) also found on the basis of model simulations that the increase of mean sea level of 0.2

m/100 year results in an increase of the tidal range of at most 1% which is much less than the observed increase of approximately 5%/100 year.

The results for Vlissingen as found by Hollebrandse were reproduced for the present project[14]. Figure C.2 shows the *reduced tidal range* for the period 1862-2008, which is 5 years longer than the data set of Hollebrandse. The reduced tidal range has been obtained by subtracting the average tidal range for the whole period from the data set. The time-averaged value of the reduced tidal range for the whole period is thus nil. The resulting data still contain the nodal variation with a period of about 18.6 years. This variation was derived from the data on yearly-averaged tidal ranges using a regression model. The regression model simultaneously computes parameters for a linear trend and parameters for the oscillation according to a cosine-function. In the latter case the amplitude of the oscillation as well as the frequency (or period) are estimated including their uncertainties. For Vlissingen the period of the oscillation was estimated as 18.73 ± 0.26 year and the amplitude of the oscillation amounted 6.6 cm ± 1.3 cm (both with 95% lower and upper bounds). Hereafter a period of 18.71 year has been used resulting in a reduced tidal range similar to Hollebrandse. The computed nodal oscillation with a maximum in e.g. 1978.4 is also shown in Figure C.2.

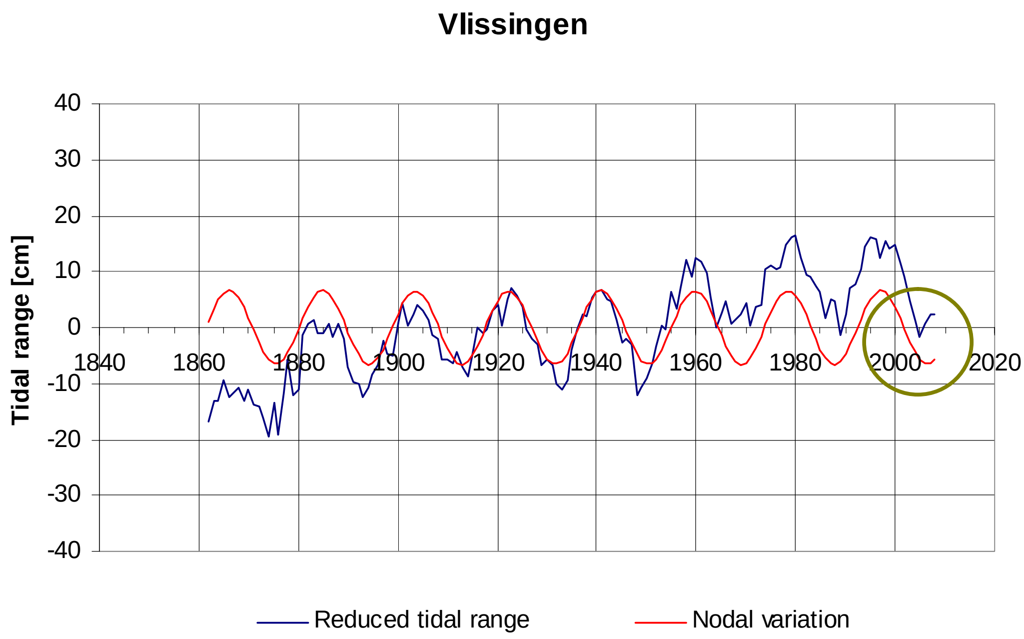



*Figure C.2: Reduced tidal range (= record minus record-averaged value, blue line) and nodal oscillation (red line) in Vlissingen.*

From Figure C.2 it can be seen that before 1910 the reduced tidal range (blue line) was less than the nodal oscillation (red line). After 1950 the reduced tidal range becomes larger than this oscillation. Apparently some trend is present. The green circle indicates that presently (2011) the yearly-averaged tidal range is increasing due to the nodal variation only. Whether there will be a net increase depends on the long term variation. This *residual variation* is shown in Figure C.3 and is obtained after subtracting the nodal oscillation from the reduced tidal range in Figure C.2 (blue line).

[14] *Model set-up and computations were done by Dr. H.F.P. van den Boogaard of Deltares.*

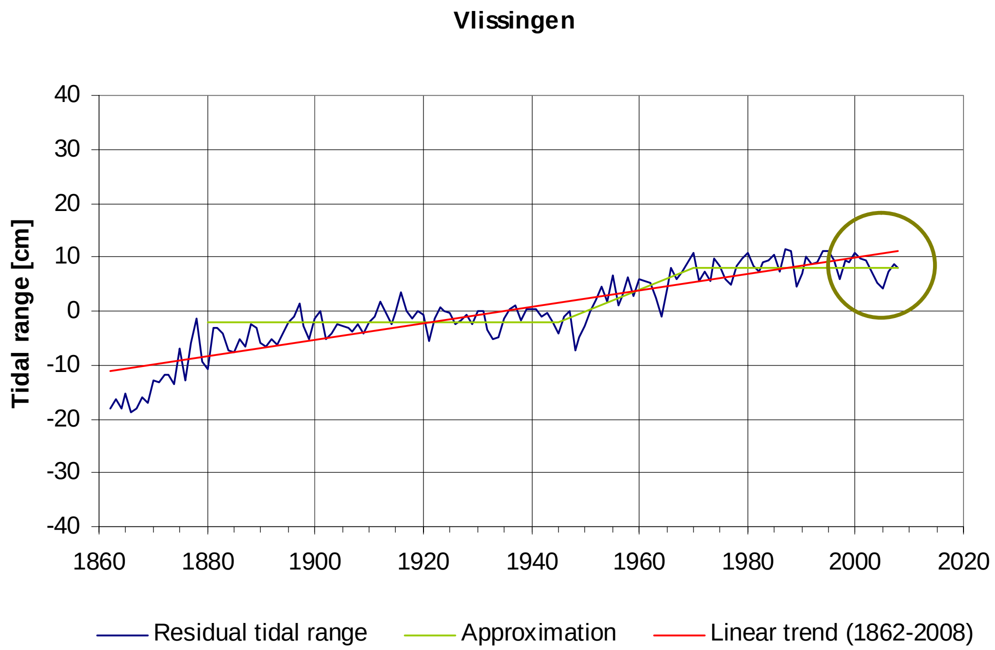



*Figure C.3: Residual tidal range (relative tidal range minus 18.6 year oscillation, blue line) with assumed approximation (green line) and linear trend (red line).*

The final result as shown in Figure C.3 is similar to the result found by Hollebrandse for Vlissingen (see Appendix A6, Figure 1c in that report). It can be interpreted in two ways:

- **Case 1:** If only the period after 1880 is considered (as has been done in Figure C.1 for the average value of Dutch stations along the Dutch coast) the residual tidal range appears to be constant before 1945 (green line). Next, the residual tidal range increases between 1945 and 1970 with approximately 10 cm (~ 2.5%). This is again followed by a period with an almost constant tidal range.
- **Case 2:** If the whole period is considered than the overall increase can be approximated with a sloping line (red line in Figure C.3). Superimposed on this line a long-term variation seems to be present with a period of approximately 75 year.

It is difficult to decide whether Case 1 or Case 2 is true. With Case 1 the increase in tidal range is episodic whereas with Case 2 the variation is the combined effect of a linear increase with a long-term oscillation. In both cases a real explanation for the observed increase is lacking (see hereafter). The closure of the tidal inlets as part of the Delta Works took mainly place between 1960 and 1970 (with the Eastern Scheldt partially closed in 1986). A sudden change in the residual tidal range at Vlissingen cannot be derived from the data during this period. Furthermore, the observed residual tidal range in Vlissingen was not constant before 1860 and actually shows an increase between 1880 and 1900. In addition the supplementary five years (2003-2008) now available (green circle in Figure C.3) seem to indicate a decrease of the residual tidal range.

Therefore it is hypothesized that the variation of the yearly-averaged tidal range in Vlissingen is the result of:

- an oscillation with a period of approximately 18.6 year and an amplitude of 6.6 $\pm$ 1.3 cm;
- a linear increase with a rate of 15.6 $\pm$ 2.5 cm/100 year, combined with

- a cyclic variation over a period of approximately 75 years and an amplitude of 3 ± 0.8 cm.

The causes for the linear trend and the long-term cyclic variation are not clear yet. They may be influenced by:

- the sea level rise, although the increase of the mean sea level may only explain an increase of the tidal range by 1% (see Hollebrandse, 2005, and Langendoen, 1987);
- “changes in the geometry of the estuary and its mouth” (Langendoen, 1987);
- “a complex interaction between the North Atlantic Ocean, the North Sea and the meteorological system” (Hollebrandse, 2005) possibly influenced by global climatic changes.

Figure C.4 shows the long-term variation with a period of 75 years superimposed on the linear trend of the *residual tidal range* (green line) showing that a ‘local’ minimum has been reached in 2007. If the linear trend and long-term oscillation continues in the forthcoming years a ‘local’ maximum will occur around 2060. Furthermore the nodal variation, which had its minimum in 2006, will produce maximum values in 2016 and successive years with intervals of 18.6 years. This is however a deterministic approach neglecting uncertainties, such as the fact that the 75 year oscillation has only occurred twice during the observation period.

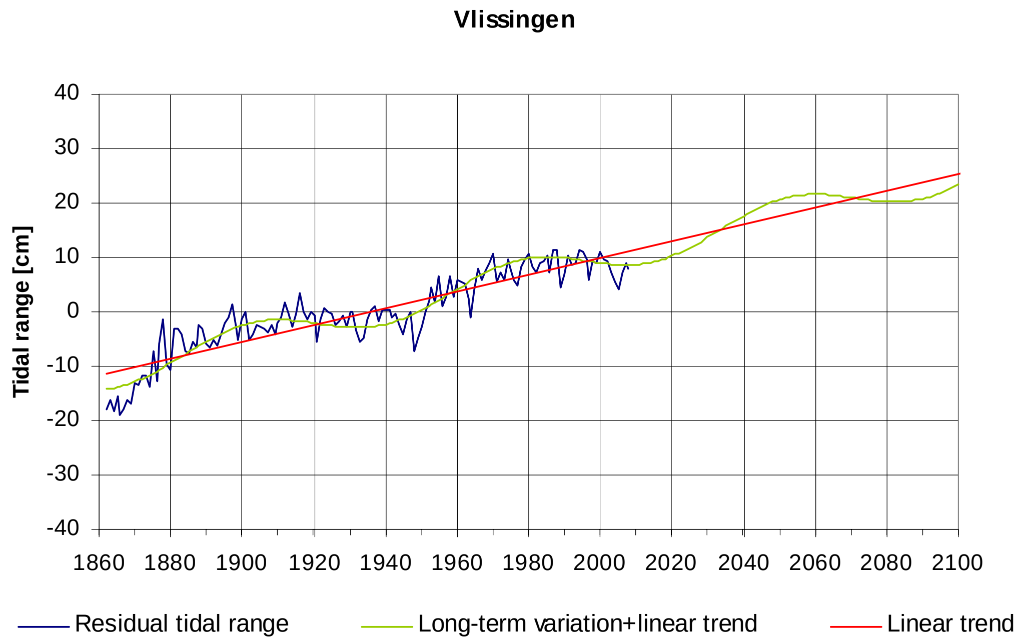



*Figure C.4: Predicted increase of residual tidal range (i.e. without 18.6 year oscillation) in a fully deterministic mode.*

The applied regression model can be used in prediction mode taking into account uncertainties in the model and uncertainties in the observations resulting in 95%-prediction intervals for the tidal range. In Figures C.5a the statistical model was first ‘trained’ (calibrated) with data up to 1980. The confidence intervals (upper graph) reflect the accuracy with which the model parameters could be estimated on the basis of the available data. A larger number of data points will decrease the bandwidth around the centre line. The 95%-prediction intervals as shown in the lower graph in Figure C.5a give the bands within which the measurements are to be expected. In total 95% of the data points should lie within the prediction intervals. For the period 1862-1980 (the period used for training of the model) this is actually the case. However, for the period 1980-2008 the observed tidal ranges seem to deviate from what is expected on the basis of the historical data. A prediction for the year 2040 using the complete data set on tidal ranges is shown in Figure C.5b. In this way upper and lower bounds are obtained for the predicted tidal ranges between 2008 and 2040. In this case it can be seen that only 6 data point are outside the predicted intervals which is 4% of the total number of data points.

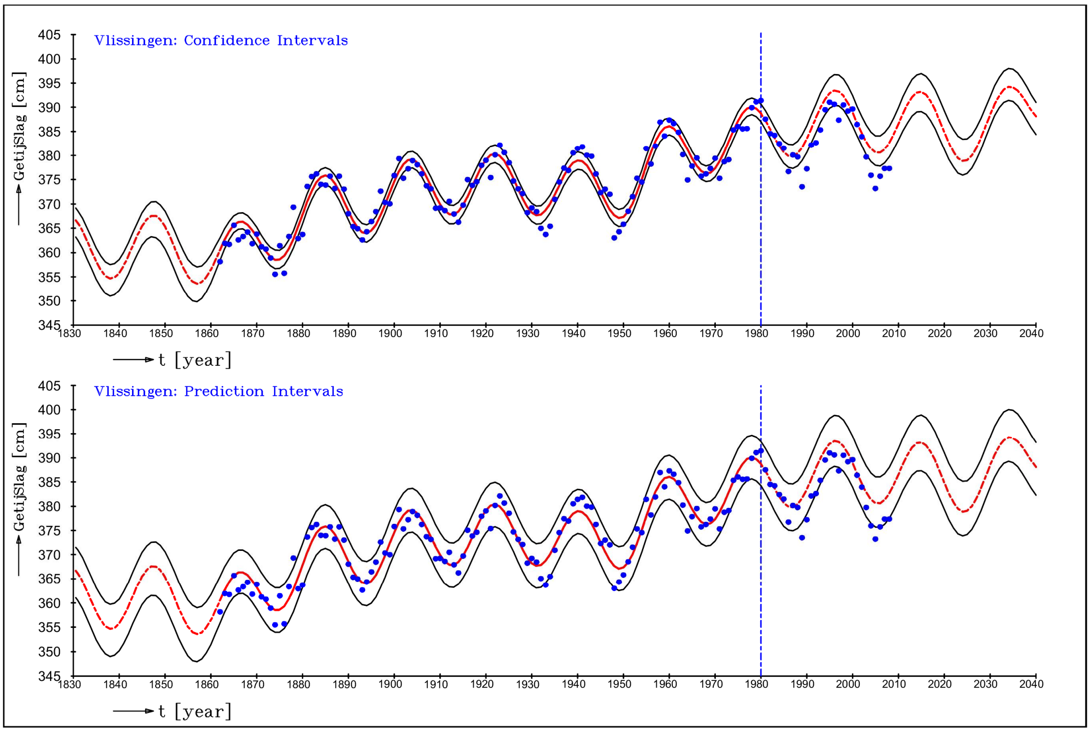



*Figure C.5a: Predicted tidal range for Vlissingen with regression model calibrated for the period 1862-1980. Predicted values for the period 1981-2040.*

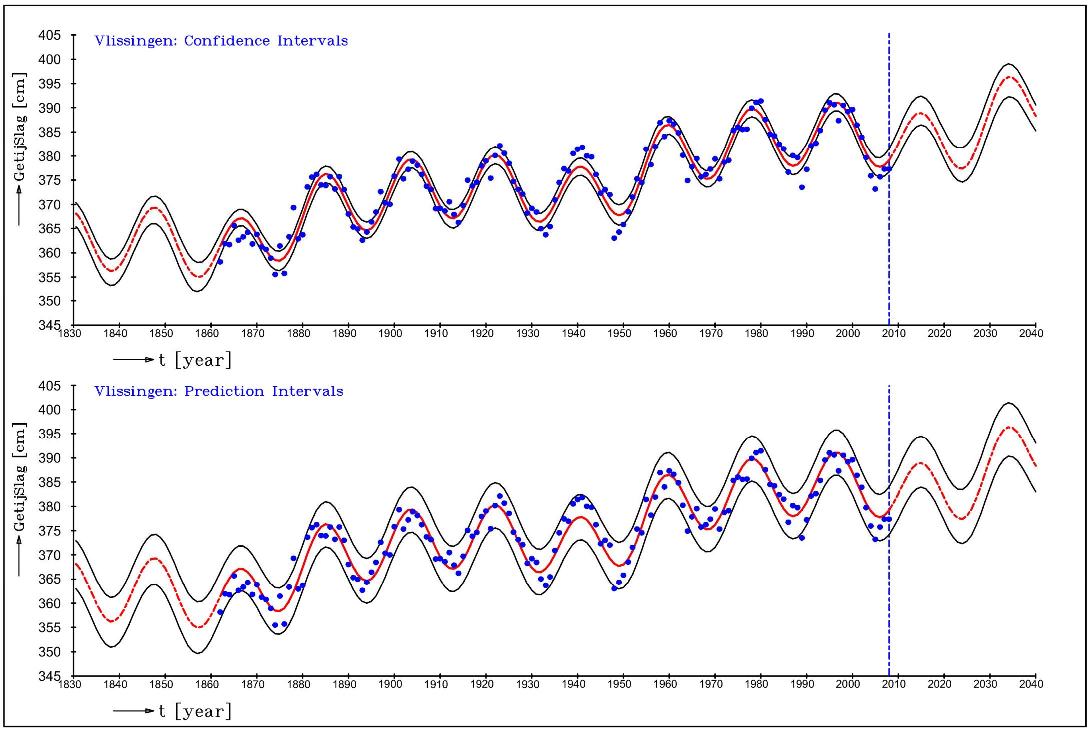



*Figure C.5b: Predicted tidal range for Vlissingen with regression model calibrated for the period 1862-2008. Predicted values for the period 2009-2040.*

Figures C.6a-c give for all stations in the Western Scheldt the results for the amplitude of the nodal variation, the slope of the linear regression line and the amplitude of the long-term variation. The period of the long-term oscillation in the stations Terneuzen and Hansweert is 56/57 year and deviates from the period in Vlissingen. For Bath a long-term variation of either 56 or 74 years is found. Uncertainties are large but an average amplitude of 3 cm seems to be applicable to all stations.

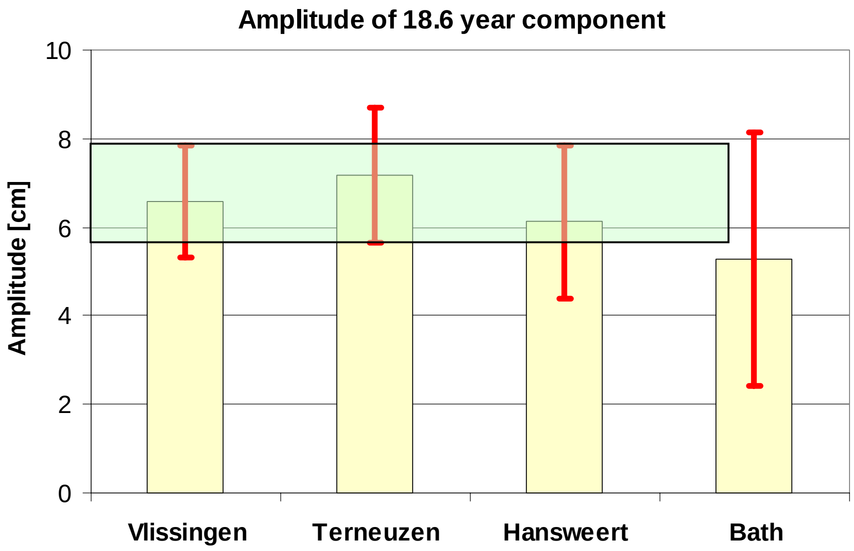



*Figure C.6a: Amplitude of the nodal oscillation in Vlissingen, Terneuzen, Hansweert and Bath as derived for the period 1862/1871 until 2008.*

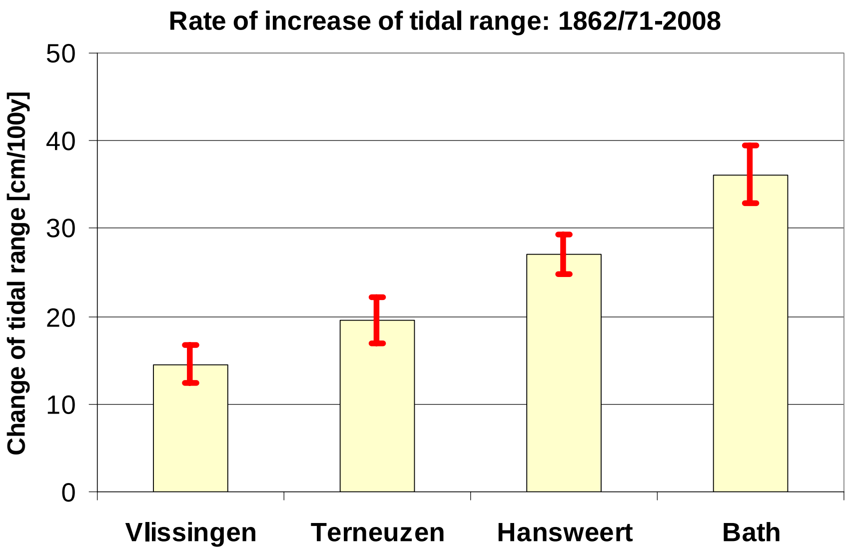



*Figure C.6b: Rate of increase of tidal range in Vlissingen, Terneuzen, Hansweert and Bath as derived for the period 1862/1871 until 2008.*

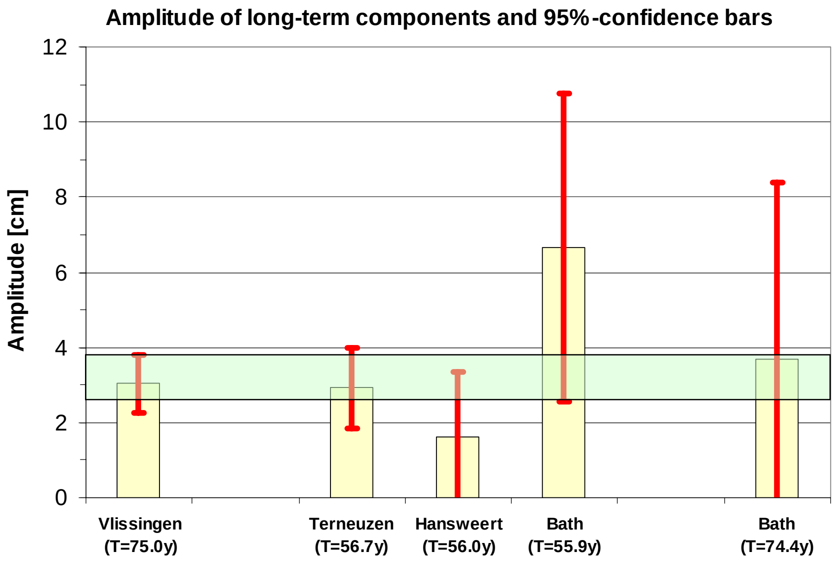



*Figure C.6c: Amplitude of long-term oscillation in Vlissingen, Terneuzen, Hansweert and Bath as derived for the period 1862/1871 until 2008.*

## References

Hollebrandse, Florenz A.P., 2005, Temporal development of the tidal range in the southern North Sea, M.Sc. thesis, Delft University of Technology.

Langendoen, E.J., 1987, Onderzoek naar de vergroting van het tijverschil te Vlissingen. Faculteit der Civiele Techniek. Delft, TU Delft.