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Enabling Delta Life

Understanding the present-day morphodynamics of Ameland inlet

Kustgenese 2.0, product ZG-A02

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Title
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Summary
This literature study describes the present-day morphodynamics of Ameland inlet including the main transport patterns and mechanisms. This knowledge is essential for future sustainable coastal management of Ameland inlet and teaches us valuable lessons for the other inlets present in the Netherlands. An extensive summary of the main findings and their contribution to answering the research questions of sub-project 'Systeemkennis Zeegaten' of Kustgenese 2.0 is presented in the report.

The main conclusions are:
- A large date-set with high-frequent and detailed observations of both hydrodynamics and morphodynamics of Ameland inlet exists. This dataset allows us to quantify the morphodynamic changes that have occurred over the last decades.
- Flow in the inlet is dominated by tides. The most recent discharge measurements (2001) indicate that the ebb-discharge (418 to 454 million m^3) exceeds the flood discharge (407 to 416 million m^3), resulting in a net outflow of 10 to 38 million m^3.
- The ebb-tidal delta volume has decreased over the 1989-2016 timeframe (-0.7 million m^3/year), but shows a positive trend over the 2005-2016 timeframe (+0.1 million m^3/year). Over the 2005-2016 time-frame the net change of 1.6 million m^3 is negligible compared to the gross change of (~200 million m^3).
- A net northward sediment bypassing exists. Bypassing shoals periodically migrate over the ebb-tidal delta. The Bornrif bankje can be considered a new bypassing shoal that has almost merged with the Ameland coastline. The distinct ebb-shield formed on the Kofmansbult is likely the start of the new formation of a bypassing shoal.

References
Plan van Aanpak Kustgenese 2.0 versie januari 2017. Bijlage B bij 1220339-001-ZKS-0005-vdef-r-Offerte Kustgenese 2.0. Deltares, 27 januari 2017.

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Samenvatting; de recente morfologische veranderingen in het zeegat van Ameland en een overzicht van maatgevende processen en mechanismen

Achtergrond

Het Nederlandse kustbeleid streeft naar een structureel veilige, economisch sterke en aantrekkelijke kust. Dit wordt bereikt door het onderhouden van het gedeelte van de kust dat deze functies mogelijk maakt; het Kustfundament. Dit gebeurt door middel van zandsuppleties; het suppletievolume is ongeveer 12 miljoen m^3/jaar sinds 2001.

In 2020 neemt het Ministerie van Infrastructuur en Waterstaat een beslissing over een eventuele aanpassing van het suppletievolume. Het Kustgenese 2.0 programma heeft als doel hiervoor de kennis en onderbouwing te leveren. Deltares richt zich in opdracht van Rijkswaterstaat binnen het project Kustgenese 2.0 op de volgende hoofdvragen:

1. Is er een andere zeewaartse begrenzing mogelijk voor het kustfundament?
2. Wat is het benodigde suppletievolume om het kustfundament te laten meegroeien met zeespiegelstijging?

Deze twee vragen beslaan het grootste gedeelte van het onderzoek binnen het project. Een derde belangrijk onderwerp wat daarbij ook behandeld zal worden is:

3. Wat zijn de mogelijkheden voor de toepassing van grootschalige suppleties rond zeegaten?

Deze literatuurstudie maakt deel uit van het deelproject ‘Systeemkennis Zeegaten’. Het vergroten van onze kennis over zeegatsystemen is belangrijk om vragen te kunnen beantwoorden over de zandvraag van de getijbekkens van de Waddenzee. Deze zandvraag kan gezien worden als een belangrijke verliespost voor zand uit het kustfundament, en is daarom een belangrijke parameter om het benodigde suppletievolume te berekenen wat nodig is voor het onderhoud van het kustfundament. Daarnaast is systeemkennis van getijbekkens ook nodig om vragen te beantwoorden over de mogelijkheden van grootschalige ingrepen rondom zeegaten.

Het deelproject ‘Systeemkennis Zeegaten’ draagt dus bij aan het beantwoorden van de tweede en de derde hoofdvraag van het project Kustgenese 2.0. Dit gebeurt door een combinatie van literatuurstudies, analyse van (veld)data en modelstudies en –ontwikkeling.

De hoofdvragen van Kustgenese 2.0 zijn vertaald in meerdere onderzoeksvragen. De onderzoeksvragen waar het deelproject ‘Systeemkennis Zeegaten’ zich op richt zijn:

- SVOL-07 Wat zijn de drijvende (dominante) sedimenttransportprocessen en -mechanismen en welke bijdrage leveren ze aan de netto import of export van het bekken?
- SVOL-08 Hoe beïnvloeden de morfologische veranderingen in het bekken en op de buitendelta de processen en mechanismen die het netto transport door een zeegat bepalen? Hoe zetten deze veranderingen door in de toekomst, rekening houdend met verschillende scenario's voor ZSS?
- SVOL-09 Wordt de grootte van de netto import of export beïnvloed door het aanbod van extra sediment in de kustzone of de buitendelta?

- SVOL-10 Wat zijn de afzonderlijke bijdragen van zand en slib aan de sedimentatie in de Waddenzee, als gevolg van de ingrepen en ZSS? En wat betekent dat voor het suppletievolume?
- INGR-01 Hoe beïnvloedden de ontwikkelingen van een buitendelta (inclusief de verandering van omvang) de sedimentuitwisselingen tussen buitendelta, bekken en aangrenzende kusten en welke consequenties en/of randvoorwaarden levert dat voor een suppletieontwerp?
- INGR-02 Is het, op basis van beschikbare kennis van het morfologisch systeem, zinvol om grootschalige suppleties op buitendeltas te overwegen?

Morfologische veranderingen in het zeegat van Ameland en een overzicht van maatgevende processen en mechanismen
De grootste verliezen in het Nederlandse kustsysteem vinden plaats langs de kust van de Waddenzee (Elias et al. 2012). In de periode 1935-2005 is er 450 miljoen m^3 zand de Waddenzee in getransporteerd. Gedeeltelijk is dit transport gerelateerd aan de afsluiting van de Zuiderzee en Lauwerszee en gedeeltelijk zal dit veroorzaakt zijn door processen zoals zeespiegelstijging en bodemdaling. Hoe dit transport precies plaatsvindt en welke processen en mechanismen verantwoordelijk zijn wordt nog niet volledig begrepen. Willen we de Waddenzee en de aanliggende kusten op lange termijn goed kunnen beheren is een goede kennis van de processen essentieel. Een belangrijk doel van het Kustgenese project is dan ook om de processen die spelen in de zeegaten beter te begrijpen. Met deze kennis kunnen de effecten van toekomstig kustbeheer beter worden ingeschat en voorspeld. Het zeegat van Ameland wordt hiervoor in detail bestudeerd. Dit zeegat is slechts beperkt verstoord door ingrepen, waardoor het goed mogelijk is de onderliggende, natuurlijke processen te bestuderen. Deze inzichten dragen bij tot een beter begrip van alle zeegaten.

In deze memo wordt een eerste belangrijke stap in de kennisontwikkeling gezet door inventarisatie en analyse van de bestaande hydrodynamische en morfodynamische metingen. Een goede analyse van deze metingen geeft al veel inzicht in de huidige ontwikkelingen en het functioneren van het zeegat en voorziet ons van een kennis basis voor de meetcampagne en de modelering.

Het zeegat van Ameland ligt ingeklemd tussen de eilanden Terschelling en Ameland (zie Figuur 1.3). In de keel van het zeegat bevindt zich het Borndiep (de hoofdgeul) met ten zuiden een ondiep geul-bank gebied (Boschplaat). De uitstroom van het Borndiep, de buitendelta op wordt Akkepollegat genoemd. Aan de Noordoostzijde van het Akkepollegat bevindt zich het grote bankengebied (platform) Bornrif. Relatief grote morfologische veranderingen doen zich voor ten westen van de geul op het platengebied van de Kofmansbult. Hier hebben zich recentelijk kleinere geulen en banken (eb-scharen en eb-schilden) gevormd. De buitendelta bestaat voornamelijk uit zand met een korreldiameter tussen de 150 en 250 μm.

Getij en golven zijn beide belangrijk voor de vorming van de geulen en banken in het Zeegat van Ameland. Het dubbeldaags getij heeft een gemiddelde getijslag van 2.15m. Eerder uitgevoerde debietmetingen in de keel van het zeegat geven een gemiddeld eb- en vloeddebiet van ongeveer 400 miljoen m^3. Het residuele debiet (ongeveer 10% van het totaal) is eb-dominant. Het golfklimaat word gedomineerd door windgolven. Het merendeel van deze golven is kleiner dan 2m (83%). Golven uit de Noord-noordwestelijke sector domineren (63%).

Cyclisch morfologische ontwikkeling beschrijft het gedrag van het zeegat op de middellange termijn. Er kan dan binnen deze cyclus onderscheidt gemaakt worden tussen een morfologie gekenmerkt door 1 of 2 geulen en een Boschplaat (eilandstaart van Terschelling) welke ver is uitgebouwd of zich juist heeft teruggetrokken. Het korte-termijn gedrag beschreven in deze studie richt zich op periode 1989-2016. Hierbij is nog een extra analyse uitgevoerd op de periode 2005-2016 ter ondersteuning van de modelering. Een belangrijke reden dat deze periodes geselecteerd zijn, is de beschikbaarheid van gedetailleerde bodemdata. Daarnaast is deze periode is representatief voor het huidige gedrag, waarbij (1) er in het zeegat 1 hoofdgeul (Borndiep) aanwezig is, (2) er een Noord-westelijke uitstroom van het Borndiep op de buitendelta plaatsvind, (3) de bulk van het zandvolume oostelijk van de hoofdgeul bevindt (in het Bornrif) en (4) er een ondiep gebied doorsneden door kleine geulen is gevormd tussen het Borndiep en de Boschplaat. De Boschplaat is hierbij sterk geërodeerd. Verschillen tussen de 1986 en 2016 bodems zijn zichtbaar in (1) de locatie en grootte van het Westgat. Deze geul is sterk in omvang afgenomen, (2) de afname van de hoogte van Bornrif sinds 2005, (3) de vorming van een primaire en secundaire eb-schaar en eb-schild op de Kofmansbult, (4) de vorming en landwaartse verplaatsing van het Bornrif Bankje. Dit Bankje is zich (bijna) aan het verhelen met de kust van Ameland.

De sedimentatie-erosie patronen van de buiten-delta geven een afwisselend beeld van gebieden met aanzanding en verlies. De ruwe bodemdata vertoont grote, onrealistische, veranderingen in de volumes in de periode 1989-2005. In de ruwe data vindt er een volume verlies van 31 miljoen m^3 plaats tussen 1989-1993 m^3, gevolgd door een toename van 60 miljoen m^3 (1993-1999) en een afname van 45 miljoen m^3 (1999-2005). Gecorrigeerd voor deze fluctuaties kan worden geconcludeerd dat er een gemiddeld zandverlies van de buitendelta is opgetreden van 13 miljoen m^3, terwijl het volume van de aanliggende kusten is toegenomen met 19 miljoen m^3. Dit geeft netto een beperkte volume toename van 6 miljoen m^3 . Deze toename is gelijk aan de uitgevoerde suppleties langs de westkust van Ameland [SVOL-08; SVOL-09; INGR01].

Een sedimentbudget opgesteld over de periode 2005-2016 vertoont een consistenter (betrouwbaarder) beeld van de recente volumeveranderingen. De bruto veranderingen van de buitendelta en kust over deze periode zijn groot (200 miljoen m^3) ten opzichte van netto toename in volume van 7 miljoen m^3. In deze periode is er 4.7 miljoen m^3 gesuppleerd.

Op basis van de geobserveerde morfologische ontwikkelingen, aangevuld met inzichten uit eerder uitgevoerde modelstudies, kan worden geconcludeerd dat de buitendelta in 2 delen kan worden onderverdeeld gescheiden door de geulen Westgat – Borndiep. Sediment dat zich dicht tegen de kust van Terschelling bevindt (ten zuiden van het Westgat en ten Westen van Borndiep), wisselt via de kleine geulen en platen van de Boschpaat uit met het westelijke gedeelte van het bekken. Sediment in het Borndiep wisselt voornamelijk uit met het oostelijke gedeelte van het bekken. Dit sediment voedt ook de buitendelta (zeewaarts van het Westgat) en uiteindelijk wisselt het uit met de kust van Ameland. De aanlanding van de Bornrif Strandhaak rond 1986 en de huidige aanlanding van het Bornrif Bankje zijn 2 voorbeelden van deze uitwisseling.

Samenvattend zijn de belangrijkste conclusies van deze memo:

1. Een grote, waardevolle dataset van hoogfrequente metingen van zowel hydrodynamica en morfodynamica is aanwezig. Dit vormt een goede kennis basis voor het Kustgenese 2.0 project [SVOL-07; SVOL-08; SVOL-09; INGR01; INGR02].

2. De stroming in het zeegat word gedomineerd door het getij. De meest recente debietmetingen geven aan dat het eb-debiet in het zeegat (418 - 454 million m^3) groter is dan dan het vloeddebiet (407 - 416 million m^3) wat resulteert in een netto uitstroom van 10 - 38 million m^3. [SVOL-07]
3. Het volume van de buitendelta is met -0.7 miljoen m^3/jaar afgenomen over de periode 1989-2016, maar is toegenomen over de periode 2005-2016 (+ 0,1 miljoen m^3/jaar). De totale netto verandering van 1.6 miljoen m^3/jaar is eigenlijk verwaarloosbaar ten opzichte van de 200 miljoen m^3/jaar aan bruto veranderingen (en ten opzichte van de meetnauwkeurigheid) [SVOL-017; SVOL-08; SVOL-09; INGR01].
4. Er is een netto noordelijk gerichte sedimentstroom aanwezig over de buitendelta. Dit resulteert in de vorming van banken op het Bornrif. De aanlanding van de Bornrif Strandhaak, de huidige aanlanding van het Bornrif Bankje vormen onderdeel van deze sedimentstroom (bar bypassing process). De vorming van de platen (ebschild) op de Kofmansbult is waarschijnlijk de start van een nieuwe aanlandingscyclus. [SVOL-08; SVOL-09; INGR01; INGR02].
5. Er is een tweedeling in sedimenttransportpaden op de buitendelta. (1). Sediment dat zich bevindt tussen het Westgat en Terschelling wisselt voornamelijk uit met het Boschgat en is ebdominant. Dit sediment draagt bij tot de invulling van het westelijke deel van het bekken en tot de instandhouding van Terschelling. Sediment dat zich in of zeewaarts van het Westgat bevindt wisselt uit met het Borndiep. Dit sediment beweegt zich voornamelijk het oostelijke deel van het bekken in en verplaatst zich zeewaart de buitendelta op en uiteindelijk worden ze richting Ameland verplaatst [SVOL-08; SVOL-09; INGR01; INGR02].

Een vertaling van de inzichten naar de onderzoeksvragen van Kustgenese 2.0
Een rechtstreekse en volledige beantwoording van de onderzoeksvragen (Tabel 1) is met deze studie niet mogelijk. Toch kan er, met uitzondering van vraag SVOL-09, wel al veel inzicht in de vragen worden verkregen.

[SVOL-07] – Het zeegat vertoont de kenmerken van een “mixed-energy” systeem. Zowel getij als golven zijn belangrijk. Met de tweedeling van de keel van het zeegat in een ondiep gedeelte (westelijk) en diep gedeelte (oostelijk) is het waarschijnlijk dat golven een grotere rol in de sediment transporten spelen in het westelijke deel en getij belangrijker is in het oostelijk (Borndiep) deel. Aangezien de bodemdata een respons over een langere tijd laten zien (1-3 jaar interval) is het niet rechtstreeks mogelijk het relatieve belang van de afzonderlijke processen te kwantificeren. Hiervoor is sedimenttransportmodelering benodigd. Op basis van de in deze studie verzamelde bodem en stromingsdata kunnen hiervoor de modellen worden opgesteld.

[SVOL-08; SVOL-09; INGR-01] – De morfologische veranderingen op de buitendelta laten grote veranderingen in de ligging van de geulen en banken zien. Het is zeer waarschijnlijk dat deze direct de sediment transporten richting het bekken beïnvloeden (zie uitleg boven). Een belangrijk morfologisch fenomeen is het ontstaan, verplaatsen en aanlanden van grote banken vanuit de buitendelta op de kust. Dit proces is in het verleden waargenomen (aanlanding Bornrif Strandhaak rond 1986) en kan in de huidige dataset (ontstaan en verplaatsing Bornrif Bankje) worden waargenomen. De recente sedimentatie (eb-schild vorming op de Kofmansbult) geeft waarschijnlijk het begin van een nieuwe sediment-bypassing cyclus.

Het aanlanden en verhelen van de banken gaat gepaard met een extra zandaanbod op het aanliggende eiland. Direct na aanlanding verplaatst een puls zand zowel oostwaarts (langs de kust het Borndiep in) en westwaarts langs het eiland. Dit laatste transport blijft dan tijdens het verhelen nog lang plaatsvinden. Indirect leren we uit deze natuurlijke aanlandingen dat het mogelijk is relatief grote volumes aan zand, in de vorm van een bank, te verplaatsen over een buitendelta. Het versnellen of intensiveren van dit "sediment-by-passing" process kan een manier zijn om het sediment aanbod naar de Waddenzee en de eilandkust te vergroten. Een nadere studie hiervan kan ons inzicht verschaffen in toekomstige suppletie vormen en volumes.

INGR-02 - De aanlandingen van het Bornrif laten zien dat het zinvol is grootschalige suppleties op de buitendelta te overwegen. Het Bornrif Bankje laat zien dat een relatief groot volume zich over de rand van de buitendelta kan verplaatsen zonder het gedrag van het zeegat grootschalig te beïnvloeden. Het verhelen van de Bornrif Strandhaak geeft aan dat deze zandvolumes vervolgens langdurig het kustsysteem voeden. Vertalen we dit terug naar de suppleties dan zou dit betekenen dat we op een relatief gemakkelijke plaats (diep water) een zandvolume kunnen aanbrengen, dat zich natuurlijk kan verplaatsen en over lange tijd zand kan leveren.

De vorming van het eb-schild op het Bornrif, de vervorming en verplaatsing van dit ebschild, het dichtdrukken van het Akkepollegat en de daarbij behorende veranderingen in het geulenstelsel laten echter ook zien dat een suppletie aangelegd op het westelijke deel van de buitendelta wel het grootschalig gedrag van de buitendelta kan beïnvloeden. Dit hoeft niet per definitie nadelig te zijn, maar gezien de ligging van de hoofdgeul vlak langs de zuidwest kust van Ameland kan dit meer risico's met zich mee brengen.

Vervolgstappen Kustgenese 2.0
Volumeverandering in het bekken; Deze studie is gebaseerd op de data die begin 2016 aanwezig was. Een belangrijke tekortkoming hierin was het ontbreken van een recente bodem in het bekken van Ameland. Hierdoor is er gekozen de beschouwing van de sedimentatie-erosie volumes te beperken tot de buitendelta. Met het beschikbaar komen van de 2016 bekkendata is het mogelijk de volumebalans van het gehele systeem te beschouwen. Dit geeft ons een beter inzicht in de import van sediment het bekken in.

Detailanalyse Bornrif Strandhaak, Bankje, en eb-schild Akkepollegat; Deze morfologische eenheden hebben alle drie een grootte en volume, dat (1) eventueel met een grootschalige buitdendelta zou kunnen worden aangelegd en (2) duidelijk zichtbaar en daardoor analyseerbaar is. Een verdere detailanalyse van het gedrag en maatgevende processen kan veel inzicht verschaffen in het gedrag van toekomstige suppleties. Daarnaast kan een idee verkregen worden van de effectiviteit van dit soort banken op sediment toevoer naar de Waddenzee en het eiland. Dit geeft een directe beantwoording van een aantal van de onderzoeksvragen. Bovengenoemde vervolgstappen worden in 2018 binnen Kustgenese 2.0 project opgepakt en de uitkomsten worden verwerkt in de systeembeschrijving Zeegaten.

Table 1.1 Overzicht onderzoeksvragen KustGenese 2.0

Code	Onderzoeksvraag	Bijdrage
SVOL-07	Wat zijn de drijvende (dominante) sedimenttransportprocessen en -mechanismen en welke bijdrage leveren ze aan de netto import of export van het bekken?	JA
SVOL-08	Hoe beïnvloeden de morfologische veranderingen in het bekken en op de buitendelta de processen en mechanismen die het netto transport door een zeegat bepalen? Hoe zetten deze veranderingen door in de toekomst, rekening houdend met verschillende scenario's voor ZSS?	JA NEE
SVOL-09	Wordt de grootte van de netto import of export beïnvloed door het aanbod van extra sediment in de kustzone of de buitendelta?	JA
SVOL-10	Wat zijn de afzonderlijke bijdragen van zand en slib aan de sedimentatie in de Waddenzee, als gevolg van de ingrepen en ZSS? En wat betekent dat voor het suppletievolume?	NEE
INGR-01	Hoe beïnvloedden de ontwikkelingen van een buitendelta (inclusief de verandering van omvang) de sedimentuitwisselingen tussen buitendelta, bekken en aangrenzende kusten en welke consequenties en/of randvoorwaarden levert dat voor een suppletieontwerp?	JA
INGR-02	Is het, op basis van beschikbare kennis van het morfologisch systeem, zinvol om grootschalige suppleties op buitendeltas te overwegen?	JA

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1 Introduction

1.1 Background

1.1.1 Kustgenese 2.0 (“Coastal Genesis 2.0”)

The Dutch coastal policy aims for a safe, economically strong and attractive coast (Deltaprogramma, 2015). This is achieved by maintaining the part of the coast that supports these functions; the coastal foundation. The coastal foundation is maintained by means of sand nourishments; the total nourishment volume is approximately 12 million m^3/year since 2000.

In 2020, the Dutch Ministry of Infrastructure and Environment will make a decision about the nourishment volume. The Kustgenese 2.0 (KG2) programme is aimed to deliver knowledge to enable this decision making. The largest part of the scope of the project, commissioned by Rijkswaterstaat to Deltares, is determined by the following main (policy) questions:

1 *What are possibilities for an alternative offshore boundary of the coastal foundation?*
2 *How much sediment is required for the coastal foundation to keep up with sea level rise?*

These two questions take up the largest part of the research within the project. Another, third, important topic which will have to be addressed is:

3 *What are the possibilities (and effects) of applying large-scale nourishments around tidal inlets?*

1.1.2 Knowledge of tidal inlet systems

This literature study is part of the sub-project ‘Systeemkennis Zeegaten’ (‘system knowledge tidal inlets’). Expanding our knowledge of tidal inlet systems is paramount for answering questions about the sand demand of the tidal basins of the Wadden Sea. The sand demand can be seen as an important ‘sediment sink’ for the coastal foundation, and is therefore also an important parameter to determine the required nourishment volume to maintain the coastal foundation. Additionally, knowledge of tidal inlet systems is also needed to answer questions about the morphological response to large-scale nourishments around the inlets.

The sub-project ‘Systeemkennis Zeegaten’ therefore contributes to the second and third of the main policy questions within the project. It will do so by a combination of literature research, analysis of field data and modeling.

1.2 Objective of this study

It is well known that the largest sediment losses in the Dutch sediment budget occur along the North Sea coastline of the Wadden Sea Area. Elias et al. (2012) showed that a vast quantity of sand (roughly 450 million m^3) was transport from the coastal zone into the Wadden Sea since Closure of the Zuiderzee in 1932. The processes behind this sediment import are not fully understood, but are essential if a sustainable and resilient future coastal management strategy is to be designed and executed.

Fundamental understanding of the physical processes underlying the inlet behaviour and development can be obtained through numerical (process-based) modelling, and/or the detailed analysis of field-data. Field data analysis can greatly help improve knowledge of the present-day system and processes steering the observed morphodynamic developments. However, models are essential if one aims to understand and to predict future behaviour.

Especially, since this future behaviour is expected to change due to e.g. climate change and the related sea-level rise and anthropogenic influence (e.g. coastal maintenance, gas and salt extraction).

One of the major objectives of the coastal research programme Kustgenese 2.0 is to further understand inlet processes to such extend that the effect of future coastal maintenance (e.g. nourishments) can be understood and predicted (Van Oeveren et al. 2016). To achieve this goal, Elias and Tonnon (2016) proposed a 3-step approach for model development (see Figure 1.1). The research presented in this report especially contributes to step 1. Through detailed analysis of literature and concepts and existing field data a base knowledge level for the present-day Ameland inlet morphodynamics and behaviour is obtained.

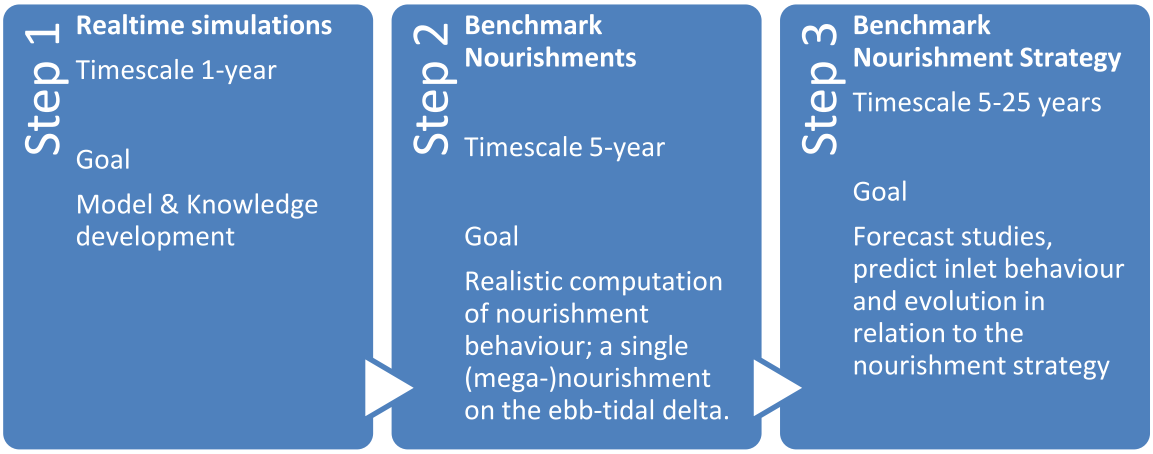


Figure 1.1 Overview of model development in Kustgenese2 (based on Elias and Tonnon, 2016).

The specific research goals of this study are:

1. to improve the understanding of the sediment dynamics of Ameland Inlet and its influence on the adjacent coast. Such knowledge is not only essential for future sustainable coastal management of Ameland inlet but can also teach valuable lessons for the other inlets present in the Netherlands;
2. to derive and explain the main transport patterns and mechanisms, and
3. to disclose the data available. This data describes the present-day morphodynamics of Ameland inlet to the Kustgenese researcher and are considered to form a base for future testing, validation and calibration of the numerical models used in the Kustgenese 2.0 project (Figure 1.1).

1.3 Approach

To achieve these goals, we analyze the available measurements of hydrodynamics and morphodynamics. Especially. the extensive record of well-monitored morphodynamic changes provides background for an in-depth analysis of the ebb-tidal delta changes.

Chapter 2 provides a general overview of the study area, and the location of the present-day channels, shoals and sediment composition. Chapter 3 discusses the hydrodynamic forcing conditions that control the inlet. Overviews of the tidal characteristics, the wind and wave climate and the measured discharges through the inlet gorge are provided. Chapter 4 provides an overview of the morphodynamic changes and sediment budget. In this Chapter also a brief overview of existing concepts, and a detailed analysis of the present-day changes

(1989-2016) is provided. Descriptions of sediment transports rely on model results of previous studies as measurements are not available.

We conclude by a synthesis and discussion of the results (Chapter 5) and concluding remarks in Chapter 6. Note that the conceptual description summarized in Figure 5.2 is a work in progress. This conceptual description will be updated in 2018 as new measurements, analysis, results and insights from Kustgenese 2.0 become available.

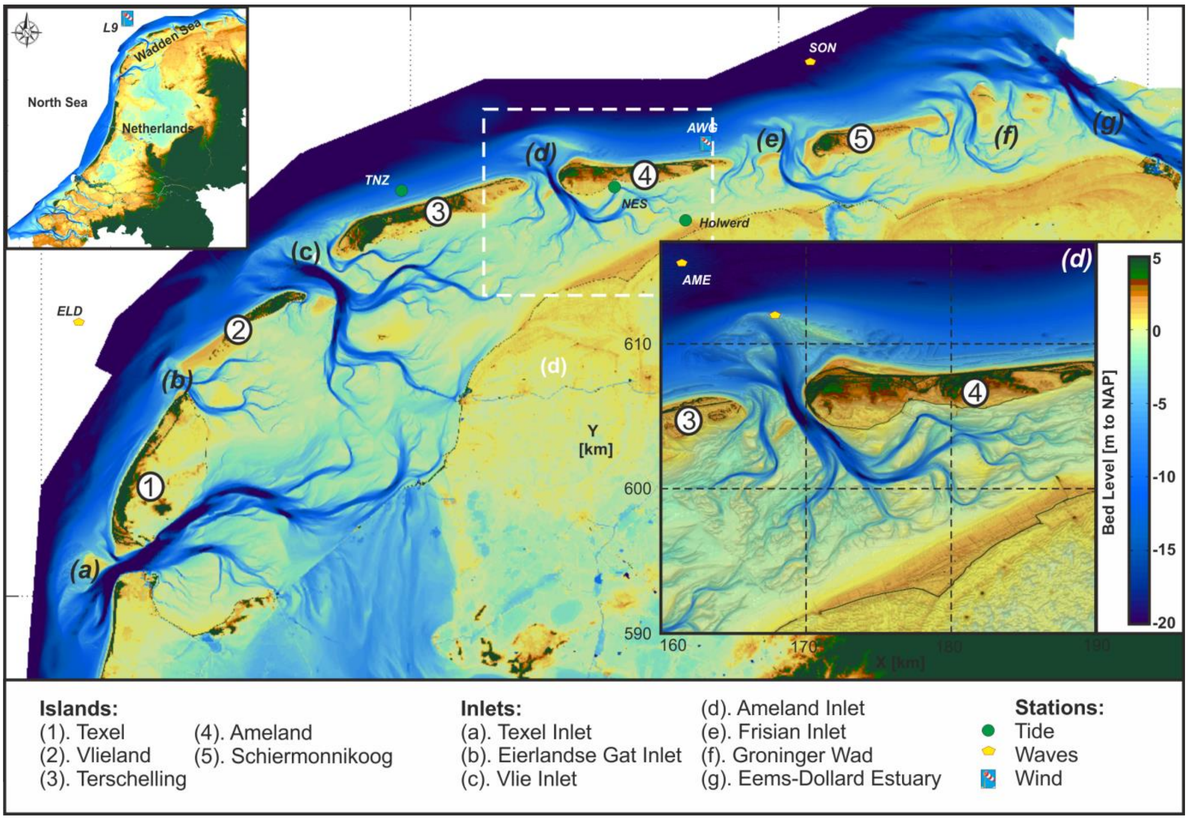


Figure 1.2 Location plot of the Dutch part of the Wadden Sea area and details of the Ameland inlet (lower right insert). Measurement locations are indicated by the yellow dots.

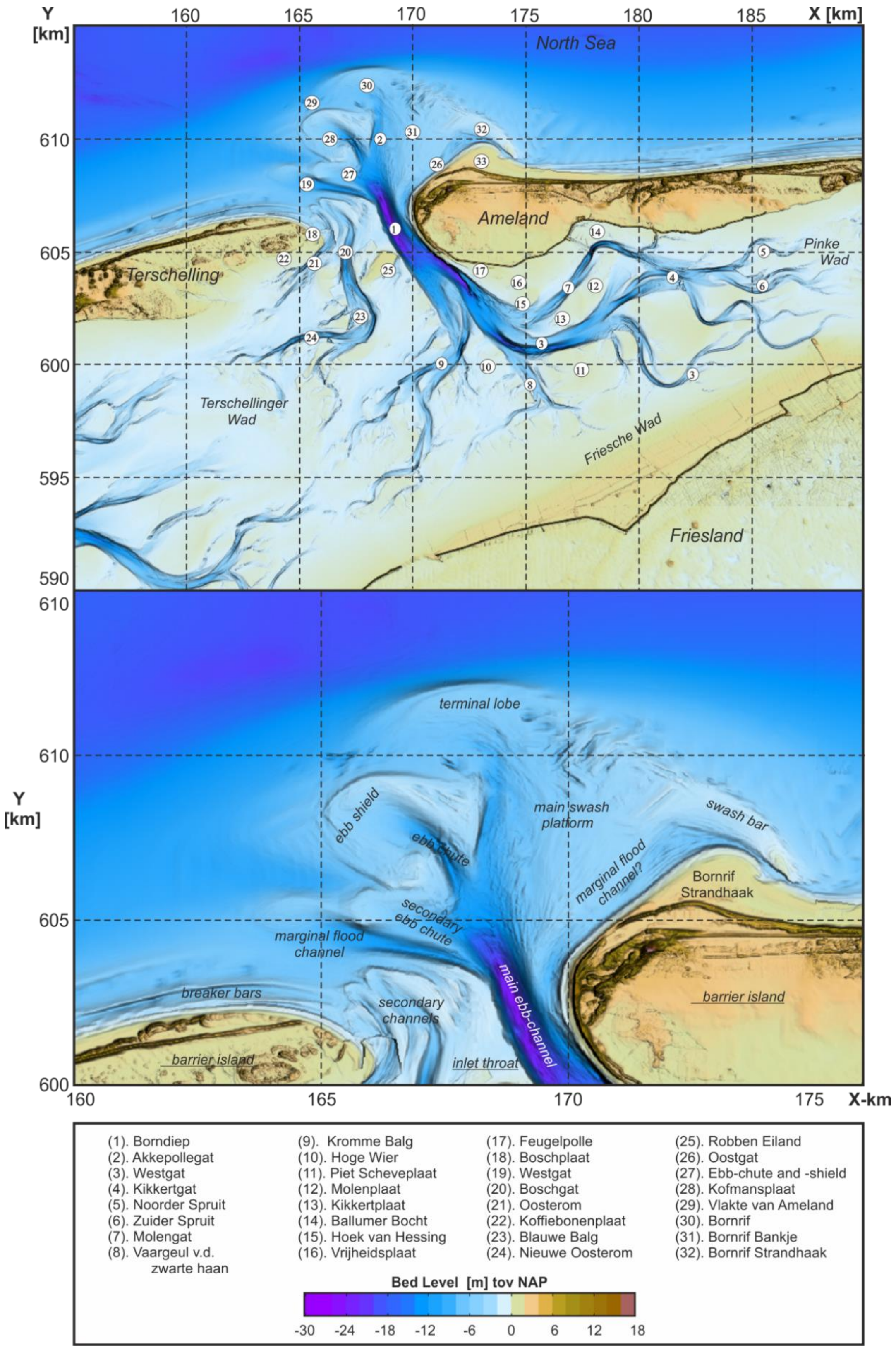


Figure 1.3 Overview of the channels and shoals that form the present day Ameland Inlet. DEM is based on the 2016 measurements of the ebb-tidal delta and main channels in the basin. The remaining areas (especially in the basin) are filled with 2011 measurements.

2 Study area

2.1 General Setting

The Wadden Sea is connected to the North Sea through of a series of 33 tidal inlets. In total it extends over a distance of nearly 500 km along the northern part of the Netherlands, and the German and Danish coasts. Figure 1.2 illustrates the Dutch part of the Wadden Sea area. Ameland Inlet is centrally located bordered by the islands Terschelling to the west and Ameland to the east.

Both tides and waves play an important role in shaping and maintaining the Wadden system. In general, following the classification of Davis & Hayes (1984), the Dutch inlets, and also Ameland Inlet, qualify as mixed-energy wave-dominated, even under spring-tide conditions. However, the morphology of the major inlets shows tide-dominated characteristics such as a large ebb-tidal delta and deep entrance channels. These features result from large tidal prisms (in Ameland Inlet ~475 million m^3) and relatively low wave energy (Davis & Hayes, 1984). The change in coastline orientation from South-North to West-East relates to the underlying Pleistocene morphology.

The tidal processes of flooding and draining are the driving force for the fractal channel patterns in the basin (Cleveringa & Oost, 1999; Marciano et al., 2005). Tidal divides are formed where the tidal waves travelling through two adjacent inlets meet and sedimentation due to near-zero velocities results in tidal-flat formation. These tidal divides are often considered to form the boundaries of the separate inlet systems and are located somewhat eastward of the centre of the barrier islands due to the amplitude differences between the neighbouring inlets (Wang et al., 2011) and the prevailing eastward wind direction (FitzGerald, 1996). The tidal divides at Ameland are formed by the Terschellinger Wad and Pinke Wad, respectively to the west and east of the inlet (Figure 1.2 and Figure 1.3). The associated Ameland basin has a length of roughly 30 km and covers an area of 270 km^2. Roughly 60% of the Ameland basin consists of shoals (Eysink, 1993).

2.2 Present day channels and shoals

Figure 1.2 provides an overview of the main channels and shoals that form Ameland Inlet. In the inlet gorge, between the islands of Terschelling and Ameland, a deep main ebb-channel exists along the west coast of Ameland (Borndiep, see Figure 1.3[1]). The deepest parts of the channel exceed 25m of depth. In the basin, Borndiep connects to Dantziggat [3] that curves eastward into the basin towards the tidal divide of Ameland (Pinke Wad), through the channels Kikkertgat [4], Noorder Spruit [5] and Zuider Spruit [6]. Several smaller side channels connect to Dantziggat such as Molengat [7] near the island of Ameland, and Vaargeul vd Zwarte Haan [8].

Between Borndiep and the tip of the island Terschelling (called Boschplaat [18]) a shallow area with several small channels can be observed. This shallow area connects to the main channel Westgat [19] on the ebb-tidal delta, and the channel Boschgat [20] in the basin. A smaller channel (Oosterom [21]) is located along the southern side of the Koffieboonenplaat [22] and Boschplaat. In the basin, Boschgat connects to Blauwe Balg [23] and Nieuwe Oosterom [24]. The large shoal, in the middle of the inlet, between Boschgat and Borndiep is called Robben Eiland [25].

The ebb-tidal delta contains 3 main shoal areas and 3 named channels. The outflow from Borndiep onto the ebb-tidal delta is called Akkepollegat [2], and forms the main ebb-channel. Along the two adjacent shorelines 2 named flood channels are present Westgat [19] and Oostgat [26]). In the past decades, Westgat formed a pronounced channel, but in the recent 2016 bathymetry this channel is distorted by a smaller secondary ebb-chute and sill near its connection to Borndiep. In addition, a more direct connection to Boschgat seems to form along Boschplaat (Figure 1.3).

A small and a large ebb-chute [27,28] have formed on the shoal area between Westgat and Akkepollegat. A pronounced large ebb-shield now covers most of the shoal area known as Kofmansplaat [28]. The shoal area (terminal lobe) facing Akkepollegat is called Vlakte van Ameland [30].

The largest shoal area on the ebb-tidal delta lies eastward of Akkepollegat, which is downdrift in relation to the littoral drift. This large shoal area or swash platform is named Bornrif [31]. A large, narrow swash bar, Bornrif Bankje [32], has formed along its eastern margin. This Bankje has almost connected to the Ameland coastline. Along the coastline of Ameland the remnants of the Bornrif Strandhaak [33], a former ebb-delta shoal that attached to the coastline around 1985 are still clearly visible. This natural “zandmotor” has supplied the (downdrift) coastline with sand over the past decades.

2.3 Bed Composition

Information on the bed composition in Ameland inlet is available through the SedimentAtlas (Rijkswaterstaat 1999). This atlas contains the analysed output of roughly 7000 samples collected between 1989 and 1999. The data for Ameland inlet were collected between April and July 1995 with a sample resolution of 0,5 km in the inlet and main channels, increasing to 1 km spacing elsewhere. Sediment samples of the top 10cm of the bed were taken with a van Veen grab sampler and processed using the Malvern 2600L Laser Particle Sizer. The results for Ameland inlet (Figure 2.1) indicate an average d_{50} of around 200 μm in the intertidal areas, increasing to values between 240-300 μm in the Borndiep and Boschgat channels. On Bornrif the grain size reduces to values around 150 μm. More recently (2011-2014) grain size data for the basin were collected through the Synoptic Intertidal BEnthic Survey (SIBES), see Compton et al. (2013). Data along the coast and ebb-tidal delta was collected in 2001 by Imares/NITG-TNO (Leopold and Baptist, 2016).

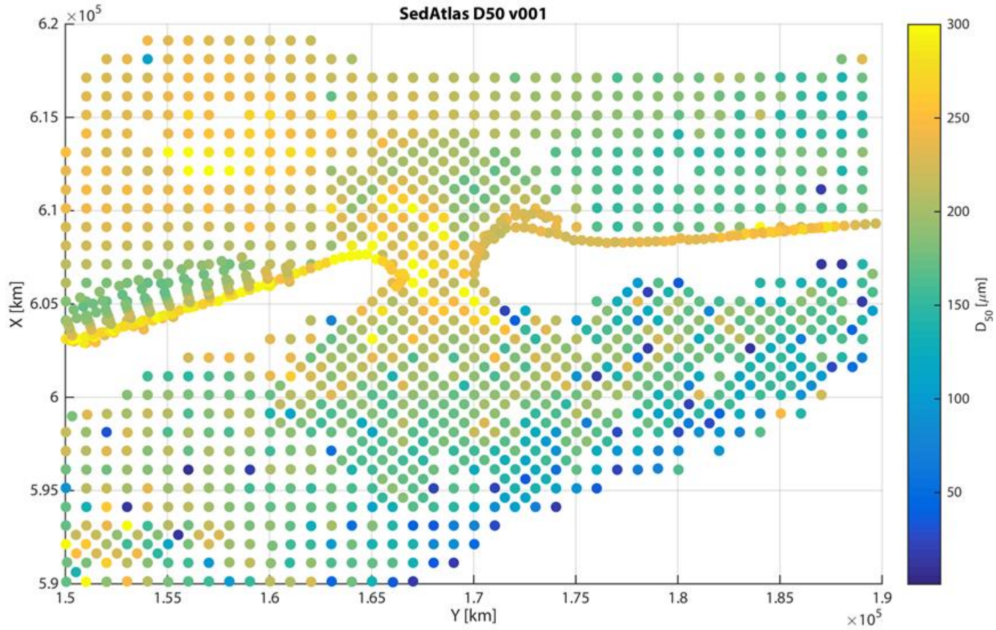


Figure 2.1 Overview of the median grain size (d_{50}) in Ameland Inlet (derived from Wadden Sea Sediment Atlas, Rijkswaterstaat, 1999).

3 A Mixed-energy inlet

3.1 Tides and Tidal Prism

3.1.1 Waterlevels

The tidal movement at Ameland inlet is generated mainly by the tidal wave from the southern part of the North Sea that enters the Wadden Sea through the inlets. The North Sea tides are driven by the tidal (Kelvin) waves entering from the Atlantic Ocean between Scotland and Norway in the north, and through the Dover Strait in the south. Interference of these two waves, distortion due to Coriolis effects and bottom friction, generates a complicated tidal flow pattern in the southern part of the North Sea (Pugh, 2004). The tides spin in a whirl with anti-clockwise rotation around 2 central (amphidromic) points. At these points the tidal amplitude is zero and the tidal range increases with distance to the amphidromic point. Along the Dutch coast, the tides propagate from south to north in a form that is between a standing and progressive tidal wave propagates from south to north, thereby generating maximum shore parallel tidal velocities in the range of 0.5 to 1.0 m/s. Near Texel inlet this northward-travelling tidal wave meets a second eastward travelling tidal wave (that rotates around the second amphidromic point), and the combined waves propagate from the west to east along the Wadden Sea Islands and into the basins. The mean tidal range thereby increases from 1.4 m at Den Helder to 2.15 m at Ameland inlet and 2.5 m in the Ems estuary (Eems-Dollard Inlet) and increases even further in eastward direction along the German Wadden coast.

Tides are measured at 3 stations surrounding Ameland inlet e.g. Terschelling North Sea located offshore of Terschelling (TNZ), and the stations NES and Holwerd in the basin. An overview of the 12 main tidal constituents for TNZ, based on t_tide analysis (Pawlowicz et al., 2002) of the timeseries presented in Figure 3.1, is presented in Table 3.1.

Table 3.1 Overview 10 main constituents for Station Terschelling North Sea (based on 2016 data).

Constituent		***Amplitude***	***Phase***
Name	*ϕ*	*[m]*	*[deg]*
M2	28.98	0.86	234.07
S2	30.00	0.24	296.12
N2	28.44	0.15	211.71
O1	13.94	0.10	206.38
M4	57.97	0.08	330.04
K1	15.04	0.07	0.53
L2	29.53	0.07	237.37
K2	30.08	0.07	295.26
MU2	27.97	0.06	321.76
MS4	59.98	0.05	42.08
SSA	0.08	0.05	233.59
M6	86.95	0.05	60.42

The semi-diurnal tidal movement is the main driving force behind the horizontal water flow through the inlet. The M_2 constituent with an amplitude of 0.86 m is the dominant component. Distortion of the M_2 tide results in a significant asymmetry (M_4 amplitude is 0.08 m) and faster rise than fall of the tide. A considerable spring neap variation (S_2 amplitude is 0.24 m) results in an increase of the tidal range to 2.0 m during spring tide and a drop to about 1.0 m during neap.
The tidal signal only partly represents the measured water levels. Meteorological distortion due to air pressure and wind-generated set-up or set-down can reach significant heights along the Dutch coast (Figure 3.1). At TNZ, set-ups can exceed 1.5 m during major storm events (see

Figure 3.1, bottom). In the Wadden Sea, with its complex bathymetry, set-up-gradients can drive complicated residual flow fields, generate shore-parallel velocities and throughflow between adjacent basins (Duran-Matute et al., 2014). In addition, the volume of water stored in the Wadden Sea due to the larger set-up can considerably enlarge the outflow velocities in the inlets following the storm events, thereby affecting channel dimensions, the ebb-tidal delta development and adjacent beaches (Elias, 2006).

Tidal divides between the basins are formed where the tidal waves travelling through two adjacent inlets meet and sedimentation due to near-zero velocities results in tidal-flat formation. These tidal divides are often considered to form the boundaries of the separate inlet systems. The model study of Duran Matute et. al. (2014) illustrates that a closed boundary at the Terschelling tidal divide does not really exist. In this study, model simulations driven by tides, wind and temperature over the 2009-2010 timeframe were made and estimates of the tidal prisms through the individual inlets and over the Terschelling watershed are presented. The averaged tidal prism through Ameland inlet was estimated at 383 x10^6 m^3 (mcm), with a net seaward residual of -12 mcm. The tidal prism over the watershed is an order of magnitude smaller 33 mcm. However, the eastward residual flow of -23 mcm is comparable in magnitude to the residual flow through the inlets. It was concluded that this residual flow results from the wind effects and the variability in extreme events that can enhance, weaken or invert the tidally driven residual flow. The large residual flow across the Terschelling watershed, especially during strong south-westerly winds is a crucial component in the overall circulation of the Dutch Wadden Sea and is much larger than was previously assumed. Given this finding, assuming closed boundaries at the watersheds, common practice in morphodynamic model studies, may not produce accurate results.

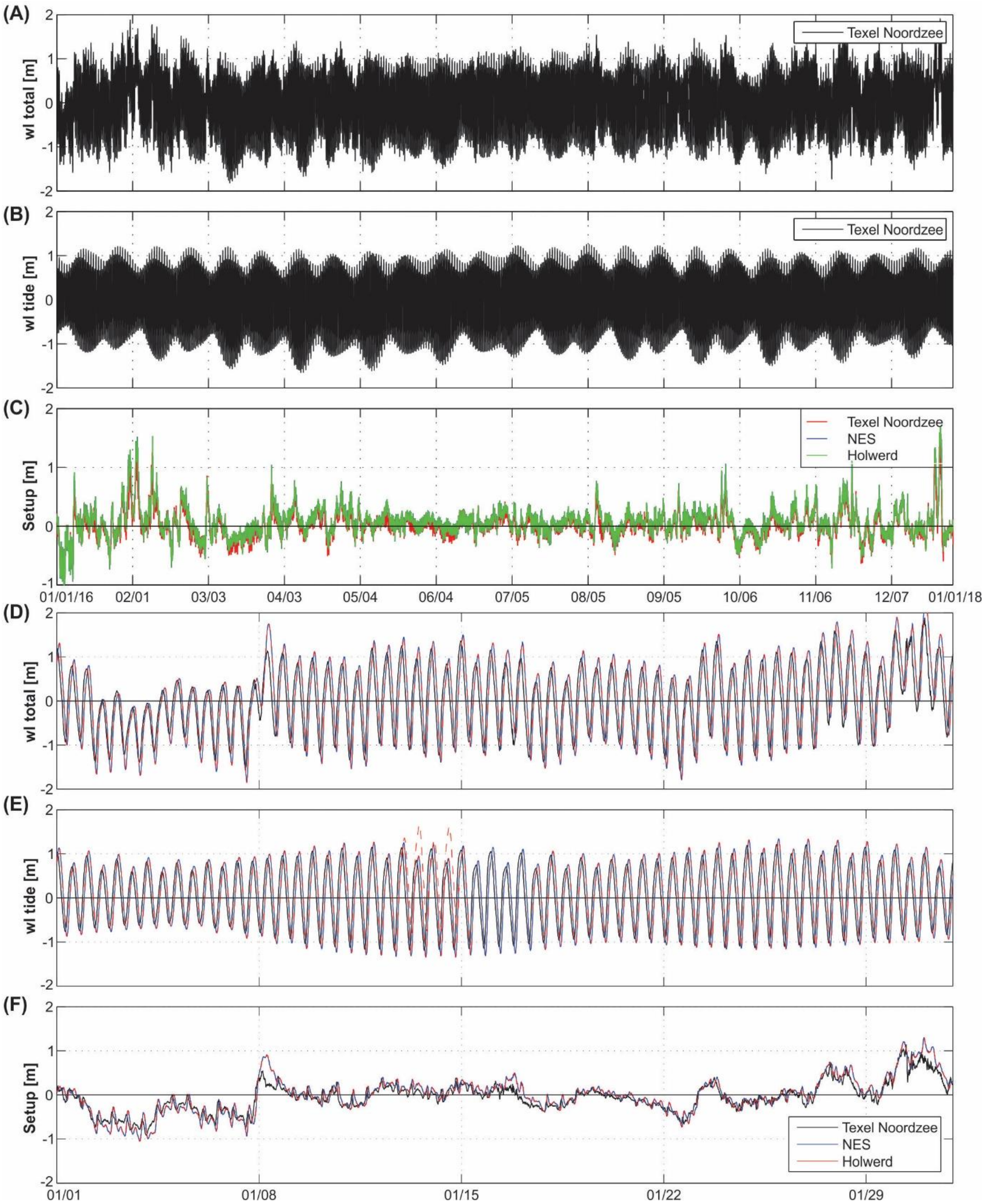


Figure 3.1 (A) Overview of water level measurements at station Terschelling NoordZee -TNZ, (B) estimate of the tidal water levels based on t_tide analysis of TNZ, (C) computed setup at stations TNZ, NES and Holwerd (setup = wl total – wl tide), (D) details of the water levels at TNZ, NES and Holwerd for the month of January 2016, (E) details of the tides at TNZ, NES and Holwerd, and (F) computed setup at TNZ, NES and Holwerd..

3.1.2 Discharges in Borndiep

In the inlet gorge Borndiep, the semi-diurnal tidal movement is the main driving force behind the horizontal water flow through the inlet. The most recent discharge measurement was executed in 2001 (Briek et al. 2003) and show on average ebb- and flood volumes through the inlet of around 400 million m^3. The peak ebb- and flood-tidal velocities are around 1 m/s in the central Borndiep channel. All available discharge measurements are summarized in Table 3.2. The values presented in this table are based on Israel (1998) as in this study all measurements (with the exception of the year 1937) were recalculated to a mean tide using a coherent method (Van Sijp, 1989). The oldest available measurement (1937) has a similar value to the 2001 measurement.
A comprehensive study of ebb and flood volumes was presented by Studiedienst Hoorn (1973). In this report 109 flood and 110 ebb tides obtained from roving ship measurements (taken over the time frame 1968 -1971) and continuously operating current stations (1971) were analysed. The average discharge value during this time frame is significantly higher compared to the more recent measurements (1996, 1999, 2001). Both the 1999 and 2001 measurement indicate that a small residual ebb dominance prevails that is less than 10 % of the ebb and flood volumes.

Table 3.2 Overview of measured ebb and flood volumes in Borndiep based on 13-hours measurements.

Survey year	dates	Average Tidal Ampl. [m]	Measured Discharge [10^6 m^3]			Mean Discharge [10^6 m^3]			Reference
			Flood	Ebb	Total	Flood	Ebb	Total	
1937	-	-	-	-	-	406	-431	-25	Beckering Vinkers (1943)
1968 - 1973	109 flood 110 ebb tides	1.95	-	-	-	518	494	24	Studiedienst Hoorn (1973)
1996			502	450		448	395		Hut (1997)
1999	26-10-1999 04:00-18:00		542	-573	-31	416	-454	-38	Visser (1999)
2001	22-01-2001 05:30-18:30		557	547	10	407	418	-11	Briek et al (2003).

3.1.3 Flow velocities

An impression of the flow patterns that dominate Ameland inlet is obtained from the flow model of De Fockert (2008). This process-based (Delft3D) model covers the entire Ameland Inlet and basin and is driven by a representative morphological tide. The flow patterns presented Figure 3.2 illustrates the typical flow velocities that can be assumed to be present in Ameland inlet due to tidal forcing. Note that the flow computations are based on a morphological tide schematization. In terms of the water level such tide typically exceeds the mean tide by approximately 10%. The patterns shown in Figure 3.2 may therefore be slightly larger than the mean velocities, but are certainly smaller than the peak (spring) flow.

The tidal flow in and around the inlet is complex due to the interaction of the alongshore (east-west running) open-sea tide and the cross-shore (Northwest – Northeast) inlet currents, with the compound channels and shoals that form the inlet bathymetry. Following high tide (7:30), the largest ebb velocities (~ 0.5-0.7 m/s) initially occur along Boschplaat (Figure 3.2, [1]), while flow in Borndiep is still limited. These larger velocities persist over an approximate 2-hour time frame. Maximum flow velocities (discharge) in Borndiep occur roughly 2 hours after high tide (10:30 [2]). During a time interval of 1,5 hours high velocities (~1.2 m/s) dominate the inlet. At this time flow velocities in Boschgat are slightly smaller (~ 0.75 m/s). Noticeable, however is the large gradient due to flow acceleration along the tip of Boschplaat. From the inlet, the area of strong velocities extends over the ebb-tidal delta [2, 3]. Especially in Westgat, Akkepollegat and the ebb-chutes and shoals in between large, over 0.5 m/s velocities occur. These velocities persist over an almost 3-hour timeframe.

Reversal from ebb to flood flow occurs around 13:30 in the open sea [4] and around 14:10 in the inlet. The flood flow first enters the inlet along the coast of Terschelling and Boschplaat. A clear segregation in flow patterns between Boschgat and Borndiep can be observed [5, 6]. Flow along Boschplaat is mainly directed through Boschgat into the southern part of the basin. Flow through Westgat and Akkepollegat is mainly directed into the eastern part of the basin through Borndiep. The largest flood velocities clearly occur in Borndiep [6]. On the ebb-tidal delta distinctively larger flow velocites are observed west of Akkepollgat, compared to the flow to the east, over the Bornrif shoal. Here flood flow velocities are rather limited.

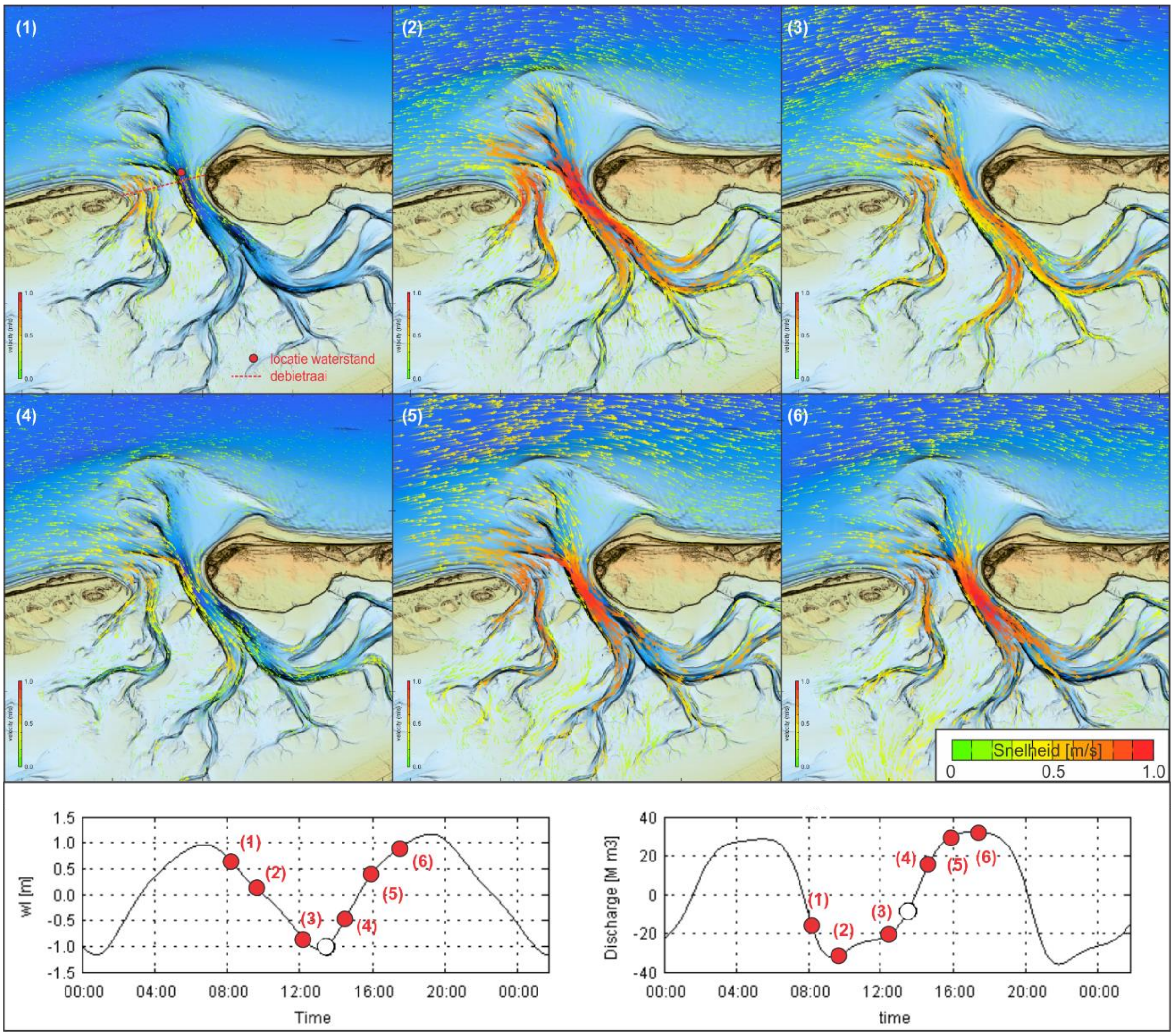


Figure 3.2 Flow velocity vectors in Ameland inlet for selected intervals during a morphological tide cycle (see De Fockert, 2008 for model details).

3.2 Waves and Wind

3.2.1 Waves

On the ebb-tidal deltas, waves redistribute the sediments and contribute to the sediment bypassing mechanism (FitzGerald, 1988; Sha, 1989). Long-term wave measurements have been conducted at the nearby stations Eierlandse Gat (ELD) and Schiermonikoog (SON), respectively east and west of Ameland inlet, since 1979 (see Figure 1.2 for locations). Additionally, at Ameland inlet, detailed wave measurements at multiple locations have been taken since 2007. Initially these measurements were part of the SBW project (Zijderveld & Peters, 2008), but measurements have been continued since. Only during summer time, the wave buoys are taken out for service and maintenance. Wave roses, summarizing the wave statistics for the Eierlandse gat (ELD), SON and 2 of the wave buoys present at Ameland are shown in Figure 3.3.

The offshore wave climate at Ameland (Figure 3.3c) shows a mean wave significant wave height of 1.37 m with a corresponding peak wave period of 7.2 s. Analysis of the measurements over the period 2007-2017, reveals that the wave climate mainly consists of local wind-generated waves in the shallow North Sea basin. The wave climate is fairly mild. Typically, waves are below 2 m (83% of the record), only during severe storms significant wave heights can occasionally reach heights between 4.5 and 9.1 m (less than 1 % of the record). Roughly 33% of the wave directions lie between west-southwest and north-northwest (235° – 305°). Most waves (62%) are from directions between north-northwest and east (305° – 90°). The remaining 4% is offshore directed and do not significantly contribute to the sediment transports. Waves from the easterly direction (0°-360°) are smaller due to the sheltering by the mainland (offshore directed) and occur less frequently. Wave periods ($T_{1/3}$) typically vary between 3 to 6 seconds for lower wave conditions (89 % of the measurements). For typical storm waves (H_{sig}= 2-3 m) a mean wave period of 6,0 s occurs increasing to 7.6 s for severe storms (H_{sig} > 4m). Contributions of swell are minor. Wave periods over 9 seconds are only measured occasionally (0,1% of the record). The differences between the wave-roses of the two Ameland stations illustrate the important wave reduction effect of the ebb-tidal delta. As a result of wave-breaking on the ebb-tidal delta shoals the wave heights in the nearshore (inlet) Ameland station reduced to 1,0 m while wave directions are constrained almost entirely to the north-westerly quadrant (in line with the main channel).

Due to the relative short record of observations at the Ameland buoys and missing data early summer, when the buoys are out of the water for maintenance, it is not possible to create a long-term representative wave climate for these buoys. Comparing the wave direction and wave heights between ELD – SON and the Ameland wave buoys shows that SON best resembles the Ameland wave record with a close correlation in height and direction (Elias, 2017). For future wave climate schematizations it is recommended to use the SON data as basis.

3.2.2 Wind

Wind measurements taken at the nearby AWG station (see Figure 1.2 for location) show a mean wind velocity of 4.9 m/s from a south-southwesterly direction (200°). This nearshore wind velocity is considerably smaller compared to the averaged measured velocities of 5.7 m/s at the offshore (L9) location; see Figure 3.4 for details. A noticeable difference is present between the dominant wind and wave directions. The largest and most frequent winds occur from the Southwest, a direction hardly present in the wave record due to the sheltering of the mainland.

Limited knowledge is present on the importance of the wind and wind-driven flow on the ebb-tidal delta and in the inlet gorge. Inside the basin, we can expect the wind to be important for mixing and estuarine circulations, and in shallow areas wind is effective in generating large currents and tidal flat degeneration by locally generated waves. Also the eastward migration of the tidal divides in the Wadden Sea may for a major part be related to the prevailing wind direction (de Boer et al, 1991, FitzGerald et al., 1984; Van Veen et al., 2005).

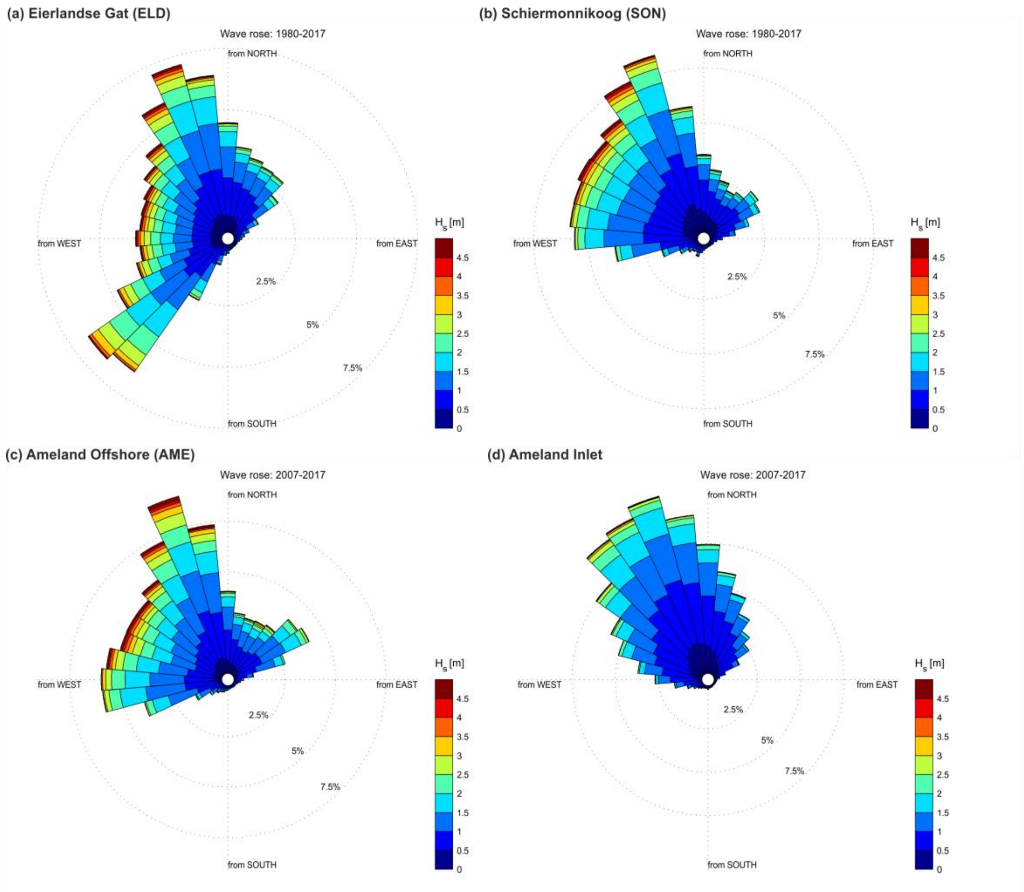


Figure 3.3 Wave roses for stations (a) Eierlandse Gat (ELD), (b) Schiermonnikoog (SON), and Ameland offshore (AME) and Ameland Inlet (see Fig. 1.2 for locations).

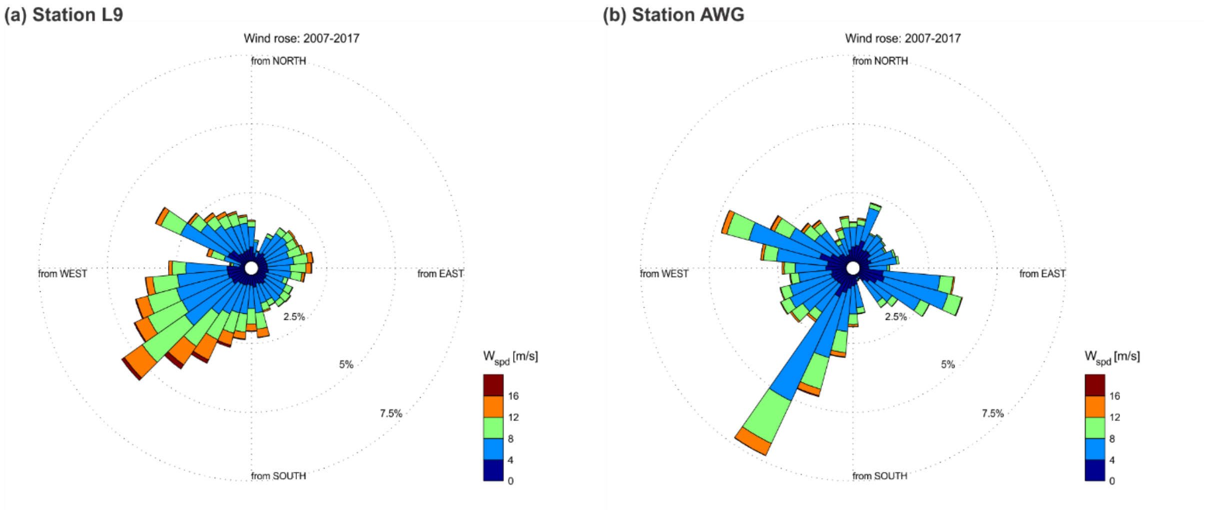


Figure 3.4 Wind roses for stations (a) L9 (offshore) and (b) AWG (Ameland). See Fig. 1.2 for locations.

4 Morphodynamics of Ameland inlet

4.1 History of the Ebb-tidal delta

4.1.1 Introduction

The present day Wadden Sea was shaped over a period of over 7000 years. A wide variety of barrier islands, channels, sand and mud flats, gullies and salt marshes formed under a temperate climate, rising sea-level (Eisma & Wolff, 1980; Vos et al., 2011), and, in particular during the last century, human interventions (Oost & de Boer, 1994; Elias & van der Spek, 2006; Elias et al. 2012). Today's basin coastline was formed mainly by construction of dykes, levees and land reclamation. Around 1000 AD. the Middelzee, a late Holocene tidal basin, reached its maximum size. Infilling with marine sediments and subsequent dike building on the deposits resulted in reclamation of the landward part of the basin. The present-day location of the Frisian coastline was formed around 1600. The change in basin geometry introduced in large scale alterations of the channels in the remaining basin. The watershed migrated towards the east and the inlet channel rotated to a more NW-SE orientation, thereby eroding the western end of Ameland island.

The more recent changes can be derived from the regular bathymetric surveys of Ameland inlet that are available (on paper) since 1798, and digitally since 1925 (De Kruif, 2001). Previous studies have identified 3 major morphodynamic phenomena that will be briefly discussed in the following sections: chapter 4.1.2 Cyclic morphodynamic evolution of the ebb-tidal delta, chapter 4.1.3, migration of the main inlet channel Borndiep, and chapter 4.1.4 the attachment of the Bornrif Strandhaak to the Ameland coast.

4.1.2 Cyclic morhodynamic evolution

"Cyclic morphodynamic evolution" is considered to be an important concept describing the medium to long-term evolution of the Ameland inlet. Based on the analysis of 200 years of historic data (1798-1999), Van der Spek en Noorbergen (1992), Israël en Dunsbergen (1999) and Cheung et al. (2007) point to the mechanism of cyclic morphodynamic channel-shoal evolution in Ameland inlet. The observed cycle spans between 50 and 60 years, and consists of 4 distinct stages in evolution, as summarized in Figure 4.1.

Phase 1 (Figure 4.1a), is characterised by the presence of a single main channel between the island tips. The main channel connects to both channels (Westgat and Akkepollegat) on the ebb-tidal delta. The west-east oriented tip of Terschelling, Boschplaat, extends far into the inlet. The easterly directed Boschgat is located south of Boschplaat, separated by a (large) shoal area, and connects directly to Borndiep. Gradually this system migrates towards a two-channel system (***Phase 2,*** Figure 4.1b). During this re-adjustment, Boschgat migrates westward towards Boschplaat, and Boschplaat forms as a spit type feature. ***Phase 3*** (Figure 4.1c), is reached as Boschgat and Westgat connect, breaching the Boschplaat, forming a continuous second channel on the ebb-tidal delta. This channel is small compared to the main channel Borndiep. A two-channel configuration in the inlet characterises both ***phases 3 and 4*** of the conceptual model.

Recent analysis by Elias (2017) indicates that the present day morphodynamic development of the Boschplaat deviates from this concept. This deviation may result from an increasing depth of the ebb-tidal delta and the resulting increase in wave energy in the Boschplaat and Boschgat region.

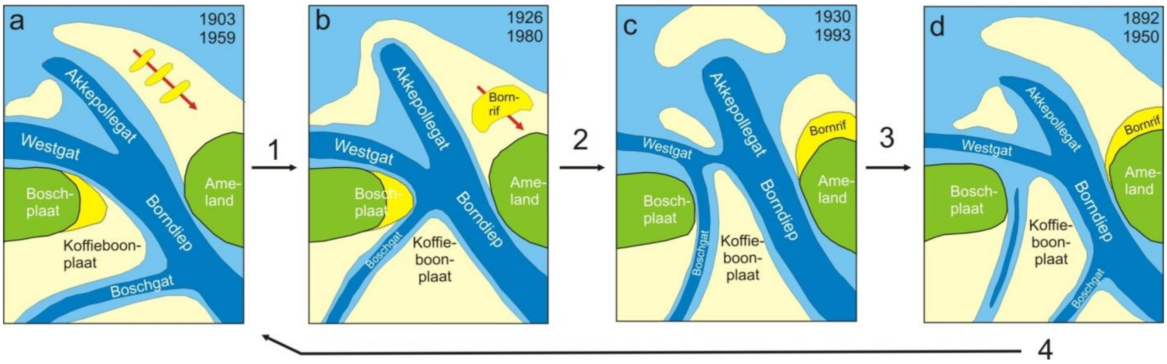


Figure 4.1 Cyclicity in the Ameland inlet (from Israël en Dunsbergen, 1999).

4.1.3. Migration of Borndiep

A long-term erosional trend, as a result of migration of Borndiep, has induced severe erosion of the western side of Ameland. This has resulted in extensive soft and hard coastal protection works (see Figure 4.2 for an impression). Already in 1947 the first stone revetments were placed. Additional groins and an alongshore stone revetment on the inner channel slope in 1979 and further expanded in 1994. Additional nourishments were frequently repeated to keep the beaches in place, Between km 1.00 and km. 4.01, nine nourishments have taken place since 1979 and over 6 million m^3 of sand was added to the system by 2015 (see Table 4.1 for an overview).

Table 4.1 Overview of the nourishments placed along the North-West coast of Ameland (km. 1-4.02).

	Type (1)	Year	Km. Start	Km. End	Volume (*cm*)
1	B	1979	1.6	2.2	300.000
2	B	1997	1.2	3	510.804
3	B	2000	1	2.6	401.002
4	B	2004	2	3.2	403.636
5	SF	2007	1.95	3.02	1.201.234
6	B	2007	2	3.2	303.444
7	B	2011	2.00	4.00	1.888.934
8	B	2015	1.40	4.02	1.300.000
				Total	6.309054

(1) B= Beach, D = Dune, SF= Shoreface, CS = Channel Slope Nourishment.

Studies by Beckering Vinckers (1943) and Cleveringa et al., (2005) indicate that migration of Borndiep is related to: (1). The eastward migration of the basin. Both the Terschelling and Ameland tidal divides, that roughly indicate the position of the basin, have migrated eastward. Since 1830 this migration is on the order of several km-s (van der Spek, 1995). This migration was partly introduced by infilling of the former basin (Middelzee), but also the prevailing eastward residual transports due to wind and tides may contribute to the ongoing movement (de Boer et al. 1991a,b). (2). The connection of Boschplaat with the main island of Terschelling in the 19th century by a dike. This now "permanent" connection prohibits channels to dissect the Boschplaat. As a result, Borndiep transports the majority of the flow. (3). Cyclic morphodynamic evolution of the ebb-tidal delta (see previous section). Elias et al. (2013) present a detailed analysis of the recent morphodynamic changes in Borndiep (summarized in Figure 4.3). The left panel of this figure shows the movement of the main channel using the -10m contour. Channel migration has mainly taken place between 1926 and 1971. Since 1971, the channel itself has roughly remained in place. The construction of hard coastal protection works in the form of a stone protection along the inner channel slope must have contributed to this stabilization. These protection works are capable of reducing, but not completely eliminating coastal erosion. The large flow velocities in Borndiep make frequent maintenance and nourishment necessary (Table 4.1).

Figure 4.2 Impression of the coastal protection works along the west coast of Ameland (https://beeldbank.rws.nl, Rijkswaterstaat). Left panel: Groins protecting the beach in 1954. Upper left: impression of the protection works in 2007, and (lower right) a nourishment taking place along the coast.

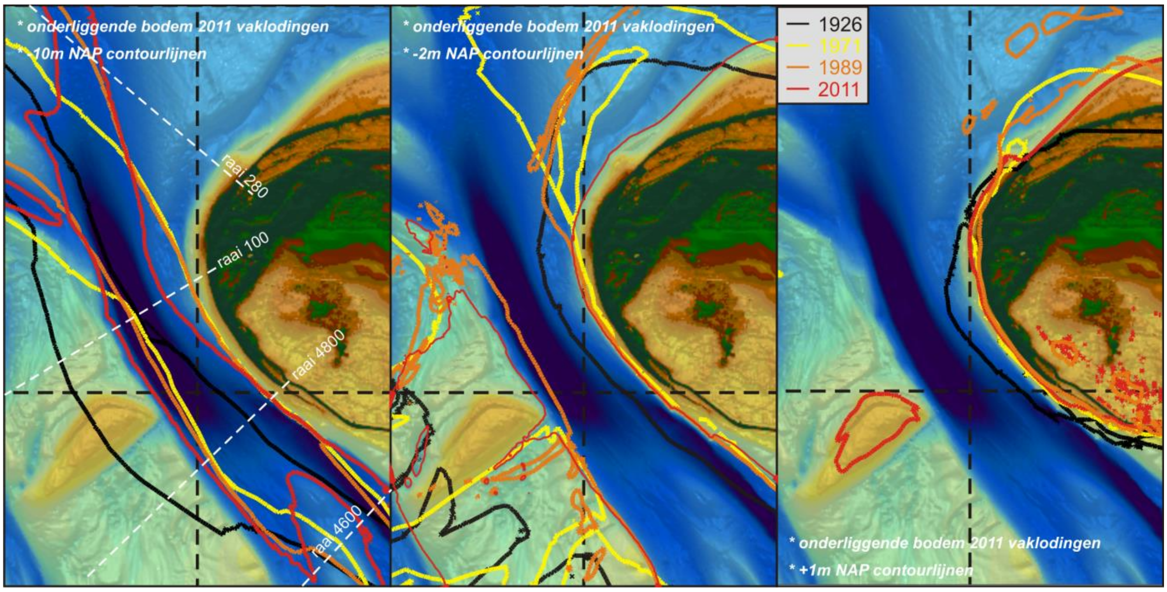


Figure 4.3 Migration of Borndiep based on Vaklodingen data over the time frame 1927-2011. Left to right: migration of the -10 m contour (mid channel depth), -2 m contour (upper channel slope) and +1 m contour (beach). From: Elias and Bruens 2013.

4.1.3 Bornrif Strandhaak

One of the most renowned morphodynamic features of the Ameland ebb-tidal delta is the Bornrif Strandhaak. As part of sediment-by-passing process, periodically large volumes of sand migrate over the ebb-tidal delta and eventually attach to the Ameland coastline. A visualisation of the JarKus measurements over the 1965-2011 timeframe illustrates this attachment process (Figure 4.4).

The ebb-delta shoal is first visible around 1970, and connects to the Ameland coast between 1985 and 1989. After attachment, a large volume of sand migrates into the basin, but most reshapes into the form of an eastward, cuspate shaped, spit or in Dutch called “strandhaak”. The eastern tip of the shoal quickly migrates eastward, eventually connecting to the Ameland coast around (1989-1995). Sediments for this eastward extension are supplied by erosion of its seaward side. After attachment, a small lagoon is formed and the process of erosion of the spit front and eastward extension continues. In 2011 the spit had extended eastward over a length of 8 km. On the ebb-tidal delta a new bar (Bornrif Bankje) is than clearly present on the ebb-delta ready to attach to the coastline (see Figure 4.5 and Figure 4.6).

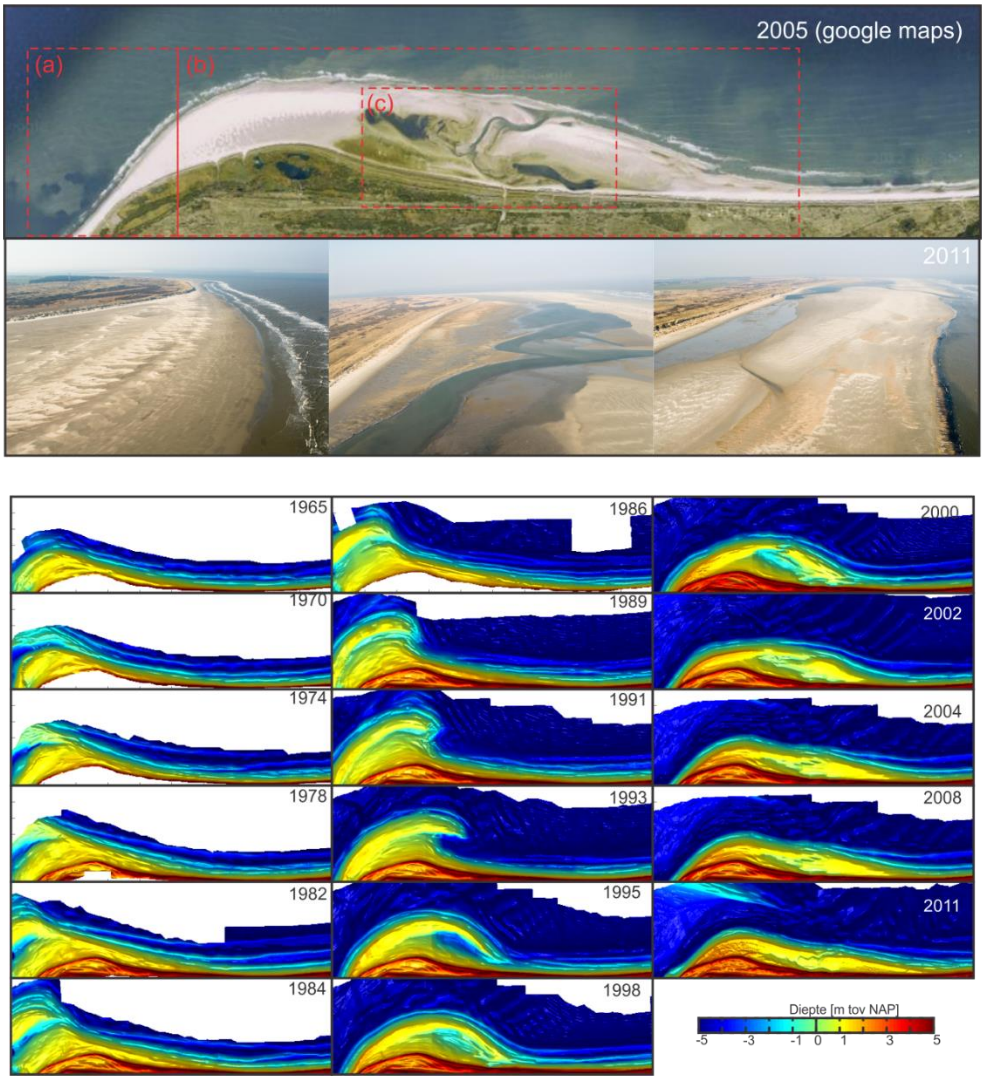


Figure 4.4 Formation and evolution of the Bornrif strandhaak based on JarKus measurements over the timeframe 1965-2011 (from: Elias and Bruens, 2013).

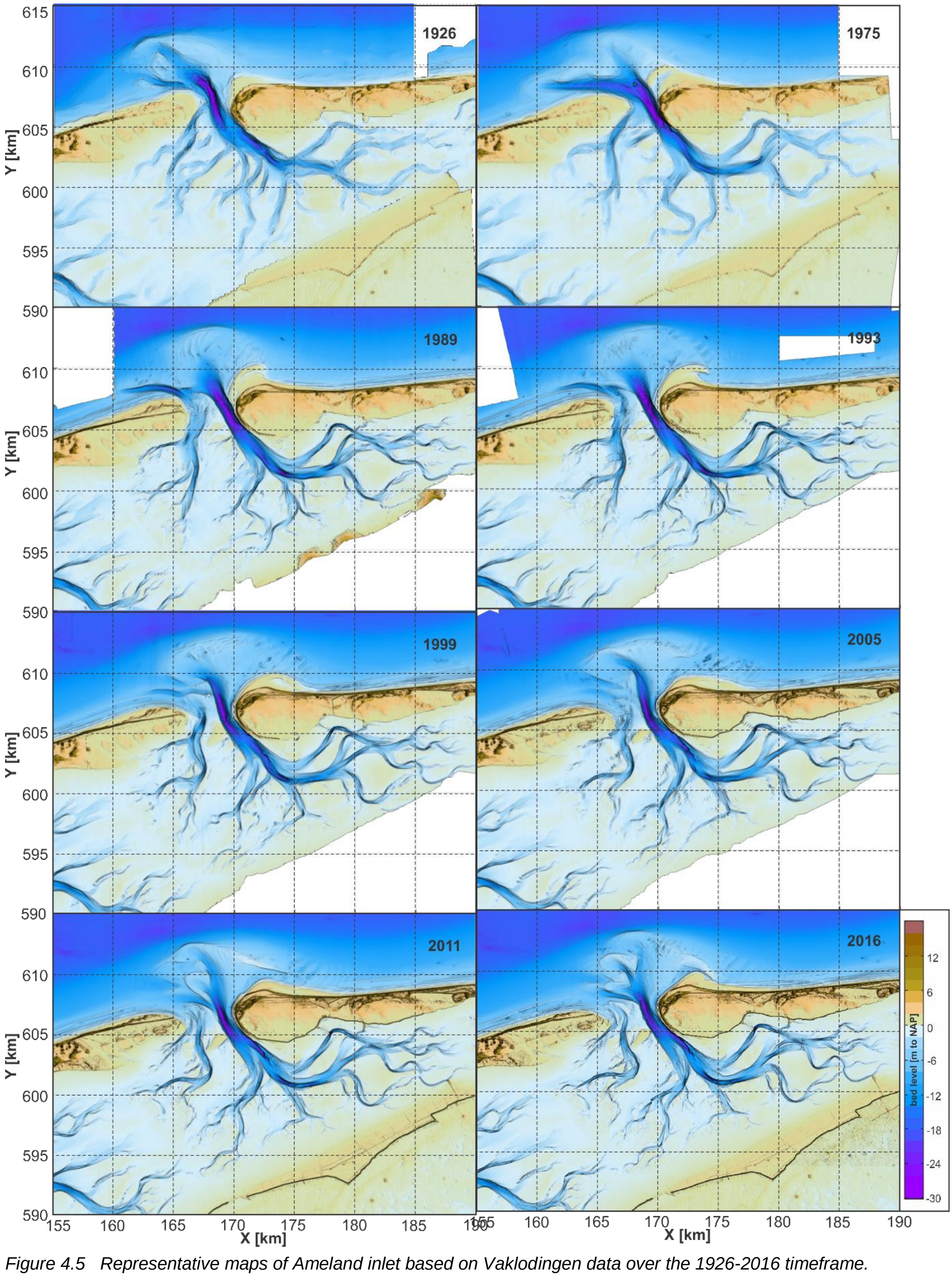


Figure 4.5 Representative maps of Ameland inlet based on Vaklodingen data over the 1926-2016 timeframe.

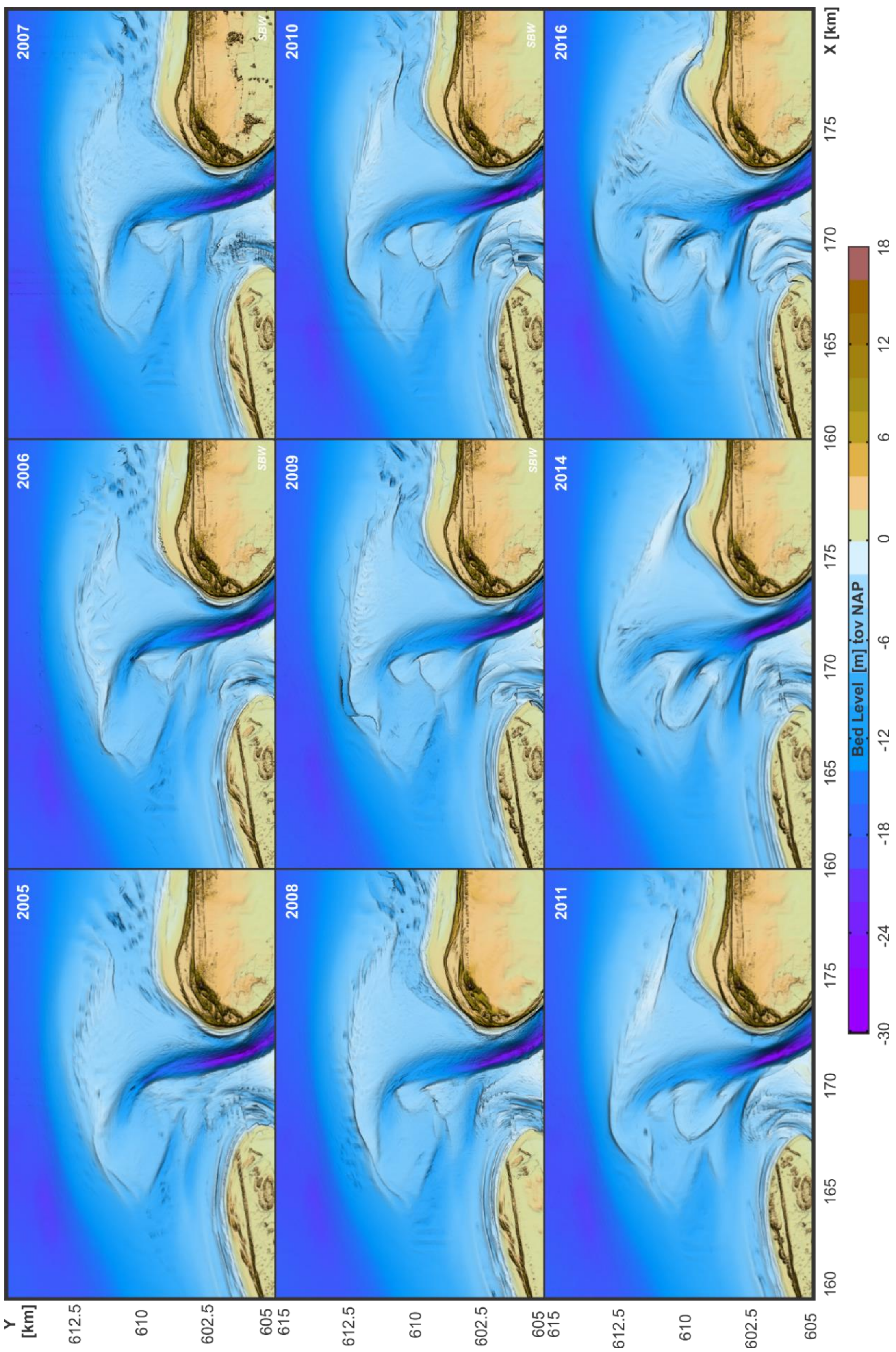

2005
2006
2007
2008
2009
2010
2011
2014
2016
SBW
Y [km]
X [km]
Bed Level [m] tov NAP
18
12
6
0
-6
-12
-18
-24
-30

Figure 4.6 Detailed maps of the ebb-tidal delta, based on Vaklodingen and additional SBW measurements (2006, 2007, 2009, 2010) over the timeframe 2005-2016.

4.2 Recent Morphodynamic changes and sediment Budget.

4.2.1 Introduction

Important goals of this report are (1) to improve our understanding of the dominant sediment transport patterns and rates by detailed morphodynamic analysis of the present-day processes and (2) provide datasets suitable for model validation. Based on an initial assessment of morphological features, the timeframes 1989-2016 and 2005-2016 have been selected. Comparison of the 1975 and 1989 bathymetries shows a clear difference in morphological setting (Figure 4.5). In 1975 Boschplaat extends well in the inlet and a relative narrow inlet gorge is present with Borndiep as sole channel. On the ebb-tidal delta Westgat forms the largest channel with a distinct westward orientation. Westgat appears unrealistically large compared to the older maps so questions can be raised on the accuracy of this map. In 1989, we observe Borndiep as largest and deepest channel on the ebb-tidal delta. Between Boschplaat and Borndiep a shallow area with secondary channel (Boschgat) is present. On the ebb-tidal delta the main platform Bornrif is located seaward and eastward (downdrift) of the main ebb channel. The Bornrif Strandhaak just started to merge with the Ameland coastline. Although channels and shoals differ in dimensions and exact location, the main characteristics of this morphological state remain present in the subsequent maps. The change from single-channel to a double-channel configuration is well-explained through the conceptual model of “cyclic morphodynamic behaviour”. In this paper the focus is on the short- to medium-term timescales describing the present-day behaviour of the inlet. The timeframe 1989-2016 is therefore selected.

In addition, a detailed sedimentation-erosion map over the time-frame 2005-2016 is provided. During part of this time frame, yearly maps of the morphodynamic change are present that can provide more insight in the morphodynamic changes and variability on the shorter timescales. For example, the maps capture the formation of a distinct large ebb-chute on the ebb-tidal delta in detail. Such a clear morphodynamic signal provides an essential base for model validation and calibration.

Table 4.2 Overview of the available bathymetric data (see Figure 4.5 and Figure 4.6 for bathymetric renderings). ETD = Ebb Tidal Delta.

Year	Dataset	Coverage		Year	Dataset	Coverage	
		Basin	**ETD**			**Basin**	**ETD**
1926	Vakloding	X	X	2005	Vakloding	X	X
1948	Vakloding	X	-	2006	SBW	channels	X
1971	Vakloding	X	X	2007	SBW	X	X
1975	Vakloding	X	X	2008	Vakloding	X	X
1981	Vakloding	X	X	2009	SBW	channels	X
1989	Vakloding	X	X	2010	SBW	X	X
1993	Vakloding	X	X	2011	Vakloding	X	X
1996	Vakloding	-	X	2014	Vakloding	-	X
1999	Vakloding	X	X	2016	KG2	Partial	X
2002	Vakloding	-	X	2017(1)	Vakloding	X	X

(1) Not officially released.

4.2.2 Available data

The analysis of bathymetric changes and construction of a detailed sediment budget are based on a series of bathymetric datasets, starting from 1986 that are digitally available from the Donar database at Rijkswaterstaat (Table 4.2). The maps are based on data collected frequently, in approximately 3-year intervals for the ebb-tidal delta and 6-year intervals for the basin. Following quality checking for measurement errors, data are combined with nearshore coastline measurements, interpolated to 20x20 m grids and stored digitally as 10x12 .5 km blocks called *Vaklodingen* (De Kruif, 2001). Each of these maps was visually inspected and clear data outliers or missing (individual) data points were corrected. Maps with missing data along the island shores have been completed using *JarKus* survey data (JarKus, from Jaarlijkse Kustmetingen, Annual Shoreline Surveys) or linear interpolation between the nearest available data points. In addition, between 2007 and 2010 yearly surveys of most of the ebb-tidal delta and main channels in the basin were measured in the frame work of the SBW-Waddenzee project (Zijderveld and Peters, 2008). These data were processed and saved in a similar format as the Vaklodingen. Example Digital Elevation Models (DEMs) based on these measurements are presented in Figure 4.5 and Figure 4.6. Kustgenese 2 half-yearly bathymetric surveys of the ebb-tidal delta started in 2016, and will be continued till the end of 2019. These measurements are executed and stored following the Vaklodingen protocol.

It must be noted that changes in survey techniques and instruments, positioning systems, and variations in correction and registration methods over time make it difficult to estimate the exact accuracy of the measurements and therefore the DEMs. Wiegmann et al. (2005) and Perluka et al. (2006) estimate the vertical accuracy of Vaklodingen data to range between 0.11 - 0.40 m. However, the sediment budget reveals unrealistically large changes (beyond this error range) in some of the maps that can only be explained as measurement error.

4.2.3 Channel and shoal distributions on the ebb-tidal delta

The distribution, evolution, shape and size of typical, large-scale ebb-tidal delta elements, such as ebb and flood channels, channel-margin linear bars, terminal lobes and swash-bar patterns can provide useful insights in sediment transport patterns (see e.g. Hayes, 1975; Hine, 1975; Hubbard et al., 1979; Boothroyd, 1985; Sha, 1989b; FitzGerald, 1996).

An overview of the bathymetric changes of the ebb-tidal delta since 1989 is presented in Figure 4.5 and Figure 4.6. Both the 1989 and 2016 bathymetry have in common that: (1) The inlet gorge consists of a shallow western part along the tip of Terschelling and a deep eastern part along the Ameland coastline that contains the main ebb-channel Borndiep. (2) Borndiep has an northwest outflow onto the ebb-tidal delta. (3) The main ebb-delta volume is stored north-eastward (downdrift) of Borndiep in the Bornrif shoal. (4) In the shallow part of the inlet secondary channels occur that directly connect (1989) or not connect (2016) to the Westgat channel on the ebb-tidal delta.

Despite these commonalities, the details of the channels and shoals of the ebb-tidal delta show very different characteristics. Most noticeable differences include:

(1) Position and size of Westgat.

In 1989 a pronounced west-east running Westgat channel extends along the Terschelling coastline and is directly connected to Boschgat. A continues secondary channel has thereby formed in the inlet gorge. In 2016 only a small Westgat remains, that is not clearly connected to Borndiep. A clear Borndiep-Westgat connection was present over the 2005-2011 time frame.

(2) Sediment volume on the westside of Borndiep.
With a clearly defined Westgat, a westward outbuilding of the ebb-tidal delta was present along the channels margin. This resulted in a shallow shoal area that extended along the Terschelling coastline. Through time this shoal area has dissipated and since 2005 this part of the ebb-delta is distinctively deeper. Model results by Elias (2017) illustrate that as a result the wave energy and gradients along the Boschplaat and in the Boschgat region have increased, which may (partly) explain the ongoing erosion of Boschplaat (see Figure 4.7).

(3) Ebb-chute formation on the Kofmansbult.
It is likely that a reduction of Westgat has increased the dominance of Borndiep-Akkepollegat. As a result, major shoal development has taken place seaward of Westgat on the shoal area Kofmansbult. A clear ebb-chute and -shield started to form around 2006, and continued to grow and built out onto the Kofmansbult shoal (Figure 4.6). In the recent 2014 and 2016 bathymetries a second ebb-chute seems to form just south, further constraining the Westgat channel. The formation of this ebb-shield, and the higher shoal to the north are likely contributors to the confined flow in the main channel and the observed curvature of the channel (Akkepollegat) around the shoal.

(4) Shoal formation on Bornrif.
The Bornrif Strandhaak connected to the Ameland coast between 1985 and 1989 (see Figure 4.4 for details). While the shoal merged with the coastline in the following decades, a new shoal (Bornrif Bankje) formed offshore. The initial formation of this Bornrif Bankje most likely originates between 1999 and 2002 as the ebb-tidal delta front slightly migrates onshore thereby increasing in height, forming a shallow shoal facing Akkepollegat (Figure 4.5). Between 1999 and 2005 this shallow area develops a long linear bar along the Northeast side of Borndiep. This shoal continues to migrate towards the Ameland coast and is nearly attached in the 2016 survey. Shoal attachment occurs eastward of the original strandhaak

The sedimentation-erosion patterns presented in Figure 4.8 summarize the morphodynamic changes since 1989. Most noticeable is the variation of subsequent areas of erosion and sedimentation over the ebb-tidal delta over both the 1989-2011 and 2011-2016 timeframes.

Between 1989 and 2011, the ebb-tidal delta loses approximately 8 million m^3 (mcm) of sediment (Fig. 4.8A). Three major areas contribute to these losses: (1) the ebb-delta front is pushed landward and to the north-east (eventually forming Bornrif Bankje. As a result nearly 35 mcm is eroded [polygon 6, Fig. 4.8A], of which most can be traced back to the increasing height of Bornrif (Bankje): +34 mcm [13]. Erosion of the Bornrif Strandhaak introduces an additional loss of nearly 25 mcm [14]. Only a minor portion (8 mcm) contributes to the outbuilding of the coast to the east of the Strandhaak [15]. A similar volume (25 mcm) is eroded from the Boschplaat [9]. The eroded deposits likely contribute to the accretion of Borndiep and in the southern part of the basin. Most of the accretion of Westgat (10 of the 14 mcm) occurs in the first interval [8]. Such large change may be the result of an inaccuracy in the measurements.

The volume development between 2011 and 2016 (Fig. 4.8B) displays opposite trends for most areas on the ebb-tidal delta. The ebb -delta front shows an outbuilding (+12 mcm [9]) with a general trend of lowering of the main shoal area of Bornrif (-22 mcm [11]). Bornrif is pushed seaward, while Bornrif Bankje continues to migrate landward towards Ameland locally introducing erosion (-3.5 mcm [10]) as flow accelerates in the confined area between the shoal and the coast. Most accretion is observed on the ebb-delta front (+12 mcm [9]), the ebb-shield (Kofmansbult, +13,5 mcm [12]) and the infilling of the area around Westgat (+8,5 [14]). Erosion continues at the adjacent coastlines (Boschplaat -3,5 mcm [6] and Bornrif Strandhaak -1,4 mcm [10]).

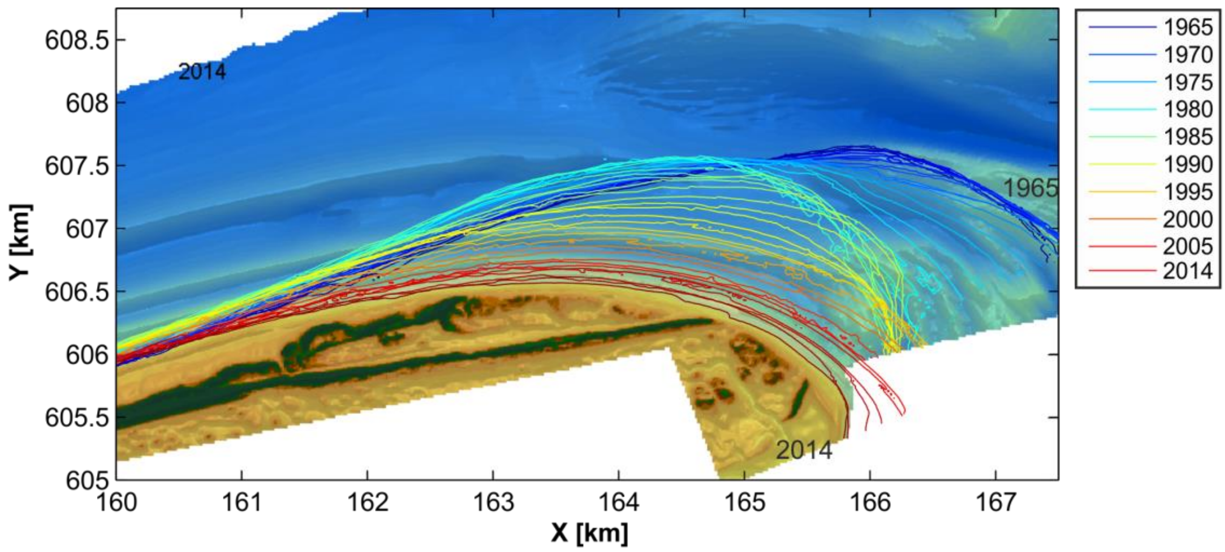


Figure 4.7 Details of the coastline erosion of Boschplaat (1965-2014).

4.2.4 Sediment Budget

4.2.4.1 1989 - 2016

Figure 4.8A and B summarize the sediment budget over the timeframe 1989-2016. The sedimentation erosion maps are divided in two parts, 1989-2011, and 2011-2016. The first time frame allows for the complete analysis of the entire inlet system including basin. An analysis of the volume changes including the basin is presented in Vermaas (2015). In 2014 and 2016 only partial coverage of the basin is present. For both time-frames the sedimentation-erosion maps are subdivided in polygons that bound the main sedimentation and erosion areas. The volume changes for each of the polygons and time-frames are summarized in Figure 4.8A and B, and Table 4.3 and Table 4.4. The polygon areas are subdivided in the “wet” area (below +1m NAP), beach (volume changes between +1m and +3m NAP) and dunes (volume changes for heights exceeding 3m). For both years a similar subdivision can be made in coast (polygons 1-5) and ebb-tidal delta (polygons 6-15 and 6-18).

Timeseries of the volume changes over the entire time frame (1989 – 2016) are summarized in Figure 4.9. In these timeseries the polygons as defined in Figure 4.8A (based on 1989-2011) are used. Most noticeable in the “raw data” timeseries (left column) are the large volume fluctuations prior to 2005. Both the ebb-tidal delta and coast show an initial reduction in volume between 1989 and 1993 (-31 mcm), an increase of nearly 60 mcm till 1999, followed by a 45 mcm reduction in the subsequent map (2002). Such fluctuations, that are for a major part related to the offshore polygons (polygons 2 and 3), are unrealistic and point to possible inaccuracies in the data. For the offshore polygons the volume change between 1989 and 1993 is therefore assumed to be zero.

Omitting the outliers from the sediment budget computations considerably reduces the observed erosion rates (Table 4.3 and Table 4.4). Only the ebb-tidal delta over the 1989-2011 and 1989-2016 time frames still show a small volume loss, while more recently (2005-2016) a net gain in ebb-tidal delta volume can be observed. Note that the net changes are considerably smaller than the gross- changes and well within the accuracy of the data. Firm conclusions or statements on ebb-delta state (erosional – accretional) should not be based on this. Note that the timeseries are not corrected for nourishments. During this timeframe 6 mcm of sand was added along Ameland Northwest.

Table 4.3 Uncorrected volume changes for polygons shown in Figure 4.8, trends based on linear regression analysis of the time series presented in Figure 4.9 (left column).

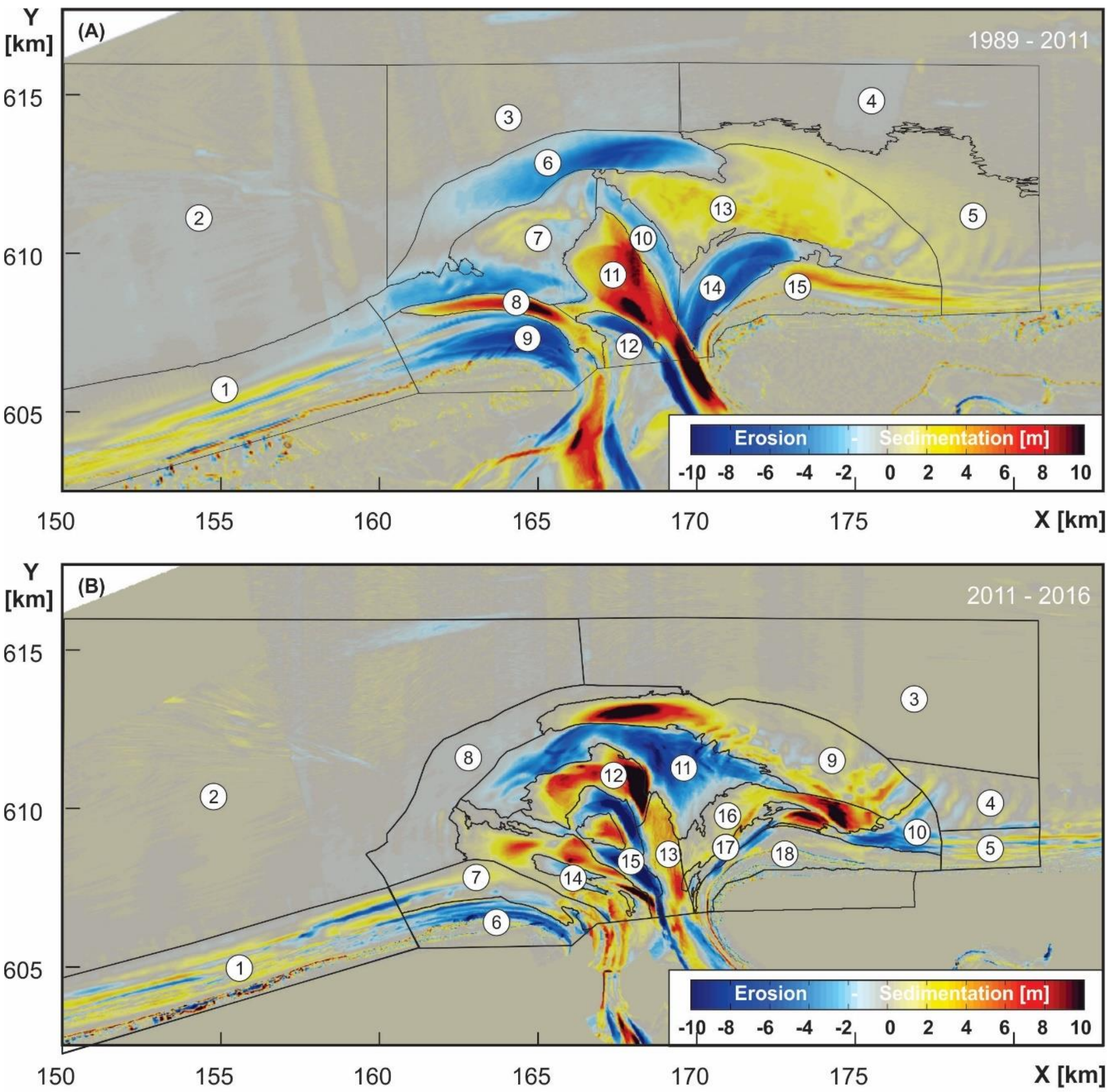
	Volume changes in million m^3 and million m^3/yr*					
	1989-2011		1989-2016		2005-2016	
	m^3	m^3/yr	m^3	m^3/yr	m^3	m^3/yr
ETD	-19	-0.9	-13	-0.7	-1	0.1
Coast	-13	-0.6	-11	-0.4	1	0.6
Total	-32	-1.5	-24	-1.1	1	0.7

Table 4.4 Corrected volume changes for polygons shown in Figure 4.8, trends based on linear regression analysis of the time series presented in Figure 4.9 (right column).

	Volume changes in million m^3 and million m^3/yr*					
	1989-2011		1989-2016		2005-2016	
	m^3	m^3/yr	m^3	m^3/yr	m^3	m^3/yr
ETD	-19	-0.9	-13	-0.7	-1	0.1
Coast	16	0.7	19	0.7	4	0.7
Total	-3	-0.2	6	0	3	0.8

4.2.4.2 2005 - 2016

The availability of additional DEMs between 2005-2009, the large fluctuations in volume indicating plausible inaccuracies in measurements prior to 2005, and the more consistent trends in ebb-delta evolution motivate the selection of the 2005-2016 time-frame for a detailed sediment budget (Figure 4.10 and Figure 4.11). We anticipate that the observed trends are representative for the present-day processes, and can form a basis for future process-based model calibration and validation. In total, the ebb-tidal delta and coast show a net increase in sediment volume of 7mcm. During this time-frame 4,7 mcm was nourished along Ameland Northwest. Correcting for these nourishments reduces the gain to 1.3 mcm. This net change is small compared to the gross changes (~200 mcm). The increase mainly results from the two recent (2014, 2016) bathymetries. The observed changes correlate strongly with the 2011-2016 timeframe. In both maps alternating areas of sedimentation and erosion dominate the ebb-tidal delta. Erosion is observed along the adjacent coasts with a 5.6 mcm loss at Boschplaat (these losses increase to 9 mcm if the losses in polygon 23 are added). A similar volume gain occurs in the Boschgat area, suggesting that sediments from Terschelling are transported cross-shore, into the inlet, at the tip of Boschplaat. These sediments contribute to the accretion in the Boschgat region [polygon 12] and likely to the infilling of Borndiep and the development of the ebb-shield on Akkepollegat. This ebb-shield increases in volume by nearly 18 mcm. An additional 7 mcm is deposited just seaward of the former Westgat channel. Erosion of the Bornrif shoal is a likely contributor to the observed sedimentation (25 mcm) on the ebb-delta front, and for the increasing volume of Bornrif Bankje (10 mcm).



Poly-gons	Volume change [mcm]			Poly-gons	Volume change [mcm]		
	Wet(1)	Beach(2)	Dune(3)		Wet(1)	Beach(2)	Dune(3)
1	3,6	0,1	4,2	11	42,6	-	-
2(4)	0,1	-	-	12	-7,2	-	-
3	1,4	-	-	13	33,7	-	-
4	-3,5	-	-	14	-24,5	-1,1	0
5	9,3	0,5	0,4	15	16,7	-1,9	-2,5
6	-34,9	-	-				
7	-17,1	-	-				
8	13,6	-	-				
9	-24,7	-5,2	0,5				
10	-7,1	-	-				
(A)				Total	-3,0	-7,6	2,6

Poly-gons	Volume change [mcm]			Poly-gons	Volume change [mcm]		
	Wet(1)	Beach(2)	Dune(3)		Wet(1)	Beach(2)	Dune(3)
1	0,9	0,7	1,6	11	-22,2	-	-
2	-3,2	-	-	12	13,5	-	-
3	2,1	-	-	13	5,1	-	-
4	0,6	0,2	0,1	14	8,5	-	-
5	-0,1	-	-	15	-10,9	-	-
6	-3,8	-1,2	-0,7	16	9,5	0,3	-
7	1,1	-	-	17	-1,4	0,1	-
8	-2,5	-	-	18	-0,2	0	-
9	14,1	-	-				
10	-3,5	-0,2	-				
(B)				Total	7,7	-0,2	0.9

(1). Wet = volume change for bed level <+1 NAP. (2). Beach = volume change for bed level between +1 and + 3m NAP. (3). Dune = volume change for bed level > +3m NAP.
(4). Erosion in polygon 2 (2005-2007) is unrealistic. Therefore a zero change is assumed over this time frame.

*Figure 4.8 Observed sedimentation-erosion patterns and volume changes over the time period 2005-2011 **(A)** and 2011-2016 **(B)**.*

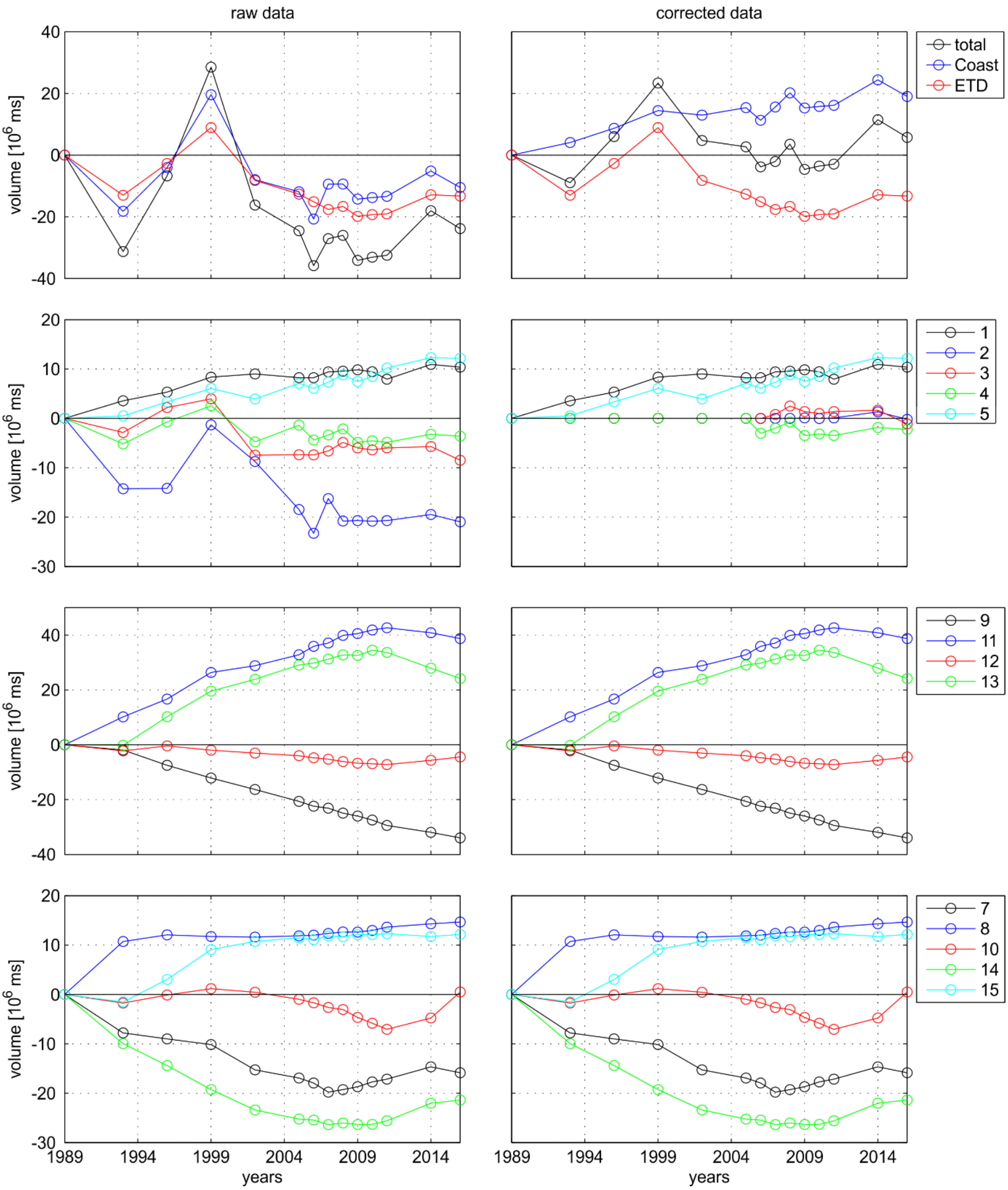
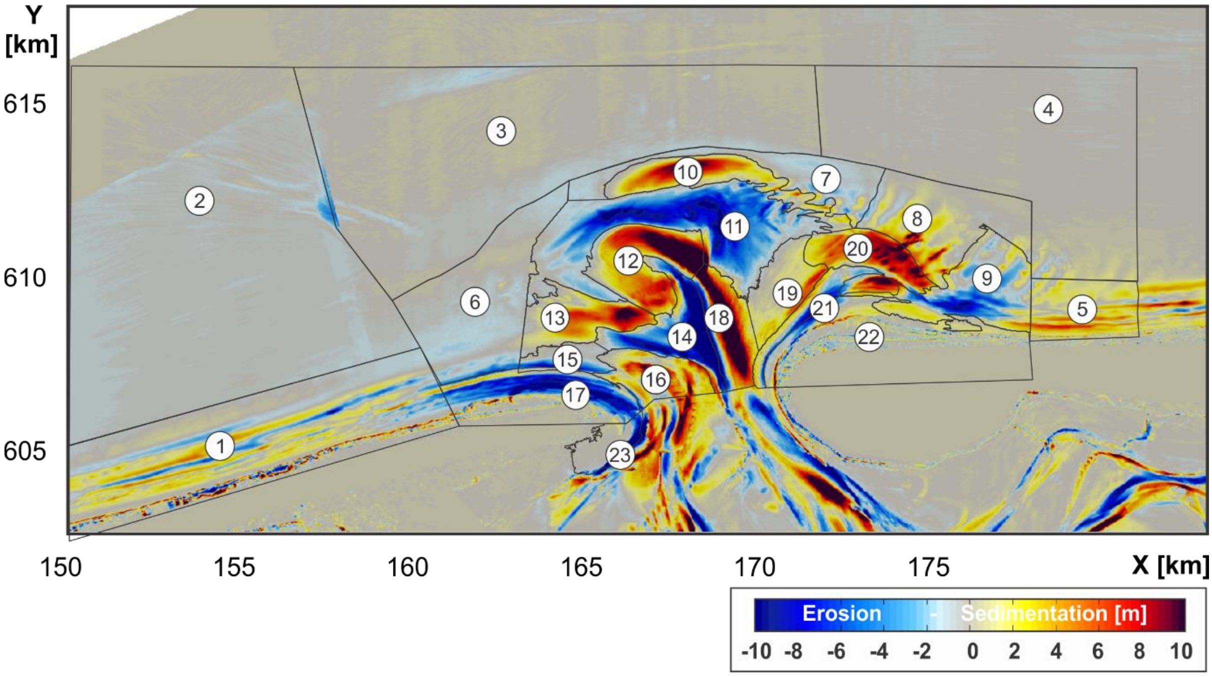


Figure 4.9 Timeseries of volume change over the timeframe 1989-2016, based on the polygons shown in Figure 4.8A. Left panels show timeseries for “raw data” and right panels the timeseries for the corrected data of volume change.(note that ETD = Ebb-tidal delta).



Poly-gons	Volume change [mcm] Wet(1)	Beach(2)	Dune(3)	Poly-gons	Volume change [mcm] Wet(1)	Beach(2)	Dune(3)
1	0,9	0,7	2,0	12	17,8	-	-
2*	-0,5	-	-	13	6,9	-	-
3	-0,9	-	-	14	-17,7	-	-
4	1,1	-	-	15	-1,6	-	-
5	4,1	0,6	0,3	16	5,9	-	-
6	-4,9	-	-	17	-5,6	-1,5	-0,6
7	-2,5	-	-	18	12,4	-	-
8	3,8	-	-	19	3,5	-	-
9	-5,4	1,7	0	20	10,3	-	-
10	7,6	-	-	21	-3,3	-0,4	-
11	-25,1	-	-	22	0,2	0,2	0,1
				Total	6,7	1,3	1,8

Name	Polygons	Volume change [mcm] Wet(1)	Beach(2)	Dune(3)	Total
Coast	1,2,3,4,5	4,6	1,3	2,3	8,3
ETD	6-22	2,1	0	-0,4	1,6
		6,7	1,3	1,9	9,9
Bornrif	8,9,19-22	9,1	1,5	0,1	10,8
Boschplaat	15,16,17	-1,4	-1,5	-0,6	-3,5
Westgat	13,14	-10,8	-	-	-10,8
Kofmans-bult	12	17,8	-	-	17,8
Borndiep	18	12,4	-	-	12,4
Bornrif (front)	11,10,7	-20,1	-	-	-20,1
		7	0	-0,5	6,5

(1). Wet = volume change for bed level <+1 NAP.
(2). Beach = volume change for bed level between +1 and + 3m NAP.
(3). Dune = volume change for bed level > +3m NAP.
* erosion in polygon 2 (2005-2007) is unrealistic. Therefore a zero change is assumed over this time frame.

Figure 4.10 Observed sedimentation-erosion patterns and volume changes over the time period 2005-2016. Tables show the values for the individual polygons (left) and aggregated features (right).

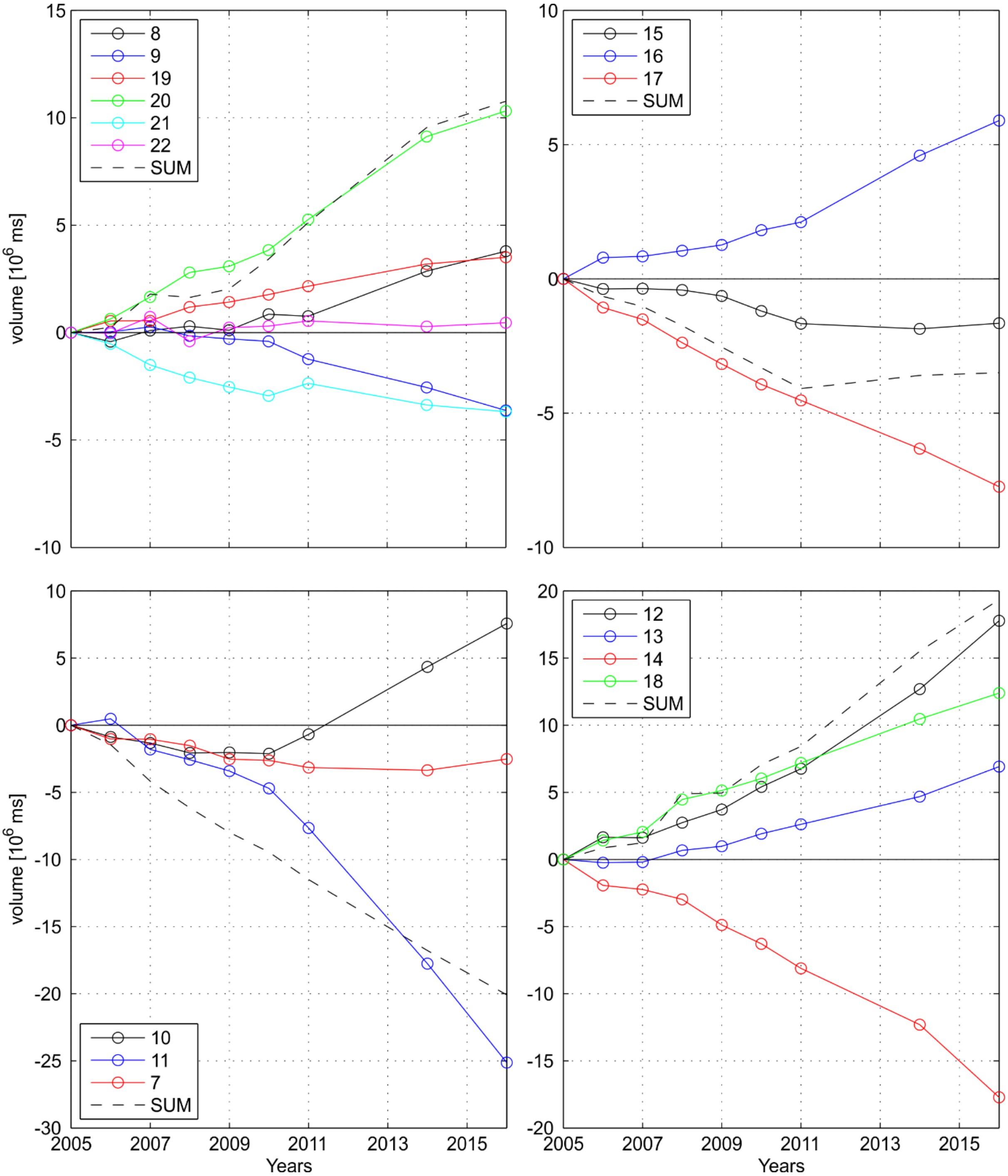


Figure 4.11 Timeseries of volume change over the timeframe 2005-2016, based on the polygons shown in Figure 4.10.

4.3 Sediment transports.

Direct measurements of sediment transports are not yet present for Ameland inlet. In the future, an analysis of available bed-form data may provide valuable clues, but at this stage we have limited to a summary of the results of a recent model study by Elias (2017); summarized in the form of Figure 4.12. In the study of Elias, the numerical model (Delft3D 4.03.02) was used to resolve flow, waves and sediment transport on a high-resolution (30-40 m) grid covering Ameland inlet, the ebb-tidal delta and its basin (the basics of this model are described in De Fockert, 2008, and Teske, 2013). The open-sea boundaries are forced by a morphological tide, and a schematized set of wind and wave conditions that represent the (long-term) year-averaged conditions. Estimates of the residual sediment transport potential (Figure 4.12a) are obtained from running a morphostatic model over the full set of schematized wind-wave conditions and summing the weighted average for each of the individual simulations (see Elias & Hansen, 2012 for details on the method).

The residual sediment transports (Figure 4.12a) show a net eastward sediment bypassing over the ebb-tidal delta and eastward transports along the adjacent coasts. A minor part of the ebb-tidal delta, landward of Westgat, is flood-dominant. Sediment supplied from littoral drift along the Terschelling coastline is transported into the basin over the shallow channel-shoal area (Boschgat) into the basin. The major part of the ebb-tidal delta (seaward of Westgat) and the main-channel Borndiep is ebb-dominant. Sediment transport from Borndiep is transported towards the western margin of the ebb-tidal delta through the two ebb-chutes, and through Akkepollegat onto the ebb-delta front. A relative large net sediment transport occurs along the seaward margin of the ebb-tidal delta (predominantly driven by waves). These transports explain the formation and migration of Bornrif Bankje. In general, the sediment transports on the ebb-tidal delta shoals are predominantly driven by waves. As a result of tides alone we only observe transports in the main channel. Waves enhance the sediment transport directly, as wave-breaking and setup gradients drive flow and sediment transport (most noticeable in the surfzone areas). Indirectly waves contribute by stirring up sediments that can be transported by the tidal flow.

An efficient method to visualize and increase understanding of the sediment transport pathways can be obtained from sediment tracer simulations (Elias, 2017). Figure 4.12b-e summarize the results for a series of numerical experiments in Ameland inlet in which tracer material was placed in various locations of the ebb-tidal delta. As a forcing condition, a 2.47m height wave from a west-northwesterly direction (293°) was used (which can be seen as representative for a medium storm condition). The results for the sediment tracer dispersal show comparable results compared to the residual sediment transport patterns.

Sediments are delivered to the inlet by the surfzone transports along Boschplaat. These sediments initially enter the basin along the margin of Boschplaat. With each tide sediments move in and out of the inlet, and they show a small net eastward movement (Figure 4.12b). Eventually sediments enter Borndiep (Figure 4.12c). Sediments in Borndiep show a net inward migration along the western margin of Borndiep and a net seaward migration in the centre and along the eastern side. Only a minor portion of the sediments re-enter Westgat; the majority of the tracer material is transported through the ebb-chute onto the Kofmansbult (ebb-shield). No clear sediment exchange between Borndiep and Bornrif occurs. Sediments that are located on the ebb-shield move in and out of Borndiep as a result of tides, but are eventually transported eastward along the margin of the ebb-tidal delta through wave-driven flow (Figure 4.12c and d). Eventually the wave-driven transport along this margin accumulates on the Bornrif Bankje and along the Ameland coastline (Figure 4.12e).

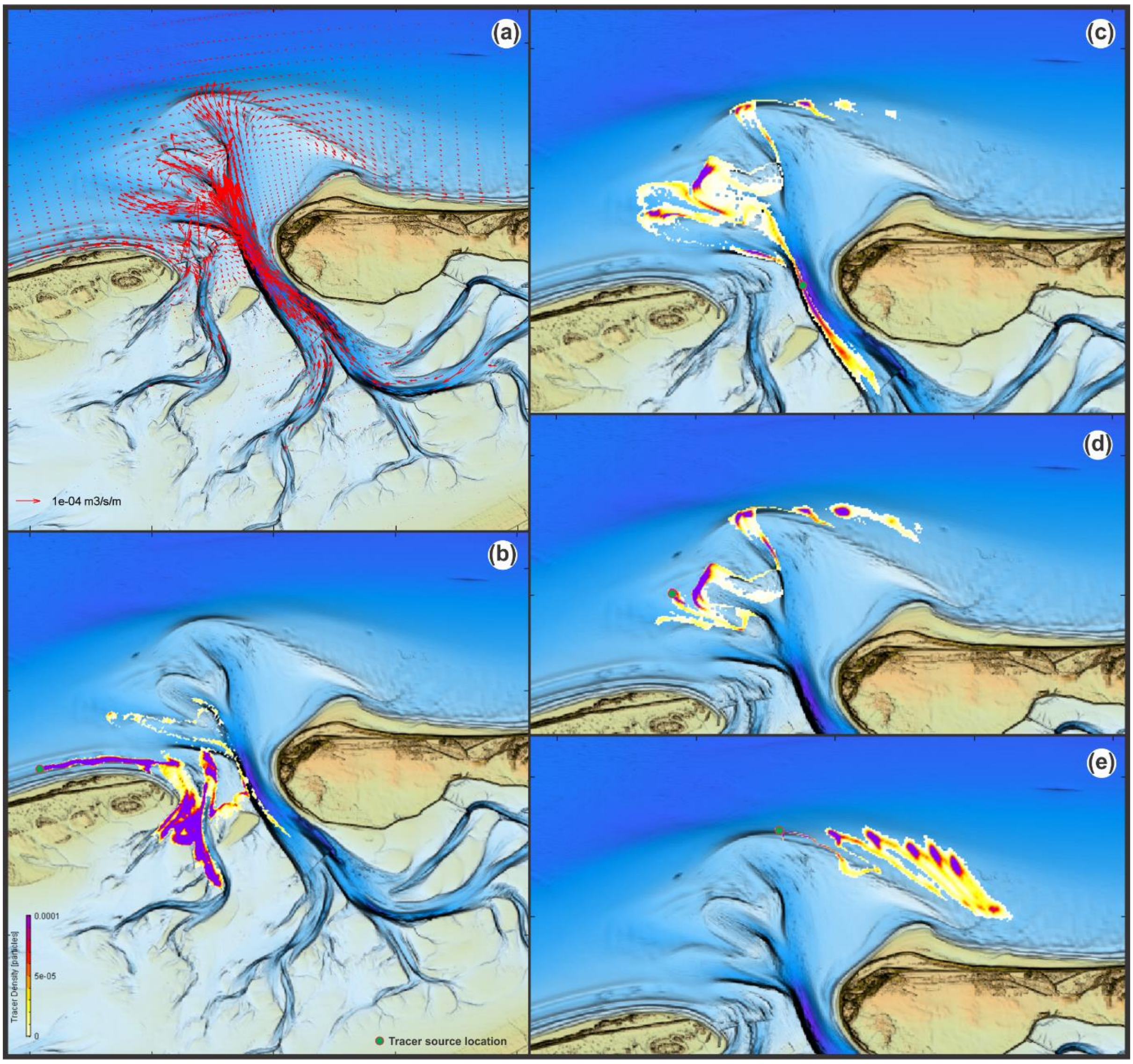


Figure 4.12 Modeled sediment transports on Ameland inlet (based on Elias 2017); (a) an estimate of the year-averaged residual sediment transport due to tides and waves. (b-d) end results for tracer simulations illustrating the sediment transport pathways on the ebb-tidal delta. Green dots indicate the initial release location of the tracer (see explanation in text).

5 Synthesis and discussion; understanding the observed morphodynamic changes and underlying processes

One of the major challenges in tidal inlet research are the scales of these systems, both in time and space. Tidal inlet systems, such as Ameland, typically consist of a basin, coupled to the ebb-tidal delta through the inlet gorge, and two adjacent barrier islands or coasts on either side. It is also known that these systems are sand sharing and strive to maintain a (dynamic) equilibrium state between its elements. A distortion of the equilibrium state, both natural as man-made, imposes changes between the elements until the equilibrium state is restored. In order to provide structure in the large, both in time and space, range of morphodynamic responses and developments that can occur, De Vriend (1991) introduced the concept of the scale cascade; not every process is important for the morphological scale of interest.

A clear definition of the time and space scale one aims to investigate is essential to distinguish between dominant forcing process and “noise”. As a first step of this synthesis, in Figure 5.1 we present a scale-cascade focussed on Ameland Inlet. This scale cascade allows us to structure, summarize and thereby better understand the observed morphological developments of the system. In this study, we focus on step 2 in the scale cascade, the evolution of the ebb-tidal delta on a timescale of years to decades.

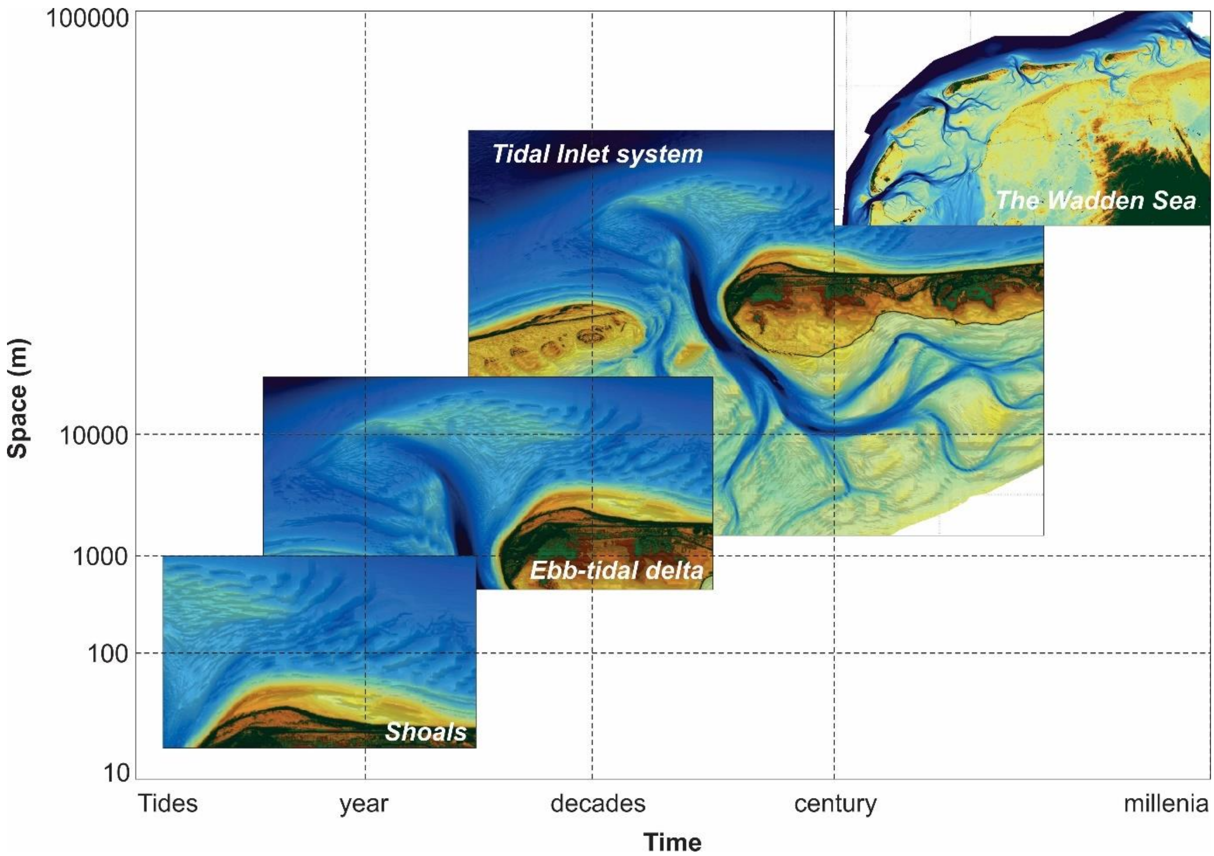


Figure 5.1   A scale cascade describing various morphological elements in Ameland tidal inlet.

On the largest level (scale 1), the sediment budget and morphological evolution of the entire Wadden Sea was previously summarized in Elias et al. (2012). An important conclusion from this study is that the Wadden Sea imports sediments, and most of these sediments are delivered from the adjacent coasts and especially the ebb-tidal deltas. Partly this sediment import may be related to sea-level rise as tidal flats grow in height, but for a major part this sediment import results from the man-made changes (basin closures of Zuiderzee and Lauwerszee). Also in Ameland inlet a small net volume gain (roughly 50 mcm) was observed since 1935, and both the ebb-tidal delta and coast lost sediment. This sediment loss was largest between 1935 and 1975, while in recent times volume losses are near absent (and plausibly dominated by measurement error). Based on the sediment budgets presented in this study, we must conclude that no clear net gain or loss of sediment from the ebb-tidal delta can be observed (net changes are small compared to the gross changes and well within the limits considered to be measurement error).

A second large-scale process that impacts the inlet, is the eastward migration of the tidal divides bounding Ameland basin. This migration may partly be related to the closure of the Middelzee, further augmented by the net eastward wind driven transports have resulted in a migration of Borndiep and subsequent volume losses from the western side of Ameland (Cleveringa et al. 2005). However, the morphological changes since 2005 indicate that the change in channel position, reallocation and realignment of Akkepollegat is related to the formation and migration of the Kofmansbult ebb-shield on a time scale of 5-10 years.

Inlet scale developments (scale 3 in the scale cascade) are described by the cyclic development of channel and shoal patterns with a return interval of 50 to 60 years (Israel & Dunsbergen, 1999). The stage within this cycle determines among others the erosion of the island tips, and the presence of a 1 or 2 channel system.

Cyclicity of the ebb-tidal delta is a relevant process for the decadal changes on the ebb-tidal delta. However, based on the observed present-day morphodynamic changes that do not correspond to the cyclic morphodynamic model, we conclude that this model has limited value for the present study. Cylcic behaviour may occur, but this behaviour is not fully (or accurately) described by the conceptual model.

The study presented in this report, focussed on the slightly smaller scale of the ebb-tidal delta (Figure 5.1, scale 2). Figure 5.2 summarizes the measurements used and observed morphodynamic changes.

Since 2005 the net sediment volume change of the ebb-tidal delta is small. Less than 1% of the gross changes. Nevertheless, large morphodynamic changes can be observed on the ebb-tidal delta. Most noticeable is the formation of a large shoal (ebb-shield) in the central-western part (on the Kofmansbult). This shoal started to clearly develop around 2006 and nearly 18 mcm of sediment accumulated since. Eastward movement and outbuilding of the shoal has already constricted flow in Akkelpollegat and pushed the channel outflow more northward. This process is expected to continue and eventually a new main outflow channel will form on the western margin of the ebb-delta.

A second distinct feature is the near-attachment of the Bornrif Bankje to the coastline of Ameland. This would complete a second cycle of shoal sediment bypassing. Sediment bypassing over the Ameland ebb-tidal delta can be described as follows; sediments enter the inlet system from the west along the Terschelling coastline, and are initially transported into the southern part of the basin (Boschgat). Here sediments migrate back and forth with the tide. A net eastward residual transport exists that eventually drives the sediment transports into Borndiep. The present-day ebb-tidal delta that is deeper near Westgat, may form a crucial aspect in these losses as this allows more waves to penetrate the inlet. In Borndiep, part of these sediments are transported into the basin, part of the sediments are transported onto the ebb-tidal delta, were they contribute to the outbuilding of the ebb-chute on the Kofmansbult, and partly sediments are transported onto the ebb-delta front. In this bypassing cycle sediments continuously recirculate in the inlet, but with each tide they show a small net contribution to the bypassing process. Only little sediment is expected to migrate from Borndiep back into Boschgat.

The observed changes lead to the conclusion that the ebb-delta can be subdivided into 2 parts. (1) sediments that are present between Terschelling and Westgat exchange with the Boschgat and are ebb-dominant. These sediments contribute to the Terschelling part of the basin and to Terschelling island. This area does not form a closed cell but a net loss occurs towards Borndiep. (2) Sediments in Borndiep exchange with the ebb-tidal delta seaward of Westgat and are eventually transported towards Ameland. Little, or no sediment feedback back onto Terschelling is expected to occur. This may explain the continues erosion of Boschplaat.

A net eastward transport is present along the margin of Bornrif. Sediments then contribute to the formation of Bornrif Bankje, a sediment bypassing shoal, and partly sediments are directly transported towards the coast of Ameland. Shoal bypassing is a common feature at Ameland. In 1986 a shoal attachment was observed in the form of Bornrif Strandhaak. At present the Bornrif Bankje is about to compete it final attachment to the coast.

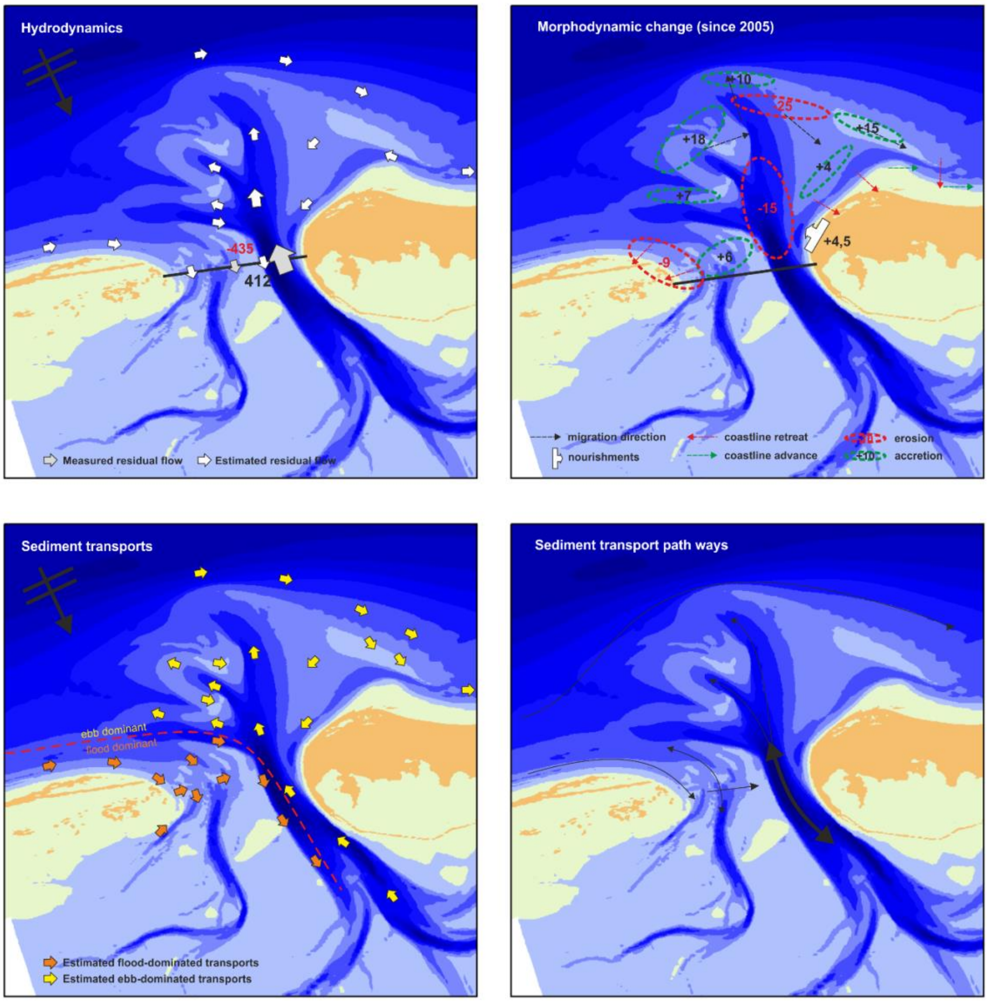


Figure 5.2 A summary (not yet complete) of the hydrodynamic and morphodynamic processes of the present day Ameland ebb-tidal delta.

6 Concluding remarks

1. A large date-set with high-frequent and detailed observations of both hydrodynamics and morphodynamics of Ameland inlet exists. This dataset allows us to quantify the morphodynamic changes that have occurred over the last decades.
2. Flow in the inlet is dominated by tides. The most recent discharge measurements indicate that the ebb-discharge (418 to 454 million m^3) exceeds the flood discharge (407 to 416 million m^3), resulting in a net outflow of 10 to 38 million m^3.
3. The ebb-tidal delta volume has decreased over the 1989-2016 timeframe (-0.7 mcm/year), but shows a positive trend over the 2005-2016 timeframe (+ 0,1 mcm/year). Over the 2005-2016 time-frame the net change of 1.6 mcm is negligible compared to the gross change of (~200 million m^3) compared to the gross volume changes.
4. A net northward sediment bypassing exists. Bypassing shoals periodically migrate over the ebb-tidal delta. The Bornrif Bankje can be considered a new bypassing shoal that has almost merged with the Ameland coastline. The distinct ebb-shield formed on the Kofmansbult is likely the start of the new formation of a bypassing shoal.
5. The observed changes lead to the conclusion that the ebb-delta can be subdivided into 2 parts. (1) sediments that are present between Terschelling and Westgat exchange primarily with the Boschgat and are ebb-dominant. These sediments contribute to the Terschelling part of the basin and to Terschelling island. This area does not form a closed cell but a net loss occurs towards Borndiep. (2) Sediments in Borndiep exchange with the ebb-tidal delta seaward of Westgat and are eventually transported towards Ameland.

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