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Long term morphological development of the tidal inlet systems in the Dutch Wadden Sea

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Summary

This literature study describes the long-term morphological development of the Dutch Wadden Sea including the main transport patterns and mechanisms. 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:

- The Dutch Wadden Sea has been accreting by importing sediment from the ebb-tidal deltas and the North Sea coasts of the barrier islands. The average accretion rate since 1926 has been higher than that of the local relative sea-level rise. The large sediment imports are predominantly caused by the damming of the Zuiderzee and Lauwerszee rather than due to response to this rise in sea-level. In the future, these human interferences will remain influencing the morphological development, especially in the western part of the Dutch Wadden Sea. If the rate of sea-level rise increases, the sediment import to the Dutch Wadden Sea will increase, especially in the eastern part.
- The tidal flats in all tidal basins, even in Eierlandse gat which has been eroding as a whole, increased in height to compensate for sea-level rise. The long-term development of the height of the tidal flat is apparently governed by the increase of high water level.
- The barrier islands, the ebb-tidal deltas, and the tidal basins including tidal channels and -flats together form a sediment-sharing system. The residual sediment transport between a tidal basin and its ebb-tidal delta through the tidal inlet is influenced by barotropic and baroclinic processes and mechanisms. In the Dutch Wadden Sea, the barotropic processes and mechanisms (residual flow, tidal asymmetry and dispersion) are dominant. The interaction between tidal channels and tidal flats is governed by both tides and waves. The height of the tidal flats is the result of the balance between sand supply by the tide and resuspension by waves.
- At present, long-term modelling for evaluating the effects of accelerated sea-level rise mainly relies on aggregated models. These models can be used to evaluate the maximum rates of sediment import to the various tidal basins in the Dutch Wadden Sea.

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 lange-termijn morfologische ontwikkeling van de zeegaten in de Nederlandse Waddenzee

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 2000.

In 2020 neemt het Ministerie van Infrastructuur en Milieu 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 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 sedimentvraag van de getijbekkens van de Waddenzee. Deze sedimentvraag 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 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 suppleties op buitendelta's te overwegen?

Lange-termijn morfologische veranderingen van de zeegaten in de Nederlandse Waddenzee

De grootste sedimentverliezen in het Nederlandse kustsysteem vinden plaats langs de kust van de Waddenzee (Elias et al. 2012). In de periode 1935-2005 is er orde half miljard m^3 zand vanuit de kustzone 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 zich in de toekomst zal ontwikkelen is onzeker omdat de verantwoordelijke factoren en de toekomstige ontwikkeling daarvan nog niet volledig begrepen worden. Willen we de Waddenzee en de aanliggende kusten op lange termijn goed kunnen beheren is een goede kennis over de ontwikkeling van dit transport essentieel. Een belangrijk doel van het Kustgenese 2.0 project is dan ook om de lange-termijn ontwikkelingen van de zeegaten beter te begrijpen. Met deze kennis kunnen de effecten van toekomstig kustbeheer beter worden voorspeld.

In dit rapport wordt een eerste stap in de kennisontwikkeling gezet middels een literatuurstudie naar de morfologische ontwikkelingen van de Nederlandse Waddenzee. De sedimentbalans-analyses op basis van bodemhoogtegegevens tot nu toe worden samengevat. Aan de hand daarvan wordt een conceptueel model gepresenteerd voor het sedimentdelende systeem van de Waddenzee. De relevante fysische processen en mechanismen voor de sedimentuitwisseling tussen de Waddenzee en de Noordzeekust worden geïnventariseerd. Verder wordt de state-of-the-art voor de modellering van lange-termijn grootschalige morfologische ontwikkelingen van de zeegaten beschreven. Deze inventarisaties geven inzicht hoe de sedimentuitwisseling tussen de Waddenzee en de Noordzeekust zich in de toekomst kan ontwikkelen. Ook worden de kennishiaten duidelijker, wat voor het verdere onderzoek van belang is.

In de Nederlandse Waddenzee is er sedimentatie opgetreden in de afgelopen eeuw. Vanaf de tijd rondom de aanleg van de Afsluitdijk zijn digitale gegevens van de bodemhoogtes in het Nederlandse Waddenzeegebied beschikbaar. De sedimentbalans van het Waddenzeesysteem op basis van die gegevens laten zien dat er sedimentatie in de Waddenzeebekkens is opgetreden. De totale hoeveelheid sedimentatie vanaf de aanleg van de Afsluitdijk is orde een half miljard m^3. Dit betekent dat de gemiddelde sedimentatiesnelheid in de Waddenzee duidelijk hoger (ongeveer 2 keer) dan de snelheid van zeespiegelstijging is geweest. Ongeveer dezelfde hoeveelheid sediment is geërodeerd buiten de zeegaten, i.e. op de buitendelta's en langs de Noordzeekust. De duidelijk grotere snelheid van sedimentatie dan van zeespiegelstijging is een gevolg van de menselijke ingrepen, voornamelijk de afsluitingen van de Zuiderzee (in 1932) en Lauwerszee (in 1969). De afsluitingen hebben een grote sedimentvraag in de Waddenzee veroorzaakt, die vooral in het westelijke deel van de Nederlandse Waddenzee (Marsdiep en Vlie) nog steeds niet is weggewerkt. De afsluiting van de Zuiderzee heeft dus nog steeds invloed op de morfologische ontwikkelingen in het Waddenzeegebied.

Aan de hand van de sedimentbalans analyse is er een conceptueel model voor het Waddenzeesysteem opgezet, waarin het Waddenzeebekken met de geulen en wadplaten een sediment-delend systeem vormt met de bijbehorende buitendelta en de daar aanliggende kust. De sedimentuitwisseling tussen het bekken en het buitengebied, i.e. het netto sedimenttransport door het zeegat, wordt door drie factoren beïnvloed: sedimentvraag in het bekken, sedimentbeschikbaarheid in het buitengebied en de sedimenttransportcapaciteit. Mede door zandsuppleties voor het kustonderhoud is er nog steeds ruime hoeveelheid sediment beschikbaar in het buitengebied. Daarom wordt als hypothese geformuleerd dat het netto sedimenttransport door een zeegat door de sedimentvraag in het bekken gestuurd en door de transportcapaciteit gelimiteerd wordt. Op basis hiervan wordt er een onderscheid tussen het westelijke deel (Marsdiep + Eierlandsegat + Vlie) en het oostelijke deel (Amelanderzeegat + Friesche Zeegat) van de Nederlandse Waddenzee gemaakt voor de beschouwing naar de ontwikkelingen in de toekomst. In het westelijke deel is er nog steeds een grote sedimentvraag aanwezig. Zeespiegelstijging zal in dat deel relatief weinig invloed hebben op de totale sedimentvraag in de bekkens. Dit betekent dat de sedimentimport naar dit deel van de Waddenzee niet veel zal toenemen als de zeespiegelstijging versnelt, omdat het gelimiteerd is door de transportcapaciteit. Het oostelijke deel is dichter bij het morfologische evenwicht, en de sedimentimport naar de bekkens is meer beperkt door gebrek aan sedimentvraag. Versnelde zeespiegelstijging kan daar de sedimentvraag en dus ook de sedimentimport wel vergroten.

Sedimentatie is opgetreden in de afgelopen periode van bijna een eeuw in alle bekkens in de Nederlandse Waddenzee behalve in het Eierlandse gat. Maar de intergetijdengebieden, dus de wadplaten, zijn verhoogd in alle bekkens, inclusief het Eierlandse gat. Blijkbaar wordt de ontwikkeling van de wadplaten gestuurd door de verandering van het hoogwater, zoals in de literatuur is gesuggereerd.

Getij, wind-gedreven stroming en golven zijn de belangrijkste aandrijvende processen voor sedimenttransport en morfologische veranderingen in het Waddenzeesysteem. In het westelijke deel van de Nederlandse Waddenzee speelt zoetwaterafvoer ook een rol. Door het getij wordt er grote hoeveelheid sediment door de zeegaten in en uit getransporteerd tijdens vloed en eb. Het netto sedimenttransport door een zeegat is een relatief klein verschil tussen het vloedtransport en het ebtransport. Dit kleine netto transport, ofwel import/export, wordt door subtiele fysische processen en mechanismen bepaald. Deze processen en mechanismen kunnen in twee groepen worden verdeeld, barotropisch (niet beïnvloed door gradient in dichtheid van water) en baroclinisch (gedreven door gradient van waterdichtheid). In de Nederlandse Waddenzee zijn de barotropische processen en mechanismen reststroming, getijasymmetrie en dispersie zijn dominant. Alleen in het Marsdiep speelt het baroclinische proces dichtheidsstroming een rol van betekenis voor sedimentimport. Binnen de Waddenzeebekkens wordt de interactie tussen de geulen en de platen bepaald door zowel getij als golven. De hoogte van de wadplaten is het resultaat van de balans tussen sedimentaanvoer door getij en erosie door golven.

Voor de modellering van morfologische ontwikkelingen van het Waddenzeesystemen zijn er twee typen modellen beschikbaar: de proces-gebaseerde modellen met Delft3D als voorbeeld en de geaggregeerde modellen met ASMITA als typisch voorbeeld. Lange-termijn modelleringen, om bijvoorbeeld de effecten van (versnelde) zeespiegelstijging te evalueren, berust op dit moment vooral op de geaggregeerde modellen. Voor ieder zeegatsysteem in de Nederlandse Waddenzee is er een ASMITA model beschikbaar, waarmee bijvoorbeeld de kritische zeespiegelstijgingssnelheid voor verdrinking van het Waddenzeebekken kan worden berekend.

Samenvattend zijn de belangrijkste conclusies van deze memo:

1. De Nederlandse Waddenzee is gesedimenteerd door sediment te importeren uit de buitendelta's en de Noordzeekusten. De gemiddelde sedimentatiesnelheid sinds 1926 was hoger dan die van de lokale relatieve zeespiegelstijging. De grote sedimentimport wordt voornamelijk veroorzaakt door de afsluitingen van de Zuiderzee en de Lauwerszee en in mindere mate door de zeespiegelstijging. In de komende eeuw zullen deze menselijke ingrepen de morfologische ontwikkeling blijven beïnvloeden, vooral in het westelijk deel van de Nederlandse Waddenzee. Als de zeespiegelstijging versnelt, neemt de sedimentimport naar de Nederlandse Waddenzee toe, vooral in het oostelijke deel.

2. De wadplaten in alle getijbekkens zijn in hoogte toegenomen om de zeespiegelstijging te compenseren. Dit is ook in het Eierlandse Gat gebeurd, hoewel er door het zeegat export van sediment is opgetreden door de erosie in de geulen. De lange-termijn ontwikkeling van de hoogten van de wadplaten worden kennelijk bepaald door de ontwikkeling van de hoogwaterstanden.
3. De Waddeneilanden, de buitendelta's en de getijbekkens inclusief geulen en wadplaten vormen samen een sediment-delend systeem. Het netto sedimenttransport tussen een getijbekken en zijn buitendelta door het zeegat wordt beïnvloed door barotropische en baroclinische processen en mechanismen. In de Nederlandse Waddenzee zijn de barotropische processen en mechanismen reststroming, getijasymmetrie en dispersie dominant. De plaat-geul interactie binnen de bekkens wordt bepaald door zowel getij als golven. De hoogte van de wadplaten is het resultaat van de balans tussen zandtoevoer door het getij en erosie door golven.
4. Op dit moment berust de lange-termijn morfodynamische modellering, voor bijvoorbeeld het evalueren van de effecten van een versnelde zeespiegelstijging, voornamelijk op geaggregeerde modellen. Deze modellen kunnen worden gebruikt om de maximale snelheid van sedimentimport naar de verschillende getijbekkens in de Nederlandse Waddenzee te evalueren.

Een vertaling van de inzichten naar de onderzoeksvragen van Kustgenese 2.0
Een rechtstreekse en volledige beantwoording van de onderzoeksvragen (Table 1.1) is met deze studie niet mogelijk. Toch kan er, met uitzondering van vraag SVOL-10, wel al veel inzicht in de vragen worden verkregen.

[SVOL-07] – Dit literatuuronderzoek heeft twee beschouwingen op de invloedfactoren voor het netto sedimenttransport door de zeegaten geleverd: de beschouwing van sedimentvraag en de beschouwing van gedetailleerdere processen en mechanismen.
De beschouwing van de sedimentvraag heeft geresulteerd in een conceptueel model voor het sediment-delende systeem rondom een zeegat. Volgens dit conceptueel model, dat globaal overeen komt met de formulering van het ASMITA model, stuurt de sedimentvraag veroorzaakt door menselijke ingrepen en zeespiegelstijging sedimentimport naar een Waddenzeebekken (ASMITA: sedimentuitwisseling tussen twee morfologische elementen wordt bepaald door het verschil in sedimentvraag ertussen). Op basis van dit model wordt er een onderscheid gemaakt tussen het westelijke en het oostelijke deel van de Nederlandse Waddenzee m.b.t de huidige morfologische toestand en de toekomstige ontwikkeling.
Een inventarisatie is gemaakt voor de relevante processen en mechanismen voor het netto sedimenttransport door een zeegat. Deze processen en mechanismen kunnen alleen door proces-gebaseerde modellen zoals Delft3D worden gemodelleerd. Hoewel de bijdragen van de individuele processen en mechanismen niet precies kunnen worden vastgesteld, is er geconcludeerd dat voor de Nederlandse Waddenzee de barotropische processen en mechanismen (reststroming, verschillende soorten getijasymmetrie, dispersie) belangrijker zijn dan de baroclinische processen en mechanismen (dichtheidsstroming / gravitatiecirculatie).

[SVOL-08] – De morfologische veranderingen in de bekkens hebben directe en indirecte invloeden op de sedimentvraag. Elk m^3 sedimentatie betekent een m^3 vermindering van de sedimentvraag. Verder beïnvloedt sedimentatie ook het getijprisma en daarmee het morfologische evenwicht waardoor de sedimentvraag indirect wordt beïnvloed. Sedimentvraag kan ook worden gedefinieerd voor de buitendelta van een zeegatsysteem. Het netto sedimenttransport door het zeegat wordt bepaald door het verschil in sedimentvraag tussen de buitendelta en het bekken. Daarom beïnvloedt de morfologische verandering van de buitendelta het netto sedimenttransport door het zeegat.
De morfologische veranderingen, zowel binnen als buiten het zeegat, hebben invloed op de relevante processen en mechanismen voor het netto sedimenttransport door het zeegat. De

reststroming door het zeegat en de verschillende soorten getijasymmetrie worden vooral beïnvloed door de morfologische veranderingen in het bekken. Een analyse hiervoor is mogelijk aan de hand van de beschikbare gegevens maar is nog niet uitgevoerd in deze studie. De morfologische veranderingen op de buitendelta hebben invloed op het mechanisme dispersie en asymmetrie in stromingspatroon en netto sedimenttransportpatroon. Een beschouwing daarvan vereist echter meer gedetailleerde analyse van de morfologie.
De sedimentbalans analyse en het daarop gebaseerd conceptuele model geven ook inzicht in de toekomstige ontwikkeling van de sedimentvraag. Daarvoor wordt er een onderscheid gemaakt tussen het westelijke en het oostelijke deel van de Nederlandse Waddenzee. Een uitspraak over de ontwikkelingen van de verschillende processen en mechanismen relevant voor de netto sedimentimport of –export is niet mogelijk op basis van deze literatuurstudie.

[SVOL-09] – Vanuit de sedimentvraag beschouwing geredeneerd heeft de omvang van de buitendelta invloed op de netto sedimentimport of –export door een zeegat. De import / export wordt dus wel door sedimentaanbod op de buitendelta beïnvloed. Maar er is nog steeds ruime hoeveelheid sediment beschikbaar in het buitengebied en deze invloed is tot nu toe beperkt. De voldoende sedimentaanbod hangt echter af van de kustsuppletie, vooral als de sedimentvraag in de toekomst toeneemt door versnellende zeespiegelstijging.

[SVOL-10] – In de uitgevoerde analyse van sedimentbalans wordt er geen onderscheid gemaakt tussen zand en slib.

[INGR-01] – De omvang van de buitendelta in verhouding tot de evenwichtswaarde ervan heeft invloed op de sedimentuitwisseling tussen de buitendelta en de omgeving (het bekken en de aanliggende kusten). Of het randvoorwaarden levert voor suppletieontwerp kan nu nog weinig worden gezegd.

INGR-02 - De omvang van de buitendelta in verhouding tot de evenwichtswaarde ervan heeft invloed op de sedimentuitwisseling tussen de buitendelta en de omgeving. Bovendien zal de sedimentvraag in het kustsysteem van het Waddengebied toenemen door de versnellende zeespiegelstijging in de toekomst. De buitendelta is centraal in het sediment-delende systeem van een zeegatsysteem. Daarom is het zinvol suppleties op de buitendelta’s te beschouwen.

Aanbevelingen voor aanvullend onderzoek
Deze literatuurstudie maakt ook duidelijk waar de kennisleemtes nog zijn. Aan de hand daarvan zijn de volgende aanbevelingen gedaan voor verder onderzoek, niet alleen binnen het kader van Kustgenese 2.0, maar ook in andere onderzoekprogramma’s zoals KPP Beheer & Onderhoud Kust, KPP Wadden.

Onderscheid tussen zand en slib in de sedimentbalans.
Een onderscheid tussen de twee sedimentfracties is vooral relevant voor het kustonderhoud, omdat alleen de zandfractie wordt geërodeerd van de buitendelta's en de kusten van de eilanden.

Geïntegreerd modellering door gecombineerd gebruik van de verschillende morfodynamische modellen.
De grootschalige en lange-termijn ontwikkelingen van de zeegatsystemen voor de verschillende scenario's kunnen worden gesimuleerd met de geaggregeerde (ASMITA) modellen. Deze modellen zijn echter aan het eind van de vorige eeuw opgezet. Recentelijk zijn verbeteringen van de modellen gesuggereerd (Townend et al., 2016a, 2016b). Daarom wordt aanbevolen om deze suggesties te overwegen en eventueel te implementeren. De modellen kunnen vervolgens opnieuw worden gekalibreerd met behulp van de meest actuele veldgegevens, voordat de toekomstige scenario's worden gesimuleerd. De proces-

gebaseerde (Delft3D) -modellen kunnen worden gebruikt om het netto sedimenttransport en kortere, meer gedetailleerde ontwikkelingen te onderzoeken.

Onderzoek naar de ontwikkeling van het getijframe (LW en HW).
Tot nu toe richten onderzoeken naar zeespiegelstijging zich meer op de ontwikkeling van MSL en HW. De ontwikkeling van LW is echter het meest relevant voor de verandering van het areaal van het intergetijdengebied. Bovendien kan door het koppelen van de veranderingen van het getijframe aan de morfologische veranderingen meer inzicht worden verkregen in de ontwikkeling van de factoren die het netto sedimenttransport beïnvloeden.

Onderzoek naar plaat-geul interactie met geschematiseerde proces-gebaseerde (geïdealiseerde) modellering.
Plaat-geul interactie is nog steeds een zwak punt in de proces-gebaseerde morfodynamische modellering. Verbetering hiervan is essentieel voor het voorspellen van de toekomstige ontwikkeling van de Waddenzee en voor het verbeteren van de morfodynamische modellen in het algemeen.

Onderzoek naar de ontwikkeling van de wantijen.
De onzekere ontwikkeling van de wantijen zullen de verdeling van de bekkenoppervlaktes bepalen. De verdeling van de bekkenoppervlaktes hebben grote invloed op de totale sedimentvraag van de Waddenzee. Daarom zal de ontwikkeling van de wantijen een aanzienlijke invloed hebben op de response van de Waddenzee op versnelde zeespiegelstijging.

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?	JA
	Hoe zetten deze veranderingen door in de toekomst, rekening houdend met verschillende scenario's voor ZSS?	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	JA
	en/of randvoorwaarden levert dat voor een suppletieontwerp?	Nee
INGR-02	Is het, op basis van beschikbare kennis van het morfologisch systeem, zinvol om suppleties op buitendeltas te overwegen?	JA

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 maintenance is done by means of sand nourishments, with a total annual volume of approximately 12 million m^3 since 2000.

In 2020, the Dutch Ministry of Infrastructure and Environment will make a new 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

The Coastal Genesis II project is carried out to improve our knowledge for supporting the long-term coastal maintenance strategy and policy. For the Wadden Sea area there are two main research questions:

1. How will the sediment exchange between the North Sea and the Wadden Sea through the tidal inlets, i.e. import/export, develop?
2. What are the possibilities and effects of large-scale nourishment at the ebb-tidal deltas?

Especially the first research question concerns large scale processes. The objective of this literature review is to provide an overview of our knowledge concerning the large scale processes, especially those concerning the sediment exchange through the inlets. We attempt to answer the following research questions:

- Which factors determine the sediment exchange through the inlets?
- How will the influencing factors develop in the future?
- What are the relevant processes and mechanisms?
- Can the long-term large-scale development of the Wadden Sea system be predicted by modeling?

1.3 Structure of the report

After a description of the study area, Chapter 2 reviews on studies on historical development, presents the sediment budget of the tidal inlets in the Wadden Sea. In Chapter 3 the sediment sharing system of the Dutch Wadden Sea is described, followed by processes and mechanisms for residual sediment transport. A conceptual model for the channel-shoal interaction in the tidal basins is also presented. Chapter 4 reviews morphodynamic modeling in general, and modeling of effects of relative sea-level rise in particular. In the final chapter the findings are summarized in order to answer the research questions.

The content of the chapters 2, 3 and 4 are included in the position paper by Wang et al. (2018) written for Wadden Academy.

2 The Dutch Wadden Sea as study area

2.1 General information

The Wadden Sea is a unique coastal wetland, consisting of an uninterrupted stretch of tidal flats and barrier islands that span a distance of nearly 500 km along the northern coasts of the Netherlands and Germany and the North Sea coast of Denmark (Fig. 2.1). Sea-level rise has been a primary driver in the formation of the present-day Wadden Sea. Over a period of more than 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, and, especially during the last century, human interventions. However, (accelerated) sea-level rise may threaten the Wadden Sea's future sustainability. Field observations suggest that some systems remain stable as sediment import and tidal-flat and salt marsh accretion can keep pace with certain rates of relative sea-level rise (Nichols, 1989; Van der Spek & Beets, 1992; Canon et al., 2000; Morris et al., 2002; Bartholdi et al. 2010; Madsen et al., 2007), while other systems degrade and finally drown (Kentish, 2001; Van Wine & Bakker, 2001).

Figure 2.1 The Wadden Sea (based on picture from www.waddensea-secretariat.org)

A general understanding of these systems adapting to sea-level rise

Valuable lessons on the effects of sea-level rise on the natural system can be learned from the past, as the formation and subsequent evolution of tidal basins under the influence of rising sea levels largely determined the Holocene evolution of the Dutch coast (Zagwijn, 1986; Van der Spek, 1994, 1995; Beets & van der Spek, 2000; De Mulder et al., 2003;). Several cycles of marine ingression and subsequent basin sedimentation, and sufficient sediment supply to retain or even prograde the coastline due to the presence of major sediment sources, finally filled in the entire western part of the Dutch coastal plain. Van der Spek (1994) summarizes: rising sea levels and/or land-surface subsidence create storage potential in the coastal plain, leading to ingression by the sea. Available accommodation space induces net landward sediment transport and basin infilling. Erosion of the adjacent shorelines contributed significantly to the sediment supply, leading to landward retreat of the entire barrier-inlet-basin system with conservation of its basic characteristics (see e.g. Van Straaten, 1975; Flemming & Davis, 1994). Sediment supply along the Wadden Sea was sufficient to retain the extensive systems of tidal flats and salt marshes over the past 7000 years, but insufficient to fill in the basin completely (see, e.g., Van der Molen & Van Dijck, 2000; Beets & van der Spek, 2000).

In this simple conceptual model, the long-term development of systems like the Wadden Sea depends highly on this balance between change in accommodation space and sediment supply. An abundant supply will lead to infilling of the basins and even progradation of the coast (Nichols, 1989). A deficient sediment supply will prevent infilling of the basins and will lead to landward shift of the coastal system with relative sea-level rise. Such a model is not only applicable to systems in their natural state, but is also applicable in the Anthropocene, when human activity starts to have a dominant influence on climate and environment.

From the Middle Ages onward dyke construction along the mainland, (partial) damming of estuaries and the building of closure dams (Van der Spek, 1995; Oost, 1995, Elias & van der Spek. 2006) fixed the basin dimensions, and eventually, after the closures of the Zuiderzee and Lauwerszee, the Wadden Sea basin as we know it today was formed. On the seaward side, the barrier islands are effectively kept in place by hard structures at some of the islands tips and the coastal policy of Dynamic Preservation. This policy prescribes that the North-Sea coastlines of the barrier islands may not retreat landward of a reference line that is based on their 1990 position (Van Koningsveld & Mulder, 2004). As the basin and barrier dimensions are basically fixed in position, the effects of sea-level rise now have to be resolved within the fixed dimensions of the Wadden Sea. The historically observed roll-over mechanisms of landward barrier and coastline retreat in case of sediment deficit (Van Straaten, 1975; Flemming & Davis, 1994; Van der Spek, 1994) cannot be sustained. Sediment import through the tidal inlets and sediment delivery onto the tidal flats needs to be at least equal to the relative sea-level rise, in order to maintain the intertidal morphology. In reality the sediment import needs to exceed these rates as sediments are still needed to compensate for the effects of human intervention and in particular to the closure of the Zuiderzee (Elias et al., 2012). As sediments can only be imported through the tidal inlets, the sediment transport capacity into the basin plays an important role. Even with ample supply of sediment, an insufficient sediment transport capacity will eventually lead to drowning of the system.

2.2 Observations – The present-day Wadden Sea (1927 – 2015).

Based on the research carried out within the framework of the Coastal Genesis Programme (project Kustgenese, see, e.g., Stive & Eysink, 1989), Stive et al. (1990) concluded that the Wadden Sea imports sediment from the North Sea coast. This conclusion is mainly based on a conceptual model for the long-term development of the Dutch coastal system under influence of sea-level rise: “A characteristic feature of the Wadden Sea region is its continuous sedimentation of the tidal flats in order to keep pace with relative sea-level rise, and its siltation along the Wadden shores. These processes are responsible for an important influx of sand, which is basically delivered by the adjacent coastal system. This is the cause of a structural retreat of the Wadden island shores”. Stive et al. (1990) thus identified the Wadden Sea as a major sediment sink of in the Dutch coastal system and they ascribe this as effects of the relative sea-level rise based on the consideration of the very long (geological) time scale.

2.2.1 General setting

Figure 2.1 provides a clear overview of the tidal inlets and basins that form the present-day Dutch Wadden Sea (from left to right Texel inlet [1], Eierlandse Gat Inlet [2], Vlie Inlet [3], Ameland Inlet [4], Frisian Inlet [5], Groninger Wad [6] and the Ems-Dollard Estuary [7]). With the exception of the Ems-Dollard Estuary, the inlets comprise relatively large ebb-tidal delta shoals and narrow and deep inlet channels that are connected to extensive systems of branching channels, tidal flats and salt marshes in the back-barrier basins. The back-barrier area of the eastern part (Ameland inlet, Frisian inlet, and Groninger Wad) is relatively narrow and shallow, with comparatively large tidal-flat areas and small channels; the ratio of intertidal area versus total surface area varies between 0.6 and 0.8 (Stive & Eysink, 1989). In the western part, the basins are wider and the ratios of intertidal area versus total surface area are 0.3 to 0.4. 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 accretion (Figure 2.1). 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 differences in tidal amplitude between the neighbouring inlets (Wang et al., 2013) and the prevailing eastward wind direction (FitzGerald, 1996). These tidal divides are useful to partition the Wadden Sea into smaller basins, but model studies (e.g., Duran-Matute et al. 2014) illustrate that net flow is present between the individual basins and may be larger than commonly assumed.

The tidal flats are mainly composed of sand (~90%; grainsize 0.15-0.20 mm) and fine-grained muddy sediments (~10%), with decreasing grain size diameters away from the inlet (Van Straaten, 1961; De Glopper, 1967; Flemming & Ziegler, 1995; Nyandwi, 1998; Bartholomä & Flemming, 2007) due to the settling lag effects of suspended sediments (Postma, 1961; Van Straaten & Kuenen, 1957; Groen, 1967). The ebb-tidal deltas primarily consist of sand (0.10-0.40 mm).

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 inlets qualify as mixed-energy wave-dominated, even under spring-tide conditions. The mean tidal range increases from 1.4 m in the southwest at Den Helder to 2.5 m in the east at the Eems-Dollard, and continues to increase eastwards. 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).

The wave-climate mainly consists of local wind-generated waves in the shallow North Sea basin with an average significant wave height of 1.37 m and corresponding peak wave period of c. 7 seconds.

Tide gauge measurements over the last 120 years reveal a fairly constant increase of the mean sea level of 0.20 m per century along the entire Dutch coast (Deltacommissie, 1960; Baart et al., 2012). Along the Wadden Sea, the rise in sea level is slightly smaller, about 0.14 m per century.

2.2.2 Morphodynamic changes

On a geological time-scale the Wadden Sea is still a young landscape, being formed over a period of around 7000 years. Under a temperate climate, a rising sea level, and, especially during the last century, human interventions, the individual inlets and basins with their distinct channels and shoals have been formed. Since the Middle Ages, anthropogenic influence started to increasingly influence the natural dynamics. Rising sea-levels, but also land subsidence due to peat compaction, excavation and drainage for agricultural use may have played an important role in the formation and expansion of the western part of the Wadden Sea and Texel Inlet. Dyke construction and reclamation of flooded areas began around the 10th century, intensified in the 16th century , and with the closure of the Zuiderzee (completed in 1932) and Lauwerszee (1969), the Wadden Sea as we know it today was formed (see Elias & van der Spek., 2006, 2012; Oost, 1995; Van der Spek, 1995).

Especially the closure of the Zuiderzee has had an important effect on the morphological changes in the western Wadden Sea and the sediment budget as a whole (Figure 2.2). A detailed overview of the morphological changes over the 1935-2005 time-frame was presented by Elias et al. (2012). The addition of more recent measurements to provide the sediment budget through 2012 (Figure 2.2 Figure 2.3; based on the volumes presented in Nederhoff et al., 2017), does not alter the main findings. In the section below we summarize the findings of the 2012 study, but volumes are updated to reflect the most recent values.

Elias et al. (2012) conclude that over the interval 1935-2005 abundant sediment supply, primarily by eroding ebb-tidal deltas, has so far delivered sufficient sediment to increase the sediment volume in the Dutch Wadden Sea. Over the period 1927-2012 a near-linear increase in gross volume of about 550 million m^3, (5.9 million m^3/year) was observed. The value increases to 650 million m^3 if sand mining and dredging and dumping are accounted for (Elias et al., 2012).

This sediment gain was more than sufficient to compensate for the recorded sea-level rise of c. 0.14 m in the Wadden Sea. Complete compensation of this sea-level rise of 0.14 m would only have taken a sediment volume of c. 280 million m^3. Elias et al. (2012) also show that the largest part (nearly 75%) of the volume change occurs in the western Wadden Sea where the influence of human interventions is dominant and the large infilling rates in closed-off channels, and along the basin shorelines (coasts of Friesland and Noord-Holland), rather than a gradual increase in tidal flat heights, render it likely that this sedimentation is primarily a response to the closure of Zuiderzee and not an adaptation to sea-level rise.

The intertidal flats, however, have been accreting in all basins; the hypsometric curves show a clear increase in level (Figure 2.4). The closures of Zuiderzee and Lauwerszee have both caused sedimentation in the channels of the corresponding basins. However, the sedimentation in the basins of Texel and Vlie Inlet occurred almost entirely in the shallow parts, above -6 m, whereas the sedimentation in the basin of Frisian Inlet occurred over the whole subtidal part. This difference can be explained by the fact that the closure of Lauwerszee caused a substantial decrease of the tidal prism of Frisian Inlet, rendering the tidal channels oversized, whereas the closure of Zuiderzee only had very limited influence on the tidal prisms of Texel and Vlie Inlet.

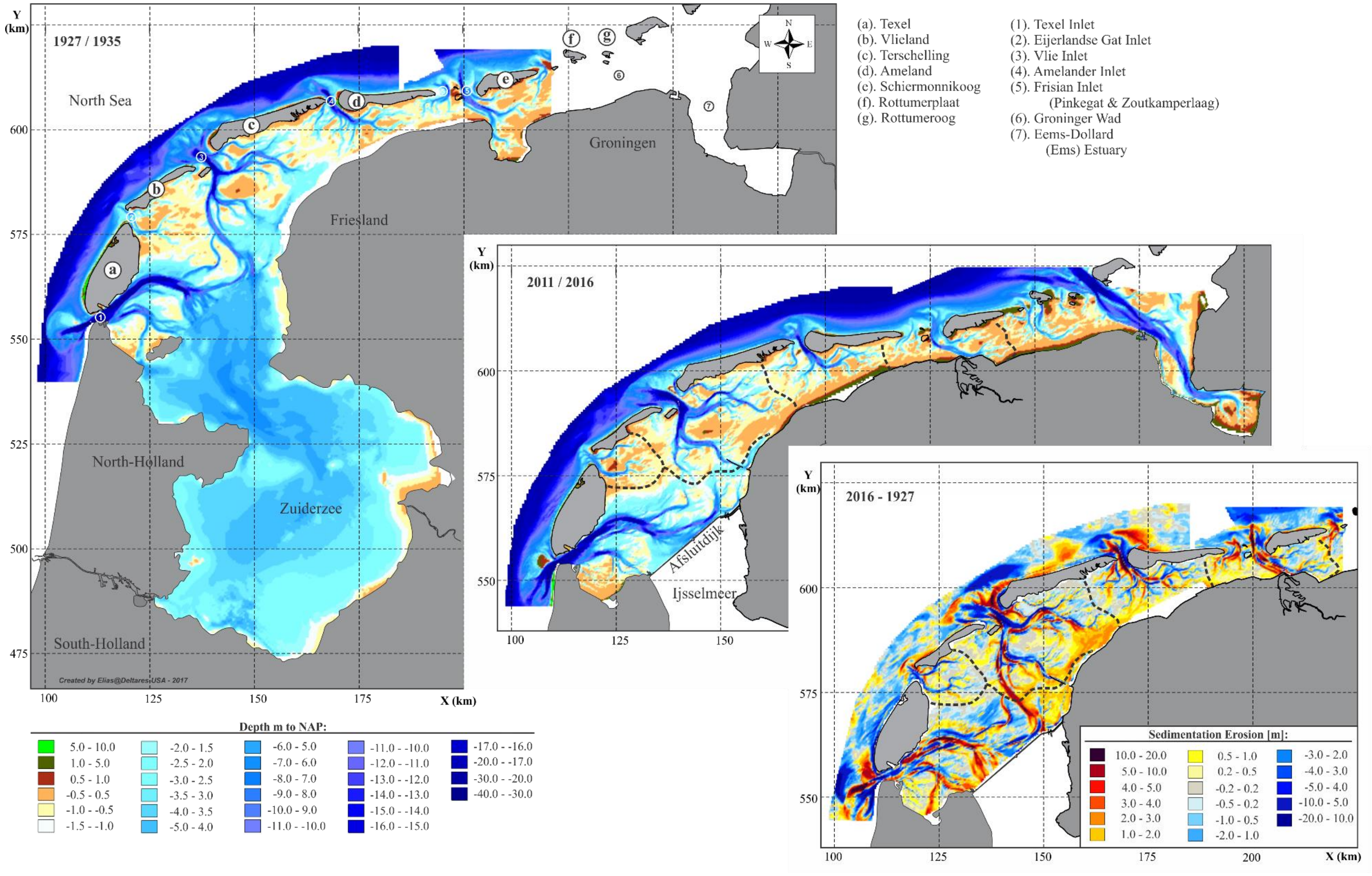


Figure 2.2 Changes in channels and shoals in the Dutch Wadden Sea over the 1927 and 2016 time-frame. Upper panel: bathymetry representative for the 1927-1935 time frame (prior to closure of the Zuiderzee), Middle panel: recent bathymetry based on 2011-2016 Vaklodingen. Lower panel: Sedimentation-erosion patterns over the 1927-2016 timeframe.

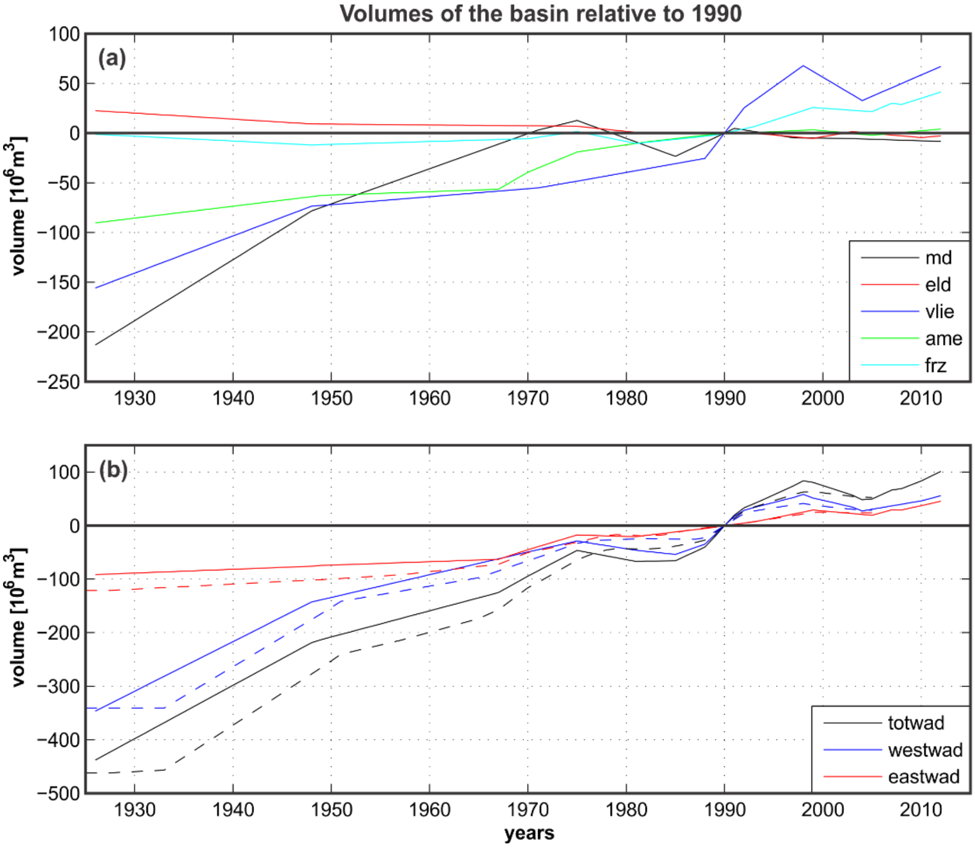


Figure 2.3 Computed volume changes of the individual tidal inlets (a) and Wadden Sea as a whole (b). The dashed lines indicate the volumes found in Elias et al. (2012).

The observed stability of the bed in the basins of Vlie Inlet, Frisian Inlet and at the Groninger Wad and Ems-Dollard estuary illustrates that sediment delivery was sufficient to compensate for increased accommodation space due to subsidence of the sea bed. In these basins, gas extraction should have created an estimated 38 million m^3 extra increase in water volume in the tidal basins and along the North Sea coast of Ameland. However no morphological changes of the sea bed have been observed. We assume that this increase in accommodation space has almost instantaneously been filled in with imported sand.

Elias et al. (2012) showed that sedimentation has been taking place in all the Dutch Wadden Sea basins except Eierlandse Gat, see Figure 2.5. The average accretion rates per basin over the period 1935-2005 are all much higher than the rate of relative sea-level rise of about 1.4 mm/year. These import figures are significantly influenced by human interventions (Elias et al., 2012). The three basins with the highest sedimentation rates, viz. Texel and Vlie Inlet (both 4.69 mm/yr) and Frisian Inlet (6.66 mm/yr) have been influenced by large-scale interventions in the past. Texel Inlet and Vlie Inlet were impacted by the closure of the Zuiderzee in 1932. The Frisian Inlet is strongly influenced by the closure of the Lauwerszee in 1969. The Ameland basin has not been subjected to interventions and shows the lowest accretion rate (2.52 mm/yr).

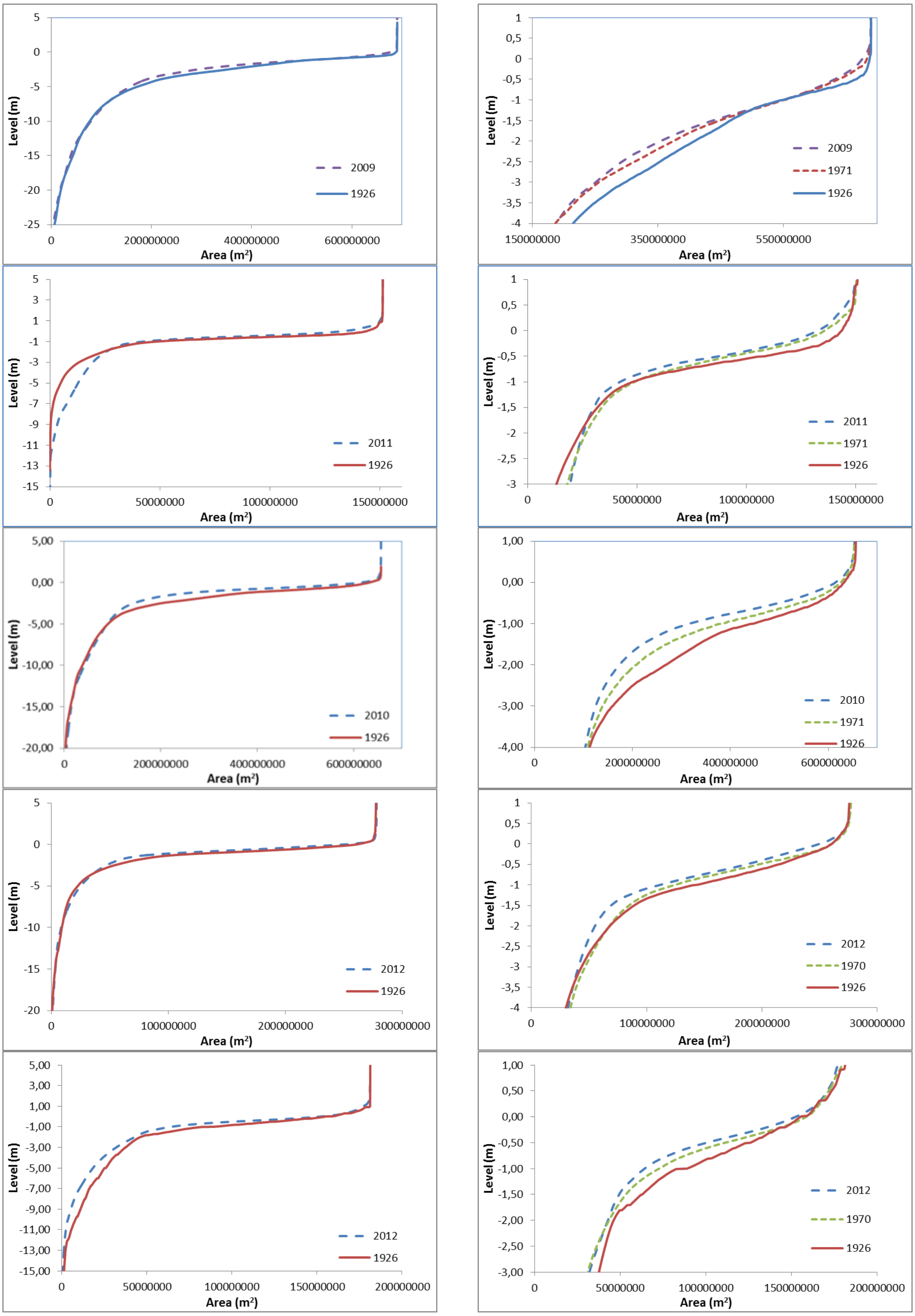
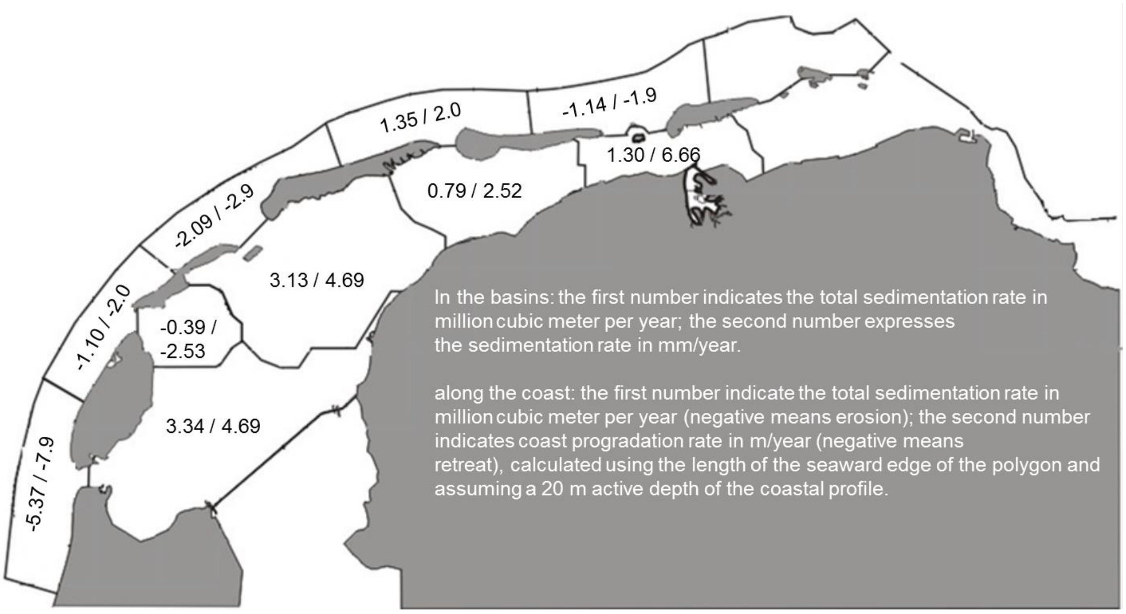


Figure 2.4 hypsometric curves of the basins, rows from top to bottom: Texel Inlet, Eierlandsegat, Vlie, Ameland Inlet, Frisian Inlet. Left column: overview for the earliest and latest year; right column: zoom in around intertidal part for three years.

Along the North Sea coast of the islands, outside the tidal inlets, erosion is observed in the same period. The total amount of erosion along the North Sea coast is about the same as the total amount of sedimentation in the Wadden Sea basins (Figure 2.4). Note that the basins of Texel and Vlie Inlet are not separated and that their development is connected. The bulk of the volume change can be directly related to the abandonment and subsequent erosion of (parts of) the ebb-tidal deltas following the closures of Zuiderzee and Lauwerszee. Their rapid adjustments and the large accretion numbers in the affected tidal basins prove that the human interferences are the dominant driver for the observed changes. Elias et al. (2012) thus confirm the conclusion of Stive et al. (1990) that the Wadden Sea is an important sediment sink in the Dutch coastal system but they emphasise the effects of human interferences in addition to the effects of relative sea-level rise.



In the basins: the first number indicates the total sedimentation rate in million cubic meter per year; the second number expresses the sedimentation rate in mm/year.

along the coast: the first number indicate the total sedimentation rate in million cubic meter per year (negative means erosion); the second number indicates coast progradation rate in m/year (negative means retreat), calculated using the length of the seaward edge of the polygon and assuming a 20 m active depth of the coastal profile.

Figure 2.5 Sedimentation-erosion rates over the period 1935-2005, based on the results of Elias et al. (2012). Note that the basins of Texel and Vlie Inlet are in reality connected and that their development should be considered as such.

3 Sediment sharing system

3.1 Conceptual model

3.1.1 Introduction

One of the major topics in tidal inlet research are the scale relations of these systems, both in time and space. On various levels of aggregation, the Wadden Sea as a whole, the separate tidal inlets and basins and even the individual channels and shoals systems continuously exchange sand between their elements. Each (sub) system continuously strives to maintain a dynamic equilibrium between its morphology and the forcing conditions[1]. A distortion of the equilibrium state, either natural or man-made (and sometimes both), induces exchange of sediment between the elements until the equilibrium state is restored. Individual channels and shoals may find equilibrium on short time scales (days to decades), individual inlets may find equilibrium on timescales of decades to centuries, while the complete Wadden Sea may seek but never find equilibrium as it takes centuries to millennia to complete. The shift from natural processes, to human-influenced changes makes predictions on future development of the Wadden Sea as a whole difficult, since our datasets are too short to fully determine the processes and mechanisms underlying the changes on these larger scales, and hence predict a new future equilibrium.

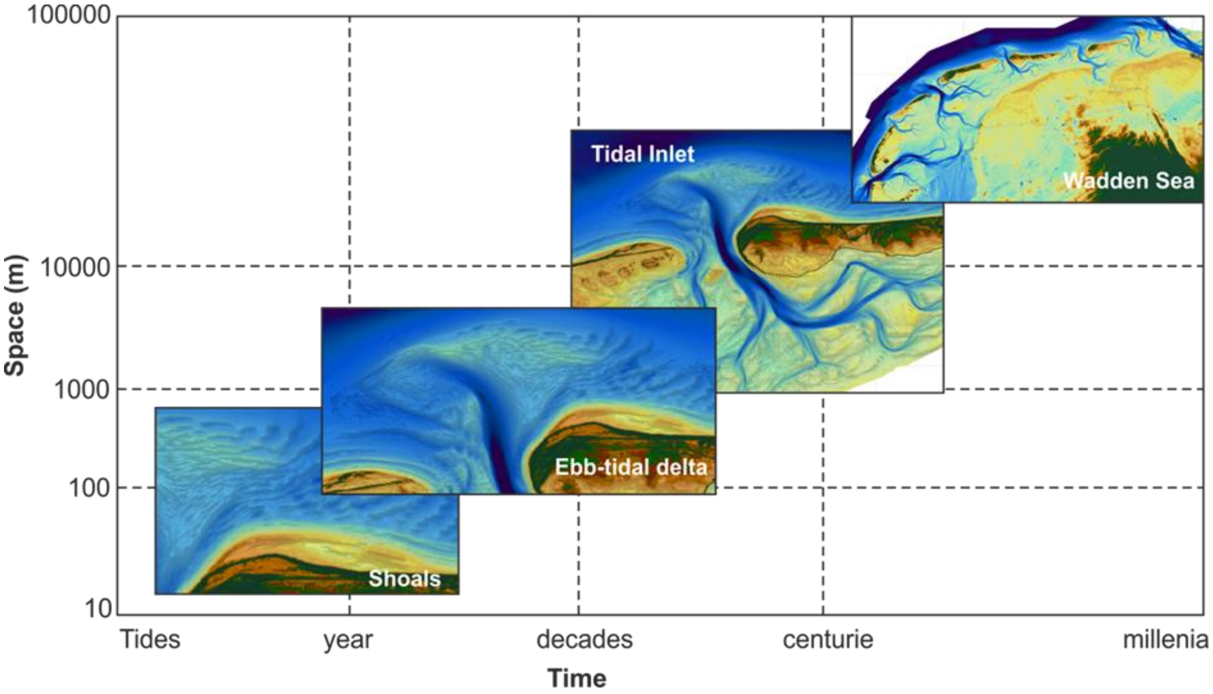


Figure 3.1 . A scale cascade illustrating the relations between the various morphological elements of the Wadden Sea (as an example the Ameland tidal inlet is used for the smaller scales). Based on Elias (2017).

In order to provide structure in the large range of morphodynamic responses and developments, both in time and space, that can occur, De Vriend (1991) introduced the

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[1] It is important to realize that despite morphologic equilibrium, which means that net changes in sediment volume are small, there is a continuous exchange of sand fractions, which is illustrated by the increase in sediment sorting with time as discussed by Krögel (1995) and Bartholomä & Flemming (2007).

concept of the scale cascade (Figure 3.1). An important finding is that not every process is important for each morphological scale of interest, which allows us to focus on the relevant processes only once we can distinguish between dominant forcing process and "noise". The scale cascade also allows us to structure, summarize and thereby better understand the observed morphological development of the system. We hypothesize that if we better understand the evolution of the individual tidal inlet systems and the relevant processes, in combination with various forms of modelling, we can make an improved prediction of the future state of the Wadden Sea as a whole.

3.1.2 Sediment-sharing system Wadden Sea

The sediment-sharing system of the Wadden Sea consists of the barrier islands, the inlet and its associated ebb-tidal delta and the tidal basin that includes tidal flats and channels (Fig. 6). Its main characteristic is the net sediment import from the North Sea coastal zone. Since no rivers are debouching into the Wadden basins (with the exception of the Ems estuary), alluvial sediment input can be ruled out and all sediment has to be imported from the North Sea. As was already indicated in the Introduction, the evolution of a coastal system under the condition of a rising sea level depends on the balance between the creation of accommodation space for sediment, that can be considered as sediment 'demand', and the rate of sediment supply to fill that space (based on Nichols, 1989). In a 'surplus' situation the accommodation space is filled in and the coastal system will finally accrete seaward, whereas in a 'deficit' state coastal erosion is not sufficient to fill the space and the coastline will recede landward. When we apply this principle to the Wadden Sea, the accommodation space in the basins is the driving 'demand' and the sediment import by the tidal inlets is the supply. Note that a 'surplus state' will in the end lead to (almost) complete infilling of the tidal basin and disappearance of the intertidal morphology. Hence, a small deficit in the sediment budget of a tidal basin is a prerequisite for the continued existence of intertidal flats.

- *Sediment 'demand'*

The accommodation space in a back-barrier basin gradually increases due to (1) a rise in mean sea level and (2) regional subsidence of the sea bed due to isostatic compensation, tectonics and compaction of sedimentary layers in the subsurface (see the individual chapters on these subjects in this report). Both components are contributing to an increase in water depth and are lumped into *relative* sea-level rise. Additionally, local subsidence due to gas and salt extraction (currently occurring in the basins of the Ameland and Frisian Inlets and the Groninger Wad) increases accommodation space at a higher rate. Finally, abrupt changes in the accretionary status of a basin can be caused by the impact of interventions. For example, the closure of the Zuiderzee transformed the back-barrier basins of Texel and Vlie Inlet from lagoonal areas with relatively small intertidal areas and dominated by the transit of the tide into the Zuiderzee, into two tidal basins with a large sediment deficit (compare the situations 1927/1935 and 2011/2016 in Figure 2.2).

- *Sediment supply*

The ebb-tidal deltas of Texel and Vlie Inlet and the Zoutkamperlaag (Fig. 2.2) have been the major sources of sand for the Wadden Sea over the last 85 years (Elias et al., 2012). If this will be the case in the future is unclear since the morphodynamic changes in these areas are reaching a near-equilibrium state (see Elias & van der Spek, 2017, for an analysis of Texel Inlet). The erosion of the North Sea shorelines of the barrier islands, especially the tips of the islands if not protected, and the Noord-Holland coast is additional sediment sources, the sand is predominantly transported into the tidal inlets by littoral drift. Since coastal erosion is compensated with sand nourishments, the latter are becoming a sediment source as well. Currently, sand is nourished on the beach and shoreface and in the future possibly on ebb-tidal deltas. Finally, the sea bed further offshore is potentially a source of sediment, although this is a largely unknown component.

The supply of sand to the tidal basins not only depends on the volume of sand available along the North Sea shoreline, including the ebb-tidal deltas, but also on the transport capacity of the processes in the tidal inlet. In cases of a large accommodation space and a sufficient sand volume along the North Sea coast, as was the situation at Texel and Vlie Inlet after the closure of the Zuiderzee, we still see a more or less linear increase in sediment volume in the basins (Fig. 3 a, b). Apparently, there is a maximum transport capacity that limits the rate of sediment transport into the basins (Lodder, 2015).

The import of mud into the Wadden Sea contributes to the infilling of the accommodation space as well. Mud is suspended in the coastal water that enters the basins and is transported along the Holland coast to the Wadden Sea. The mud concentration of water entering the Wadden Sea is not depending on local sources. The deposition of mud depends on the energy conditions in the basin: it will settle only under quiet conditions.

- *Redistribution in basins*

Sand that is imported into the Wadden Sea will be transported further into the basin through the tidal channels and finally end up on the tidal flats. Tides, waves and wind are the three forcing processes behind the water and sand movement in the Wadden Sea. These processes are capable of transporting large quantities of sand back and forth, quantities that are an order of magnitude larger than the net displacement of sand. Although an inlet system in the Wadden Sea is often considered as a semi-enclosed system, it is important to realize that back-barrier basins of the adjacent inlets are not separated from each other in most cases. The tidal watersheds are considered as the borders between the basins but water and sediment exchanges over these tidal watersheds do take place. Moreover, the locations of the tidal divides are not fixed but can change in time, especially after major human interferences (Van der Spek, 1995; Vroom, 2011; Wang et al., 2013).

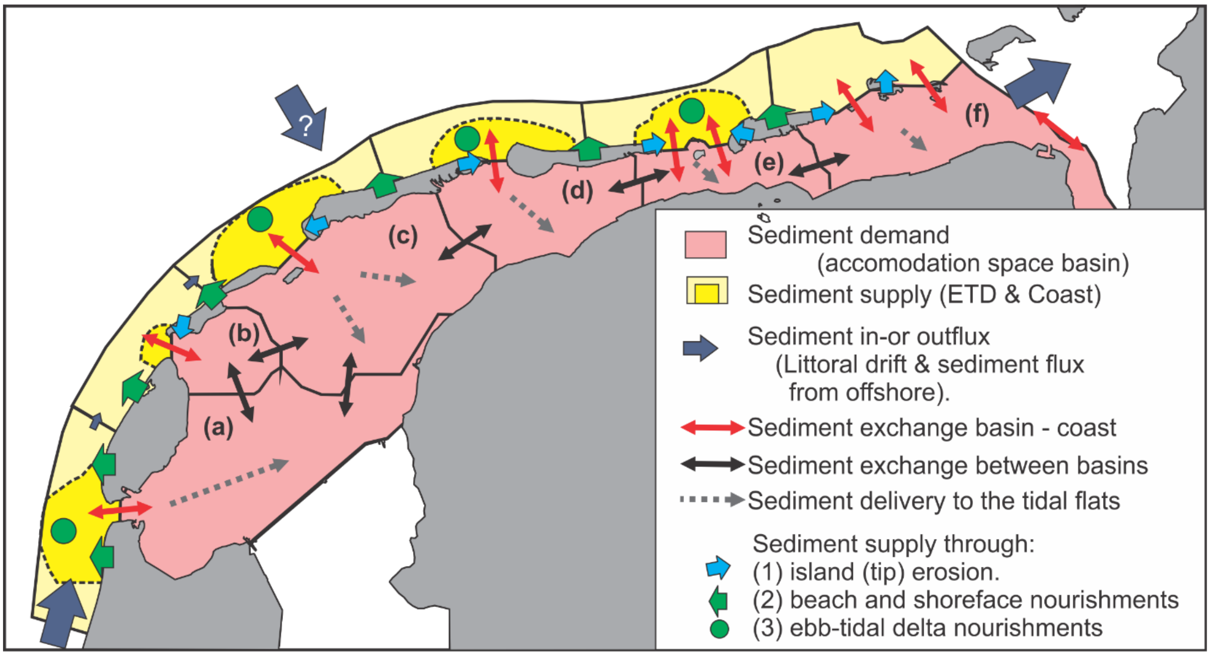

Figure 3.2 . Schematic overview of the elements, linkages, sources and sinks, that form the sediment-sharing system of the Wadden Sea.

The above sketched sediment-sharing system of the Dutch Wadden Sea is depicted in Figure 3.2 It shows the sediment source area, viz. the Noord-Holland coast, the barrier islands, the bounding tidal inlets with their ebb-tidal deltas, and the connected, sediment-demanding tidal basins of Texel Inlet (a), Eierlandse Gat Inlet (b), Vlie Inlet (c), Ameland Inlet (d), Frisian Inlet (e) and the Groninger Wad and Ems estuary (f). The exchange of sediment between the different elements, both inside the Wadden Sea and along the North Sea coast, is indicated with arrows.

3.2 Residual sediment transport through the inlet – the relevant processes and mechanisms

Net sediment import into a tidal basin is the difference between the sediment transport through the tidal inlet during flood and that during ebb. It is important to understand the physical processes and mechanisms causing this residual sediment transport.

Physical processes influencing sediment transport in tidal inlet systems like those in the Wadden Sea include flow driven by tide, wind and freshwater input, as well as short waves. Because of the limited freshwater input, the amount of water flowing into a basin during flood differs little from the amount of water flowing out the basin during ebb. This also applies for sediment transport, implying that the residual transport through a tidal inlet concerns a small difference between two relatively large gross transports. The relatively small residual sediment transport through, e.g., a tidal inlet is caused by some subtle mechanisms. These mechanisms, into which many studies have been carried out (Van Straaten & Kuenen, 1957; Postma, 1961; Groen, 1967; Dronkers, 1986; Friedrichs & Aubrery, 1988, Gatto et al., 2017), are briefly described in the following. Which mechanism dominates the resulting sediment transport in tidal inlets is not clear. It is noted that in literature the mechanisms are explained in different ways, some in a Lagrangian framework and others in an Eulerian framework. Especially in the early days various mechanisms, e.g., the effects of settling lag and scouring lag, are often explained in a Lagrangian framework (see, e.g., Van Straaten & Kuenen, 1957; Postma, 1961; Groen, 1967). Explained in an Eulerian framework, these mechanisms are classified differently, see Gatto et al. (2017) for an overview. In the description below we focus on the Eulerian framework.

A distinction can be made between the barotropic and baroclinic mechanisms. The barotropic mechanisms include:

- *Residual flow*. Residual flow causes a residual sediment transport in the same direction and the tidal flow fluctuations strengthen it (Van de Kreeke & Robaczewska, 1993; Chu et al., 2015). Residual flow through an tidal inlet can be due to the following causes:
    - Due to freshwater input. River discharge causes a seaward residual flow in an estuary. For the Dutch Wadden Sea the discharge of freshwater is limited except that from Lake IJssel which influences especially Texel Inlet.
    - Compensation flow due to Stoke’s drift. The tide in the Wadden Sea is in between a standing wave and a progressive wave. The Stoke’s drift causes a landward water flux which is compensated by a seaward-directed residual flow. The Stoke’s drift depends on the morphology of the back-barrier basin. The residual sediment transport through the inlet due to this mechanism will therefore be mainly influenced by the morphological development of the basin and the inlet.
    - Meteorological effects. Wind can have a substantial influence on the hydrodynamics in the Wadden Sea area and thereby also on the residual sediment transport, especially during and just after storm events. Wind-driven flow can significantly influence the tidal flow pattern which may result in import through

    one inlet and export through another inlet. Set-up or set-down of the water level in the Wadden Sea due to wind and air-pressure change can also influence the flow through the inlet after a storm/wind event. Furthermore, wind generated waves also influence the sediment transport processes. These effects are also dependent on the morphology of the back-barrier basins.

- *Tidal asymmetry*. Due to deformation during propagation in shallow seas, a tidal wave becomes asymmetric: the period of rising water levels becomes shorter whereas the period of falling water levels increases. This causes flood velocities to increase and ebb velocities to decrease. Asymmetry of the tidal flow velocities causes residual sediment transport and thus import or export of sediment through the tidal inlets, even though there would not be any residual water flux through the inlets.
    - Asymmetry in peak flow velocities during flood and ebb associated with asymmetry in flood- and ebb-durations. If the flood period is shorter than the ebb period, the peak flow velocity during flood will be higher than that during ebb. This results in an import of sediment to the Wadden Sea because of the strongly non-linear relationship between flow velocity and sediment transport.
    - Asymmetry in the durations of high-water- and low-water slacks. A longer HW-slack than LW-slack causes import of fine sediment because the sediments in suspension have more time to settle during HW-slack (see Dronkers, 1986).

Both types of tidal asymmetries are also influenced by the morphology of the back-barrier basin. This means that residual sediment transport through the inlet due to tidal asymmetries will depend on the morphological development in the basin as well.

- *Jet-flow asymmetry*. Asymmetry in the velocity of the flow jet that develops in the inlet gorge results in a net sediment import. Oertel (1988) describes the tidal flow leaving the constricted inlet as a jet flow. The jet erodes material from the inlet gorges and carries it away from the inlet. The material is deposited in the far field region of the jet. During the opposing tidal phase the flow towards the inlet is more uniformly distributed, which results in generally lower flow velocities and distinct zones of ebb- and flood-dominant flow and sediment transport near the inlet. The sediment deposited in the far-field zone of the jet will not be returned to the inlet by the weaker currents of the opposing flow and hence ‘escapes’ from the inlet. This results in net export to the ebb-tidal delta and net import into the basin. However, on the ebb-tidal delta the waves are continuously redistributing and recirculating the sediments and transporting sediments back to the inlet. In the basin such mechanism does not exist and with the predominant wind and local wave direction directed away from the inlet, this results in a net import of sediments to the basin.

- *Spatial asymmetry in net sediment transport and deposition*. Detailed analysis of the three-dimensional current patterns in Texel Inlet shows that the northern part of the inlet that includes the main ebb channel, is ebb dominant, whereas flood currents dominate in the southern part of the inlet (Elias, 2006; Elias & van der Spek, 2017). This causes a net flux of sand along the southern shore which is not counteracted by sediment fluxes in the ebb direction. Moreover, sediment that is carried into the tidal basin with flood currents is deposited during the following slack water. Since the flood waters are entering both channels and tidal flats, the sediment is distributed over a large area. During the following ebb the tidal flats are drained comparatively slowly and only part of the deposited sediment is removed and transported seawards again. This enhances the net gain of sediment in the basin.

- *Dispersion*. Tidal flow functions as a mixing agent for dissolved and suspended matters, causing a residual transport in the direction opposite to the concentration gradient. This is one of the mechanisms causing residual sediment transport from the ebb-tidal delta to the basin (and thus causing import) of Texel Inlet because stirring by waves causes higher sediment concentrations on the ebb-tidal delta (Elias, 2006).

The analysis of sand transport in tidal inlets with a process-based model (see, e.g., Elias, 2017) indicates that net transport into the basin occurs even in ebb-dominant channels. Stepwise landwards sand transport occurs during successive tides, which is simply explained by settling lag- and scour lag mechanisms.

The working of these mechanisms also depends on the sediment properties. This means that the importance of a mechanism is different for the different sediment fractions. In particular, a distinction should be made between mud and sand. Mud can only accumulate in areas of low energy level (due to flow and waves). Import of mud through an inlet will therefore depend on the amount of such accumulation areas within the back-barrier basin.

The baroclinic mechanisms are caused by the effects of density flows as a result of spatial gradients in salinity and water temperature. Density flow can cause residual circulations with, e.g., flow near the bed directed landwards and at the water surface directed seawards. Such a circulation results in a landward residual sediment transport because the sediment concentration is higher at the lower part of the water column than in the higher part. For an inlet in which the back-barrier basin receives substantial fresh water input, like the Texel Inlet, the effect of density flows can be significant (Elias, 2006).

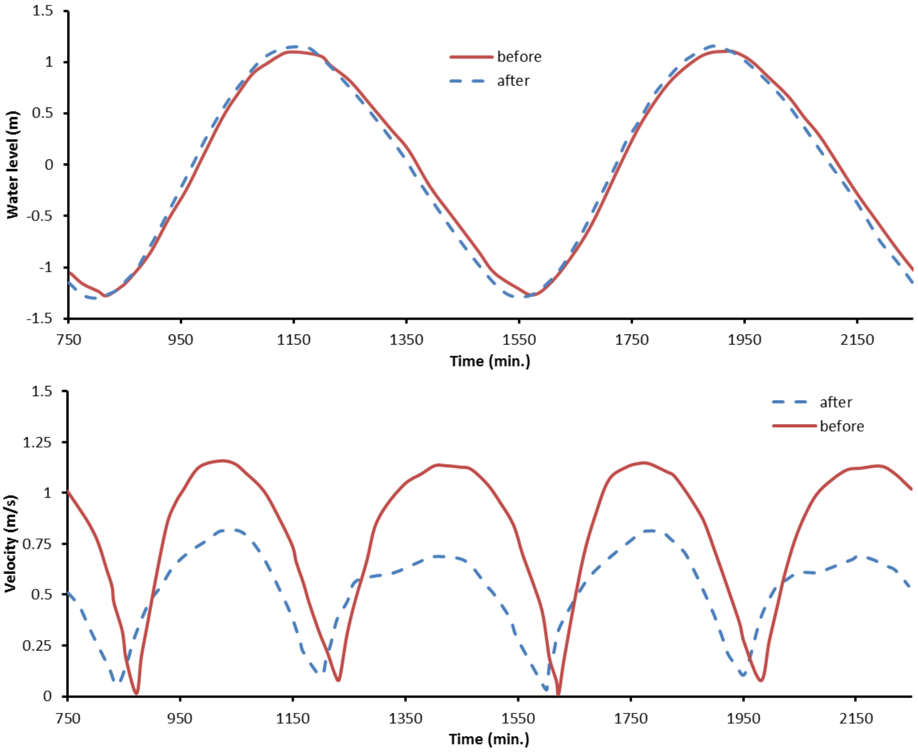

Figure 3.3 Influence of the closure of Lauwerszee on the water level (top) and flow velocity (bottom) at the inlet of Zoutkamperlaag (based on Wang et al., 1995).

The other Dutch and many German Wadden Sea inlets do not receive substantial freshwater input. Even for those inlets discussions on whether the barotropic or the baroclinic mechanisms are dominant are still going on (Wang et al., 2012). The most recent study based on field measurements suggests that the baroclinic mechanisms are less important than the barotropic ones (Becherer et al., 2016). Moreover, the relative importance of the two types mechanisms can also be evaluated by considering the effects of the closures. It is evident that the closures of, e.g., the Zuiderzee and the Lauwerszee have caused increased sediment import to the corresponding basins. In Elias (2006) it is shown that the discharge supplied through the sluices can introduce a significant increase in sediment import. This mechanism was most likely not present before closure of the Zuiderzee. However, it is not likely that this is the dominant mechanism, since the increased sediment transport after closure of the Zuiderzee is better explained by the effects on the barotropic mechanisms.

Figure 3.3 shows as an example how the processes and mechanisms relevant for residual sediment transport are influenced by human interference. Due to the closure of the Lauwerszee the flow velocity in the channel is substantially decreased in magnitude. This influences the mechanism dispersion causing sedimentation in the channels in the basin and thus import of sediment. Furthermore, the tidal flow through the inlet becomes clearly asymmetric in the sense that the peak velocity during flood becomes clearly larger than the peak velocity during ebb. Also this change causes import of sediment into the basin.

3.3 Channel-shoal interaction[2]

3.3.1 Sediment on tidal flat (shoals)

The (inter)tidal flats in the Dutch Wadden Sea consist mainly of fine-grained sand with average grain sizes of c. 0.100-0.200 mm (de Glopper, 1967), a range that is found in other intertidal areas as well (e.g., Eastern Scheldt Estuary, The Netherlands, Kohsiek et al. 1987; Skallingen, Denmark, Christiansen et al., 2006). About 70% of the intertidal surface area in the Dutch Wadden Sea consists of sand deposits. Mud flats are found on the sheltered lee sides of the barrier islands and in front of the land reclamation works along the mainland dikes. The grainsize distributions of the sediments are sorted according to the energy gradient in the basins: the general trend shows a decrease in both tidal and wave energy and, hence, in grain size from the inlet to the landward side of the basin (Figure 3.4). Local morphology determines second-order variations on top of this general trend, with fining trends away from the channels (de Glopper, 1967). Studies of Flemming and co-workers in the East-Frisian Wadden Sea showed that a distinct zoning in the average grainsizes on the tidal flats can be determined (Flemming & Ziegler, 1995; Nyandwi, 1998; Bartholomä & Flemming, 2007), see Figure 3.4. Besides, accumulation of mud particles as pellets by filtering organisms such as mussels results in mud deposits that are not related to the energy level of the environment.

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[2] *Note that in this section the words 'shoal' and 'tidal flat' are used as synonyms.*

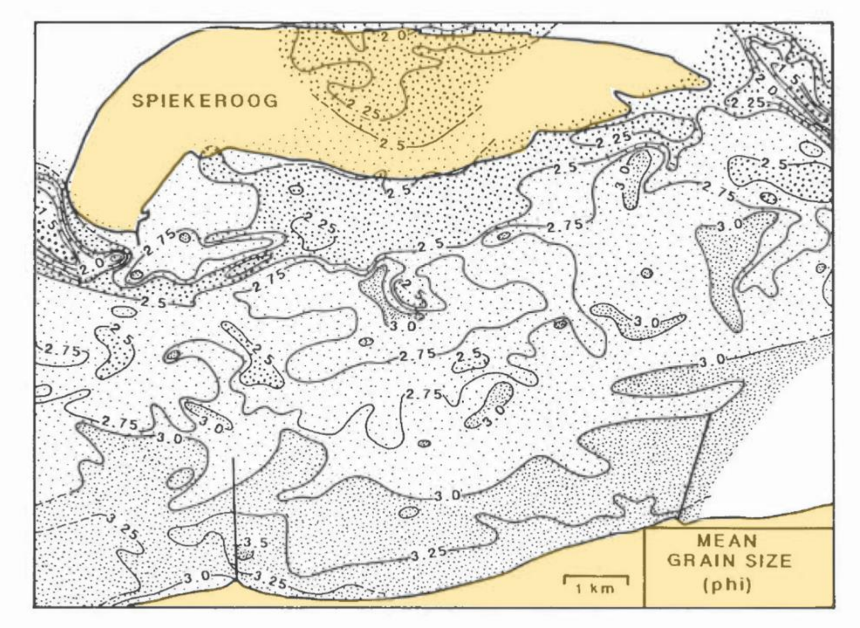

Figure 3.4 Spatial pattern of the mean sediment grain-size in the back-barrier area of Spiekeroog Island. Note the landward-fining trend. Sediment grain sizes are indicated in phi classes. The phi unit (ø) is a logarithmic transformation of millimetres into dimensionless numbers, according to the formula: ø = -^{2}log d, where d = grain diameter in millimetres. The grain size decreases with increasing phi number. (From Flemming & Ziegler, 1995.)

3.3.2 Sand transport

Sand is supplied by the tidal channels. The relevant grain sizes that are deposited on the tidal flats are transported in suspension (e.g., Eisma & Ridderinkhof, 1998, p. 373; Evans & Collins, 1975; Collins et al., 1981). Measurements (Postma, 1961; 1967) show an inward increase in fine-grained sand and silt concentrations in the channels. The suspended fine-grained sand is transported onto the tidal flats by flood tidal currents, especially during spring tides. The net sediment transport from channel to shoal during spring tide is 4 to 5 times higher than during neap tide. Moreover, calm weather with limited wave action results in accretion of the shoal, in which the edge of the shoal shows, in general, greater sedimentation and erosion rates than the central part (Kohsiek et al., 1988).

Strong winds will result in higher waves along the North Sea coast of the barrier islands and in the ebb-tidal deltas, which will increase the suspended sand concentrations and, consequently, the import of sand into the tidal basin during flood. When the sediment-laden water moves onto the flat, the current velocity is reduced by friction and the sand starts to settle, the coarsest grains first. Hence, tidal levees are formed along the edge of the shoal. The finer fractions will remain suspended and are transported away from the shoal edge. Small waves over the shoal will keep the finer sand fractions suspended. Depending on the intensity of the wave activity, the finer sand fractions will finally settle on the shoal or remain in suspension and being carried over the shoal and end up in a tidal channel (during the ebbing tide) where they will become part of the suspended load in the channels again. In the vicinity of the inlets, this general shoal-feeding mechanism can be modulated by North Sea waves that are penetrating through the inlet into the tidal basins where they will break on the shoal edge and increase the shoal-ward sand transport and cause upbuilding of beach-like features. In case of sufficient fetch, waves generated within the tidal basin can grow to such dimensions that they can cause migration of the intertidal flats. Large-scale bedforms on intertidal shoals are usually found only in parts of the basin where large water volumes are flowing over the shoals during flood tide. Besides, the range of grain sizes on the flats limits the bedform dimensions.

With increasing wind speeds, the locally-generated waves in the tidal basin will increase in height and/or period which results in wave breaking on the shoal edge that will cause erosion and flattening of the levees that were formed during quiet weather (Postma, 1961; p. 188). Moreover, the increased turbulence over the shoal during high water will prevent settling of the suspended sand or even cause erosion. The (re-) suspended sediment will be carried away by wave- and wind-driven currents and the ebbing tide and the level of the shoal is lowered or at best unchanged. Kohsiek et al. (1988) determined that on the Galgeplaat shoal in the Eastern Scheldt, the total sand transport in a flood-ebb cycle during storms increases by 3 to 8 times and that net sediment transport is mainly directed off the shoal. The most intense storm erosion occurs during neap tides, since during springtides the water depths are larger which reduces the wave attack on the shoal edge and part of the erosion will be compensated by the larger sediment supply (Kohsiek et al., 1987).

Hence, the height of the intertidal flats is the outcome of the supply of suspended sand by the flood tide, predominantly during spring tides, and deposition on the flats. Deposition on the flat during high water is depending on the intensity of the turbulence in the water column: during quiet weather sand will settle, whereas under more turbulent conditions sand will remain in suspension or even be eroded from the shoal. In general, the supply of suspended sand will be less variable than the rate of sedimentation or erosion, which means that the net effect of the balance between supply and deposition or erosion will predominantly be determined by the latter. The water depth over the flat during high water will influence the sedimentation and erosion as well. Greater inundation depths during high water will *de facto* result in the supply of a larger sand volume (under a constant sand concentration), which will result in higher sedimentation rates under quiet conditions. On the other hand, greater water depths over shoals will allow for larger waves and more turbulent conditions. Christiansen et al. (2006) give a detailed account of the high-frequent bed-level changes of a tidal flat in reaction to tides, waves and winds.

3.3.3 Mud and organisms

The overall development of intertidal shoals is influenced by the settling of mud over the shoal’s surface and the activity of benthic organisms. Under very quiet conditions, predominantly during summer, mud is deposited on the shoals that after some consolidation will protect the shoal surface against erosion. However, under energetic conditions these mud layers will break up again and be removed. The formation of algal/diatom mats on the shoal surface during summer conditions will armour the sediment surface and restrict or preclude sediment erosion. Burrowing benthic animals can have both positive and negative impacts on sediment stability. Complete bioturbation of heterolithic sediment sequences results in (almost) homogeneous sand-mud mixtures that show cohesive behaviour and are difficult to erode. On the other hand, intensive burrowing can destroy the layer structure of the top of the shoal which diminishes the sediment strength against erosion. Moreover, burrowing often results in deposition of excreted sand in little mounds at the surface that will increase the bed roughness and hence, the turbulence of the flow over the flats.

3.3.4 Conceptual model

The above described processes can be summarized in a conceptual model for sandy tidal-flat development over longer timescales. In this conceptual model the effects of mud deposition and biota will be ignored. Fine-grained sand is constantly supplied by the flood tide and transported in suspension from the channels onto the flats. The larger part of this sediment supply is deposited on the shoal edge and forms tidal levees. The deposition of the suspended sand on the more central part of the flat depends on the energy level of the water over the flat: an increasing energy level results in a decreasing percentage of the total sand supply that will settle. Hence, there is a constant flux of sand over the flats and the meteorological conditions determine the rate of deposition. This sand flux can be compared with a ‘conveyor belt’ that more or less constantly carries sand over the flat. The net accretion of the flat over longer intervals will be determined by the alternation of intervals with deposition and intervals of non-deposition or even erosion, wherein the average wave conditions over the flat determine whether sand is deposited or not. This is in principle a stochastic process that will result in fluctuating flat levels. However, over longer intervals the flat level will have a more or less constant value that depends on the average local wave conditions. This level can be considered an equilibrium level. A rise in local mean high water level, e.g. as a consequence of relative sea-level rise or the impact of an intervention in the tidal basin, will create new *accommodation space*. This space is determined by the offset between the actual sediment level and the (new) equilibrium level that is determined by the average wave conditions. The more or less constant supply of suspended sand by the channel will deliver the sand to raise the flat level and to fill the accommodation space. After the accommodation space has been filled, again sand will at best be stored only temporarily on the shoal and is likely to be eroded and removed under more energetic conditions.

This conceptual model can be expanded to the entire tidal basin. When we consider the tidal channels as an active distribution system of sand, all the intertidal flats will receive sand. The sand concentration in the channels is determined by resuspension of sand from the tidal flats. In addition to this, the tidal basins of the Wadden Sea are receiving their sand from the North Sea coast, so the sand concentrations in the channels are increased by the sand concentration of the flood water entering the basin. This means that both the sediment volume available for transport seawards of the inlet and the transport capacity of the flow through the inlet are crucial in supplying sand to the tidal basin. Under the present-day conditions very large volumes of sand are transported through the tidal channels, both in basin and inlet. Only a very small portion of these large gross sediment transports remains in the basin and results in net accretion. However, the surplus of sand that moves through the system in the form of the gross transports can be considered to be a strategic reserve that can buffer an increase in sediment demand in the system caused by the creation of new accommodation space. Only in case of an extreme increase in sediment demand, e.g. caused by a significant acceleration of sea-level rise, the gross sediment flux of sand into the basin might in the long run show to be inadequate to satisfy the increased demand and fill in the newly created accommodation space. This makes both the sand budget of the North Sea coast and the transport capacity into the basin crucial factors in the sustainability of the intertidal flats of the Wadden Sea.

The impact of gas extraction in the North Sea and Wadden Sea illustrates the above explained conceptual model. Gas extraction north of the eastern tip of Ameland since 1986 has resulted in subsidence of both the sea bed of North Sea and Wadden Sea and of the island of Ameland. Monitoring of the subsidence (Piening et al., 2017) shows that the centre of the extraction area has subsided about 0.4 m. However, current morphodynamic processes have largely compensated the subsidence, both on the island and in the Wadden Sea. On the island, the subsidence can be observed in areas that are excluded from direct sand supply such as vegetated dune valleys (Kuiters et al., 2017). In the Wadden Sea, the tidal-flat level shows no signs of subsidence. Monitoring of the sediment accretion in the affected areas by bi-monthly measuring the thickness of the sediment layer above a reference level (Krol, 2017) shows that the accommodation space created by subsidence is

filled with sediment almost instantly. This can be explained with deposition of sand from the gross sand fluxes. Large-scale sand nourishment on the shoreface of Ameland (20 million cubic meter since 1980; data Rijkswaterstaat) maintained the island's coastline position and probably also provided the sediment buffer that fed the net sand import into the tidal basins.
The above stated conceptual model for sandy tidal-flat development does not explain completely how subtidal flats grow to an intertidal level. At locations sheltered from wave activity, the sand supplied by the channels is likely to stay in place since resuspension by waves will be limited. However, the accretion of flats in locations exposed to wave action and strong tidal currents is not understood.

3.4 Present state of the sediment budget of the Wadden Sea

We can summarise the current status of the Dutch Wadden Sea as follows. The sediment budget of tidal basins is determined by the balance between the accommodation space in the basin, the 'demand' for sediment, and the supply of sediment from the North Sea coastal zone. The latter depends on both the available sediment volume in the source area and the total transport capacity of the flood tide that carries the sand into the basin. When considering the accretionary status of the Dutch Wadden Sea, we can distinguish the western Wadden Sea that consists of the basins of Texel and Vlie Inlet, from the eastern Wadden Sea (Ameland and Frisian Inlet and the Groninger Wad). The accommodation space in the tidal basins of the western Wadden Sea is large (see Section 2.2), despite the import of over 450 million cubic meters of sediment since 1935. Since there is still an ample volume of sand available in the ebb-tidal deltas and island coasts of these basins, the transport capacity must be a limiting factor. The almost linear annual increase in sediment volume in these combined basins of 6.5 million cubic meters (Figure 2.3) possibly indicates the maximum transport capacity for these inlets under the current hydrodynamic conditions. Hence, we hypothesise that the sediment import in the western Wadden Sea is limited by the sediment transport capacity (Fig. 3.5). Both the large present accommodation space in the basins and the limited sediment transport capacity in the inlet render these basins vulnerable for acceleration in the rate of sea-level rise.

Over 70% of the surface area of the eastern part of the Dutch Wadden Sea consists of intertidal flats. This implies that there is little accommodation space for sediment and that this area must be close to morphological equilibrium. Any increase in accommodation space, for instance caused by subsidence of the sea bed due to gas extraction, is almost instantly filled with sediment. This indicates that the sediment budget of this part of the Wadden Sea is accommodation-limited: the sediment import follows the fluctuations in the accommodation space (Figure 3.5).

The different states of the western and eastern parts of the Dutch Wadden Sea have implications for the future development of the sediment import to the Wadden Sea. In the western part, (accelerating) sea-level rise will only have relatively limited influence on the total sediment demand in the Wadden Sea basins. Major increase of the import due to accelerating sea-level rise is thus not expected for this part. In the eastern part, however, increase of sea-level rise rate will increase the sediment import.

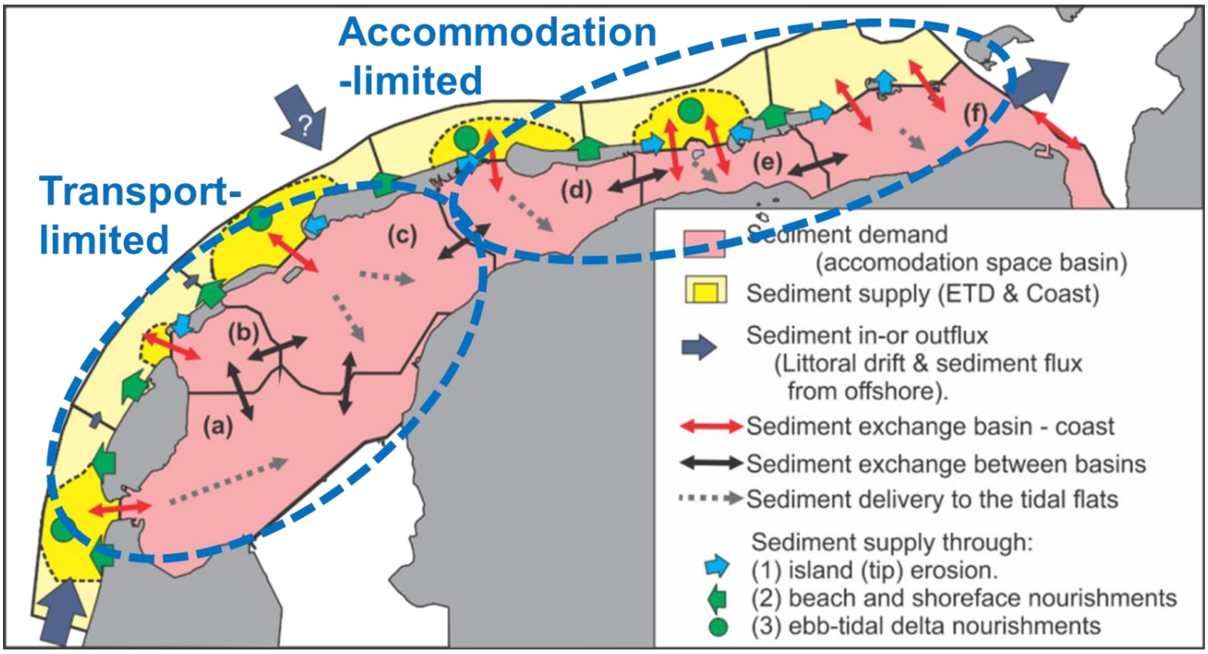

Figure 3.5 Summary of the sediment budget of the Dutch Wadden Sea. The western Wadden Sea is transport-limited: the annual import volume does not depend on the dimension of the accommodation space in the basins. The eastern Wadden Sea is accommodation-limited. There is little accommodation space and consequently there is little net sediment import.

4 Morphodynamic modelling

4.1 Morphodynamic modelling approaches

Modelling is essential for the projection of future scenarios of morphological development. It is also helpful for improving our system understanding and is thus an important research tool.

Models for simulating the morphological development of tidal inlet systems such as those in the Wadden Sea can be divided into the following types (e.g., Wang et al., 2012):

- *Process-based models*. These models aim at the best possible description of the relevant physical processes. An example is the Delft3D system (Lesser et al., 2004), in which the mathematical equations representing the physical processes of water movement and sediment transport are solved numerically to determine the morphological changes based on a mass-balance for sediment. Such models, also indicated as “complex” and “quasi–realistic” in the literature, can be used for detailed simulation of morphological changes. More importantly, they can be used to determine the underlying physical processes and mechanisms for, e.g., the observed morphological developments. It is important to realize that even process-based models are not reality, but aim to represent reality as closely as possible. This representation of reality is as good as the underlying equations and model deployment. Some of these equations are well-studied and well-known (e.g., hydrodynamics), some contain a considerable margin of error and unknowns (sediment transport).
- *Aggregated models*, or empirical and semi-empirical models, also known as behaviour-oriented models. These models make explicit use of empirical relationships to define a morphological equilibrium. An important assumption is that the morphological system after a disturbance (through natural evolution or human interference) always tends to develop to a state satisfying the empirical equilibrium relationships. The ASMITA model (Stive et al., 1998; Stive & Wang, 2003), which is used as an important tool for determining the effects of interferences in the Wadden Sea, is a typical example of this type of models. The model uses a schematisation in which a tidal-inlet system is divided into the main morphological elements ebb-tidal delta, channels in the basin and intertidal shoals and flats. These elements exchange sediment with each other and with the adjacent coast, to develop a morphological equilibrium as defined by the empirical relationships. The model is easy to handle and simulates long-term developments. This makes it suitable to study the effects of sea-level rise (Van Goor et al., 2003) and large-scale human interferences (Kragtwijk et al., 2004) on the morphology of the Wadden Sea. Since these models are depending on the basic assumption concerning morphological equilibrium, sufficient historical data for the calibration and validation is essential.
- *Idealized models*. This type of model is in fact a process-based model that makes use of simplified physical and mathematical descriptions to analyse the behaviour of a morphodynamic system. The difference with the 'complex' models is that they do not pursue full description of all physical processes, but try to reduce these to essential principles. An example of this type of models is the conceptual model of Postma (1961) on landward sediment transport in the Wadden Sea. The various models developed at IMAU for the different morphological elements within the Wadden Sea system (see review in De Swart & Zimmerman, 2009) belong to this type. Another example is the schematised 1D model of Van Prooijen & Wang (2013).

Recently, Townend et al. (2016a, 2016b) demonstrated that the difference between ASMITA and a process-based model such as Delft3D is in the level of (spatial and temporal) aggregation rather than the extent of empiricism. The ASMITA model is based on the same principles as a process-based model in the case that the suspended sediment transport is dominant. Both models try to represent the same physical processes, but at different levels of aggregation. The difference between the two models is in the formulations for the exchange between the bottom sediment and the water column. In Delft3D this is arranged via the bottom boundary condition in 3D mode or a formulation derived from an asymptotic solution of the (3D) advection-diffusion equation (Galappatti & Vreugdenhil, 1985; Wang, 1992) in 2DH mode. In both cases, the local equilibrium concentration for sediment needs to be calculated. This requires a sediment transport formula that relates the transport capacity to the strength of the flow and the properties of sediment. A sediment transport formula is often derived by considering the relevant physical processes, but it always contains parameter(s) to be calibrated with observations from the field and/or laboratory. In that sense, a sediment transport formula is thus empirical. One must also take into account the uncertainties associated with the application of such a formula. This is shown by the fact that there are not one but many sediment transport formulas available. An indication of the uncertainty is given by Van Rijn (1984a,b) who suggested that sediment transport estimates and measurements can differ by a factor of 2. In ASMITA, a single formulation is used for the exchange between the bottom and the water column for each large morphological element, e.g., the whole ebb-tidal delta. This is based on morphological equilibrium relationships of the elements and aggregated hydrodynamic parameters, reflecting the aggregation in time and space. These relationships are, like the sediment transport formula, based on physical considerations (to determine relevant hydrodynamic parameters and morphological relationships) and observations from the field (to calibrate the parameters in the relationship). The local equilibrium concentration is related to the ratio between the equilibrium volume and the actual volume. The empirical relationships for the morphological equilibrium also contain uncertainties, just like the empirical aspects of a sediment transport formula in Delft3D.

The Delft3D models have reached a stage that they can be used to investigate hydro- and morphodynamics and greatly improve our fundamental understanding of the processes driving sediment transport (see Elias, 2006; Lesser, 2009; van der Wegen, 2009; Elias & Hansen, 2012). Van der Wegen (2009) illustrated that long-term (centuries) morphodynamic simulations are capable of reproducing concepts and equilibrium relationships based on measurements and laboratory experiments (similar findings were presented in the studies of Hibma et al., 2003a, 2003b, 2004; Marciano et al., 2005; Dastgheib et al., 2008; Dissanayake et al., 2009a, 2009b). Lesser (2009) demonstrated, through agreement between modelled and measured morphodynamic behaviour of Willapa Bay (WA, USA), that a process-based numerical model could reproduce the most important physical processes in the coastal zone over medium term (5 year) timescales. Also the recent modelling of the Zandmotor illustrates that the Delft3D model can capture the morphodynamic developments on a decadal scale. Studies that aimed to predict the morphodynamics of the Wadden Sea inlets (e.g. Ameland Inlet) were less successful (De Fockert, 2008; Teske, 2013; Elias et al., 2015; Wang, Yu et al., 2016). One of the important lessons learned from the above models is that these are very well capable to predict the morphodynamic evolution after large-scale distortion of the system (e.g. construction of the Zandmotor) but cannot easily predict the smaller-scale (natural) evolution of inlets, unless abundant field data (and model development) are available (Lesser, 2009). Applications of process-based models for simulating impact of sea-level rise to the Wadden Sea (Dissanayake et al., 2012; Hofstede et al., 2016; Becherer et al., 2017) has only been limited successful.

4.2 Morphological equilibrium

4.2.1 General – philosophy and theoretical background

Morphodynamic equilibrium is a widely adopted concept in the field of geomorphology of coasts, rivers and estuaries (Zhou et al., 2017). Yet it is also an elusive concept and there are still discussions going on about the sense and nonsense of it. Zhou et al. (2017) made a distinction between morphodynamic equilibrium in the “real world” (nature) and the “virtual world” (model). The concept of morphodynamic equilibrium should be mathematically unequivocal in the virtual world and interpreted over the appropriate spatial and temporal scale in the real world. The choice of a temporal scale is thus imperative when the morphodynamic equilibrium is used.

O’Brien (1931) was first to introduce an empirical relationship for morphological equilibrium in tidal regions, viz. a relationship between estuary tidal prism P and entrance cross-sectional area A. A theoretical substantiation for this relation is first provided by the stability analysis of Escoffier (1940). This so called PA-relationship has been argued to be applicable along the length of the tidal channel as well (D’Alpaos et al., 2010; Friedrichs, 1995; Guo et al., 2014, 2015; van der Wegen et al., 2010). It is also the basis for the relationship between the tidal prism and the total volume of the channels within a back-barrier basin in the Wadden Sea (Eysink, 1990). It is argued from a geometric consideration that the total length of the channels should be proportional to the square root of the basin area. For the short (relative to tidal wave length) basins the tidal prism is proportional to basin area. Therefore, the channel volume should be proportional to the tidal prism p to a power close to 1.5, as according to the PA-relationships the cross-sectional area is proportional to P^n with n close to 1. Including certain rules for the shape of channel cross-sections such as a relation for the aspect ratio B/h (B=width and h=depth of a channel), it can be argued that there must be a relationship for the proportion of channels in the basin area. This provides a theoretical background for the relationship for the horizontal area of the (inter)tidal flat in a back-barrier basin (Renger & Partenscky, 1974, Eysink & Biegel, 1992). Similar to the analysis of Escoffier (1940), Fagherazzi et al. (2007) provide a theoretical substantiation for the equilibrium height of tidal flats.

Walton and Adams (1976) indicated that the volume of an ebb-tidal delta is proportional to the tidal prism to a power 1.23. It is likely that such a relationship in principal exists. Larger tidal prisms can induce large flows and velocities that would scour deeper channels and thus erode larger sediment volumes that result in larger ebb-tidal deltas. However, many other external controls exist that can modify or change the volumes. Hayes (1975; 1979) was among the first to classify barrier islands and their related inlet systems on the basis of the ratio of wave versus tidal range: wave-dominated ebb-tidal deltas are pushed close to the inlet throat, while tide-dominated ebb-tidal deltas extend offshore. Additionally, Davis and Hayes (1984; their Fig. 7) showed that tidal prism is more important than tidal range, large tidal prisms can explain large, well-developed ebb-tidal deltas (no direct relation between tidal range and tidal prism was observed; see also Davis, 1989, 2013). Reduction of the tidal prism of an inlet will result in a decrease in sand supply by the ebb current and, hence, wave-driven sand transport will increase relatively. This results in net sediment transport in landward direction and erosion of the delta front.

FitzGerald (1996) and Davis and Hayes (1984) point to the importance of sediment supply, basin geometry, sedimentation history of the back-barrier, regional stratigraphy and occurrence of bedrock, river discharge, and sea-level changes. With all these different forcing conditions a wide diversity in inlet morphologies exists. Elias and Van der Spek (2006) and

Elias et al. (2012) illustrate the large influence of anthropogenic change on the evolution of the ebb-tidal deltas of the Dutch Wadden Sea. The response of Texel Inlet’s ebb-tidal delta to closure of the Zuiderzee illustrates that engineering works can significantly influence the inlet dynamics and can cause the inlet to develop differently from what would be derived from the generally accepted equilibrium relationships and conceptual inlet models.

4.2.2 Sediment demand and accommodation space

In addition to analysing the physical processes and mechanisms, another way to understand the residual sediment transport through the inlets is by considering the ‘sediment demand’, which is defined as the sediment volume needed for a certain morphological element to restore morphological equilibrium. For the tidal basins it is in fact equivalent to the accommodation space as described in Chapter 3. The aggregated morphodynamic models are based on the principle that residual sediment transport is driven by gradients in sediment demand.

Appendix A describes how the empirical relationships for the volume of the tidal flats and for the volume of the channels in a tidal basin are applied to determine the sediment demand in the basin. According to these relationships the equilibrium state of a basin is determined by two basic parameters: the total basin area A_b and the tidal range H. Thus, the water volume below the high-water level in a basin at equilibrium is a function of these two parameters:

$$V_e = F\left(A_b, H\right) \tag{4-1}$$

The difference between the basin volume at a certain stage and this equilibrium basin volume is the sediment demand.

The tidal divides, which form the inner boundaries between the tidal basins and thus determine the basin areas, are not fixed. In the Appendix it is shown that the movement of the tidal divide between two basins, e.g., the Texel and Vlie Inlet, can be very important for the total sediment demand of the two-basin system.

4.3 Modelling response to relative sea-level rise

4.3.1 Modelling approaches

Only a few proven predictive methods are available to assess the impact of accelerated sea-level rise on inlet systems. Predictions of shoreline change as proposed by Bruun (1962) and Stive & Wang (2003) might work along uninterrupted beach/dune coasts, although the assumptions underlying the concept are not supported by oceanographic and geologic evidence (Pilkey et al., 1993). However, these types of predictions are generally too simplistic to account for complex inlet processes, where ebb-tidal delta, inlet channel and back-barrier basin tend to remain in dynamic equilibrium to the large-scale hydraulic forcing, individually as well as collectively (Dean, 1988; Oost & de Boer, 1994; Stive et al., 1998; Stive & Wang, 2003). Van Goor et al. (2003) explicitly assume such dynamic equilibrium in order to predict critical rates of sea-level rise for various tidal inlet/basin systems in the Dutch Wadden Sea. Their model needs parameters which ideally should be derived from process-based modeling or measurements (Wang et al., 2008). Coastal process-based models that contain the necessary physics to account for these complex interactions, like Delft3D (Lesser et al., 2004), and ROMS (Shchepetkin & McWilliams, 2005), are only just starting to address morphodynamic changes on relevant long time scales (see examples in Hibma et al., 2003; Marciano et al., 2005; Dastgheib et al., 2008; Van der Wegen & Roelvink, 2008; Van der Wegen et al., 2008).

Up to now, the assessment of the impact of sea-level rise relies mainly on aggregated morphological models (ASMITA; Van Goor et al., 2003). In the EIA studies for gas and salt mining under the Wadden Sea the quantitative assessment of the impact of land subsidence is also based on the ASMITA model (Wang and Eysink, 2005; Cleveringa and Grasmeijer, 2010; Wang et al., 2017).

The application of ASMITA for modelling the effect of sea-level rise can readily be demonstrated by using the single element model, in which a back-barrier basin is considered as one single element with the water volume under high water as system variable (see Stive and Wang, 2003). In case of constant rate of sea-level rise, a 'new' dynamic equilibrium volume which is larger than the original equilibrium volume can be achieved as long as the sea-level rise rate is below a critical value (see Fig. 4.1). There is a permanent difference between the (dynamic) equilibrium volume with sea-level rise and the (original) equilibrium volume without sea-level rise. This difference in equilibrium volume is necessary to maintain the demand of sediment that drives sediment imports into the system to an extent that the system does not drown. When the sea-level rise rate is equal to the critical value the dynamic equilibrium volume becomes infinitely large (Fig. 4.1). This means that that the system will drown if sea-level rise becomes faster than the critical rate.

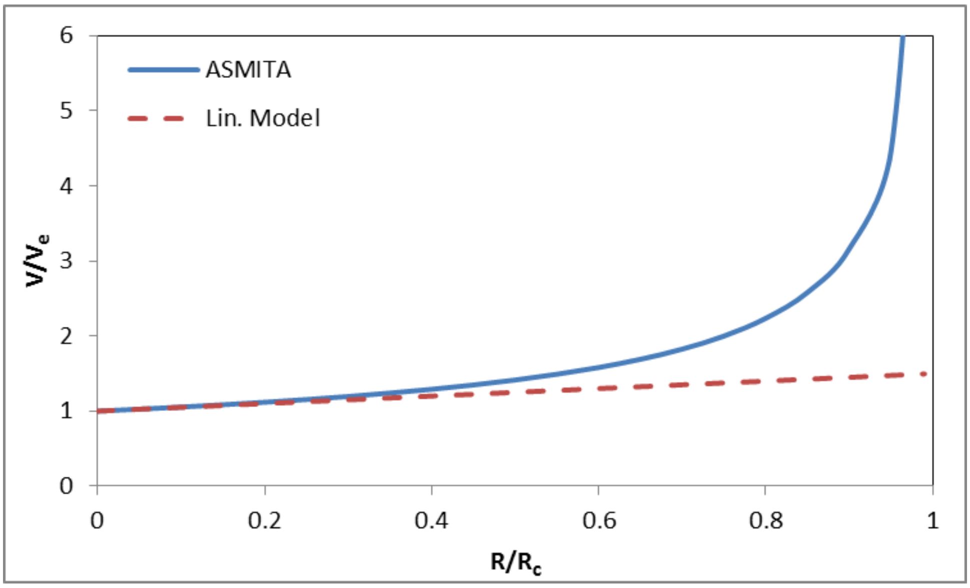

Figure 4.1 Relation between the dynamic equilibrium volume V (normalised by the original equilibrium volume V_e) the sea-level rise rate R (normalised by the critical rate R_c).

Wang et al. (2017) demonstrated that the non-linearity of the ASMITA model is essential to be able to predict a critical rate of sea-level rise. According to a linear model, such as the classic empirical model assuming exponential decay of disturbances to morphological equilibrium, a dynamic equilibrium volume can always be found and no critical sea-level rise rate exists. Physically the non-linearity represents the limitation of sediment transport capacity. The limited transport capacity is not correctly represented in the classic empirical model in which a disturbance to morphological equilibrium, e.g. sediment demand, decays exponentially as the rate of decay increases linearly with the magnitude of the disturbance. In a process-based model as well as in the semi-empirical (or the aggregated) model (like ASMITA) the limited transport capacity can be well represented. This is the reason why the classic empirical model does not predict any critical rate for sea-level rise for the Wadden Sea to keep pace with, whereas the ASMITA model does (Van Goor et al., 2003).

It is noted that the dynamic equilibrium state as shown in Fig. 9 is only achieved if the sea-level rise rate remains constant for a long (relative to the morphological time scale) time. For considering the effect of accelerated sea-level rise the transient morphological development needs thus to be considered. When e.g. the sea-level rise accelerates to a rate above the critical value, it will still take a long time before all the tidal flats are inundated (drowning).

The only application of process-based models to the Dutch Wadden Sea thus far for simulating impact of sea-level rise (Delft3D; Dissanayake et al., 2012) predicted an unrealistically low critical rate of sea-level rise because only a single sand fraction is included (Wang and van der Spek, 2015). The aggregated models also only include one sediment fraction but they produce more realistic results because their parameter setting is such that the sand-mud mixture is better represented (Wang and Van der Spek, 2015). However, the parameter setting is then empirically determined and does not follow the theoretical rules (Wang et al., 2008), making the model results uncertain. Both type models need thus to be improved in dealing with the sand-mud mixture, in agreement with the findings in modelling river deltas (Edmonds and Slingerland, 2010; Geleynse et al., 2011) and other tidal systems (Van der Wegen et al., 2016). Hofstede et al. (2016) showed that process-based modelling on impact of sea-level rise on the Wadden Sea can indeed be successful if sand as well as mud are considered in the model.

4.3.2 Critical rate of sea-level rise for drowning

Van Goor et al. (2003) studied the effect of sea-level rise to the tidal inlet systems Eierlandsegat Inlet and Ameland Inlet using an ASMITA model in which the tidal inlet system is schematised into three morphological elements: tidal flats in the basin, channel in the basin and the ebb-tidal delta. The same schematisation is used for setting up ASMITA models for the other inlet systems in the Dutch Wadden Sea (Kragtwijk et al., 2004; Bijsterbosch, 2003; Hinkel et al., 2013). According to this 3-elements model the critical rate of sea-level rise can be calculated as follows (Bijsterbosch, 2003; Hinkel et al., 2013).

$$R_c = \frac{C_E}{\dfrac{1}{w_{sf}} + \dfrac{A_f + A_c + A_d}{\delta_{od}} + \dfrac{A_f + A_c}{\delta_{dc}} + \dfrac{A_f}{\delta_{cf}}} \tag{4-2}$$

Herein

R_c = critical rate of sea-level rise
C_E = Overall equilibrium sediment concentration
w_{sf} = Vertical exchange coefficient for the morphological element tidal flat
A_f = Horizontal area tidal flat element
A_c = Horizontal area channel element
A_d = Horizontal area ebb-tidal delta
δ_{od} = Horizontal exchange coefficient between outside world and ebb-tidal delta
δ_{dc} = Horizontal exchange coefficient between ebb-tidal delta and channel
δ_{cf} = Horizontal exchange coefficient between channel and tidal flat

For each of the tidal inlets in the Dutch Wadden Sea an ASMITA model exists. Based on the most up to date parameter settings the critical rates of sea-level rise for these tidal inlet systems are calculated. The results of the calculation are given in Table 4.1, together with the used parameter settings.

Figure 4.2 Parameter settings for the ASMITA model and critical sea-level rise rate for the various tidal inlets in the Dutch Wadden Sea.

Inlet	Texel	EG	Vlie	AME	PG	ZK
C_E (-)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
w_{sf}(m/s)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
A_f (km^2)	133	105	328	178	38.1	65
A_c (km^2)	522	52.7	387	98.3	11.5	40
A_d (km^2)	92.53	37.8	106	74.7	34	78
δ_{od} (m^3/s)	1550	1500	1770	1500	1060	1060
δ_{dc} (m^3/s)	2450	1500	2560	1500	1290	1290
δ_{cf} (m^3/s)	980	1000	1300	1000	840	840
R_c (mm/y)	**7.0**	**18.0**	**6.3**	**10.4**	**32.7**	**17.1**

4.3.3 Implication for managing gas and salt extraction

An important management issue for the Dutch Wadden Sea concerns gas and salt extraction below the Wadden Sea. The extractions cause subsidence which can be considered as relative sea-level rise. Permissions for the extractions are under the condition that they do not cause significant environmental impact which is mainly the loss of intertidal areas. Therefore it is required that the total averaged rate of relative sea-level rise, i.e. subsidence plus sea-level rise, must below a predefined limit. This is the ‘Hand on the Tap’ control (De Waal et al., 2012). Ever since the introduction of this control the limit of acceptable averaged rate of relative sea-level rise has been the subject of discussions. It is evident that this limit should not be the same as the critical sea-level rise rate for drowning as discussed in the previous section, as at that limit significant environmental damage would occur on the long-term.

In Fig. 4.1 the results of the corresponding linear model (derive by linearization of the single element ASMITA model) are also shown. If the sea-level rise rate is below around 40% of the critical rate, the difference between the linear and non-linear model is small. Based on this observation Wang et al. (2017) suggested that 40% of the critical sea-level rise rate can be used as the limitation for relative sea-level rise in managing gas extraction in the Frisian Inlet (Pinkegat and Zoutkamperlaag). The reason behind this is that according to the linear model the cumulative effect of subsidence, represented by the time integral of the deviation from equilibrium volume, depends on only the total subsidence and not on the distribution of the subsidence in time: subsidence with twice the rate during half of the time results in the same cumulative effect (Figure 4.2, left panel). If the relative sea-level rise is larger than the 40% limit the non-linear model is needed. Then not only the maximum instantaneous effect, but also the cumulative effect will become larger if the total subsidence is concentrated in a shorter period (Figure 4.2, right panel).

This suggested limit requires another condition as Wang et al. (2017) mentioned: the maximum effect should be acceptable as well. It is evident that concentrating the subsidence in a shorter period leads to larger maximum effect (Figure 4.2). Moreover, this suggested limit is only applicable for basins not too far deviated from morphological equilibrium, e.g. the Pinkegat. In basins which are already far from morphological equilibrium the consideration about the applicability of linear models does not make sense. As an example, the Texel and Vlie Inlets still have a very large sediment demand due to the interferences in the past. As a consequence, the sedimentation rates in these basins have been close to the critical rate for drowning (See Figure 2.4 and Figure 4.1). The increase of sediment demand due to relative sea-level rise in these basins is negligible compared to the existing sediment demand, and therefore will only have negligible influence on the sedimentation rates. This explains that the limit of acceptable averaged rate of relative sea-level rise in these basins can be close to the observed sedimentation rate. The recently updated limit for these two basins is 5 mm/year (Cleveringa and Grasmeijer, 2010) is indeed close to the 4.7 mm/year shown in Figure 4.1.

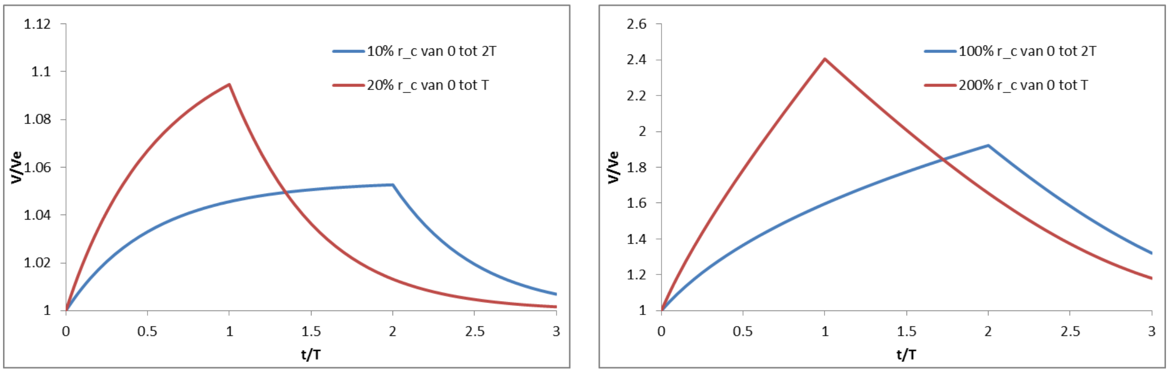

Figure 4.3 Effect of temporal relative sea-level rise as function of time at low rate (left) and high rate (right) according to the single element ASMITA model. T is the morphological time scale

5 Concluding discussions

5.1 Answers to the research questions:

Which factors determine the sediment exchange through the inlets?

In the last century human interferences have been the main driving force for the morphological development of the Dutch Wadden Sea. The closures of the Zuiderzee and the Lauwerszee explain the much higher sedimentation rate than sea-level rise rate in the Wadden Sea. For the inlet systems significantly influenced by these closures (Texel Inlet, Vlie Inlet, Frisian Inlet) sea-level rise has played a less important role. For Ameland Inlet, which is less influenced by the closures, sea-level rise has probably been more important.

The morphological state of the back-barrier basin with respect to the morphological equilibrium determines to a large extent the residual sediment transport through the inlet. At present, the western part of the Dutch Wadden Sea (Texel Inlet, Eierlandsegat and Vlie) still has a large sediment demand. Sediment import to this part is limited by the transport capacity. In the eastern part, the sediment import is limited by the sediment demand.

How will the influencing factors develop in the future?

In the coming century human interferences will remain important for the development of the Wadden Sea. Depending on the scenarios of sea-level rise, accelerated sea-level rise may become the main driving force for the morphological development in the coming century, especially in the eastern part of the Dutch Wadden Sea. There is a critical rate of sea-level rise above which the extended tidal flat will be inundated.

With accelerated sea-level rise the intensified coastal nourishment will become an important human interference influencing the Wadden Sea system.

What are the relevant processes and mechanisms?

Transport, deposition and erosion of sand as well as mud influence the morphological development of the Wadden Sea system. These sediment transport processes are influenced by flows and waves driven by tide and wind.

A distinction between the barotropic and baroclinic mechanisms can be made for residual sediment transport. For most of the tidal inlets in the Dutch Wadden Sea the barotropic mechanisms including tidal asymmetries, tidal dispersion and meteorological effects are most important. The relative importance of these mechanisms is difficult to determine. For the Texel Inlet density flow does play an important role for the residual sediment transport through the inlet.

Can the long-term large-scale development of the Wadden Sea system be predicted by modeling?

Process-based and aggregated models are available for modeling morphodynamic development for the Wadden Sea tidal inlet systems. The process-based models (based on e.g. Delft3D) still need to be improved for simulating medium-term (years to decades) morphological development of the Wadden Sea system. The aggregated models (e.g. ASMITA) can be used for long-term development but they only provide information at large (aggregated) scales without detailed spatial distribution of the morphological changes. Theoretical rules for their parameter setting are available, strictly following those rules need to be accompanied the implementation of multi (at least two) fraction sediment transport in the models. The different type models are complementary rather than competitive for studying morphodynamic development of the Wadden Sea system. The gap between the two types models can only be closed by improving both.

5.2 Discussions

5.2.1 Sediment availability and coastal nourishment

An important conclusion from the study of Elias et al. (2012) is that still a large amount of sediment is needed to regain equilibrium, and this amount increases with sea-level rise. Due to the limited sediment transport capacity it is very unlikely that the morphological equilibrium in the Western part of the Dutch Wadden Sea will ever be restored. The rate at which future sea-level rise will increase the sediment demand in the basins will be equal to or higher than the sediment import depending on the sea-level rise scenario.

In the last decades, much of the basin infilling is supplied by the ebb-tidal deltas (Texel Inlet in particular) that are limited in size and rapidly reducing in volume. Unless sufficient sediment is delivered to let the system accrete in place, permanent drowning of large parts of the intertidal basin is to be expected. Repeated beach and shoreface nourishment and optional ebb-tidal delta nourishment to mitigate erosion, adding to the sediment budget of both islands and basins, will be needed to sustain sufficient sediment availability, allowing the natural system to respond to future sea-level rise.

The required sand nourishment amount for maintaining the (North Sea) coast will increase with increasing rate of relative sea-level rise (Van der Spek et al., 2015). The accelerating sea-level rise will make the nourishment more and more important among the local human activities in the future. The nourishment will be essential for the safety against flooding and the conservation of the environmental value of the Wadden Sea, but they can also have negative side effects e.g. temporally damaging the ecological system at the nourishment sites. Optimizing the nourishment strategy in maximizing the intended beneficial effects and minimizing the coasts and negative side effects will require research. The optimization will concern amounts, locations, frequency and methods of the nourishments, and depend on the intended beneficial effects. At present the nourishments are intended to maintain the coastline and the sediment amount in the coastal foundation relative to rising sea-level (coastal area between the NAP-20 m iso-bath and landwards edge of the dunes). In the future, maintaining the ebb-tidal deltas and stimulation of sediment import to the Wadden Sea may become additional intended purposes of the nourishments.

5.2.2 Uncertainties

Finally, the most important uncertainties concerning the future large-scale development of the Wadden Sea system are identified:

- Development of the sea-level rise. This will especially be important for the long-term (end of the century) development.
- Will the western part of the Dutch Wadden Sea develop into similar configuration as the eastern part in the long-term? In other words, are the empirical relations for morphological equilibrium applicable for this part?

- How will the tidal divides develop? Where are they going to move? Can the sedimentation make them following accelerated sea-level rise?
- Concerning shorter term development, is the sedimentation in the western part of the Wadden Sea slowing down or not?

5.3 Recommendations

The future development of the Wadden Sea system will have consequences for the various management issues. For the coastal maintenance increase of required nourishment amount is expected. Although the nourishment is easy to adapt to the uncertain development, changes in the nourishment strategy anticipating to the increasing nourishment amount and to possibly changing purposes need to be prepared. For the conservation of the natural value the uncertainty in the future development is more a problem. Maintenance of sufficient sediment availability at the ebb-tidal deltas and along the coasts of the barrier islands should be considered as a prerequisite. Anticipating to accelerated sea-level rise development of nourishment strategies for increasing sediment import to the Wadden Sea is recommended.

For the sustainable management of the Wadden Sea system monitoring of the development is essential. Effective monitoring to detect the relevant changes is challenging because sea-level rise as well as the morphological development concern long-term and slow processes.

More accurate predictions for the future development of the Wadden Sea system are required for all the management issues. The following researches are recommended to improve the predictions:

- Sedimentations in the Wadden Sea are due to sand and mud. A distinction between these two sediment fractions is especially relevant for the coastal maintenance, as only the sand fraction is eroded from the ebb-tidal deltas and the coasts of the islands. The distinction between sedimentations due to mud and sand can only be made after a more detailed analysis on the morphological changes in the tidal basins.
- Carry out an integrated modelling study by combined use of the various morphodynamic models. The large scale and long-term development of each of the tidal inlet systems for the various scenarios can be simulated with the aggregated (ASMITA) models. However, these models were set up at the end of the last century. Improvements of the models have been suggested recently (Townend et al., 2016a, 2016b). Therefore it is recommended to consider these suggestions and implement the relevant ones first. The models can then be recalibrated using the most up to date field data, before simulating the future scenarios. The process-based (Delft3D) models can be used to investigate the residual sediment transport and short-term more detailed development. For a selected tidal inlet system the process-based model can also be used for long-term simulations. Compared to the present projections such integrated modelling study will provide more accurate and more detailed information on the development of the tidal flats in the various basins and on the sediment supply from the North Sea coast to the Wadden Sea.
- Carry out a study on the development of the tidal frame (LW and HW) in the Wadden Sea. Up to now sea-level rise studies focus more on the development of MSL and HW. However, the development of LW will be most relevant for the change of the intertidal flat area. First, the historical water level data should be analysed with special attention to the LW development. Then hydrodynamic simulations for the historic situations can be carried out to understand the effects of sea-level rise and morphological changes on the tidal propagation. Then the various future scenarios can be investigated by modelling. Moreover, by relating the tidal frame changes to the

morphological changes more insight in the development of the factors influencing the residual sediment transport can be gained.

- Carry out research on channel-shoal interaction using schematised process-based (idealised) modelling. Channel-shoal interaction is still a weak point in the process-based morphodynamic modelling. The processes and mechanisms described in 3.3 need to be better implemented in the models. Then the models can be used to investigate how the development of the intertidal shoals will be influenced by accelerated sea-level rise. The results of such a research will be essential for predicting the future development of the Wadden Sea and for improving the morphodynamic models in general.
- Carry out research on the development of the tidal divides. The uncertain development of the tidal divides will have substantial influence on the response of the Wadden Sea to accelerated sea-level rise. Therefore research continuing the work of Vroom (2011, see also Wang et al., 2013) is needed to understand the development of the divide in the past and to predict the development for the future scenarios.

A Application of empirical relations for morphological equilbrium

A.1 Single inlet system

Within a tidal basin two morphological elements are distinguished, viz. the aggregated intertidal flat and channel elements (Figure A.1). For both elements empirical relationships are available defining their morphological equilibrium dimensions. With these relationships the morphological equilibrium state of a tidal basin is the fully determined if the basin area A_b and the tidal range H are given.

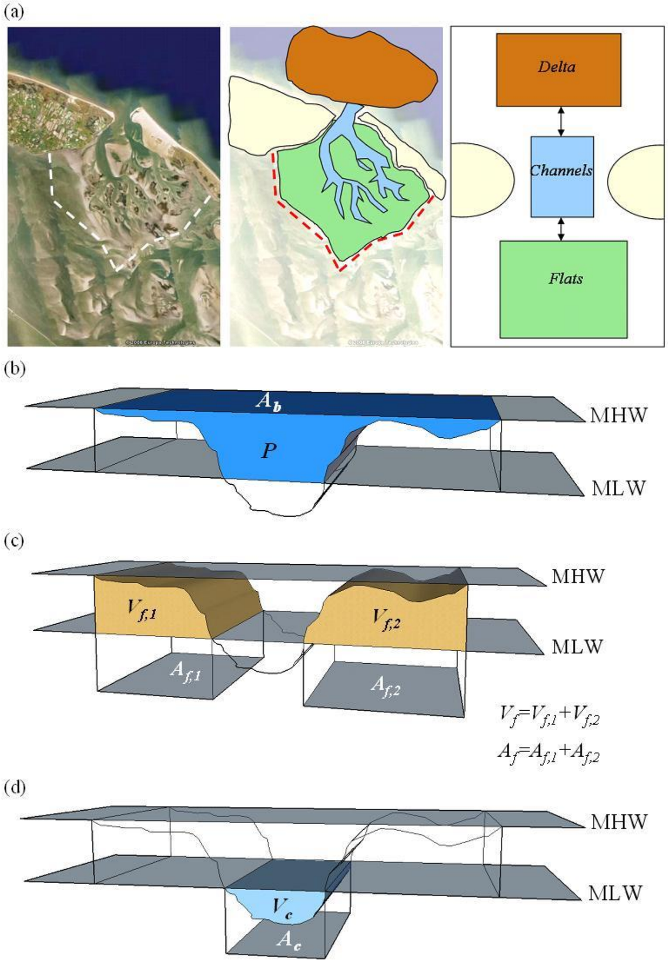

Figure A.1 . Morphological elements of a tidal basin and its ebb-tidal delta (a) and the definitions of the hydrodynamic and morphological parameters tidal prism (b), area and volume of tidal flats (c), area and volume of channels (d).

For the intertidal flat there are two empirical relationships, one for its area and one for its height (Renger and Partenscky, 1974, Eysink and Biegel, 1992).

$$\frac{A_{fe}}{A_b}=1-2.5\cdot 10^{-5}\cdot A_b^{0.5} \tag{A1}$$

$$h_{fe} = \alpha_{fe} \cdot H \tag{A2}$$

Herein A_{fe} [m^2] is equilibrium tidal flat surface area; A_b [m^2] is basin surface area; H is tidal range and according to Eysink (1990)

$$\alpha_{fe} = \alpha_f - 0.24 \cdot 10^{-9} \cdot A_b \tag{A3}$$

with α_f = 0.41. The equilibrium volume of the intertidal flat, i.e. the sediment volume between low water (LW) and high water (HW), is thus per definition:

$$V_{fe} = A_{fe} h_{fe} \tag{A4}$$

The channel volume V_c is defined as the water volume under LW in the basin. Its equilibrium value is related to the tidal prism as follows:

$$V_{ce} = \alpha_c P^{1.55} \tag{A5}$$

The tidal prism P is the wet volume in the basin between LW and HW, thus

$$P = A_b H - V_f \tag{A6}$$

Using these equations the morphological equilibrium of a tidal basin can be determined from two parameters, the total basin area A_b and the tidal range H. As an indication for the sediment demand in a basin one can use the total wet volume of the basin under HW:

$$V_b = V_c + P \tag{A7}$$

The difference between the actual value of V_b and its value at equilibrium is the amount of sediment a basin needs to achieve equilibrium, i.e. the sediment demand of the basin.

A.2 Multiple-inlet system

The Wadden Sea is in fact a multiple-inlet system. The tidal divides behind the barrier islands are considered as the borders between the back-barrier basins. However, these borders are not really closed as water and sediment exchange across them do take place (Duran-Matute et al., 2014). Moreover, the locations of the tidal divides are not fixed and they especially move after major human interferences such as the closure of the Zuiderzee. The migration of the tidal divides can have substantial effects on the morphology (Wang et al., 2013) as demonstrated by the application of the empirical relations for morphological equilibrium to a two-inlets system in the following.

Consider two adjacent and inter-linked tidal basins with a fixed total basin area (Figure A.2):

$$A_{b1} + A_{b2} = A_b = \text{constant} \tag{A8}$$

with subscript 1 and 2 referring to basin 1 and basin 2. Consider first the situation that the tidal ranges in the two basins are the same:

$$H_1 = H_2 = H \tag{A9}$$

As the boundary between the basins is movable the area of each basin can vary between zero and A_b, thus

$$0 \le \beta = \frac{A_{b1}}{A_b} \le 1 \tag{A10}$$

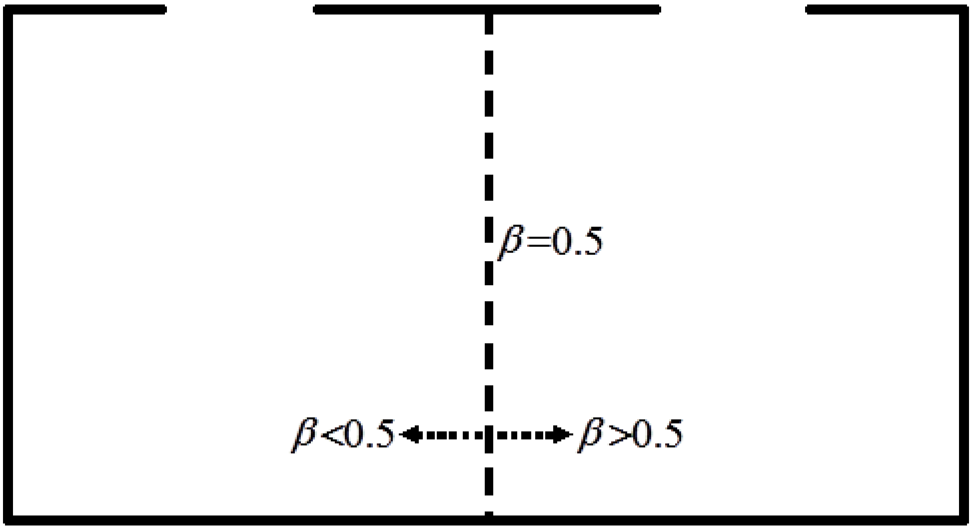

Figure A.2 Schematic sketch of a two basin system. The dashed lines represent three locations of the tidal watershed separating the two basins.

For each division between the two basins, i.e. for each value of β between 0 and 1, the equilibrium volume of the inter-tidal flat, the corresponding tidal prisms and the equilibrium volume of the channel can be calculated for each basin, using the equations in the previous subsection. As an example for the tidal prisms we have:

$$\begin{aligned} P_1 &= \beta\left(1-\alpha_{fe1} + 2.5\cdot 10^{-5}\alpha_{fe1}\sqrt{\beta}\sqrt{A_b}\right)A_b H \\ P_2 &= \left(1-\beta\right)\left(1-\alpha_{fe2} + 2.5\cdot 10^{-5}\alpha_{fe2}\sqrt{1-\beta}\sqrt{A_b}\right)A_b H \end{aligned} \tag{A11}$$

So for the total tidal prism in the two basins we have:

$$\frac{P_1+P_2}{A_b H} = 1-\alpha_{fe2} - \beta\left(\alpha_{fe1}-\alpha_{fe2}\right) + 2.5\cdot 10^{-5}\sqrt{A_b}\left[\alpha_{fe1}\beta^{1.5} + \alpha_{fe2}\left(1-\beta\right)^{1.5}\right] \tag{A12}$$

Similar relations can be derived for the wet volumes under HW in the two basins and for the two basins together we have:

$$\frac{V_{b1}+V_{b2}}{A_b H} = F\left(A_b, \beta\right) \tag{A13}$$

From Equation (A12) it becomes clear that the total tidal prism is maximal when the two-basin system becomes a single basin, and it is minimal when the two basins are equal in size. The same behaviour applies for the total wet volume under HW. This is illustrated in Figure A3, which shows the results calculated using the values of the Texel Inlet -Vlie system concerning the total basin area and the tidal range. Note that the difference between the two extreme cases (β=0 and β=0.5) concerning the sediment demand can be very large as shown by the figure. Note also that it is assumed through the analysis that the tidal range *H* is not influenced by the position of the tidal watershed.

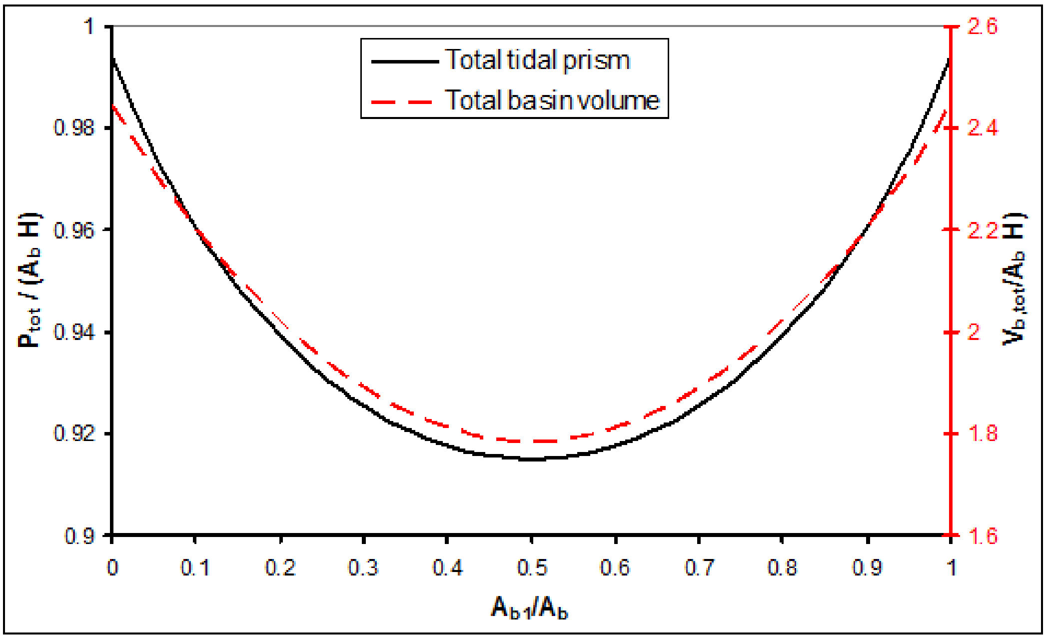

Figure A.3 The total tidal prism and the total (wet) volume under HW of a two-basin system. Used values: A_b=1370 km^2, H=1.8 m, α_c=10^{-5} m$^{-0.55}$

In reality the tidal ranges in the two basins are not always the same, as the Texel Inlet -Vlie case clearly illustrates. Also for such a case the same calculations can be carried out, see Figure A.4 in which the tidal range in basin 1 (representing Texel Inlet) is taken as 1.52 m and for basin 2 (representing Vlie) is taken as 1.89 m, following Van Geer (2007). The minimum value of the total tidal prism as well as of the total wet volume under HW now occurs at a larger value of β (>0.5), i.e. when the Texel Inlet basin is larger than the Vlie basin. For making both parameters dimensionless (see Eq. A12 & A13) the average value of the two tidal ranges is used.

As mentioned above, the total wet volume is an indication of the sediment demand. As an example, the sediment demand with respect to the initial condition in 1970 concerning the volumes of the intertidal flats and the channels as reported by Steetzel and Wang (2003), is shown in Figure A.5 The sediment demand is maximal when the total equilibrium wet volume in the two basins is minimal. For the system under consideration this will occur when the

Texel Inlet basin is slightly larger than the Vlie basin. At present the Texel Inlet basin is still smaller than the Vlie basin but the Texel Inlet basin is increasing in size at the cost of the Vlie basin. The system is thus developing towards a situation with larger sediment demand.

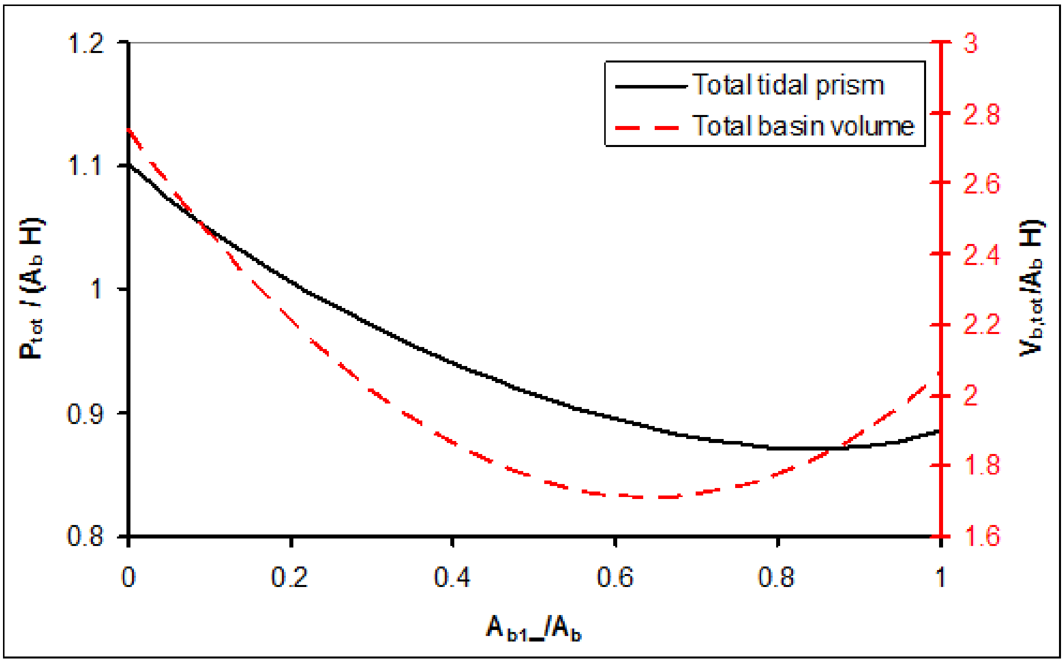

Figure A.4 The total tidal prism and the total (wet) volume under HW of a two-basin system. Used values: A_b=1370 km^2, H_1=1.52 m, H_2=1.89 m, α_c=10^{-5} m$^{-0.55}$

The total sediment demand in such a two-basin system depends thus on the location of the tidal watershed between them, or the area distribution between the two basins.

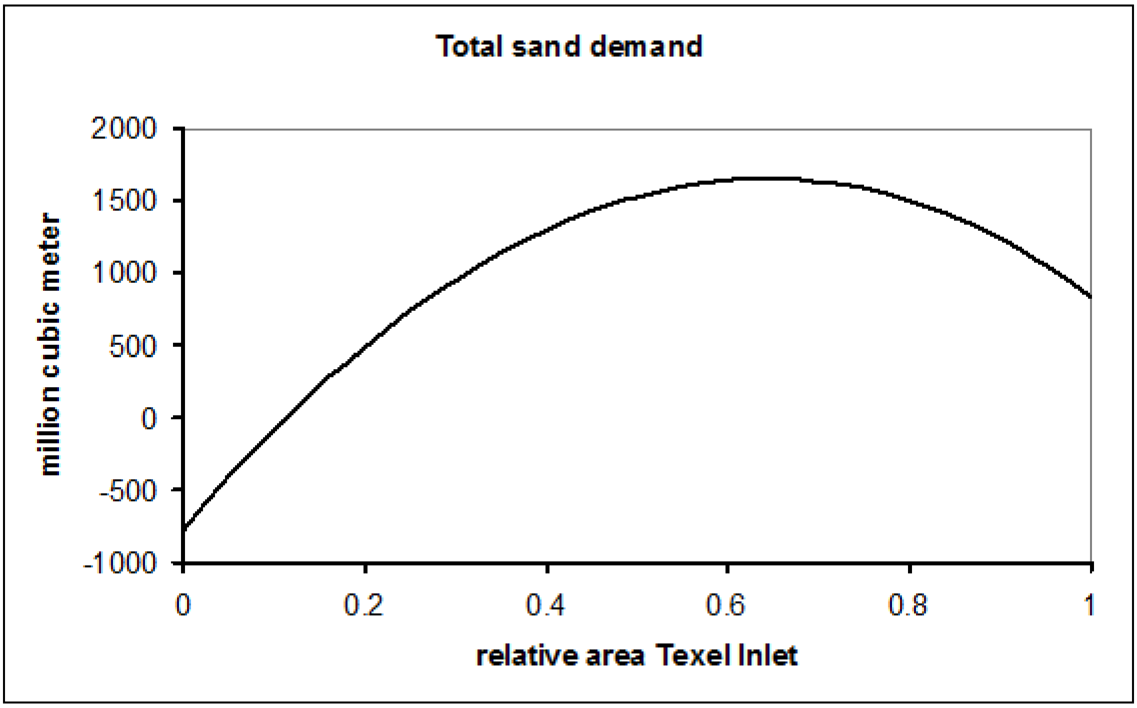

Figure A.5 The total sediment demand. Used values: A_b=1370 km^2, H_1=1.52 m, H_2=1.89 m, α_c=10^{-5} m$^{-0.55}$

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