Quirijn Jacob Lodder

Connecting science and policy in Dutch coastal management

The role of system understanding and conceptual models

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The role of system understanding and conceptual models

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Summary

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Globally coasts are under pressure owing to stressors such as human use and climate change. From the 1970s onwards, Integrated Coastal Management gradually emerged as a strategic approach that strives for sustainable integration of the sometimes conflicting interests of human use, natural values and protection against flooding. The European Union defines Integrated Coastal Management as "*a dynamic, multidisciplinary and iterative process to promote sustainable management of coastal zones. It covers the full cycle of information collection, planning (in its broadest sense), decision making, management and monitoring of implementation*"

Developing and implementing effective integrated (coastal) policy requires meaningful interaction between policymakers and scientists, in the Netherlands and globally. However, bridging the gap between science and policy remains problematic. On the one hand, it is challenging for scientists to link their specialized knowledge directly to policy issues. On the other hand, coastal managers around the world struggle to translate scientific insights into feasible and targeted policies and practice. Accordingly, developing, implementing and conducting research specifically for policy is an ongoing challenge for both coastal managers and scientists. It is with reason that the United Nations Environment Program (UNEP) identifies connecting science with policy as one of the greatest challenges to sustainability in the 21st century.

The Netherlands has a long history of coastal flood and erosion risk management, based on system understanding and supported by monitoring data and simulation and conceptual models. Dutch coastal research and policy networks are interconnected, making research into the interaction between science and policy feasible and, moreover, intriguing. Therefore, the central question in the research presented here is: How can we connect science and policy in support of sustainable coastal management, not at a global scale, but regionally in the Netherlands?

This study examines the interactions between science and policy in the Coastal Genesis 2 programme, a large-scale policy-oriented scientific research programme in the Netherlands. The Coastal Genesis 2 programme was examined to deepen

insight into the set-up of the research programme, to establish how the challenge of connecting science and policy was overcome, and to understand how policy impact was created. By examining this case study in depth, both the interactions at the interface between science and policy and the context in which these interactions took place can be explored.

This research has two parts. The first part examines how the Coastal Genesis 2 programme has influenced Dutch coastal policy and management. Specifically, it analyses how the programme has contributed to bridging the gap between science and policy. The (revised) conceptual model of the long-term sediment budget of the Dutch coast plays a central role in the analysis. The second part of the research addresses one of the most important uncertainties in this conceptual model, namely the long-term morphological development of the Dutch Wadden Sea. The first part of this research aims to answer the following research questions:

1. How did the Coastal Genesis 2 research programme originate and how is it organised? and
2. How has the Coastal Genesis 2 research programme influenced Dutch coastal management policy and practice?

The second part of the research aims to answer the following research questions:

3. How will the tidal basins in the Wadden Sea evolve morphologically in the long-term and how will this influence the long-term sediment budget of the Dutch coast? and
4. What are the implications of the evolution of the Wadden Sea basins for the sustainability of Dutch coastal management policy and practice?

Case Study Background

In the Netherlands, coastal management is a task of the Ministry of Infrastructure and Water Management, whereby Rijkswaterstaat, as the operational agency of this ministry, has two roles: to advise policy directorates on policy and to implement policy in coastal management practice. Coastal policy is formulated by the policy directorates of the ministry and established by parliament. In addition to Rijkswaterstaat, the water boards specifically have an important role in coastal management practice. The water boards are responsible for managing the majority of the sandy and hard flood defences along the coast and must ensure that these flood defences continue to meet the flood risk management standards.

The essence of the current coastal policy was formulated in the first coastal policy white paper in 1989. This white paper introduced the 'dynamic preservation' of the coast, a coastal policy that was subsequently adopted by Parliament. The goals of the policy are to "*sustainably maintain the flood protection level and sustainably preserve values and functions of the dune areas*" with sand nourishments chosen as the most important measure for coastal defence. Since the first coastal policy white paper, there have been several refinements of the dynamic preservation policy. However, the essence of the policy has remained the same, with the introduction of the coastal foundation as the most important refinement around the year 2000.

However, this coastal management strategy may require a significant increase in the annual sediment nourishment volume under the accelerated sea level rise anticipated in future. In 2014, this led to questions about the sustainability of the policy of 'dynamic preservation' in the long term. In response, Rijkswaterstaat initiated the Coastal Genesis 2 research programme on behalf of the Ministry of Infrastructure and Water Management. The aim of this programme was to generate knowledge for the development of a future-proof long-term coastal management strategy. Drawing on research results from this programme, Rijkswaterstaat has formulated advice on the preferred coastal nourishment strategy for the coming years. Soon after the Coastal Genesis 2 programme ended in 2021, the Minister of Infrastructure and Water Management decided to adopt the advised preferred strategy.

Methods

The first part of this thesis involves policy analytical research in which the frameworks and conceptual models applicable to the Coastal Genesis 2 programme are investigated. This involves the explication of frameworks and conceptual models developed within the programme itself as well as the distillation of the frameworks and conceptual models in published literature that are considered applicable. This serves to elucidate which concepts can be used to describe the process followed, the knowledge types developed, the existing and recommended policy, and the outputs, outcomes and impact of the programme.

In the second part of the thesis, the effect of (accelerated) sea level rise on the long-term morphological development of the Wadden Sea is elaborated theoretically using the aggregated long-term morphodynamic model ASMITA. In this analysis, the morphology of the Wadden Sea basins is schematised as a single element, using the average depth of a Wadden Sea basin as a system variable. Projections of the long-term development of the Wadden Sea are made for various sea level rise scenarios. The effect of sea level rise on the export of sediment from the North Sea coast to the Wadden Sea is examined specifically, as this affects the long-term sediment budget of the coast and hence determines the sustainability of the 'dynamic preservation' policy. For this analysis, the Wadden Sea basins are schematised into three elements, namely: the tidal flats, the channels and the ebb tidal delta.

Conclusions and insights

Policy analysis methods were applied in determining the strategic goals, tactical approach and operational objectives of the 'dynamic preservation' policy. The analysis shows that in the translation of the tactical objectives to operational practice, the sediment budget of the coast plays a crucial role. The tactical approach depends upon a conceptual model of the long-term sediment budget under the influence of relative sea level rise. In the Coastal Genesis 2 programme, the pivotal role of this conceptual model of the long-term sediment budget of the Dutch coast, and its underlying assumptions, was explicated. Proposals for revising and renewing this key conceptual description of the sediment budget have arisen as a result of the Coastal Genesis 2 programme. Substantiating and refining the sediment budget, in combination with experience gained in sediment nourishment practice, formed the core of the Coastal Genesis 2 knowledge programme.

The case study reveals that the policy development process can be described by a "Research for Policy" cycle, an adapted form of the Integrated Coastal Management (ICM) learning cycle. The case study also reveals that outputs of the Coastal Genesis 2 research programme cover a variety of knowledge types, namely measurement data, simulation models, system understanding, conceptual models, and policy and practice, as distinguished in a 5-element framework. The research outcomes are shown to arise from the interactions between these knowledge types, through research activities which collect and analyse new and existing measurement data, calibrate, develop and run simulation models, and deliver new insights that build system understanding. Policy and practice impacts are shown to arise through the revision of the shared conceptual model of the long-term sediment budget of the Dutch coast under the influence of relative sea level which acts as intermediary in knowledge interactions between science and policy. Within the Coastal Genesis 2 programme, the translation of the new scientific insights into an updated conceptual model of the sediment budget enabled the formulation of policy alternatives (in this case nourishment strategies). This conceptualization provided the connecting link between scientists and policy makers. Essentially, it is the degree to which the revised or new conceptual models represent a shared conceptualisation of the biophysical dynamics and management of the (Dutch) coastal system that determines whether the policy advice is adopted or not. This highlights the pivotal role of shared conceptual models as intermediary between science, policy and practice - an insight that may prove useful in the design of future research programmes aiming to influence policy, nationally and internationally.

The theoretical analysis of the long-term morphological development of the Wadden Sea shows that the development of a Wadden Sea basin is determined by both sea level rise and the current morphological state of the basin. As sea level rises, there is a lag in the morphological response, which means that the basin will be deeper than the systems morphological equilibrium. However, as long as the rate of sea level rise is constant and remains below the critical rate for drowning, this difference becomes constant and a dynamic equilibrium is established. The magnitude of the deviation from the morphological equilibrium, and the time required to reach a dynamic equilibrium, increase non-linearly with increasing rates of sea level rise. As a result, the response of a tidal basin to relatively rapid sea level rise is similar regardless of whether the rate of sea level rise is just below, at or above the critical limit. A tidal basin will experience a long process of “drowning” when the sea-level rise rate exceeds about 80% of the critical limit.

It is the basin-specific critical rate of sea level rise that determines the response of a tidal basin to accelerated sea level rise. This means that different tidal basins in the Wadden Sea will respond very differently to the same acceleration of sea level rise. A Wadden Sea basin that experiences a rate of sea level rise that is higher than its critical rate will extract sediment from the North Sea coast at a maximum rate. The magnitude of this export is equal to the maximum transport capacity of the tidal inlet. Although the magnitude is relatively uncertain, the trend in sediment exchange is very clear. There will continue to be significant exports from the North Sea coast to the Wadden Sea basins. Such an export of sediment to the Wadden Sea will lead to a negative sediment budget in the coastal zone and thus to the retreat of the North Sea coast of North North-Holland and the Wadden Islands, if no additional sources of sediment are available for these areas. In order to sustainably and dynamically preserve the coasts of these areas in the future, policy and management will have to take into account an almost continuous sediment export from the North Sea coast to the Wadden Sea.

Projections of the sediment export from the North Sea coast to the Wadden Sea show that there are distinct differences between the western part of the Wadden Sea (the basins of Texel, Vlie and Eierland inlets) and the eastern part (the basins of Ameland, Pinkegat and Zoutkamperlaag inlets). In the eastern part, where the present morphology is likely close to dynamic equilibrium, the export rate in 2100 varies from about 0.8 million m^3 per year for the lowest sea level rise scenario (2 mm per year) to about 2.5 million m^3 per year for the highest sea level rise scenario (17 mm per year), a factor of 3.1 (310%). For the western part, where the large sediment demand due to the closure of the Zuiderzee in 1932 has still not damped out, the sediment export rate varies between about 4.2 and 6.0 million m^3 per year, a factor of 145% between the highest and lowest sea level rise scenarios. This shows that the western and eastern Wadden Sea responds differently to the same sea level rise.

Application

By pinpointing the uncertainties and assumptions associated with the conceptual models underpinning coastal policy, this research revealed that the Coastal Genesis 2 programme has served to refine and influence future coastal policy. Indeed, the revision of the conceptual model of the long-term sediment budget of the Dutch coast, and the associated calculation rule, enabled the development of a range of potential nourishment strategies and facilitated decision-making on a preferred strategy at the political level. With the adoption of the preferred nourishment strategy, the updated conceptual model now directly underpins the current coastal policy.

Scientists and policy makers can draw inspiration from this research at the science-policy interface. The “Research for Policy” cycle, the Strategic, Tactical and Operational objectives hierarchy, and the 5-element framework of knowledge types are conceptual models and frameworks that may be applied in setting up research programmes that aim to influence coastal policy, and possibly other environmental policy domains. It is crucial to connect the scientific insights to the conceptual models underpinning policy when setting up such new Research for Policy programmes as it is through this conceptualization that impact on policy can be achieved. However, the applicably of the frameworks and conceptual models identified in this research is likely limited to situations where integrated coastal management is institutionally anchored, policy development is ongoing, and measurement data is available as a basis for developing system knowledge and refining conceptual models.

Research outlook

Many aspects of the frameworks and conceptual models analysed in this research require further research, including deepening of the scientific insights that underpin them, and further investigation regarding their applicability in Dutch and international coastal flood and erosion risk management. Without aiming to be complete, suggestions for further research are:

- International application and testing of the developed policy analytical frameworks and conceptual models. Initial application in neighbouring countries would seem to offer suitable testing grounds, because these countries resemble the Netherlands in terms of their biophysical environment and organisational settings.

- Further reducing uncertainties in the long-term sediment budget of the Dutch coast by further elaboration of the revised conceptual model presented in this study.

- Improvement and further development of the models for the long-term morphological development of the Wadden Sea. Specifically, attention is needed for the development of the equilibrium morphology concept within the Wadden Sea basins. The interaction of channels and flats is particularly important here, because the channels are both the sink and the source for the tidal flat sediments and the tidal flats play a crucial role in the Wadden ecosystem.

- Continued assessment of the suitability of the 'dynamic preservation' policy for maintaining flood safety levels, uses, and values of the Dutch coastal system in the long term.

- International research into the role of conceptual models in flood and erosion risk management. The results of this study highlight the pivotal role of shared conceptual models in policy development. Results from international case studies could support these conclusions or provide additional perspectives on the science-policy interface in coastal management.

Samenvatting

Verbinden van wetenschap en beleid in het Nederlands kustbeheer
De rol van systeembegrip en conceptuele modellen

Wereldwijd staan kusten onder druk, onder andere door intensief menselijk gebruik en klimaatverandering. Vanaf de jaren '70 van de vorige eeuw kwam geleidelijk het integraal kustbeheer en -beleid op, een strategische benadering waarbij gestreefd wordt naar duurzame integratie van de soms tegengestelde belangen van menselijk gebruik, natuurwaarden en bescherming tegen overstromingen. De Europese Unie definieert integraal kustbeheer als "*een dynamisch, multidisciplinair en iteratief proces ter bevordering van het duurzame beheer van kustgebieden. Het omvat de volledige cyclus van het verzamelen van informatie, planning (in de breedste zin van het woord), besluitvorming, beheer en monitoring van de implementatie*".

Voor het ontwikkelen en implementeren van doelmatig integraal (kust)beleid is een betekenisvolle interactie tussen beleidsmakers en wetenschappers nodig, niet alleen in Nederland maar wereldwijd. Het overbruggen van de afstand tussen wetenschap en beleid blijft daarbij vaak problematisch. Voor wetenschappers is het niet eenvoudig precies die toegespitste kennis te vergaren die direct gekoppeld kan worden aan beleidsvraagstukken. Anderzijds staan kustbeheerders over de hele wereld voor de uitdaging om wetenschappelijke inzichten te vertalen naar haalbaar en doelgericht beleid en de praktijk. Het ontwikkelen, implementeren en (laten) uitvoeren van specifiek onderzoek voor beleidsprogramma's blijft uitdagend, zowel voor kustbeheerders als voor wetenschappers. Niet voor niets identificeert het Milieuprogramma van de Verenigde Naties (UNEP) het verbinden van wetenschap met beleid als een van de grootste uitdagingen voor duurzaamheid in de 21e eeuw.

Nederland heeft een lange geschiedenis van overstromings- en erosierisicobeheer voor de kust, ondersteund door systeembegrip, gebaseerd op monitoringsdata en simulatie- en conceptuele modellen. In Nederland zijn de onderzoeks- en beleidsnetwerken voor de kust met elkaar verbonden, waardoor onderzoek naar de interactie tussen wetenschap en beleid daadwerkelijk mogelijk, en bovendien intrigerend is. Dit is dan ook de centrale vraag in het hier gepresenteerde onderzoek: hoe kunnen wetenschap en beleid verbonden worden voor duurzaam kustbeheer, niet op wereldschaal, maar regionaal in Nederland?

Deze studie onderzoekt de interactie tussen wetenschap en beleid aan de hand van het Kustgenese 2 programma, een grootschalig beleidsvoorbereidend wetenschappelijk onderzoeksprogramma in Nederland. Het Kustgenese 2 programma is onderzocht om meer inzicht te krijgen in de wijze waarop dit onderzoeksprogramma is opgezet, hoe de uitdaging is aangegaan om wetenschap en beleid met elkaar te verbinden en hoe beleidsimpact is ontstaan. Door deze casestudy diepgaand te onderzoeken kunnen zowel de interacties op het grensvlak tussen wetenschap en beleid, als wel de context waarin deze interacties plaats hebben gevonden worden vastgesteld.

Dit onderzoek bestaat uit twee delen. Het eerste deel onderzoekt hoe het Kustgenese 2 programma heeft bijgedragen aan kustbeleid en kustbeheer. Specifiek wordt gekeken naar de wijze waarop het programma heeft bijgedragen aan het overbruggen van de afstand tussen wetenschap en beleid. Het (herziene) conceptuele model van de lange-termijn sedimentbalans van de Nederlandse kust speelt een centrale rol in deze analyse. Het tweede deel van het onderzoek gaat in op een van de belangrijkste onzekerheden in dit conceptuele model, namelijk de lange-termijn morfologische ontwikkeling van de Nederlandse Waddenzee. Het eerste deel van dit onderzoek is gericht op het beantwoorden van de volgende onderzoeksvragen:

1. Hoe is het onderzoeksprogramma Kustgenese 2 ontstaan en hoe is het georganiseerd?, en
2. Hoe heeft het onderzoeksprogramma Kustgenese 2 het Nederlandse kustbeleid en -beheer beïnvloed?

Het tweede deel van het onderzoek is gericht op het beantwoorden van de volgende onderzoeksvragen:

3. Hoe zullen de getijdenbekkens in de Waddenzee zich op de lange termijn morfologisch ontwikkelen en welke invloed zal dit hebben op de lange-termijn sedimentbalans van de Nederlandse kust?, en
4. Wat zijn de implicaties van de ontwikkeling van de Waddenzeebekkens voor de houdbaarheid van het Nederlandse kustbeleid en -beheer?

Achtergrond casestudy

In Nederland is het beheer van de kust een taak van het Ministerie van Infrastructuur en Waterstaat, waarbij Rijkswaterstaat, als uitvoeringsorganisatie van dit ministerie, twee rollen heeft: die van beleidsadviseur en van uitvoerder van het beleid. Het beleid wordt opgesteld door de beleidsdepartementen van het ministerie en vastgesteld door het parlement. Naast Rijkswaterstaat hebben specifiek de waterschappen een belangrijke rol in het beheer van de kust. De waterschappen zijn verantwoordelijk voor het beheer van het grootste deel van de zandige en harde waterkeringen langs de kust en moeten ervoor zorgen dat die waterkeringen blijven voldoen aan de daaraan gestelde eisen.

De kern van het huidige kustbeleid is vastgelegd in de eerste kustnota uit 1989. Deze nota introduceert het 'dynamisch handhaven' van de kust, een kustbeleid dat vervolgens aangenomen is door het parlement. Het doel van dit beleid is het "*duurzaam handhaven van de veiligheid en duurzaam behoud van functies en waarden in duingebieden*". Waarbij er gekozen is voor zandsuppleties als belangrijkste middel voor kustverdediging. Sinds de eerste kustnota zijn er verschillende aanscherpingen van het beleid tot dynamisch handhaven van de kust geweest. De kern van het beleid is echter gelijk gebleven, met als belangrijkste aanscherping de introductie van het kustfundament rond 2000.

Door (versnelde) zeespiegelstijging zal het jaarlijks te suppleren volume zand geleidelijk toenemen. Dit leidde rond 2014 tot vragen over de houdbaarheid van het beleid van 'dynamisch handhaven' op langere termijn. Om die reden heeft Rijkswaterstaat in opdracht van het Ministerie van Infrastructuur en Waterstaat het onderzoeksprogramma Kustgenese 2 gestart. Dit programma had tot doel specifieke kennis te genereren over het Nederlandse zandige kustsysteem, om besluiten over toekomstig beleid en beheer van de Nederlandse kust te onderbouwen. Rijkswaterstaat heeft op basis van de resultaten van dit programma een advies voor de suppletiestrategie voor de komende jaren opgesteld. Met het overnemen van dit advies door de Minister van Infrastructuur en Waterstaat werd het Kustgenese 2 programma in 2021 afgesloten.

Methoden

Het eerste deel van het hier gepresenteerde onderzoek bestaat uit beleidsanalytisch onderzoek. Op basis van literatuur is voor het Kustgenese 2 programma onderzocht welke beleidsanalytische raamwerken en conceptuele modellen van toepassing zijn. Dit betreft zowel de raamwerken en conceptuele modellen die in het programma zijn ontwikkeld, als wel de raamwerken en conceptuele modellen die van toepassing blijken te zijn op het programma. Uitgewerkt is welke raamwerken gebruikt kunnen worden voor het beschrijven van het gevolgde proces, de ontwikkelde kennistypen, het bestaande en geadviseerde beleid en de producten, resultaten en impact van het programma.

Voor het tweede deel van het onderzoek zijn de effecten van (versnelde) zeespiegelstijging op de lange-termijn morfologische ontwikkeling van de Waddenzee theoretisch uitgewerkt met behulp van het geaggregeerde morfodynamische model voor de lange termijn ASMITA. Voor de theoretische analyse is morfologie van de Waddenzeebekkens beschreven als één element, met de gemiddelde diepte van een Waddenzee bekken als systeemvariabele. Mede op basis van deze theoretische analyse zijn met ASMITA projecties gemaakt van de lange-termijn ontwikkeling van de Waddenzee voor verschillende scenario's van zeespiegelstijging. Daarbij is specifiek gekeken naar het effect van zeespiegelstijging op de export van sediment van de Noordzeekust naar de Waddenzee omdat deze export van direct belang is voor de lange-termijn sedimentbalans van de kust en de houdbaarheid van beleid van 'dynamisch handhaven'. Voor deze analyse zijn de Waddenzeebekkens geschematiseerd in drie elementen, de wadplaten, de geulen en de buitendelta.

Conclusies en inzichten

Door middel van beleidsanalyse is bepaald wat de strategische doelen, tactische benadering en operationele werkwijze van het 'dynamisch handhaven'-beleid zijn. Uit deze analyse blijkt dat op tactisch niveau, met doorvertaling naar operationele werkwijze, de sedimentbalans van de kust een cruciale rol speelt. De tactiek van het beleid blijkt gestoeld te zijn op een conceptueel model van de lange-termijn sedimentbalans onder invloed van relatieve zeespiegelstijging. Voor het Kustgenese 2 programma zijn het conceptuele model van de lange-termijn sedimentbalans van de Nederlandse kust en de onderliggende aannamen kritisch beschouwd. Op basis van de resultaten zijn voorstellen gedaan voor het herzien en vernieuwen van deze conceptuele beschrijving van deze sedimentbalans. Het uitwerken en onderbouwen van de sedimentbalans vormde, samen met de in de praktijk opgedane ervaring met suppleties, de kern van het kennisprogramma Kustgenese 2.

De casestudy laat zien dat het beleidsproces kan beschreven worden door middel van een "Research for Policy" cyclus geïnspireerd op de "Integrated Coastal Management (ICM) learning cycle". Tevens laat de casestudy zien dat de resultaten van het Kustgenese 2 kennisprogramma uit verschillende kennistypen bestaan, namelijk meetgegevens, systeembegrip, simulatiemodellen, conceptuele modellen en kennis over de achtergrond van beleid en beheer. De nieuwe wetenschappelijke inzichten ontstaan uit de interactie tussen deze kennistypen. De ontwikkelde kennistypen en hun interacties kunnen beschreven worden aan de hand van een Vijfelementen raamwerk. Uit dit raamwerk blijkt dat de doorvertaling van wetenschappelijke inzichten naar gedeelde nieuwe of vernieuwde conceptuele modellen, cruciaal is om een brug te slaan tussen wetenschap en beleid.

Binnen het Kustgenese 2 programma maakte de doorvertaling van de nieuwe wetenschappelijke inzichten naar een geactualiseerd conceptueel model van de sedimentbalans van de kust, het formuleren van beleidsalternatieven (in dit geval suppletiestrategieën) mogelijk. Deze conceptualisatie was hierbij de verbindende schakel tussen wetenschappers en beleidsmakers. Deze conclusie laat zien dat in de Nederlandse situatie voor het opereren op het grensvlak tussen wetenschap en beleid cruciaal is dat wetenschappelijke inzichten leiden tot gedeelde, vernieuwde conceptualisaties van de werking van de kust. Met een dergelijke gedeelde conceptualisatie kan de impact van wetenschappelijk onderzoek op beleid en uitvoering vergroot worden.

De theoretische analyse van de lange-termijn morfologische ontwikkeling van de Waddenzee laat zien dat de ontwikkeling van een Waddenzeebekken bepaald wordt door zowel de zeespiegelstijging als de huidige morfologische toestand van het bekken. Naarmate de zeespiegel stijgt, treedt er een vertraagde morfologische respons op, wat betekent dat een bekken dieper zal zijn dan het morfologische evenwicht van het systeem. Zolang de snelheid van de zeespiegelstijging echter constant is en onder de kritische snelheid voor verdrinking blijft, wordt dit verschil constant en ontstaat er een dynamisch evenwicht. De grootte van de afwijking van het morfologisch evenwicht, en de tijd die nodig is om het dynamische evenwicht te bereiken, nemen niet-lineair toe met toenemende snelheid van zeespiegelstijging. Als gevolg hiervan is de reactie van een getijdenbekken op een relatief snelle stijging van de zeespiegel vergelijkbaar, ongeacht of de snelheid van de zeespiegelstijging net onder, op of boven de kritische grens ligt. Een getijdenbekken zal een langdurig proces van "verdrinking" ondergaan wanneer de zeespiegelstijging ongeveer 80% van de kritische zeespiegelstijgingssnelheid overschrijdt.

Het is de bekken specifieke kritische snelheid van zeespiegelstijging die de reactie van een getijdenbekken op versnelde zeespiegelstijging bepaalt. Dit betekent dat verschillende getijdenbekkens in de Waddenzee heel verschillend zullen reageren op dezelfde versnelling in de snelheid van zeespiegelstijging. Een Waddenzeebekken dat een snelheid van zeespiegelstijging ondervindt die hoger is dan zijn kritische snelheid zal maximaal sediment onttrekken uit de Noordzeekust. De grootte van deze export is gelijk aan de maximale transportcapaciteit van het zeegat. Hoewel de omvang van deze export relatief onzeker is, is de trend in de sedimentuitwisseling zeer duidelijk. Er zal aanhoudend een aanzienlijke export plaatsvinden van de Noordzeekust naar de Waddenzeebekkens. Een dergelijke export van sediment naar de Waddenzee zal leiden tot een negatieve sedimentbalans in de kustzone en daarmee tot terugtrekking van de Noordzeekust van Noord Noord-Holland en van de Waddeneilanden, als er geen aanvullende bronnen van sediment beschikbaar zijn voor deze gebieden. Om ook in de toekomst de kust van deze gebieden duurzaam dynamisch te handhaven, zullen beleid en beheer rekening moeten houden met een vrijwel voortdurende sedimentexport uit de Noordzeekust naar de Waddenzee.

De projecties van de sedimentexport uit de Noordzeekust naar de Waddenzee laten zien dat er duidelijke verschillen zijn tussen het westelijke deel van de Waddenzee (de bekkens van de Zeegaten van Texel en het Vlie en het Eierlandse Gat) en het oostelijk deel (de bekkens van Ameland, Pinkegat en Zoutkamperlaag). In het oostelijke deel, waar de huidige morfologie waarschijnlijk dicht bij het dynamische evenwicht ligt, varieert de exportsnelheid in 2100 van ongeveer 0,8 miljoen m^3 per jaar voor het laagste zeespiegelstijgingsscenario (2 mm per jaar) tot ongeveer 2,5 miljoen m^3 per jaar voor het hoogste scenario (17 mm per jaar), een factor 3,1 (310%). Voor het westelijk deel, waar de grote vraag naar sediment als gevolg van de sluiting van de Zuiderzee in 1932 nog steeds niet is weggewerkt, varieert de exportsnelheid van sediment tussen ongeveer 4,2 en 6,0 miljoen m^3 per jaar, een factor van ongeveer 145% tussen de hoogste en laagste SLR-scenario's. Hieruit blijkt dat de westelijke en oostelijke Waddenzee anders reageren op gelijke zeespiegelstijging.

Toepassing
Dit onderzoek laat zien dat het Kustgenese 2 programma, door het identificeren en aanscherpen van de aan het kustbeleid ten grondslag liggende conceptuele modellen met bijbehorende onzekerheden en aannames, het toekomstige kustbeleid direct heeft beïnvloed. Het vernieuwen van het conceptuele model van de lange-termijn sedimentbalans van de Nederlandse kust, met bijbehorende rekenregel, maakte het opstellen van suppletiestrategieën en besluitvorming op politiek niveau mogelijk. Met de overname van de voorkeurssuppletiestrategie ligt het vernieuwde conceptuele model nu direct ten grondslag aan het vigerende kustbeleid.

Dit kan als inspiratie dienen voor zowel wetenschappers als beleidsmakers. De "Research for Policy" cyclus, de Strategisch-Tactisch en Operationele doelen hiërarchie en het Vijfelementen raamwerk voor kennistypen kunnen toegepast worden voor het opzetten van beleidsvoorbereidende wetenschappelijke onderzoeksprogramma's voor de kust, maar mogelijk ook voor andere beleidsdomeinen. Bij het opzetten van dergelijke nieuwe onderzoeksprogramma's is het terugbrengen van de wetenschappelijke inzichten naar de conceptuele modellen die ten grondslag liggen aan het beleid cruciaal. Het is via deze conceptualisatie dat impact op beleid bereikt kan worden. De toepasbaarheid van de geïdentificeerde raamwerken en conceptuele modellen is waarschijnlijk beperkt tot situaties waarbij sterke kustbeheerorganisaties geleidelijke beleidsontwikkeling kunnen begeleiden en organiseren en waar veel data beschikbaar is als basis voor de ontwikkeling van systeemkennis en modellen.

Vervolg onderzoek
Vanuit wetenschappelijk perspectief kunnen vele aspecten van de beschreven raamwerken en conceptuele modellen worden onderzocht, variërend van verdere doorontwikkeling tot verdieping van de wetenschappelijke inzichten die eraan ten grondslag liggen en de mogelijke verdere toepasbaarheid in het Nederlandse en internationale kust overstromings- en erosierisicobeheer. Zonder compleetheid te beogen, volgen hier suggesties voor vervolgonderzoek:

- Internationale toepassing en evalueren van de ontwikkelde beleidsanalytische raamwerken en modellen. In eerste instantie lijkt toepassing in de buurlanden het meest voor de hand liggend omdat deze landen qua fysische en bestuurlijke setting op Nederland lijken.

- Het verder verkleinen van onzekerheden in de lange-termijn sedimentbalans van de Nederlandse kust aan de hand van aanscherping van het in dit onderzoek gepresenteerde herziene conceptuele model.

- Verbetering en doorontwikkeling van de modellen voor de lange-termijn morfologische ontwikkeling van de Waddenzee. Specifiek met aandacht voor de ontwikkeling van de evenwichtsmorfologie binnen de Waddenzeebekkens. Met name de interactie van geulen en platen is hierbij van belang, omdat de geulen zowel de bron als de put voor het sediment van de platen zijn en de platen een cruciale rol vervullen in het Waddenecosysteem.

- Blijvend toetsen van de geschiktheid van het 'dynamisch handhaven' beleid voor behoud van veiligheid, functies en waarden van de Nederlandse kust op de lange termijn.

- Internationaal onderzoek naar de rol van conceptuele modellen in overstromings- en erosierisicobeheer. De resultaten van dit Nederlandse onderzoek benadrukken de cruciale rol van gedeelde conceptuele modellen in beleidsontwikkeling. De resultaten van internationale casestudies zouden deze conclusies kunnen ondersteunen of aanvullende perspectieven op beleidsontwikkeling kunnen bieden.

1

Introduction

1.1 Integrated Coastal Management and its challenges

1

Integrated coastal management (ICM) is a comprehensive approach to managing coastal areas, including all their water, land and living resources. It aims to address environmental and social issues while stimulating sustainable development by balancing uses and demands for coastal resources. Although ICM definitions abound (see Cicin-Sain and Knecht 1998; Olsen 1998; Stojanovic, Ballinger, and Lalwani 2004; Christie 2005; Godschalk, 2009), in essence Integrated Coastal Management is a simple and common sense approach to the use, protection and conservation of oceans, coastal waters and landscapes (DFO, 2002). Historically, many coastal management concepts were introduced in the 1970s and then progressively embedded in national policies and legislation (Botero, et al., 2023). Over time, the term "integrated" was added to coastal management to highlight the need for the integration of (often opposing) interests of stakeholders and disciplinary knowledge (Post and Lundin, 1996; Taljaard et al., 2011). By 2000 the European Union formalized the adoption of integrated coastal management, defining it as "*a dynamic, multidisciplinary and iterative process to promote sustainable management of coastal zones. It covers the full cycle of information collection, planning (in its broadest sense), decision making, management and monitoring of implementation*" (EEA, 2000). ICM draws upon *"the informed participation and cooperation of all stakeholders to assess the societal goals in a given coastal area, and to take actions towards meeting these objectives. ICM seeks, over the long-term, to balance environmental, economic, social, cultural and recreational objectives, all within the limits set by natural dynamics."* (EEA, 2000).

Adapting and refining the ICM concept and the policies for its implementation have been essential for the sustainable development of coastal areas within Europe and globally. Many challenges remain, as over-development and the overuse of coastal areas is still widespread (EEA, 2003; Neumann et al., 2017). In the coming decades, sustainable ICM policies will be required as population growth, biodiversity loss and climate change effects continue to increase along coasts (Godschalk, 2010; Neumann et al., 2017). Climate change is predicted to cause a significant rise in global mean sea level in the coming century and thereafter. Projections range from an increase of 0.3 m to 1.0 m in 2100 (likely range, Shared Socio-economic Pathway 1-2.6 to 5-8.5, 17th-83rd percentile) depending on the global greenhouse gas emissions (IPCC, 2021). Climate change will also cause higher storm surge and increased erosion of sedimentary coasts (Hinkel et al., 2013). Combined with the increasing pressure of human activities, this will have a detrimental impact on coastal zones. If coastal management practices and policies do not accommodate these changes, many coasts will face increased vulnerability to flooding, erosion, biodiversity loss, and the risks to, and costs of coastal infrastructure will increase.

Therefore, new in-depth knowledge is needed on an ongoing basis to adapt and refine ICM policy and practice. Scientists, policy-makers and practitioners recognise and have agendised these issues (see Godschalk, 2010; Wang et al., 2023). However, bridging the science-policy interface remains problematic. The challenge of translating scientific insights into feasible and fit for purpose policies and practices is faced by coastal management authorities globally, as is developing, implementing and executing dedicated research for policy programmes. It is with reason that the United Nations Environment Programme identifies connecting science to policy as one of the top challenges for sustainability in the 21st century (UNEP, 2012). Indeed, complex recursive interactions have been identified at the interface between science and policy (Engels, 2005), refuting the traditional linear and technocratic model of scientific advice to governments (van Eeten, 1999). Within the fields of science studies and policy analysis, the science policy interface (SPI) is defined as *"social processes which encompass relations between scientists and other actors in the policy process, and which allow for exchanges, co-evolution, and joint construction of knowledge with the aim of enriching decision-making"* (van den Hove, 2007). As the relationship between science and policy has moved towards a recursive rather than a unidirectional relationship, the boundaries have become less clear (Weingart, 1999), and the necessity for boundary spanning work more apparent (Bednarek et al., 2018). Managing the integration of science and policy therefore continues to pose a significant challenge (Bednarek et al., 2018), with many authors investigating how to bring scientific advice to policy makers and practitioners (Briggs and Knight, 2011; Wesselink et al., 2013; Lidskog, 2014; Sokolovska et al., 2019; Gluckman et al., 2021) and more specifically how to equip them with information and tools to assess and manage their coasts (Bremer and Glavovic, 2013a, 2013b; Dale et al., 2019). In the Netherlands there is a long history of coastal flood risk management, supported by extensive data-based assessment, simulation and conceptual modelling (see Rijkswaterstaat, 1990) that serves to deepen insights into biophysical changes in the Dutch coastal system. Moreover, the science and policy networks are interconnected, making research on knowledge flows at the science-policy interface possible and intriguing (see Lodder and Slinger, 2022). Indeed, the central issue at the heart of the thesis is: how to connect science and policy in developing sustainable coastal management policies, not at the global scale, but regionally in the Netherlands.

1.2 Dutch Coastal Flood and Erosion Risk Management

The Netherlands is a low-lying country with a sediment-rich coastal system, comprising a closed beach-dune coast (Holland Coast) and interrupted barrier coasts with tidal basins (Wadden Sea and Southwest Delta, see Figure 1-1, Map of The Netherlands with key geographic locations.

Figure 1-1, *Map of The Netherlands with key geographic locations.*

Due to its geographical position in the delta of the rivers Rhine, Meuse and Scheldt, the coast consists in the main of sediments; no natural bedrock exists, only man-made hard structures (TNO-GDN, 2023). As a consequence, the coast is vulnerable to coastal erosion. Indeed, gradual erosion of the Dutch coast occurs owing to sea level rise, the natural redistribution of sand, and large scale human interventions such as the construction of tidal barriers. On longer timescales, the gradual erosion is anticipated to cause an increased risk of flooding and enhanced erosion of coastal dunes and infrastructures located in dune areas. Concomitant impacts on the natural environment, recreation and potable water extraction are also anticipated.

Major parts of the Dutch coastal zone comprise areas with high natural value, fulfilling an important function in the coastal ecosystem. The Wadden Sea is of special interest in this respect. It is *one of the last remaining large-scale, intertidal ecosystems where natural processes continue to function largely undisturbed.* Indeed, it *is the largest coherent system of intertidal sand and mud flats in the world. It is a temperate, relatively flat, coastal wetland environment, formed by intricate interactions between physical and biological factors that have given rise to a multitude of transitional habitats such as tidal channels, sandy shoals, sea-grass meadows, mussel beds, sandbars, mudflats, salt marshes, estuaries, beaches and dunes. The area is home to numerous plant and animal species (adapted from Unesco, 2009).* The Wadden Sea is key in managing coastal flood and erosion risk in The Netherlands. The Wadden Sea imports sediments from the coastal zone in response to sea level rise (SLR) and engineering interventions (e.g. the Closure Dam) and is therefore considered a sediment sink in the sediment budget of the Dutch coast (Wang et al., 2018). Further, the Wadden Sea (including the barrier islands) reduces the flood risk of the low-lying coastal areas in the provinces of North-Holland, Friesland and Groningen as it acts to dampen the height of incoming waves from the North Sea. The Dutch Coastal Flood and Erosion Risk Management (CFERM) policy (Min. VenW, 1990; Min. VenW, 2000) aims to compensate the erosive loss of sediment from the coast, and keep pace with SLR, by nourishing the beach or the shoreface with sediment sourced from the bed of the North Sea. This policy, known as the “dynamic conservation strategy” (also referred to as dynamic preservation) was developed using scientific insights from the Coastal Genesis (Kustgenese) research programme from the 1980’s and 1990’s. This earlier research programme can be viewed as a concerted scientific and policy effort focused on halting structural erosion of the Dutch coastline (Min. VenW, 1990; Stive et al., 1991; Mulder et al., 2011). Nowadays the coastline and the coastal foundation (the area between the landward boundary of the dunes and the 20 m iso-depth line) are nourished with offshore sediments. Anticipating a future acceleration in sea level rise, this management strategy may require a significant increase in the annual nourishment volume, raising questions on the sustainability of the strategy. Therefore, Rijkswaterstaat initiated, funded, and coordinated (together with research institutes and universities) the Coastal Genesis 2 (Kustgenese 2) research programme from 2015 to 2021, aiming for the development of a future-proof long-term coastal management strategy (Wang et al., 2023; Rijkswaterstaat, 2020).

1.3 Organisation of Dutch Coastal Flood and Erosion Risk Management and Coastal Genesis 2

Coastal Flood and Erosion Risk Management in the Netherlands is organized across three levels of government, namely at (i) national, (ii) regional and (iii) local level (Mulder et al., 2011). At the national level the Ministry of Infrastructure and Water Management is tasked with the development and implementation of CFERM policy for the whole Dutch coast. The five coastal provinces and the six water boards operating along the coast are tasked with implementing the national policy at regional level. At local level, municipalities also play a role in the implementation of CFERM. Within the Ministry of Infrastructure and Water Management the legislative responsibilities relating to policy development are split from the executive responsibilities relating to policy implementation. Accordingly, there are policy directorates and operational directorates. Policy directorates are tasked with developing and setting policy, whereas the executive/operational directorates are tasked with implementation and control (auditing). For CFERM the responsible policy and operational directorates are the Directorate General Water and Soil (DGWB) and Rijkswaterstaat (DG RWS), respectively. DGWB sets policy, provides policy advice to elected decision makers, and determines the assignments and funding of the relevant operational directorates. Rijkswaterstaat's tasks are (i) to implement policy, (ii) to organize and conduct research to support policy development and implementation, and (iii) to advise relevant policy directorates on policy. In the latter task of providing advice on policy to DGWB, Rijkswaterstaat acts as policy advisor or broker, whereas in the first role of implementing policy Rijkswaterstaat is a coastal management practitioner. In the Dutch situation there is a long history of CFERM and strong links between science and policy, with personal communication between scientists and high-ranking policy makers, which is often not the case internationally (see Engels, 2005). This makes policy-driven research possible and the Dutch CFERM science-policy interactions particularly interesting to investigate (see Lodder and Slinger 2022). The initiation of the Coastal Genesis 2 research programme (CG2), as a follow on to the knowledge and understanding acquired in the first Coastal Genesis programme, also provides a fit-for-purpose case study on bridging the science-policy interface.

1.4 The knowledge gap and research questions

To address the challenge of connecting science to policy, this thesis investigates the role of science in contributing to Dutch CFERM policy and practice. In particular, it seeks to discover how the CG2 research programme has contributed to coastal management policy and practice.

The process is guided by four research questions. The first two research questions focus on the science-policy interface, first on the origin and organisation of the Coastal Genesis 2 research programme and then on its outputs, outcomes and impact:

1. How did the Coastal Genesis 2 research programme originate and how is it organised?
2. How has the Coastal Genesis 2 research programme influenced Dutch coastal management policy and practice?

In answering the first two questions, the role of key uncertainties in Dutch Coastal Flood and Erosion Risk Management policy and practice, particularly in relation to the long-term sediment budget of the Dutch coast came to light. This led to the choice to focus further on the Dutch Wadden Sea area, addressing the following questions:

3. How will the tidal basins in the Wadden Sea evolve morphologically in the long-term and how will this influence the long-term sediment budget of the Dutch coast?
4. What are the implications of the evolution of the Wadden Sea basins for the sustainability of Dutch coastal management policy and practice?

1.5 Research approach and the positionality of the author

A two-pronged strategy is followed. First the focus lies on the science-policy interface and then the focus shifts to the area of the Dutch coast with the most uncertain geomorphological future development, the Wadden Sea. For the science-policy aspects, this thesis draws on theories and methods from the fields of policy analysis and integrated coastal management (see Slinger, Taljaard, d'Hont 2022) and applies these to the single case study of the Coastal Genesis 2 research programme. For the Wadden Sea investigations, geomorphological system understanding and aggregated simulation modelling with ASMITA (Stive et al., 1998; Stive and Wang, 2003; Townend et al., 2016a, 2016b) provide the theoretical background and methods of analysis. The details of the theories and methods applied are described in each of the 4 papers forming the core of the thesis, as summarized in Table 1-1.

This thesis takes a single case study approach to investigate the role of science in contributing to Dutch coastal flood and erosion risk management policy and practice. It takes the CG2 programme single case study as "an intensive study of a single unit for the purpose of understanding a larger class of units" (Gerring, 2004). In other words, we use the CG2 case to deepen understanding of how policy-driven research programs can be set-up and so address the challenge of connecting science to policy. This is motivated by a conviction that when studying social interactions such as at the science-policy interface, learning from practical examples is as key as developing theories. As Flyvbjerg (2012) states: "*Practical rationality is best understood through cases – whether experienced or narrated – just as judgement is best cultivated and communicated via the exposition of cases*". Through the CG2 case study we pinpoint not only "Why" Dutch CFERM has adapted over time, but also "How" that has happened (Flyvbjerg, 2012, P43) and how this continues to be possible. In focusing on the CG2 as single case study we adhere to three of the five rationales for employing a single case study approach (Yin, 2008, p47-49). Firstly, the CG2 programme represents a "*unique*" case in Dutch science-policy interaction as it is the only case covering CFERM from 2001 onwards. Second it represents a "*relevatory*" case, as the author has unique full access to the CG2 material (see positionality below). Third, it represents a "*longitudinal*" case because the CFERM science-policy interaction can be tracked and analysed at multiple points in time. Since the CG2 programme consisted of multiple sub-projects and diverse aspects of the programme are assessed, the single case study can also be viewed as an "*embedded*" case study (Yin, 2008, p50).

Positionality of the Author

Full access to material on the Coastal Genesis 2 case study was uniquely feasible because the author (Quirijn Lodder) is employed as Principal Advisor: Coastal Flood Risk Management at Rijkswaterstaat (2017 to date). In this position, he is responsible for initiating and guiding Rijkswaterstaat's research projects focusing on the present and future adaptation of the Dutch coast to climate change effects. Drawing on insights from such research and from ongoing coastal management practice, he provides strategic advice to the senior leadership at the Ministry and other Dutch flood risk management organizations.

His position at the interface between science and policy provided the opportunity to investigate, synthesize and reflect upon how science has contributed to Dutch coastal management policy and practice over the last twenty years and what the future holds. He has been intricately involved with coastal policy development and management practice in the Netherlands over this time – a period in which the Coastal Genesis 2 (CG2) programme played a key role.

The CG2 programme is therefore selected as the central case study for this thesis. The initiation phase leading up to the CG2 is taken into account, as are the future implications and impact of the CG2. Major results from the CG2 research programme, demonstrating how scientific insights are implemented in Dutch coastal policy and practice, are published in the "Future Dutch Coast", a virtual special issue of Ocean and Coastal Management (Wang et al., 2023), for which the author served as a guest editor. Three of the independently reviewed articles in the virtual special issue form chapters in this thesis.

The value of adopting such a retrospective insider perspective of a policy process can be that boundary spanning work at the heart of policy process does not go untold (Slinger, 2023). The accompanying, stringent requirement for transparent research methods, a strong theoretical basis, and triangulation between case study data sources to guard against research bias is addressed in this thesis through the independent review process followed for each of the publications (Table 1.1).

Table 1-1, *Theories and methods applied*

	Chapter	Methods	Description
Part I: science-policy interface in Dutch Coastal Flood and Erosion Risk Management	2. The 'research for policy' cycle in Dutch coastal flood risk management: *the Coastal Genesis 2 research programme* Lodder and Slinger, 2022 https://doi.org/10.1016/j.ocecoaman.2022.106066	Analysis of literature and secondary data on the CG2 single case study through the lens of policy analysis and integrated coastal management	This chapter analyses the origin and organization of the Coastal Genesis 2 research programme
	3. The Coastal Genesis 2 research programme: *Outputs, Outcomes and Impact.* Lodder, Q.J. et al., 2023 https://doi.org/10.1016/j.ocecoaman.2023.106499.	Impact analysis of the outputs, outcomes and impacts of the CG2 case study using a 5-element framework developed from policy analysis, literature on the science-policy interface and secondary data from CG2.	This chapter analyses how the Coastal Genesis 2 research programme influenced Dutch coastal management policy and practice
Part II: Future response of the Wadden Sea to Relative Sea Level Rise, assessing one of the key uncertainties in Dutch Coastal Flood and Erosion Risk Management policy and practice	4. Future response of the Wadden Sea tidal basins to Relative Sea Level rise – *An Aggregated Modelling Approach.* Lodder, Q.J. et al., 2019 https://doi.org/10.3390/w11102198.	Theoretical analysis of the impact of SLR on a tidal basin using a simplified single-element aggregated ASMITA model	This chapter analyses the long term sediment budget of the Dutch coast, in particular the Wadden Sea coast. It focusses on the long term evolution of the Wadden Sea basins
	5. Future sediment exchange between the Wadden Sea and North Sea Coast – *Insights based on ASMITA modelling.* Lodder, Q.J. et al., 2022 https://doi.org/10.1016/j.ocecoaman.2022.106067	Analysis and projections of future sediment exchange between the Dutch Wadden Sea and the North Sea using an aggregated three element ASMITA model	This chapter focuses on the implications of uncertainties in the evolution of the Wadden Sea basins for the sustainability of Dutch coastal management policy and practice
Appendix	Dutch experience with sand nourishments for dynamic coastline conservation – *An operational overview.* Brand, E. et al., 2022 https://doi.org/10.1016/j.ocecoaman.2021.106008	Literature and data analysis. Primary data derive from annual bathymetry measurements. Secondary data derive from reports on coastal management practice	Review and analysis of operational implementation of 30 years of Dutch coastal flood and erosion risk management

1.6 Contribution and originality of the research

This thesis brings together the science and policy of managing the Dutch coast in a new way. The role of conceptual models as an intermediary between (empirical) data, system understanding, simulation models and policy and practice is highlighted (Chapters 2 and 3). By developing, investigating and describing the key conceptual models that underpin the current coastal management policy, this research is grounded in science yet deeply linked with the practical implementation of coastal management in The Netherlands. The modelling of key morphological processes has deepened coastal systems understanding (Chapters 4 and 5) and led to key uncertainties being addressed at the science-policy interface of coastal management (Chapters 2, 3 and 6). The research is envisaged to inform policy makers, practitioners and scientists and to help them in navigating the science-policy interface. As such, the research aims to inspire this audience, nationally and internationally, to improve the efficacy of future “research for policy” programmes enhancing both science-based decision-making and policy-driven research pertaining to coasts. In particular, this research aims to serve as an inspiration to the Ministry of Infrastructure and Water Management, including Rijkswaterstaat, in drawing up and developing knowledge programs for policy and practice, for the coast and for other infrastructural networks and application areas, such as rivers, flood defences, waterways and roads.

The specific research contributions are:

- A ‘Research for Policy’ cycle to generate policy-driven research is described.
- Key uncertainties in Dutch coastal policy and practice are identified.
- A conceptual model of the long-term sediment budget for the Dutch coast is identified as playing a pivotal role at the science-policy interface.
- A 5-element framework elucidates the role of measurement data, simulation modelling, systems understanding and conceptual models in the interactions between science and policy and practice.
- Outputs, outcomes and impacts of policy-driven research are analysed using the 5-element framework.
- The dynamic equilibrium and transient development of the Dutch Wadden Sea tidal basins under sea level rise are investigated and described.

- Tidal basins are shown to respond very differently to accelerated sea level rise due to differences in the critical rate of sea level rise.
- A drowning basin is shown to import sediments at the maximum rate so that drowning processes are very slow. This implies that for centuries to come the Wadden Sea will continue to import sediments from the coastal zone.

1.7 Outline

The thesis consists of two main parts and is depicted in Figure 1-2. Part I analyses the science-policy interface in Dutch CFERM, using the CG2 research programme as a case study. Part II analyses the future response of the Wadden Sea to relative sea level rise, one of the key uncertainties in Dutch CFERM policy and practice. The thesis is structured as follows:

- Chapter 1 introduces Integrated Coastal Management and its challenges, Dutch Coastal Flood and Erosion Risk Management, the role of Rijkswaterstaat in Dutch CFERM, the knowledge gap, research questions and the research approach.
- Part I includes Chapters 2 and 3. These chapters analyse the origin and organization of the Coastal Genesis 2 research programme (Chapter 2) and how the CG2 research programme has influenced Dutch coastal management policy and practice (Chapter 3).
- Part II includes Chapters 4 and 5. These Chapters analyse the long-term sediment budget of the Dutch coast, in particular the Wadden Sea coast. Chapter 4 focusses on the long-term evolution of the Wadden Sea basins under sea level rise. Chapter 5 focusses on the implications of uncertainties in the evolution of the Wadden Sea basins for the sustainability of Dutch coastal management policy and practice.
- Chapter 6 presents a synthesis of the research findings and reflects on the role of system understanding and conceptual models in connecting science and policy in coastal management.
- Finally in support of this research, the appendix reviews and analyses the operational implementation of 30 years of Dutch coastal flood and erosion risk management practice.

Figure 1-2, *Structure of the thesis.*

Part I

Science-Policy Interface in Dutch Coastal Flood and Erosion Risk Management

In Part I of this research the science-policy interface in Dutch Coastal Flood and Erosion Risk Management is analysed, using the Coastal Genesis 2 research programme as a case study.

The aim of Chapters 2 and 3 is gain insight into the contribution of the Coastal Genesis 2 program to coastal policy and management. Specifically these chapters present how the program has contributed to bridging the gap between science and policy. The (revised) conceptual model of the long-term sediment budget of the Dutch coast plays a central role in this analysis.

2

The 'Research for Policy' cycle in Dutch coastal flood risk management: the Coastal Genesis 2 research programme

This chapter has been published as:

Lodder, Q.J., Slinger, J.H., 2022. The "Research for Policy" cycle in Dutch coastal flood risk management: The Coastal Genesearch programme. Ocean and Coastal Management 219, 106066. https://doi.org/10.1016/j.ocecoaman.2022.106066

Abstract

The development of the Coastal Genesis 2 research programme and its role in contributing to Dutch coastal policy are described in this chapter. The organisation of policy development related to coastal flood risk and erosion in The Netherlands is addressed, highlighting the division of responsibilities between the policy and operational directorates of the Ministry of Infrastructure and Water Management. A conceptual model of the long term sediment budget of the Dutch coast that underpins the current Coastal Flood and Erosion Risk Management policy is detailed. The role of the operational directorate Rijkswaterstaat in coordinating a 'Research for Policy' cycle as a means of generating new insights on the coastal system and ensuring their subsequent inclusion in a new/revised conceptual model, is highlighted. By detailing the new conceptual model of the long term sediment budget, this chapter demonstrates how key uncertainties related to this model guided the determination of the research agenda for Coastal Genesis 2. The chapter concludes by reflecting briefly on the outcomes of the research programme and the role of the 'Research for Policy' cycle in ensuring the sustainable future of the Dutch coast.

2.1 Introduction

The Netherlands is a low-lying country with a sediment-rich coastal system, comprising a closed beach-barrier coast (Holland Coast) and an interrupted barrier coast with tidal basins (Wadden Sea and Southwest Delta, comprising the Eastern and Western Scheldt). At present the Dutch coast is maintained using a dynamic conservation strategy (also referred to as dynamic preservation), developed using the results from the Coastal Genesis (Kustgenese) research programme from the nineteen eighties and –nineties (Min. VenW, 1990, Zitman et al., 1991, Stive et al., 1991, Mulder et al., 2011). The coastline and the coastal foundation (the area between the landward edge of the dunes and the 20 m depth contour of the North Sea) are maintained using sand nourishments. With accelerating sea level rise (IPCC, 2019 and 2021) this management strategy could require a significant increase in nourishment volumes in the future, raising questions regarding the sustainability of the strategy. Accordingly, Rijkswaterstaat - the operational agency of the Ministry of Infrastructure and Water Management-, initiated the Coastal Genesis 2 (Kustgenese 2) research programme in 2015 aimed at developing a robust and sustainable long term coastal management strategy. This research programme was carried out from 2015 to 2021 in cooperation with Deltares, various universities (via the Dutch Research Council (NWO) project SEAWAD) and private parties. It has culminated in policy advice to the Directorate General Water and Soil, responsible for the coastal management policy of The Netherlands, and has generated scientific insights on the dynamics (both ecological and physical) of the Dutch coastal system, potentially of interest to coastal scientists and managers worldwide. The focus of this chapter does not lie on the specific outcomes of the Coastal Genesis 2 research programme nor on the science-policy interface in general, but on describing and understanding how the research programme originated and its role in contributing to coastal policy development in the Netherlands. In this chapter we therefore first describe how policy development related to coastal flood risk and erosion is organised (Section 2), highlighting a ‘Research for Policy’ cycle. Then we describe the current Coastal Flood and Erosion Risk Management (CFERM) policy (Section 3), including the conceptual model underpinning the policy (Section 4). Next, we move towards a new conceptual model of the long term sediment budget of the Dutch coast (Section 5) and demonstrate how key uncertainties guide the determination of the research agenda for Coastal Genesis 2, highlighting the outcomes of the research programme

(Section 6). We close in Section 7 by reflecting briefly on the role of the 'Research for Policy' cycle in ensuring the sustainable future of the Dutch coast.

2.2 How is Dutch coastal flood risk management policy development organised?

Coastal Flood and Erosion Risk Management in the Netherlands is organized across three levels of government, namely at (i) national, (ii) regional and (iii) local level (Mulder et al., 2011). At the national level the Ministry of Infrastructure and Water Management is tasked with the development and implementation of CFERM policy for the whole of the Dutch coast. The five coastal provinces and the six water boards operating along the coast are tasked with implementing the national policy at regional level. At local level, municipalities also play a role in the implementation of CFERM. Within the Ministry of Infrastructure and Water Management the legislative responsibilities relating to policy development are split from the executive responsibilities relating to policy implementation. Accordingly, there are policy directorates and operational directorates (Figure 2-1), following the Dutch model of separation of power (see Nwanazia, 2021). Policy directorates are tasked with developing and setting policy, whereas the executive/operational directorates are tasked with implementation and control (auditing). All directorate staff are non-elected public servants. The Minister and State Secretary of the Ministry of Infrastructure and Water Management are elected officials, carrying political responsibility for the ministry.

For CFERM the responsible policy and operational directorates are the Directorate General Water and Soil (DGWB) and Rijkswaterstaat (DG RWS), respectively. As specified in Figure 2-1, DGWB sets policy, provides policy advice to elected decision makers, and determines the assignments and funding of the relevant operational directorates. The latter task also incorporates funding allocation to regional government levels and occasionally to local government. Rijkswaterstaat's tasks are (i) to implement policy, (ii) to organize and conduct research to support policy development and implementation, and (iii) to advise relevant policy directorates on policy. In the latter task of providing advice on policy to DGWB, Rijkswaterstaat acts as policy advisor or broker, whereas in the first role of implementing policy Rijkswaterstaat is a coastal management practitioner. A policy advisor or broker always takes the interests and perspective of the client, DGWB in this case, into account whereas a practitioner takes their own experience of applying and implementing policy into account. This means that a balancing act is required at times, when what would suit Rijkswaterstaat as practitioner does not cohere entirely with advice in support of the overarching aims of flood safety and erosion control of DGWB. Explication of these dilemmas is inherent to Rijkswaterstaat tasks. An example of such a dilemma can be found in decision making on the Sand Motor in 2009 (Aukes et al., 2017, Bontje, 2017). This mega sand nourishment was proposed as an innovative CFERM pilot, explicitly aiming for knowledge development, while enhancing flood defense, nature development and recreation on the South Holland coast (Stive et al., 2013, Bontje and Slinger, 2017). This initiative aligned with coastal development policy goals of DGWB (then DGW) and was therefore supported by Rijkswaterstaat in their role as policy advisor. However, in their operational role, Rijkswaterstaat advised against implementation of the Sand Motor on the grounds that it was unnecessary for flood defence in the short term. In this example the policy perspective predominated and the Sand Motor was constructed in 2011.

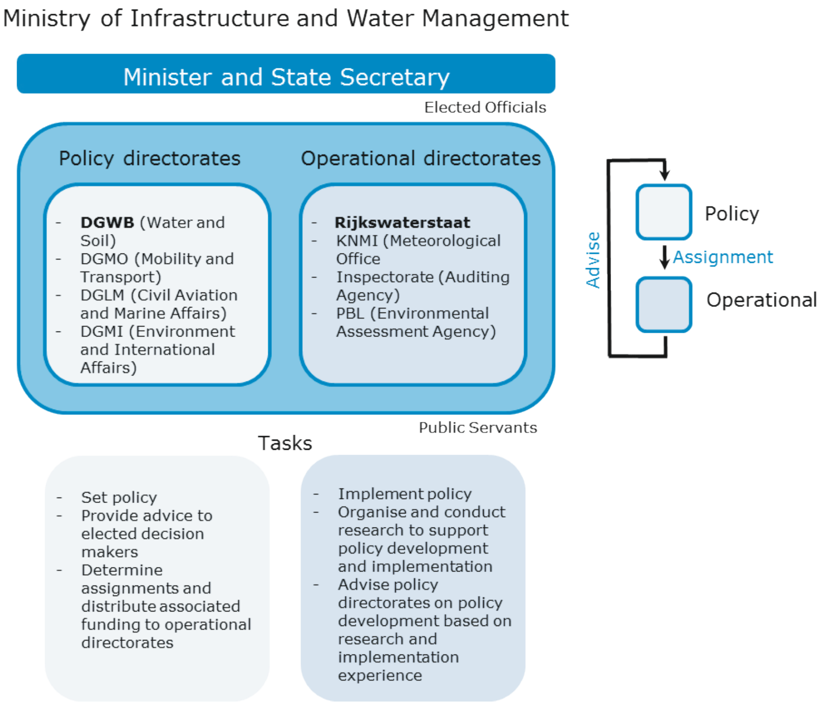

Figure 2-1, *Organisation of policy development and implementation within the Ministry of Infrastructure and Water Management.*

The Coastal Genesis 2 project forms an example of how Rijkswaterstaat organises and undertakes research to inform and improve existing CFERM policy, one of the three tasks allocated to Rijkswaterstaat by the Directorate General Water and Soil. The process of setting a research agenda, organising and undertaking the research, and then synthesising the outcomes into policy advice is illustrated based on the Integrated Coastal Management (ICM) learning cycle introduced by Olsen et al. (1997) (Figure 2-2). A 'Research for Policy' loop initiated by Rijkswaterstaat departs from the existing CFERM policy as described in Section 3. The existing policy together with the underpinning conceptual models form the input to the process. Here we define conceptual models as a description of a coastal system that can be understood in natural language aided by tools such as box and arrow diagrams, causal models and cognitive maps (Beers and Bots, 2009). Although the coastal system is generally understood to include physical, biological and social aspects and their dynamics in space and time (Slinger et al., 2020), here the dominance of the flood risk issue in coastal management (Mulder et al., 2020, Slinger and Taljaard, 2020) means that emphasis is placed on the physical and biological aspects and their dynamics.

Figure 2-2*, The 'Research for Policy' cycle to support coastal policy development in the Netherlands, based on the ICM cycle by Olsen et al. (1997).*

In the first phase of the 'Research for Policy' cycle, problematic issues or concerns related to the existing policy and the associated conceptual models – and their assumptions - are identified. This provides the backbone and justification for the research agenda, which is drafted in phase 2. The research agenda cannot be comprehensive, but aims to address the key uncertainties related to the identified issues. Often these key uncertainties are associated with the assumptions underpinning the existing policy. The draft research agenda is not yet prioritised; prioritisation occurs in transitioning from phase 2 to phase 3. Criteria such as the available budget, the anticipated reduction in uncertainty, the expected increase in system understanding and the feasibility of conducting the research play a role in prioritising the research tasks. The actual research is undertaken in phase 3 in collaboration with research organisations like Deltares, universities and private companies. Overall coordination is undertaken by Rijkswaterstaat. In phase 4 the results are synthesized into new or revised conceptual models describing how the Dutch coastal system functions. The output of phase 4 is advice to policy directorates (phase 5) on revisions or amendments to the existing CFERM policy or even recommendations for new CFERM policy. Following Bontje and Slinger (2017), we contend that whether such advice is adopted or not, depends on the extent to which the revised or new conceptual models are embraced by stakeholders, academic scholars and senior leadership at the ministry. Essentially, it is the degree to which the revised/new conceptual models represent a shared conceptualisation of the working and management of the Dutch coastal system that determines whether the policy advice is adopted or not. If this is the case, the policy development process then transitions into phase 6 where draft policy is brought formally to the political level. Whether and when there is enough political support to draft and promulgate revisions to a formal policy has long been the subject of policy research with explanations varying from the degree of fit with the problem (Hoogerwerf, 1998), to the convergence of political, problem and solution streams into a 'policy window' (Kingdon, 1995), to the success of coalitions in lobbying or advocating their policy solutions (Sabatier, 1998) and even to analogies to the rounds fought in a boxing ring (Teisman, 1995). Exerting influence and informing this component of the 'Research for Policy' cycle is the ambit of Directorate General for Water and Soil rather than Rijkswaterstaat. The task of Rijkswaterstaat in organising and conducting research for policy is complete when a full round of the ICM 'Research for Policy' cycle, from phase 1 through phase 5 is completed. Indeed, the cycle is iterative with the new/revised conceptual model serving as the input for a new cycle. However, if the revised/new conceptual models do not address the problematic issues and concerns adequately or are not yet sufficiently shared by stakeholders, scholars and senior leadership at the ministry, the policy process already loops back from phase 4 to phase 1. In this case, the ICM 'Research for Policy' cycle iterates and adapts the research programme to address the problematic issues and concerns more effectively. This ultimately yields revised/new coastal policy and shared underpinning conceptual models.

It is also possible for research insights, increases in system understanding and even new conceptual models to derive from sources other than those directly aligned with 'Research for Policy'. This new knowledge can highlight issues in existing policy and so contribute to triggering phase 1 and determining the policy-related research agenda.

2.3 Current Dutch Coastal Flood and Erosion Risk Management policy

In 1990 a new Coastal Policy white paper was published in the Netherlands (Min. VenW, 1990). The strategic goals of the dynamic conservation policy embraced in this white paper can be translated directly from the Dutch as "sustainably maintain the flood protection level and sustainably preserve values and functions of the dune areas" (Min. VenW, 1990, Min. VenW, 2000). In other words, conserving the dunes so that they continue to serve as natural flood defences for the low-lying hinterland (predominantly located below storm surge level or even mean sea level), and continue to sustain habitats and ecological functions, as well as infrastructure. The underlying thought is that maintaining the physical basis of the coast serves to guarantee coastal uses (functions) in the long term. The dynamic conservation strategy encompassed in the Coastal Policy white paper of 1990, and later ratified in the Flood Defence Act of 1996 (Wet op de Waterkering, 1996), represents a reaction to centuries of gradual coastal retreat and newly gained system understanding from the first Coastal Genesis research programme (Min. VenW, 1990). Through this early research programme, it was recognized that on long time scales (decades to centuries) gradual coastal retreat would endanger existing (and future) coastal uses, including protection of the hinterland from flooding. The conclusion was drawn that gradual coastal retreat was no longer acceptable if the Netherlands wished to sustain a full range of coastal uses in the future and that active coastline management was required (Hermans et al., 2013).

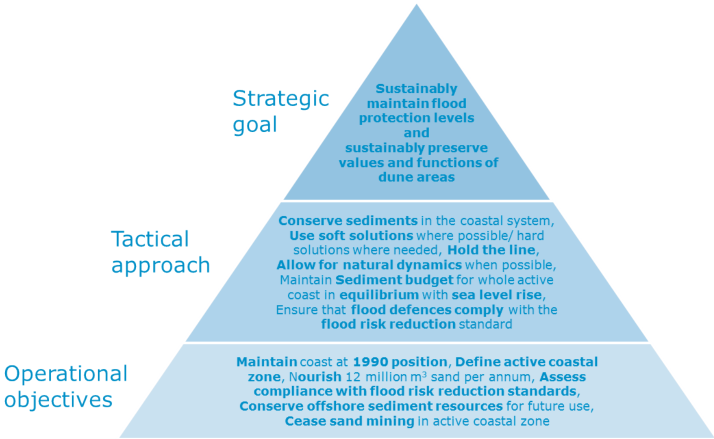

Figure 2-3, *Strategic goal, tactical approach and operational objectives of the current dynamic conservation policy (adapted from Lodder et al., 2019).*

In the 1990 Coastal Policy white paper, the strategic goals for the coast were set out and a number of operational choices were made, such as the choice to adopt sand nourishment as the primary means of maintaining the coast at a reference position. In evaluating the efficacy of the policy five years later in the 2nd Coastal Policy document (Min. VenW, 1995), the structural loss of sand from the coast and dunes was found to have been halted. In the evaluation of the implementation of the dynamic conservation policy from 1990 to 2003, van Koningsveld and Mulder (2004) adopted a frame of reference lens. They concluded that a frame of reference is implicitly used in taking the periodic or cyclical operational decisions on sand nourishment of the coast and evaluating these choices against the operational and strategic objectives. Examining more recent key policy reports and operational and annual monitoring documents, we concur that the process of taking operational decisions regarding sand nourishment of the coast is indeed taken cyclically with both strategic and operational goals in mind (Rijkswaterstaat, 2020a, Rijkswaterstaat 2020b). However, in their 2004 analysis of the dynamic conservation strategy Van Koningveld and Mulder (2004) did not take into account that the strategic goals and operational objectives are linked via choices at the tactical level. The need to include the tactical level was later recognized by Mulder et al., (2011), leading them to extend the frame of reference application to include this level. In synthesizing these insights on the dynamic conservation strategy and visualizing the relationship between the strategic and operational goals via choices at an intermediate tactical level, we therefore adopt a three level hierarchical framework in presenting the current CFREM policy (Figure 2-3). Clearly, there is no direct connection between the strategic goal and the operational objectives. This is mediated by the tactical approach.

By 2001, the strategic goal of the policy had been translated into a coherent set of tactics, namely:

- Conserve sediments in the active coastal system (no sediment extraction shoreward of the 20 m depth contour);
- Use soft solutions (e.g. sand) where possible, hard solutions (e.g. concrete structures) where necessary;
- Hold the line (dynamically maintain the coastline at a set position);
- Allow for natural coastal dynamics where possible given (existing and future) coastal functions;
- Maintain the sediment budget of the active coastal zone in equilibrium with sea level rise;
- Ensure that flood defences comply with the flood risk reduction standard as set in Dutch law; initially this was in compliance with the Flood Defence Act (1996) and later with the Water Act (2009) which replaced it.

By 2009, this tactical approach was made operational by defining the following set of operational objectives:

- Maintain the coast at the 1990 position, defined so that the volume in a coastal transect should (in principle) not be less than the 1990 reference volume;
- The active coastal zone is defined as extending from the inner dunes to the 20 m depth contour;
- Nourish the active coast with an average of 12 million m^3 of sand annually, extracting the sand for these nourishments offshore seaward of the 20 m depth contour;
- Assess the compliance of flood defences to flood risk reduction standards every 12 years (Water Act, 2009);
- Conserve offshore sediment resources for future use;
- Cease sand mining in the active coastal system (i.e. shoreward of the 20 m depth contour).

Underpinning the translation of the dynamic conservation policy into a tactical approach and accompanying operational objectives are conceptual models with associated assumptions on the dynamic processes acting in the coastal system. For instance, the concept of an active coastal zone along a sandy coast explicates the assumption that there is a nearshore area where net sediment transport is active and ongoing in contrast to a deeper area offshore in which this is negligible (see Hillen et al., 1991, Van Koningsveld and Mulder, 2004). For the Dutch sandy coast, the active coastal zone is envisaged to extend to the 20 m depth contour. In order to identify the issues and key uncertainties to be addressed through research, phase 1 in the 'Research for Policy' cycle (Figure 2-2), we now move from presenting the existing coastal policy in the Netherlands to describing the primary conceptual model of the long term sediment budget.

2.4 Conceptual model of the long term sediment budget of the Dutch coast

The current conceptual model of the long term sediment budget of the Dutch Coast was introduced in the 3rd Coastal Policy white paper (Min. VenW, 2000). It is based on a historical sediment budget analysis by Mulder (2000), with a later refinement by Nederbragt (2006) (Figure 2-4). In the 3rd Coastal Policy white paper, the nourishment volume required to maintain the sediment volume in the active coastal zone in equilibrium with sea level rise is estimated as an average of 12 x 10^6 m^3 per annum. Nederbragt (2006) considers the uncertainty in determining the sediment budget for the coast to be significant, introducing a calculation rule for the nourishment requirement of the coast in natural language in an effort to communicate this. The calculation rule can be written as follows (Lodder, 2016):

$$V_{nour} = \left(A_{cf} + A_{ws} + A_{w.sch}\right) * SLR \tag{2-1}$$

where:

V_{nour} = *Nourishment volume* $\left(m^3\ yr^{-1}\right)$

A_{cf} = *Area coastal foundation* (m^2)

A_{ws} = *Area Wadden Sea* (m^2)

$A_{w.sch}$ = *Area Western Scheldt* (m^2)

SLR = *Current relative Sea Level Rise rate* $(m\ yr^{-1})$

The principal assumption made by Nederbragt (2006) is that the long term annual nourishment volume should be equal to the sediment demand of the active coastal zone, calculated as the area of the active coastal zone multiplied by the current rate of sea level rise (SLR). The active coastal zone is defined precisely as the coastal foundation, the area to the 20 m depth contour, plus the area of the Wadden Sea and the Western Scheldt. Here SLR is the relative sea level rise rate as measured by tide gauges along the Dutch coast. These tide gauges are subject to both absolute sea level rise and geological subsidence. At a relative SLR rate of 1.8×10^{-3} m per annum, a required nourishment volume of 12.5×10^{6} m^3 per annum is then calculated.

In addition to this principal assumption, many other assumptions are made in applying this calculation rule, as clarified by Lodder (2016) and depicted in Figures 2-4 and 2-5:

a. net sediment exchange across the 20 m depth contour is negligible (defined as -20 m NAP, the Dutch reference level equivalent to MSL), forming the seaward boundary of the coastal foundation;
b. net sediment exchange over the inner dune row is negligible, forming the land boundary of the coastal foundation;
c. sediment export from the coastal foundation to the Wadden Sea is equal to the area of the Wadden Sea multiplied by the current Sea Level Rise rate;
d. sediment export from the coastal foundation to the Eastern Scheldt is negligible owing to the morphological constraint of the Eastern Scheldt storm surge barrier;
e. sediment export from the coastal foundation to the Western Scheldt is equal to the area of the Western Scheldt multiplied by the current Sea Level Rise rate;
f. sediment import over the Dutch-Belgian (NL-BE) border is equal to sediment export across the Dutch-German border (NL-DE);
g. relative sediment loss in the coastal foundation arises from the current relative Sea Level Rise rate.

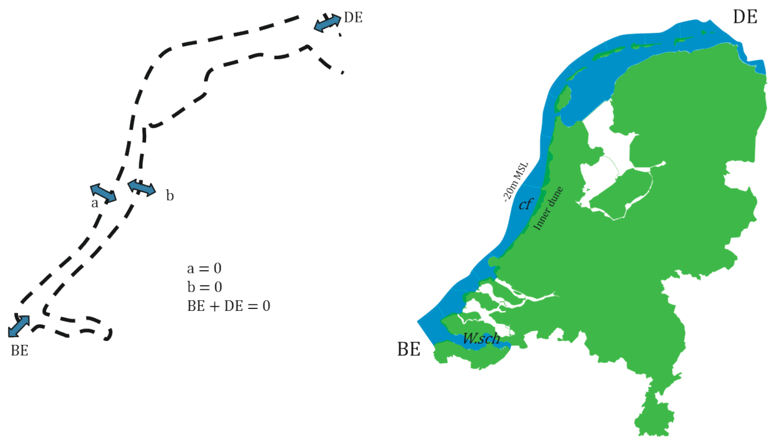

Figure 2-4, *Schematic of the boundary assumptions of the 2006 conceptual model of the long term sediment budget of the Dutch coast (left panel adapted from Nederbragt, 2006; right panel for geographical orientation). The net sediment exchange at the seaward boundary (a: assumed zero), the net sediment exchange over the inner dune row (b: assumed zero) and the sediment import/export over the border with Belgium and Germany (BE + DE = 0) are indicated.*

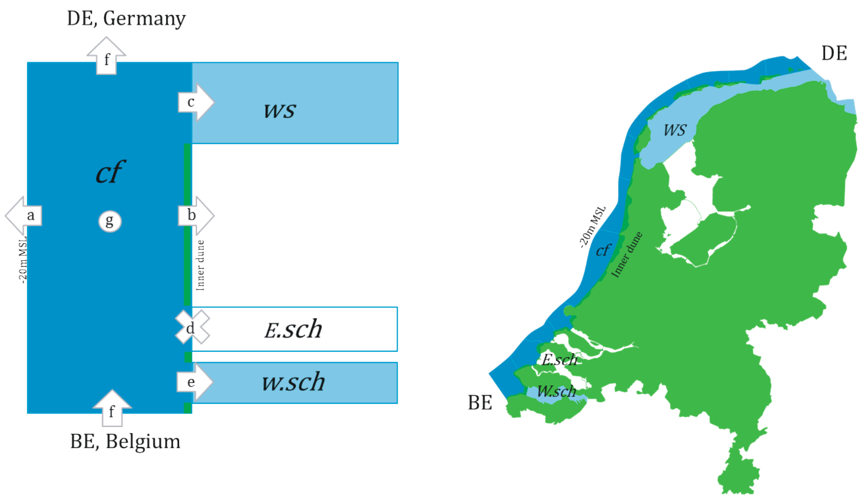

Figure 2-5, *Schematic of the terms in the 2016 conceptual model of the long term sediment budget of the Dutch coast and the key uncertainties (a – g) deriving from the 2006 conceptual model. In 2016, the coastal foundation, Western and Eastern Scheldt and the Wadden Sea are included as separate terms.*

In the 2006 conceptual model, the Wadden Sea and Western Scheldt are assumed to act as sediment sinks for the coastal foundation. In contrast, the Eastern Scheldt is assumed to have no significant exchange of sediment with the coastal foundation due to the constraining effect of the Eastern Scheldt storm surge barrier and the evidence of scour and erosion near the barrier (Mulder, 2000; Geurts van Kessel et al., 2004). The net sediment export to the Wadden Sea and Western Scheldt are assumed to be equal to their area multiplied by the current relative sea level rise rate, following Eysink (1990). Accordingly, the annual volume of sediment required to keep pace with sea level rise is given by the sum of the annual rate of sediment export to the Wadden Sea and the Western Scheldt together with the annual sediment volume needed by the coastal foundation itself.

Over the last two decades, however, studies have shown that multiple assumptions underpinning the current conceptual model of the long term sediment budget for the Dutch coast are potentially partially invalid. For example, studies of sediment export to the Wadden Sea from 1932 to 2015, (Elias et al., 2012) show that up to 1975 the sediment export has been significantly higher than would be expected for the Wadden Sea basins to keep pace with sea level rise. Further, Vermaas et al. (2015) and van der Spek and Lodder (2015) show that there are indications that the net cross-shore sediment exchange is negligible at water depths shallower than -20 m MSL over timescales of two to four decades. In addition, the net cross-shore sediment exchange is likely to be negligible closer to the shoreline than at the boundary of the inner dunes. These research insights allow issues and key uncertainties associated with the current conceptual model and its assumptions to be identified. The question also arises whether the whole sediment demand should be compensated by nourishment or whether there is room for more nuanced decision making in this regard. Is meeting the full sediment demand a fixed obligation under the policy or could it be an option?

2.5 Moving towards a new conceptual model of the long term sediment budget of the Dutch coast

The key uncertainties in the current (2006) conceptual model of the long term sediment budget of the Dutch Coast and its underlying assumptions relate to the following five aspects, specified according to the terms in the calculation rule:

a. What is an appropriate seaward boundary for the coastal foundation, and should this lie at a depth shallower than the 20 m depth contour?
b. What is an appropriate landward boundary of the coastal foundation, and should this be shifted seaward of the inner dunes?
c. What volume of sediment is needed by the Wadden Sea to keep pace with sea level rise given that the sediment export from the coastal foundation to the Wadden Sea has historically been larger than the required volume calculated using equation 2-1?
f. What are the differences between the annual import of sediment over the Dutch-Belgium (NL-BE) border and the annual export of sediment over the Dutch-German (NL-DE) border, as these are unlikely to be equal given the differences in the orientation of the shorelines (SW-NE versus W-E) and the wave climates?
g. What is the contribution of anthropogenically induced subsidence (from gas, oil and salt extraction) and sand extraction to the relative sediment loss of the coastal foundation in addition to the effect of the current relative Sea Level Rise rate?

Taking these issues and uncertainties into account, a new conceptual model and calculation rule (2-1) to determine the required annual nourishment volume was first proposed by Lodder (2016). In the 2016 conceptual model, the nourishment volume is not calculated directly. Instead the annual sediment demand of the coastal foundation is calculated based on the sediment volume needed in the coastal foundation to keep pace with relative sea level rise, local subsidence, and the export of sediments from the coastal foundation to the Wadden Sea and Western Scheldt (Figure 2-5). In contrast to the current conceptual model associated with calculation rule (2-1), the calculated annual nourishment volume is not considered as a fixed obligation arising from the policy, but as a coastal management decision based on information on the annual sediment demand. This shift in conceptual thinking creates the room to adopt different nourishment strategies under a given sediment demand. Accordingly in the 2016 conceptual model the annual sediment demand can vary depending on changes in the terms of the new calculation rule:

$$V_{sd} = \left(A_{cf*} * SLR\right) + V_{e,ws} + V_{e,w.sch} + V_{sub,\,cf*} + V_{e,bd} \qquad (2\text{-}2)$$

where:

V_{sd} = *Sediment demand* $(m^3\ yr^{-1})$

A_{cf*} = (*adjusted*) *Area coastal foundation* (m^2)

SLR = *Current relative Sea Level Rise rate* $(m\ yr^{-1})$

$V_{e,ws}$ = *Export cf to Wadden Sea* $(m^3\ yr^{-1})$

$V_{e,w.sch}$ = *Export cf to Western Scheldt* $(m^3\ yr^{-1})$

$V_{sub,\ cf*}$ = *Anthrophogenic subsidence cf* $(m^3\ yr^{-1})$

$V_{e,bd}$ = *Export cf over Dutch borders* $(m^3\ yr^{-1})$

The 2016 conceptual model (Figure 2-5), and it's associated calculation rule, therefore explicitly allows for:

- A possible reduction in the area of the coastal foundation (extending to a depth contour shallower than -20 m MSL) which then needs to keep pace with sea level rise;
- The actual net export of sediments to the Wadden Sea and Western Scheldt regardless of the cause of this export (eg. sea level rise, subsidence or adaptation to large scale engineering works like the Afsluitdijk, built in 1932);
- The local sediment demand in the coastal foundation caused by anthropogenically induced subsidence (from gas, oil and salt extraction) and anthropogenic sand extraction, both of which are not accounted for in the relative Sea Level Rise;
- The potential net export of sediments to bordering countries; and
- A differentiation between the sediment demand and the selected nourishment strategy.

2.6 A research programme for the Dutch Coast - Coastal Genesis 2

To align with the strategic and operational objectives and the tactical approach of the current coastal policy, a research programme focused on the biophysical aspects of the Dutch coast must at least address how much, when, where, and how additional sediment is supplied to the coast. These aspects are critical in dynamically maintaining the coastline and conserving the dunes so that they can continue to serve as natural flood defences for the low-lying hinterland and continue to sustain habitats, ecological functions and human uses such as recreation. Key questions include:

- How much sediment is needed in the active coastal zone to keep the sediment budget in equilibrium with sea level rise?
- When is the sediment needed?
- Where is the sediment needed?
- How should the sediment be provided to the coastal system while allowing for natural dynamics?
- What are ecological impacts of sediment nourishments?

The first three questions of how much, when and where additional sediment is needed in the coast can be answered through dedicated research on the different aspects of the proposed new conceptual model and associated calculation rule. Such research (phase 3 of the 'Research for Policy' cycle) is envisaged to deliver state-of-the-art estimates of the annual sediment demand of the Dutch coast, to lead to the adoption of a new conceptual model (phase 4 of the 'Research for Policy' cycle) and to policy advice to the Directorate General Water and Soil (DGWB) (phase 5 of the 'Research for Policy' cycle) and hence to the Minister of Infrastructure and Water Management (phase 6 of the 'Research for Policy' cycle). The final envisaged outcome is decision making on future coastal sediment management in the Netherlands based on the new, formally adopted conceptual model.

In addition, how the sediment can be supplied to the coastal system requires an enhanced understanding of different nourishment techniques, the ecological impacts of nourishments and knowledge of local natural morphology and dynamics. Accordingly, in determining the Coastal Genesis 2 research agenda, priority (transition phase 2 to 3) was given to developing an enhanced understanding of the following components – termed the research themes (Table 2-1):

1. Long term shoreface hydro-morphodynamics of the closed barrier coasts of Holland and the Wadden Islands - **determining term** A_{cf*}
2. Current and past relative sea level rise rates, historical and future geological and anthropogenic subsidence along the whole coast – **determining terms** SLR **and** $V_{sub,\,cf*}$
3. Long term sediment exchange between the North Sea and the Wadden Sea with a focus on the Ameland inlet, and the sediment exchange between the North Sea and the Western Scheldt – **determining terms** $V_{e,ws}$ **and** $V_{e,w.sch}$

4. Nourishment techniques and determining the ecological impacts of nourishments.

Research themes 1 and 3 collectively address long term morphodynamics and so were dubbed 'lange termijn kustonderzoek' in Dutch. Given financial and time constraints, choices were made not to undertake dedicated research on the net export of sediments to bordering countries (terms $V_{e,bd}$), nor to study the sediment exchange between the coastal zone and the inner dunes (a component of the term A_{cf*}). Similarly, developing regionally specific SLR rate projections does not form part of Coastal Genesis 2 as this is a task of the Metrological Office (KNMI).

The knowledge base on the dynamics of the Dutch coastal system and its response to sand nourishments has deepened extensively. Selected key policy-relevant insights deriving from the Coastal Genesis 2 programme include:

The direction of net sediment transport at the Dutch lower shoreface is in all likelihood onshore, although its magnitude remains relatively uncertain. This means that little if any sediment is lost from the coastal profile seaward of the abrupt change of slope between the lower shoreface and the seabed. Accordingly, from a morphological perspective this represents the seaward boundary of the coastal foundation and could be adopted as such. This would result in a narrower coastal foundation with a locally differentiated, non-uniform depth as seaward boundary, and would reduce the calculated annual sediment demand (Grasmeijer et al., 2019; Van der Spek et al., 2020a and 2020b, Van der Werf et al., 2019 and submitted). On timescales of 50 to 200 years this boundary could locally be as shallow as the 10 or 15 m depth contour respectively (Van der Spek et al., 2020b, Deltares, 2020, Rijkswaterstaat. 2020b). (research theme 1, determining term A_{cf*} and the overarching V_{sd}).

Current relative sea level rise at the Dutch coast is approximately 0.002 myr^{-1} with geological subsidence contributing approximately 25% (Baart et al., 2019). Local anthropogenic subsidence contributes to a limited but not insignificant degree to the sediment deficit of the coastal foundation: approximately 0.5 x 10^6 m^3yr^{-1} (Hijma and Kooi, 2018a, 2018b). (research theme 2, determining term $sSLR$, $V_{sub,cf*}$, the overarching V_{sd})

Table 2-1, *Research tasks and methods applied within each of the four research themes of Coastal Genesis 2 and their geographical focus.*

Coastal Genesis 2 research themes	**1) Long term shoreface hydro-morphodynamics**	**2) Current and past relative sea level rise rates, historical and future geological and local anthropogenic subsidence**	**3) Long term sediment exchange between the North Sea and the Wadden Sea and the North Sea and the Western Scheldt**	**4) Nourishment techniques and ecological impacts of nourishments**
Research tasks and methods	1. Bathymetrical analysis using long term single beam survey data and short term high resolution multi beam data 2. Geological cores, lacquer peels, box cores 3. In situ hydro and morphodynamic measurement campaign and analysis 4. Model setup, calibration and application for medium term (5 years) of shoreface sediment transport using brute force (real time) time series	1. Statistical analysis of water level measurements of key tidal gauge stations since end 19th century 2. Data analysis and modelling of geological subsidence 3. Data analysis of historical and future subsidence due to gas, oil and salt extraction	1. Historical sediment budget analysis including sand extraction using morphological assessments 2. Box cores and sediment samples 3. In situ hydro and morphodynamic measurement campaign and analysis 4. Model setup, calibration and application to calculate medium term sediment exchange between North Sea and Wadden Sea 5. Modelling long term sediment exchange between North Sea and Wadden Sea	1. In situ ecological measurement campaign and analysis 2. Pilot nourishment of 5 million m^3 at Ameland inlet ebb tidal delta ebb shield

2

Coastal Genesis 2 research themes	1) Long term shoreface hydro-morphodynamics	2) Current and past relative sea level rise rates, historical and future geological and local anthropogenic subsidence	3) Long term sediment exchange between the North Sea and the Wadden Sea and the North Sea and the Western Scheldt	4) Nourishment techniques and ecological impacts of nourishments
Geographical focus area	Whole Dutch coast with Terschelling and Noordwijk as measurement campaign sites. These sites are considered representative for the Wadden Sea and Holland lower shoreface.	Whole Dutch coast including Wadden Sea	1-4: Wadden Sea with focus on the Ameland inlet for measurement campaign. 1. Western Scheldt	Ameland Inlet to link to measurement campaign
Key reports and publications produced during Coastal Genesis 2 (* results are also published in the special issue Future Dutch coast, Wang et al., 2022)	Grasmeijer et al., 2019* ; van der Werf et al., 2017*; van der Werf et al., 2019 *; Schrijvershof et al., 2019*; Oost et al., 2019a*; Oost et al., 2019b*; van der Spek et al., 2020a and 2020b*	Baart et al., 2019; Hijma and Kooi, 2018a, 2018b;	Elias, 2019*, Elias and Wang, 2020; van Prooijen et al., 2020; Wang and Lodder 2019*; Lodder et al., Submitted*	Holzhauer et al., 2021*; van Prooijen et al., 2020; Ebbens, 2019.
	Synthesised in Deltares, 2020 and Rijkswaterstaat. 2020b			

The current annual sediment export from the coastal foundation to the Wadden Sea, excluding the Eems basin, is approx. 5.2 x 10^6 m^3yr^{-1} including sand and mud (Elias, 2019). This sediment export forms a component of the total sediment deficit of the coastal foundation. The total sediment deficit is estimated to lie between 11 and 17 x 10^6 m^3yr^{-1} (Deltares, 2020), with 13.3 x 10^6 m^3yr^{-1} as the most likely value (Rijkswaterstaat, 2020a), under current relative SLR (thus including geological subsidence) and anthropogenic subsidence rates. Moreover, the sediment export to the Wadden Sea is predicted to increase with accelerating relative sea level rise, with a delay in the order of decades. This delay leads to a limited expected increase in annual sediment loss from the coastal foundation to the Wadden Sea within the coming century (Wang and Lodder, 2019; Lodder et al., 2022, Rijkswaterstaat, 2020b) (research theme 3, determining terms $V_{e,ws}$, $V_{e,w.sch}$ and V_{sd})

In regard to nourishment techniques, the designated borrow area’s for sand extraction in the North Sea seaward of the 20 m depth contour are estimated to contain enough supply for the implementation of the dynamic conservation policy up to a sea level rise rate of at least 0.008 myr^{-1} (Rijkswaterstaat, 2020a). A narrower coastal foundation with a locally differentiated, non-uniform depth as seaward boundary will not automatically shift the boundary of the sand mining area. This boundary is determined by the potential morphological effects of sand mining and Natura2000 regulations (North Sea policy agenda (Min. IenM and Min. EZ, 2015), research theme 4)

The insights deriving from the Coastal Genesis 2 research programme, phase 3 in the ‘Research for Policy cycle, have supported the revision of the conceptual model of the long term sediment demand of the Dutch coast from that based on calculation rule (1) to that based on calculation rule (2). This synthesis of understanding into the revised conceptual model represents phase 4 of the ‘Research for Policy’ cycle. The insights and remaining uncertainties deriving from this phase of the ‘Research for Policy’ cycle are captured in an overarching synthesis report (Rijkswaterstaat, 2020b) and three scientific advisory reports (Elias, et al., 2020, Nolte et al., 2020, Van der Spek et al., 2020b). Integral to this synthesis was a series of workshops between researchers and staff from Rijkswaterstaat and the policy directorates structured around the 2016 conceptual model and calculation rule. Moreover the synthesis report was reviewed by the Dutch national advisory committee on flood safety (ENW).

The understanding resulting from the workshops and reports, shared by academic scholars and stakeholders involved in the research programme, is captured in the policy advice offered by Rijkswaterstaat to the policy directorate DGWB. This represents phase 5 of the 'Research for Policy' cycle. In this case, the remaining uncertainties are included in follow-up research activities (looping back to phase 1), but were are not substantial enough to negatively influence the consensus on policy advice. Accordingly four potential strategies for implementing the dynamic conservation policy on the basis of the revised conceptual model were drafted (Figure 2-6). With each of the strategies, the strategic goal of the coastal policy will be achieved on a time scale up to 20 years, under current and anticipated relative SLR rates (Rijkswaterstaat, 2020b). The differences between the strategies lie in the degree to which morphological developments in the Wadden Sea and the coastal foundation on time scales longer than 20 years are accounted for in annual nourishment volume from now on. The four strategies therefore range from a conservative approach of doing the minimum necessary along the entire coast to a strategy of nourishing the total long term sediment demand including all uncertainties from now on with a particular focus on the long term nourishment on the Wadden Coast. The tactical approach would then become 'maintain the sediment budget of the active coastal zone in equilibrium with sea level rise in the long term'. Rijkswaterstaat advised a preferred strategy by applying a multi-criteria analysis that placed emphasis on long term coastal safety, the carbon footprint, costs, ecological impacts and nourishment implementability (Rijkswaterstaat, 2020a). The document detailing the four strategies, including the preferred strategy of Rijkswaterstaat, has been accepted by the policy directorate DGWB, completing phase 5 of the 'Research for Policy' cycle.

Currently, the Directorate General Water and Soil (DGWB) is formalising the policy advice for the Minister of Infrastructure and Water Management. This document will advocate the formal adoption of the new conceptual model for the long term sediment budget of the Dutch Coast (i.e. calculation rule (2-2)) in determining the annual sediment demand and deciding on the sand nourishment volume for the Dutch Coast, phase 6 of the 'Research for Policy' cycle (Figures 2-2 and 2-6). In addition, in November 2021 the Minister of Infrastructure and Water Management communicated to the Dutch parliament her intention to adopt the preferred strategy of Rijkswaterstaat from 2024 onwards (Kamerstukken/2021D43934). She also affirmed that the remaining uncertainties related to maintaining the sediment budget of the Dutch coast in the long term will be addressed as part of a follow-up research programme on Sea Level Rise ('Kennisprogramma Zeespiegelstijging' in Dutch), triggering phase 1 of a new 'Research for Policy' cycle (Kamerstukken/2021D43934).

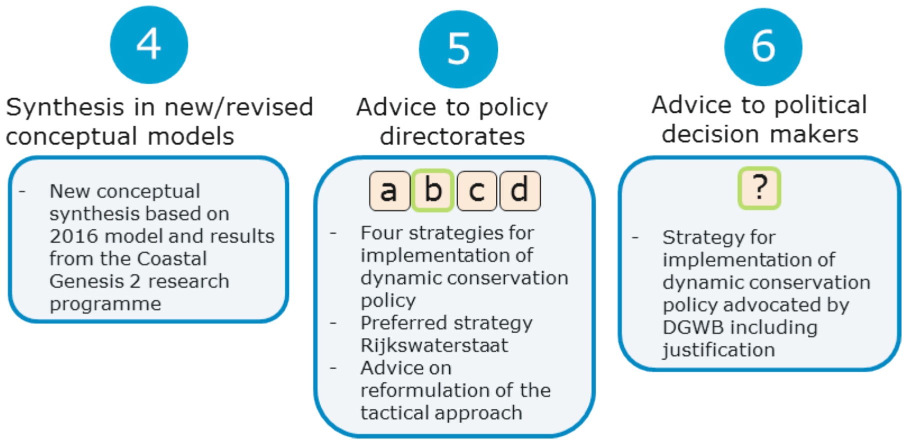

Figure 2-6, *Details of the final steps of the 'Research for policy' cycle of Coastal Genesis 2, comprising phase 4: the synthesis of research insights into a revised conceptual model, phase 5: the advice to policy directorates, phase 6: the advice to political decision makers.*

Concluding remarks

The motivation for initiating the Coastal Genesis 2 research programme was to address the sustainability of the dynamic conservation policy under sea level rise by focusing on key uncertainties identified in the current conceptual model that is used in determining the sediment budget of the Dutch coast. By initiating research aimed at addressing these uncertainties and gaining insight in how the Dutch coastal system functions, the future annual sediment demand of the coast could be determined and captured in a new/revised conceptual model. The outputs of the research programme, comprised of four primary research themes, are synthesised via the new conceptual model and associated calculation rule (Deltares, 2020, Rijkswaterstaat, 2020b). Furthermore, the resultant policy advice to the Directorate General Water and Soil is based upon a shared conceptual model of coastal system dynamics.

Naturally, a research programme cannot address all the uncertainties related to the development and implementation of coastal policy. There has to be prioritisation of issues and in particular, such a programme cannot address the fundamental uncertainty of whether the package of implementation measures, grouped under a tactical approach, will actually lead to the sustainable preservation of the Dutch coast and retention of its use functions for future generations, the strategic goal of the policy. However, by adopting a cyclical 'Research for Policy' approach, that configures and manages research to synthesise policy relevant insights and explicitly acknowledges the role of conceptual models underpinning policy, careful coastal management decisions can be made that sustain uses such as protection of the hinterland from flooding, ecological functions, and recreational use along the coast. Indeed, the adaptive 'Research for Policy' cycle reflects the ongoing reflexive learning practices common to integrated coastal management implementation (Olsen et al. 1997, Taljaard et al., 2011, 2013). Integrated coastal management in the Netherlands has a strong focus on flood risk management and monitoring (Mulder et al., 2020, Slinger and Taljaard, 2020, Rijkswaterstaat 2020a) and in this light the Coastal Genesis 2 research programme can be viewed as an endeavour to supply appropriate state-of-the-art research insights into policy development to support adaptive coastal management and a sustainable Future Dutch Coast.

3

The Coastal Genesis 2 research programme: Outputs, Outcomes and Impact

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Abstract

The long-term sediment demand of the Dutch coast is integral to the current Dutch Coastal Flood and Erosion Risk Management policy. The Coastal Genesis 2 research programme was initiated to address the sustainability of this policy under sea level rise by focusing on key uncertainties in the conceptual model of the sediment demand of the Dutch coast. The substantive scientific contributions of the Coastal Genesis 2 research programme are analysed in this chapter by applying an output-outcome-impact framework. The direct outputs of the programme are categorised in terms of the knowledge types of a 5-element framework, namely measurement data, simulation models, system understanding, conceptual models, and policy and practice. The research outcomes arise from the interactions of these knowledge types. Our analysis of these outcomes highlights that synthesising new scientific insights into shared conceptual models is critical to achieving impact in policy and practice. In the Dutch situation, a new shared conceptual model of the long-term sediment demand enabled the development of four potential nourishment strategies aiming to meet the strategic goals of the Coastal Flood and Erosion Risk Management policy on a timescale up to 20 years. In 2021, the Minister of Infrastructure and Water Management officially articulated her intention to adopt the advised nourishment strategy from 2024 onwards. This represents a lasting impact of the Coastal Genesis 2 research programme in policy and practice. Further, the insight regarding the pivotal role of shared conceptual models as intermediary between science, policy and practice may prove useful in the design of future research programmes aiming to influence policy.

3.1 Introduction

Connecting science to policy is seen as one of the top challenges for sustainability in the 21th century (UNEP, 2012) with the traditional linear and technocratic model of scientific advice to governments having been refuted within the fields of science studies and policy analysis (van Eeten, 1999). Rather, there are complex recursive interactions at the interface between science and policy (Engels, 2005). The science policy interface (SPI) can be defined *"as social processes which encompass relations between scientists and other actors in the policy process, and which allow for exchanges, co-evolution, and joint construction of knowledge with the aim of enriching decision-making"* (van den Hove, 2007). As the relationship between science and policy becomes recursive rather than unidirectional, the boundaries become less clear (Weingart, 1999), and the necessity for boundary spanning work more apparent (Bednarek, 2018). Managing the integration of science and policy therefore remains a significant challenge (Bednarek, 2018), with many authors investigating how to bring scientific advice to policy makers and practitioners (Briggs et al., 2011; Wesselink et al., 2013; Lidskog, 2014; Sokolovska et al., 2019; Gluckman et al., 2021) and more specifically how to equip them with tools to assess and manage their coasts (Bremer and Glavovic, 2013a; Bremer and Glavovic, 2013b; Dale et al., 2019). In the Dutch situation there is a long history in Coastal Flood and Erosion Risk Management (CFERM) and a strong link between science and policy, with personal communication between scientists and high-ranking policy makers, which is often not the case internationally (see Engels, 2005). This makes policy-driven research possible and the Dutch CFERM science-policy interactions particularly interesting to investigate (see Lodder and Slinger 2022).

The Coastal Genesis 2 research programme, conducted from 2015 to 2021, is a prominent example of coastal science-policy interaction in the Netherlands. This programme has deepened the scientific understanding of the bio-geophysical coastal system in The Netherlands and contributed to formal policy development (Elias et al., 2020a; Nolte et el., 2020; Van der Spek et al., 2020b; Deltares, 2020; Rijkswaterstaat, 2020b; Kamerstukken/2021D43934; Wang et al., 2022). This multi-faceted process of science-policy interaction formed the focus of analysis in a paper by Lodder and Slinger (2022 and chapter 2) on the 'Research for Policy' cycle. The six-phase 'Research for Policy' cycle in Dutch Coastal Management was introduced, based on the integrated coastal management learning cycle of Olsen et al. (1997).

The phases of the 'Research for Policy' cycle are: (1) Identify issues in policy and conceptual models, (2) Draft research agenda, (3) Research to increase system understanding, (4) Synthesis in new or revised conceptual models, (5) Advice to policy directorates, and (6) Advice to political decision makers. Whereas Lodder and Slinger (2022) focussed on the cyclic process of science-policy interactions, the aim of this study is to identify the type of substantive knowledge generated by CG2 in the time period 2015 to 2021 (phases 1-3) and how this has contributed to changing policy and practice (phases 4-6). The emphasis in this chapter is therefore to describe the key scientific findings, their synthesis and the impact on policy. Accordingly, we adopt an output-outcome-impact framework to characterize the results of the research programme and also develop a conceptual framework of knowledge types and recursive interactions and apply it to the CG2 research programme.

This chapter is structured as follows. First, we situate the Coastal Genesis 2 (CG2) research programme in the coastal environment and policy context of the Netherlands (Section 2). Next, we describe the output-outcome-impact framework applied in analysing the results of the CG2 (Section 3), and specify the 5-element framework used to identify and categorize the different types of knowledge and knowledge interactions generated within CG2. The subsequent characterization of CG2 scientific results both in terms of the 5-element framework and the output and outcome components of the output-outcome-impact framework follows in the Results (Section 4). The lasting policy and practice impacts of the CG2 research programme are then discussed (Section 5). Finally, we close with a brief reflection on the ongoing role of the 'Research for Policy' cycle in ensuring the sustainable future of the Dutch coast (Section 6).

3.2 Context of the Coastal Genesis 2 research programme

3.2.1 CG2 and the practice of nourishing the Dutch coast

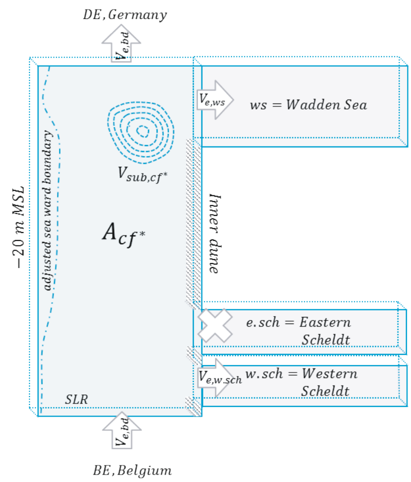
The Dutch coast is characterized in the southwest by the (former) estuaries of the Eastern and Western Scheldt, Grevelingen, Haringvliet, in the centre by a closed sandy coast and in the northeast by the Wadden Sea. While the Eastern Scheldt is protected from flooding by a storm surge barrier, the Western Scheldt remains an open estuary. The Grevelingen and Haringvliet estuaries are separated from the sea by respectively a closure dam and a storm surge barrier. On the Wadden Sea coast, the mainland of the northern Netherlands is protected from flooding by dikes, some of which have vegetated foreshores (salt marshes), while the islands are protected in the northwest by extensive dunes. In contrast, the IJsselmeer area is protected from flooding by the Afsluitdijk (Closure Dam). Between the (former) tidal basins in the south and those in the northeast lies the Holland Coast, a stretch of predominantly sandy coast with dunes. Presently, coastal recession in The Netherlands is counteracted using sand nourishments, under a policy termed Dynamic Coastal Conservation (or Dynamic Preservation) to sustainably maintain the flood protection level and sustainably preserve values and functions of the dune areas. Details of this policy and arrangements for its implementation are provided in Lodder and Slinger (2022, p2-4). The policy entails regularly dredging sandy sediments from designated areas offshore in the North Sea and depositing them at the shoreface, beach or, if necessary, directly to the dune areas, at locations along the coast that are considered to be under threat of erosion. To determine which areas are under threat of erosion, the volume of sand located between the dune foot and two times the vertical distance to the low water line is calculated based on survey data collected each year and this volume is compared with the volume required to maintain the coastline at the 1990 reference position, which is set for the whole coastline except for the extremities of the Wadden Islands, some hard flood defences and the storm surge barriers (Van Koningsveld and Mulder, 2004, Mulder et al., 2011; Brand et al., 2022). Where there is a volume deficit, Rijkswaterstaat - the operational agency of the Ministry of Infrastructure and Water Management- then plans to address the deficit within the coastal maintenance programme whereby approximately 10 to 11 million cubic metres of sand is nourished annually; this includes additional dedicated nourishments to maintain the sediment volume of the larger active coastal system (Rijkswaterstaat, 2020a, 2020b; Brand et al., 2022).

As the rate of sea level rise (SLR) is expected to increase under climate change (IPCC, 2019 and 2021), the sand volumes required for coastal nourishment under this policy will increase in the future (Rijkswaterstaat, 2020b). This raises questions regarding the sustainability of the approach, leading to the initiation of the Coastal Genesis 2 (Kustgenese 2) research programme in 2015 by Rijkswaterstaat. Whereas the earlier Coastal Genesis (Kustgenese) research programme (1980's and 1990's) can be viewed as a concerted scientific and policy effort focused on halting the structural erosion of the Dutch coastline (Min. VenW, 1990; Stive et al., 1991; Mulder et al., 2011), the CG2 research programme aimed at developing a robust and sustainable long-term coastal management strategy. The research programme commenced in

2015 and in 2021 delivered policy advice to the Directorate General Water and Soil – the policy directorate responsible for the Dutch coastal management policy within the Ministry of Infrastructure and Water Management (see chapter, Figure 2-1). The programme developed scientific insights into the long-term dynamics of the Dutch coastal system, in cooperation with Dutch research institute Deltares, various universities (via the Dutch Research Council (NWO) project SEAWAD) and private parties. In essence, Rijkswaterstaat organised and coordinated the research to inform and improve existing Coastal Flood and Erosion Risk Management (CFERM) policy and then synthesised the outcomes into policy advice, fulfilling its role as operational directorate within the Ministry of Infrastructure and Water Management. This iterative process whereby research supports policy development is termed the 'Research for Policy' cycle (Lodder & Slinger, 2022) and is based on the Integrated Coastal Management (ICM) learning cycle introduced by Olsen et al. (1997). Here, the research aimed to provide answers regarding the sustainability of the current policy and associated practice of nourishing the Dutch coast with a focus on flood safety rather than addressing socio-economic developments.

3.2.2 The calculation rule as basis of the research programme

The Coastal Genesis 2 research programme aimed specifically to enhance understanding of the long-term dynamics of the Dutch coast and hence enable the development of a robust and sustainable long-term coastal management strategy in line with the Dynamic Coastal Conservation policy. A core assumption of the policy is that sediment is the carrier of coastal uses (functions). Hence to sustainably maintain the flood protection level and sustainably preserve values and functions of the dune areas requires the maintenance of the sediment budget in the coastal system. The CG2 research programme therefore used as its basis the 2016 calculation rule for the long-term sediment budget (or sediment demand) of the Dutch coast (Figure 3-1), as described in Lodder and Slinger (2022).



$$V_{sd} = A_{cf^*} \cdot SLR + V_{e,ws} + V_{e,w.sch} + V_{sub,cf^*} + V_{e,bd}$$

where:

V_{sd} = *Sediment demand* ($m^3 yr^{-1}$)
A_{cf^*} = *(adjusted) Area coastal foundation* (m^2)
SLR = *Current relative Sea Level Rise rate* ($m\ yr^{-1}$)
$V_{e,ws}$ = *Export cf to Wadden Sea* ($m^3 yr^{-1}$)
$V_{e,w.sch}$ = *Export cf to Western Scheldt* ($m^3 yr^{-1}$)
V_{sub,cf^*} = *Anthropogenic subsidence cf* ($m^3 yr^{-1}$)
$V_{e,bd}$ = *Export cf over Dutch borders* ($m^3 yr^{-1}$)

Figure 3-1, *Visualisation of the terms in the 2016 conceptual model of the long-term sediment budget of the Dutch coast, adapted from Lodder and Slinger, 2022.*

In formulating the objectives of the research programme and determining the key activities, priority was given to enhancing the understanding of the most uncertain components in the calculation rule, and evaluating nourishment techniques and the ecological impacts associated with nourishments. Although also uncertain, the component of the calculation rule dealing with the sediment export from the coastal foundation over the Dutch border with Germany and Belgium received no specific attention in CG2, given the operative time and budget constraints. Similarly, research attention was not directed at the landward boundary of the coastal foundation (for the definition see Lodder and Slinger, 2022). Instead, the attention was directed at uncertainties in the seaward boundary (lower shoreface) and sediment exchange with the Wadden Sea. The research themes (see Lodder and Slinger, 2022) were defined as:

1. Long-term shoreface hydro-morphodynamics of the closed barrier coasts of Holland and the Wadden Islands – determining term A_{cf^*}
2. Current sea level rise rate, historical and future geological and anthropogenic subsidence along the whole coast – determining terms SLR and $V_{sub,\,cf^*}$
3. Long-term sediment exchange between the North Sea and the Wadden Sea, and the sediment exchange between the North Sea and Western Scheldt – determining terms $V_{e,ws}$ and $V_{e,w.sch}$

4. Nourishment techniques and determining the ecological impacts of nourishments.

3.3 Method

The knowledge generated by the Coastal Genesis 2 research programme in the time period 2015 to 2021 is analysed by applying two frameworks, namely: an output-outcome-impact framework, and a 5-element framework, as described below. The secondary data used in the analysis derives from the synthesis reports by Deltares (2020) and Rijkswaterstaat (2020b), and individual key reports and publications produced during CG2, namely: van der Werf et al. (2017), Baart et al. (2019), Ebbens (2019), Elias (2019), Grasmeijer et al. (2019a, 2019b, 2022), Hijma and Kooi (2018a, 2018b), Oost et al. (2019a, 2019b), Schrijvershof et al. (2019), van der Werf et al. (2019, 2022), Wang and Lodder (2019), Elias and Wang (2020), van der Spek et al. (2020a, 2020b), van Prooijen et al. (2020), Holzhauer et al. (2021), Lodder et al. (2022).

3.3.1 The output-outcome-impact framework

We use an output, outcome and impact framework (NWO, 2020) in detailing the products and describing the influence of the Coastal Genesis 2 research programme (Figure 3-2). The outputs are considered to be the direct deliverables of the programme (e.g. journal papers, reports and workshop proceedings). The outcomes include the new insights and opportunities resulting from the research activities of the programme and the deliverables. The impacts are viewed as the lasting effects in policy and practice.

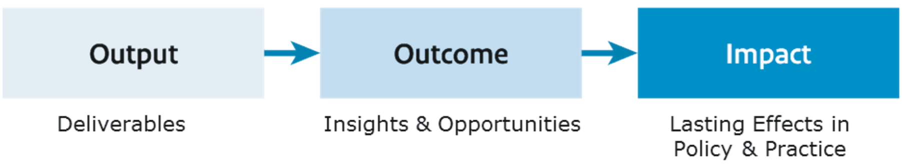


Figure 3-2, *The Output-outcome-impact framework applied in analysing the results of the Coastal Genesis 2 research programme.*

Such an approach draws on longstanding evaluative practice in business and development, notably the logic model formulation (McLaughlin and Jordan, 1999). It has been applied routinely within the Urbanising Deltas of the World Research Programme (2012 to 2021) of the Dutch Research Council (NWO, 2021; 2022) in reviewing the progress of individual research projects and assessing their influence in policy and practice. In analysing collaborative planning, design and transdisciplinary research activities, policy analysts have successfully applied similar frameworks to evaluate (i) the direct substantive and process-based outputs, and (ii) the outcomes of such activities (McEvoy, 2019; McEvoy et al. 2019; 2020, d'Hont, 2020).

3.3.2 The 5-element framework

In addition to classifying results from the research in terms of the output-outcome-impact framework, we are interested in examining the type of knowledge developed and used by the Coastal Genesis 2 research programme over the time period from 2015 to 2021 and how this has contributed to changing policy and practice. Accordingly, we specify a 5-element framework of knowledge types and interactions and describe how the development of such knowledge within a research programme can lead to change in policy and practice.

The 5-element framework distinguishes five knowledge types and their interactions within a research programme (Figure 3-3). First, measurement data is generated through empirical research. In a coastal system this can range from hydro-morphological data to ecological data and social use data. Second, system understanding on relevant time and spatial scales and corresponding relevant processes is obtained through assessments and analysis of such data. Examples of system understanding include insights regarding sediment budgets in the Wadden Sea, the effects of sea level rise (SLR) or alterations in social use patterns of the coast. Third, measurement data can also be used directly to run numerical simulation models. For coastal hydro-morphodynamics, models such as Delft3D (Lesser et al., 2004) and ASMITA are relevant (Stive et al., 1998; Stive and Wang, 2003; Townend et al., 2016a, 2016b; Lodder et al., 2022). Fourth, new or revised conceptual models can capture the increased system understanding or can be based on simulation models. All four of these knowledge types are connected by knowledge interactions. For instance, measurement data, system understanding, and conceptual models are used to develop and run numerical simulation models.

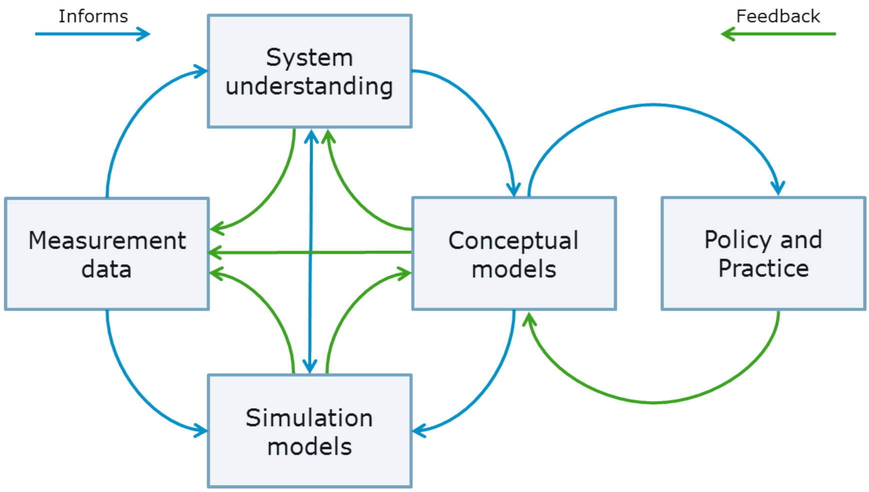


Figure 3-3, *The 5-element framework of knowledge types and interactions. Conceptual models are indicated as playing an intermediary role between science and policy.*

These simulation models in turn can inform the collection of measurement data (e.g. planning new campaigns to fill the knowledge gaps identified by numerical simulation modelling). Or, they can add to system understanding and conceptual models by providing insight in the underlying physical processes active on the coast. Similarly, conceptual models can lead to enhanced system understanding through the clarification of concepts or the visualisation of new relations, and can require new forms of measurement data to be collected. In the 5-element framework, conceptual models (and their associated assumptions) are viewed as the knowledge type connecting science to policy and practice. We contend that it is through shared conceptual models that new knowledge is acquired in policy and practice, the fifth element of the 5-element framework. Specifically, shared conceptual models are viewed as the intermediary in knowledge interactions between science and policy. Further, the implementation of policy in practice serves to provide feedback and update the conceptual models, but often with significant time delay.

In applying, the 5-element framework to the coast, we define conceptual models as a description of a coastal system that can be understood in natural language aided by tools such as box and arrow diagrams, causal models and cognitive maps (Beers and Bots, 2009).

In contrast to the 'Research for Policy' cycle (Lodder and Slinger, 2022), the 5-element framework does not represent a process. It specifies the knowledge types generated in a specific time period by a research process aiming to inform policy and practice, and the interactions between the knowledge types. Specifically, phases 1, 2 and 6 of the 'Research for Policy' cycle are process phases without substantive knowledge results, so they cannot be placed within the 5-element framework. These phases focus on determining the research agenda (phase 1), prioritizing (phase 2), and finally bringing draft policy to the political level (phase 6). However, phases 3, 4, and 5 of the 'Research for Policy' cycle can be associated with the knowledge types that are most important or usually generated in that phase. So, the traditional research focus of phase 3 involves measurement data and simulation models in an effort to build system understanding. Phase 4 focusses on the synthesis in new or revised conceptual models, while phase 5 focusses on providing advice to policy directorates, and is therefore most strongly associated with the knowledge type policy and practice.

3.4 Results: Outputs and Outcomes

3.4.1. Categorizing the outputs and knowledge types

For each of the four research themes of the CG2 programme (Section 2), the research tasks, summarized methods, key reports and publications forming the direct research outputs are listed in Table 3-1. The categorization of knowledge types in terms of the 5-element framework is provided for the research tasks, methods and outputs per research theme (right hand side of Table 3-1).

Table 3-1, *Direct research outputs related to each of the Coastal Genesis 2 research themes, and the accompanying categorization of knowledge types in terms of the 5-element framework for the associated research tasks and methods.*

Coastal Genesis 2 research themes	Research tasks and methods	Outputs: reports and publications	Measurement Data	System Understanding	Simulation Models	Conceptual Models	Policy and Practice
1) Long term shoreface hydro-morphodynamics	1. Bathymetrical analysis using long term single beam survey data and short term high resolution multi beam data	Vermaas et al., 2015; Treurniet, 2018; Oost et al., 2019b; van der Spek et al., 2020a; van der Spek et al., 2020a; van der Spek et al., 2020b	●	●		●	
	2. Geological cores, lacquer peels, box cores	Oost et al., 2019a; van der Spek et al., 2020a; van der Spek et al., 2022a	●	●			
	3. In situ hydro and morphodynamic measurement campaign and analysis	van der Werf et al., 2019 and 2022; Schrijvershof et al., 2019	●	●			
	4. Model setup, calibration and application for medium term (5 years) of shoreface sediment transport using brute force (real time) time series	Grasmeijer, 2018; Zijl et al., 2018; Grasmeijer et al., 2019a; Grasmeijer et al., 2019b; Grasmeijer et al. 2022		●	●		
2) Current and past relative sea level rise rates, historical and future geological and local anthropogenic subsidence	1. Statistical analysis of water level measurements of key tidal gauge stations since end 19th century	Baart et al., 2019	○	●			
	2. Data analysis and modelling of geological subsidence	Hijma and Kooi, 2018a; Hijma and Kooi, 2018b		●	●		
	3. Data analysis of historical and future subsidence due to gas, oil and salt extraction	Hijma and Kooi, 2018a; Hijma and Kooi, 2018b		●	●		

Table 3-1, *Direct research outputs related to each of the Coastal Genesis 2 research themes, and the accompanying categorization of knowledge types in terms of the 5-element framework for the associated research tasks and methods. (continued)*

3) Long term sediment exchange between the North Sea and the Wadden Sea and the North Sea and the Western Scheldt	1. Historical sediment budget analysis including sand extraction using morphological assessments	Elias, 2017; Elias and Vermaas, 2017; Elias, 2018a; Elias, 2019; Elias et al., 2019; Elias and Wang, 2020; Elias and Pearson, 2020; Oost et al., 2018; Dam et al., 2022		●		●	
	2. Box cores and sediment samples	Oost et al. 2019a; van der Spek et al., 2020a	●	●			
	3. In situ hydro and morphodynamic measurement campaign and analysis	van Weerdenburg, 2019; van Weerdenburg et al. 2021; van der Werf et al., 2019; Gawehn, 2020; van Prooijen et al., 2020;	●	●			
	4. Model setup, calibration and application to calculate medium term sediment exchange between North Sea and Wadden Sea	Elias, 2018b; Nederhoff et al., 2019a; Nederhoff et al., 2019b		●	●		
	5. Modelling long term sediment exchange between North Sea and Wadden Sea and North Sea and Western Scheldt	Wang, 2018; Wang and Lodder 2019; Lodder et al., 2019; Lodder et al., 2022; Dam, 2017; Röbke et al., 2019			●	●	○
4) Nourishment techniques and ecological impacts of nourishments	1. In situ ecological measurement campaign and analysis	Holzhauer et al., 2020; Holzhauer et al., 2022; Schipper en Van Dalfsen, 2017; van den Bogaart et al., 2019; van Hal et al., 2021;	●	●			
	2. Pilot nourishment of 5x106 m3 at Ameland inlet ebb tidal delta ebb shield	van Prooijen et al., 2020; Ebbens, 2019	●	●	●		
Synthesis	Scientific synthesis	Elias, et al., 2020; Nolte et al., 2020; Van der Spek et al., 2020b; Deltares, 2020		●		●	○
	Overall synthesis	Rijkswaterstaat, 2020b		●		●	●

● Integral component ○ Partial component

3

3.4.2. Outcomes per research theme

The Outcomes are the new insights and opportunities resulting from the research activities of the programme and the deliverables. In other words “what we understand or can do differently after the research”. Accordingly, for each research theme, we highlight the research set-up and provide detailed substantive information on the associated outcomes. This enables categorization of the outcomes in terms of the 5-element framework of knowledge types and interactions.

Theme 1: Long-term shoreface hydro-morphodynamics

A particular focus is the direction and magnitude of the gross and net sediment fluxes on the shoreface at multiple spatial scales (10^{-1} to 10^{5} m) and time scales (10^{-2} to 10^{2} yr), so as to enable determination the sediment budget of the shoreface along the entire coast (Delta, Holland and Wadden Islands). For this, additional measurement data, increased system understanding and simulation models are needed (see Figure 3-3). Therefore, the research activities comprised:

- Bathymetrical analysis using long-term single beam survey data and short-term high-resolution multi beam data capturing small-scale surface details. (Oost et al., 2019a and 2019b).
- Vibro coring (depth up to 5.5 m below seabed), box cores with lacquer peels (depth 0.5 m below seabed) (Van der Spek et al, 2022; Oost et al, 2019a).
- *In situ* hydro- and morphodynamic measurements (currents, wave height and period, sediment concentration and bedforms) and analysis (Van Prooijen et al., 2020, van der Werf et al., 2019, 2022).
- Model set-up, calibration and application of shoreface sediment transport for the medium term (5 years) using observed time series for the driving forces (Grasmeijer et al., 2019a, 2019b, 2022).

Key outcomes from this research theme are:

- 30 to 50 years of bathymetrical surveys (depending on the location) reveal that the active morphological zone is limited to depths of 15 m and shallower, allowing a smaller coastal foundation to be adopted; this was originally assumed to extend to the 20 m depth contour. The vertical variation in bathymetry exhibits a minimum near -10 to -15 m NAP (depending on the location), indicating that this depth might be considered as the lower boundary of the shoreface (Vermaas et al., 2015).

- Orbital currents up to 1.5 ms^{-1} have been observed at the lower shoreface seabed under storm conditions (significant wave height Hs 4m, -16 m NAP at Ameland and Hs 2.5m, -14 m NAP at Terschelling). This indicates high sediment mobility under sheet flow conditions at the seabed. Ripple bed forms are observed to disappear under these conditions (van der Werf et al., 2022; Brakenhoff et al., 2020).
- The net sediment transport is likely directed onshore at a rate of 3 to $7x10^6$ m^3yr^{-1} with density currents near the bed probably driving this cross-shore transport (Grasmeijer et al., 2018, 2019a, 2019b, 2022). However, the accuracy of this figure is questionable as it is uncertain if all processes are captured well by the model. For instance, there is some evidence of seaward sediment flows at depth greater than - 15 m NAP after a high energy wave event. This is the first time circumstantial evidence of such transports has been found (van der Spek et al., 2022b). The significance of these possibly rare sediment flows for long-term morphological development remains uncertain.
- Residual flow at -20 m NAP is directed onshore at the bed, whereas depth-averaged and surface residual flows are predominately longshore with an offshore component (Grasmeijer et al., 2022).
- Most parts of the lower shoreface of the Dutch coast are deepening slightly. For example, the coastal profile at Noordwijk shows a gradual landward retreat below -7 m NAP. Between 1965 and 2015, the 10 m contour shifted about 225 m landward. At the 1965 location of the 10 m depth contour, the seabed has deepened almost 1 m (Van der Spek et al., 2020a, 2022b).
- Combining box core data with high resolution bathymetry of the seabed provides an insightful way to understand the morphology. By combining these two information sources it became evident that ridges in the bathymetry are formed geologically rather than by local hydrodynamics.

Theme 2: Current and past relative sea level rise rates, historical and future geological and local anthropogenic subsidence

To determine terms SLR and $V_{sub,cf*}$ in the 2016 calculation rule (Figure 3-1) it is necessary to study current and past rates of relative SLR and to disentangle the contribution of historical and future geological and local anthropogenic subsidence to the relative SLR. Sea level rise triggers sediment demand in the coastal system as does geological and anthropogenic subsidence. Increased system understanding through statistical analysis of relative SLR and subsidence measurement data as well as running geological simulation models, are needed (see Figure 3-3). Therefore, the research activities comprised:

- Statistical analysis of water level measurements of key tide gauge stations since end 19th century (around 1890).
- Data analysis and modelling of geological subsidence.
- Data analysis of historical and future subsidence due to groundwater, gas, oil and salt extraction.

Key outcomes from this research theme are:
- The observed average relative SLR based on measurements from tide gauge stations is 0.186 m per century since 1890 (Baart et al., 2018). The estimate of current relative SLR rate is therefore about 0.002 myr^{-1}.
- There is no statistically significant difference between a linear and a quadratic regression model in explaining the observed trend in relative sea level rise. This led to the inference that linear extrapolation is an adequate method in determining the sediment deficit owing to relative SLR until 2032 (i.e. over two of the 6 yearly policy evaluation cycles - see section 5.4). This analysis does not indicate that the relative SLR is not accelerating, only that the methods applied cannot yet detect such a phenomenon in the measurements.
- Geological subsidence along the Dutch coast is 0.05 m (±0.02) per century on average with a range from 0.02 to 0.06 m from the south (Vlissingen) to the north (Harlingen) (Hijma and Kooi, 2018a, 2018b). This subsidence is thought to represent about 25% of the relative SLR, but it is not certain if this geological subsidence is captured fully in the tide gauge measurements.
- Historical and future subsidence due to gas, oil and salt extraction contributes an additional 0.5 x 10^6 m^3yr^{-1} to the sediment deficit of the Dutch Coast (Deltares, 2020).

Theme 3: Long-term sediment exchange between the North Sea and the Wadden Sea and the North Sea and the Western Scheldt

To determine the terms $V_{e,ws}$ and $V_{e,w.sch}$ (Figure 3-1) it is necessary to deepen the understanding of the long-term sediment exchange between the North Sea and the Wadden Sea and between the North Sea and the Western Scheldt. For this, the full range of knowledge types is needed (Figure 3-3). These include new data collection, the development of new simulation models, extended application of existing simulation models, increased system understanding and finally the synthesis in new conceptual models. Therefore, the research activities comprised:

- Historical sediment budget analysis including sand extraction volumes based on morphological assessments (Elias, 2019).
- Box coring and sediment sampling (Oost et al., 2019a, 2019b).
- *In situ* hydro- and morphodynamic measurements and subsequent analysis (Van Prooijen et al., 2020; van der Werf et al., 2019, 2022).
- Delft3D model development, calibration and application to calculate the medium-term sediment exchange between the North Sea and the Wadden Sea (Van Weerdenburg et al., 2021).
- ASMITA modelling of the long-term sediment exchange between the North Sea and the Wadden Sea for different rates of SLR (continuation of present rate 0.002 myr^{-1} accelerating to 0.004, 0.006, 0.008 and 0.017 myr^{-1}) (Lodder, et al., 2022).
- Assessment of the sediment budget of the Wadden Sea (Elias, 2019) and Western Scheldt (Dam, et al., 2022; Röbke et al., 2019).
- Contributing to the overall synthesis and formulation of a new conceptual model.

3

Key outcomes from this research theme are:
- The sediment import into the Wadden Sea has at present a higher rate than needed for the Wadden Sea to keep pace with SLR. This is caused by the human interventions in the past, especially the closures of the Zuiderzee (in 1932) and Lauwerszee (in 1969). The modelling results project the import rate to initially decrease with time as the system persists in its dampening response to past human interferences (Wang et al., 2018, Lodder et al. 2022).
- Acceleration of relative SLR is projected to cause the initial decreasing trend to change, but not until 2040, according to ASMITA model projections (Lodder, et al., 2022).
- Differences between the projections of sediment export from the coastal foundation to the Wadden Sea under SLR are much less than the differences in SLR rate might suggest until 2100. The export rate in 2100 varies from about $5x10^6$ m^3yr^{-1} (for the lowest scenario, 0.002 myr^{-1}) to about $8.6x10^6$ m^3yr^{-1} (for the highest scenario, 0.017 myr^{-1}), with the difference between the two scenarios only about $3.5x10^6$ m^3yr^{-1} (Lodder et al., 2022).
- Compared to the present situation, no substantial increase of sediment export to the Wadden Sea is projected until 2100. For the highest SLR scenario (0.017

myr^{-1}), the import is projected to increase by about 2.5x10^{6} m^{3}yr^{-1} in 2100 compared to the present rate of about 6x10^{6} m^{3}yr^{-1} (Lodder et al., 2022)
- During westerly winds there is a net flux of water over the tidal divides resulting in net outflow of water at the Ameland Inlet. This is observed in measurements as well as reproduced in model simulations (Van Weerdenburg et al., 2021). The effect of this phenomenon on the long-term development of the Wadden Sea remains uncertain.
- The long-term sediment export from the coastal foundation to the Western Scheldt is estimated at 0.5 ±0.5x10^{6} m^{3}yr^{-1} (Rijkswaterstaat 2020b, Table 6-5). The internal reworking of sediments through dredging and placement to maintain navigability is in the order 12x10^{6} m^{3}yr^{-1}, i.e. a factor 10 larger. This indicates that the morphological development is and will likely remain strongly steered by human activities, also under an increase in the rate of SLR (Van der Wegen and Taal, 2022).
- The magnitude of working with sediments in Western Scheldt shows that it is possible to influence this type of systems at the system scale. This might be leveraged for future adaptation to SLR, especially when applying dredged sediment for the implementation of nature-based solutions for flood risk management.
- Increased system understanding and model development have enabled novel tools and techniques to assess sediment pathways in coastal systems such as ebb-tidal deltas (Pearson, 2022). These tools are proving useful in the design of future nourishment projects and schemes (Elias et al., 2021).

Theme 4: Nourishment techniques and ecological impacts of nourishments
Experiments and measurements are necessary to test new nourishment techniques, specifically designed for ebb tidal deltas rather than regular sandy shores, and determine the ecological impacts of nourishments. In particular ebb-tidal deltas of the Wadden Sea had not previously been nourished, but have decreased in volume over the last decades (Elias, 2019, 2021). Such experiments and the collection of new data together with the development of ecological simulation models can lead to increased system understanding (see Figure 3-3) of abiotic-biotic interactions and enhance the degree of fit of pilot studies with existing policy and practice (Vreugdenhil, 2010). Therefore the research activities comprised:

- A pilot nourishment to test the practice of nourishing the coastal zone via an ebb-tidal delta, the permitability, and the ecological and morphological impact.

- A measurement campaign and data analysis, including the sampling of sediment, macrobenthos and fish.
- Habitat mapping based on geophysical parameters such as grainsize, shear stress, depth, slope (Holzhauer et al. 2020 and 2021).

Key outcomes from this research theme fall into two categories, insights & opportunities for innovative nourishments and for ecology:

- The new approach of ebb-tidal delta nourishment was applied at the Ameland inlet. The sediment added into the coastal system did not cause a strong disturbance of the large-scale morphology – an underlying hypothesis of this experiment. The nourished sediments were found to disperse over the local coastal system (Ebbens, 2019; Elias, 2021).
- Under the present permitting procedures, the pilot nourishment proved permitable, meaning that operational practices do not necessarily need to be adapted to implement such a nourishment approach more widely in the Wadden Sea area.
- This, together with the observation that the associated morphological changes were confined to the local coastal system, imply an ebb-tidal delta nourishment approach is potentially more widely applicable, e.g. at other inlet systems in the Wadden Sea of similar morphology.
- Differences in macrobenthic species assemblage composition and functionality were observed across the environmental gradients and geomorphology of the ebb-tidal delta, enabling the development of novel habitat mapping tools (Holzhauer et al., 2021).
- Overall, the ecological impact of the ebb-tidal-delta pilot nourishment is (very) limited due to the quick colonisation of the nourishment site by opportunistic species (Ebbens, 2019; Schipper, 2020).

3.4.3 Scientific synthesis across the research themes

The 2016 calculation rule formed the organizational basis for the CG2 research programme, and also served as the means of synthesizing the research outcomes. This was undertaken in a series of project meetings per theme, but also in general programme meetings and a synthesis workshop (van Oeveren-Theeuwes, 2018). It is here that the deepened system understanding deriving from measurement data and simulation models, captured in turn in new simulation modelling tools, was drawn together coherently to support the new conceptual model. This represents step 4 in the 'Research for policy' cycle. The knowledge integration process is now described by summarizing the insights per theme and indicating the substantive contributions to the conceptual model per calculation term.

First, regarding the area of the coastal foundation (A_{cf*}): the net cross-shore sediment transport at the Dutch lower shoreface is highly uncertain, but primarily directed onshore with uncertain magnitude and likely negligible (if any) sediment transported seaward offshore of the zone with minimum vertical variation around -10 to -15 m NAP (depending on location). This zone represents the seaward boundary of the coastal foundation from a morphological system perspective on short to medium timescales (up to 50 years). On timescales of 50 to 200 years, the seaward boundary could locally lie at the 10 or 20 m depth contour, respectively (Van der Spek et al., 2020b; Deltares, 2020, Rijkswaterstaat, 2020b). In morphodynamic terms therefore the coastal foundation is narrower than originally assumed and has a locally differentiated seaward boundary with a non-uniform depth (Grasmeijer et al., 2019; Van der Spek et al., 2020a and 2020b, Van der Werf et al., 2019, 2022). The magnitude of net sediment transport at the seaward boundary remains uncertain. Second, regarding SLR and anthropogenic subsidence ($V_{sub,\,cf*}$): on the coast of The Netherlands, the current relative SLR is about 0.002 myr^{-1}. Geological subsidence is responsible for about 25% of this number (Baart et al., 2019). The contribution of local anthropogenic subsidence to the sediment deficit of the coastal foundation is limited, yet significant, and amounts to about 0.5 x 10^6 m^{3}yr^{-1} (Hijma and Kooi, 2018a; 2018b). Third, regarding sediment export to the Wadden Sea ($V_{e,ws}$) and the Western Scheldt ($V_{e,w.sch}$): whereas the export to the Western Scheldt is around 0.5 x 10^6 m^{3}yr^{-1}, the current annual sediment export to the Wadden Sea from the coastal foundation is about 5.2 x 10^6 m^{3}yr^{-1} (Elias, 2019). Sand and mud are included in this calculation, but the Ems estuary at the northeastern border is excluded. The sediment export to the Wadden Sea is predicted to increase with accelerating relative SLR, with a delay in the order of decades.

The system understanding, deriving particularly from research themes 1, 2 and 3, and captured in the new conceptual model based on the 2016 calculation rule implies that under current relative SLR and anthropogenic subsidence rates, the total annual sediment deficit of the Dutch coast (V_{sd}) is considered to range from 11 x 10^6 m^{3}yr^{-1} to 17 x 10^6 m^{3}yr^{-1} (Deltares, 2020), with 13.3 x 10^6 m^{3}yr^{-1} as the median value (Rijkswaterstaat, 2020b). However, an increasing rate of relative SLR and annual sediment loss from the coastal foundation to the Wadden Sea are expected to further increase the total annual sediment deficit of the Dutch coast within the coming century (Wang and Lodder, 2019; Lodder et al., 2022, Rijkswaterstaat, 2020b).

Regarding nourishment techniques and effects (research theme 4), the ecological impact of the ebb-tidal delta nourishment was found to be (very) limited due to quick colonisation of nourishment site by opportunistic benthic species. This insight from the Ameland pilot study is expected to apply at similar spatial and temporal scales more widely. The nourishment is observed to disperse locally and not disturb the larger-scale morphology of the ebb-tidal delta (Elias, 2021). This indicates that the new approach of ebb-tidal delta nourishment is potentially more widely applicable at locations with similar morphological characteristics.

Insights regarding the source of potential sediment for nourishing the Dutch coast were also obtained in the CG2 research programme. Presently, sand for coastal nourishment is extracted from specified mining areas in the North Sea seaward of the 20m depth contour. The volume of sediment in the designated sand mining areas is estimated to be sufficient to supply the total annual sediment deficit under a SLR rate of 0.008 myr^{-1} for at least a century (Rijkswaterstaat, 2020b).

3.5 Policy and Practice Impacts

3.5.1 Synthesis in terms of sediment demand and nourishment volumes

The outcomes of the research programme are synthesised in Table 3-2 in terms of nourishment volumes for three geographical areas, namely the Wadden Area, the Holland Coast and the southwestern Delta Coast (Rijkswaterstaat, 2020b).

Table 3-2, *Synthesis of practice and scientific insights regarding sediment demand (in yellow), annual nourishment volumes (in green), leading to the definition of four possible annual nourishment strategies (in blue). The minimum and maximum annual nourishment volumes per area are indicated by light and dark grey shading, respectively.*

Ranges in Annual Sediment Demand or Nourishment Volumes	**Wadden Area**	**Holland Coast**	**Delta Coast**	**Total**
Sediment demand including uncertain export to Ems and Western Scheldt (10^6 m^3yr^{-1})	9.1	1.6	2.6	13.3
Sediment demand excluding uncertain export to Ems and Western Scheldt (10^6 m^3yr^{-1})	7.9	1.6	2.2	11.7
Minimum annual nourishment volume (10^6 m^3yr^{-1})	4.8	3.1	2.2	10.1
Maximum annual nourishment volume, including uncertain export to Ems and Western Scheldt (10^6 m^3yr^{-1})	9.1	3.1	2.6	14.8
Maximum nourishment volume excluding uncertain export to Ems and Western Scheldt (10^6 m^3yr^{-1})	7.9	3.1	2.2	13.2
Possible Annual Nourishment Strategies	**Wadden Area**	**Holland Coast**	**Delta Coast**	**Total**
A. Indispensable coastal protection (10^6 m^3yr^{-1})	4.8	3.1	2.2	10.1
B. Generous continuation of current practice (10^6 m^3yr^{-1})	5.7	3.1	2.2	11.0
C. Robust (10^6 m^3yr^{-1})	7.9	3.1	2.2	13.2
D. Maximum protection (10^6 m^3yr^{-1})	9.1	3.1	2.6	14.8

In addition to the scientific insights derived from the CG2 research programme, data from nourishments undertaken or planned in the period 2012-2023 are used. These historical data provide a practice-based indication of the sediment volumes needed to hold the coastline at the 1990 reference position over a timescale of up to 20 years, and support a core assumption that using this reference coastline method to determine nourishment volumes and locations will ensure that the strategic policy objective is satisfied at this timescale. Accordingly the historical data are used to derive the minimum annual nourishment volumes required (Table 3-2, row 3). The median annual sediment demand, including and excluding the uncertain export to the Ems and Western Scheldt (Table 3-2, rows 1 and 2 respectively) are derived from the CG2 research programme. The scientific and practice-based insights are combined to determine maximum annual nourishment volumes, including and excluding the uncertain export to the Ems and Western Scheldt (Table 3-2, rows 4 and 5 respectively). This synthesis of potential minimum and maximum annual nourishment volumes is subsequently used in generating potential nourishment strategies and preparing policy advice (Step 5 of the 'Research for Policy' cycle).

3.5.2. Possible annual nourishment strategies

Based on the range of potential nourishment volumes in Table 3-2, four possible nourishment strategies were developed (Rijkswaterstaat, 2020b). All these strategies maintain the coastline at the 1990 position and are therefore deemed to meet the strategic objective - to sustainably maintain the flood protection level and sustainably preserve values and functions of the dune areas - as outlined in Lodder and Slinger (2022) on timescales up to 20 years. The differences between the strategies lie in their broader tactical approach i.e. the degree to which the sediment demand of the coastal foundation - especially in the Wadden area - is compensated annually. The strategies addressing a higher percentage of the sediment demand of the coastal foundation are more likely to meet the strategic objective for longer than 20 years. The strategies therefore range from a conservative approach of doing the minimum necessary along the entire coast to a strategy of nourishing the total annual long-term sediment demand including all uncertainties from now on with a particular focus on the long-term nourishment of the Wadden Coast. The four strategies are:

A. Indispensable coastal protection
B. Generous continuation of current practice
C. Robust
D. Maximum protection

Strategy A is termed 'Indispensable coastal protection' and maintains the coastline at its position for up to 20 years but does not address the annual sediment demand of the coastal foundation (Figure 3-1). At the Holland coast multiple exposed sandy promontories need to be nourished to sustainably maintain the local flood protection levels, in line with the strategic goal of Dutch coastal management (Chapter 2, Figure 2-3). Examples of such promontories are located at Katwijk, Noordwijk, Scheveningen and Maasvlakte 2. The sum of these required nourishments exceeds the annual sediment demand of the total Holland coast ($3.1 > 1.6\ x10^6 m^3 yr^{-1}$). Hence the nourishment volume for the Holland coast is set at $3.1\ m^3 x10^6 yr^{-1}$ for each strategy. In the Wadden area the annual sediment demand of the coastal foundation exceeds the practice-based minimum annual nourishment volume. This reflects the facts that the sandy coastlines of the Wadden islands only form a percentage of this total coastal area and that on the extremities of these islands no reference coastline is defined and hence no nourishments are needed.

Strategy B differs from Strategy A in that dedicated additional nourishments are implemented in the Wadden area to partly meet its sediment demand. The additional volume is chosen so that the annual sediment demand of the coastal foundation plus roughly 50% of estimated annual sediment export from the coastal foundation to the Wadden Sea is nourished annually.

Strategy C differs from strategy A in that the full estimated annual sediment demand of the coastal foundation excluding the uncertain export to Ems and Western Scheldt is nourished.

Strategy D comprises nourishing the total annual long-term sediment demand including all uncertainties, and is therefore the only strategy addressing the maximum sediment demand of the Delta Coast and Wadden Area.

These 4 strategies clearly differentiate between the Delta coast, Holland Coast and Wadden Area and so represent a departure from previous policy nourishment strategy which considered the coastal foundation as a single entity. This facilitates distinguishing between sediment demand (determined by the geophysical system) and nourishment demand (determined by the geophysical system and social uses of the coast), which is critical for achieving the strategic objective for the Holland coast.

The 4 strategies also differentiate in the level of risk accepted due to increasing sediment deficit in the Wadden Area. For all strategies this risk is deemed acceptable with regard to achieving the strategic objective on a timescale up to 20 years (with initial implementation till 2032). The level of accepted risk decreases from strategy A to D.

3.5.3. Multi Criteria Analysis of three possible annual nourishment strategies

Three of the four strategies are subsequently evaluated using a multi-criteria analysis (MCA). Strategy D was not evaluated, because the annual sediment demands of the Delta Coast and Wadden Area included in this strategy were deemed too uncertain. The criteria upon which the three remaining strategies were evaluated are listed in Table 3-3.

The MCA serves to support Rijkswaterstaat in formulating a preferred strategy and in communicating the costs, benefits and important aspects of the strategies to the policy directorate DGWB to advise them and aid in their decision making on the strategy to be adopted. According to Arcadis (2020) the criteria included in the analysis where established to be meaningful, decisive and informative for both DGWB and Rijkswaterstaat. The criteria 'Robustness long-term flood safety', 'emissions' and 'costs' are directly related to the annual nourishment volume. A nourishment volume closer to the maximum annual sediment demand of the coastal system is deemed more robust for long-term flood safety, because a lower level of sediment deficit is accepted. This criterion is assessed in a relative fashion, ranging from 0, through 0/+ to + (0 is neutral, + is positive). The criterion also reflects the timescale at which the strategies are likely to meet the strategic objective to sustainably maintain the flood protection level and sustainably preserve values and functions of the dune areas. All strategies are deemed to meet this objective at a timescale up to 20 years. However strategies which account for a higher percentage of the sediment demand will probably meet the objective for longer.

Table 3-3, *Multi criteria analysis of strategies A, B and C.*

Criteria	Strategy A. Indispensable coastal protection	Strategy B. Generous continuation of current practice	Strategy C. Robust
Total nourishment volume (10^6 m^3yr^{-1})	10.1	11.0	13.2
Robustness long-term flood safety	0	0/+	+
Emissions (CO_2-eq KT yr^{-1})	35.6	37.9	43.4
Costs (10^6 €yr^{-1}, reference year 2018)	42.9	46.2	53.8
Burial of benthic animals at beach (ha yr^{-1})	378	378	378
Burial of benthic animals at shoreface (ha yr^{-1})	316	341	461
Long-term effects of burial benthic animals	Limited	Limited	Limited
Expected sediment flux to the dunes (10^6 m^3yr^{-1})	3.0	3.3	3.3
Availability of nourishment sand (borrow sites)	+	+	+
Available locations for nourishments	+	+	?
Permitability i.r.t. environmental legislation	+	?	-

It is not possible to indicate exactly how much longer, because the relationship between the sediment volume in the coastal foundation and the sustainable preservation flood safety and values and functions of the dune areas remains uncertain (Rijkswaterstaat, 2020). The formulae used in calculating the emissions are presented in Arcadis (2020). The costs are determined using a ratio of 70 to 30 percent shoreface to beach nourishment and the average cost per unit volume for the year 2018 (Rijkswaterstaat, 2020). Ecological effects are based on the rate of burial of benthic animals on the beach and shoreface (Arcadis, 2020). The direct short-term ecological effects predominate in the MCA because the long-term effect of the burial of benthic animals was found to be limited (Rijkswaterstaat, 2020b, Schipper, 2020). Because of the long-term importance for flood risk management and dune ecosystems a rough estimate of the expected sediment flux to the dunes is also included in the MCA. The availability of nourishment sand (borrow sites) is included to show that all strategies are embraceable when considering this criterion. The availability of locations for nourishments and whether it would be problematic to obtain permits in terms of existing environmental legislation are included as criteria because larger nourishment volumes require more nourishment locations. Only for strategy C there is uncertainty in the availability of locations. Particularly for nourishments primarily aimed at addressing the sediment deficit around the Wadden Sea it is uncertain whether additional environmental permits are needed and if they can be acquired. This is reflected in the relative score from + to ? to – for strategies A to C.

3.5.4 Preferred annual nourishment strategies

Strategy B was selected as the preferred strategy by Rijkswaterstaat. This strategy is considered to supply sufficient sand to the coast annually to ensure that coastal functions can be conserved for the next 20 years at least. The strategy allows for some dedicated nourishment in the Wadden Area to address the sediment deficit in the long-term (>20 years). There is also room to experiment with nourishment techniques to reduce emissions and ecological impacts further while supplying the coastal system with enough sediments to adapt to relative SLR. The dedicated nourishments in the Wadden Sea area can potentially occur in the form of ebb-tidal-delta nourishments such as in the Ameland inlet pilot study (Section 4.4). However other nourishment types like shoreface nourishments near the coast of the island are also possible (Elias et al., 2021, Pluis et al., 2022). Table 3-4 summarizes the characteristics of the preferred nourishment strategy.

The policy directorate DGWB was advised by Rijkswaterstaat to adopt this strategy until 2032 (step 5 of the 'Research for Policy' cycle). DGWB accepted this advice, and the Minister of Infrastructure and Water Management subsequently communicated to the Dutch parliament her intention to adopt the preferred strategy of Rijkswaterstaat from 2024 onwards (Kamerstukken/2021D43934). This represents step 6 of the 'Research for Policy' cycle (Lodder and Slinger, 2022) in which the knowledge deriving from science influences policy via a shared conceptual model of the underlying system. In 2026 an evaluation of the performance of the preferred strategy in practice is planned as a component of the six yearly re-evaluation of the Dutch Delta Programme (Ministry of Infrastructure and Water Management et al., 2021, Van Alphen, 2014), while remaining uncertainties related to the sediment budget of the Dutch coast in the long-term will be addressed as part of a follow-up Research Programme on Sea Level Rise ('Kennisprogramma Zeespiegelstijging' in Dutch).

Table 3-4, *Characteristics of the preferred nourishment strategy, to be adopted as policy until 2032.*

Total Nourishment volume total (10^6 $m^3 yr^{-1}$)	**11.0**		
Regional nourishment volume (10^6 $m^3 yr^{-1}$)	Wadden Area: 5.7	Holland Coast: 3.1	Delta Coast: 2.2
Emissions (CO_2-eq KT yr^{-1})	37.9		
Costs (10^6 €yr^{-1} , reference year 2018)	46.2		

Concluding Discussion

The emphasis in this study lies on the type of substantive knowledge generated within the Coastal Genesis 2 (CG2) research programme in the period 2015 to 2021 and how this has contributed to changing Dutch policy and practice. An output-outcome-impact framework was applied, together with a 5-element framework of knowledge types and recursive interactions, in analysing the CG2 research programme. This analysis reveals:

1. The *outputs* of the CG2 research programme cover all of the knowledge types distinguished in the 5-element framework, namely measurement data, simulation models, system understanding, conceptual models, and policy and practice.
2. The *outcomes* arise from the interactions of different knowledge types, through research activities which collect and analyse new and existing measurement

data, calibrate, develop and run simulation models, and deliver new insights that build system understanding. The deeper system understanding deriving from the research activities is synthesized in terms of the 2016 conceptual model of the long-term sediment demand of the Dutch coast, which also acted as the organisational basis for the CG2 research programme. The substantive outcomes of the CG2 research programme are summarised in Box 1.

3. Policy and practice *impacts* arise through the revision of the shared conceptual model underpinning Dutch coastal policy, which acts as intermediary in knowledge interactions between science and policy. Science-based insights from the CG2 research programme and practice-based insights are used to determine four possible nourishment strategies, each meeting the strategic objective of the Dutch coastal policy on timescales up to 20 years, but differing in their tactical approach. The lasting effect in Dutch coastal management policy is the adoption of the coastal nourishment strategy specified for the Delta Coast, Holland Coast and Wadden area as advised by Rijkswaterstaat (until 2032) from 2024 onwards (see Kamerstukken/2021D43934). An additional policy impact is the initiation of a follow-up research programme on Sea Level Rise ('Kennisprogramma Zeespiegelstijging' in Dutch), triggering phase 1 of a new 'Research for Policy' cycle (Kamerstukken/2021D43934).

Box 1: *Synopsis of the science-based insights from the Coastal Genesis 2 research programme*

- The net cross-shore sediment transport at the Dutch lower shoreface is highly uncertain, but primarily directed onshore with uncertain magnitude and likely negligible (if any) sediment transported seaward offshore of the zone with minimum vertical variation around -10 to -15 m NAP (depending on location). This zone represents the seaward boundary of the coastal foundation from a morphological system perspective on short to medium timescales (up to 50 years). On timescales of 50 to 200 years, the seaward boundary could locally lie at the 10 or 20 m depth contour. In morphodynamic terms therefore the coastal foundation is narrower and has a locally differentiated, non-uniform depth at the seaward. The magnitude of net sediment transport at the seaward boundary remains uncertain.
- On the coast of The Netherlands, the current relative sea level rise is about 0.002 myr^{-1}. Geological subsidence is responsible for about 25% of that number. The contribution of local anthropogenic subsidence to the sediment deficit of the coastal foundation is limited, yet significant, and amounts to about $0.5x10^6$ m^3yr^{-1}.
- Whereas the export to the Western Scheldt is $0.5x10^6$ m^3yr^{-1}, the current annual sediment export to the Wadden Sea from the coastal foundation is about $5.2x10^6$ m^3yr^{-1}.

The sediment export to the Wadden Sea is projected to increase with accelerating relative sea level rise, with a delay in the order of decades.

- Under current relative SLR and anthropogenic subsidence rates, the total annual sediment deficit of the Dutch coast (V_{sd}) is considered to range from 11×10^6 m^3yr^{-1} to 17×10^6 m^3yr^{-1}, with 13.3×10^6 m^3yr^{-1} as the median value. An increase in the rate of sea level rise and the increasing annual sediment loss from the coastal foundation to the Wadden Sea is expected to further increase the total annual sediment deficit of the Dutch coast within the coming century.
- The Ameland pilot study revealed that the ecological impact of the ebb tidal delta nourishment is limited due to quick colonisation of the nourishment site by opportunistic benthic species. The nourishment is observed to disperse locally and not disturb the larger scale morphology of the ebb tidal delta. This indicates the new approach of ebb tidal delta nourishment is potentially more widely applicable.
- At present sand for coastal nourishment is extracted from specified mining areas in the North Sea seaward of the 20 m depth contour. The volume of sediment in the designated sand mining areas is estimated to be sufficient to supply the total annual sediment deficit under a sea level rise rate of 0.008 myr^{-1}.

The study has taken place within the context of Dutch coastal management and this places constraints on the generalisability of the findings and the international applicability. Constraining contextual factors include a relatively short coastline (about 330 km), a predominantly sedimentary coastal system owing to the location in the delta of the Rhine and Meuse, and an historical focus on flood safety resulting in strong and centralized governance arrangements and less focus on socio-economic development in the coastal zone. A regional rather than a national focus could be required to address the issue of a longer or more diverse coastal environment, while synthesizing insights in terms of the long-term sediment budget has limited applicability in partial sedimentary or predominantly rocky coastal systems, for instance. Care also needs to be taken in extrapolating the learning on the Coastal Genesis 2 research programme to situations where governance arrangements are less centralised and there are multiple priorities to be considered simultaneously in coastal management policy and practice. Additionally, the willingness on the part of the individual scientists and coastal managers to integrate the research findings from the Coastal Genesis 2 research programme into a revised and shared conceptual model is remarkable and may not be present in other research contexts. Nevertheless, we consider the explicit attention paid to knowledge synthesis in terms of a shared conceptual model pivotal to the success of the CG2 research programme in impacting policy, and advocate that other research programmes desirous of achieving policy impact consider adopting this element in their project design.

More generally, the 5-element framework and the 'Research for Policy' cycle can be combined to identify the knowledge types necessary to develop science-based policy insights and to initiate a process to enable incremental policy development. The 5-element framework serves to track knowledge development and to build awareness of the knowledge underpinning policy, and the recursive interactions between knowledge types, helping to identify knowledge gaps to be filled by future research. This approach builds on the refinement of existing conceptual models and their underlying assumptions in structuring the associated research programme. It may therefore be less appropriate for less pre-established policy domains or when first setting up coastal management policy and is not designed to initiate or support paradigm shifts in policy and practice. Instead, it is deemed more appropriate for situations in which coastal policy and practices are established and ongoing adjustments and adaptation to changing conditions such as climate change and associated relative SLR are required.

Part II

Future Response of the Wadden Sea to Relative Sea Level Rise.

Assessing one the key uncertainties in Dutch Coastal Flood and Erosion Risk Management policy and practice

The second part of this research analyses the future response of the Wadden Sea to relative sea level rise.

The aim of Chapters 4 and 5 is to address one of the key uncertainties in the (revised) conceptual model of the long-term sediment budget of the Dutch Coast, namely the long-term morphological development of the Dutch Wadden Sea. Specifically these chapters elaborate the theoretical long-term evolution of the Wadden Sea basins under relative sea level rise, quantifying the projected future sediment exchange between the North Sea and the Wadden Sea basins, and discussing the implications of uncertainties in the evolution of the Wadden Sea basins for the sustainability of Dutch coastal management policy and practice.

4

Future Response of the Wadden Sea Tidal Basins to Relative Sea-Level rise — An Aggregated Modelling Approach

This chapter has been published as:

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Abstract

Climate change, and especially the associated acceleration of sea-level rise, forms a serious threat to the Wadden Sea. The Wadden Sea contains the world's largest coherent intertidal flat area and it is known that these flats can drown when the rate of sea-level rise exceeds a critical limit. As a result, the intertidal flats would then be permanently inundated, seriously affecting the ecological functioning of the system. The determination of this critical limit and the modelling of the transient process of how a tidal basin responds to accelerated sea-level rise is of critical importance. In this contribution we revisit the modelling of the response of the Wadden Sea tidal basins to sea-level rise using a basin scale morphological model (aggregated scale morphological interaction between tidal basin and adjacent coast, ASMITA). Analysis using this aggregated scale model shows that the critical rate of sea-level rise is not merely influenced by the morphological equilibrium and the morphological time scale, but also depends on the grain size distribution of sediment in the tidal inlet system. As sea-level rises, there is a lag in the morphological response, which means that the basin will be deeper than the systems morphological equilibrium. However, so long as the rate of sea-level rise is constant and below a critical limit, this offset becomes constant and a dynamic equilibrium is established. This equilibrium deviation as well as the time needed to achieve the dynamic equilibrium increase non-linearly with increasing rates of sea-level rise. As a result, the response of a tidal basin to relatively fast sea-level rise is similar, no matter if the sea-level rise rate is just below, equal or above the critical limit. A tidal basin will experience a long process of 'drowning' when sea-level rise rate exceeds about 80% of the critical limit. The insights from the present study can be used to improve morphodynamic modelling of tidal basin response to accelerating sea-level rise and are useful for sustainable management of tidal inlet systems.

4.1 Introduction

4.1.1 Study Area

The Wadden Sea contains the world largest coherent area of tidal flats and spans nearly 500 km along the northern coast of the Netherlands and the North Sea coasts of Germany and Denmark (Figure 4-1). It is separated from the North Sea by a series of barrier islands, and characterized by a wide variety of channels, sand and mud flats, gullies and salt marshes.

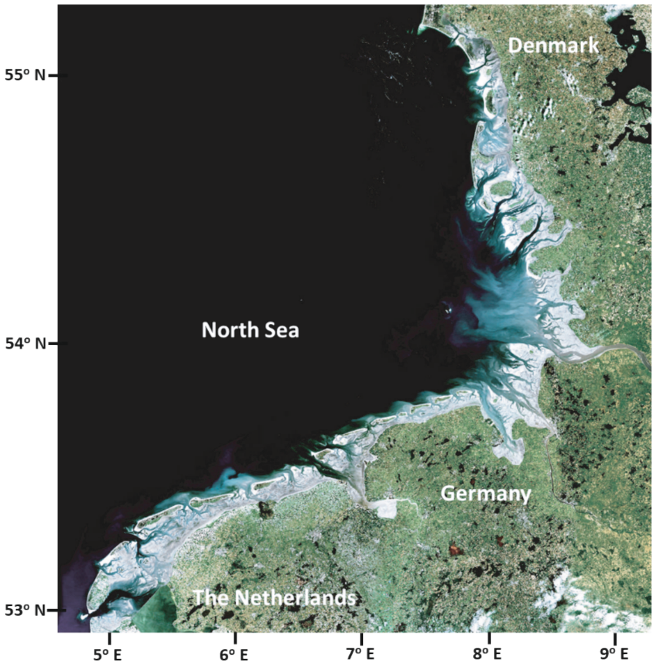


Figure 4-1, *Wadden Sea, the light-coloured areas between the barrier islands and the main-land coast (based on picture from www.waddensea-secretariat.org).*

The Dutch Wadden Sea, bounded by the tip of the Holland coast in the south and the Ems Estuary in the east, consist of six tidal inlet systems, as indicated in Figure 4-2. In this sediment-rich system, the inlets all 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. Tidal divides (indicated by dotted lines) are formed where the tidal waves travelling through two adjacent inlets meet (Figure 4-2) and are often considered to form the morphological boundaries of the tidal basins, although model studies (e.g. Duran-Matute et al., 2014) and field measurements (Van Prooijen et al., 2019; Van Weerdenburg, 2019) illustrate that net flow is present between the individual basins and may be larger than commonly assumed. The tidal divides are located somewhat eastward of the center of the barrier islands due to the eastward increase of tidal amplitude (Wang et al., 2013) and the prevailing westerly wind (FitzGerald, 1996).

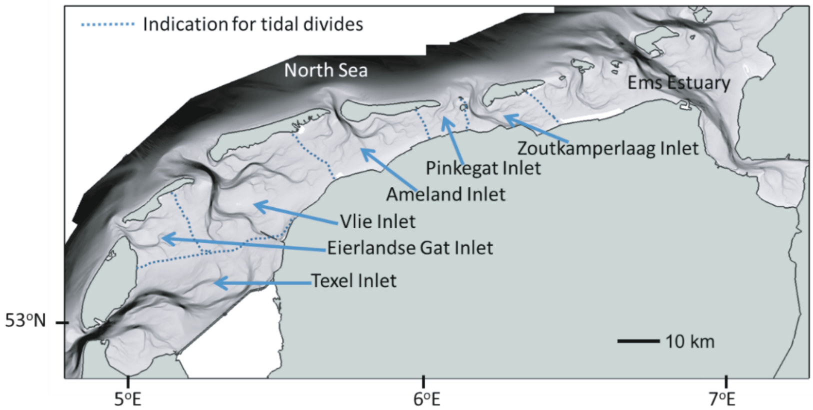


Figure 4-2, *Tidal inlets in the Dutch Wadden Sea (the locations of the tidal divides are indicative).*

The tidal flats consist mainly of sand (~90%; grain size 0.10–0.20 mm) and fine-grained muddy sediments (~10%), with decreasing grain size diameters away from the inlet (Van Straaten, 1961; De Glopper, 1984; Flemming, 1995; Nyandwi, 1998; Bartholomä and Flemming, 2007) due to the settling lag effects of suspended sediments (Postma, 1961; Van Straaten, 1957; Groen, 1967; Gatto et al., 2017). The ebb-tidal deltas primarily consist of sand (0.10–0.40 mm), which is finer on the shoals and coarser in the channels. Similar sand is found in the channels within the basins.

Following the classification of Davis and Hayes (1984), the inlets of the Dutch Wadden Sea belong to the mixed-energy wave-dominated class. Both tides and waves play an important role in shaping and maintaining the Wadden system. The mean tidal range increases from about 1.5 m in the west at the Texel Inlet to 2.2 m in the east at the Zoutkamperlaag. The North Sea wave climate mainly consists of locally generated wind waves with an average significant wave height of about 1.4 m and corresponding peak wave period of about 7 s. The tidal flow is the driving force for the fractal channel patterns in the back-barrier basins (Cleveringa and Oost, 1999; Marciano et al., 2005). For the tidal inlet in morphological equilibrium, the total area of the tidal flats in the basin is related to the basin area; the average height of the tidal flats (measured from low water (LW)) is related to the tidal range; the total volume of channels in the basin and the volume of the ebb-tidal delta are related to the tidal prism (Eysink, 1990; Wang et al., 2013).

4.1.2 Influence of Sea-Level Rise

Sea-level rise (SLR) has played an important role in the development of the Wadden Sea since its formation more than 7000 years ago (Van der Spek, 1992). The temperate climate and rising sea level have been essential in the formation of this wetland system. More recently, especially during the last century, human interventions have become important to the formation of the present day Wadden Sea (Elias et al., 2012; Wang et al., 2018). The presence of a wide-variety of (inter) tidal flats, branching channels and salt marshes provide habitats for a wide variety of salt water plants, marine species and birds. Accelerated SLR may threaten this system as the intertidal flats and marshes may become permanently submerged. 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 SLR (Nichols, 1989; Van der Spek, 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 Wijnen and Bakker, 2001).

Water level measurements over the last 120 years reveal a fairly constant average relative SLR of about 2 mm/y, consisting of about 1.5 mm/y increase of mean sea level and about 0.5 mm/y subsidence (Baart et al., 2019), along the entire Dutch coast (Deltacommissie, 1960; Deltacommissie, 2008; Baart et al., 2019; Walton and Adams, 1976). It is anticipated that worldwide SLR will accelerate, although exact rates are still uncertain; a SLR of between 0.3 and 3 m by 2100 has been presented in the literature (Meehl et al., 2007; Church et al., 2013; KNMI, 2019; Le Bars et al., 2017; IPCC, 2019). For the Dutch Wadden Sea, various scenarios, with the SLR rate in 2100 varying from 2 to 20 mm/y, have been presented in (Vermeersen et al., 2018), highlighting the uncertainties in the future projections of SLR.

Undoubtably, accelerated SLR will influence the future morphological development of the Wadden Sea. The large intertidal flats in the basins are ecologically important and they help protect against flooding along the mainland coast. Future acceleration of SLR can reduce the intertidal flat area, or even cause the permanent drowning if the rate becomes too high. For the management of the system it is therefore essential to predict the development of the intertidal flats area and the associated sediment import to the basin for various SLR scenarios, and to evaluate possible mitigating measures for protecting the ecological value of the system and for flood risk management.

Relative SLR in the Wadden Sea is not only caused by global rise of the sea-level and tectonic and isostatic subsidence, but also due to local gas and salt extraction under the Wadden Sea. Extraction permits require that the total relative SLR, i.e., subsidence plus SLR, does not exceed some critical, predefined limit (De Waal et al., 2012), with the aim of ensuring that no significant environmental impact occurs.

It is also anticipated that faster SLR will cause more sediment transport from the North Sea to the Wadden Sea, implying larger sediment losses from the adjacent coasts and barrier islands. Since 1990, the Dutch coastal policy is to maintain the North-Sea coastline at its 1990 position. Erosion of the coastline is counterbalanced with sand nourishments. Acceleration of SLR will thus result in an increase of nourishment volumes. Predicting the increase in these nourishment volumes is essential for future sustainable coastal management.

4.1.3 Modelling the Response to Sea-Level Rise

Various morphodynamic models have been developed to simulate morphodynamic processes in complex areas such as the Wadden Sea. Generally, three types of models can be distinguished: process-based, aggregated and idealized (De Vriend, 1996; De Vriend et al., 1996; Wang et al., 2012; Wang et al., 2018).

Morphodynamic modelling using process-based models for tidal regions started from the end of the last century (Wang et al., 1995). Nowadays, software systems like Delft3D (Lesser et al., 2004), are available to simulate morphodynamic changes for rivers, coasts and estuaries. For tidal waters like the Wadden Sea, process-based models have been successful in simulating short-term changes and investigating physical processes and mechanisms for morphological changes (Elias, 2006; Lesser, 2009; Van der Wegen, 2009; Elias and Hansen, 2012). Since the pioneering study of Hibma et al. (2003) many long-term morphodynamic simulations have been reported in the literature (see e.g., (Marciano et al., 2005; Dastgheib et al., 2008; Van der Wegen and Roelvink, 2008; , Van der Wegen et al., 2008; Geleynse, 2011; Van Maanen, 2013; Gao et al., 2018; Gao et al., 2019; Tao et al., 2019). However, most of the simulations are carried out for simplified geometry and initial bathymetry, and they mainly concern the morphology at the end of the simulation. Extension of this type of modelling by including SLR (see e.g. Van der Wegen, 2013) provides qualitative rather than quantitative information about the response of tidal basins to SLR. Predicting the morphodynamics of the Wadden Sea inlets (e.g., Ameland Inlet) over the medium to long-term is still a very challenging task (Elias et al., 2015; Wang et al., 2016). In general, the models are better at predicting the morphodynamic evolution after large-scale disturbances rather than predicting the smaller-scale gradual evolution such as the development of inlets under the influence of SLR. Apparently, process-based morphodynamic models have been set up and calibrated either for reproducing the morphological timescales well (by correctly reproducing the hydrodynamic and sediment transport processes and the short-term morphological changes) or for correctly representing the (characteristics of) morphological equilibrium (end state of the long-term schematized simulations), not both. Models with correct morphological timescales are suitable for simulating evolution after large-scale distortion if their error in representing the morphological equilibrium are much smaller than the distortion. For simulating the response of tidal inlet systems to SLR the model is required to reproduce both the morphological equilibrium as well as the morphological timescale. This implies that most existing process-based morphodynamic (application) models, are in fact, not suitable for simulating responses of tidal inlets to SLR. The only application of process-based models to the Dutch Wadden Sea thus far for simulating impact of SLR (Dissanayake et al., 2012) predicted an unrealistically low critical rate of SLR because only a single sand fraction was included (Wang and Van der Spek, 2015). Hofstede et al. (2018) presented process-based modelling of the impact of future SLR on the (German) Wadden Sea by including sand as well as mud in the model (see also Becherer et al., 2018), but their model has not been verified for the response to SLR. Moreover, a general problem with process-based modelling is that due to the complexity of the model and the high computational efforts it is difficult to determine the critical sea-level rise rate for drowning of the tidal flats in the Wadden Sea, even if the model used has been carefully set up and verified.

Idealized models (see review in De Swart and Zimmerman, 2009) are in fact simplified process-based models but they have not been used to model sea-level rise effects on the Wadden Sea, although they are potentially well-suited to the task.
Up to now, the assessment of the impact of relative SLR relies mainly on aggregated morphological models like ASMITA (Stive et al., 1998; Stive and Wang, 2003; Townend et al., 2016a; Townend et al., 2016b). The aggregated scale morphological interaction between tidal basin and adjacent coast (ASMITA) model can be used to determine the critical SLR rate (Van Goor et al., 2003; Wang et al., 2018). It has also been used to assess the impact of land subsidence quantitatively, as an input to the environmental impact assessment for gas and salt mining projects in the Dutch Wadden Sea (Wang et al., 2018). Empirical relations for morphological equilibrium are implemented in this type of model and calibration of the model depends mainly on the morphological timescale, making them better suited for simulating responses to SLR.

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, in part, empirically determined during model calibration, rather than being based on observed or theoretically derived values (Wang et al., 2008). As pointed out by Wang et al. (2008), the validity of the model for certain applications, depends on two characteristics of the field data used for the calibration: the length of the time period covered by the data and the spatial resolution of the data. A major problem is then that the effect of sea-level rise on the morphological development has a very long timescale, at least centuries. Reliable field data over such a long period is not generally available, even for a data-rich system like the Dutch Wadden Sea. Geological data may be used but they can only indicate a range of the critical SLR for a system. Calibrating a morphodynamic model for simulating the effects of sea-level rise using field data of limited duration is therefore still a challenging task.

The study of Van Goor et al. (Van Goor et al., 2003) focused on the evaluation of critical SLR rate and did not consider the transient development when the SLR rate changes. In addition, process-based modelling for the effects of SLR is often based on comparison between simulations with different rates of SLR and pays little attention to the transient process when SLR accelerates. However, the transient process can take a long time before a new dynamic equilibrium is established, or the drowning is completed (if the critical SLR rate is exceeded). Knowledge of both the new dynamic equilibrium, and the transient development to the new equilibrium, is important for the management of the system.

The objective of the present study is to improve our insight into the morphological development of the tidal basins in the Dutch Wadden Sea due to accelerated SLR. This will be achieved by analyzing the dynamic morphological equilibrium state and the transient state of a tidal basin when the SLR changes using the ASMITA model. Although, the study focuses on the tidal basins in the Dutch Wadden Sea, the insights obtained are relevant for other similar tidal basins when examined at the aggregated scale implicit in this type of model formulation.

4.2. Modelling Approach—Aggregated Model ASMITA

The ASMITA (aggregated scale morphological interaction between tidal basin and adjacent coast) model was first proposed by Stive et al. (1998) for modelling the long-term morphological development of tidal inlet systems in the Wadden Sea. For a detailed description of the model formulations we refer to (Stive and Wang., 2003; Townend et al., 2016a and 2016b).

ASMITA has a high level of spatial aggregation. A tidal inlet system is schematized into a limited number of morphological elements, similarly to how Walton and Adams (1976) describe natural systems. For each element a water volume below a certain reference level or a sediment volume above a certain reference plane acts as a state variable. A tidal inlet is typically schematized into the following three elements (Figure 4-3):

- The ebb-tidal delta, with its state variable V_d = total excess sediment volume relative to an undisturbed coastal bed profile [L^3],
- The inter-tidal flat area in the tidal basin, with its state variable V_f = total sediment volume between mean low water (MLW) and mean highwater (MHW) [L^3],
- The channel area in the tidal basin, with its state variable V_c = total water volume below MLW [L^3].

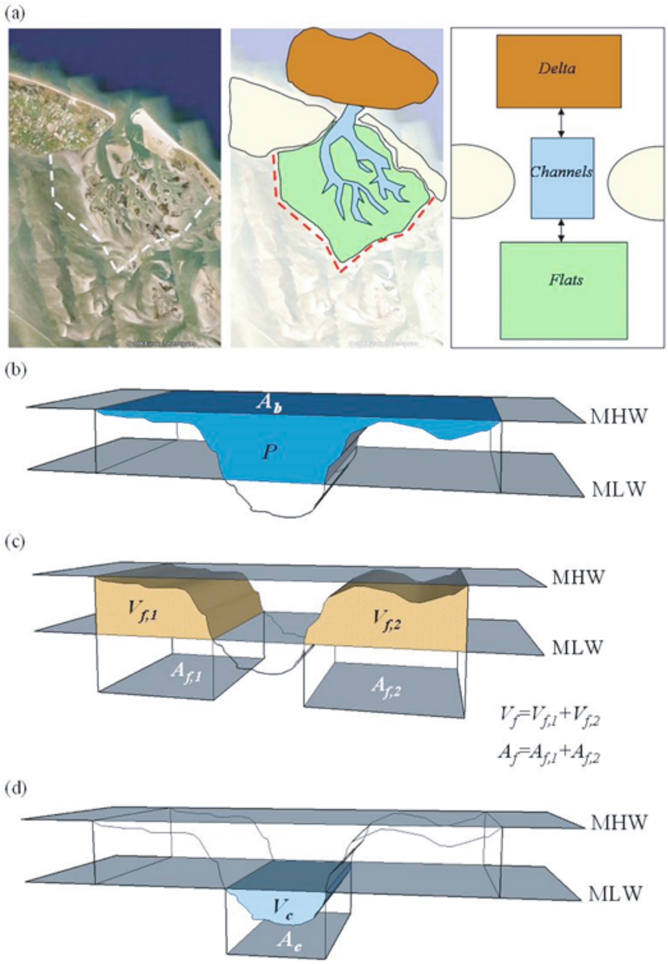


Figure 4-3, *The three-elements schematisation **(a)** for a tidal inlet in the aggregated scale morphological interaction between tidal basin and adjacent coast (ASMITA) and the definitions of the hydrodynamic and morphological parameters tidal prism P **(b)**, area A_f and volume V_f of tidal flats **(c)**, area A_c and volume V_c of channels **(d)**. Figure Wang et al. 2013*

The adjacent coastal areas, which can exchange sediment with the inlet system, are considered as an open boundary, 'the external world'. For the present analysis the single-element model for the tidal basin with the water volume below highwater *V* as state variable will be used. Following the definitions (see Figure 4-3) we have:

$$V = V_c + P \tag{4-1}$$

As the tidal basins are relatively small compared to the tidal wave length, the tidal prism *P* can be calculated as:

$$P = 2A_b a - V_f \tag{4-2}$$

4

Herein A_b is the basin area and *a* is the tidal amplitude. As the equilibrium values of V_c and V_f can be calculated from *a* and *P* (see Townend et al., 2016a), the equilibrium value of *V* is thus a function of *a* and A_b:

$$V_e = F\left(A_b, a\right) \tag{4-3}$$

The single element ASMITA model yields (see Van Goor et al., 2003):

$$\frac{dV}{dt} = \frac{w\delta c_E A_b}{\delta + wA_b}\left[\left(\frac{V_e(t)}{V(t)}\right)^n - 1\right] + A_b R \tag{4-4}$$

where
t = time [T]
w = vertical exchange coefficient [LT^{-1}],
δ = horizontal exchange coefficient [L^3T^{-1}],
n = power in the formulation for the local equilibrium concentration [-],
c_{E} = overall equilibrium concentration [-],
R = relative sea-level rise rate [LT^{-1}].

The power *n* should be the same as that in a power law relationship between sediment transport rate *s* and flow velocity *u* in a process-based model (Wang et al., 2008). Its value is an indication of the non-linearity of the relationship. For the general case, in which sediment transport rate is a function of the flow velocity and other factors, such as those indicating the sediment properties, the value of *n* should be calculated as:

$$n = \frac{\partial s}{\partial u}\frac{u}{s} \tag{4-5}$$

Many sediment transport formulas may be written as the following general form, with *M* as a constant coefficient depending on sediment properties and *k* as a constant.

$$s = M\left(u - u_c\right)^k \tag{4-6}$$

For this relation:

$$n = k\frac{u}{u - u_c} \tag{4-7}$$

In these relations u_c is the critical flow velocity for incipient movement of sediment particles. It is larger for coarser sediment than for finer sediment. This means that for the same hydrodynamic condition *n* is larger for coarser sediment than for finer sediment.

4.3 Analysis and Modelling Results

4.3.1 Dynamic Equilibrium and Critical SLR Rate

Stive and Wang (2003)(see also Van Goor et al., 2003, Wang et al., 2018) use Equation (4-4) to demonstrate that there is a critical limit R_c of sea-level rise rate beyond which the tidal basin will drown:

$$R_c = \frac{w\delta c_E}{\delta + wA_b} \tag{4-8}$$

Equation (4-4) can be also be written in terms of depth

$$\frac{dH}{dt} = \frac{w\delta\, c_E}{\delta + wA_b}\left[\left(\frac{H_e(t)}{H(t)}\right)^n - 1\right] + R \tag{4-9}$$

With

$$H = \frac{V}{A_b} \qquad \text{and} \qquad H_e = \frac{V_e}{A_b} \tag{4-10}$$

The equations can be made dimensionless using

$$h = \frac{H}{H_e} = \frac{V}{V_e} \tag{4-11}$$

and

$$\tau = \frac{t}{T} \qquad \text{with} \qquad T = \frac{V_e}{A_b w c_E} + \frac{V_e}{\delta c_E} = \frac{H_e}{w c_E} + \frac{A_b H_e}{\delta c_E} \tag{4-12}$$

yielding

$$\frac{dh}{d\tau} = \left[\left(\frac{1}{h} \right)^n - 1 \right] + r \tag{4-13}$$

Herein

$$r = \frac{R}{R_c} \tag{4-14}$$

It is noted that using Equations (4-8) and (4-12) the critical sea-level rise rate can be written as:

$$R_c = \frac{H_e}{T} \tag{4-15}$$

It should also be noted that the timescale T is not equal to the morphological timescale T_m as defined by linearizing Equation (4-4) or Equation (4-9) for the case R = 0 (Kragtwijk et al., 2004). The morphological time scale is the time needed for a small deviation from the morphological equilibrium to decrease by a factor e. The relation between the two timescales is:

$$T = nT_m \tag{4-16}$$

These relations revealed a number of interesting things worth knowing:

- Equation (4-15) for R_c revealed the importance of T. In this relation H_e is the equilibrium depth. Empirical relations (Townend et al., 2016a) were available from which its value can be evaluated if the tidal amplitude a and the size of the tidal basin is known, $H_e = F(A_b, a)$. Moreover, it was also connected to direct observations. For basins which are approximately in equilibrium, as, for example, when the basin has not been impacted by human interference for a long time, the equilibrium depth can be evaluated from the measured bathymetry. Note that a correction is necessary when it is in a dynamic equilibrium as it has been forced by sea-level rise with a constant rate for a long time (See Figure 4-4). An example within the Dutch Wadden Sea is the Ameland Inlet.

- Equation (4-15) can also be used for estimating the timescale T if R_c can be derived from observations. This is the case for the Texel Inlet, for example, in which a large sediment deficit arose after the closure of the Zuiderzee in 1932 (Elias et al., 2012; Wang et al., 2018). The large sediment deficit (depth of the basin much larger than equilibrium depth, or h much larger than 1) in the basin has practically the same effect on sediment import as a 'drowned' system (see Figure 4-8), implying that the observed sedimentation rate is close to the critical sea-level rise rate.
- The power n influences the morphological timescale, but not the critical sea-level rise rate. It does influence the dynamic equilibrium state.

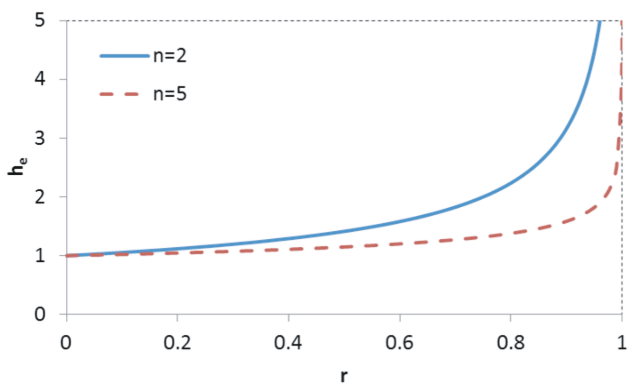


Figure 4-4, *Influence of the power n on the dynamic morphological equilibrium.*

In dimensionless form, the dynamic equilibrium morphological state can be derived from Equation (4-13):

$$h_e = (1 - r)^{-\frac{1}{n}} \tag{4-17}$$

This relation is shown in Figure 4-4 which clearly indicates that the dynamic equilibrium morphological state is sensitive to the value of *n*. If the *n* value increases, the h_e value for the same dimensionless sea-level rise rate *r* is smaller. This means that for larger *n* values, the deviation of the dynamic equilibrium from the morphological equilibrium as defined by the empirical relations is smaller. Figure 4-4 also shows that for larger *n* values, the transition from gradual increase to rapid increase of h_e occurred at a larger value of *r*. However, the magnitude of *n* also has an influence on the critical SLR rate according to Equations (4-15) and (4-16): the larger the *n* value, the lower the critical rate for the same morphological timescale.

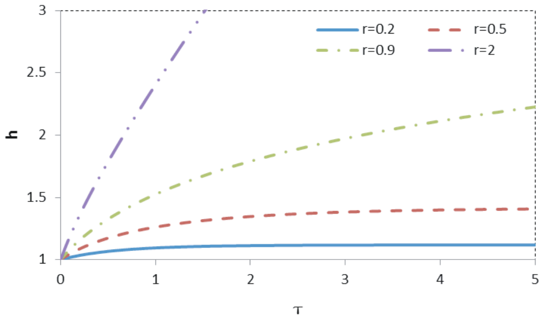
4.3.2 Transient Development

It is also important to know about the time process of the development towards the new dynamic equilibrium when SLR accelerates. Some insight into this process can already be obtained from the morphological timescale, determined by linearizing Equation (4-13) around $h = h_e$ (the dynamic morphological equilibrium state):

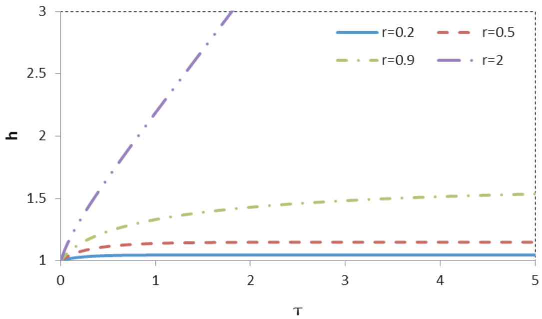
$$\tau_a = \frac{1}{n(1 - r)^{\frac{n+1}{n}}} \tag{4-18}$$

τ_a is the dimensionless time (value of τ) after which a deviation from the dynamic equilibrium would be decreased with a factor *e* according to the linearized model. For $r = 0$, $\tau_a = 1/n$ which is the same relation between the morphological timescale and the timescale *T* as given by Equation (4-16), implying that a larger *n* results in a smaller morphological timescale, for the same value of *T*. The morphological timescale depends on the SLR rate *r*, the larger the *r* value, the larger the morphological timescale. This means that for a higher accelerated SLR rate it takes longer for the new dynamic morphological equilibrium to be reached.

Figure 4-5 shows the results of the non-linear model (solution of Equation (4-13)) for various combinations of *n* and *r*. For all the simulations $h(0) = 1$ is used as initial condition, i.e., starting at equilibrium for $r = 0$. The influence of the magnitudes of *n* and *r* on the transient development, as indicated by the morphological timescale described above, agrees well with the results of the non-linear model.



(**a**) n = 2



(**b**) n = 5

Figure 4-5, *Transient development for various sea-level rise (SLR) rates starting from equilibrium state (h(0) = 1). Influence of the power n can be seen by comparing the two panels, (**a**) for n = 2 and (**b**) for n = 5.*

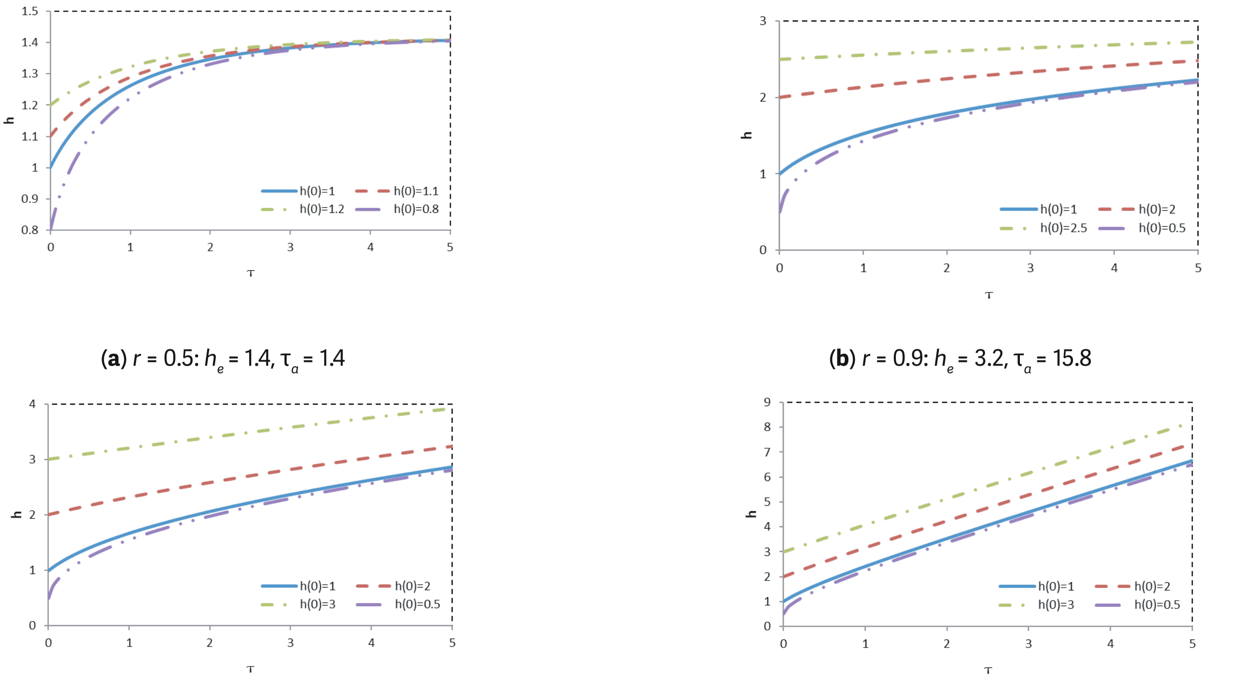
Sea-level rise is often considered as a constant value over the past centuries. However, fluctuations are common and it is therefore unlikely that a system is ever completely in equilibrium, especially if one factors in other forcing conditions (spate river flows, nodal tidal cycles, etc.), even if it is not influenced by human interference. Consequently, it is unlikely that tidal basins are in equilibrium (h = 1) at the onset of a period of acceleration, also because of the ongoing SLR. The influence of the initial condition is investigated for four SLR rates (Figure 4-6), two below and two above the critical rate. For the two cases with SLR rate below the critical rate, a finite dynamic equilibrium depth exists and this state is being achieved in all simulations. However, there are also some notable differences in terms of both the dynamic equilibrium that is reached and the morphological timescale.

If SLR is relatively small compared to the critical rate (r = 0.5, Figure 4-6a) the dimensionless timescale is short (about 1.4) and the equilibrium depth is relatively shallow (h_e = 1.4). However, if the SLR rate is equal to 90% of the critical value (r = 0.9, Figure 4-6b) then both are larger. The equilibrium depth increases to more than doubled to 3.2, while the dimensionless timescale increases by an order of magnitude to 15.8. When the SLR rate approaches the critical value, the morphological timescale increases to a very large or even infinitely large value (Figure 4-7).

For the two cases with SLR greater than the critical SLR rate, no dynamic equilibrium can be reached, and the water depth increases indefinitely. The behaviour of the development is not heavily influenced by the initial depth. Especially for the case when the SLR rate is far above the critical rate (Figure 4-6d) all lines are parallel. In such case, h increases rapidly to a large value and when h is large, the right-hand side of Equation (4-13) becomes near constant. Physically, this means that there is a maximum rate of sediment transport to the basin, which can be obtained when the water depth in the basin becomes large, implying that further change of the depth has little influence on the sediment transport rate.

This can be made clear by considering the two terms on the right-hand side Equation (4-4). The second term represents the volume increase due to SLR and the first term represents the change due to sediment transport from the basin to the coastal zone. For $V > V_e$, or $h > 1$, it is negative and its magnitude is the sediment import rate to the basin. With the help of Equations (4-5) and (4-8) the following relation can be derived for the sediment import rate S (depicted in Figure 4-8):

$$\frac{S}{S_{max}} = 1 - \left(\frac{1}{h}\right)^n \qquad \text{with } S_{max} = A_b R_c \text{ is the maximum value of } S \tag{4-19}$$



(**a**) r = 0.5: h_e = 1.4, τ_a = 1.4

(**b**) r = 0.9: h_e = 3.2, τ_a = 15.8

(**c**) r = 1.1: h_e = ∞

(**d**) r = 2: h_e = ∞

Figure 4-6, *Transient development starting from various initial conditions (h(0)) for four SLR rates:* ***(a)*** *r = 0.5 (SLR far below critical rate),* ***(b)*** *r = 0.9 (SLR just below critical rate),* ***(c)*** *r = 1.1 (SLR just above critical rate),* ***(d)*** *r = 2 (SLR far above critical rate), in all cases n = 2. The dynamic equilibrium h_e and the morphological timescale τ_a are given in the title of the panels.*

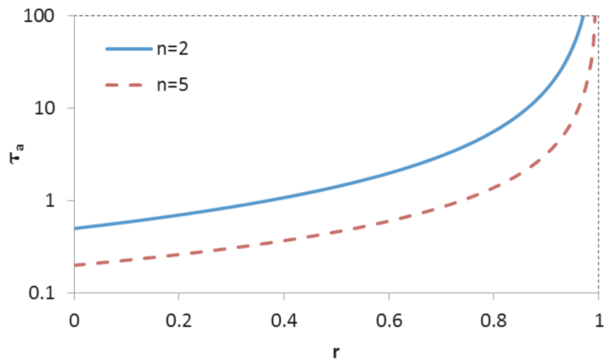


Figure 4-7, *Morphological timescale as function of sea-level rise rate.*

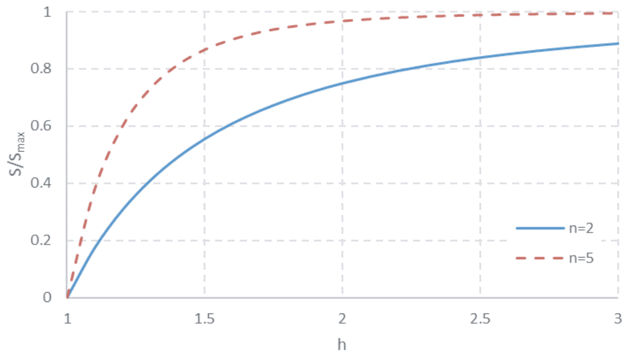


Figure 4-8, *Relation between sediment import rate and the morphological state. h = 1 represents the morphological equilibrium without SLR. The import rate approaches the maximum value for large h.*

4.3.3 Application to the Dutch Wadden Sea

It is the dimensionless SLR rate *r* that influences the behaviour of a tidal basin responding to accelerated SLR. This means that the different tidal basins in the Wadden Sea will respond very differently when SLR accelerates, as the SLR rate will be the same but the critical SLR rate for drowning is very different for the different basins. In Table 4-1, the critical SLR rates for the six tidal basins in the Dutch Wadden Sea (Figure 4-2), as calculated in (Wang et al., 2018) are given together with the dimensionless SLR rate *r* for four SLR rates (2, 4, 6 and 8 mm/y).

Table 4-1, *Critical SLR rate for drowning of the various tidal inlet systems in the Dutch Wadden Sea from (Wang et al., 2018) and the dimensionless SLR rate r for four different SLR rates (2, 4, 6 and 8 mm/y). The equilibrium depth He calculated using the empirical relations and the parameters for basin area Ab and tidal range H are also given. The listed time scale T is calculated using the relation with Rc and He.*

Inlet	A_b (km^2)	H (m)	H_e (m)	R_c (mm/y)	T (Year)	r for SLR Rate =			
						2 mm/y	4 mm/y	6 mm/y	8 mm/y
Texel	655	1.65	2.8	7.00	400	0.29	0.57	0.86	1.14
ELGT	157.7	1.65	1.7	18.0	90	0.11	0.22	0.33	0.44
Vlie	715	1.9	3.5	6.30	560	0.32	0.63	0.95	1.27
Amel	276.3	2.15	2.7	10.4	260	0.19	0.38	0.58	0.77
PinkeG	49.6	2.15	1.7	32.7	55	0.06	0.12	0.18	0.24
ZoutK	105	2.25	2.1	17.1	125	0.12	0.23	0.35	0.47

Figure 4-9 depicts how the dimensionless SLR rate *r* increases with the increasing SLR rate *R* for the various tidal basins in the Dutch Wadden Sea. For the present SLR rate (2 mm/y) *r* is less than 0.4 for all tidal inlets, so SLR has very limited impact on the Wadden Sea (see Figures 4-4 and 4-7). For the inlets with large back-barrier basins, Texel Inlet and Vlie, the level above which significant impact of SLR is expected (*r* = 0.8) will be exceeded at a SLR rate R between 4 and 5 mm/y, whereas for the inlets with the smaller basins Pinkegat, Zoutkamperlaag and Eierlandse Gat this level is unlikely to be exceeded.

Figures 4-4 and 4-7 suggest that that two indicative limits in the response of tidal basins to SLR can be identified. Below a value of *r* = 0.6 the morphological timescale increases approximately linearly with increasing values of dimensionless SLR rate, *r*. In contrast, above a value of about *r* = 0.8 the morphological timescale increases rapidly and non-linearly. When *r* is above this limit, tidal basins will experience a long process of ‘drowning’. In order to ensure that tidal basins remain resilient to accelerating SLR it is advisable to ensure that *r* does not exceed 0.6 due to anthropogenic causes like gas mining. Wang et al. (2018) advised using *r* = 0.4 as the limit for managing gas and salt mining.

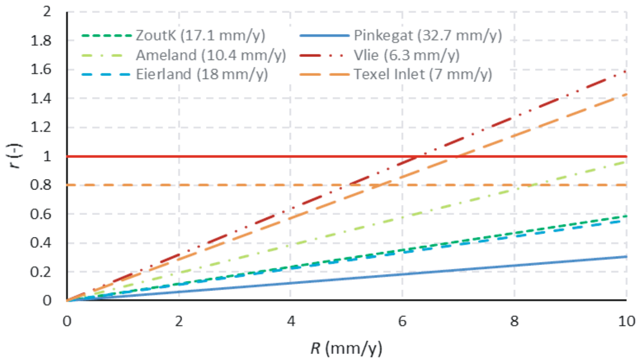


Figure 4-9, *Dimensionless SLR rate r, i.e., normalized with the critical rate (given between brackets in the legend) as calculated in (Wang et al., 2018) for the tidal inlets in the Dutch Wadden Sea, increases linearly with the SLR rate R. The solid red line (r = 1) indicates the initiation of drowning and the dashed orange line (r = 0.8) indicates the level above which significant impact of SLR is expected.*

4.4. Concluding Discussions

In summary, the findings from the theoretical analysis provide insights into the response of tidal basins to SLR concerning the critical SLR rate as well as concerning the transient development when SLR rate changes.

The non-linear behaviour of the system concerning dynamic morphological equilibrium (Figure 4-4) and the corresponding morphological timescale (Figure 4-7) implies that a tidal basin responds to a relatively high SLR rate in a similar way, no matter if the SLR rate is below, equal or above the critical rate (Figure 4-4). Furthermore, the timescale of the response of tidal basins to changing SLR is very large (in the order of centuries (Kragtwijk et al., 2004)). It will thus be very difficult if not impossible to determine the critical rate of SLR by monitoring. The present analysis shows that the critical SLR rate can be determined from the morphological equilibrium and the morphological timescale (with respect to morphological equilibrium). The combination of Equations (4-11) and (4-12) yields $R_c = H_e/nT_m$. The equilibrium depth H_e can be determined from the field observations, directly or indirectly via empirical relations. The morphological timescale T_m can also be derived from observed development if the considered system is disturbed from its equilibrium. A system can be disturbed not just due to human interventions but also due to, e.g., nodal tidal cycle (Townend, 2007; Wang and Townend, 2012), or major storm events (de Vet et al., 2019). This relation thus makes it possible to determine the critical rate of SLR from field observations of limited time period.

The influence of the power n according to this relation implies that the type of sediment is important. A sandy system can behave very differently to a muddy system. This explains also the findings in (Wang and Van der Spek, 2015): After increasing the n value from two to five the critical SLR rate became much lower even though the model was calibrated to have the same morphological timescale in both cases. This reveals also the importance of sediment grading in tidal systems. Sediment composition varies within tidal basins: fine sediment being found on the flats and coarser fractions in the channels. In order to respond to sea level rise and maintain elevations relative to the tidal frame of reference, the sediment demand of these different zones needs to be met. Hence, a tidal inlet system with a relatively large range in sediment fractions is less vulnerable to drowning than systems with only highly sorted sediment fractions available.

The morphological timescale with respect to the dynamic morphological equilibrium is strongly influenced by the SLR rate. It is essential to realize that it is the morphological timescale with respect to the dynamic morphological equilibrium that determines how long it takes before the new dynamic morphological equilibrium is achieved when SLR accelerates. This morphological timescale is different from the one with respect to the morphological equilibrium for $R = 0$ (i.e., no SLR). It can be estimated by linearizing the model with respect to the dynamic morphological equilibrium. This morphological timescale increases with increasing SLR rate non-linearly (Figure 4-7). It increases to infinity as SLR rate approaches the critical value. Physically this can be explained by the delayed response of the tidal basin to acceleration of SLR and the limitation of sediment transport capacity through the inlet (Wang et al., 2018). The delayed response has the consequence that the effect of acceleration in SLR on sediment exchange between the basin and the coastal area will only be noticeable after a long time. The limit imposed by sediment transport capacity implies that even over the long-term the sediment import to the basin cannot increase in proportion to the SLR rate. For the tidal basin itself it means that acceleration of SLR will cause loss of tidal flat areas, but the total loss will only be achieved after a long period of time. When a basin is drowning, it is importing sediments at the maximum rate and the processes of drowning will be very slow.

The availability of sediments to be transported into the basins then becomes important (see the conceptual model in Wang et al. (2018)). Tidal basins in this state are perpetually adapting to changing conditions. This helps to explain why tidal basins can exist for centuries to millennia, even with highly changing conditions, as is the case of the Wadden Sea. It is therefore likely that the Wadden Sea tidal basins will persist for a long time even after the process of drowning has started, in the case of strongly accelerated SLR. However, even though a slow drowning process implies no immediate morphological need for mitigation and adaptation, this does not reflect the ecological need and significant changes to the ecosystem may result from these pervasive morphological changes.

It is the dimensionless SLR rate, i.e., the ratio between the SLR rate and the critical rate for drowning, that determines how a tidal basin responds. This means that the morphological responses of the different basins to future accelerated SLR will be very different. For the larger basins Vlie and Texel Inlet, the critical SLR rate is lower and they will likely be seriously affected if SLR rate exceeds 4 mm/y. For the smaller basins, Pinkegat and Eierlandse Gat, the critical SLR rates are high and they are unlikely to be seriously affected by an accelerating SLR. However, the distinguished responses of the different tidal basins to accelerating SLR can only remain if the tidal divides can remain functioning as boundaries between the neighbouring basins. Therefore, it is important to study the more detailed local morphological development around tidal divides.

The insights from the analysis with the aggregated model are also relevant for the process-based modelling. The importance of the correct value of *n* implies that in a process-based morphodynamic model, it is essential to choose the right sediment transport formulation, and not merely to reproduce the correct order of magnitude of sediment transport rate. Furthermore, it is important that the graded sediment is well represented in the model. The large timescale for achieving the new dynamic equilibrium, especially when the SLR rate is relatively high, makes it impossible to conclude from the model results of limited period if the tidal flats are drowning (total disappearance of tidal flats in the long term) or not. This is confirmed by the findings of Van der Wegen et al. (2016) and Elmilady et al. (2019) who modelled the development of intertidal flats in San Pablo Bay using a 150 year hindcast and a 100 year forecast, for various SLR scenarios. That (accelerated) SLR rise causes continuous loss of intertidal areas over the forecast period does not necessarily mean that all SLR scenarios are causing drowning of the tidal flats. The simulated period (100 years) can simply be too short compared to the morphological timescale with respect to the dynamic equilibrium.

5

Future sediment exchange between the Dutch Wadden Sea and North Sea Coast - Insights based on ASMITA modelling

This chapter has been published as:

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Abstract

The sediment exchange between the Dutch Wadden Sea and the North Sea coastal zone is of key importance to Dutch coastal management. Net sediment import from the coastal zone to the Wadden Sea results in coastal erosion which needs to be compensated through nourishments. At the same time net sediment import is the source of sediment for the intertidal flats in the Wadden Sea to adapt to sea level rise (SLR). Understanding the current and future sediment exchange is therefore essential for sustainable coastal management. Insights in the sediment exchange directly influence the coastal nourishment strategies applied to the Dutch coasts. Projections of the future sediment exchange between the Dutch Wadden Sea and the North Sea are established using the aggregated morphodynamic model ASMITA for five sea level rise scenarios, viz. the present rate of 2 mm/yr. and accelerated rates of 4, 6, 8 and 17 mm/yr. in 2100. The differences in the projected import rates between the five sea level rise scenarios until 2100 are not as large as the differences in sea level rise rates may suggest. For the Eastern part of the Dutch Wadden Sea, where the morphology is near its dynamic equilibrium, the projected import rate in 2100 varies with a factor 3 (300%), for sea level rise rates from 2 to 17 mm/yr. (factor 8.5, 850%). In the western part of the Dutch Wadden Sea, where the morphology is still far from equilibrium due to the closure of the Zuiderzee, the projected import rate in 2100 varies a factor 1.45 (145%) for these sea level rise rates. For the total Dutch Wadden Sea this is a factor 1.7 (170%). The projected increase of the import rate until 2100 with respect to the present situation (2020) is up to a factor 1.45 (145%) for the highest sea level rise scenario, which is significant but not substantial.

5.1 Introduction

The Wadden Sea spans nearly 500 km of the northern coast of the Netherlands and the North Sea coasts of Germany and Denmark. The Wadden Sea is connected to the North Sea by a series of tidal inlets and estuaries between barrier islands, and characterized by a wide variety of channels, sandy shoals and mud flats, gullies and salt marshes. The Dutch Wadden Sea, bounded by the tip of the Holland coast in the southwest and the Ems Estuary in the east, consists of six major tidal inlet systems (Figure 5-1), and several smaller inlets that form the Groninger Wad area just west of the Ems Estuary. The eastern Dutch Wadden Sea, consisting of Ameland Inlet, Pinkegat Inlet and Zoutkamperlaag Inlet, is close to its morphodynamic equilibrium (Wang et al., 2018). The Western part of the Dutch Wadden Sea, consisting of Texel Inlet, Eierland Inlet and the Vlie Inlet, is still far from equilibrium as the morphological changes are still influenced by the closure of the Zuiderzee in 1932 (Elias et al., 2012; Wang et al., 2018). Specifically, by morphodynamic equilibrium in this chapter we mean that the average vertical sedimentation rate in the basin is equal to the sea level rise (SLR) rate. This means that a basin in morphodynamic equilibrium, experiencing sea level rise, is importing sediments and therefore has a net positive absolute sediment budget and a net zero sediment budget relative to mean sea level. For an in-depth review of the concept of morphodynamic equilibrium we refer to Zhou et al. (2017).

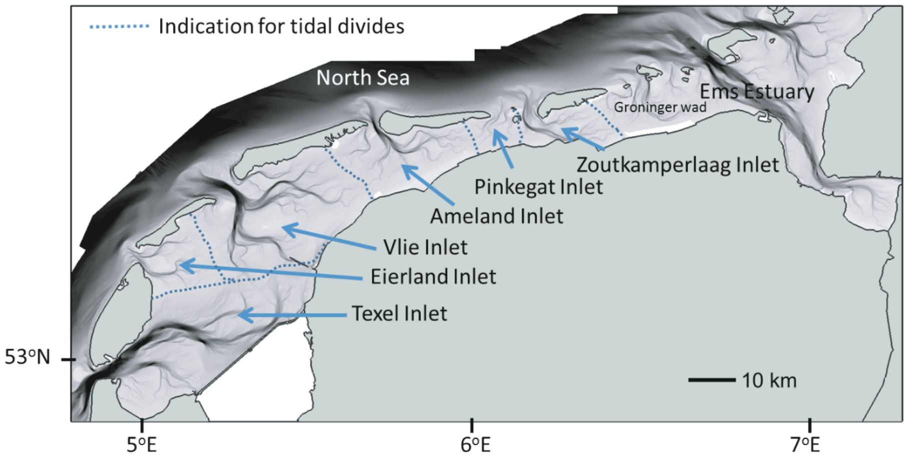

Figure 5-1, *Tidal basins in the Dutch Wadden Sea (after Lodder et al., 2019a).*

Knowledge of sediment exchange between the (North Sea) coastal zone and the Wadden Sea informs policy and decision making in the Netherlands. In particular, long-term flood protection and the associated coastline maintenance require an understanding of the sediment budget of the coast (Mulder et al., 2011; Lodder et al., 2019b). In Dutch coastal management policy, the total average annual sand nourishment volume for the coast is among others determined by the sediment exchange through the tidal inlets of the Wadden Sea (Rijkswaterstaat, 2020). The degree of adaptation of Wadden Sea intertidal flats, which have high ecological values, to sea level rise also depends on this sediment exchange. Therefore, insight into the sediment exchanges between the coastal zone and the Wadden Sea through the various tidal inlets is essential for the management of the Dutch coastal system. The objective of the present study is to project the long-term development in sediment exchanges through the tidal inlets between the Dutch Wadden Sea and the (North Sea) coastal zone. Future system behaviour and relative import rates are key parameters informing Dutch coastal policy, since one of the objectives of the coastal nourishments is to compensate sediment losses from the coastal zone (Rijkswaterstaat, 2020 and Lodder et al., 2019b)

Field measurements and data analysis form core components in gaining insight into the sediment exchange between the coastal zone and the Wadden Sea. Sediment budget analyses based on bathymetric data not only provide information on historical sediment exchanges through the inlets, but also provide insight into the morphological status of the Wadden Sea (Elias et al., 2012; Wang et al., 2018). For example, sediment exchanges are not only determined by SLR but are also influenced by past human interventions, such as the closure of the Zuiderzee in 1932 and closure of the Lauwerszee in 1969. Extrapolating present-day trends provides a direct projection of trends in sediment exchange for the near future. For this short timescale (years to decades), we can safely assume that large-scale processes remain the same. On longer timescales (decades to centuries) accelerating SLR will start to become increasingly important for sediment exchange processes, and this assumption may no longer be valid.

Sea level rise creates a sediment demand in the basin as the tidal flats tend to grow in height, following the development of high-water levels (Wang et al., 2018). As a result, more sediment needs to be imported into the basins. Especially in the basins that are presently close to equilibrium (e.g. the eastern Dutch Wadden Sea), this sediment demand will be a dominant factor in the sediment loss of the nearshore zone.

How the sediment exchange between the coast and the basins develops quantitatively can only be projected by numerical modelling, as the response of the system to the development of SLR will be delayed and the time scale of the delay is dependent on morphological characteristics of the inlet systems and the SLR rate (Lodder et al., 2019a).

In the Western Dutch Wadden Sea, the effect of SLR is even more difficult to project. At present the system is still far from equilibrium due to past human interference (Elias et al., 2012; Wang et al., 2018) and it is not known when or how the effects of SLR will start to dominate the sediment exchanges.

This study focusses on the following research questions:

- How will the sediment exchange rates through the tidal inlets develop in the future (up to 2100)?
- How are the sediment exchange rates influenced by sea level rise?

The modelling approach in combination with recent insights from field observations and data analysis is described first. Then the existing models of the tidal inlets of the Dutch Wadden Sea are characterized and a selection is made regarding the future sea level rise scenarios for the projections. Next, the adjustments to the parameter settings of the existing models to adequately reflect current understanding of the responses of the tidal basins to a continuation of the present sea level rise rate are reported. The projections for the selected sea level rise scenarios are then described. A discussion on the interpretation of the model results and the implications for coastal management and policy follows. The chapter ends with recommendations for future model developments.

5.2 Method

5.2.1 Modelling approach

Three methods for predicting sediment exchange through the Wadden Sea inlets can be applied:

1 Data analysis (e.g. sediment budgets).
2 Process-based modelling (e.g. Delft3D).
3 Aggregated modelling (e.g. ASMITA).

The first approach cannot be used to investigate Wadden Sea sediment exchange processes on long timescales. Extensive sediment-budget analyses based on bathymetric datasets (the so-called Vaklodingen) have been carried out (Elias et al., 2012; Elias, 2019). However, extrapolation of sediment budgets is only valid on short timescales. Numerical modelling approaches are needed to project sediment exchange on long timescales.

Various Delft3D process-based models for the Dutch Wadden Sea are available. However, applications of process-based models for simulating impact of SLR to the Dutch Wadden Sea (Dissanayake et al., 2012; Wang et al., 2018) have not been very successful yet. The major problem is that these models do not reproduce a realistic morphologic equilibrium. As a consequence, the models spin up due to the discrepancy between morphodynamic equilibriums according to model and reality, and the changes due to spin up cannot be distinguished from the development to be simulated. Furthermore, long-term morphodynamic simulations at the scale of the entire Dutch Wadden Sea would result in infeasible long run times and computational expense. Potentially, process-based models can be useful in the future for long-term morphodynamic simulations including those for studying the effects of (accelerating) SLR by evaluating the results of the different projections in a relative manner, as demonstrated by applications in the German Wadden Sea (Becherer et al., 2018; Hofstede et al., 2018).

The ASMITA model was developed to simulate the long-term large-scale morphological developments of tidal inlet systems (Stive et al., 1998; Stive and Wang, 2003). In addition to the higher level of aggregation, the most important difference from the process-based models is the implementation of the empirical relationships for morphodynamic equilibrium. This allows the model to reproduce morphodynamic equilibrium if the forcing conditions remain constant over time. Reproduction of the morphodynamic equilibrium is an essential requirement for projecting the effect of SLR on morphological development (Lodder et al., 2019a). The sediment exchange through the inlet is a direct output of the model. When appropriately set up and calibrated, this type of model is suitable for achieving the objective of this study.

As a basis for this study, previously developed ASMITA models are used (van Goor et al., 2001; Kragtwijk, 2002, Van Goor et al., 2003, Kragtwijk et al., 2004). The model settings are updated to include the latest morphodynamic insights from data analysis studies (Wang et al., 2018; Elias, 2019). In addition, the insights from Lodder et al.'s (2019a) theoretical analysis on the impact of SLR on a tidal basin using a simplified (single-element) ASMITA model are used in interpreting the ASMITA model results of this study. The projections extend from the present till 2100, using five scenarios with different SLR rates.

5

5.2.2 Existing parameter settings for ASMITA models

For ASMITA each tidal inlet system is schematized into three morphological elements, comprising tidal flats (sediment volume) and channels (water volume) in the basin and the ebb-tidal delta (sediment volume) (Figure 5-2). The effect of SLR on the Eierland Inlet and the Ameland Inlet were studied by Van Goor et al. (2003) after which his schematization was used for setting up the ASMITA models for the other inlet systems in the Dutch Wadden Sea (Kragtwijk et al., 2004; Bijsterbosch, 2003; Hinkel et al., 2013). The parameter settings reported by Wang et al. (2006), presented in Table 5-1, are considered the most representative, despite several attempts to improve the models further (Van Geer, 2007; Wang et al., 2008; Wang and Van der Spek, 2015).

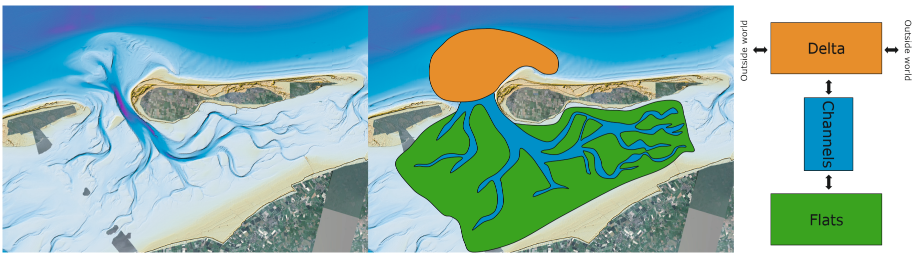

Figure 5-2, *Schematization of a tidal inlet system into a 3-element ASMITA model.*

Table 5-1, *Input parameters of the existing ASMITA models for the tidal inlets of the Dutch Wadden Sea (Wang et al., 2006).*

Inlet	Texel	Eierland	Vlie	Ameland	Pinkegat	Zoutkamperlaag
Basic configuration: tidal range H and horizontal area A of the three elements. The subscripts indicate the elements, i.e. f=flat, c=channel, d=ebb tidal delta.						
H (m)	1.65	1.65	1.90	2.15	2.15	2.25
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
Parameters influencing the morphological timescale: n=power in the relationship for the local equilibrium sediment concentration, C_E=global equilibrium concentration, w_s=vertical exchange coefficient in the element indicated by the second subscript (f=flat, c=channel, d=ebb tidal delta), δ=horizontal exchange coefficient between the two elements indicated by the two subscripts (o=outside world).						
n (-)	2	2	2	2	2	2
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
w_{sc} (m/s)	0.0001	0.00005	0.0001	0.00005	0.0001	0.0001
w_{sd} (m/s)	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
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
Initial conditions: volumes of the three morphological elements in 1970						
V_{f0} (million m^3)	51.5	55	162	120	29.6	69
V_{c0} (million m^3)	2160	106	1230	302	18.5	177
V_{d0} (million m^3)	509.1	132	369.7	131	35	151
Parameters for defining the morphodynamic equilibrium: V_{fe}=equilibrium volume of the flat element, τ=coefficient in the relationship between the equilibrium volume (V) of the element indicated by the subscript and the tidal prism (P): $V_{ce} = \alpha_c P^{1.55}$, $V_{de} = \alpha_d P^{1.23}$ Volumes f and d are sediment, c is water.						
V_{fe} (million m^3)	151	57.83	190	131.2	30.3	70
α_c (10^{-6})	10	13.13	9.6	10.241	10.14	27.266
α_d (10^{-3})	4.025	8	2.662	2.92157	6.9278	9.137

Wang et al. (2018) used these parameter settings to calculate critical rates of SLR (R_c) for drowning of the tidal flats in the inlet systems following the formulation of Van Goor et al. (2003) (see also Bijsterbosch, 2003; Hinkel et al., 2013). Therefore, the starting point for the parameter setting in this study is Wang et al. (2006), see Table 5-1. These are adjusted with new insights from data-analysis (Elias, 2019) and theoretical analysis (Lodder et al., 2019a), as elaborated in the section "Improvement of parameter settings".

5.2.3 Sea Level Rise (SLR) Scenarios for projections

The objective of the present study is to project changes in sediment import to the Wadden Sea under different probable SLR rates in order to assess system behavior and the sensitivity to SLR rates. The selected scenarios are respectively a continuation of the observed present relative SLR rate and 2, 3, 4 and 8.5 times the current rate (Table 5-2 and Figure 5-3). The scenarios span the likely range (17^{th}-83^{rd} percentile) of sea level rise rates for Representative Concentration Pathway (RCP) 2.6 to RCP 4.5 in 2100 by Vermeersen et al. (2018) and Shared Socio-economic Pathway (SSP) 2-4.5 of the IPCC sixth assessment report (IPCC, 2021, Fox-Kemper et al., 2021, NASA, 2021). For the accelerating scenarios a SLR rate is used that increases linearly in time until a maximum is reached at the end of the acceleration period (except for the highest scenario where the maximum is reached in 2100), in line with the methodology of Vermeersen et al. (2018). The rate of increase is higher, and the period of acceleration is longer, for a higher scenario. The acceleration ends in 2050, 2060, 2070 respectively for the three intermediate scenarios. In the scenarios of Vermeersen et al. (2018), the acceleration of SLR commenced earlier than 2020. However, this feature was not incorporated in the scenarios used in this study to preserve coherence with the observed present relative SLR rate of 2mm/yr. in 2020 based on tide gauges at the Dutch coast as reported by Baart et al. (2019).

Table 5-2, Definitions of the considered SLR scenarios.

Scenario	Definition
SLR-2	Continuation of the present SLR rate: *R* is constant and equal to 2 mm/yr.
SLR-4	*R*=2 mm/yr. until 2020, from 2020 to 2050 *R* increases linearly to 4 mm/yr., and then remain constant, *R*=4 mm/yr..
SLR-6	*R*=2 mm/yr. until 2020, from 2020 to 2060 *R* increases linearly to 6 mm/yr., and then remain constant, *R*=6 mm/yr..
SLR-8	*R*=2 mm/yr. until 2020, from 2020 to 2070 *R* increases linearly to 8 mm/yr., and then remain constant, *R*=8 mm/yr..
SLR-17	*R*=2 mm/yr. until 2020, from 2020 to 2100 *R* increases linearly to 17 mm/yr.

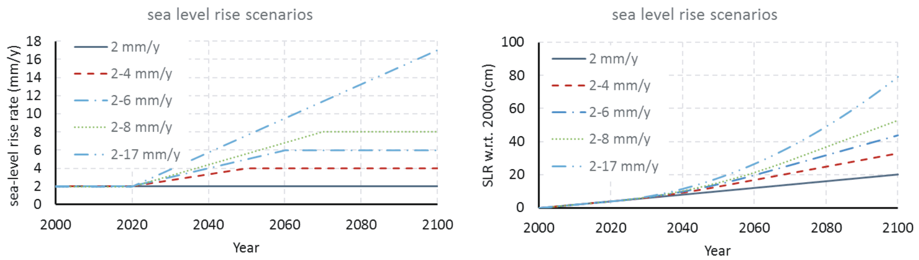

Figure 5-3, *The sea level rise scenarios considered in the present study. Left: change of SLR rate; right: SLR since 2000.*

5.3 Improvement of parameter settings

As part of this study, the parameter settings of the models were optimized. The models were run using the present SLR rate (scenario SLR-2). The results were compared with insights derived from field observations and data analyses of sediment exchange between the Wadden Sea and the coastal zone. Adjustments are made in the parameter settings (Table 5-1) to achieve enhanced agreement with the most recent insights.

The most recent sediment budget model based on field data analysis (Elias, 2019) distinguishes between the long-term trend and the present trend (see Table 5-3). The long-term trend is determined using all the available bathymetry data since the closure of the Zuiderzee in 1932, estimates of the local subsidence (Hijma en Kooi, 2018a,b) and data on dredging and dumping of sediments. The present trend is determined using data from a recent period in which the development exhibited a linear trend in the considered system (since around 2000, variable per system). The trends in basin volume change and the sediment transport rate through the inlets are not in full agreement with each other due to sediment exchange across the tidal divides between the basins (Table 5-3). The net sediment exchange between the basins is estimated to be 0% (Eierland), 18% (Vlie), 25% (Ameland), 28% (Pinkegat + Zoutkamperlaag) and 38% (Texel) of the sediment import through the inlet (Elias, 2019, figure 7.3). Due to the model setup of ASMITA it is not (yet) possible to include sediment exchanges between the basins as basins have closed borders in ASMITA. Ignoring the inter-basin interaction results in differences in the projected net sediment import per basin. However, the overall relative trends, the total net sediment import rate to the basins combined and large-scale system behavior are not significantly influenced. These parameters are most important for informing the coastal nourishment policy and strategy.

Table 5-3, *Results of the sediment budget analysis, in sediment volume change trends (Elias, 2019).*

Inlet	**Texel**	**Eierl.**	**Vlie**	**Amel.**	**Pinkeg. + Zoutk.**
Long-term trend basin volume change (10^6 m^3/yr.)	3.53	-0.15	2.30	1.25	2.02
Present trend basin volume change (10^6 m^3/yr.)	1.23	-0.32	1.43	1.63	0.35
Long-term transport rate through inlet (10^6 m^3/yr.)	4.40	-0.15	1.77	1.01	2.12
Present transport rate through inlet (10^6 m^3/yr.)	1.98	-0.32	1.18	1.23	0.45

The present trend in the basin volume change of the Frisian Inlet (Pinkegat + Zoutkamperlaag) approximates the dynamic equilibrium value, i.e. the increase rate of the accommodation space (=basin area * SLR rate = 0.31 million m^3 per year). Therefore, for the Pinkegat and Zoutkamperlaag the results of Elias (2019) confirm the conclusion of Wang et al. (2018) that this system is close to morphodynamic equilibrium at present. The much larger long-term trend is caused by the closure of the Lauwerszee. Wang et al. (2018) characterize the Ameland Inlet as in morphodynamic equilibrium. However, the present and the long-term trends in the basin volume change determined by Elias (2019) are much larger than the increase rate of the accommodation space (about 0.55 million m^3 per year). As we do not yet have a sound explanation for the extra sedimentation and are not certain if the observed trend will continue, we adhere to the conclusion of Wang et al. (2018) here. Accordingly, for the three inlets in the eastern Dutch Wadden Sea (Ameland, Pinkegat, Zoutkamperlaag), the model results (Figure 5-5) for the present SLR rate (2 mm/yr.) largely agree with the insight that they are in or close to morphodynamic equilibrium. The sediment imported through the inlets balances the effect of SLR in the basins and the existing ASMITA models for these three inlets were therefore not modified.

For the three inlets in the western Dutch Wadden Sea (Texel, Eierland, Vlie), the existing ASMITA models were adjusted by changing the parameters determining the morphodynamic equilibrium in the basins, i.e. the equilibrium volume of the tidal flat V_{fe} and the coefficient in the relationship for the equilibrium channel volume α_c (see Wang et al. (2020) for details of the empirical relationships for morphodynamic equilibrium). In the parameter setting of Wang et al. (2006) for Texel Inlet, V_{fe} was increased following the empirical relationships that determine V_{fe} from the basin area A_b and the tidal range. However, the tidal flat area A_f in the basin of Texel Inlet is relatively small (Table 5-1), and is constant during the model simulation. This has the consequence that the (effective) equilibrium height of the tidal flat is almost 70% of the tidal range, instead of the more typical 40% found in the other basins of the Wadden Sea (Eysink, 1990; Wang et al., 2020). Therefore, V_{fe} is decreased so that the effective equilibrium height of the tidal flat is 40% of the tidal range (V_{fe}=88 million m^3 instead of 151 million m^3). This change has also consequences for the equilibrium of the channel and the ebb-tidal delta, because a smaller tidal flat volume means a larger tidal prism. This causes the sediment import to the basin to decrease, but the effect is limited (decrease less than 5%). Therefore, α_c is also increased (from $10*10^{-6}$ to $15*10^{-6}$). This choice is motivated by the consideration that the anticipated change of subtidal areas (belonging to the channel element) to intertidal areas (flat) will likely not happen because the strong flow prevents the deposition of fine sediment. There seems to be limited effective sedimentation space (i.e. area's with energy levels are low enough to allow for net sedimentation), which limits the amount of accretion. In other words, the potential sediment demand according to the empirical relationships is not yet an effective sediment demand (Elias et al., 2019). This argument also supports the choice to decrease the V_{fe} value. The simulation outputs for an increased α_c value and for an increase in α_c combined with a decrease in V_{fe} are shown in Figure 5-4.

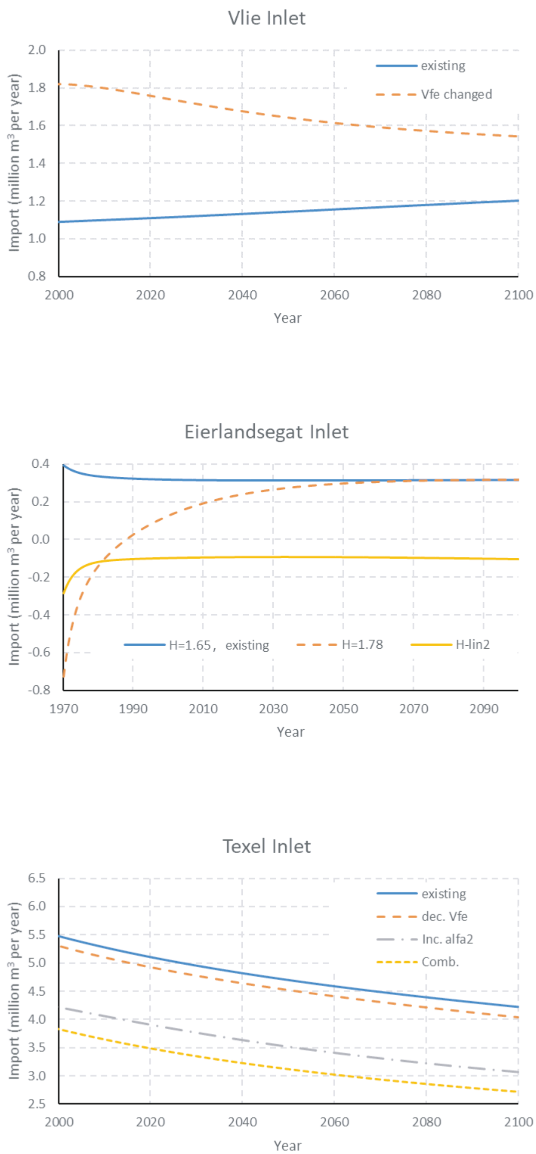

Figure 5-4, *Improving the parameter settings concerning morphodynamic equilibrium in the ASMITA models for the three tidal inlets in the western Dutch Wadden Sea. The final settings used in the projections are:* V_{fe} *changed (Vfe increased from 190 to 250 million m3) for the Vlie Inlet, H-lin2 (Linear increase of tidal range, starting from 1.73 m in 1970 with 3 mm/yr.) for the Eierland Inlet, and Comb. (*V_{fe} *decreased from 151 to 88 million m3 combined with increase of αc from 10*10-6 to 15*10-6) for the Texel Inlet. Note that the vertical and horizontal scales vary among the basins.*

5

The effect of decreasing V_{fe} is dependent on the value of α_c because of its effect on the tidal prism. The combined changes yielded the lowest sediment import, although this was still higher than the results from the data analysis (Table 5-3) of Elias (2019). As further changes in the parameter settings are difficult to justify, the parameter setting with increased α_c combined with a decreased V_{fe} were used for the projections of sediment exchange under SLR for Texel inlet.

Similar reasoning was applied in determining the V_{fe} value for the Vlie Inlet. According to the existing parameter setting (Table 5-1) the effective equilibrium height of the tidal flat is about 30% of the tidal range. This was altered to about 40% so that V_{fe} increased from 190 to 250 million m^3. The effect of this change is illustrated in Figure 5-4. The import rate is decreasing in time and has a magnitude between 1 and 2 million m^3 per year (see also Table 5-3). As the updated model results are more or less in line with recent insights derived from data analysis (Elias, 2019), this parameter setting was used in the projections of sediment exchange under SLR scenarios for Vlie inlet.

The Eierland Inlet is the only inlet through which net sediment export has taken place according to field observations and data analysis (Elias et al., 2012; Wang et al., 2018). Such export is not reproduced using the existing ASMITA model. In the model an incorrect value for the tidal range was used. Using a correct tidal range of 1.78m initially resulted in sediment export (about 0.8 million m^3/yr.), which however quickly (within less than 20 years) turned to a simulated import and approached a similar level as that of the simulation with the lower original tidal range (1.65m). In both simulations, the import approaches the morphodynamic equilibrium (import rate equal to basin area multiplied by SLR rate), about 0.3 million m^3 per year. Given the relationships used for the morphodynamic equilibrium in ASMITA, a constant export through the inlet with rising sea level is only possible if the tidal prism increases consistently with time. An increase in the tidal prism can be caused by an increasing tidal range, a decreasing tidal flat volume, or an increasing basin area. Field observations indicate that the tidal flat volume in the basin has not been decreasing. Therefore, the only options are an increasing tidal range or an increasing basin area. Observations of the changes in the tidal divides suggest that the basin area of this inlet is increasing (Wang et al., 2013). However, in the present version of ASMITA the horizontal areas of the morphological elements remain constant in time, so it is not possible to simulate the situation of an increasing basin area. Therefore, various scenarios of linearly increasing tidal range were simulated. The simulations show that the sediment transport through the inlet at the dynamic equilibrium is dependent upon and sensitive to the rate of increase of the tidal range. Export can occur consistently under conditions of rising sea level and increasing tidal range. The increasing tidal range increases the tidal prism which in turn causes the equilibrium volumes (water) of the channels in the basin and the ebb-tidal delta (sediment) to increase. The resulting sediment demand on the ebb-tidal delta and the sediment surplus in the channels drive sediment transport from the channels to the ebb-tidal delta – the export of sediment.

The parameter setting scenario H-lin2 (tidal range starts at 1.73 m in 1970 and increases with 3 mm per year) shown in Figure 5-4 was used to project the sediment exchange using the five SLR scenarios for Eierland inlet. This parameter setting maintains an export rate of about 0.1 million m^3 per year, which is lower than observed (Table 5-3). However, with this increase rate, the tidal range will increase by 39 cm over the simulation period (130 years). This is already very high even though it is meant to represent increasing basin area. The increase in tidal range has the same effect on the total sediment demand in the basin as an increase of basin area of about 20 km^2 (i.e. a relative increase with a factor 1.125 (112.5%), which is in the same order of magnitude as reported by Wang et al. (2013)). Given the objective to assess future system behaviour and relative transport rates to inform long-term coastal policy development, the applied approach is deemed sufficient. The reproduced trends and magnitudes of sediment transport are adequate to inform coastal policy (Rijkswaterstaat, 2020). Important in this aspect is the comparatively limited contribution of 6% of Eierland inlet to the observed net sediment transports from the coastal zone.

5.4 Model results and interpretation

The projected sediment imports into the tidal basins are depicted in Figure 5-5. The differences between the five SLR scenarios start in 2020 (Figure 5-3), however the differences between the simulated imports to the Wadden Sea basins become noticeable later in time (Figure 5-5). For the inlets Pinkegat and Eierland Inlet significant increase (+10% difference between lowest and highest scenario's) in the projected sediment import starts around 2025, i.e. 5 years later than those in the development of SLR. For Zoutkamperlaag and Ameland inlets this difference in increase is projected around 2050. For the Vlie and Texel inlets the projection is respectively 2080 and 2090. The difference in delay in response depends on two factors, the size of the basin and the present morphological state of the basin. Larger tidal basins have a longer delay compared to smaller basins. In addition, the existing sediment demand in the basin due to past human interference can make the delay longer. This explains the long delay exhibited by the Texel Inlet. The development of this tidal inlet system in ASMITA is almost fully controlled by the sediment demand due to the closure of the Zuiderzee, also for the accelerating SLR scenarios.

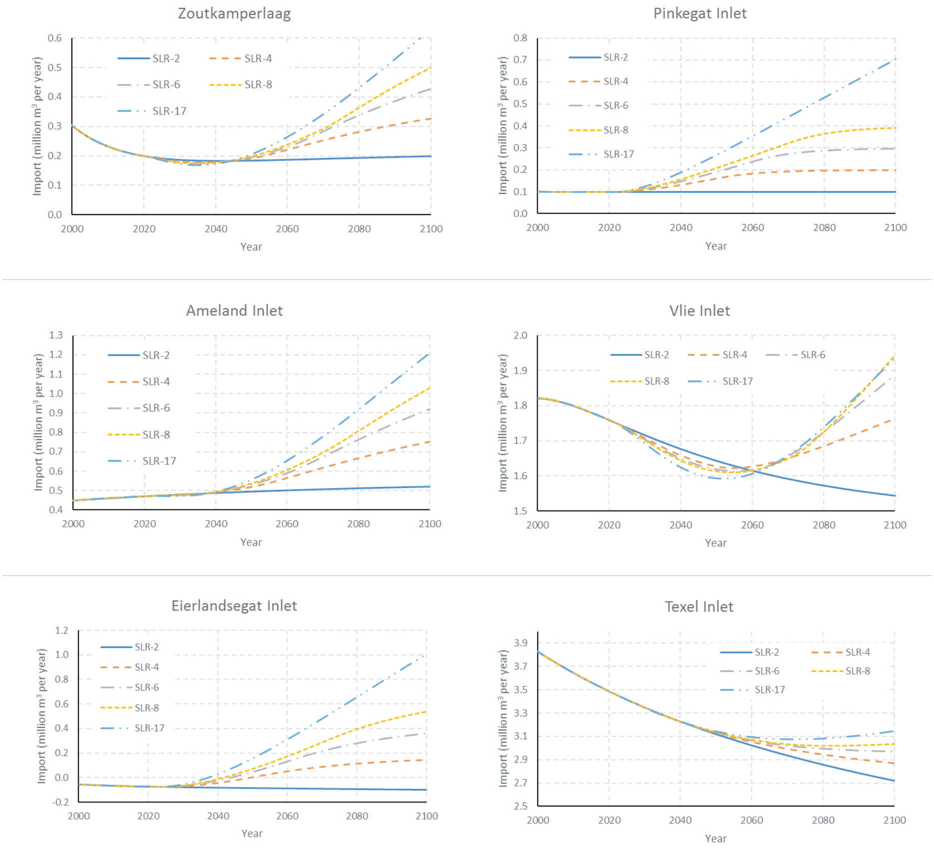

Figure 5-5, *Sediment transport exchange between the Wadden Sea basins and the North Sea coasts through the various tidal inlets (positive = directed to Wadden Sea, i.e. import). Note that the vertical scales vary among the basins.*

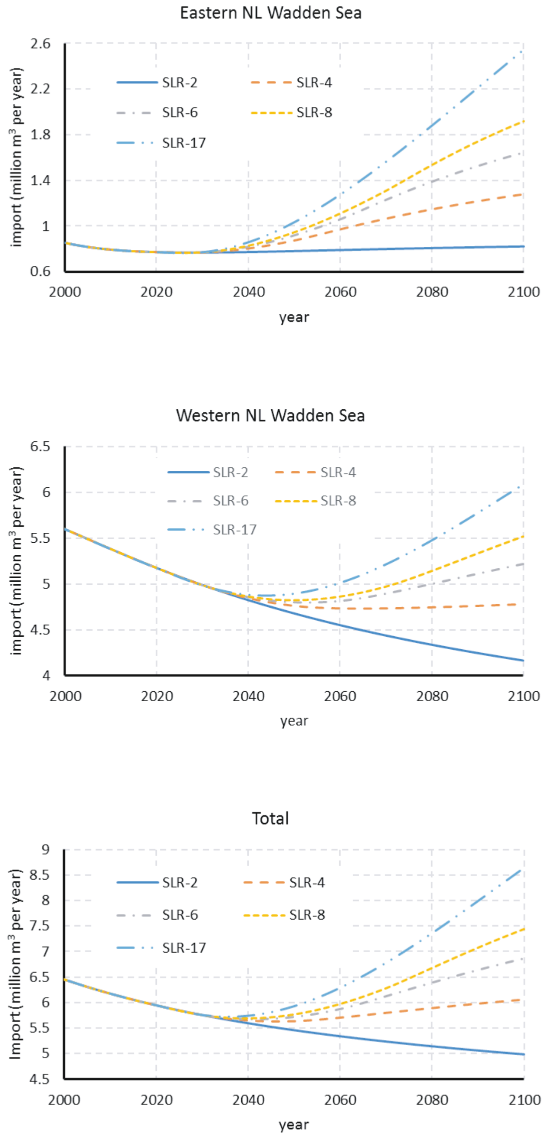

Figure 5-6, *Total sediment import to the eastern part, the western part and the total Dutch Wadden Sea. Note that the vertical scales vary among the basins.*

In Figure 5-6, Total sediment import to the eastern part, the western part and the total Dutch Wadden Sea. Note that the vertical scales vary among the basins.5-6, the total import to the western part (Texel, Vlie and Eierland inlets), eastern part (Ameland, Pinkegat, and Zoutkamperlaag inlets) and the total Dutch Wadden Sea are presented. There is a clear distinction between the eastern and western parts in terms of changes in their projected sediment imports under the five SLR scenarios. For the eastern part, where the present morphology is close to dynamic equilibrium (Wang et al., 2018), the import rate in 2100 varies from about 0.8 million m^3 per year for the lowest SLR scenario (2 mm/yr.) to about 2.5 million m^3 per year for the highest SLR scenario (17 mm/yr.), a factor of 3.1 (310%). For the western part, where the large sediment demand due to the closure of Zuiderzee is still not damped out, it varies between about 4.2 and 6.0 million m^3 per year, a difference of about 145% between the highest and lowest SLR scenarios. The current sediment import is at nearly the same rate as projected for the highest scenarios (8 and 17 mm/yr.) in 2100., indicating that human impact on the sediment import is likely to remain dominant over SLR in the coming century.

Considering the total projected sediment import to the whole Dutch Wadden Sea, the differences between the five projections do not become significant (+5 - 10%) until about 2060 (Figure 5-6). The differences increase in time, but even in the last 40 years of this century the differences are relatively restricted: in 2100 the total import varies between 5 million m^3/yr. (SLR-2) and 8.5 million m^3/yr. (SLR-17), i.e. a difference of about 70% between the highest and lowest SLR scenarios. Note that the SLR rate varies by a factor 8.5 (850%) between the scenarios. The restricted differences are due to the delayed response of the system to variation of SLR and due to the existing sediment demand caused by past human interferences.

The differences between the four scenarios with SLR acceleration are relatively small compared with the difference between the lowest acceleration scenario SLR-4 and the scenario without acceleration of SLR (SLR-2). This can be explained by the time variations of the rate of sea level rise (shift from accelerating to linear) according to the scenarios (Figure 5-3) and the delay in response of the system to SLR. The sensitivity of the model is directly related to the variations of SLR over time and is thus expected to be limited.

Due to the delay in response of the system to SLR, the sediment import at present provides a good indication of the sediment import for the coming years to decades, despite the uncertainty in future SLR development. Projections based on extrapolating the present trend are thus potentially valid for longer than we initially thought. This means that the projections of tidal flat losses in the Dutch Wadden Sea made by Wang et al. (2018) by extrapolating with a constant sedimentation rate are reasonable. This also emphasizes the importance of studying the present system state using measurement observations and process-based modelling.

No substantial increase of sediment import to the total Dutch Wadden Sea is projected until 2100. The import rate is projected to decrease in time if the present SLR rate continues, because the adaptation of the system due to past human interference is dominant over SLR. An acceleration of SLR is projected to change this decreasing trend, however not until 2050. For the highest SLR scenario (17 mm/yr.), the import rate is projected to increase by about 2.5 million m^3 per year in 2100 compared to the present (2020, about 6.0 million m^3 per year) import rate, i.e. an increase with a factor 1.45 (145%).

5.5 Concluding discussion

5.5.1 Characteristics of the updated ASMITA models

The new parameter settings in the ASMITA models represent a second update since the original model setup. Both this and the 2006 update of the parameters defining the morphodynamic equilibrium in these basins, were based on new insights from data analyses (Elias, 2006, Elias, 2019). The update reflects improved insights in the morphological development of the Wadden Sea. However, the necessity of changing the parameters in the relationships defining the morphodynamic equilibrium to obtain agreement between the model results and observations reveals that our understanding of the future morphodynamic equilibrium in the Texel and Vlie inlet systems is still not satisfactory. Investigations of future morphological developments of the basins are needed to improve our understanding of the morphodynamic equilibrium and to assess if further updates to the parameters are necessary.

Interpreting the model results

According to the model results, the tidal inlet systems in the Wadden Sea will respond differently (i.e. delay and magnitude of sediment import) when SLR accelerates. These differences can be explained by three factors: (i) the morphological time scales of a tidal inlet system (Kragtwijk et al., 2004), (ii) the morphological state with respect to equilibrium, and (iii) the dimensionless SLR rate (*r*) which is defined as the ratio between SLR rate and the critical SLR for drowning (Lodder et al., 2019a). In Table 5-4 the critical SLR rates for the six studied tidal basins in the Dutch Wadden Sea, as calculated by Wang et al. (2018), are presented together with the dimensionless SLR rate *r* for the five SLR rates used in this study (2, 4, 6, 8 and 17 mm/yr.). The dimensionless SLR rate *r* determines the morphodynamic equilibrium and the morphological timescale for achieving the dynamic equilibrium (Lodder et al., 2019a). We see that for the same SLR rate, *r* is different for the basins as the critical SLR rate for drowning is different. This explains the key differences in the simulated behavioral responses of the different basins to SLR. A basin with $r > 1$ has a sediment import rate which is lower than is needed to compensate for SLR. Although it is still importing sediment, the average vertical sedimentation rate in the basin is lower than the SLR rate. Such a basin will therefore eventually transit into a drowned system like a lagoon (Lodder et al., 2019, Huismans et al., 2022). No morphodynamic equilibrium is possible for such a basin. A basin with $r > 0.8$ is experiencing such a rapid SLR rate that the average vertical sedimentation rate can only just follow the SLR in the long term. Due to the delay in response and morphological timescale of adaptation, it will take centuries for such a basin to reach morphodynamic equilibrium (Lodder et al., 2019). Morphodynamic equilibrium can only be reached when SLR acceleration stops and becomes linear like in scenarios 2, 3 and 4. The differences in critical SLR rate for drowning depend on the size of the basin (van Goor et al., 2003), as also shown in the German GETM study (Hofstede et al., 2018). The critical rate of SLR for drowning also depends on the tidal range, which varies in the whole Wadden Sea from 1.6 to 3.5 m. Larger basins and basins with a present depth exceeding the equilibrium depth are more vulnerable to drowning.

Table 5-4, *Critical SLR rate (R_c) for drowning of the various tidal inlet systems in the Dutch Wadden Sea from Wang et al. (2018) and the dimensionless SLR rate r for five different SLR rates (2, 4, 6, 8 and 17 mm/yr.). The area (A_b) is provided for reference.*

Inlet	A_b (km²)	R_c (mm/yr.)	*r for SLR rate =*				
			2 mm/yr.	*4 mm/yr.*	*6 mm/yr.*	*8 mm/yr.*	*17 mm/yr.*
Texel	655	7.0	0.29	0.57	0.86	1.14	2.43
Eierland	157.7	18.0	0.11	0.22	0.33	0.44	0.94
Vlie	715	6.3	0.32	0.63	0.95	1.27	2.70
Ameland	276.3	10.4	0.19	0.38	0.58	0.77	1.63
Pinkegat	49.6	32.7	0.06	0.12	0.18	0.24	0.52
Zoutkamperlaag	105	17.1	0.12	0.23	0.35	0.47	0.99

5.5.2 Uncertainties in the model results

Various sources of uncertainty affect the presented results. First, as already mentioned, the models have previously not been extensively calibrated for reproducing the morphological developments since 1970. This uncertainty was overcome by using the results from data analysis studies (e.g. Elias, 2019). An exact match with the results of Elias (2019) was not possible. However, the new parameters provide a good estimation of the observed quantitative import rate. These parameter settings where then used to project future developments, especially focusing on relative differences in sediment transport. Relative trends and magnitudes of sediment exchange are the most important parameters for informing policy, the main objective of this study.

A major uncertainty concerns SLR development itself, as indicated by the five different scenarios. However, the model results indicate that the effects of these differences on the sediment import to the Wadden Sea are relatively limited in the coming decades (less then relative change in SLR). This reduces the uncertainty in the conclusions relevant for the management of the coastal system (e.g. nourishment strategy) significantly. This means also that the uncertainty introduced in the exact definition of the scenarios, i.e. how the acceleration of SLR takes place in time, is of less importance. Many more high-end projections of global and local sea level rise surpass the used scenarios (i.e. IPCC, 2019, IPCC, 2021), however the morphological response of the Wadden Sea under these projections is likely to be comparable. The delayed response of the Wadden Sea will manifest itself as well, just as in the projections for the used scenarios. A significant increase in sediment import is projected to happen but with a delay (decades), first in the Eastern part later also in the Western part of the Dutch Wadden Sea.

The remaining source of uncertainty relates to shortcomings in the models. By considering the tidal divides as fixed and closed boundaries between the basins, and by keeping the internal distribution between the subtidal and intertidal areas unchanged during the simulation, the sediment demand of a basin is affected. The effect on the model results can be determined by varying the parameters in the relationships for the morphodynamic equilibrium as was done in updating the models for Texel Inlet and the Vlie Inlet. The conclusion that the update did not significantly affect the model results concerning the relative differences and trends (Figure 5-4) implies that the uncertainty associated with these particular model shortcomings remains limited. For the Eierland Inlet the effect of increasing basin area due to moving tidal divides is simulated by introducing an increasing tidal range in time. This also causes uncertainty however its effect on the total sediment import to the Dutch Wadden Sea is limited because of the relatively small share of this inlet. More important is the shortcoming that the change in tidal range due to morphological development of the system is not taken into account. The model results are sensitive to an increase in tidal range, as demonstrated by the update of the model for Eierland Inlet (Figure 5-4). Acceleration of SLR is expected to increase the tidal range in the Wadden Sea slightly (Pickering et al., 2017, Becherer et al., 2018; Hofstede et al., 2018). According to the results for the Eierland Inlet, an increase tidal range results in a lower import (c.q. higher export) rate. This effect might increase the delay in the response of the basin to an increase in SLR, and represents a significant source of uncertainty.

Another aspect is that the ASMITA models do not consider waves explicitly as driving force for the morphological development. However, the effects of waves are implicitly considered via the used relationships for morphodynamic equilibrium and via the parameters determining the morphological time scales. This is a source of uncertainty if wave climate in the Wadden Sea area will significantly change in the future.

A further shortcoming relates to the single fraction sediment transport module. On the one hand, as explained by Wang and Van der Spek (2015), the parameter settings of the models take the effects of sand-mud mixture in the system into account, limiting the effect of this uncertainty on model results. On the other hand, the theoretical analysis by Lodder et al. (2019a) shows that the value of the power *n* in the equilibrium concentration formulation influences the critical SLR rate for drowning at the same morphological timescale (related to decay of disturbances with respect to the morphodynamic equilibrium without SLR). Wang et al. (2008) showed that the value used (*n*=2) is quite low. According to the theoretical analysis, this results in a critical rate of SLR that is too high, implying that errors are introduced into the model results at very long timescales (related to the drowning process, centuries). However, in this study the projected period (until 2100) is relatively short in comparison with the timescale of drowning. Therefore, the uncertainty corresponding to this model shortcoming is considered limited.

5.5.3 Relevance of system understanding for management and policy

The enhanced system understanding derived from the interpretation of the ASMITA model results and the consideration of the uncertainties in these results, is used to support long-term management of the Dutch coast. In particular, the system understanding is used to determine the sediment nourishment strategy aimed at maintaining the position of the Dutch coastline. The magnitude and trends in sediment import from the coastal zone to the Wadden Sea is directly used in the assessment of current and future nourishment volumes. Especially the limited relative differences in sediment import to the Wadden Sea for different rates of SLR are very relevant (Rijkswaterstaat, 2020).

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In particular, this study reveals that the effect of SLR acceleration on the projected sediment import for the whole Wadden Sea is not noticeable before 2040, even if the acceleration starts in 2020. Further, the differences between the projections of sediment import to the Wadden Sea under SLR are much less than the differences in SLR rate might suggest until 2100. The difference in import rates between the highest (17 mm/yr.) and the lowest (2 mm/yr.) scenarios is only about 3.5 million m^3 per year in 2100, and varies from about 5 million m^3 per year (for the lowest scenario) to about 8.6 million m^3 per year. Most significantly, no substantial increase of sediment import to the Wadden Sea is projected until 2100. If the present SLR rate continues, the import rate is projected to initially decrease with time as the system persists in its dampening response to past human interferences. The acceleration of SLR is projected to cause this initial decreasing trend to change, but not until 2040, according to all projections. For the highest SLR scenario (17 mm/yr.), the import is projected to increase by about 2.5 million m^3 per year in 2100 compared to the present rate of about 6 million m^3 per year (Figure 5-6).

This means that the effect of accelerating SLR on the loss of sand from the coastal zone due to import to the Wadden Sea is projected to be limited until 2100. In terms of sediment nourishment for coastline maintenance, this limited effect of changing SLR on the sediment import to the Wadden Sea can be considered positive. However, it is likely to have negative consequences for the conservation of the ecological value of the Wadden Sea as the acceleration of SLR is expected to result in an increased loss of intertidal flat area (Huisman et al., 2022). Given the uncertainty in the development of SLR and the potentially conflictual effects of sediment import on the nourishment requirements compared with the conservation of the ecological value in the Wadden Sea, strategies for influencing the sediment import rates through the inlets become of management interest. Strategies such as nourishments on the ebb-tidal deltas, at or directly landwards of the tidal inlets are among the possibilities that will need to be considered. These strategies might benefit both mitigation of sediment loss from the coastal zone and provide sediment for the shoals of the Wadden Sea to adapt to SLR. How the import of sediments can be influenced by ebb-tidal delta nourishments remains uncertain. The studies of Wang et al. (2018) and Lodder et al. (2019) indicate that the net sediment transport is mainly dependent on either the accommodation space of the basin or the sediment transport capacity of the inlet, indicating that the availability of sediments at the North Sea coast is of less importance. Following the ASMITA model formulation it can be reasoned that ebb-tidal delta nourishments will only have very limited influence on the import unless if the nourishment amount is so large that the ebb-tidal delta volume (in the order of 10^8 m^3) is significantly influenced. In any case, a delay in increased sediment import should be expected, just as the projected delay due to accelerating SLR in this study.

In terms of monitoring, field measurements can be used to determine the morphological development under SLR, however this study has indicated that combined modelling and field observations will be needed to ascertain whether relevant limits such as those pertaining to the drowning of a tidal basin will be exceeded or not. Recent research indicates that inter-basin interaction might be of more importance than previously assumed in ASMITA (Herrling and Winter, 2015; Duran-Matute et al., 2016). Field investigations of the development of and sediment transport over the tidal divides in the Wadden See, like Van Weerdenburg et al. (2021), in response to SLR are therefore required to determine whether the assumption that the tidal divides form a closed boundary between the tidal basins as applied in the ASMITA model simulations is justified. Further, model results indicate that sediment exchange between the North Sea coasts and the Wadden Sea is sensitive to the development of the tidal range in the Wadden Sea, e.g., for the Eierland inlet. Accordingly, the changes in tidal range in the tidal basins caused by SLR and morphological development will also need to be investigated, special focus on the Eierland inlet is recommended.

In conclusion, this study has affirmed the relevance of ASMITA modelling for informing long-term coastal management and policy making. However, it has also highlighted necessary future model developments. These include extending the present focus on the sediment exchange through the inlets to an analysis of the development of morphological elements such as the ebb-tidal deltas, channels and intertidal flats within the tidal inlet systems, including interaction between basins. It is recommended that a graded sediment transport module is implemented within ASMITA. The parameter settings indirectly take the effects of sand-mud mixture in the system into account. However, directly including a sand and a mud fraction is important for improved projection of the critical SLR rate for drowning, and is also important for understanding the behavior of the tidal inlet systems in response to accelerating SLR as determined by the dimensionless SLR rate. A further step is to implement morphodynamic equilibrium relationships like in ASMITA in process-based models like Delft3D.

6

Synthesis, findings and reflections

6.1 Motivation and approach to the research

This research seeks to address the challenge of connecting science to policy in coastal management. To take on this challenge for the Netherlands, the role of science in contributing to Dutch Coastal Flood and Erosion Risk Management (CFERM) policy and practice was investigated through a single "*embedded*" case study (Yin, 2008, p50) of the Coastal Genesis 2 research programme.

The investigation was guided by four research questions. The first two questions focus on the science-policy interface, first on the origin and organisation of the Coastal Genesis 2 research programme and then on its outputs, outcomes and impact:

1. How did the Coastal Genesis 2 research programme originate and how is it organised?
2. How has the Coastal Genesis 2 research programme influenced Dutch coastal management policy and practice?

In addressing these two research questions, literature and secondary data analysis methods from policy analysis and integrated coastal management science, complemented by impact analysis of the Coastal Genesis 2 case study, were applied. A "Research for Policy" cycle that agendizes, prioritizes and guides research on Dutch CFERM policy and practice, was identified. As in the earlier Coastal Genesis project (Rijkswaterstaat, 1990), conceptual models of the long-term sediment budget of the Dutch coast were observed to underpin Dutch CFERM policy and practice. However, key uncertainties in these conceptual models, particularly in relation to the long-term sediment budget of the Dutch coast and the critical role of the Wadden Sea, came to light. This led to the development of a new conceptual model of the long-term sediment budget of the Dutch coast which guided the CG2 research programme, and the choice to focus further on the Wadden Sea area, addressing the following questions:

3. How will the tidal basins in the Wadden Sea evolve morphologically in the long-term and how will this influence the long-term sediment budget of the Dutch coast?
4. What are the implications of the evolution of the Wadden Sea basins for the sustainability of Dutch coastal management policy and practice?

These questions were tackled first through a theoretical analysis of the impact of sea level rise (SLR) using a simplified single-element aggregated ASMITA model, then through the application of an aggregated three element ASMITA model to analyse and project sediment exchange between the Dutch Wadden Sea and the North Sea. The three-element model study was undertaken to quantify the different responses of the different basins. However, the singe-element theoretical analysis proved critical in interpreting the results of the three-element study.

Because the behaviour of the Wadden Sea coast forms a key uncertainty in the long-term sediment budget of the Dutch coast, we first describe the findings related to research questions 3 and 4 before addressing the implications for the science-policy interface (questions 1 and 2). Insights from all four chapters (2 to 5) are applied in connecting science to policy in Dutch coastal management.

6.2 Findings on the long-term sediment budget of the Dutch coast, in particular the Wadden Sea coast

Dutch CFERM policy and practice aims to provide a robust and sustainable long-term coastal management strategy. The current CFERM policy was first adopted in 1990 when a new Coastal Policy white paper was published (Min. VenW., 1990). The strategic goals of the Dynamic Coastal Conservation policy embraced in this white paper can be translated directly from Dutch as “sustainably maintain the flood protection level and sustainably preserve values and functions of the dune areas” (Min. VenW., 1990, Min. VenW., 2000). Over the years the essence of the dynamic conservation policy has remained the same, however the tactical and operational approach have been fine-tuned (Chapter 2).

A core assumption of the policy is that sediment is the carrier of coastal uses (functions). Hence to sustainably maintain the flood protection level and sustainably preserve values and functions of the dune areas requires the maintenance of the long-term sediment budget in the coastal system. The first explicit conceptual model of the long-term sediment budget of the Dutch Coast was introduced in the 3rd Coastal Policy white paper (Min. VenW, 2000). It is based on a historical sediment budget analysis by Mulder (2000), with a later refinement by Nederbragt (2006). The principal assumption made by Nederbragt is that the long-term annual nourishment volume should be equal to the sediment demand of the active coastal zone (the coastal foundation), calculated as the area of the active coastal zone multiplied by the current rate of relative sea level rise (SLR) (Chapter 2).

The key uncertainties in the 2006 conceptual model of the long-term sediment budget of the Dutch Coast and its underlying assumptions triggered the development of a new conceptual model and calculation rule to determine the required annual nourishment volume (Lodder, 2016; Lodder & Slinger, 2022; Rijkswaterstaat, 2020; see also Chapter 2). In the 2016 conceptual model, the nourishment volume is not calculated directly. Instead, the annual sediment demand of the coastal foundation is calculated based on the sediment volume needed in the coastal foundation to keep pace with relative sea level rise, local subsidence, and the export of sediments from the coastal foundation to the Wadden Sea and Western Scheldt. In contrast to the 2006 conceptual model and associated calculation rule, the calculated annual nourishment volume is not considered as a fixed obligation arising from the policy, but as a coastal management decision based on information on the annual sediment demand.

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Accordingly in the 2016 conceptual model the annual sediment demand can vary depending on changes in the terms of the calculation rule (see Chapter 2 and 3):

$$V_{sd} = \left(A_{cf*} * SLR\right) + V_{e,ws} + V_{e,w.sch} + V_{sub,\,cf*} + V_{e,bd} \tag{6-1}$$

where:

V_{sd} = *Sediment demand* ($m^3\ yr^{-1}$)
A_{cf*} = (*adjusted*) *Area coastal foundation* (m^2)
SLR = *Current relative Sea Level Rise rate* ($m\ yr^{-1}$)
$V_{e,ws}$ = *Export cf to Wadden Sea* ($m^3\ yr^{-1}$)
$V_{e,w.sch}$ = *Export cf to Western Scheldt* ($m^3\ yr^{-1}$)
$V_{sub,\,cf*}$ = *Anthrophogenic subsidence cf* ($m^3\ yr^{-1}$)
$V_{e,bd}$ = *Export cf over Dutch borders* ($m^3\ yr^{-1}$)

To determine the future sediment budget or demand of the Dutch coast, insight is needed in the projected changes in each of the terms of the calculation rule. For a set area (A_{cf*}) of the coastal foundation the sediment demand of the coastal foundation is a linear function of the relative sea level rise rate. This is not the case for the export of sediment from the coastal foundation to the Western Scheldt ($V_{e,w.sch}$) and the Wadden Sea ($V_{e,ws}$). The sediment export to this estuary and these tidal basins depends not only on the rate of relative SLR, but also on the sediment transport mechanisms, time lag effects and past human interventions (Chapters 2 and 3). The current and future sediment export to the Wadden Sea is significantly larger than the sediment export to the Western Scheldt, which makes this one of the most significant and uncertain terms in the sediment budget of the Dutch Coast.

Extrapolating present-day trends for the Dutch coast provides a direct projection of sediment exchange for the near future. For this short timescale (years to decades), we can safely assume that large-scale processes remain the same. On longer timescales (decades to centuries) accelerating SLR will start to become increasingly important for sediment exchange processes, and this assumption no longer holds. Numerical modelling was required for quantitative projections of future sediment exchange between the coast and the Wadden Sea basins, as the response of the system to the development of SLR will be delayed and the timescale of the delay is dependent on morphological characteristics of the inlet systems and the SLR rate (Lodder et al., 2019a, Chapter 4).

The evolution of the Wadden Sea Basins

The theoretical single element ASMITA analysis revealed that the critical SLR rate for drowning is influenced by the morphological equilibrium and the morphological timescale (the time to reach dynamic equilibrium), which depends on the grain size distribution of sediment in the tidal inlet system. As sea level rises, there is a lag in the morphological response, which means that the basin will be deeper than the systems morphological equilibrium. However, as long as the rate of sea level rise is constant and below the critical rate for drowning, this offset becomes constant and a dynamic equilibrium is established. The equilibrium deviation as well as the time needed to achieve the dynamic equilibrium increases non-linearly with increasing rates of sea level rise. As a result, the response of a tidal basin to relatively fast sea level rise is similar, no matter whether the sea level rise rate is just below, equal or above the critical limit. A tidal basin will experience a long process of "drowning" when the sea level rise rate exceeds about 80% of the critical limit.

It is the dimensionless SLR rate (*r* = SLR rate / critical SLR rate) that influences the behaviour of a tidal basin in responding to accelerated SLR. This means that different tidal basins in the Wadden Sea will respond very differently when SLR accelerates, as the SLR rate will be the same, but the critical SLR rate for drowning is very different for the different basins.

The morphological timescale increases non-linearly with increasing SLR rate (Chapter 4, Figure 4-7). It approaches infinity as the SLR rate approaches the critical value. Conceptually this can be explained by the delayed response of the tidal basin to accelerating SLR and the physical limitation of the sediment transport capacity through the inlet (see conceptual model introduced in Wang et al., (2018)). The delayed response means that the effect of accelerating SLR on sediment exchange between a basin and its coastal area will only be noticeable after a long time. The physical constraint imposed by the sediment transport capacity implies that even over the long term the sediment import to the basin cannot increase in proportion to the SLR rate. This means that when a basin is drowning, it imports sediments at the maximum rate (the maximum sediment transport capacity) and the process of drowning is very slow.

The insights from the theoretical ASMITA-based analysis are of critical importance to Dutch CFERM policy and practice. Even though the magnitude of the sediment exchange taking place in practice remains relatively uncertain, because it is dependent on the actual SLR and the unknown maximum transport capacity, the trend in sediment exchange is very clear. There will be an ongoing significant export from the North Sea coast to the Wadden Sea basins. Such sediment import by the Wadden Sea will trigger a negative sediment budget and hence coastal retreat for the North Holland and Wadden island coasts if no additional sources of sediment are available to the area. To ensure the future sustainability of Dutch CFERM, policy and practice will need to accommodate near perpetual sediment export to the Wadden Sea. This serves to answer research question 4, what are the implications of the evolution of the Wadden Sea basins for the sustainability of Dutch coastal management policy and practice?

Using the aggregated three element ASMITA model, sediment exchange between the Dutch Wadden Sea and the North Sea was quantified and future projections were made (see Chapter 5). The study revealed that the effect of SLR acceleration on the projected sediment import for the whole Wadden Sea is not noticeable before 2040, even if the acceleration starts in 2020. Further, the differences between the projections of sediment import to the Wadden Sea under SLR are much less than the differences in SLR rate might suggest until 2100. The difference in sediment import rates between the highest (17 mm.yr^{-1}) and the lowest (2 mm.yr^{-1}) SLR scenarios is only about 3.5 million m^3.yr^{-1} in 2100, and varies from about 5 million m^3.yr^{-1} (for the lowest scenario) to about 8.6 million m^3.yr^{-1} (for the highest scenario). Most significantly, no substantial increase in the sediment export to the Wadden Sea is projected until 2100. If the present SLR rate persists, the sediment export rate is projected to initially decrease with time as the system persists in its dampening response to past human interferences (e.g. closure of the Zuiderzee). The acceleration of SLR is projected to cause this initial decreasing trend to change, but not until 2040. For the highest SLR scenario (17 mm.yr^{-1}), the export is projected to increase by about 2.5 million m^3.yr^{-1} in 2100 compared to the present rate of about 6 million m^3.yr^{-1} . This means that the effect of accelerating SLR on the loss of sand from the coastal zone due to export to the Wadden Sea is projected to be limited until 2100.

Both the theoretical one-element and the three-element studies, as well as the study of Wang et al. (2018), indicated that the net sediment transport is primarily dependent on either the accommodation space of a basin or the sediment transport capacity of an inlet, indicating that the availability of sediments at the North Sea coast is currently of less importance for the sediment exchange to the Wadden Sea basins. Here the accommodation space means the space available for the deposition of sediments; in tidal basins this space is determined by the difference between the average actual depth and the equilibrium depth (see conceptual model introduced in Wang et al., (2018)). The availability of sediments at the North Sea coast, however, is of critical importance for Dutch CFERM, which is focussed on dynamically maintaining the sedimentary coastal foundation by nourishment so as to prevent structural erosion of the coast. The ASMITA analyses project that the loss of sediment from the coastal zone due to export to the Wadden Sea will be limited until 2100. This may be viewed as positive for CFERM, since less sediment nourishment will be needed. However, it is likely to have negative consequences for the conservation of the ecological value of the Wadden Sea as the acceleration of the SLR rate is expected to result in an increased loss of intertidal flat area (Huismans et al., 2022).

The quantitative three-element ASMITA analysis revealed that there are distinct differences between western part of the Wadden Sea (Texel, Vlie and Eierland inlets) and the eastern part (Ameland, Pinkegat and Zoutkamperlaag inlets). In the eastern part, where the present morphology is likely close to dynamic equilibrium (Wang et al., 2018), the import rate in 2100 varies from about 0.8 million $m^3.yr^{-1}$ for the lowest SLR scenario (2 $mm.yr^{-1}$) to about 2.5 million $m^3.yr^{-1}$ for the highest SLR scenario (17 $mm.yr^{-1}$), a factor of 3.1 (310%). For the western part, where the large sediment demand due to the closure of the Zuiderzee in 1932 has still not damped out, the sediment import rate varies between about 4.2 and 6.0 million $m^3.yr^{-1}$, a factor of about 145% between the highest and lowest SLR scenarios (see Chapter 5, Figure 5-6). This serves to answer research question 3, how will the tidal basins in the Wadden Sea evolve morphologically in the long-term and how will this influence the long-term sediment budget of the Dutch coast?

A conceptual model for state dependent SLR response for tidal basins

The insight that the present morphological state and the relative sea level rise co-determine the long-term evolution of the Wadden Sea tidal basins represents a novel finding of this research. Indeed, the difference between the sediment demand in the highest and lowest SLR scenarios highlights the importance of such system understanding for the long-term sediment budget of the Dutch coast and hence for Dutch CFERM policy and practice. To capture this insight, a new state dependent sea level rise response model for tidal basins is conceptualized and depicted in Figure 6-1. The blue line in Figure 6-1 indicates the dynamic equilibrium state of a tidal basin. The dynamic equilibrium depth, made dimensionless with the equilibrium depth without SLR, increases with SLR rate, made dimensionless with the critical SLR rate for drowning. The relation between the dynamic equilibrium depth and the SLR rate is highly nonlinear when SLR rate approaches the critical value for drowning. The equilibrium depth becomes infinitely large when the critical SLR is exceeded.

The concept of accommodation space is employed in this conceptual model. Accommodation space is the space available for the deposition of sediments; in tidal basins this space is determined by the difference between the average actual depth and the dynamic equilibrium depth. Accommodation space can be positive, demanding sediment import, or negative, occasioning sediment export. Four system states are identified in the conceptual model of state-dependent SLR response for tidal basins (Figure 6-1):

Basins with an average dimensionless depth at their equilibrium depth (located on the blue line) import sediments to maintain their depth when subjected to SLR acceleration. The volume and rate of sediment import is determined by the accommodation space in the basin occasioned in turn by the accelerating SLR.

Basins with an average dimensionless depth greater than their dynamic equilibrium depth (located above the blue line) become less deep by importing sediments. The volume of sediment imported depends on the accommodation space in the basin, which is determined both by past human interventions and the SLR rate.

Basins with an average dimensionless depth less than their equilibrium depth (located below the blue line) become deeper owing to the rising sea level or the export of sediments, but still reach an equilibrium depth if the dimensionless SLR rate is less than 1. The volume of sediments exported depends on the negative accommodation space in the basin occasioned by e.g. changes in basin geometry.

Basins subjected to a dimensionless SLR rate (*r*) higher than 1 become deeper without reaching an equilibrium depth. These basins will deepen and eventually drown, although they continue to import sediments at the maximum possible rate. Because sedimention cannot keep pace with sea level rise, such systems transitions into basins with limited tidal flat area.

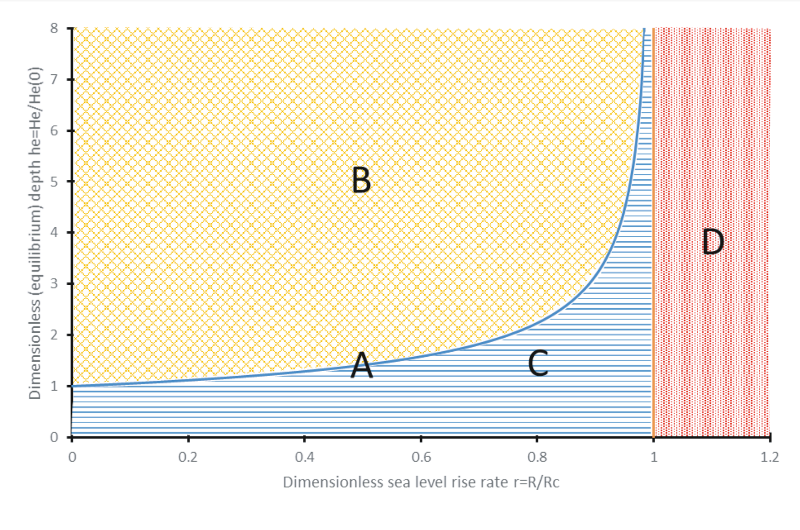


Figure 6-1, *State dependent SLR response for tidal basins.*

The western part of the Dutch Wadden Sea is currently deemed to be in system state B. The average depth is larger than would be expected based on the empirical relations which underpin ASMITA (Eysink, 1990; Stive et al., 1998; Stive and Wang, 2003; Townend et al., 2016a, 2016b). The eastern part of the Dutch Wadden Sea is close to, or at, system state A (see also Wang, et al., 2018). If we assume the average mean relative sea level rise to be around 3 mm.yr^{-1} along the Dutch coast, as reported by Deltares in the Zeespiegelmonitor 2022 (Stolte et al., 2023), all of the basins of the Dutch Wadden Sea have a dimensionless SLR rate (*r*) below 0.5. According to Figure 6-1, this implies that the increase in equilibrium depth with SLR will be limited to about 50%. At higher dimensionless SLR rates, the average equilibrium depth increases quickly. These insights, captured in the conceptual model of the state-dependent response of tidal basins to SLR, represent a new synthezed system understanding of the evolution of the Wadden Sea basins. Insights on the associated effects on intertidal mudflat loss are reported in Huismans et al. (2022).

6.3 Findings on the science-policy interface in Dutch Coastal Flood and Erosion Risk Management

Having discussed the findings on the long-term sediment budget of the Dutch coast, and the evolution of the Wadden Sea coast in particular, we now move on to present and discuss the findings on the science-policy interface in Dutch coastal management.

The Coastal Genesis 2 research programme (CG2) case study is central to this investigation. Through the case study, a number of frameworks and conceptual models are identified, developed and applied in this research. These frameworks and conceptual models are used in answering research questions 1 and 2. We recap how the frameworks and conceptual models played out in the case study and then reflect on whether they acted normatively to give form to the Coastal Genesis 2 research programme.

In the Netherlands Rijkswaterstaat, as the operational agency of the Ministry of Infrastructure and Water Management initiated the Coastal Genesis 2 research programme in 2015 aiming to develop and advise on a robust and sustainable long-term coastal management strategy, given sea level rise. The case study of the CG2 research programme revealed that the process of setting a research agenda, organising and undertaking the research, and synthesizing the outcomes into policy advice could be described by a "Research for Policy" cycle based on the Integrated Coastal Management (ICM) learning cycle introduced by Olsen et al. (1997). All six phases of the "Research for Policy" cycle namely: (1) Identify issues in policy and conceptual models, (2) Draft research agenda, (3) Research to increase system understanding, (4) Synthesis in new or revised conceptual models, (5) Advice to policy directorates, and (6) Advice to political decision makers, occurred during the timeframe of the CG2 case study. Further, the application of the STO framework, resulting in the description of the Strategic goal, Tactical approach and Operational objectives of CFERM policy and practice, was shown to facilitate targeted policy and practice adaptations based on scientific and operational insights. However, both the "Research for Policy" cycle and the STO framework are viewed as non-normative to the Coastal Genesis 2 research project, because they were not purposely applied up front.

In contrast, the components in the calculation rule describing the long-term sediment demand of the Dutch coast were used normatively to set up the research themes. After prioritisation (Chapter 2, Figure 2-2, transition from phase 2 to 3), the four research themes were identified as:

1. Long-term shoreface hydro-morphodynamics of the closed barrier coasts of Holland and the Wadden Islands - determining term A_{cf*}
2. Current and past relative sea level rise rates, historical and future geological and anthropogenic subsidence along the whole coast – determining terms SLR and $V_{sub,\ cf*}$
3. Long-term sediment exchange between the North Sea and the Wadden Sea with a focus on the Ameland inlet, and the sediment exchange between the North Sea and the Western Scheldt – determining terms $V_{e,ws}$ and $V_{e,w.sch}$
4. Nourishment techniques and determining the ecological impacts of nourishments.

This process of initiation, prioritisation and organisation into research themes reveals how the CG2 research program originated and was organised, answering research question 1.

The case study analysis reveals that insights from the Coastal Genesis 2 research programme have supported the revision of the conceptual model of the long-term sediment demand of the Dutch coast from that based on Nederbragt (2006) to that based on 2016 calculation rule (Chapter 2). The insights and remaining uncertainties were captured in an overarching synthesis report (Rijkswaterstaat, 2020b) and three scientific advisory reports (Elias, et al., 2020, Nolte et al., 2020, Van der Spek et al., 2020b). The synthesis and sharing of insights with academic scholars and stakeholders was crucial in ensuring the adoption of the resulting policy advice offered by Rijkswaterstaat to the policy directorate DGWB. This adoption occurred when the Minister of Infrastructure and Water Management communicated to the Dutch parliament her intention to adopt the preferred strategy of Rijkswaterstaat from 2024 onwards (Kamerstukken/2021D43934). From this communication it is also evident that the remaining uncertainties related to maintaining the sediment budget of the Dutch coast in the long-term inform the follow-up research programme on Sea Level Rise ("Kennisprogramma Zeespiegelstijging" in Dutch), providing an example of the completion of a full "Research for Policy" cycle and a new trigger starting a new cycle.

An output-outcome-impact framework was applied to analyse the CG2 research programme. Outputs, outcomes and impact could be identified for the complete project across the different research lines. The outputs of the CG2 research programme cover a variety of knowledge types, namely measurement data, simulation models, system understanding, conceptual models, and policy and practice, as distinguished in the 5-element framework (Chapter 3). Similar to the STO framework and the *"Research for Policy"* cycle, the output-outcome-impact framework and the 5-element framework are found to be applicable to the Coastal Genesis 2 project, although they were not used normatively at the initiation of the research programme.

The outcomes are shown to arise from the interactions of different knowledge types, through research activities which collect and analyse new and existing measurement data, calibrate, develop and run simulation models, and deliver new insights that build system understanding. It is shown that the 2016 conceptual model of the long term sediment demand of the Dutch coast, which also acted as the organisational basis for the CG2 research programme, enabled synthesizing the deeper system understanding from the research activities. A synthesis of the substantive outcomes of the CG2 research programme is provided in Chapter 6, box 1. Contrary to the other frameworks and conceptual models, the 2016 conceptual model of the long-term sediment demand of the Dutch coast was used explicitly in the project initiation. The conceptual model was applied to draft the research agenda, but also to synthesize the findings of the different research lines. As such this conceptual model can be considered a normative element of the CG2 research programme.

The case study reveals that policy and practice impacts arise through the revision of the shared conceptual model underpinning Dutch coastal policy, which acts as intermediary in knowledge interactions between science and policy. Science-based insights from the CG2 research programme and practice-based insights enabled the definition of four possible nourishment strategies, each meeting the strategic objective of the Dutch coastal policy on timescales up to 20 years, but differing in their tactical approach. The lasting effect in Dutch coastal management policy is highlighted by the adoption of the coastal nourishment strategy specified for the Delta Coast, Holland Coast and Wadden area as advised by Rijkswaterstaat (until 2032) from 2024 onwards (see Kamerstukken/2021D43934). An additional policy impact is the initiation of a follow-up research programme on Sea Level Rise ("Kennisprogramma Zeespiegelstijging" in Dutch), triggering phase 1 of a new "Research for Policy" cycle (Kamerstukken/2021D43934). This serves to answer research question 2, for the Coastal Genesis 2 research programme.

A major overarching policy-analytical conclusion of this study is that we have identified a "Research for Policy" cycle operating to support CFERM policy and practices in the Netherlands. Critical phases in this "Research for Policy" cycle are identified. These are firstly phase 1 when problematic issues or concerns related to the existing policy and the associated (biophysical) conceptual models – and their assumptions - are identified. Secondly, phase 4 when the scientific research results are synthesised into new or revised conceptual models describing how the (in our case study Dutch) coastal system functions. Thirdly, phase 5 when revisions or amendments to the existing CFERM policy or even recommendations for new CFERM policy are advised to the policy directorates. It is argued that whether such advice is adopted or not, depends on the extent to which the revised or new conceptual models are embraced by stakeholders, academic scholars and senior leadership at the ministry. Essentially, it is the degree to which the revised/new conceptual models represent a shared conceptualisation of the biophysical working and management of the (Dutch) coastal system that determines whether the policy advice is adopted or not. This highlights the pivotal role of shared conceptual models as intermediary between science, policy and practice - an insight that may prove useful in the design of future research programmes aiming to influence policy, nationally and internationally.

Indeed, for applications beyond our the case study, the 5-element framework and the "Research for Policy" cycle may be combined to identify the knowledge types required to develop science-based policy insights and to initiate a process for incremental policy development. The 5-element framework serves to track knowledge development and to build awareness of the knowledge underpinning policy, and the recursive interactions between knowledge types, helping to identify knowledge gaps to be filled by future research. This approach builds on the refinement of existing conceptual models and their underlying assumptions in structuring the associated research programme.

In particular, in this case study, the overall strategic goal of the coastal policy could be reached by adaptations in the tactical approach and operational objectives; the required changes fell "within" the sphere of the STO hierarchy framework. But what happens when this is not the case, when a complete new set of strategic goal, tactical approaches and operational objectives is needed? We speculate that such a process of incremental policy development may not be sufficient in such a situation. As such we argue that the identified frameworks acting at the science-policy interface are most fitting for gradual, evolutionairy if you will, policy development. For more radical policy change, process designs other than the "Research for Policy" cycle and 5-element framework might be more fitting. For example the frameworks suggested or identified by authors such as Hoogerwerf (1998), Kingdon (1995), Sabatier(1998) and Teisman (1995).

6.4 Overview of frameworks and conceptual models applicable to coastal flood and erosion risk management in the Netherlands

This research seeks to address the challenge of connecting science to policy in coastal management. The research is envisaged to inform policy makers, practitioners and scientists and to help them in navigating the science-policy interface. As such, the research aims to inspire this audience, nationally and internationally, to improve the efficacy of future "research for policy" programmes enhancing both science-based decision-making and policy-driven research pertaining to coasts. In particular, this research aims to serve as an inspiration to the Ministry of Infrastructure and Water Management, including Rijkswaterstaat, in drawing up and developing knowledge programmes for policy and practice, for the coast and for other infrastructural networks and application areas, such as rivers, flood defences, waterways and roads.

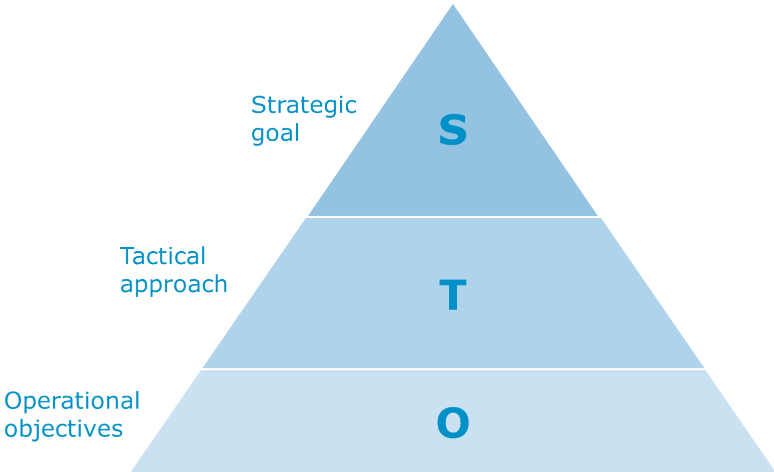
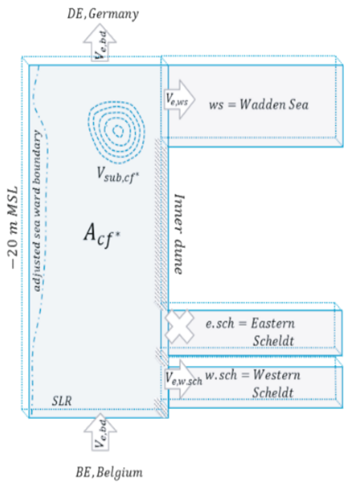
Table 6-1 describes the multiple conceptual models and frameworks identified, and developed in this thesis. Their potential applications in coastal management both within CFERM in the Netherlands and elsewhere are also summarised. Applications and opportunities specific to the Ministry of Infrastructure and Water Management, including Rijkswaterstaat, are discussed in more detail in the next section.

Table 6-1, *Overview of frameworks and conceptual models applicable to coastal flood and erosion risk management in the Netherlands and elsewhere*

Name	Visualisation
Research for Policy cycle	

Description	Application in coastal management	Reference
A policy analytical framework describing the process of setting a research agenda, organising and undertaking the research, and then synthesising the outcomes into policy advice based on the Integrated Coastal Management (ICM) learning cycle introduced by Olsen et al. (1997). A "Research for Policy" cycle departs from the existing CFERM policy. The existing policy together with the underpinning conceptual models form the input to the process.	The "Research for Policy" cycle is (implicitly) applied in Dutch CFERM research. The CG2 research program was found to be following this cycle. Future, national and international, "Research for Policy" programs can apply the cycle by including the phases of the cycle explicitly in the design of research for policy programs. Considerable effort should be devoted to: Phase 1 when problematic issues or concerns related to the existing policy and the associated conceptual models – and their assumptions - are identified. Phase 4 when the scientific research results are synthesised into new or revised conceptual models describing how the coastal system functions. Phase 5 when advice on revisions or amendments to the existing CFERM policy or even recommendations for new CFERM policy are offered to the policy directorates. It is argued that whether such advice is adopted or not, depends on the extent to which the revised or new conceptual models are embraced by stakeholders, academic scholars and senior leadership at the ministry. Essentially, it is the degree to which the revised/new conceptual models represent a shared conceptualisation of the working and management of the (Dutch) coastal system that determines whether the policy advice is adopted or not.	Lodder and Slinger, 2022 Chapter 2

***Table 6-1**, Overview of frameworks and conceptual models applicable to coastal flood and erosion risk management in the Netherlands and elsewhere (continued)*

Name	Visualisation
Strategic goal, Tactical approach and Operational objectives hierarchy	
Conceptual model of the long-term sediment budget of the Dutch coast	 $V_{sd} = A_{cf^*} \cdot SLR + V_{e,ws} + V_{e,w.sch} + V_{sub,cf^*} + V_{e,bd}$ where: V_{sd} = Sediment demand ($m^3 yr^{-1}$) A_{cf^*} = (adjusted) Area coastal foundation (m^2) SLR = Current relative Sea Level Rise rate ($m\ yr^{-1}$) $V_{e,ws}$ = Export cf to Wadden Sea ($m^3 yr^{-1}$) $V_{e,w.sch}$ = Export cf to Western Scheldt ($m^3 yr^{-1}$) V_{sub,cf^*} = Anthropogenic subsidence cf ($m^3 yr^{-1}$) $V_{e,bd}$ = Export cf over Dutch borders ($m^3 yr^{-1}$)

Description	Application in coastal management	Reference
A policy analytical framework describing formal coastal policy and practice through identification of the Strategic goal, Tactical approach and Operational objectives (STO).	The STO hierarchy framework is applied in Dutch CFERM to identify objectives in a structured way. The framework specifically distinguishes between Strategic objectives (What does the policy want to achieve?), the Tactical approach (How should that be done?) and the Operational objectives (How should this be implemented and the performance measured?). Strategic goals, tactics and operational objectives of coastal management policies may not be mentioned explicitly in formal policy documents. The STO hierarchy framework allows one to establish which strategies, tactical approaches and operational objectives are (implicitly) in place.	Lodder and Slinger, 2022 Chapter 2
A conceptual model of the long-term sediment budget of the Dutch coast allowing determination of issues and key uncertainties in the terms of the associated calculation rule.	This conceptual model synthesizes the system understanding of the long-term sediment budget of the Dutch coast under the influence of sea level rise, anthropogenically-induced subsidence and sediment exchange between the tidal basins and the North Sea coast. The terms of the associated calculation rule serve to quantify the sediment budget and guide further research aimed at reducing uncertainties. Future (inter)national research is needed to deepen insights into coastal sediment budgets at multiple spatio-temporal scales, under sea level rise. Conceptualizing a sediment budget is often critical when developing coastal management plans, such as England"s Shoreline Management Plans amongst others (Williams et al., 2018; Environment Agency, 2020; Bridges et al., 2020).	Lodder, et al., 2023 Chapter 3

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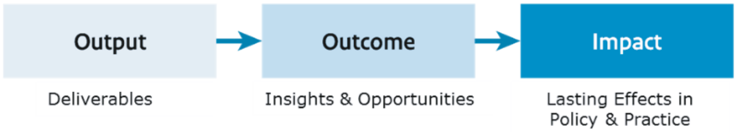
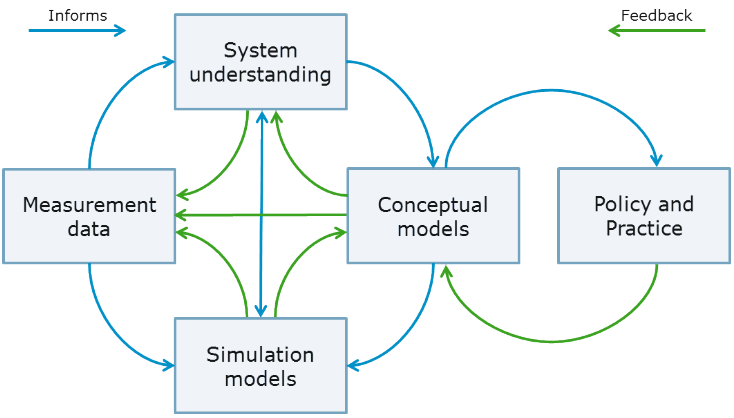
***Table 6-1**, Overview of frameworks and conceptual models applicable to coastal flood and erosion risk management in the Netherlands and elsewhere (continued)*

Name	Visualisation
Output-outcome-impact	
5-element framework of knowledge types and interactions	

Description	Application in coastal management	Reference
A science-policy interface analytical framework to identify Outputs, Outcomes and Impact of Research for Policy programmes	The output, outcome and impact framework has been applied in Dutch CFERM to identify the results of the CG2 research program in a structured way. It allows for differentiation between the deliverables, the insights & opportunities and the lasting effects of research programs. By applying the framework, the impact beyond a specific project"s scope may be assessed.	Lodder, et al., 2023 Chapter 3 NWO, 2020
A science-policy interface analytical framework to categorise the knowledge types developed and applied by "Research for Policy" programs. The framework identifies five knowledge types, namely measurement data, simulation models, system understanding, conceptual models, and policy and practice.	The 5-element framework of knowledge types and interactions is applied to categorize the knowledge types used within a research programs. A "snapshot" can be made of the knowledge interactions present at a certain moment. Multiple snapshots over time show how knowledge interactions change with time. The framework highlights the pivotal role of (shared) conceptual models in influencing policy and practice. Future national and international research programmes may apply the framework to assist in identifying the conceptual models underpinning policy, as well as the knowledge types potentially needed in adapting policy and practice.	Lodder, et al., 2023 Chapter 3

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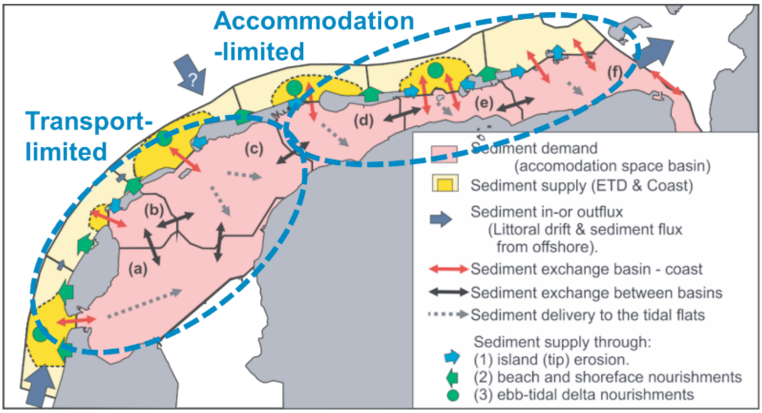
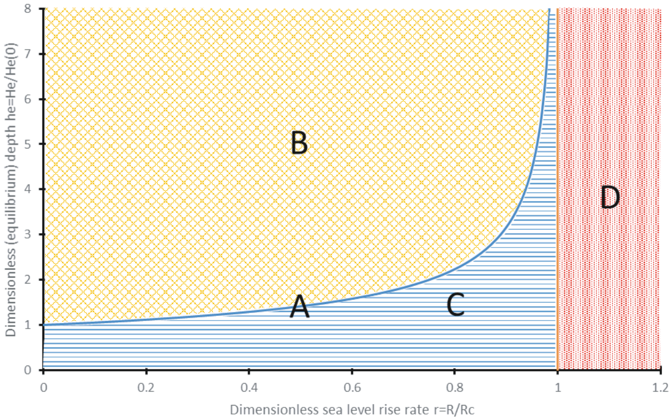
***Table 6-1**, Overview of frameworks and conceptual models applicable to coastal flood and erosion risk management in the Netherlands and elsewhere (continued)*

Name	Visualisation
Sediment-sharing system of the Dutch Wadden Sea with, the state of the sediment budget: transport or accommodation-limited	
State dependent SLR response for tidal basins	

Description	Application in coastal management	Reference
A conceptual model of the long-term sediment budget of Dutch Wadden Sea tidal basins. The sediment budget 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 (barrier islands, ebb-tidal deltas and adjacent mainland coast). The supply 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.	The conceptual model of the long-term sediment budget of the Dutch Wadden Sea tidal basins is applied to visualize and explain differences in the large scale behaviour of the Wadden Sea Tidal basins. This may help policy makers and practitioners in understanding and communicating about the long-term development of the Wadden Sea sediment budget and its key drivers. The concept can be applied to other tidal basins internationally, for example in the non-Dutch parts of the Wadden Sea. This can be undertaken by assessing the local balance between the accommodation space in the basin, the "demand" for sediment, and the supply of sediment from the North Sea, for instance. A question to address includes: whether the supply also depends on both the available sediment volume in the source area and the total flood tidal transport capacity?.	Wang et al., 2018 Chapter 6
A conceptual model of the state dependent response of tidal basins to sea level rise, determining the basins" long term morphological evolution under sea level rise.	The state dependent SLR response for tidal basins conceptual model was applied to understand the long-term evolution of the Wadden Sea tidal basins and their long-term effect on the sediment budget of the Dutch coast. The conceptual model helps in understanding the influence of the initial morphological state on their import of sediment under diverse sea level rise rates. It also facilitates assessing the transient behaviour of tidal basins and interpreting the projections of the three-element ASMITA model. The concept can be applied to other tidal basins internationally, for example in the non-Dutch parts of the Wadden Sea, and could provide insight on whether tidal basins are likely to continue to import sediments or not. As such, it may be useful in deriving a long term sediment budget for the whole Wadden Sea.	Lodder, et al., 2019 Chapter 6

6.5 Application at Ministry of Infrastructure and Water Management including Rijkswaterstaat

In the Netherlands, the CG2 programme initiated by Rijkswaterstaat provides an example of how operational agencies can draft research agenda's in a structured and coherent way. By pinpointing the conceptual models underpinning policy, identifying the associated uncertainties and assumptions, and applying these insights to set up the research agenda, the resulting "Research for Policy" research programme has directly influenced future policy. This could serve as inspiration for similar policy oriented research programmes at the Ministry of Infrastructure and Water Management.

In the CG2 programme, the "Research for Policy Cycle", the STO objectives hierarchy and the 5-element framework for interacting knowledge types have been pinpointed as useful and applicable conceptual models and frameworks in guiding policy relevant research. They enabled a coherent approach to connecting science to policy in coastal management and facilitated science-based decision-making. The long-term sediment budget of the Dutch coast played a critical role in the programme, with the renewed and refined conceptualisation of the long-term sediment budget directing research efforts at reducing uncertainties in the sediment budget. In addition, the STO objectives hierarchy provides a means of checking whether the strategic objectives are met through the operationalization of the tactical approach. A first step in such an assessment is developing a shared understanding of the STO hierarchy, the knowledge and assumptions underpinning set policy (Chapter 2, Figure 2-2; Phase 1, RfP cycle). In improving and continually adapting the Dutch CFERM, ongoing research is needed on all terms of the long-term sediment budget calculation rule, as well as persistence in challenging the assumptions that underpin the sediment budget and other aspects of Dutch CFERM.

An outcome of the CG2 programme is an updated quantification (Chapter 2 and 3) of the long-term sediment budget of the Dutch coast. This quantification has enabled the development of nourishment strategies that triggered decision making at the political level. The adoption of the nourishment strategy preferred by Rijkswaterstaat implies that key results from the CG2 programme now directly underpin policy. These include: the quantified sediment exchange between the North Sea and the Wadden Sea, the sediment demand in the active coastal zone due to sea level rise, and the anthropogenic subsidence.

Initial follow-up, at the Ministry of Infrastructure and Water Management, on the insights from this research and the CG2 research, is already in place. The Knowledge Programme on Sea Level Rise (Kennisprogramma Zeespiegelstijging) is currently in progress. The aim of this study is not to project the most probable future but to assess the robustness of the formal Dutch adaptation strategies under extreme, but possible, sea level rise projections (Ministry of Infrastructure and Water Management et al., 2021; van Alphen, 2014). In essence, these studies execute a stress test of the formal Dutch adaptation strategies. One of the tracks of this programme specifically focusses on the sustainability and implementation challenges associated with the dynamic conservation policy. This track builds on the outcomes of CG2, seeking to refine and apply the 2016 conceptual model of the long-term sediment budget for half, one, two, three and five meter sea level rise (from the mid 1990's onwards). The subdivision of the coastal zone (or coastal foundation) into three sub-area's namely the Delta, Holland and Wadden coasts are based on the CG2 research insights. The programme seeks to refine the 2016 calculation rule further, by detailing the conceptual model at sub-basin level. This research is focused strongly on the explication, refinement and sharing of the conceptual models of morphological system components on multiple spatiotemporal scales, explicitly following the "Research for Policy" cycle and applying the 5-element framework of knowledge types (Taal et al., 2023, figure 2.1, page 11)

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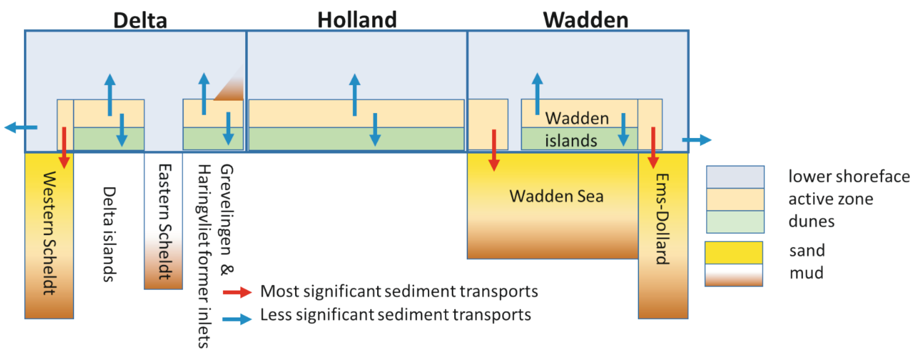

Figure 6-2, *Application and refinement of the conceptual model of the long term sediment budget from CG2 by Taal et al., 2023 for the Knowledge Programme on Sea Level Rise.*

Hence, follow-up of this thesis in new research for policy in Dutch CFERM is already in place, but can potentially be expanded to other fields and research programs at Rijkswaterstaat. This could be stimulated by developing an accompanying collective learning programme. Such a programme could help in sharing the conceptual models that underpin current policy and practice. It could also help in defining research programmes, structuring the policy advisory process, and adapting policy and practice to changing society and biophysical conditions.

6.6 Application internationally

The frameworks and conceptual models identified and developed in this research are observed to be acting in or applicable to Dutch CFERM. The question of international applicability then arises. The case study does not allow for direct extrapolation to international cases, as many aspects may be different from the Dutch situation, such as the physical setting (a fully sedimentary coast), the governance setting (national government with set statutory tasks and dedicated regional water authorities), and the risk profile (majority of the country prone to flooding). Extrapolation from a single case study is always open to contestation. A case study has been argued to be "*nothing more than a method of producing anecdotes*" (Eysenck, 1976), although the same author later in his career also concluded that "*sometimes we simply have to keep our eyes open and look carefully at individual cases—not in the hope of proving anything, but rather in the hope of learning something*!" (Flyvberg, 2006). Multiple authors (Walker and Carr, 2021; Ruddin, 2006; Yin, 2013) argue that analytic generalization from single case studies is often possible and of value, particularly where formalization in models occurs.

We contend that this is the case for this research. The insights from long-term morphological analysis of the Wadden Sea with ASMITA are likely also applicable to the German and Danish Wadden Sea areas. Indeed, it is deemed likely that for these basins it is the dimensionless SLR rate (*r*) that influences the behaviour of the tidal basins responding to accelerating SLR. This means that also in Germany and Denmark, different tidal basins may respond very differently when SLR accelerates, as the SLR rate is the same, but the critical SLR rate for drowning can be very different for each basin. It is also deemed likely that for these basins the morphological timescale, the time needed to reach dynamic equilibrium, will increase non-linearly with increasing SLR rate implying a near perpetual import of sediment from the North Sea coasts of the Wadden Sea islands.

The frameworks and conceptual models identified as acting at the Dutch science-policy interface are speculated to be most fitting for gradual, evolutionary policy development. In similar governance settings, in particular in coastal management, the identified frameworks and conceptual model will likely be valuable for scientist, practitioners and policy advisors aiming to influence policy through directed scientific research. Many of the arguments provided for application at Rijkswaterstaat are potentially valid for similar governmental coastal management agencies, such the Danish Kystdirektoratet or the German küstenschutz agencies NLWKN (Niedersächsische Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz) and LKN.SH (Landesbetrieb für Küstenschutz und Nationalpark und Meeresschutz Schleswig-Holstein). While the "Research for Policy" cycle highlights the importance of developing shared conceptual models and identifying the assumptions underpinning current policies, the STO objectives hierarchy and the 5-element framework of knowledge types might help explication of hierarchy in policies and identifying the knowledge types needed to develop new conceptual models. The applicably of the frameworks and conceptual models is speculated to be limited to contexts where there are knowledge-intensive responsible institutions (such as coastal management agencies). We speculate that the availability of measurement data is critical to the applicability of the approach in coastal 'Research for Policy'. In the Netherlands, a data-rich research and policy environment has evolved. Here research is often focussed on acquiring additional data, increasing system understanding based on existing or new data sets or expanding system understanding to situations not covered by measurements through simulation modelling. In situations without such abundant prior data, the focus may lie primarily on modelling or on collecting critical base data. However, the Coastal Genesis 2 research does highlight the importance of using measurement and model-derived data to develop system understanding, and emphasizes the pivotal role played by conceptual models in connecting scientific knowledge with policy and practice. This suggests that in seeking to bridge the science-policy divide and avoid ill-informed or interest-based policy development, a focus on explicating and sharing policy-relevant conceptual models could be beneficial, even internationally.

6.7 Research outlook

This research was motivated by a wish to address the challenge of connecting science to policy in coastal management. To take on this challenge, the role of science in contributing to Dutch Coastal Flood and Erosion Risk Management (CFERM) policy and practice was investigated through a single *embedded* case study (Yin, 2008, p50) of the Coastal Genesis 2 research programme.

The research has resulted in a set of frameworks and conceptual models applicable to Dutch coastal flood and erosion risk management and potentially elsewhere. Current and possible future applications of the frameworks and conceptual models have been discussed in the previous sections. From a coastal research perspective many aspects of the existing frameworks and conceptual models can be investigated, ranging from further development of the frameworks and conceptual models themselves to the deepening of the scientific insights underpinning them. Without aiming to be complete, the following topics are suggested for further inquiry:

- Application of the STO hierarchy framework (inter)nationally. Application of the STO framework allows for systematic identification of differences in policies at the strategic, tactical and operational level. This differentiation can reveal (mis) alignment between levels and direct research towards improving the alignment or even revising the goals at one or more levels. Application of the framework can be extended beyond coastal management to the related fields of river and groundwater management, for instance, or to applications in environmental management. In addition, the STO hierarchy framework can potentially be applied to coastal management retrospectively to elucidate the (mis)alignment in past choices at the strategic, tactical and operational levels.
- Application of the 5-element framework to identify and deepen knowledge types relevant to the long-term sustainability of the dynamic preservation policy, but not covered well in this thesis. This includes knowledge on operational implementation and the environmental effects of the dynamic preservation policy.
- Further research on the short and long term uncertainties related to the conceptual model of the long-term sediment budget of the Dutch coast, such as presently undertaken in the Knowledge Programme on Sea Level Rise.
- Reassessment of the equilibrium relations underpinning ASMITA. More specifically, the possibility to derive basin specific equilibrium relations needs to be

investigated as do the effects of changes in tidal range on the morphodynamic equilibrium and morphologic timescale of tidal basins.

- Deriving more insights on the morphological development of the Wadden Sea area close to drowning. Increasing sea level rise rates can cause long-term partial or near complete drowning of the Wadden Sea and it is imperative to understand how such a process will occur. Improved models capable of simulating the morphodynamic equilibrium (such as ASMITA) are needed to assess morphological developments within and between tidal basins. Tidal flat - channel interactions under SLR are of major interest, since the channels are both the local source and sink for tidal flat sediments. This type of research needs to be complemented by studies of the transitory morphological-state dependent response of tidal basins under SLR.
- Investigation of the role of conceptual models as linchpin between science and policy within coastal management internationally. This research has provided strong evidence of the pivotal role of conceptual models in Dutch coastal management. International case studies exploring whether conceptual models are present, and are similar or different to those underpinning Dutch policy would be of deep interest.

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Appendix

The aim of this appendix is to highlight the importance of operational insights in Dutch Coastal Flood and Erosion Risk Management. Both practice-based knowledge and scientific insights from research projects, such as the Coastal Genesis 2 research programme, influence Dutch coastal management policy and practice.

This appendix analyses the operational insights deriving from the implementation of the dynamic preservation policy over the last 30 years.


12

Appendix, the role of practice-based insights

Dutch experience with sand nourishments for dynamic coastline conservation – an operational overview

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Abstract

The Dutch coast is one of the most heavily nourished coasts globally. An average of 12 mln. m^3 is annually added to the coastline of only 432 km for dynamic coastline conservation. This study provides an overview of the operational aspects of the more than 300 nourishments for coastline maintenance that have been performed since the 1990s and discusses the evolution of the nourishment approach and lessons learned with regard to the nourishment design. The first nourishments were beach and dune nourishments to repair local beach and dune erosion. In the 1990s the nourishment efforts increased when nourishing the coastline was set in policy as the formal strategy to dynamically preserve the coastline. Simultaneously shoreface nourishments emerged, which aim to feed the coast gradually over a longer period than beach nourishments. In 2001 the volume of sand used for nourishments increased from 6.4 to 12 mln. m^3 per year, to enable the coastal zone to stay in equilibrium with sea level rise. Channel wall nourishments were introduced around that time because they can slow down the landward migration of tidal channels and can accommodate large volumes of sediment. Nowadays, underwater nourishments are preferred because of the lower costs associated, but the decision for a beach, shoreface, or channel wall nourishment also depends on the morphology, the local setting, and the purpose of the nourishment. All nourishments combined have succeeded in conserving the coastline at its desired position over the past 30 years.

Introduction

Context

The majority of the Dutch coastline is characterized by sandy beaches, which is a common type of coast globally (Luijendijk et al., 2018). These sandy shores are valuable areas for flood safety, tourism, and ecology, but they are susceptible to erosion, especially when facing sea level rise. The low-lying Netherlands is particularly prone to flooding as 60% of its surface would regularly flood without protection measures, which would affect 9 million people (Ministerie van Infrastructuur en Milieu, 2015).

The Netherlands has a long history of coastal policy to combat coastal erosion and to ensure flood safety. Within the current policy, the Dutch coastal flood and erosion risk management (CFERM) approach distinguishes three levels: strategic goals, tactical approach and operational objectives (Lodder and Slinger, 2022). The sustainable maintenance of flood protection levels and preservation of values and functions of dune areas is part of the strategic goal (Ministerie van Verkeer en Waterstaat, 1990).

To achieve this strategic goal a tactical approach that includes having soft solutions when possible and hard solutions only when needed is defined. Sand nourishments are such a soft solution for coastal protection. They have been performed globally over the last decades (Armstrong et al., 2016, Bitan and Zviely, 2020, Pinto et al., 2020). As sand allows for natural dynamics, nourishments are considered to be more environmentally friendly and less disruptive than traditional hard solutions such as dikes, groins, and seawalls. Furthermore, the coast becomes more resilient as sand nourishments can provide a sufficiently substantial beach to accommodate the natural dynamics as well as future climate change and sea level rise (Nordstrom, 2008, USAID, 2009, Pranzini et al., 2015).

Finally, to address the strategic goal and the associated tactical approach, operational objectives such as maintaining the coastline position are defined. Here, the assumption is made that the physical conditions for existing coastal functions are preserved by maintaining the coastline position (Min. VenW., 2000, van Koningsveld and Mulder, 2004). For this purpose and to ensure that the whole active coast is in equilibrium with sea level rise an average of 12 mln. m^3 is nourished each year with sand that is extracted offshore.

Sand nourishments are a common engineering solution to mitigate coastal erosion globally. They are for example common in Australia (Jackson et al., 2013), the United States of America (Ludka et al., 2018), South Korea (Chang and Yoon, 2016), and the rest of Europe (e.g. Hanson et al., 2002, Pinto et al., 2020). However, in the Netherlands, a remarkably large amount of sand is nourished compared to other countries (Hanson et al., 2002, Pinto et al., 2020). A long-term strategy for coastal maintenance exists and an overall performance evaluation program is integrated in the legal framework, which is often lacking (Hanson et al., 2002). As a result, nourishment efforts are more large-scale, both in the totally nourished volumes and in approach (e.g. shoreface and channel wall vs. beach nourishments). This is contrary to other countries where nourishments are often small-scale and for recreation purposes (de Schipper et al., 2020).

Objectives and approach

The aim of this appendix is to first provide an overview of the more than 300 nourishments that have been performed since the 1990s to address the operational objectives of the dynamic conservation policy: 'hold the line' and 'nourish 12 mln. m^3 of sand to the active coastal zone' and then to describe the different types of nourishments, the evolution of the nourishment approach, and best practices with regard to the nourishment design. We consider the strategic goals, tactical approach, and operational objectives as a given framework within which implementation of nourishments occurs. Adaptations to the framework over time are mentioned, but not elaborated upon. Instead, the focus of this appendix is on the best practices of regular nourishments for dynamic conservation of the coastline. These are aimed to actively participate in the morphodynamics of the coastal zone and to counter erosion or enhance sedimentation. Sand is also added to the coast for flood defense or land reclamation purposes. These nourishments are not considered here because they are static nourishments supposed to remain in place that have other objectives and do not actively participate in coastal processes.

To derive an overview of the best practices Rijkswaterstaat data and literature considering nourishments in the Netherlands were examined. Rijkswaterstaat is the executive agency of the Ministry of Infrastructure and Water management in the Netherlands. Rijkswaterstaat is tasked with the operation and maintenance of the coast in relation to Coastal Flood and Erosion Risk Management. The Rijkswaterstaat datasets that were used in this appendix are:

1. **Nourishment data:** Information on the length, volume, type, and period of construction is available for each nourishment. A summary of the part of this dataset used in this study (i.e. the nourishments for dynamic coastline conservation) is given at the end of this appendix.

2. **Nourishment designs:** Design reports exist with information on design aspects like the slope and elevation of the nourishment for recent nourishments (i.e. nourishments performed over the past 15 years).

3. **Yearly beach topography and bathymetry data:** Each year the topography of 200 to 250 m spaced transects is measured along the Dutch coast (JARKUS). The topography is measured from the dunes to approximately 2 km offshore. This data is used to calculate the coastline position, for example.

Evaluation reports exist for approximately 50 nourishments (e.g. Rijkswaterstaat 1987, van Onselen and Vermaas, 2020). Additionally, several reports exist in which multiple nourishments are compared (Roelse, 1996, Bruins, 2016).

The Dutch coast

Regional setting

The Netherlands is located on the southeastern edge of the North Sea basin (Figure A-1). The Dutch coast is wave-dominated with a mean wave height of 1.1 m and a micro-tidal regime, with an average tidal range of 1.6 m (van Rijn, 1995). The coastline is 432 km long (Stolk, 1989) of which approximately 75% is protected by sandy shores and dunes, 15% is protected by hard structures and 10% of the coastline is characterized by tidal flats (Min. VenW, 2000). The coast can roughly be divided into three regions: (1) the southwestern delta, which consists of multiple open and (semi-)enclosed estuaries, (2) the central coast which is relatively straight, and (3) the barrier island coast in the north which consists of multiple barrier islands and tidal inlets (Figure A-1).

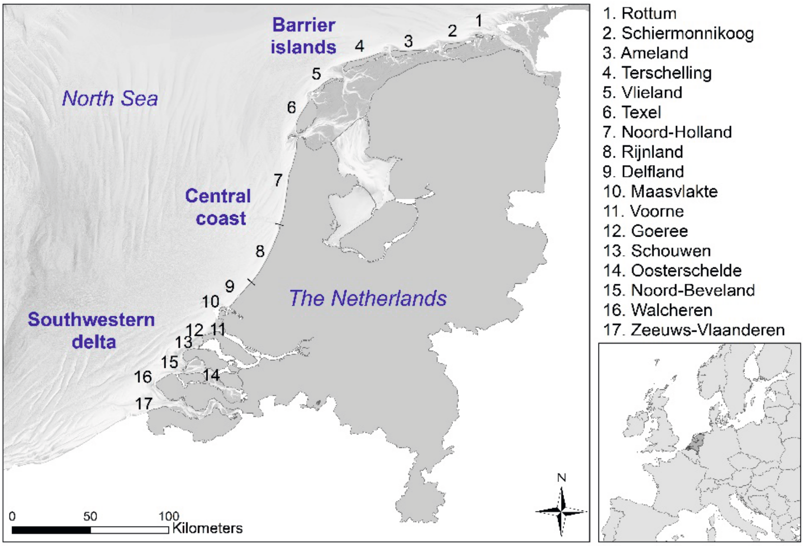


Figure A-1, *Overview of the Dutch coast with the coastal regions.*

The southwestern delta used to consist of multiple open estuaries. Nowadays, the Western Scheldt is the only open connection to the sea, while the other basins have become (semi-)enclosed due to the construction of the Deltawerken in the second half of the 20th century (van der Ham, 2018). The nearshore of the southwestern delta is characterized by (remnants of) tidal channels and tidal deltas. The beach orientation, slope, and volume vary greatly alongshore due to the complex large-scale morphology of the delta (See Figure A-2 for volume). Dunes are present along most of the southwestern delta coast. The naturally present sediment on the beaches in the southwestern delta, as measured in the 1980s (Kohsiek, 1984), is medium coarse sand with a grain size of 230 µm (Figure A-2).

The central coast of the Netherlands is relatively straight, but its orientation gradually changes from NE-SW in the south to N-S in the north. The coastline is interrupted by several sluices and harbor jetties at IJmuiden, Scheveningen, Hoek van Holland, and by the large scale harbor extension of the Maasvlakte (Figure A-1). A sequence of generally 2 or 3 alongshore sandbars are present on most of the nearshore. The beaches, i.e. the area between NAP -2 and +4 m (NAP = Normaal Amsterdams Peil, i.e. mean sea level), are typically 300 m wide and have a slope of 1:50. On the landward side the central coast is generally characterized by a dune area.

The northern coast of the Netherlands is a barrier coast with multiple barrier islands, the Wadden islands, with tidal inlets and tidal deltas in between. The barrier islands are protected by dunes on the North Sea side and dikes on the Wadden Sea side. The orientation of the barrier islands gradually changes from N-S to E-W. The central parts of the barrier islands resemble the central coast of the Netherlands with nearshore bars and dune areas. The outer ends of the islands are heavily influenced by the dynamics of the tidal inlets, with narrow, erosive beaches when tidal channels migrate landwards or wide beaches when tidal flats merge with the beach. This becomes clear from the beach volume in Figure A-2, which shows relatively high and low values at the outer ends of the islands. The naturally occurring sediment on the beach gradually becomes finer from the southwest to the northeast, with a grain size of 160 µm at Schiermonnikoog (Kohsiek, 1984).

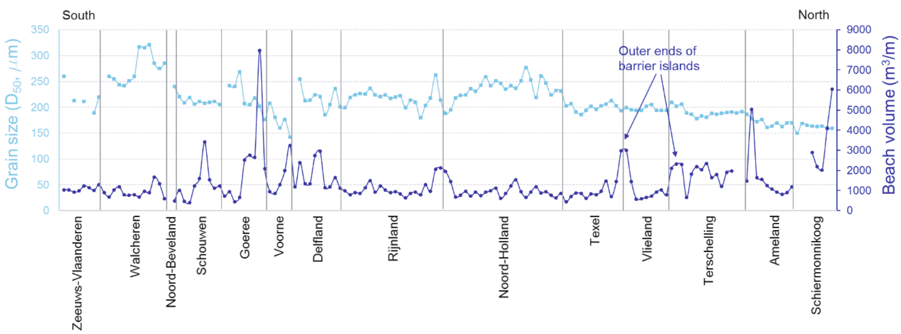


Figure A-2, *Median grain size of the dunes (Kohsiek, 1984) and the beach volume (i.e. the volume between NAP -2 and +4 m) in 2020 for every 2 km along the coast.*

Operational objectives for coastal management in the Netherlands

Due to a misbalance in the sediment budget of the coastal zone, the Dutch coast would be eroding without human interventions. This misbalance is the result of sea level rise, soil subsidence and a decreasing input of sediment from marine sources and rivers (Stive et al., 1991, Beets and van der Spek, 2000, van der Meulen et al., 2007, van der Spek and Lodder, 2015). The strategic goal within the Dutch Coastal Flood and Erosion Risk Management is sustainable maintenance of flood protection levels and preservation of values and functions (Ministerie van Verkeer en Waterstaat, 1990). The tactical approach and operational objectives to which coastal erosion was dealt with before 1990 were on a regional scale and reactive, e.g. after storms.

In 1990, as an operational objective to serve the strategic goal, the Dutch government decided to pro-actively preserve the coastline with nourishments to counter coastal erosion (Ministerie van Verkeer en Waterstaat, 1990). A reference coastline, the BKL (BasisKustLijn), was determined based on the coastline position of 1990 and the trend in changes in the coastline position between 1980 and 1990. The BKL was locally adjusted based on consultation with stakeholders and to obtain a maintainable coastline and is regularly reevaluated (Hillen et al., 1991, Hallie, 2018). The MKL-position (Momentane KustLijn, i.e. current coastline) is used as a proxy to determine the current position of the coastline. The MKL is a weighed averaged of the volume between the dune foot and the low water line and the same elevation below the low water line, which is expressed in meters relative to a reference line (Figure A-3).

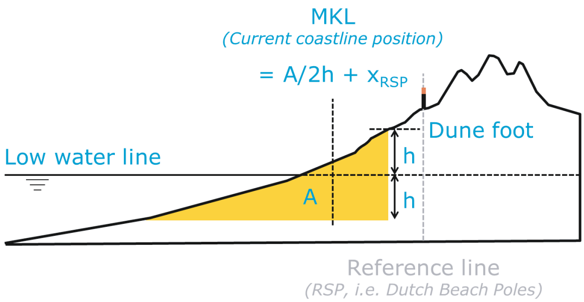


Figure A-3, *The determination of the MKL (current coastline position) from the sand volume in the MKL-zone (yellow).*

Each year the position of the MKL is assessed in relation to the BKL-position (e.g. Rijkswaterstaat, 2020). Nourishments are carried out to maintain the coastline position, especially when flood safety is directly at stake and/or when it cannot be expected that the coast will recover naturally (Rijkswaterstaat, 2021a). Besides the regular maintenance of the coastline, the flood defences are assessed for flood safety every 6 years within the Hoogwaterbeschermingsprogramma (Flood protection program, Hoogwaterberschermingsprogramma, 2019). Sandy reinforcements for safety purposes are sometimes performed within this program. These are not considered in this study, as their design and goal is often very different from regular, dynamic nourishments for coastline maintenance.

Awareness arose in 1995 about the importance to compensate for the loss of sand in deeper water and to keep the sediment budget in the coastal system (i.e. NAP -20 m up to the inner dune row) in equilibrium with sea level rise (Ministerie van Verkeer en Waterstaat, 1996). In 2000 this awareness was translated into the operational objective to nourish 12 mln. m^3 per year (Min. VenW., 2000), to provide the physical basis for all coastal values and functions (Min. VenW., 2000, Koningsveld and Mulder, 2004). This volume of 12 mln. m^3 was based on the estimates of Mulder (2000) of the sediment deficit due to the present-day sea level rise and is nourished since 2001.

It is not established in the operational objectives how and where this volume of 12 mln. m^3 should be nourished (Mulder et. al., 2011). However, it is known since a few years that the long-term deficit of sediment is largest in the southwestern delta and at the barrier islands and in the adjacent Wadden Sea (e.g. van der Spek and Lodder, 2015, Rijkswaterstaat, 2020b). Therefore, in practice the volume of 12 mln. m^3 is used for nourishments aiming to maintain the coastline at the BKL-position and for additional (underwater, i.e. shoreface or channel wall) nourishments in the southwestern delta and at the barrier islands. Due to the morphology of the southwestern delta, including extensive shoal areas and tidal channels, less locations are available for shoreface nourishments than at the barrier islands, which also partly have straight coastlines. Therefore, the nourishment efforts mainly increased at the barrier islands, both in a relative sense (Figure A-4) and in absolute volumes (40 mln. m^3 between 2000 and 2009 and 44 mln. m^3 between 2010 and 2019).

One of the strategic goals, as mentioned, is to sustainably preserve the values and functions of the dunes. Instead of simply nourishing 12 mln. m^3 for the long-term preservation of values and functions, it is always aimed to also benefit values and functions on the short-term. These functions and values include societal functions, such as the local economy, ecology, and the development of knowledge. Stakeholders are consulted before nourishments are performed (Rijkswaterstaat 2020, Rijkswaterstaat 2021a), which may result in additional nourishments or the adjustment of nourishments to benefit local functions (e.g. Ettinger en de Zeeuw, 2010) or in a study to exclude negative effects on the functions and values of an area (e.g. Elias, 2016). Even though no benchmark procedure is set, as suggested to be developed by Mulder et al. (2011), in practice the 12 mln. m^3 is distributed keeping the strategic goals and tactical approaches for coastal management in mind. Further specification and proposed research on the distribution of the sand as to how, where, and when to nourish is described in Lodder and Slinger (2022).

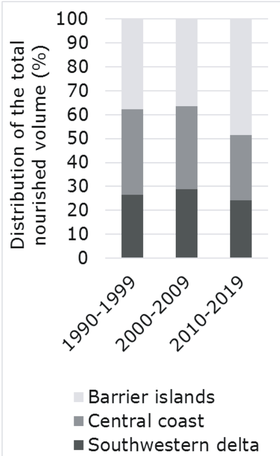


Figure A-4, *Distribution of the total nourished volume over the Dutch coastal regions.*

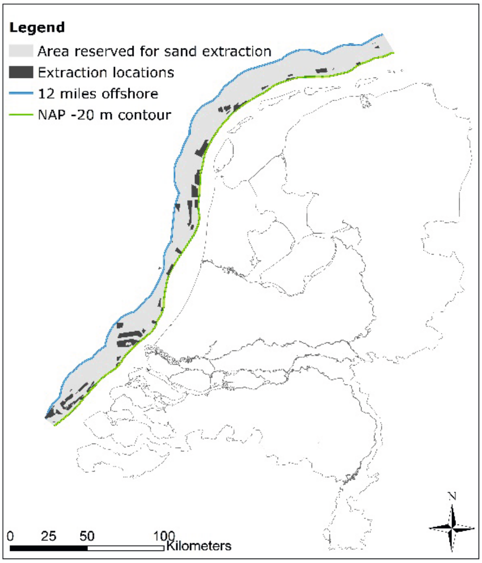


Figure A-5, *The areas used and reserved for sand extraction for nourishments.*

Sand for nourishments is in principle available in the North Sea. The North Sea is a relatively shallow basin mainly consisting of sand with an average depth of 90 m (Ducrotoy et al., 2000). Sand is preferably mined within a reach of 12 miles from the coast to limit shipping distances. However, sand that is mined above NAP -20 m, within 20 km from the coast, can lead to coastal erosion (Ministerie van Verkeer en Waterstaat, 1991). Sand is thus extracted outside of the coastal zone (i.e. deeper than NAP -20 m). Other factors that determined the extraction locations for nourishment sand (Figure A-5) are the grain size, the presence of peat layers and shell banks in the subsoil, and the presence of explosives on the sea floor.

Evolution of the nourishment approach

Globally, the first beach nourishments were performed in the early 1900s (Valverde et al., 1999). In the Netherlands the first beach nourishments date from the 1950s (Figure A-6, left). These nourishments were often small scale (i.e. <0.5 mln. m^3) and were mainly reactive to storm events (Ministerie van Verkeer en Waterstaat, 1988). The improvement of dredging and nourishment techniques in the 1970s, such as the invention of the trailing suction hopper dredger, allowed for bigger and more frequent nourishments. Between 1970 and 1990 the annually nourished volume along the Dutch coast was 3.5 mln. m^3, on average. The sand used for nourishments before 1990 was often from local sources such as nearby channels that were dredged (Ministerie van Verkeer en Waterstaat, 1988).

Interventions with sand nourishments became proactive and a part of the strategy to dynamically preserve the coastline in 1990. The nourishment volume increased to an average of 6.4 mln. m^3 per year for regular coastline maintenance alone (i.e. excluding additional nourishments for flood defense purposes or land reclamation, Figure A-6, right). Sand is generally extracted at depths larger than NAP -20 m instead of redistributed from the nearby seabed or beach since then. When it was decided to also compensate for sea level rise in 2000 the nourishment volume further increased to an average of 12 mln. m^3 per year in regular nourishments for dynamic coastline maintenance (Figure A-6, right). Between 2004 and 2015 less volume was nourished in regular nourishments, because part of the 12 mln. m^3 was used to add a buffer layer for erosion to flood defense projects. Although the nourished volume increased in 2000, the number of nourishments, on average 10 per year, did not increase. Nourishments have thus mainly become larger in volume while the nourishment frequency remained more or less similar.

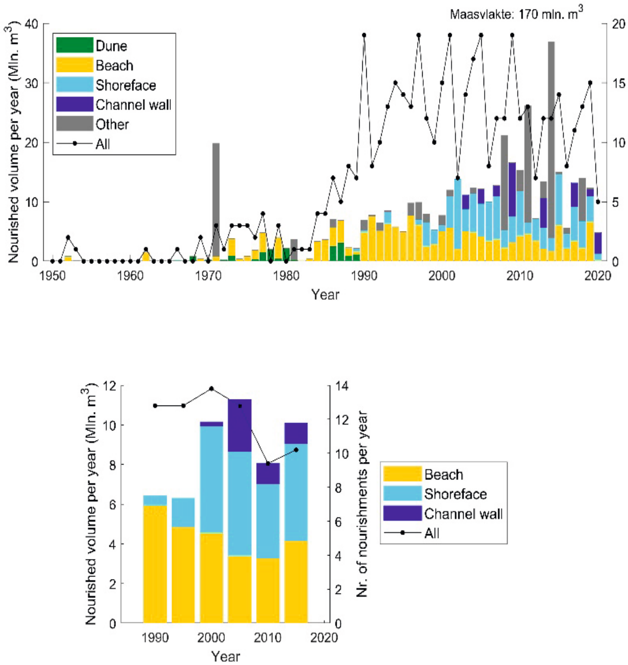


***Figure A-6**, Annually nourished volume (bars, in million m^3) per type of nourishment and the number of nourishments (line). Left: all sand nourishments, visualized per year. Right: nourishments within the dynamic conservation policy per period of 5 years.*

In this appendix only the regular beach, shoreface, and channel wall nourishments for dynamic coastline conservation since 1990 are considered (Figure A-6, right). It should be noted that many nourishments for (partly) other purposes, such as flood defense, land reclamation, or innovation and knowledge development, have been performed as well (Figure A-6, left). In total 623 mln. m^3 has has been added to the coast for various purposes over the past 70 years, of which 170 mln. m^3 was used for the seaward expansion of Maasvlakte 2. Other large nourishments that stand out in Figure A-6 (left) are the van Dixhoorndriehoek (1971), the Sand Motor (2011), the Hondsbossche Dunes (2014), and the ebb tidal delta nourishment (2018).

Not only the nourishment effort has evolved over time, nourishing techniques are also constantly changing. Roughly four types of regular nourishments can be distinguished: (1) Dune nourishments that are carried out above the dune foot, (2) beach nourishments where sand is placed on the beach, within the MKL-zone, (3) shoreface nourishments that are carried out below or in the lower part of the MKL-zone, and (4) channel wall nourishments that are placed on the landward side of a channel. Figure A-6 shows the nourished volume per nourishment type. In the previous century most of the nourishments were performed on the beach or in the dunes. Shoreface nourishments emerged in the early nineties as a way to allow for natural dynamics when possible and to reduce inconvenience on the beach (Kroon et al., 1994, NOURTEC, 1994). The first channel wall nourishment was carried out in 2003.

The different nourishment types

Nowadays, beach, shoreface, and channel wall nourishments are most common in the Netherlands (Figure A-7). Beach nourishments are placed directly in the MKL-zone (Figure A-3) and they are thus immediately effective in the zone where their effect is needed. However, their effectiveness decreases relatively fast as beach nourishments are susceptible to rapid erosion. Based on a linear regression of the MKL-position after a beach nourishment for 65 nourishments along the central Dutch coast and the central coast of the barrier islands, it was observed that the MKL is at its pre-nourishment position again after 2.9 years, on average.

Shoreface nourishments are placed outside the MKL-zone so their effect on the beach is lagging behind the actual nourishment. The volume in the MKL-zone is increased by approximately 10% of the nourished volume after one year and this will further increase up to 20-30% (Witteveen+Bos, 2006). It is not straightforward to determine the lifespan of shoreface nourishments, as their effect often cannot be isolated from beach nourishments in the same area, but they are estimated to have an effect on the MKL-zone for 4 to 10 years (Witteveen+Bos, 2006, Vermaas et al., 2013, Vermaas et al., 2019). The average recurrence time of shoreface nourishments at regularly nourished locations along the central Dutch coast is 5.2 years. The difference in the effect of beach and shoreface nourishments on the beach (i.e. MKL) zone over time is conceptually visualized in Figure A-8 for which it should be kept in mind that local differences in the lifespan and effectiveness of beach and shoreface nourishments can be large.

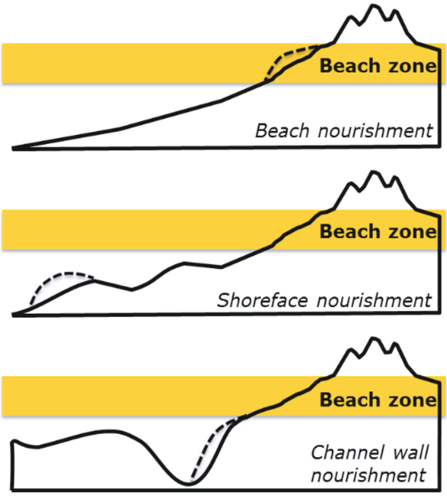


Figure A-7, *The three main types of nourishments in the Netherlands – schematized.*

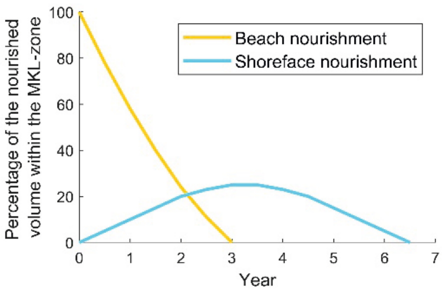


Figure A-8, *Conceptual development of beach and shoreface nourishments represented by the percentage of the nourished volume that is present within the MKL-zone.*

It is generally cheaper to nourish on the shoreface than on the beach, with an average of 3.5 €/m^3 for shoreface and 5.5 €/m^3 for beach nourishments. Shoreface nourishments are equally effective for coastline maintenance as beach nourishments, but their effect is spread over a longer time period. Shoreface and beach nourishments contribute equally to the operational objective to add a volume of 12 mln. m^3/year to the active coastal zone. As a result, shoreface nourishments are often more cost-effective than beach nourishments (Witteveen+Bos, 2006, van der Spek et al., 2007). Therefore, a nourishment is nowadays performed underwater when possible and on the beach only when it is necessary, for example due to the local morphology, regional aspects such as the presence of a harbor, or when sand is needed directly in the MKL-zone for flood safety purposes (Min. VenW., 2000).

Beach nourishments are often smaller than shoreface nourishments, both in the volume per stretch of coast as in the total length and volume. The average volume of a beach nourishment in the Netherlands is 0.5 mln. m^3, while the average volume of a shoreface nourishment is 1.6 mln. m^3. Over the past 20 years, since the introduction of shoreface and channel wall nourishments, 70% of the nourishments are beach nourishments, but in terms of volume only 40% of the total nourished volume is nourished on the beach, as beach nourishments are typically smaller than shoreface and channel wall nourishments. Regional differences in the ratio shoreface/beach nourishments are large. In the southwestern delta and on the outer ends of the barrier islands 80% of the nourishments are beach nourishments comprising 60% of the nourished volume in these regions. Underwater nourishments are often channel wall nourishments in these regions. Shoreface nourishments are more common at the central coast and the North Sea coasts of the barrier islands (Figure A-9).

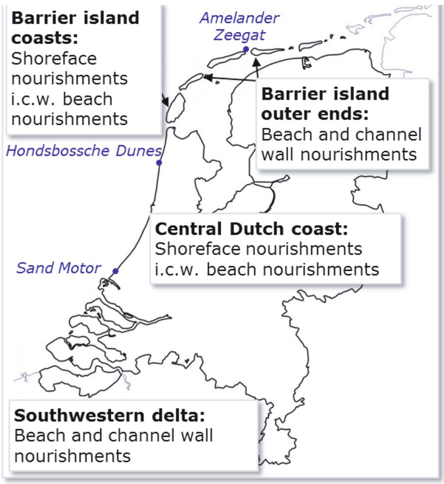


Figure A-9, *Overview map of the Netherlands with the most common type of nourishments per region.*

Regional differences in the amount and type of nourishments are presented in more detail in Figure A-10. This figure shows the nourished volume (per meter in the alongshore direction) for all transects along the Dutch sandy coast where a BKL is defined (similar to Rijkswaterstaat, 2020). Hotspots where the nourishment effort is larger than in neighboring areas stand out in this figure. These are typically coastal towns where the BKL is extended seaward to serve the functions of these locations. Other nourishment hotspots can be explained by the morphology. At Noord-Beveland, for example, a tidal channel migrates towards the shore and large nourishment volumes are needed to maintain the coastline. It also shows that two of the barrier islands, Terschelling and Schiermonnikoog, have barely or not at all been nourished.

***Figure A-10**, Total nourished volume (total m³/m in the alongshore direction since the 1990s) for regular coastline maintenance along the sandy shores of the Netherlands for the south-western delta (top), central coast (middle), and barrier islands (bottom). Transect numbers correspond to Rijkswaterstaat (2020).*

The Dutch coast is naturally eroding, however because of the dynamic conservation policy the coastline retreat due to the erosion is stopped (Figure A-11). The coastline (MKL) position was calculated from the yearly topographic data for 1970, 1990 and 2020. It appears that the median change in coastline position between 1970 and 1990 was -0.6 m, so the coastline slightly retreated. During this period the annually nourished volume was 3.5 mln. m^3. The coastline migrated seaward with a national median of 41.8 m between 1990 and 2020 m as the nourishment efforts increased. It has been reported that since 2001 the MKL-position is seaward of the BKL-position for approximately 90% of the Dutch coast (Rijkswaterstaat, 2020). Van der Spek and Lodder (2015) observed that the nourishments are especially beneficial for the upper shoreface, beach, and frontal dunes and that the sediment budget of the active coastal zone was still negative between 1990 and 2005.

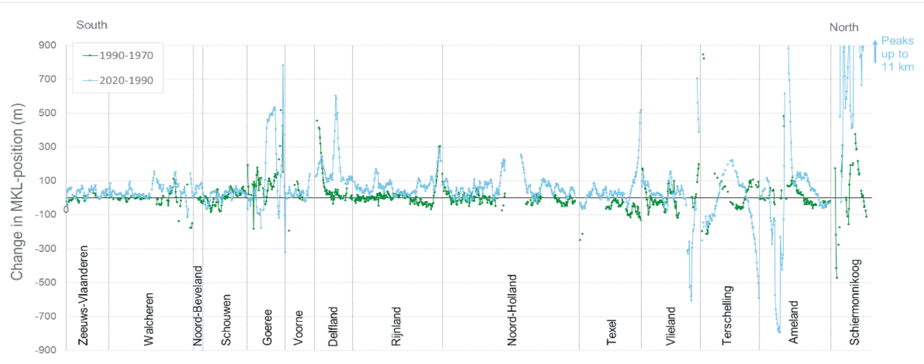


***Figure A-11**, Change in the position of the coastline (MKL) before large-scale nourishments (1990-1970) and after the start of the policy to dynamically preserve the coastline (2020-1990).*

Nourishment design

This chapter describes the general process of designing a nourishment. Each design is one of a kind, it is adjusted to; e.g. the local morphology, the regional setting (such as the proximity of a harbor), the erosion rate, stakeholder requests and ecological considerations. For example, in Figure A-10 it can be seen that nourishments end suddenly around transect 950 in Zeeuws-Vlaanderen and around transects 2400-2500 at Texel, which is due to the presence of local small scale inlets. Similarly, at Delfland, transect 10140, nourishments end because of the entrance of the harbor of Scheveningen. In Rijnland no beach nourishments are performed around transect 8600 because a polder water discharge station located at this transect. Conditions for the execution, such as water depth or legal restrictions, also play a role in the design of nourishments. Some nourishments are purposely designed in a non-traditional manner to study the effect of different design parameters, these are discussed below. Nourishments are designed to best maintain the coastline in general and not necessarily to benefit individual coastal functions, although designs are sometimes adapted in consultation with stakeholders to better fit beach functions. Therefore, the effectiveness of nourishments is here considered as their effect on the volume of sediment in the MKL-zone, rather than their effect on individual functions.

Beach nourishments

Beach nourishments are regularly carried out along the Dutch coast and in total 258 beach nourishments have been carried out since the 1990s. Beach nourishments are usually placed against the dune foot which is approximately at NAP +3 m. After a short beach platform the nourishment descends with a slope that is as similar as possible to the natural beach profile. Usually the profile is chosen around 1:30. The maximum slope of a beach nourishment is approximately 1:20 and a limited thickness to prevent scarp formation. Beach scarps are commonly observed along the Dutch coast at beaches with steep slopes and high platforms (Van Bemmelen et al., 2020). As a result of these design parameters and the accommodation capacity of most beaches in the Netherlands, the average volume of beach nourishments is 200 m^3/m. This has been constant since 1990 (Figure A-12). To minimize side effects a gradual decrease in volume towards both ends of the nourishment in the alongshore direction are incorporated in the design of beach nourishments. Beach nourishments have an average length of 2.3 km.

Sand is placed directly in the MKL-zone for beach nourishments. The volume starts decreasing soon after construction, because the beach is artificially expanded and will start to develop towards its original shape and volume. A large part of the sediment is transported seaward and is first deposited in the lower part of the MKL-zone before it disappears outside the MKL-zone. The remainder of the sediment is either transported towards the dunes or is transported alongshore (e.g. Vermaas et al., 2019). The erosion rate is strongest in the first year after construction and gradually decreases over time (e.g. Führböter, 1991), which is visible from the concave shape of the black line between nourishments in Figure A-13. Based on a linear regression of the MKL-position after a beach nourishment for 65 nourishments along the central Dutch coast and the central coast of the barrier islands, it was observed that the MKL is at its pre-nourishment position again after 2.9 years, on average, and that in the first year after a nourishment approximately 40-50% of the nourished volume erodes from the MKL-zone.

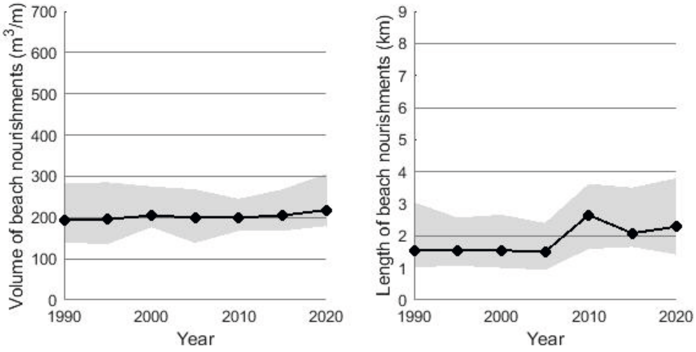


***Figure A-12**, Evolution of the dimensions (left: volume, right: length) of beach nourishments over time for regular nourishment, i.e. without mega nourishments (black line is the average, the grey area covers 50% of the nourishments).*

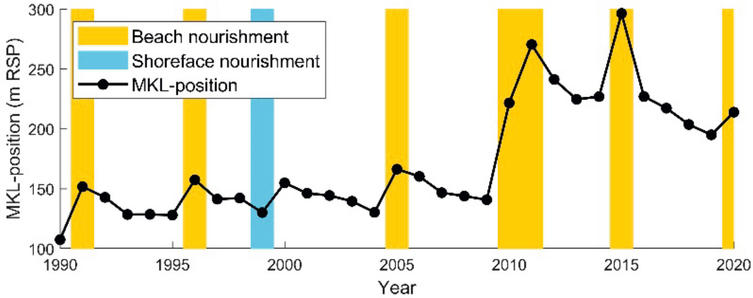
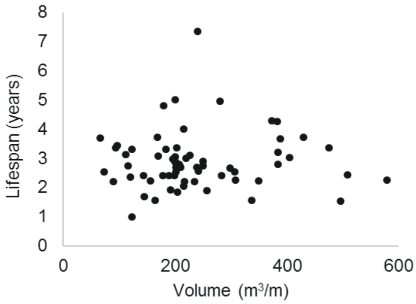


***Figure A-13**, Example of the effect of beach nourishments on the MKL-position (positive = seaward, negative = landward) for Scheveningen, transect 10025. The bar width represents the year of the nourishment. In 2010 and 2011 additional beach nourishments for flood defense purposes were performed.*



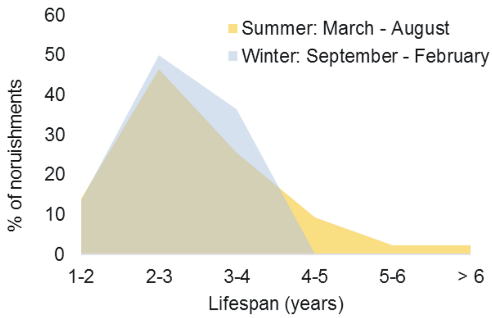


***Figure A-14**, Lifespan of beach nourishments at the central Dutch coast and the central barrier island coasts compared to their size (left) and period when construction was finished (right).*

Although many beach nourishments have been carried out over the past decades, there are still some uncertainties about their technical design and execution. It is hypothesized, for example, that larger nourishments lead to more initial erosion (Leonard et al., 1990, Dean, 1991). Furthermore, it is hypothesized that beach nourishments have a longer lifespan if they are carried out in spring, just after the storm season (e.g. Vermaas et al., 2013). To visualize these hypotheses, the lifespan of 65 beach nourishments along the central Dutch coast and the central coast of the barrier islands was determined based on a linear regression of the MKL-positions after a nourishment. The resulting lifespans were compared to the volume of the corresponding nourishments and the period of placement (Figure A-14). It indeed seems that larger nourishments do not have a larger lifespan, but this has yet to be proven. It also appears that beach nourishments that are carried out between march and august have a slightly longer lifespan, but it remains uncertain if this effect is significant. On average, the MKL is at its pre-nourishment position again after 2.9 years.

Shoreface nourishments
Shoreface nourishments are regularly carried out since the early nineties. By now a total of almost 90 shoreface nourishments have been placed. Although shoreface nourishments are commonly applied along the Dutch coast and it is observed that they have positive effects on the MKL-position (Witteveen+Bos, 2006, Vermaas et al., 2013, Vermaas et al., 2019), their behavior is not well understood. Several studies have been performed to the effect of shoreface nourishments on the local morphodynamics, but there is still some scientific discussion about how shoreface nourishments work (e.g. Huisman et al., 2019). Therefore, observations about the effects of shoreface nourishments are discussed below, but the behavior of shoreface nourishments is not further elaborated on in this study.

Shoreface nourishments are mostly placed at locations where sandbars are present on the shoreface. Generally, there is a sequence of several bars and troughs in the cross-shore direction along the Dutch coast. These bars move seaward until the zone of decay, where they fade away, after which a new bar is formed near the beach (Wijnberg 1995, Wijnberg, 2002). The amount of bars and the rate of cross-shore bar migration varies alongshore (Figure A-15).

It is observed that shoreface nourishments that are placed against the seaward side of the outer bar or seaward of the zone of decay positively affect the shoreline position (Alkyon, 2005, Witteveen+Bos, 2006, van der Spek et al., 2007, Bruins, 2016). If nourishments are placed too close to the beach, the formation of a trough landward of the nourishment can result in enhanced erosion of the beach (Grunnet and Ruessink, 2005, van der Spek et al., 2007, van der Spek and Elias, 2013). However, when a nourishment is placed too far from the coast its effectiveness decreases (Steijn, 2004, Witteveen+Bos, 2006).

The effect of a shoreface nourishment depends on the phase of the outer bar. A nourishment that is placed against an existing bar will feed this bar, which prevents it from fading away. A nourishment that is placed in the zone of decay after the outer bar has faded away the nourishment will slow down the cross-shore movement of the inner bars (Bruins, 2016, Vermaas et al., 2017). The natural cycle of cross-shore bar migration has even come to a (temporary) stop at some heavily nourished sites (Figure A-15 and van der Grinten and Ruessink, 2012, Haverkate, 2020). Nourishments do not only stop bar migration, they may even initiate a landward migration of the bars, especially when a nourishment is placed against a still existing bar, resulting in an increase of the sand volume in the MKL-zone (Alkyon, 2005, Witteveen+Bos, 2006, Spanhoff and van de Graaff, 2007, Bruins, 2016). Shoreface nourishments transform into bars and induce a trough at locations along the Dutch coast without bars, which results in a net shift of sediment to the MKL-zone (Alkyon, 2005, Witteveen+Bos, 2006, van der Spek et al., 2007, Bruins, 2016).

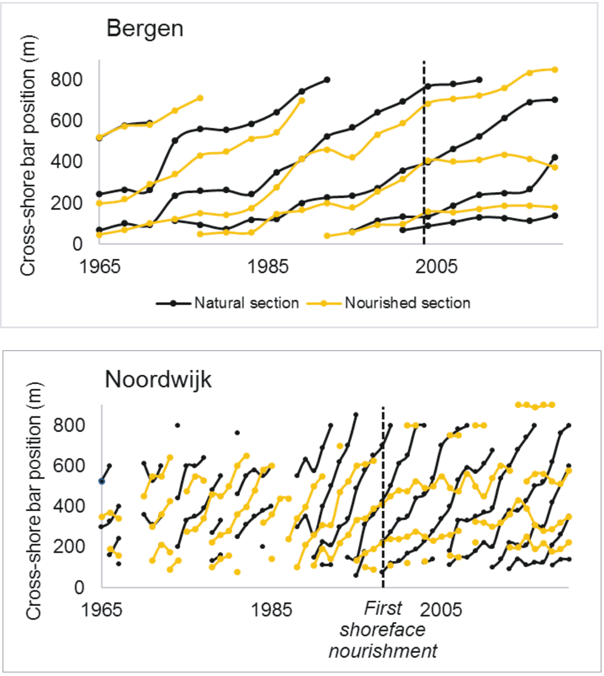


***Figure A-15**, The influence of shoreface nourishments on bar migration for two locations: Bergen (Noord-Holland, transects 4425 in black and 3850 in yellow) and Noordwijk (Rijnland transects 7150 in black and 8200 in yellow). The data represents the two-year averaged position of the top of a bar and the vertical dashed line marks the start of shoreface nourishments.*

A shoreface nourishment only influences the bar migration when the nourishment is sufficiently large compared to the dimensions of the bars. For the central Dutch coast the volume of the bars is approximately 500 m³/m in the north and 250 m³/m in the south (Wijnberg, 1995, Alkyon, 2005, Witteveen+Bos, 2006). The average volume of shoreface nourishments is 450 m³/m. The length of shoreface nourishments is 4 km, on average. These dimensions have been relatively constant since the mid-nineties (Figure A-16). The total volume of shoreface nourishments is 1.6 mln. m³, on average. A larger nourishment volume generally results in a longer lifespan of the nourishment, both for the nourishment itself as for its effect on the MKL-zone (Vermaas et al., 2013). Shoreface nourishments are designed such that their volume gradually decreases towards both ends of the nourishment to minimize side effects.

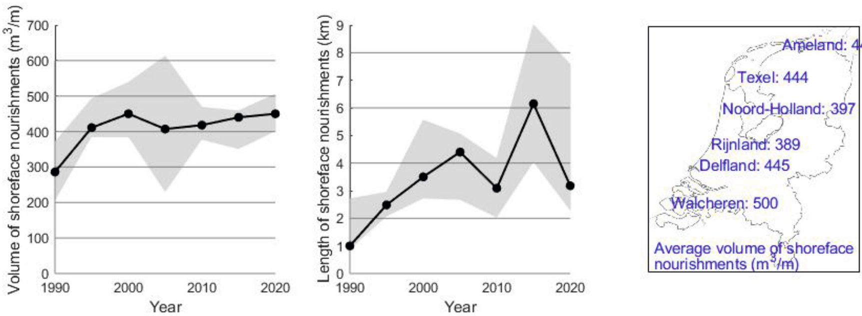


***Figure A-16**, Dimensions of shoreface nourishments. Left and middle: evolution of the volume and length over time for regular nourishment, i.e. without mega nourishments (black line is the average, the grey area covers 50% of the nourishments). Right: average volume of a shoreface nourishment along the coast since 1990.*

Along the Dutch coast, it appears that shoreface nourishments are generally most effective in terms of feeding the MKL-zone when their crest is at approximately NAP -5 m (van der Spek et al., 2007). There have been several experiments with deeper nourishments, for example at Heemskerk (NAP -6 m, Vermaas et al., 2017) and at Callantsoog (maximum elevation: NAP -7 m), and with shallower nourishments such as at Julianadorp (NAP -3.5 m, all are locations in Noord-Holland). No final conclusions can be drawn about the effect of these nourishments yet.

Shoreface nourishments are observed to positively influence the sediment budget of the beach up to a least 2 km on each side for nourishments at the central Dutch coast (van der Spek et al., 2007). At most of the barrier islands the positive influence on the sediment budget of nourishments can mainly be observed on the eastern side of the nourishment. Most of the islands are oriented east-west, resulting in a strong longshore sediment transport to the east. The bars at the barrier islands also move more in the alongshore direction than in the cross-shore direction and therefore there is no clear zone of decay at the shoreface of the barrier islands. Nevertheless, nourishments that are placed seaward of the outer bars at the barrier islands still have a positive effect on the MKL-zone, without troughs being formed (van der Spek et al., 2007, Bruins, 2016).

At the outer ends of the barrier islands regular sandbars are often lacking. Instead, saw tooth bars can be found at the tip of some barrier islands (Figure A-17). These are shore-oblique sand bars that find their origin on the ebb-tidal deltas in between the islands (Vermaas et al., 2013, Brakenhoff et al., 2019). A nourishment at Ameland showed that when a straight shoreface nourishment is carried out on top of these saw-tooth bars it will quickly adjust to the previously existing bar pattern. The presence of these bars does not influence the effectiveness of a nourishment (Vermaas et al., 2013).

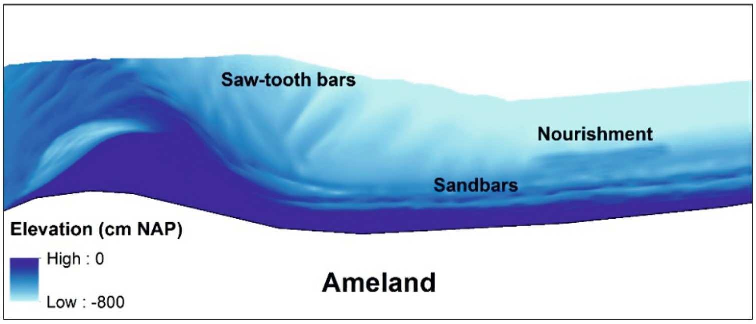
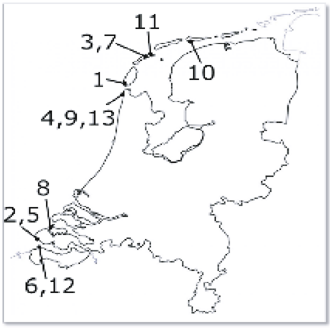


***Figure A-17**, Regular sandbars and saw-tooth bars at Ameland, one of the barrier islands.*

Channel wall nourishments

Channel wall nourishments are performed in the southwestern delta and at the outer ends of the barrier islands where the nearshore is characterized by tidal channels. The goal of channel wall nourishments is often to stop or slow down the landward migration of these channels, to prevent erosion of the MKL-zone. Besides, they provide the possibility to supply large volumes of sediment and thus aid to reach the operational objective to nourish 12 mln. m³/year. The average volume of the channel wall nourishments so far is 2.4 mln. m³. Channel wall nourishments are relatively new. The first channel wall nourishment was placed in 2003 and since then thirteen of these nourishments have been placed (Table A-1), many of which are still in place. As a result, the lifespan of channel wall nourishments is unknown yet, but as most of the first channel wall nourishments are still visible in the bathymetry, their lifespan is at least 10 to 15 years.

***Table A-1**, Overview of the channel wall nourishments that have been carried out with an indication of the design parameters. Locations are indicated on the map.*



	Location	Year	Length (km)	Volume (mln. m³)	Volume (m³/ m)	Height (m NAP)	Slope
1	Texel	2003	2.5	1.0	400	-3	
2	Walcheren	2005	2.1	2.4	1143	-5	1:12
3	Vlieland	2005	1.6	1.0	625		
4	Den Helder	2007	2.0	1.8	900	-5	
5	Walcheren	2009	3.2	6.3	1969	-5	1:13
6	Zeeuws-Vlaanderen	2009	1.7	2.7	1588		
7	Vlieland	2009	3.0	1.8	600		
8	Noord-Beveland	2013	1.8	1.5	833	-5	1:13
9	Den Helder	2013	2.1	3.5	1667	-7	1:13
10	Ameland	2017	2.0	2.5	1250	-9	1:13
11	Vlieland	2018	2.5	1.5	600	-5	1:20
12	Zeeuws-Vlaanderen	2020	1.4	1.1	786	-5	1:13
13	Den Helder	2020	2.9	3.5	1207	-7	1:13

Channel wall nourishment are most effective when they are truly placed on the side of the channel and the channel wall is displaced seaward. They are preferably placed between the top of the channel, often around NAP -5 m, and the bottom. Nourishments placed on the bottom of a channel have had varying effects. Two of them only served as a buffer for erosion and disappeared within a few years (Elias, 2013, van Onselen and Vermaas, 2020). Another channel wall nourishment placed on the bottom of a channel reduced erosion of the beach by decreasing the tidal flow through the channel (Schrijvershof, 2017).

The slope of the channel wall nourishments that have been performed was often 1:13 (Table A-1). The slope varies per nourishment as it also depends on the shape of the channel and the available space for sediment. Channel wall nourishments should not be designed too steep as the channel wall might then become unstable and collapse (Steijn, 2004, Vermaas et al., 2018). This risk has been identified for channel walls with a slope of 1:3 to 1:7 (Steijn, 2004).

A channel wall nourishment only has an impact on the tidal flow when it is sufficiently large compared to the cross-section of the channel. It appears that at least 10% of the channel should be filled for the intervention to influence the morphodynamic system (e.g. Steijn, 2004, Tonnon and van der Werf, 2014). However, the nourishment should also not be too large when there is no other channel that can take over (part of) the tidal flow. Otherwise, the currents will form a new channel which will likely increase the erosion of the MKL-zone. It was investigated whether this possibility could be limited by dredging the seaward side of the channel in Noord-Beveland, but no clear positive effects were observed (Schrijvershof, 2017).

In the best case channel wall nourishments positively influence the morphodynamics and thus reduce erosion of the MKL-zone. However, a nourishment may still have a positive effect on the MKL-zone even when it is too small to influence the flow pattern. The nourishment may serve as a buffer for erosion of the MKL-zone, or decrease the slope of the channel wall and thus reduce the risk of the flow undermining the channel wall. When the nourishment is too small it will not have an effect on the MKL-zone (Figure A-18). The effect of channel wall nourishments not only depends on the design, but also on the local morphodynamics. The wave climate, tidal flow through the channel, and geological layers may influence the development of a channel wall nourishment (Van der Werf, 2010, Tonnon and van der Werf, 2014, Vermaas and Elias, 2014, van Onselen and Vermaas, 2020).

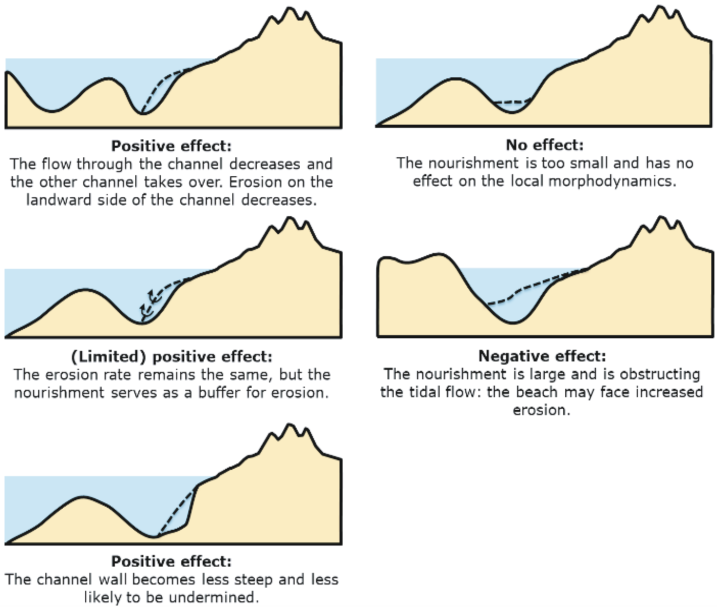


***Figure A-18**, Possible effects of channel wall nourishments on the MKL-zone.*

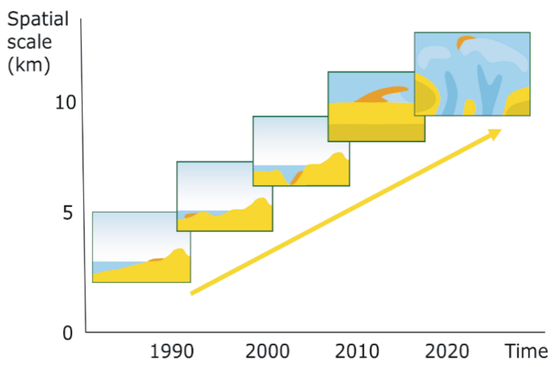


***Figure A-19**, The evolution of nourishments from beach, shoreface, channel wall, mega, to ebb-tidal delta nourishments.*

Innovative designs

Nourishment practices continually evolve (Figure A-19). While sand was originally placed directly where it was needed, on the beach and in the dunes, it is now common to nourish the shoreface and to influence the coastal morphodynamics to halt (beach) erosion. Recent innovations in nourishments are mega nourishments and tidal delta nourishments. These are pilots that are not part of the regular coastline maintenance, but they can become regular types of nourishments when proven effective. Also, they can provide valuable insights that can also be applied to nourishments within the current dynamic conservation policy.

A mega nourishment, the Sand Motor (Figure A-19) was constructed in 2011, when 19 mln. m^3 of sand (21.5 mln. m^3 including the bulking factor) was added to the coast. The Sand Motor was designed as a peninsula with the purpose to slowly feed the adjacent coast over a long period of time (Stive et al., 2013, de Schipper et al., 2016, Luijendijk et al., 2017). An ebb-tidal delta nourishment was performed at the Amelander Zeegat in 2019, when 5 mln. m^3 of sand was placed on the ebb-delta between Terschelling and Ameland (Figure A-19). These delta's are highly dynamic and are an important source of sediment for the tidal basins and barrier islands (e.g. Elias et al., 2019, Elias et al., 2020). This nourishment is still developing and is being monitored to study the impact of the nourishment on the local morphodynamics.

Synthesis

The Dutch coast is one of the most heavily nourished coasts globally. An average volume of 12 mln. m^3 is added to the coastline of 432 km each year since 2000 for coastline maintenance alone. Thanks to these regular sand nourishments the Netherlands has been successful in the dynamic conservation of the coastline since the 1990s. This study provides an overview of the best practices of these past nourishments.

1. The Dutch nourishment approach has become more large-scale over time. Before 1990 nourishments were mainly reactive to storm erosion and were carried out in the dunes and on the beach. In 1990 the nourishment efforts increased when a new coastal policy was adapted in which it was decided to dynamically preserve the coastline. The annually nourished volume almost doubled to 6.4 mln. m^3. The first shoreface nourishment was carried out in the early nineties, as the aim of nourishments shifted from fast recovery to long-term maintenance. In 2001 the nourishment volume increased further to 12 mln. m^3/year when it was decided to accommodate for sea level rise. In the past decades there have been several innovations regarding nourishments, including channel wall nourishments, mega nourishments, and an ebb tidal delta nourishment. Over time, the volume of individual nourishments increased because of the objective to nourish 12 mln. m^3/year, which resulted in an increased realization of shoreface and channel wall nourishments, which generally have larger volumes than beach nourishments.

2. The effect of the most common types of nourishments, shoreface, beach, and channel wall nourishments, are very differently. Beach nourishments have the shortest lifespan (~3 years), but the sand is placed directly where it is needed the most for the dynamic conservation of the coastline. Shoreface nourishments have a longer lifespan (4-10 years), but it takes a few years before they have an effect on the shoreline position. Channel wall nourishments have the longest lifespan (at least 10-15 years) but their effect on the coastline is highly variable and depends on the design of nourishment and the regional setting. All nourishments contribute directly to the operational objective to nourish 12 mln. m^3/year to feed the coastal zone with the sediment it needs to rise with sea level.

3. The nourishment type strongly depends on the location. Shoreface nourishments are common along the central Dutch coast and the central barrier island coasts, where the morphology of the shoreface, which is often characterized by breaker bars, allows for such nourishments. Deep tidal channels are typically present near the shore at the southwestern delta and the outer ends of the barrier islands, which renders the execution of shoreface nourishments impossible. At these locations, channel wall nourishments are more common, often in combination with beach nourishments. It is preferred to nourish underwater because shoreface nourishments are more cost-effective, but beach nourishments are still common along the entire Dutch coast, because they are sometimes needed for fast recovery, for flood safety purposes, or because it is not possible to nourish underwater. Not only the type of nourishment, but also the nourishment effort varies alongshore with hotspots that require a lot of maintenance and locations that have never been nourished.

4. Design parameters of beach and shoreface nourishments are rather constant over time, but they are adjusted to the local setting for each nourishment. In general, beach nourishments are placed at the dune foot, with a gentle slope similar to the natural slope of the beach, a volume of 200 m^3/m, and a length of 2.3 km, on average. Shoreface nourishments are usually placed against the outer bar or on the location where the outer bars fade out. This either results in the nourishment feeding the existing bar preventing it from fading away or slowing down the offshore movement of the inner bars. The volume of shoreface nourishments is typically 450 m^3/m and the average length is 4 km. Along the Dutch coast, it appears that shoreface nourishments are generally most effective when they are placed around NAP -5 m.

5. Channel wall nourishments allow to add large volumes of sediment to the coastal zone, while also potentially slowing down the landward migration of tidal channels. The first channel wall nourishment was placed in 2003 and since there have been thirteen of these nourishments at the southwestern delta and at the outer ends of the barrier islands where the nearshore is characterized by tidal channels. Channel wall nourishments can have a positive effect on the coastline when the flow through the channel decreases, when the channel wall becomes less steep, or when the nourished volume serves as a buffer for erosion. They may have a negative effect when they decrease the flow through the channel while no other channel can take over. When placed on the bottom of the channel they may not influence the coastline at all, except when they are significantly decreasing the tidal flow through a channel. The effect of channel wall nourishments not only depends on the design, but also on e.g. the local wave climate, the tidal flow through the channel, and geological layers.

Outlook to the future: Nourishment efforts along the Dutch coast are remarkably large from an international point of view. Thanks to the substantial amount of interventions in the coastal morphodynamics, the regular monitoring of the topography and bathymetry, and the evaluation of interventions, a strong knowledge base regarding the Dutch coastal system has been built over the past decades. This knowledge will remain to support the design of future nourishments, sandy flood defense projects, and for the development of coastal policy: the lessons learned from the past nourishments will help to evaluate and further develop strategic goals, tactical approaches, and operational objectives (see also Lodder and Slinger, 2022 and Chapter 2). Experience with nourishments will also help to take the growing stakes in the coastal zone due to coastal squeeze into account in the design and execution of nourishments, as we better understand how to design nourishments to benefit the MKL-position.

Sand supplies are not endless and nourishment efforts likely have to increase in the future due to accelerated sea level rise and increased storminess. Therefore the feasibility of dynamically conserving the shoreline with sand nourishments in the future is uncertain. However, it is expected that sand nourishments will remain the preferred strategy and that they will remain successful in maintaining the Dutch coastline in the coming decades (Rijkswaterstaat, 2020b). The development of new types of nourishments, such as mega or ebb tidal delta nourishments, might benefit the feasibility of sand nourishments in the future. Besides, new nourishment techniques are being developed and these may increase the efficiency or decrease the environmental impact or costs of nourishments in the future.

There are many uncertainties related to the future of coastal maintenance, such as climate change, societal and policy changes, and developments in nourishment techniques. Nevertheless, the lessons learned from past experiences remain and will benefit coastal maintenance in the future.

Background information: nourishments for regular coastline maintenance

This appendix gives an overview of the basic information regarding regular nourishments for coastline maintenance since 1990. An overview of all nourishments along the Dutch coast with more detailed information and beach topography data can be found at:

- Raw data: https://www.helpdeskwater.nl/
- Raw data: https://publicwiki.deltares.nl/display/GEC/Home
- Visualized on a map: https://www.openearth.nl/coastviewer-static/
- A yearly overview of the topography and nourishments is given in the reports of the annual assessment of the state of the Dutch coast since 1991 by Rijkswaterstaat (e.g. Rijkswaterstaat, 2020).

Beach nourishments

***Table A-2,** Beach nourishments*

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Delfland	1990	11775	11875	183000	Zeeuws-Vlaanderen	2001	1045	1130	123000
Walcheren	1990	1481	1583	245517	Vlieland	2001	5455	5485	20478
Walcheren	1990	1000	1030	20000	Rijnland	2001	6150	6450	603630
Walcheren	1990	2365	2494	105000	Rijnland	2001	6625	6750	248093
Zeeuws-Vlaanderen	1990	1350	1470	388000	Noord-Holland	2001	2832	3000	511127
Noord-Holland	1990	3225	3375	60000	Noord-Holland	2001	150	568	1290240
Noord-Holland	1990	3225	3375	385774	Walcheren	2001	2190	2380	393000
Noord-Holland	1990	3700	3850	323318	Walcheren	2002	2380	2550	462000
Texel	1990	2560	3061	2543022	Walcheren	2002	2940	3475	1130000
Rijnland	1990	6200	6325	261682	Noord-Holland	2002	1827	2035	500561
Zeeuws-Vlaanderen	1990	1330	1430	200000	Delfland	2003	11750	11850	213606
Zeeuws-Vlaanderen	1990	1040	1110	168000	Noord-Holland	2003	150	588	1305458
Delfland	1991	11775	11875	223000	Schouwen	2003	116	210	61912
Walcheren	1991	2180	2590	788000	Schouwen	2003	327	477	201847
Delfland	1991	9781	10139	1005699	Schouwen	2003	1598	1728	125220
Texel	1991	1813	2340	2008898	Schouwen	2003	994	1533	870237
Noord-Holland	1991	1100	1400	538404	Noord-Holland	2003	1110	1375	438155
Schouwen	1991	1184	1727	2672983	Noord-Holland	2003	1983	2058	230577
Noord-Holland	1991	1800	2018	371418	Noord-Holland	2003	2565	2641	357788

Table A-2, *Beach nourishments (continued)*

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Delfland	1992	11775	11875	560000	Delfland	2003	10773	11319	1252797
Walcheren	1992	1280	1742	637000	Delfland	2004	11750	11850	231323
Walcheren	1992	3160	3463	169000	Noord-Beveland	2004	135	405	502353
Walcheren	1992	2593	2783	192000	Walcheren	2004	3315	3375	67117
Noord-Holland	1992	2620	3850	1472640	Walcheren	2004	880	1070	399164
Ameland	1992	1150	1960	1442000	Walcheren	2004	1465	1885	777565
Noord-Holland	1992	100	750	615527	Ameland	2004	200	320	403636
Zeeuws-Vlaanderen	1992	1354	1487	67000	Delfland	2004	10773	11319	1155951
Walcheren	1993	1430	1585	318000	Noord-Holland	2004	1983	2058	133783
Delfland	1993	11400	11875	463000	Noord-Holland	2004	1110	1374	263972
Walcheren	1993	2763	3168	619000	Noord-Holland	2004	2565	2641	219500
Texel	1993	1210	1813	2245231	Delfland	2004	9925	9965	100000
Noord-Holland	1993	328	568	280000	Delfland	2004	9970	10110	682500
Noord-Beveland	1993	220	365	411000	Vlieland	2005	5460	5485	20000
Walcheren	1993	485	550	225000	Goeree	2005	1550	1875	1000552
Zeeuws-Vlaanderen	1993	240	312	90000	Zeeuws-Vlaanderen	2005	31	77	123917
Delfland	1993	10623	11221	1143000	Zeeuws-Vlaanderen	2005	1041	1340	304810
Walcheren	1993	935	1040	287000	Zeeuws-Vlaanderen	2005	1360	1467	105906
Rijnland	1993	6050	6335	255076	Zeeuws-Vlaanderen	2005	251	360	141927
Rijnland	1994	9425	9625	700000	Noord-Holland	2005	3225	3375	300436

Table A-2, *Beach nourishments (continued)*

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Delfland	1994	11775	11875	200000	Noord-Holland	2005	3700	3925	486023
Goeree	1994	1025	1200	505678	Noord-Holland	2005	4650	4850	519850
Schouwen	1994	159	190	40000	Voorne	2005	960	1620	691403
Schouwen	1994	259	293	49000	Zeeuws-Vlaanderen	2005	786	936	252416
Walcheren	1994	1433	1605	453000	Noord-Holland	2005	4450	4500	6000
Zeeuws-Vlaanderen	1994	806	918	348000	Texel	2005	880	1063	301384
Zeeuws-Vlaanderen	1994	1057	1346	560400	Walcheren	2006	2180	3470	1438693
Texel	1994	930	1210	761204	Ameland	2006	1100	1600	1001372
Texel	1994	2540	2820	1331225	Texel	2006	1440	1690	1012481
Rijnland	1994	6500	6730	334147	Delfland	2007	11725	11870	744124
Noord-Holland	1994	3290	3350	100683	Schouwen	2007	377	469	169643
Noord-Holland	1994	3785	3820	106343	Schouwen	2007	106	197	161689
Ameland	1994	4860	4960	190000	Schouwen	2007	1024	1742	994023
Zeeuws-Vlaanderen	1994	1363	1417	91000	Ameland	2007	200	320	303444
Texel	1995	3000	3060	300000	Noord-Holland	2007	150	590	1350448
Delfland	1995	11775	11875	200000	Walcheren	2008	1406	1633	369565
Schouwen	1995	367	643	818000	Walcheren	2008	880	1070	371217
Walcheren	1995	2550	2602	54000	Noord-Beveland	2008	140	400	461043
Walcheren	1995	1686	1889	550000	Walcheren	2008	1653	1735	110435
Walcheren	1995	2983	3306	463000	Walcheren	2008	1755	1970	1022609

Table A-2, *Beach nourishments (continued)*

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Texel	1995	2820	2960	810000	Vlieland	2009	5460	5485	20000
Noord-Holland	1995	3263	3363	306000	Zeeuws-Vlaanderen	2009	30	71	126956
Noord-Holland	1995	3725	3875	306000	Zeeuws-Vlaanderen	2009	979	1046	1514783
Delfland	1995	11221	11450	300000	Zeeuws-Vlaanderen	2009	1068	1112	191304
Vlieland	1995	5370	5440	80000	Texel	2009	900	1070	400000
Vlieland	1995	5370	5440	111000	Zeeuws-Vlaanderen	2009	802	904	230435
Noord-Holland	1995	1880	2040	361740	Zeeuws-Vlaanderen	2009	1136	1335	526957
Noord-Holland	1995	1624	1760	306840	Zeeuws-Vlaanderen	2009	1353	1467	240000
Rijnland	1996	9100	9350	500000	Voorne	2010	1320	1600	561478
Delfland	1996	11775	11875	200000	Zeeuws-Vlaanderen	2010	171	421	429565
Delfland	1996	9700	10100	800000	Ameland	2010	1140	1600	925376
Schouwen	1996	1158	1732	733000	Ameland	2010	200	400	1888934
Noord-Beveland	1996	210	380	435000	Noord-Holland	2010	3150	3400	500000
Walcheren	1996	890	1050	464000	Noord-Holland	2011	3700	3900	400000
Noord-Holland	1996	1001	1410	459000	Walcheren	2011	2950	3460	653519
Ameland	1996	720	1120	1554514	Ameland	2011	1620	2000	909565
Texel	1996	1526	1873	1490561	Noord-Holland	2011	289	628	652020
Texel	1996	2211	2340	493317	Walcheren	2011	2195	2660	701693
Noord-Holland	1996	150	750	400000	Texel	2011	1410	1763	713256
Noord-Holland	1996	5043	5100	180050	Schouwen	2011	106	469	592299

Table A-2, *Beach nourishments (continued)*

Location	Year	Start transect	End transect	Volume (m³)	Location	Year	Start transect	End transect	Volume (m³)
Texel	1997	1878	2091	658846	Texel	2012	2780	3001	700477
Texel	1997	1038	1143	340038	Walcheren	2012	1489	1632	250399
Rijnland	1997	9400	9650	552800	Schouwen	2012	1044	1719	1824901
Delfland	1997	11775	11875	200000	Texel	2012	900	1210	751589
Delfland	1997	10750	11250	834000	Vlieland	2013	5460	5480	20000
Zeeuws-Vlaanderen	1997	1353	1460	95000	Vlieland	2013	4663	5005	1000000
Noord-Holland	1997	4965	5120	304450	Zeeuws-Vlaanderen	2013	1435	1470	12000
Walcheren	1997	3393	3470	125000	Noord-Beveland	2013	180	320	360000
Walcheren	1997	2185	2707	700000	Noord-Holland	2013	1940	2041	360000
Ameland	1997	120	300	510804	Rijnland	2013	8075	8325	410000
Noord-Holland	1997	3450	3575	158000	Zeeuws-Vlaanderen	2014	1372	1467	180000
Noord-Holland	1997	3625	3880	314000	Zeeuws-Vlaanderen	2014	985	1282	600000
Vlieland	1997	4672	4844	279621	Walcheren	2014	1469	1612	350000
Noord-Holland	1997	3105	3350	352000	Zeeuws-Vlaanderen	2014	461	877	650000
Noord-Holland	1997	2600	3005	547000	Delfland	2015	9925	10125	700000
Zeeuws-Vlaanderen	1997	290	352	185000	Walcheren	2015	1755	1948	600000
Goeree	1998	925	1075	745376	Ameland	2015	140	402	1300000
Walcheren	1998	2820	3395	563550	Noord-Holland	2015	3125	3400	605000
Zeeuws-Vlaanderen	1998	1037	1178	314045	Noord-Holland	2015	3700	3900	432500
Noord-Holland	1998	3750	3875	244442	Noord-Holland	2015	150	628	1000000

Table A-2, *Beach nourishments (continued)*

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Rijnland	1998	6600	6750	253000	Ameland	2015	1240	1700	1000000
Rijnland	1998	6150	6350	193378	Goeree	2015	2240	2320	500000
Noord-Holland	1998	1925	2050	228901	Walcheren	2016	2950	3458	650000
Noord-Holland	1999	395	628	287480	Walcheren	2016	2195	2694	805000
Delfland	1999	11775	11850	200680	Goeree	2016	1525	1725	500000
Schouwen	1999	1620	1720	105000	Schouwen	2016	319	469	246750
Schouwen	1999	95	642	560000	Noord-Holland	2017	1213	1421	400000
Noord-Holland	1999	3250	3375	205793	Texel	2017	900	1190	895000
Noord-Holland	1999	3725	3875	214515	Noord-Holland	2017	4575	5075	1000000
Noord-Holland	1999	1320	1400	144000	Schouwen	2017	1044	1228	370000
Texel	1999	2600	2860	1219174	Schouwen	2017	1375	1719	800000
Noord-Holland	2000	1626	1688	120000	Noord-Holland	2017	1213	1401	1000000
Delfland	2000	11750	11850	200000	Vlieland	2018	5410	5420	20000
Noord-Beveland	2000	200	360	524470	Vlieland	2018	5440	5480	20000
Walcheren	2000	1406	1883	886127	Vlieland	2018	4663	5059	1000000
Walcheren	2000	880	1086	322529	Vlieland	2018	5059	5077	20000
Ameland	2000	100	260	401002	Texel	2018	1490	2131	1000000
Texel	2000	1703	1833	245223	Noord-Beveland	2018	160	320	250000
Texel	2000	1001	1190	357020	Ameland	2019	120	420	2542000
Texel	2000	1298	1644	701731	Walcheren	2019	1448	1632	500000

Table A-2, Beach nourishments (continued)

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Noord-Holland	2000	3275	3325	225000	Rijnland	2019	8650	8825	400000
Noord-Holland	2000	3800	3900	207445	Walcheren	2019	1735	1948	600000
Texel	2000	2550	2780	883683	Zeeuws-Vlaanderen	2019	1354	1467	150000
Walcheren	2001	2540	2710	354000	Zeeuws-Vlaanderen	2019	985	1335	600000
Vlieland	2001	4890	5010	499579	Schouwen	2019	319	469	418660
Delfland	2001	10800	11200	801178	Schouwen	2019	106	148	81500
Zeeuws-Vlaanderen	2001	800	920	132000	Delfland	2019	9925	10140	400000
Zeeuws-Vlaanderen	2001	17	87	197000	Zeeuws-Vlaanderen	2019	461	877	600000
Zeeuws-Vlaanderen	2001	260	420	168000	Noord-Holland	2019	1213	1421	400000
Zeeuws-Vlaanderen	2001	1200	1340	258000	Walcheren	2020	3165	3239	210000
Zeeuws-Vlaanderen	2001	507	570	52000					

Shoreface nourishments

Table A-2, *Shoreface nourishments*

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Zeeuws-Vlaanderen	1990	1330	1430	119000	Texel	2007	900	1392	2000970
Zeeuws-Vlaanderen	1990	1040	1110	200000	Delfland	2007	11300	11800	753277
Terschelling	1993	1370	1810	2000000	Noord-Holland	2007	200	710	3239103
Delfland	1997	11315	11485	882605	Rijnland	2008	6100	6300	1002957
Rijnland	1998	8050	8350	1266028	Rijnland	2008	6775	7025	509913
Ameland	1998	1300	2100	2030510	Walcheren	2008	1755	1970	1392722
Rijnland	1998	8750	8950	753338	Vlieland	2009	4700	5000	1780870
Delfland	1999	9773	10050	1425780	Noord-Holland	2009	700	1000	1301565
Noord-Holland	1999	3690	3910	880100	Texel	2009	2600	2880	1304348
Noord-Holland	2000	3225	3425	994000	Ameland	2010	1100	1460	1941304
Delfland	2001	10740	11250	2970879	Ameland	2010	1480	1680	1123913
Vlieland	2001	4600	4880	831892	Noord-Holland	2010	3400	3900	1713913
Noord-Holland	2001	1108	1401	1499940	Ameland	2010	1700	2000	1634783
Rijnland	2002	9100	9700	2508887	Noord-Holland	2010	3100	3400	1124348
Texel	2002	1700	2300	4593493	Noord-Holland	2011	4575	4750	719656
Rijnland	2002	7300	8000	2645601	Noord-Holland	2011	4800	5000	880344
Noord-Holland	2002	2650	3000	1972272	Noord-Holland	2011	3900	4000	360870
Noord-Holland	2003	1000	1600	2315360	Texel	2012	1332	1778	1800000
Ameland	2003	940	1370	1432000	Texel	2012	1793	2111	1350000
Noord-Holland	2003	913	943	12243	Texel	2012	1200	1312	500000

Table A-2, *Shoreface nourishments (continued)*

Location	Year	Start transect	End transect	Volume (m³)	Location	Year	Start transect	End transect	Volume (m³)
Texel	2004	2520	2780	2401361	Noord-Holland	2013	1000	1421	2000000
Noord-Holland	2004	3620	4020	1800699	Delfland	2013	11400	11800	1500000
Rijnland	2004	6575	6775	1001095	Rijnland	2014	8000	8850	2200000
Rijnland	2004	6275	6575	1202332	Ameland	2015	1240	1700	2000000
Vlieland	2005	4860	5020	1008032	Noord-Holland	2015	3100	4000	2500000
Texel	2005	1352	1690	2263950	Texel	2015	1210	2111	4004000
Noord-Holland	2005	3150	3620	1306114	Rijnland	2016	6100	6850	2400000
Delfland	2005	10860	11300	882056	Walcheren	2017	1448	1632	800000
Noord-Holland	2006	1000	1520	1651965	Walcheren	2017	1735	2215	2400000
Rijnland	2006	8150	8900	1055035	Walcheren	2017	700	1025	1500000
Ameland	2006	1200	1700	1501510	Ameland	2018	1300	2300	4460000
Texel	2006	1700	2300	1500335	Noord-Holland	2019	3100	4000	2500000
Rijnland	2006	8900	9700	800400	Noord-Holland	2019	328	708	1800000
Ameland	2007	195	302	1201234					

Channel wall nourishments

Table A-2, *Channel wall nourishments*

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Texel	2003	900	1148	972486	Noord-Holland	2013	20	230	3500000
Walcheren	2005	2475	2685	2410737	Ameland	2017	4620	4820	2500000
Noord-Holland	2007	0	200	1782263	Vlieland	2017	5110	5360	1467000
Walcheren	2009	2180	2500	6254000	Zeeuws-Vlaanderen	2019	324	461	1100000
Zeeuws-Vlaanderen	2009	271	441	2669565	Noord-Holland	2020	20	308	3500000
Noord-Beveland	2013	160	340	1500000					

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This PhD journey has been an immersive experience. An experience with a slow start and eventually a sort of quick actual PhD track. The thoughts on combining a PhD with my first job at Rijkswaterstaat have always lingered in the back of my mind. However there was always a really good reason not to embark on the journey. At first I knew I wanted to do this one day, but I had no clue on a topic. Then there where career steps at Rijkswaterstaat to make and luckily I (or we, Marcella!) was blessed with fantastic family.

This all gradually changed, largely thanks to my promotors *Jill Slinger* and *Zheng Bing Wang*. But also thanks to amongst others *Ad van der Spek, Edwin Elias, Dirk Jan Walstra* and *Koen van der Werff*. All of you encouraged me, more and less vocally, to take the step and go for it. So now here I am at the brink of defending my thesis and writing these acknowledgements. There are really a lot of people that have contributed to this. If I haven't mentioned you in person, please remember I do remember!

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Quirijn Lodder

Utrecht, april 2024.

About the author

Quirijn Lodder was born on February 23, 1979 in Utrecht, the Netherlands where he also grew up and still lives. Quirijn studied Physical Geography at Utrecht University specializing in coastal morphodynamics. He did this MSc thesis on Aeolian sediment transport processes at The Hors, Texel followed by a research internship at the University of Waikato, New Zealand. After completion of his university studies in 2002, Quirijn joined Rijkswaterstaat, the operational branch of the Dutch Ministry of Infrastructure and Water Management, as flood risk management advisor at RIZA, "Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling". Initially his work primarily focused on the hydraulic loadings on flood defences around Lake IJssel, Lake Marken and the lower reaches of the rivers Rhine and Meuse. Early 2007 Quirijn switched internally to join RIKZ, "Rijkswaterstaat Rijksinstituut voor Kust en Zee" to work on coastal morphodynamics and flood risk management. The field in which he worked in the years after. Since 2017 Quirijn is principal advisor coastal flood risk management at Rijkswaterstaat.

In this position, he is responsible for initiating and guiding Rijkswaterstaat's research projects focusing on the present and future adaptation of the Dutch coast to climate change effects. Drawing on insights from such research and from ongoing coastal management practice, he provides strategic advice to the senior leadership at the Ministry and other Dutch flood risk management organizations. His work outside the Netherlands focusses on collaboration with coastal management authorities around the North Sea and the US Army Corps of Engineers.

Since 2012 Quirijn holds a guest lecturer position at the Delft University of Technology where he supervises MSc students on coastal research and management. To broaden the collaboration between Rijkswaterstaat and Delft University of Technology and to widen his academic experience and skills Quirijn began a part-time PhD late 2019 at the faculties of Technology, Policy and Management and Civil Engineering under the supervision of Jill Slinger (Policy Analysis) and Zheng Bing Wang (Coastal Engineering). His research focussed on the role of science in contributing to Dutch coastal flood and erosion risk management policy and practice with special interest in the area of the Dutch coast with the most uncertain geomorphological future development, the Wadden Sea. Quirijn will continue to work at Rijkswaterstaat and collaborate with Delft University of Technology.

List of Publications

Selected publications related to this thesis

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