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Outputs, Outcomes and Impact

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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 paper 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.

1. Introduction

Connecting science to policy is seen as one of the top challenges for sustainability in the 21st 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 et al., 2018). Managing the integration of science and policy therefore

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Abbreviations: SPI, Science Policy Interface; CFERM, Coastal Flood and Erosion Risk Management; MCA, Multi-Criteria Analysis; DGWB, Policy Directorate Water and Soil (translated from Dutch).

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remains 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 tools to assess and manage their coasts (Bremer and Glavovic, 2013a, 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., 2020; Nolte et al., 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) 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 paper 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. We highlight the pivotal role played by research activities that are focussed on synthesising system understanding into conceptual models - developing shared conceptual models - that can then be of influence on policy. This insight can enhance the efficacy of future research programmes aiming to influence policy.

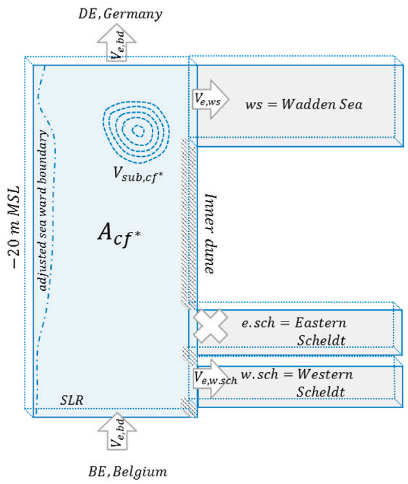
The paper is structured as follows. First, we situate the Coastal Genesis 2 (CG2) research programme in the coastal environment and policy context of the Netherlands (Section 2). Next, we describe the output-outcome-impact framework applied in analysing the results of the CG2 (Section 3), and specify the 5-element conceptual model 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).

2. Context of the coastal Genesis 2 research programme

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 10–11 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, 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., 1990; 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 Fig. 1 in Lodder and Slinger, 2022). 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 and 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.



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

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 ($m^3 yr^{-1}$)

Fig. 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).

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 (Fig. 1), as described in 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. 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. (2022), Lodder et al. (2022).

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 (Fig. 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. 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 (2012–2021) of the Dutch Research Council (NWO, 2021; 2021) 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).

3.2. *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 (Fig. 3). First, measurement data is generated through empirical research. In a coastal

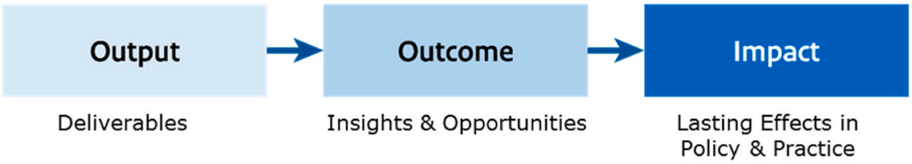


Fig. 2. The Output-outcome-impact framework applied in analysing the results of the Coastal Genesis 2 research programme.

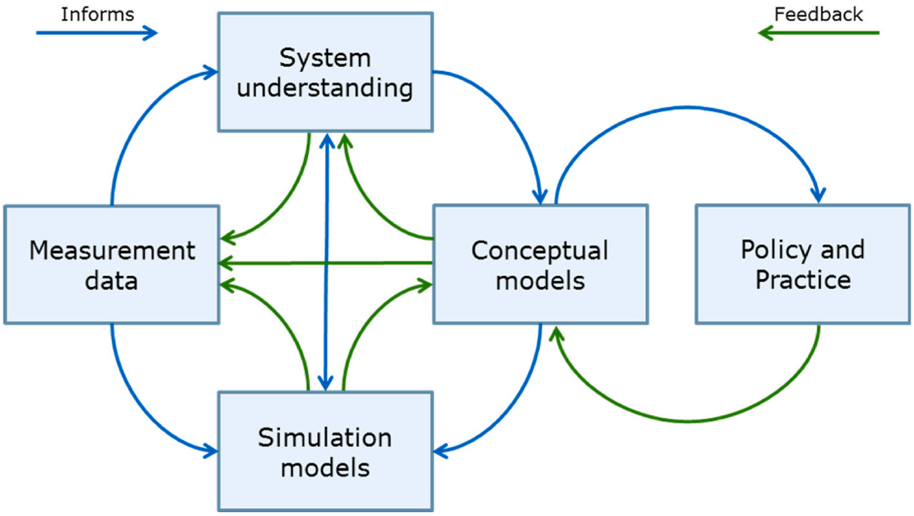


Fig. 3. The 5-element framework of knowledge types and interactions. Conceptual models are indicated as playing an intermediary role between science and policy.

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. 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.

4. Results: outputs and outcomes

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 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 1).

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”.

Table 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 (Dam, 2017; Elias, 2017, 2018a,b, Elias et al., 2019, 2020; Elias and Vermaas, 2017; Gawehn, 2020; Lodder et al., 2019; Nederhoff et al., 2019a,b; Oost et al., 2018; Schipper and van Dalfsen, 2017; Treurniet, 2018; van den Bogaart et al., 2019; van Hal et al., 2021; van Weerdenburg, 2019; Wang, 2018; Zijl et al., 2018).

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., 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	o	●			
	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		●	●		
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			●	●	o
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 5x10^6 m^3 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		●		●	o
	Overall synthesis	Rijkswaterstaat, 2020b		●		●	●

● Integral component
o Partial component

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.

4.2.1. *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 Fig. 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, 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).
- 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 4 m, −16 m NAP at Ameland and Hs 2.5 m, −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 7 × 10^6 m^{3}yr^{-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.

4.2.2. *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 (Fig. 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 Fig. 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., 2019). 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 0.5×10^6 m^3yr^{-1} to the sediment deficit of the Dutch Coast (Deltares, 2020).

4.2.3. *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 $V_{e,w.sch}$ (Fig. 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 (Fig. 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).
- 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.

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 5×10^6 m^3yr^{-1} (for the lowest scenario, 0.002 myr^{-1}) to about 8.6×10^6 m^3yr^{-1} (for the highest scenario, 0.017 myr^{-1}), with the difference between the two scenarios only about 3.5×10^6 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 2.5×10^6 m^3yr^{-1} in 2100 compared to the present rate of about 6×10^6 m^3yr^{-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 $0.5 \pm 0.5 \times 10^6$ m^3yr^{-1} (Rijkswaterstaat 2020b, Tables 6–5). The internal reworking of sediments through dredging and placement to maintain navigability is in the order 12×10^6 m^3yr^{-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).

4.2.4. *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 Fig. 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; 2022).

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., 2022).
- 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).

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 synthesising 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 50–200 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 $0.5 \times 10^6\ \text{m}^3\text{yr}^{-1}$ (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 $0.5 \times 10^6\ \text{m}^3\text{yr}^{-1}$, the current annual sediment export to the Wadden Sea from the coastal foundation is about $5.2 \times 10^6\ \text{m}^3\text{yr}^{-1}$ (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 $11 \times 10^6\ \text{m}^3\text{yr}^{-1}$ to $17 \times 10^6\ \text{m}^3\text{yr}^{-1}$ (Deltares, 2020), with $13.3 \times 10^6\ \text{m}^3\text{yr}^{-1}$ 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 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 SLR rate of 0.008 myr^{-1} for at least a century (Rijkswaterstaat, 2020b).

5. Policy and practice impacts

5.1. Synthesis in terms of sediment demand and nourishment volumes

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

Table 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

nourishment volumes required (Table 2, row 3). The median annual sediment demand, including and excluding the uncertain export to the Ems and Western Scheldt (Table 1, 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 1, 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).

5.2. *Possible annual nourishment strategies*

Based on the range of potential nourishment volumes in Table 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 (Fig. 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 (Fig. 3; Lodder and Slinger, 2022). 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 ($3.1 > 1.6 \times 10^6 m^3 yr^{-1}$). 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.

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.

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. 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, 2018). 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, 2018). 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.

Table 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	+	?	–

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 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).

6. 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

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

Total Nourishment volume total (10^6 m^3yr^{-1})	11.0		
Regional nourishment volume (10^6 m^3yr^{-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		

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 synthesised in terms of the 2016 conceptual model of the long-term sediment demand of the Dutch coast, which also acted as the organizational basis for the CG2 research programme. The substantive outcomes of the CG2 research programme are summarized 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).

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 synthesising 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 centralized 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

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 50–200 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 0.5×10^6 m^{3}yr^{-1}.
- Whereas the export to the Western Scheldt is 0.5×10^6 m^{3}yr^{-1}, the current annual sediment export to the Wadden Sea from the coastal foundation is about 5.2×10^6 m^{3}yr^{-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^{3}yr^{-1} to 17×10^6 m^{3}yr^{-1}, with 13.3×10^6 m^{3}yr^{-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}.

climate change and associated relative SLR are required.

Author contributions

QL: Idea, analytical frameworks, data analysis and synthesis, integration of policy and bio-geophysical research, visualisation, writing, editing and review. JS: Analytical frameworks, conceptual model and policy theory, writing, editing and review. ZB: Research theme overview and involvement, editing and review. CvG, HdL, JL, CS, AvdS, AN, CvO, MT, JvdW, MH, BG, EE, HH, PKT: research theme involvement, review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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