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

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ABSTRACT

The development of the Coastal Genesis 2 research programme and its role in contributing to Dutch coastal policy are described in the paper. 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, the paper demonstrates how key uncertainties related to this model guided the determination of the research agenda for Coastal Genesis 2. The paper 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.

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 paper 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 paper 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,

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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. 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 (Fig. 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 Fig. 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.

The Coastal Genesis 2 project forms an example of how Rijkswaterstaat organises and undertakes research to inform and improve existing

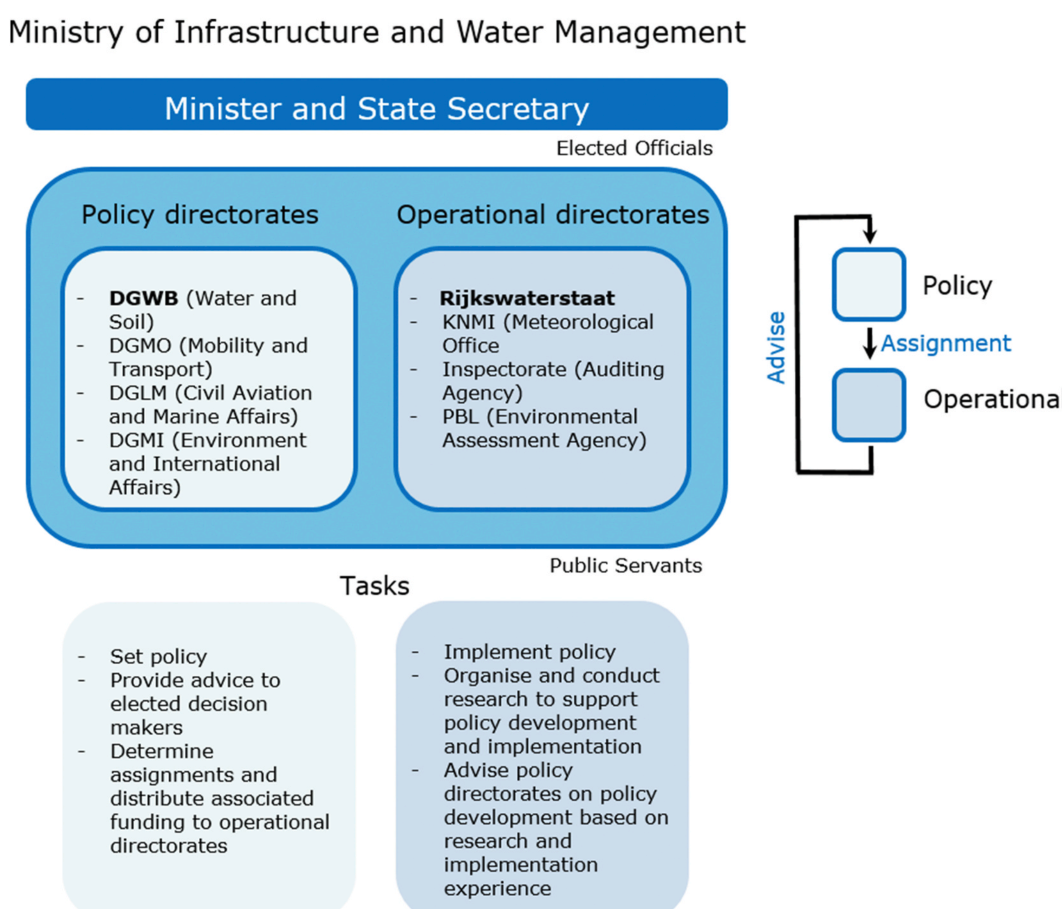

Fig. 1. Organisation of policy development and implementation within the Ministry of Infrastructure and Water Management.

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 synthesizing the outcomes into policy advice is illustrated based on the Integrated Coastal Management (ICM) learning cycle introduced by Olsen et al. (1997) (Fig. 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.

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 synthesised 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

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

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.

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).

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, 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 CFERM policy (Fig. 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;

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

- 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 (Fig. 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.

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) (Fig. 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 12×10^6 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):

$$V_{nour} = \left(A_{cf} + A_{ws} + A_{w.sch}\right) \cdot SLR \qquad (1)$$

where:

$$\begin{aligned} V_{nour} &= Nourishment\ volume\ \left(m^3 yr^{-1}\right) \\ A_{cf} &= Area\ coastal\ foundation\ \left(m^2\right) \\ A_{ws} &= Area\ Wadden\ Sea\ \left(m^2\right) \\ A_{w.sch} &= Area\ Western\ Scheldt\ \left(m^2\right) \\ SLR &= Current\ relative\ Sea\ Level\ Rise\ rate\ \left(m\ yr^{-1}\right) \end{aligned}$$

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 x 10^{-3} m per annum, a required nourishment volume of 12.5 $\times$ 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

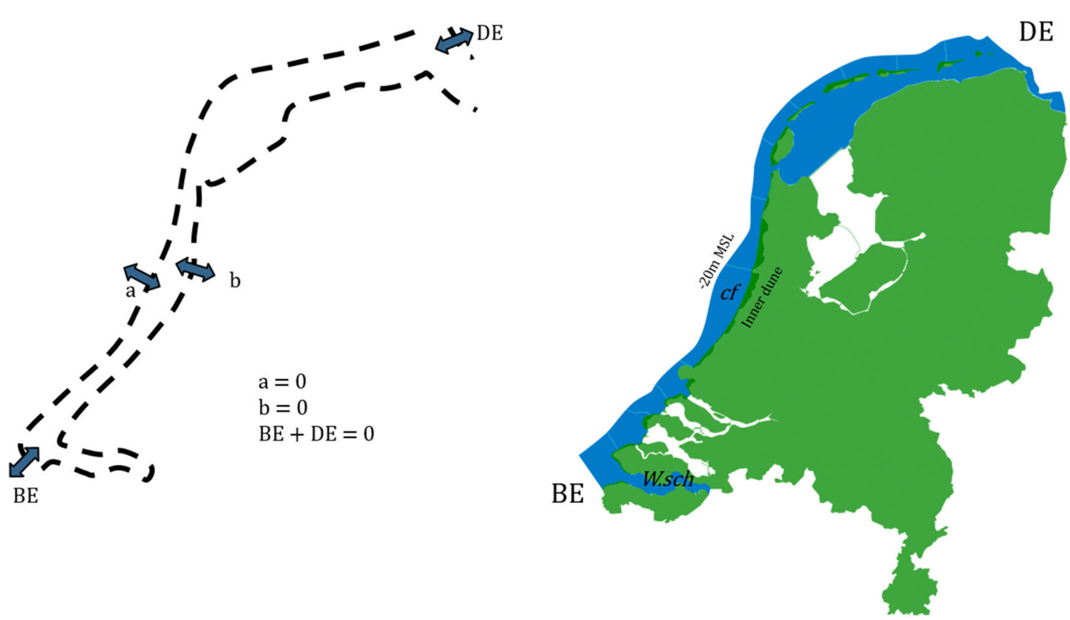

Fig. 4. Schematic of the boundary assumptions of the 2006 conceptual model of the long term sediment budget of the Dutch coast (left panel adapted from Nederbragt, 2006; right panel for geographical orientation). The net sediment exchange at the seaward boundary (a: assumed zero), the net sediment exchange 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.

depicted in Figs. 4 and 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.

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?

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 (1)?
f. What are the differences between the annual import of sediment over the Dutch-Belgian (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?

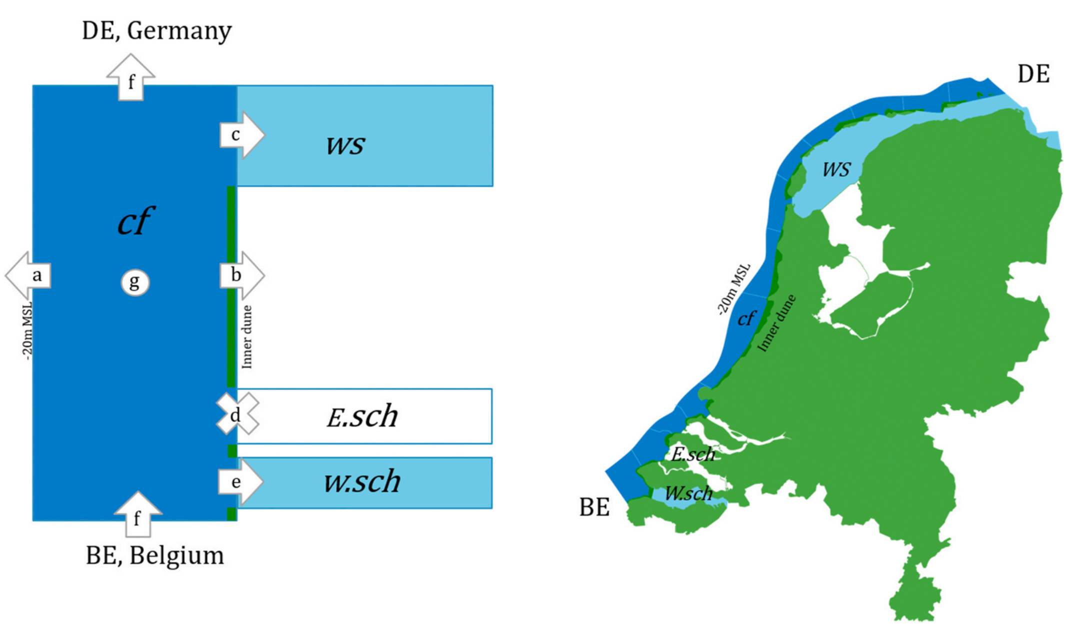

Fig. 5. Schematic of the terms in the 2016 conceptual model of the long term sediment budget of the Dutch coast and the key uncertainties (a – g) deriving from the 2006 conceptual model. In 2016, the coastal foundation, Western and Eastern Scheldt and the Wadden Sea are included as separate terms.

Taking these issues and uncertainties into account, a new conceptual model and calculation rule (2) 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 (Fig. 5). In contrast to the current conceptual model associated with calculation rule (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:

$$V_{sd} = A_{cf^*} \cdot SLR + V_{e,ws} + V_{e,w.sch} + V_{sub,cf^*} + V_{e,bd} \tag{2}$$

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

The 2016 conceptual model (Fig. 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.

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 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 (term $V_{e,bd}$), 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 50–200 years this boundary could locally be as shallow as the 10 or 15 m depth contour respectively (Van der Spek

Table 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
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 this special issue)	Grasmeijer et al. (2019)*; van der Werf et al. (2017)*; van der Werf et al. (2019) and submitted*; Schrijvershof et al. (2019)*; Oost et al. (2019a)*; Oost et al. (2019b)*; van der Spek et al. (2020a) and 2020b* Synthesised in Deltares (2020) and Rijkswaterstaat. (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. (2022)	Holzhauer et al. (2021)*; van Prooijen et al. (2020); Ebbens (2019).

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 terms *SLR*, V_{sub,cf^*}, the overarching V_{sd})
- 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 acc elerating 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 areas 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 m yr^{-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. E.Z., 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 (Fig. 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 of the Wadden Coast.

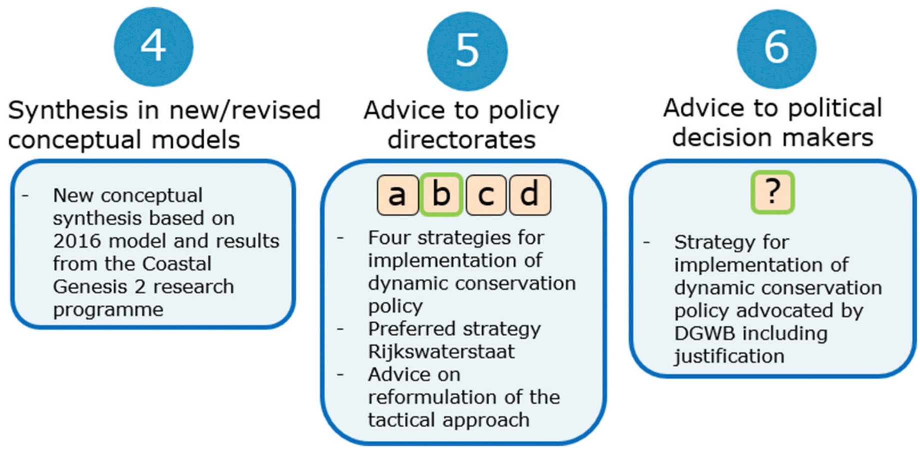

Fig. 6. Details of the final steps of the 'Research for policy' cycle of Coastal Genesis 2, comprising phase 4: the synthesis of research insights into a revised conceptual model, phase 5: the advice to policy directorates, phase 6: the advice to political decision makers.

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)) 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 (Figs. 2 and 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).

7. 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.

Author contributions

QL: Geomorphological and policy conceptualisation, analysis, visualisation, writing, editing and review. JS: Policy and ICM theory, writing, editing and 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.

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