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COASTAL MAINTENANCE AND MANAGEMENT OF THE "VOORDELTA", THE CONTIGUOUS EBB-TIDAL DELTAS IN THE SW NETHERLANDS

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Abstract

The extensive coastal protection works in the southwest of the Netherlands (the Voordelta) reflect various stages of coastal management. In the early years, decades even centuries prior to 1950, hard structures (e.g. groins, seawalls) were used to counteract coastal erosion *'No land shall be lost to the sea'*. Hard structures protecting nearly the entire coastline have proven successful in reducing, but not completely eliminating, the coastal erosion. A catastrophic flood (in 1953) triggered the building of closure dams in 3 of the 4 estuaries *'Hold the line'*. The effects of these dams continue to dominate the larger-scale morphodynamic behavior until today. Through *Dynamic Preservation* the coastline is now successfully maintained using nourishments as a primary tool. Channel-slope nourishments have proven successful in sustaining the coasts adjacent to large tidal channels. The lessons learned, from the well-documented changes and interventions in the Voordelta, contribute to an improved understanding of the functioning and effects of coastal protection works and strategies.

Key words: Coastal Management, morphodynamics, nourishments, coasts and climate

1. Introduction

"Luctor et Emergo; I struggle and I emerge' is a clear reflection of the long-lasting battle between the Dutch living in the southwest of the Netherlands and the sea. As in many similar places around the world, the coast and estuaries which form the southwest of the Netherlands have been attractive for human settlement. The sheltered estuaries provided easy and relative safe shipping, economic benefits and nowadays important recreational activities. Increasing population density has led to extensive coastal development and, in the SW Netherlands in particular, associated shoreline protection works.

The coastal protection works started from the uncoordinated building of dikes and levees to reclaim salt marshes from the sea for living and agriculture. Without proper coastal knowledge and management, dike construction and subsequent failure resulted in many disastrous floods. In more recent times, the 18th-19th centuries, more coordinated and knowledgably management resulted in the building of extensive coastal protection works such as groins, wooden pile dams, and seawalls that are still present today. These structures have proven to be successful in reducing, but not completely eliminate coastal retreat and the risk of flooding. After the historical flood in 1953, large scale flood defenses (the Delta works) were built to ensure long-lasting safety against flooding. Not surprisingly, these elaborated coastal defenses resulted in large scale morphodynamic change that still continues today (Watson and Finkl, 1990, 1992; Elias et al. 2016). Soon after the completion of the Delta works, more-and-more awareness arose that these coastal structures had severely impacted or constrained the natural dynamics. Already in the 1990's, the Dutch government understood that the future of coastal management lies in working with nature and the natural dynamics. A new coastal policy, called *'Dynamic Preservation'*, meant to fight structural erosion occurring along the major part of the Dutch coastline has been enacted (see e.g. Rijkswaterstaat, 1990; Hillen & de Haan 1993; Hillen & Roelse, 1995). Through this policy, the coastline is maintained at its 1990 position using sand nourishments as a principal source. The use of nourishments, the so-called soft interventions, allows natural coastal processes to continue. Preservation of natural dynamics is especially relevant in complex morphodynamic settings such as found in and around the tidal inlets in the SW Netherlands.

With an almost unlimited supply of sand available in the shallow North Sea, and with access to a large

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dredging fleet that can economically bring this sand to the coast, maintaining the coast through sand nourishments is a viable and successful option for the Dutch coast. Even in the future when climate change and related sea-level rise are likely to increase the sediment losses, more and larger nourishments are feasible. In many places around the world, the availability and access to sufficiently large sand deposits may limit the practicality of soft interventions as a primary tool to counteract coastal erosion. In such settings, the answer may lie in innovative combinations of hard and soft structures (e.g. ASBPA, 2011).

Our main goal of this paper is to disclose the knowledge, experience and available field data acquired from and contained in our long history of extensive coastal protection works and management. The focus is on the Southwest of the Netherlands, and especially the Voordelta (see below for definition), where both soft and hard interventions are present. Following a brief description of the study area (Chapter 2), Chapter 3 describes the effects of large-scale engineering works (the Delta Project) that triggered a system-wide scale morphodynamic response. Chapter 4 focusses on the effects of "classic" hard interventions in the form of structures with a focus on the widely applied groin fields. In Chapter 5 we present the implementation and results of the present-day coastal dynamic preservation policy. We focus on a new (innovative) nourishment method to counterbalance coastal erosion in the vicinity of a tidal channel. We conclude, by a discussion of the observed effects, our hope that contributions to essential knowledge help to ensure implementation of successful *-no regret-* coastal policies worldwide.

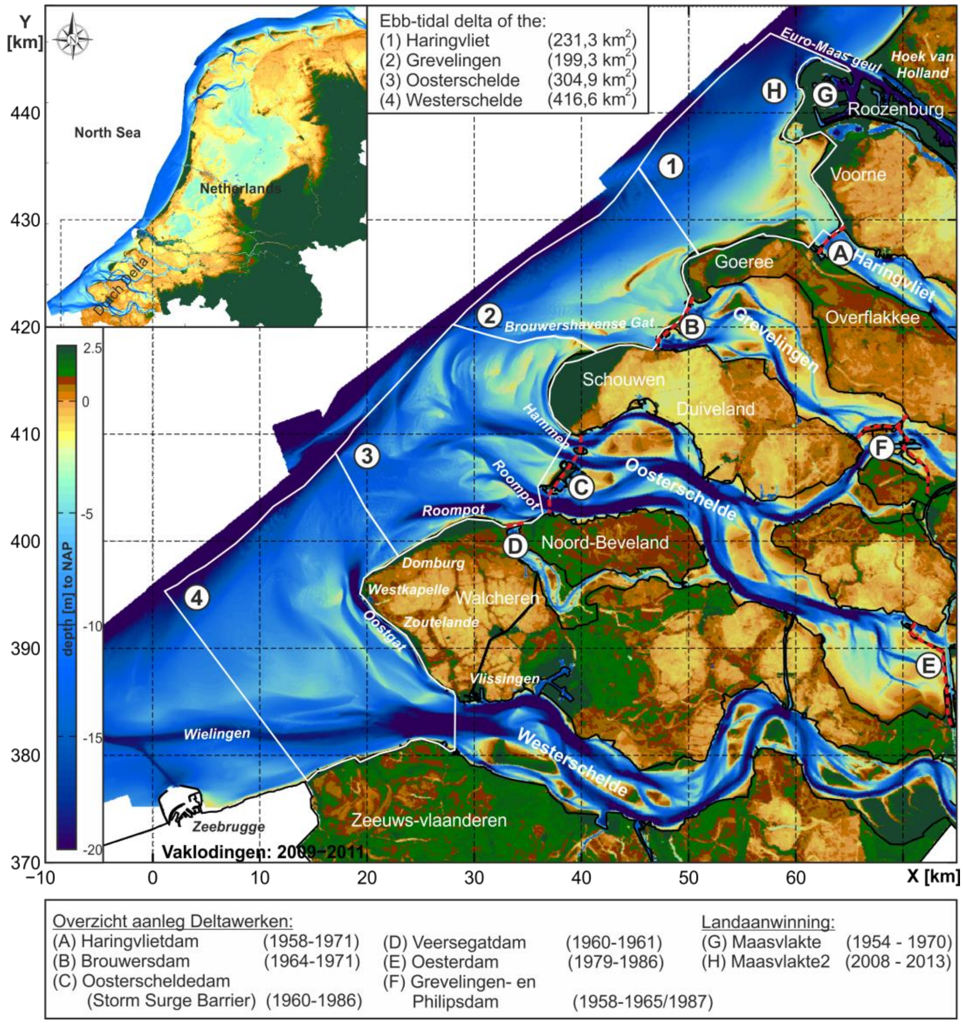

Figure 1. Overview of the Dutch Delta and the estuaries that form the Voordelta, and major dams constructed as part of the Delta Plan (red dashed lines). The boundaries of the ebb-tidal deltas of the respective estuaries are indicated with white lines. Depths are given in meters relative to NAP (Normaal Amsterdams Peil), the Dutch ordnance datum which is about present-day mean sea level (courtesy Elias et al. 2016).

2. The Voordelta; a series of coalesced (former) ebb-deltas in the SW Netherlands.

The coast of the SW Netherlands consists of a series of four (former) estuaries, from north to south Haringvliet, Grevelingen, Eastern and Western Scheldt, see Fig. 1. Haringvliet, Grevelingen and the Eastern Scheldt are distributaries of the combined rivers Rijn and Maas, and the Western Scheldt is the lower course of the river Scheldt. Only the Eastern and Western Scheldt are still connected to the sea, the former by means of an open storm-surge barrier. This open storm-surge barrier allows the tidal motion to propagate into the estuary, but the associated islands and barrier pylons reduced tidal prisms by roughly 35% (Vroon, 1994). The coalesced ebb-tidal deltas form a relatively shallow offshore area: the Voordelta, that stretches over almost 90 km between Hoek van Holland in the north and Zeebrugge (Belgium) in the south. The seaward extent of the Voordelta is c. 10 km out of the islands. From north to south, the average depth increases, whereas the surface area of the shallow shoals decreases. The sediments of the inlets and tidal deltas consist of fine to medium sand (Terwindt, 1973).

In the Voordelta, waves and tides are the dominant forcing mechanisms. Both vigorous tidal currents and heavy seas, especially during strong winds, create a highly dynamic environment that consists of rapidly shifting, shallow bars and shoals, dissected by small and large tidal channels. Only the discharge sluices in the Haringvliet dam (maximum capacity 25,000 m^3/ s) can temporarily create significant density gradients during periods of peak river discharge that might affect the local morphology.

The wave climate is dominated by wind waves generated in the shallow North Sea basin. The mean significant wave height is 1.3 m from the west-southwest, with a corresponding mean wave period of 5 seconds (Roskam, 1988; Wijnberg, 1995). During storms, wind-generated waves occasionally reach heights of over 6 m and additional water-level surges of more than 2 m have been measured. The semi-diurnal tide propagates parallel to the coast, northward during flood and southward during ebb. The tidal range decreases from 3.86 m in Vlissingen (Western Scheldt) to 1.74 m in Hoek van Holland (just north of Haringvliet). In general, following the classification of Davis & Hayes (1984), the inlets prior to damming would qualify as ranging from mixed-energy wave-dominated in the northern part, to mixed-energy tide-dominated and finally tide-dominated in the Western Scheldt mouth. However, the morphology of the major inlets shows tide-dominated characteristics such as a large ebb-tidal delta and deep channels. These result from large tidal prisms and relatively low wave energy.

Note that in this paper we will use Dutch names for tidal channels, shoals, etc. The majority of these names is ending on words that are easily recognized and translated: 'plaat'= shoal; 'bol'= (sand) bar; 'geul'=channel; 'gat'=channel or creek; 'diep'= deep (channel), 'zeewering' = sea wall.

3. The Delta Project; an example of "disaster triggered" coastal management.

The response in coastal management following catastrophic flooding can often be characterized as *"draw the line"*. To ensure that such tragedy will not reoccur, expansive coastal protection works are constructed with a primary focus on preventing future flooding and economical loss. Recent examples are the large-scale engineering works constructed, and being constructed, following the hurricanes Katrina (2005), Ike (2008) and Sandy (2012) in the United States (e.g. USACE, 2009; Link, 2010; HSRTF, 2013). A similar response was also observed after catastrophic flooding of major parts of the SW Netherlands during a major storm event on January 31, 1953. The associated storm surge bursted the dikes along the estuaries and caused 1836 casualties and an enormous economic damage. Prior to this date, numerous smaller scale structures and interventions were already built to retard coastal erosion (see next section), but after the 1953 storm, the Delta Plan was enacted. The Delta Plan included the building of closure dams in the Haringvliet, Grevelingen, and Eastern Scheldt estuaries. These dams reduced the stretch of dikes exposed to the sea by 700 km, greatly reducing the risk of flooding. Only the Western Scheldt needed to remain open to ensure unhindered shipping to the harbor of Antwerpen. Here dikes were heightened and strengthened. A process that continues up to present as new regulations and design criteria emerge. Plans for complete damming of the Eastern Scheldt were eventually abandoned to maintain the estuarine tide, and thereby its important and unique (shellfish) habitat in the estuary.

A recent reanalysis of the effects of the Delta works on the sediment budget was presented by Elias et al. (2016). These authors reveal that the complete or partial damming of the estuaries had an enormous impact on the ebb-tidal deltas: the strong reduction of the cross-shore directed tidal flow triggered a series of morphological changes that continue until today (see Fig. 2). Moreover, large-scale dredging in the Western Scheldt estuary and its ebb-tidal delta channels has changed the hydrodynamics of the estuary which will have an impact on its ebb-tidal delta too.

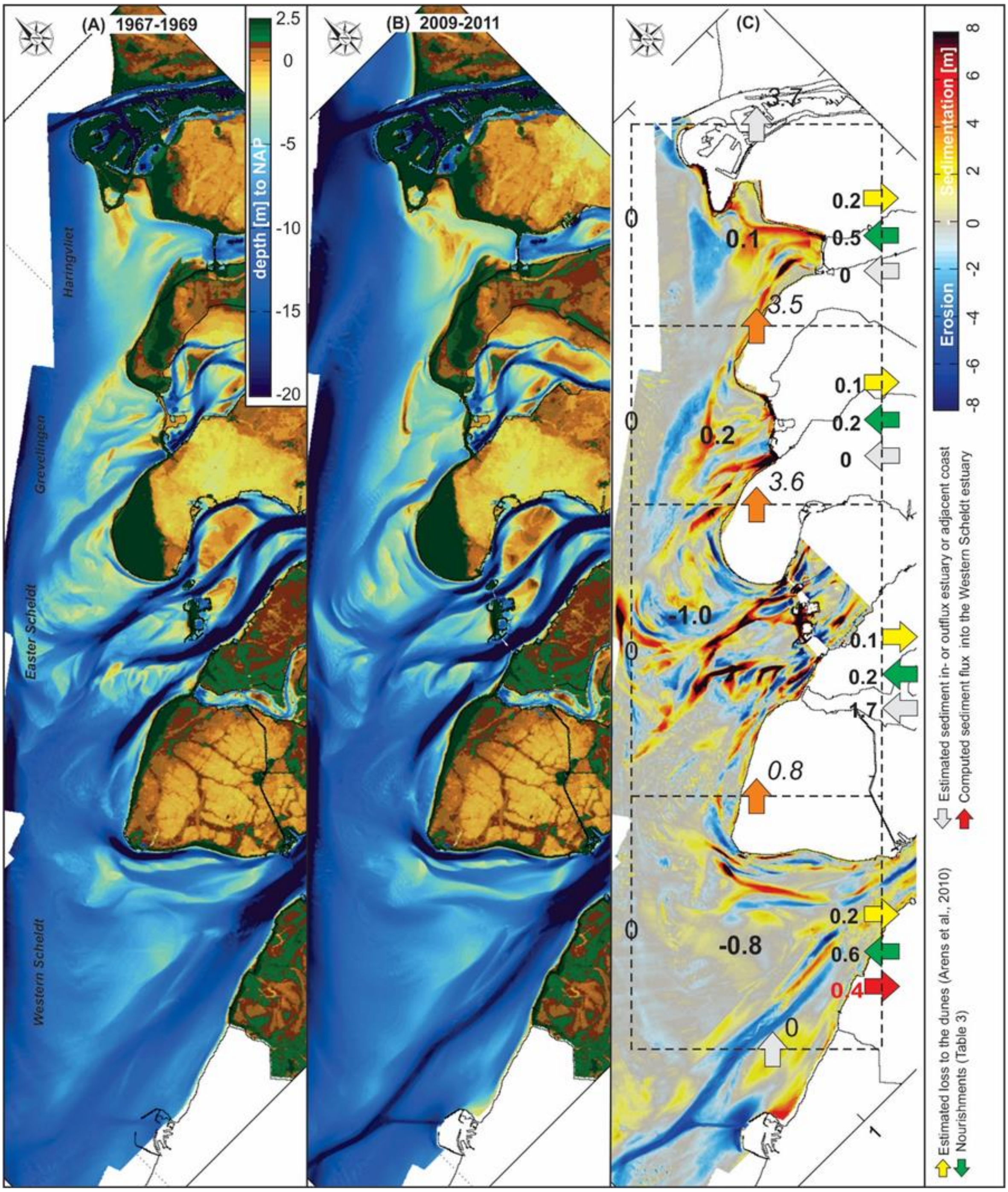

Figure 2. Impact of the Delta works on the bathymetry of the Voordelta. (A) Bathymetry prior to construction: 1968, (B) present-day bathymetry: 2010, and (C) sedimentation-erosion patterns: 2010-1968. Boxes and arrows summarize the results of the sediment budget and present estimates of the fluxes between the individual ebb-tidal deltas. Based on figures and data shown in Elias et al., 2016.

Elias et al. (2016) conclude that complete damming of the northern estuaries Haringvliet (including Brielse Maas) and Grevelingen resulted in a regime shift from mixed-energy to wave-dominated. At both the Haringvliet and Grevelingen ebb-tidal delta a long but narrow, coast-parallel, sub- to intertidal bar developed as sediments were reworked by waves on the former ebb-delta margin and pushed landward. The net volume changes are small with a 0.1 to 0.2 million m^3/year increase. Note that these values lie well within the (in)accuracy of the data. Partial closure of the Eastern Scheldt resulted in a reduced tidal volume, but the tidal flows have been sufficient to maintain the main channels in the ebb-tidal delta. The reduction of the shore-normal tidal flow resulted in (1) a dominance of shore-parallel currents on the nearshore shoal area (Banjaard), promoting scour of the north-south running channels, and (2) erosion of the ebb-delta margin due to wave attack. As a result, the largest sediment losses occurred on this ebb-tidal delta (-72 million m^3 since completion of the storm-surge barrier). Only limited net change was observed in the Western Scheldt ebb-tidal delta in the south. This ebb-tidal delta retained a near-identical two-channel configuration with large tidal channels along the southern and northern margin, despite major dredging activities in the estuary (over 400 million m^3 of sediment was dredged and dumped) and channel deepening on the ebb-tidal delta. Apparently, tide-dominated systems such as the Western Scheldt ebb-tidal delta are robust and resilient to significant anthropogenic change, as long as the balance between tides and waves does not alter significantly. Despite the smaller morphodynamic change, the volume loss of the ebb-tidal delta is estimated at 1 million m^3/year.

The large morphodynamic changes make it difficult (if not impossible) to discern the effects of sea-level rise. Water-level observations at nearby stations (Vlissingen, Hoek of Holland) suggest a rise in MSL in the order of 0.10 to 0.15m over the period 1965-2010 (Dillingh et al., 2012), but this is not reflected in the morphological changes. The effects of the damming have overwhelmed any natural development. To keep pace with that rise in MSL, the Voordelta should have gained 155 million m^3 of sediment over the time-frame.

4. “Classic (hard) coastal structures”; Safety against Flooding; Prior to 1990”

An extensive analysis of the effects of the groins constructed along the Voordelta coast since the 18th century was presented by Verhagen and van Rossum (1989). In this section (and in Fig. 3) the results of their study are summarized. We focus on the islands Walcheren and Schouwen, and the coastline of Zeeuws-Vlaanderen, as the coastlines of the two northern islands Goeree and Voorne are also strongly influenced by large-scale land reclamation during the construction of, respectively, Europoort (1964–1966), Maasvlakte (1964–1976), Slufterdam (1986–1987) and Maasvlakte 2 (2008–2013) that shifted the shoreline of the northern island Roozenburg 8 km seaward and covered the northern part of the ebb-tidal delta. The analysis of the effects of these land-reclamations is beyond the scope of this study.

Although the history of coastal protection in the Voordelta goes back many centuries, the first of the present-day groins along the coastlines of the islands Schouwen and Walcheren were built in the 19th century (Fig. 3). Initially, between 1834 and 1881, the Schouwen groins were constructed along the northern shoreline over a length of 6 km to retard dune erosion. This dune erosion was linked to the presence of a main tidal channel (Brouwershavensche Gat) along the coast. Since construction, the erosion rates greatly reduced from 0.7 - 1.8 m/year to 0 - 0.2 m/year. The reduction was even larger between km 3 and 7 were erosion rates of 5 - 6 m/year were observed prior to 1865, these reduced to near zero since. Part of this reduction is also attributed to larger scale morphological changes such as the alongshore migration of sand waves. In the south, just west of the present-day location of the storm-surge barrier, groins were placed to reduce the scour of the coastline induced by the adjacent tidal channel (the Hammen). Both constructions proved successful as erosion rates reduced from 2.4 - 4.8 m/year prior to 1861, to an average accretion of 0.5 m/year till the construction of the storm-surge barrier. In 1968 wooden pile dikes were constructed in between the two groin fields (km 10 – 12). An important lesson learned was that such wooden piles are unsuccessful in retarding erosion related to channel migration. The piles just topple over and disappear in the advancing channel. For both locations, it must be noted that more recently, the effects of the Delta works have changed the local coastal dynamics, and more severe erosion is nowadays observed as the larger-scale morphology dramatically changed. Severe erosion is now present along the southern groins and re-occurring nourishments are needed to maintain both the coastlines and groins (see Chapter 5).

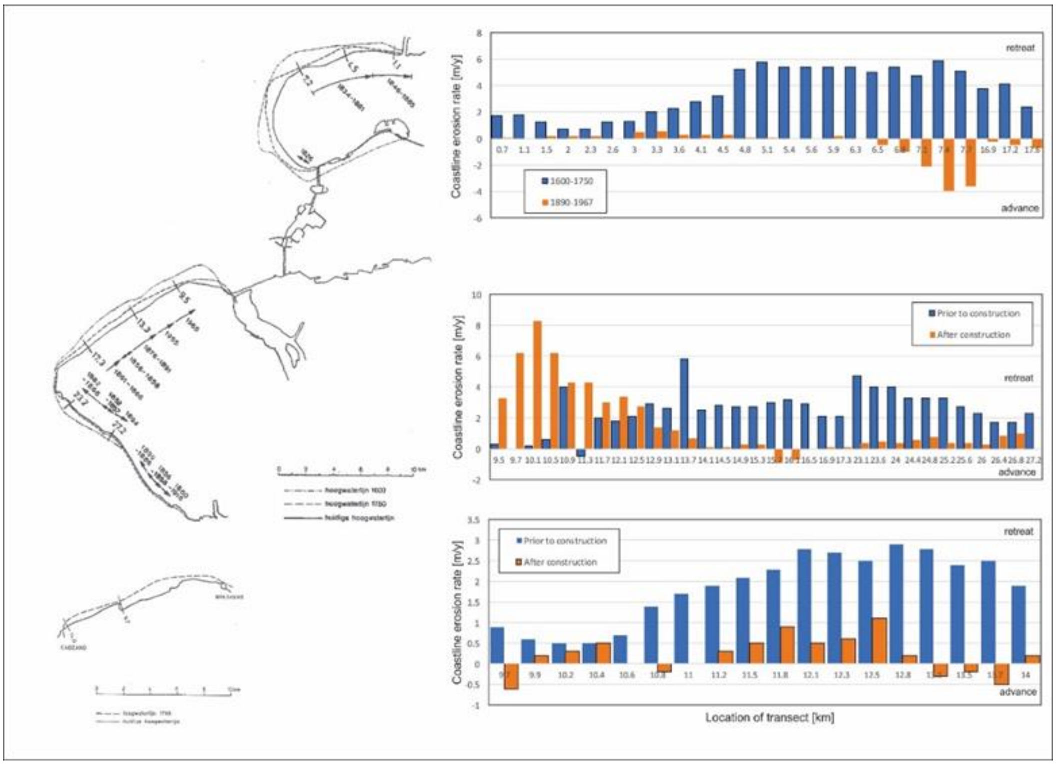

Figure 3 (left panel). Coastline evolution of the Voordelta over the timeframe 1600–1990. Right panels summarize the change in coastline change rate pre and post construction of the groins. Based on Verhagen and van Rossum (1989).

Most of the Walcheren coastline is protected by either seawalls (near Westkapelle and Vlissingen) or groins. Along the northwestern coast, the first groin fields were already placed in the 17th century to retard the over 1-km of coastline retreat that had previously occurred. Erosion of the northern and southern parts are largely related to the presence of large tidal channels (Oostgat and Roompot). Prior to 1750 erosion rates in the central part were on average 2 m/year, but locally increased to 4 to 5 m/year. Since construction of the groins (1890-1967) erosion rates have decreased to below 1 m/year in the southern part (km. 13.7-17.3), but increased to up to over 8 m/year in the northern part. The latter high values are related to the recent (1955-1967) scouring of the Roompot channel. The utmost southwestern tip of the island, where the channel Oostgat has the largest influence, is protected by a 5-km long seawall (Westkapelse Zeewering). The origins of this seawall probably date back to the early 15th century. Recent updates and retrofitting between 1986-1988 increased the crest height to 11 to 12 m, and in 2008 additional works included the placement of a large 2,5 million m^3 nourishment along the northern end of the seawall.

The coastal stretch between the seawalls of Westkapelle and Vlissingen is called SW Walcheren. With the exception of a 2 – 3 km stretch in the middle, this entire coastline is protected by groin fields to retard the erosion induced by the tidal channel Oostgat. The construction of the groins started in 1856 just north of Vlissingen. The groin field was expanded between 1861and 1866 in a northward direction, and by 1916 the last groins toward the south were added. South of Westkapelle, an approximate 5-km long groin field was constructed between 1852 and 1894. Combined, these groins were able to significantly reduce shoreline retreat due to the landward migrating channel Oostgat. Erosion rates near Westkapelle reduced from values of 3-4 m/year to 0.4-0.8 m/year, and erosion towards Vlissingen was reduced from 1.7-2.7 to below 1 m/year (Fig. 3). However, the ongoing landward migration of Oostgat made extensive protection and maintenance of the tip of the groins necessary, while on the coast frequent nourishments were needed to maintain the beaches. Initially, this maintenance was done by adding and replacing damaged stones, but since 2005, both groins and coastline are successfully maintained through channel-slope nourishments (see next section).

Already in the 19th century, the coastline of Zeeuws-Vlaanderen was protected along its entire length by a succession of seawalls, dikes and groins. These structures are needed to counteract the erosion induced by the main entrance channel to the Western Scheldt estuary (Wielingen) that runs in close proximity to the coast. The effectiveness of the groin fields in reducing the erosion can only be assessed for the stretch of coast between km 9.7 and 14.0 (Fig. 3). Here erosion rates prior to construction varied between 0-5 and 2.9 m/year, with smaller values (0.5-0.9 m/year) between km 9.7 and km 10.6, and larger values southward. Since construction, erosion rates are generally smaller, below 0.5 m/year.

In addition to the groins and seawalls mentioned above, many (smaller) sea walls, breakwaters and jetties exist in the Voordelta. Despite our present-day dynamic preservation strategy, these structures still require extensive maintenance. Between 1997 and 2014 €740 million was spent to maintain and upgrade these structures, and the 325 km of remaining levees and dikes along the open estuaries.

Table 1. Overview of seawalls and breakwaters along the coasts of Schouwen, Noord-Beveland, Walcheren and Zeeuws-Vlaanderen, and recent cost to upgrade to new safety standards.

Construction	Location	Length Km	Costs Million Euros
Jetty	Schouwen-Duiveland, Burghsluis	2.7	4
Breakwater	Noord-Beveland, Onrustpolder	1.1	4.5
Seawall	Walcheren, Schorerpolder	0.7	1
Seawall phase 1	Walcheren, Westkapelse seawall	2,75	14.8
Seawall phase 2	Walcheren, Westkapelse seawall	1.6	4.5
Breakwater	Walcheren, Zoutelande	0.9	3.5
Breakwater	Walcheren, Zuidwatering	4.4	7.8
Breakwater	Walcheren, Westkapelle Gat	1.4	2.3
Breakwater	Walcheren, Vlissingse seawall	1.7	2.4
Jetty	Zeeuws-Vlaanderen, Breskens Kom	1.7	3.5
Jetty	Zeeuws-Vlaanderen, Breskens Veerhaven	1,4	n.a.
Breakwater	Zeeuws-Vlaanderen, Hoofdplaatpolder	3.5	21.7

5. **Dynamic Preservation policy "Working with Nature" since 1990**

Already in the nineteen eighties, the Dutch government started to develop new guidelines for coastal management that eventually resulted in the *"Dynamic Preservation"* policy. This policy prescribes that the coastline of the Netherlands is maintained at its 1990 (reference) position using sand nourishments as a primary source. A yearly testing procedure was designed to ensure that the coastline does not structurally retreat beyond its reference location (see Hillen and De Haan 1995 for details). In Figure 5 (insert) the decrease in coastline exceedance through time clearly illustrates that Dynamic Preservation is successful.

Initially, a yearly sand volume of 5 to 7 million m^3 was nourished, predominantly placed on the beaches, to counterbalance shoreline retreat along the stretches of coast that failed the yearly test procedure. In 2000 the preservation policy was updated to include the lower shoreface and the dune area. By adding the entire (active) coastal profile, it allows taking into account the effects of sea-level rise. Deepening of the lower shoreface, would in the long term, threaten the coastal stability and increase structural coastal erosion of the coastline. Maintaining this larger stretch of the coastline required much larger sand volumes and since 2001 the nourishment volume averages around 12 million m^3/year. Larger nourishment volumes also necessitated the need for more (cost) efficient nourishments and a significant volume of the nourishments is therefore placed on the shoreface (see insert Fig. 5).

Figure 5 illustrates how the nourishment volumes were distributed over the various morphological cells of the Dutch coast. In the work of Van der Spek and Lodder (2015) the effects of these nourishments on the sediment budget were analyzed. These authors conclude that over the period 1991-2012 a total volume of 207 million m^3 of sand was nourished. Including recent nourishments, the volume increased to 262 million m^3 by 2016 (Fig. 5). Roughly half of this volume was placed on the beach and the other half on the shoreface (typically between 5 and 8 m below MSL). The nourishments have been successful in maintaining (increasing) the sediment volume in the shallow coastal zone (between MSL - 8 m and the landward side of the frontal dune row). The eroding trend that existed prior to 1990 has changed into an accreting trend since. As their final conclusions, Van der Spek and Lodder state: *"the aim of the Dynamic Preservation policy, to halt structural coastal erosion, is achieved. The coastline has been stabilized by nourishing regularly and in some places, the coast is even building seaward. The coastal recession has been stopped. Only in places where natural dynamics are preferred, e.g. in nature reserves, and that are deliberately not nourished, the coastline is allowed to erode without interventions"*.

Figure 4. Photos taken at the beach in Domburg prior and post-nourishment (May 1989 and June 1989). Bottom panel illustrates the massive erosion that has had taken place after a severe storm on February 28, 1990. Large-scale beach and dune erosion during this storm triggered the direct implementation of the Coastal Preservation policy.

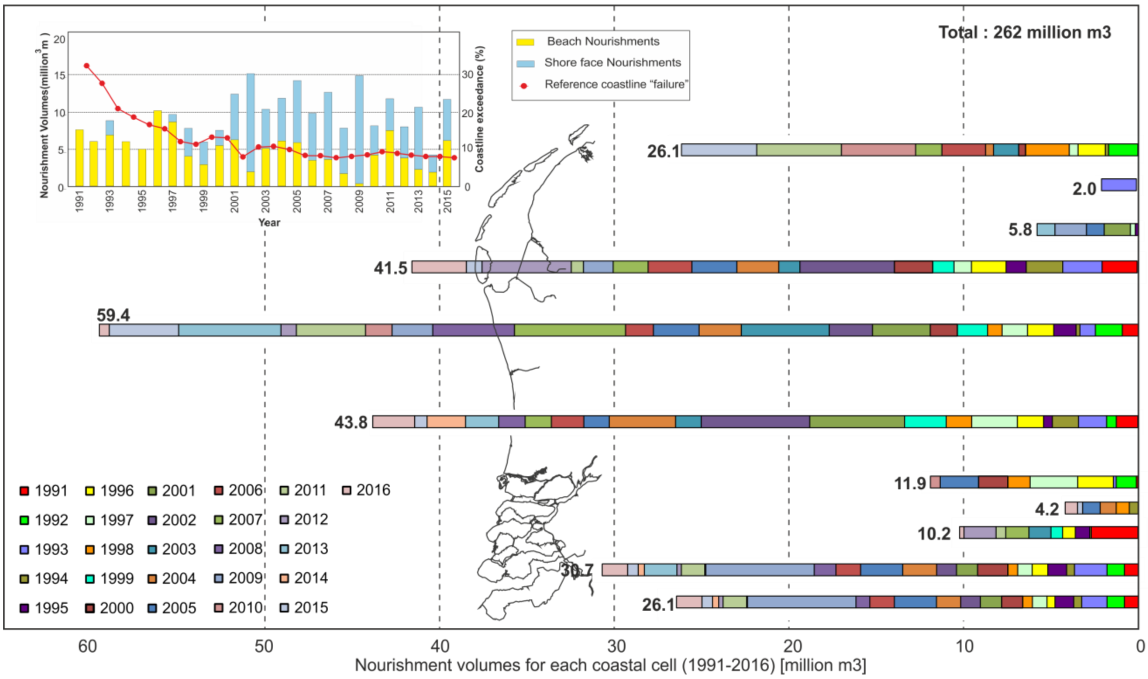

Figure 5. Overview of the volumes nourished along the Dutch Coast since the start of Dynamic Preservation (1991-2016). Volumes are subdivided into the individual coastal cells. Insert shows the yearly volumes and instances of coast-line exceedance probabilities. Yearly the position of the coastline is compared to its 1990 position. Nourishments are planned when the coastline (structurally) exceeds this position. The goal is to keep the exceedance below 10%. Since 2005 this goal is constantly achieved: *Dynamic Preservation is a success!*

In the Voordelta, a large increase in nourishment volume has been observed since 1990. Prior to 1990, 31 million m^3 of sand was nourished. The majority of these nourishments took place along the coasts of Goeree (11 million m^3, between 1973-1987) and Voorne (10 million m^3, between 1966-1985). Almost 95% of these nourishments were placed on either the dune or beach.

Since 1991, over 72 million m^3 of sand was added to the coastal system. Most of these sediments were placed on the coastlines facing Walcheren (33 million m^3) and Zeeuws-Vlaanderen (17 million m^3). Roughly 25 % of these nourishments were placed on the shoreface. The effects of the nourishments are more difficult to distinguish in terms of the sediment budget. Here the morphodynamic adaptation to the damming of the major estuaries still dominates the developments (see Chapter 3).

An early evaluation of Dynamic preservation was performed by Roelse (2002). In his summary, Roelse states: *"The results of the evaluation are satisfactory. The task, which the national government undertook in 1990, the fighting of structural erosion, can be carried out well with sand nourishment. <u>Only at a few locations in the province of Zeeland that have very steep underwater slopes, there is concern about the sustainability of the method.</u> Attention is being paid to it in the coastal research program. In the present evaluation, the entire Dutch coast is involved. It can be concluded that with the new coastal policy the structural erosion is under control. The threat to interests in the coastal zone by coastal retreat is now a part of the past. The control of the coastal development is offering opportunities for new developments. There are opportunities for allowing natural fluctuations, breaches in the foredune and drifting dunes. Unwanted developments may be stopped or reversed by sand nourishment."*

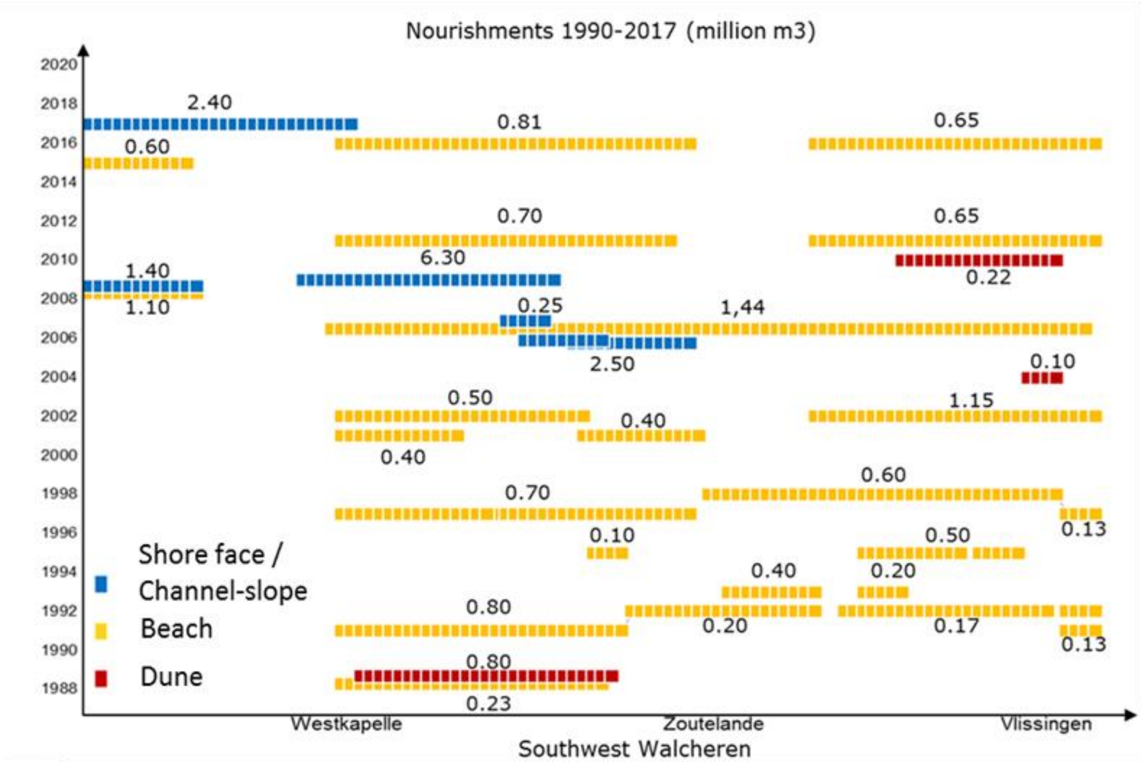

Figure 6. Overview of the nourishments that were placed on the coast of SW Walcheren between 1988 and 2017.

Walcheren being the most populated area in the Voordelta, and its beaches having a major economical and recreational value, particularly the erosion of the SW coast of Walcheren has been a major concern. The frequently reapplied nourishments clearly illustrate this statement (Fig. 6) The erosion is for a major part related to the presence of a large and deep tidal channel Oostgat along its entire length (Elias et al. 2016). Initially, beach nourishments were applied to counteract the erosion, but even in combination with the existing, extensive array of groins, these nourishments were only partly successful and had to be often repeated. A major problem was the limited accommodation space available to place the beach nourishment as only a narrow strip of beach is present between the channel and dunes. Beach nourishments are only (cost) effective if sufficient amounts of material can be placed in the profile. Additional concerns were the negative impact of nearly yearly nourishments on recreational activities that form a major economic source to the region, but more important were the concerns about the stability of the steep channel wall, a collapse could result in the slumping of a major part of the channel wall, the beach and adjacent dunes, thereby seriously threatening the coastal safety. These concerns prompted the investigation into alternative nourishment strategies, and eventually, 3 potential strategies were selected for evaluation. These strategies included:

a). Channel realignment (Figure 7a). This alternative includes the excavation of the fore lying shoal. The excavated sediments are partly used to increase the height and width of the shoal on its seaward side. This addition increases wave breaking (during storms) thereby reducing erosion of the adjacent coast. The major part of the deposits is used for the channel-slope nourishment. Redistribution of local sand reduces cost significantly, however, does not add additional sand to the system (a requirement to keep the coast in equilibrium with sea-level rise).
b). Channel-slope nourishment (Figure 7b). This alternative was executed in both 2005 and 2009. Sand was added to the system along the channel wall from a borrow pit well outside the area. This alternative adds sand to the system and promotes the channel wall stability.
c). Channel realignment and channel-slope nourishment (Figure 7c). Sand mined from the landward part of the shoal is redeposited seaward, while sand from an outside borrow pit is used to reinforce the channel wall. This alternative combines the advantages of both strategies (a) and (b).

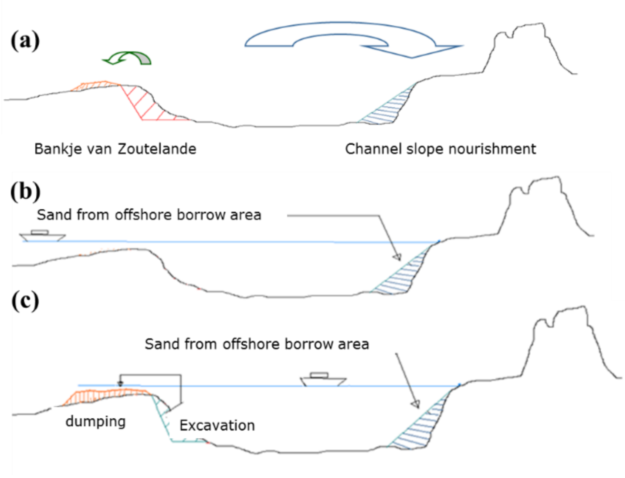

Figure 7 Alternative strategies for Oostgat nourishment: (a) channel realignment, (b) channel-slope nourishment, and (c) combination of (a+b).

Each of the alternatives has its own advantages and disadvantages. A major advantage of channel realignment is that it directly addresses the process responsible for the coastal erosion, while a channel-slope nourishment by itself only mitigates the effects of the erosion. By increasing the width of the channel, through moving the shoal seaward, the lateral stresses on the channel are decreased. Additionally, an increased height of the shoal promotes wave breaking and wave energy decay. Both of these effects reduce the erosional stresses along the coast.

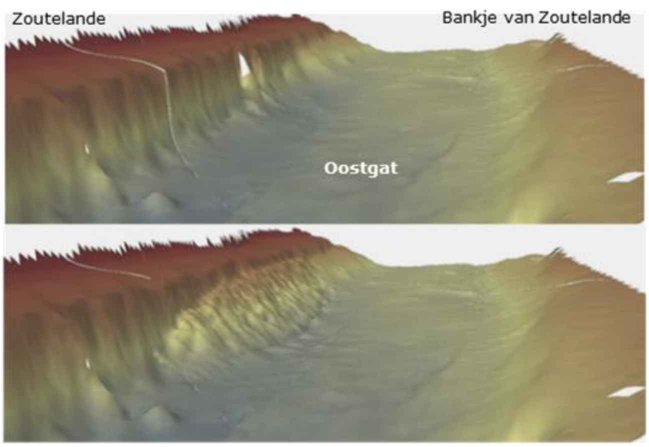

Figure 8: 3D rendering of Oostgat based on multibeam surveys prior and after placement of the nourishment (top and bottom) The channel-slope nourishment was placed at a 1:13 slope to (1) ensure stability of the channel wall, (2) for durability of the nourishment, and (3) for efficient placement by the dredge.

Major disadvantages of channel reallocation are (1) the potential distortion of the natural state, which could trigger an unexpected non-linear response on larger scales, and (2) the larger-scale impact may violate strict nature legislation rules in place for this area.

In 2005, Rijkswaterstaat therefore opted to execute a channel-slope nourishment just north of the town of Zoutelande (see Fig. 1 for location). Two and a half million m^3 of sand was placed along the channel-wall (see Figure 8). Evaluation of the nourishments performance proved that: the (1) nourishment is able to mitigate the erosion of the channel-wall, (2) increased sediment volume in the nearshore ensures that mandatory safety requirements are complied with, and (3) sediment protects the tips of the groins from erosion thereby significantly reducing damage and maintenance costs. Following a similar design template, additional channel-slope nourishments were executed. In 2009 an additional 6,3 million m^3 was placed in the Oostgat to protect the entire section of coast between Zoutelande and Westkapelle, and 2,7 million m^3 was placed in the Wielingen, Nieuwe Sluis, Zeeuws Vlaanderen. Recently, 1,5 million m^3 was placed in the Schaar van Onrust, a channel along the Noord-Beveland coast. These nourishments remain under intensively monitoring and their performance is annually reviewed in the Dutch Coastal Maintenance program.

6. Concluding Remarks

Climate change and related retreating coastlines and coastal flooding necessitate the importance of well-planned and executed coastal management. With decades of knowledge based on centuries practice and science obtained from learning by doing, the Dutch have adopted a strategy of *Dynamic Preservation*. The Dutch coastlines are now successfully maintained using sand nourishments as a primary tool. Earlier evaluations of Dynamic Preservation (Roelse 2002, Van der Spek and Lodder, 2015) have proven that this strategy is successful in maintaining the Dutch coast. Through Dynamic Preservation, even the complex coast of the Voordelta can be maintained at prescribed safety levels. Classic beach and shoreface nourishments alone are however not sufficient. The presence of large tidal channels in close proximity to the coastlines necessitates the use of new, innovative, nourishment strategies, such as channel-wall nourishments.

The coastal protection works in the Voordelta reflect different stages of coastal management. In the early years (prior to 1950) coastal management was focused on safety and economics. Hard structures were used to counteract erosion in a mindset of ‘no land shall be lost to the sea’ or *‘hold the line’*. Nearly the entire length of coastline was protected with some sort of structure (e.g. pile dikes, groins or seawalls). These structures have proven successful in reducing, but not completely eliminating, the coastal erosion (Verhagen and Van Rossum, 1989). A catastrophic flood (1953) triggered a response that can best be described as ‘*draw the line*’ ensuring safety against flooding through large-scale coastal works. Closure dams in 3 of the 4 estuaries were built. The change introduced by these dams, such as the landward sediment movement of the ebb-tidal delta, continues to dominate the larger-scale morphodynamic behavior until today. The flexibility of soft interventions allows an efficient anticipation and counterbalancing of the changes that negatively impact the coastlines, and these nourishments have proven capable of maintaining the coastlines. Nourishments are also applied to protect and reduce the maintenance of the present hard structures.

A policy of soft interventions (such as Dynamic Preservation) is an often preferred and requested strategy. However, the availability and access to sufficiently large sand deposits may limit the feasibility of soft interventions alone. Combinations of hard and soft measures may be necessary. We hope that the lessons learned, from the well-documented changes and interventions in the Voordelta, contribute to an improved understanding of the functioning and effects of coastal protection works.

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