Ocean and Coastal Management 217 (2022) 106008

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

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

Evelien Brand [a], Gemma Ramaekers [a], Quirijn Lodder [a,b,*]

[a] Rijkswaterstaat, Water Verkeer en Leefomgeving, Griffioenlaan 2, 3526, LA, Utrecht, the Netherlands
[b] TUDelft, Faculty of Technology, Policy and Management, Jaffalaan 5, 2628, BX, Delft, the Netherlands

ARTICLE INFO

Keywords:
Nourishment design
Shoreface nourishments
Beach nourishments
Channel wall nourishments
Coastal maintenance

ABSTRACT

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

1. Introduction

1.1. Context

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

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

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

Finally, to address the strategic goal and the associated tactical approach, operational objectives such as maintaining the coastline position are defined. Here, the assumption is made that the physical conditions for existing coastal functions are preserved by maintaining the

* Corresponding author. TUDelft, Faculty of Technology, Policy and Management, Jaffalaan 5, 2628, BX, Delft, the Netherlands.
E-mail addresses: evelien.brand@rws.nl (E. Brand), gemma.ramaekers@rws.nl (G. Ramaekers), q.j.lodder@tudelft.nl (Q. Lodder).

https://doi.org/10.1016/j.ocecoaman.2021.106008
Received 31 March 2021; Received in revised form 23 November 2021; Accepted 3 December 2021
Available online 28 December 2021

coastline position (Ministerie van Verkeer en Waterstaat, 2000, van Koningsveld and Mulder, 2004). For this purpose and to ensure that the whole active coast is in equilibrium with sea level rise an average of 12 mln. m^3 is nourished each year with sand that is extracted offshore.

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

1.2. Objectives and approach

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

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

1. **Nourishment data:** Information on the length, volume, type, and period of construction is available for each nourishment. A summary of the part of this dataset used in this study (i.e. the nourishments for dynamic coastline conservation) is given in the appendix.
2. **Nourishment designs:** Design reports exist with information on design aspects like the slope and elevation of the nourishment for recent nourishments (i.e. nourishments performed over the past 15 years).
3. **Yearly beach topography and bathymetry data:** Each year the topography of 200–250 m spaced transects is measured along the Dutch coast (JARKUS). The topography is measured from the dunes to approximately 2 km offshore. This data is used to calculate the coastline position, for example.

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

2. The Dutch coast

2.1. Regional setting

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

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

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

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

2.2. Operational objectives for coastal management in the Netherlands

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

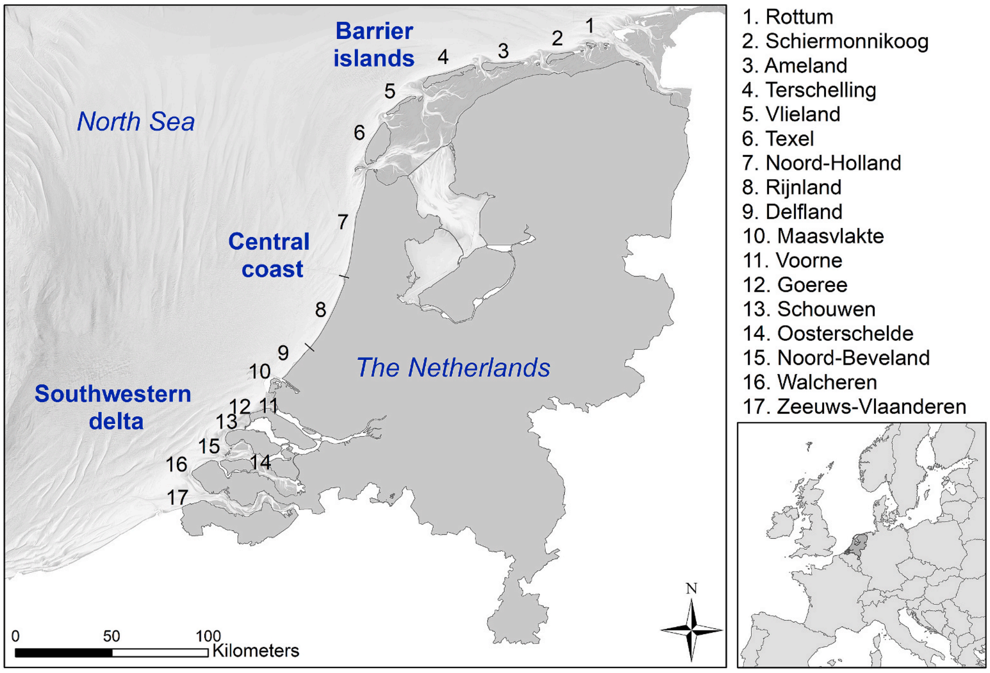


Fig. 1. Overview of the Dutch coast with the coastal regions.

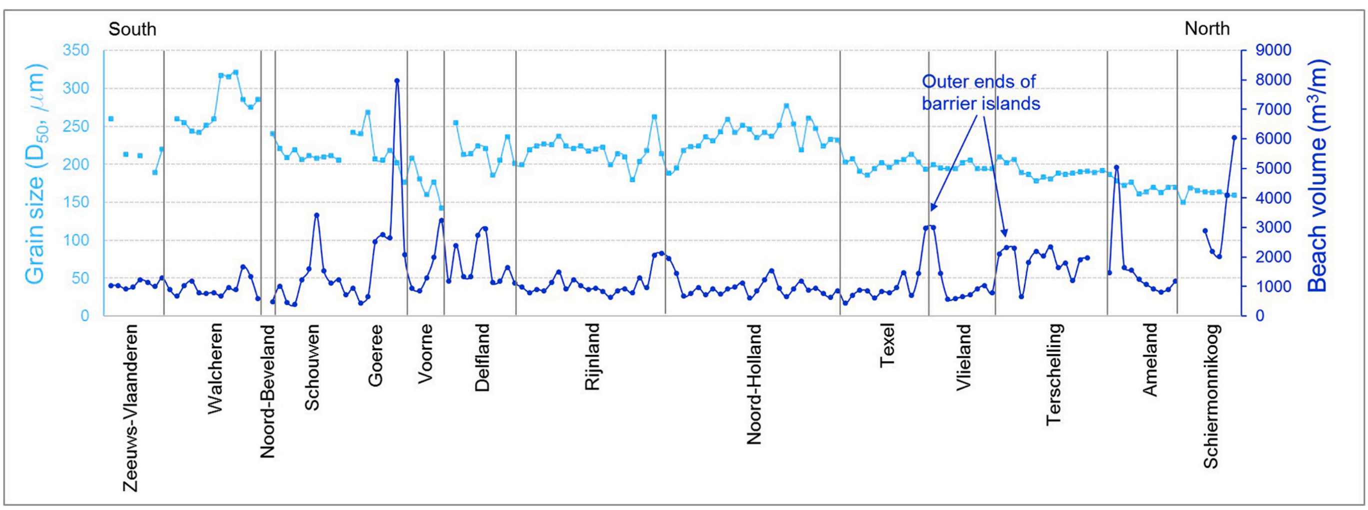


Fig. 2. Median grain size of the dunes (Kohsiek, 1984) and the beach volume (i.e. the volume between NAP -2 and +4 m) in 2020 for every 2 km along the coast.

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

Each year the position of the MKL is assessed in relation to the BKL-position (e.g. Rijkswaterstaat, 2020). Nourishments are carried out to maintain the coastline position, especially when flood safety is directly

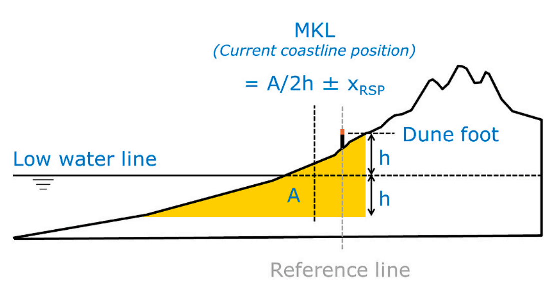


Fig. 3. The determination of the MKL (current coastline position) from the sand volume in the MKL-zone (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

at stake and/or when it cannot be expected that the coast will recover naturally (Rijkswaterstaat, 2021a). Besides the regular maintenance of the coastline, the flood defences are assessed for flood safety every 6 years within the Hoogwaterbeschermingsprogramma (Flood protection program, Hoogwaterberschermingsprogramma, 2019). Sandy reinforcements for safety purposes are sometimes performed within this program. These are not considered in this study, as their design and goal is often very different from regular, dynamic nourishments for coastline maintenance.

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

It is not established in the operational objectives how and where this volume of 12 mln. m^3 should be nourished (Mulder et al., 2011). However, it is known since a few years that the long-term deficit of sediment is largest in the southwestern delta and at the barrier islands and in the adjacent Wadden Sea (e.g. van der Spek and Lodder, 2015; Rijkswaterstaat, 2021b). Therefore, in practice the volume of 12 mln. m^3 is used for nourishments aiming to maintain the coastline at the BKL-position and for additional (underwater, i.e. shoreface or channel wall) nourishments in the southwestern delta and at the barrier islands. Due to the morphology of the southwestern delta, including extensive shoal areas and tidal channels, less locations are available for shoreface nourishments than at the barrier islands, which also partly have straight coastlines. Therefore, the nourishment efforts mainly increased at the barrier islands, both in a relative sense (Fig. 4) and in absolute volumes (40 mln. m^3 between 2000 and 2009 and 44 mln. m^3 between 2010 and 2019).

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

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

3. Evolution of the nourishment approach

Globally, the first beach nourishments were performed in the early 1900s (Valverde et al., 1999). In the Netherlands the first beach nourishments date from the 1950s (Fig. 6, left). These nourishments were often small scale (i.e. <0.5 mln. m^3) and were mainly reactive to storm events (Ministerie van Verkeer en Waterstaat, 1988). The improvement of dredging and nourishment techniques in the 1970s, such as the invention of the trailing suction hopper dredger, allowed for bigger and more frequent nourishments. Between 1970 and 1990 the annually

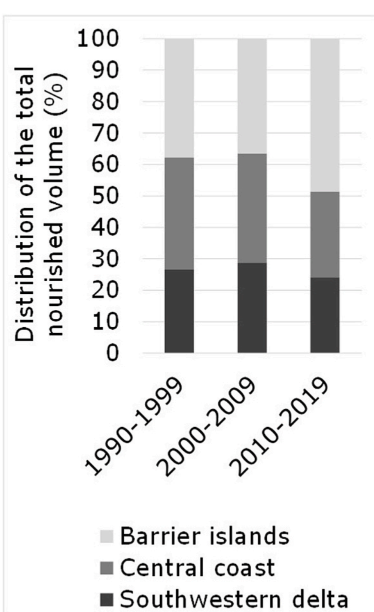


Fig. 4. Distribution of the total nourished volume over the Dutch coastal regions.

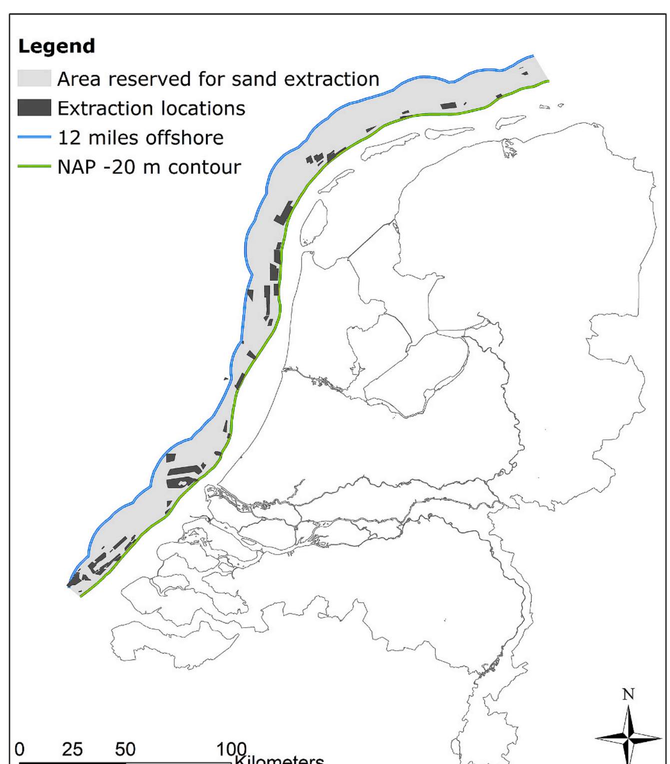


Fig. 5. The areas used and reserved for sand extraction for nourishments.

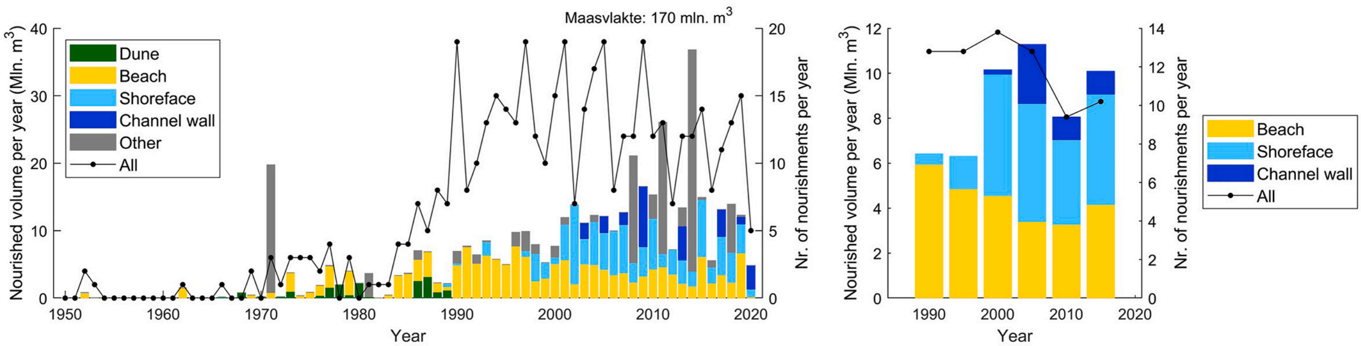


Fig. 6. Annually nourished volume (bars, in million m^3) per type of nourishment and the number of nourishments (line). Left: all sand nourishments, visualized per year. Right: nourishments within the dynamic conservation policy per period of 5 years.

nourished volume along the Dutch coast was 3.5 mln. m^3, on average. The sand used for nourishments before 1990 was often from local sources such as nearby channels that were dredged (Ministerie van Verkeer en Waterstaat, 1988).

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

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

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

4. The different nourishment types

Nowadays, beach, shoreface, and channel wall nourishments are most common in the Netherlands (Fig. 7). Beach nourishments are

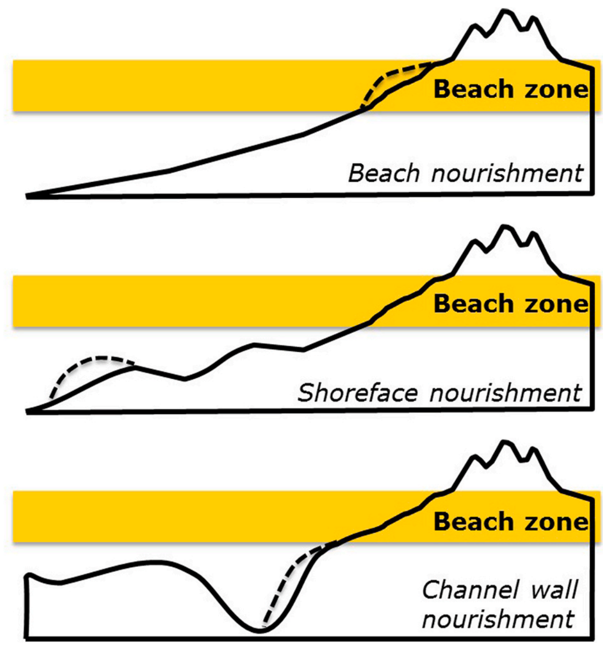


Fig. 7. The three main types of nourishments in the Netherlands – schematized.

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

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

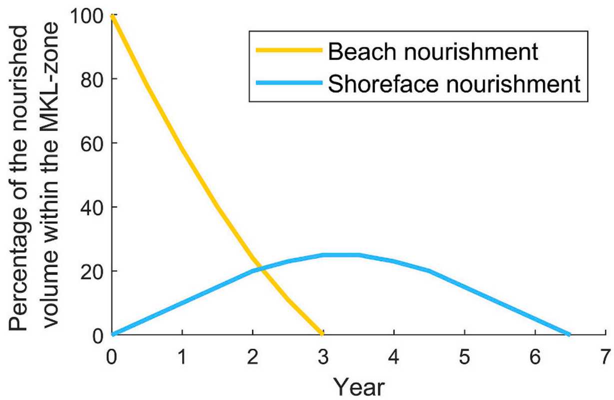


Fig. 8. Conceptual development of beach and shoreface nourishments represented by the percentage of the nourished volume that is present within the MKL-zone.

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

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

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

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

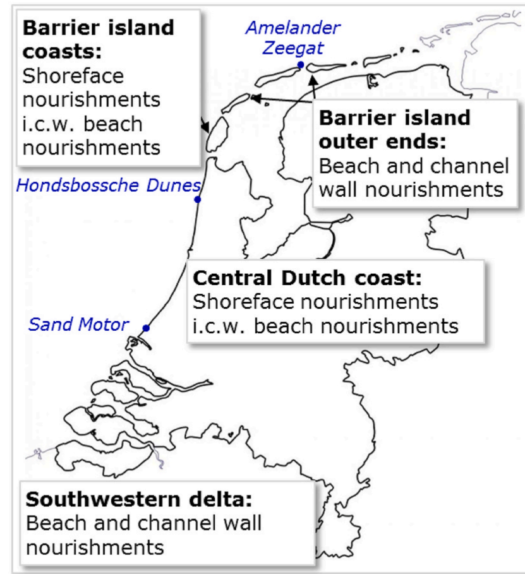


Fig. 9. Overview map of the Netherlands with the most common type of nourishments per region.

5. Nourishment design

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

5.1. Beach nourishments

Beach nourishments are regularly carried out along the Dutch coast and in total 258 beach nourishments have been carried out since the 1990s. Beach nourishments are usually placed against the dune foot which is approximately at NAP +3 m. After a short beach platform the nourishment descends with a slope that is as similar as possible to the

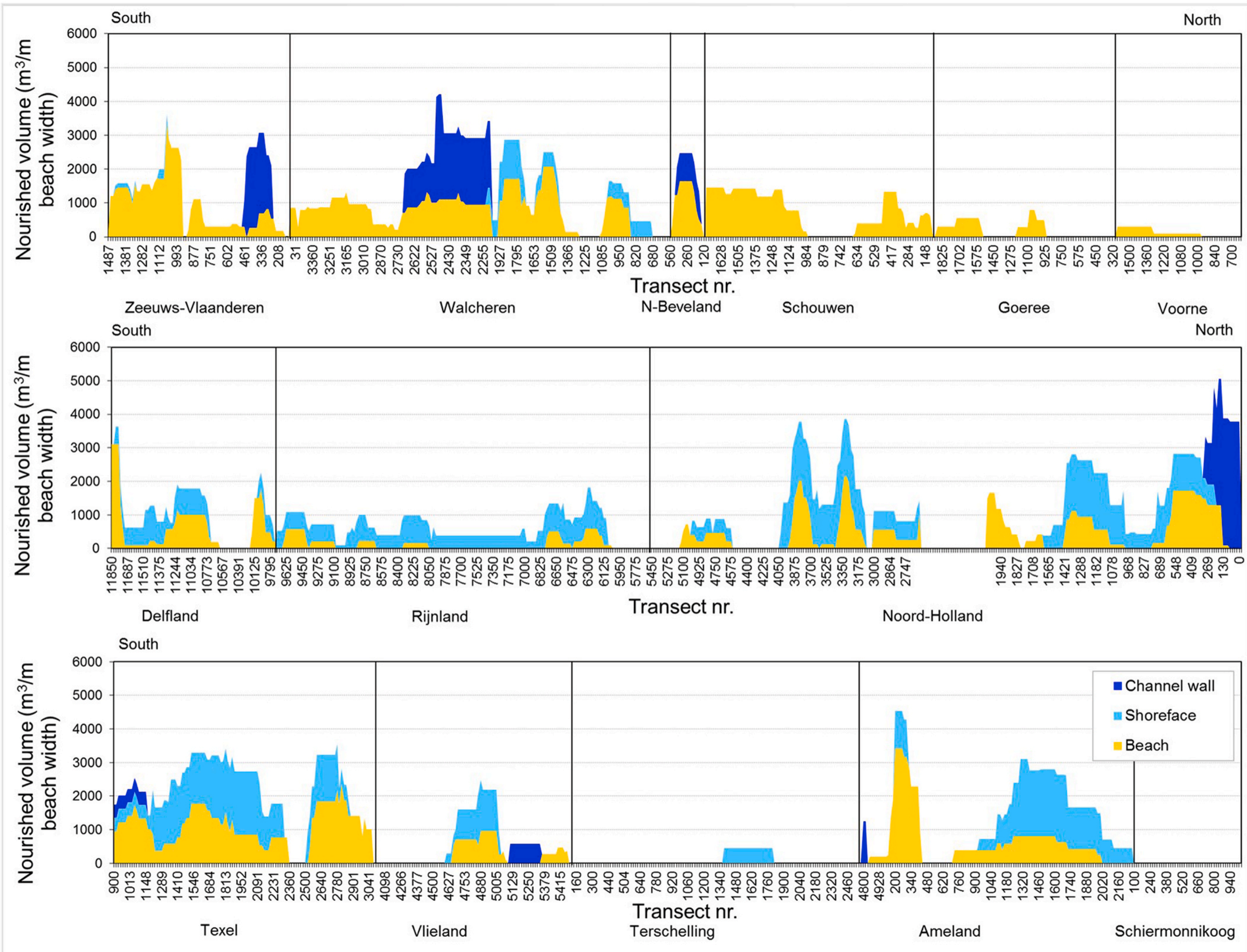


Fig. 10. Total nourished volume (total m^3/m in the alongshore direction since the 1990s) for regular coastline maintenance along the sandy shores of the Netherlands for the southwestern delta (top), central coast (middle), and barrier islands (bottom). Transect numbers correspond to Rijkswaterstaat (2020).

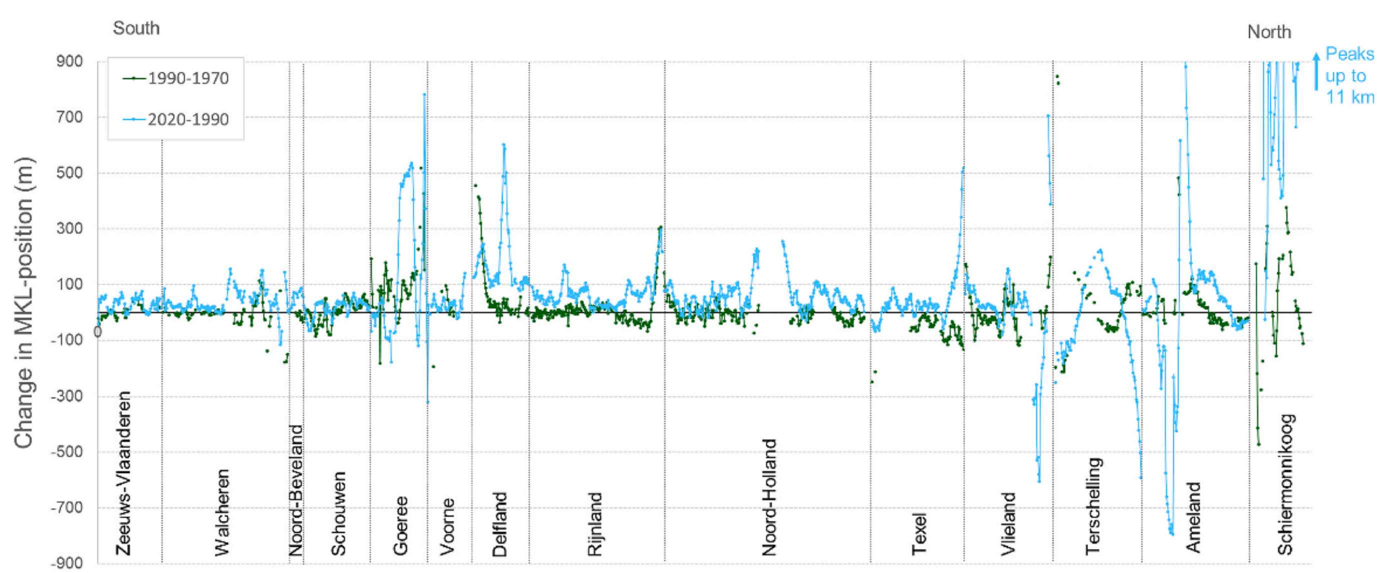


Fig. 11. Change in the position of the coastline (MKL) before large-scale nourishments (1990-1970) and after the start of the policy to dynamically preserve the coastline (2020-1990).

natural beach profile. Usually the profile is chosen around 1:30. The maximum slope of a beach nourishment is approximately 1:20 and a limited thickness to prevent scarp formation. Beach scarps are commonly observed along the Dutch coast at beaches with steep slopes and high platforms (Van Bemmelen et al., 2020). As a result of these design parameters and the accommodation capacity of most beaches in the Netherlands, the average volume of beach nourishments is 200 m^3/m. This has been constant since 1990 (Fig. 12). To minimize side effects a gradual decrease in volume towards both ends of the nourishment in the alongshore direction are incorporated in the design of beach nourishments. Beach nourishments have an average length of 2.3 km.

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

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

5.2. Shoreface nourishments

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

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

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

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

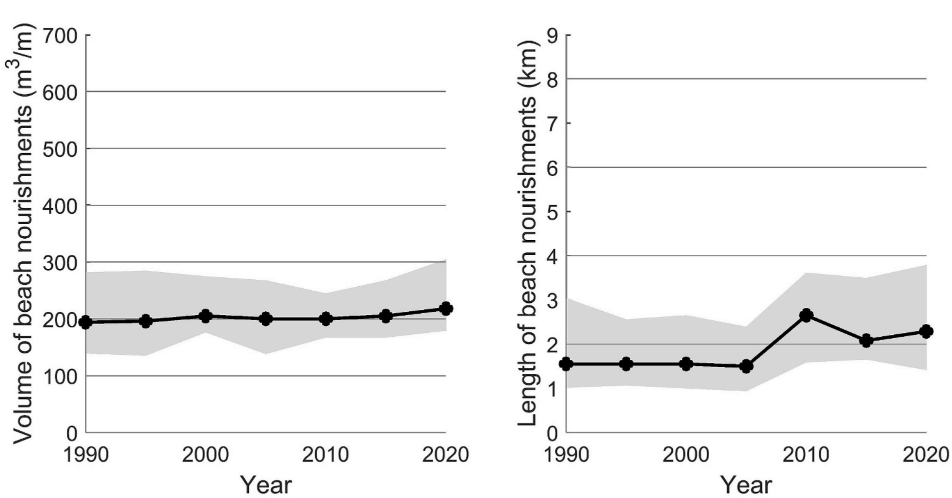


Fig. 12. Evolution of the dimensions (left: volume, right: length) of beach nourishments over time for regular nourishment, i.e. without mega nourishments (black line is the average, the grey area covers 50% of the nourishments).

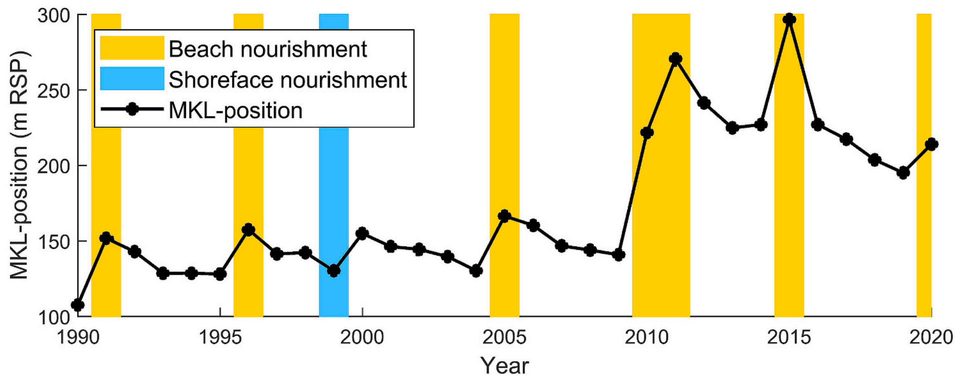


Fig. 13. Example of the effect of beach nourishments on the MKL-position (positive = seaward, negative = landward) for Scheveningen, transect 10025. The bar width represents the year of the nourishment. In 2010 and 2011 additional beach nourishments for flood defense purposes were performed.

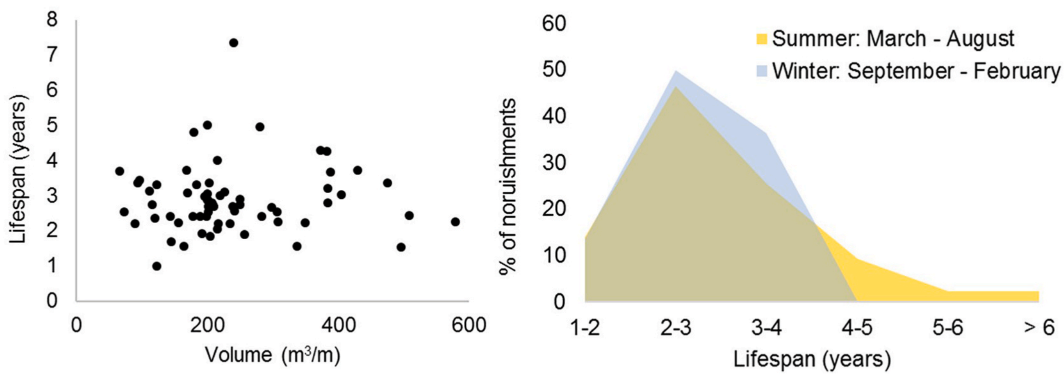


Fig. 14. Lifespan of beach nourishments at the central Dutch coast and the central barrier island coasts compared to their size (left) and period when construction was finished (right).

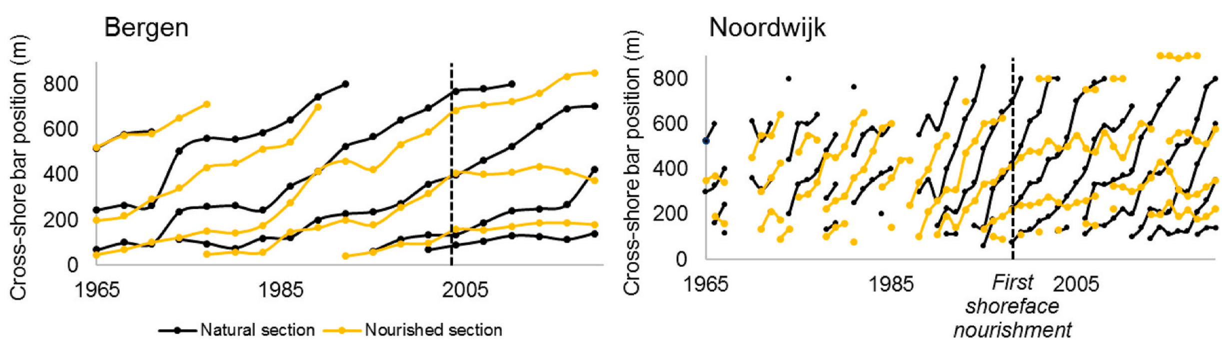


Fig. 15. The influence of shoreface nourishments on bar migration for two locations: Bergen (Noord-Holland, transects 4425 in black and 3850 in yellow) and Noordwijk (Rijnland transects 7150 in black and 8200 in yellow). The data represents the two-year averaged position of the top of a bar and the vertical dashed line marks the start of shoreface nourishments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Alkyon, 2005; Witteveen+Bos, 2006; Van der Spek et al., 2007; Bruins, 2016).

A shoreface nourishment only influences the bar migration when the nourishment is sufficiently large compared to the dimensions of the bars. For the central Dutch coast the volume of the bars is approximately 500 m^3/m in the north and 250 m^3/m in the south (Wijnberg, 1995; Alkyon, 2005; Witteveen+Bos, 2006). The average volume of shoreface nourishments is 450 m^3/m. The length of shoreface nourishments is 4 km, on average. These dimensions have been relatively constant since the mid-nineties (Fig. 16). The total volume of shoreface nourishments is 1.6 mln. m^3, on average. A larger nourishment volume generally results in a longer lifespan of the nourishment, both for the nourishment itself as for its effect on the MKL-zone (Vermaas et al., 2013). Shoreface nourishments are designed such that their volume gradually decreases towards both ends of the nourishment to minimize side effects.

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

Shoreface nourishments are observed to positively influence the sediment budget of the beach up to a least 2 km on each side for

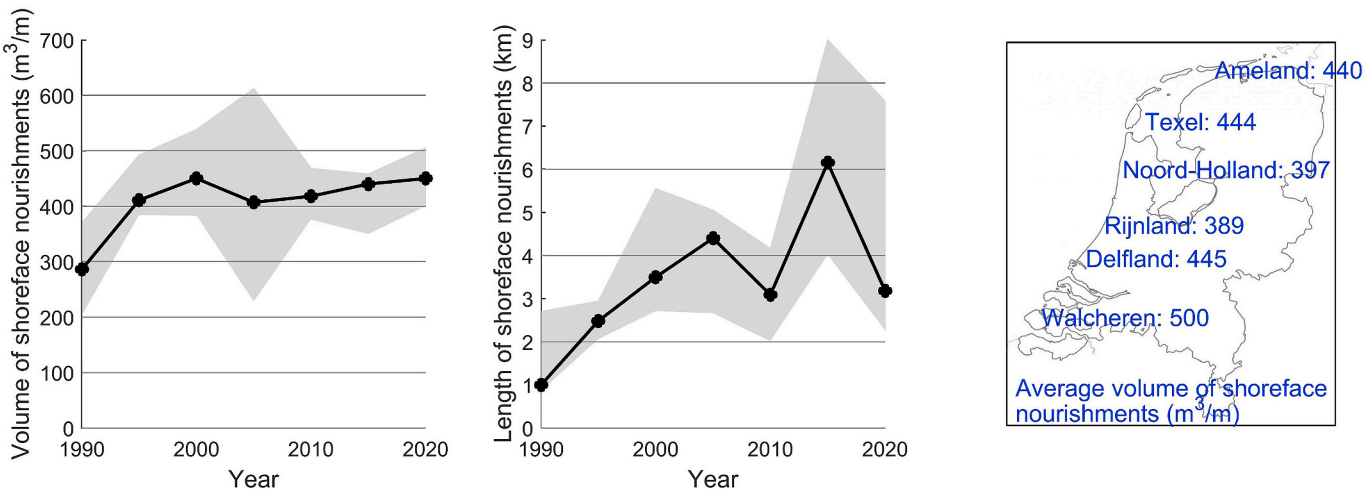


Fig. 16. Dimensions of shoreface nourishments. Left and middle: evolution of the volume and length over time for regular nourishment, i.e. without mega nourishments (black line is the average, the grey area covers 50% of the nourishments). Right: average volume of a shoreface nourishment along the coast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

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

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

5.3. Channel wall nourishments

Channel wall nourishments are performed in the southwestern delta and at the outer ends of the barrier islands where the nearshore is characterized by tidal channels. The goal of channel wall nourishments is often to stop or slow down the landward migration of these channels, to prevent erosion of the MKL-zone. Besides, they provide the possibility to supply large volumes of sediment and thus aid to reach the operational objective to nourish 12 mln. m^3/year. The average volume of the channel wall nourishments so far is 2.4 mln. m^3. Channel wall nourishments are relatively new. The first channel wall nourishment was placed in 2003 and since then thirteen of these nourishments have been placed (Table 1), many of which are still in place. As a result, the lifespan of channel wall nourishments is unknown yet, but as most of the first channel wall nourishments are still visible in the bathymetry, their lifespan is at least 10–15 years.

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

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

A channel wall nourishment only has an impact on the tidal flow

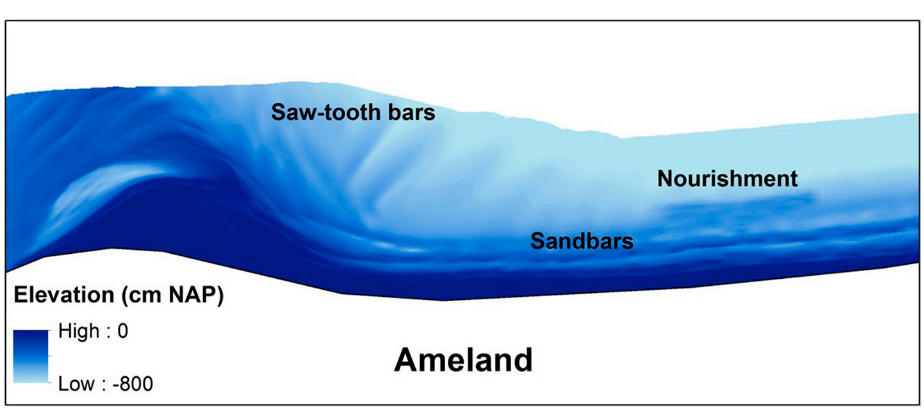
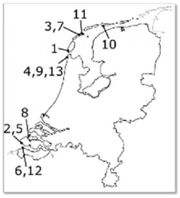


Fig. 17. Regular sandbars and saw-tooth bars at Ameland, one of the barrier islands.

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



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

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

In the best case channel wall nourishments positively influence the morphodynamics and thus reduce erosion of the MKL-zone. However, a nourishment may still have a positive effect on the MKL-zone even when it is too small to influence the flow pattern. The nourishment may serve as a buffer for erosion of the MKL-zone, or decrease the slope of the channel wall and thus reduce the risk of the flow undermining the channel wall. When the nourishment is too small it will not have an effect on the MKL-zone (Fig. 18). The effect of channel wall nourishments not only depends on the design, but also on the local morphodynamics. The wave climate, tidal flow through the channel, and

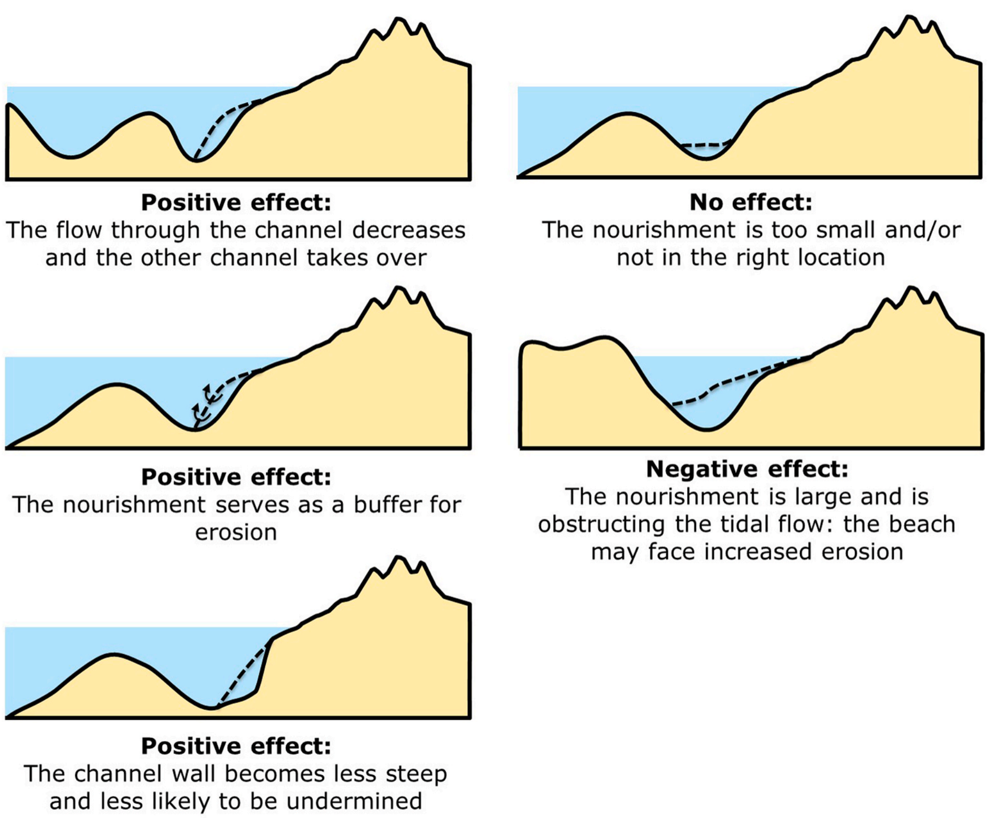


Fig. 18. Possible effects of channel wall nourishments on the MKL-zone.

geological layers may influence the development of a channel wall nourishment (van der Werf et al., 2010; Tonnon and van der Werf, 2014; Vermaas and Elias, 2014, van Onselen and Vermaas, 2020).

5.4. Innovative designs

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

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

6. Synthesis

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

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

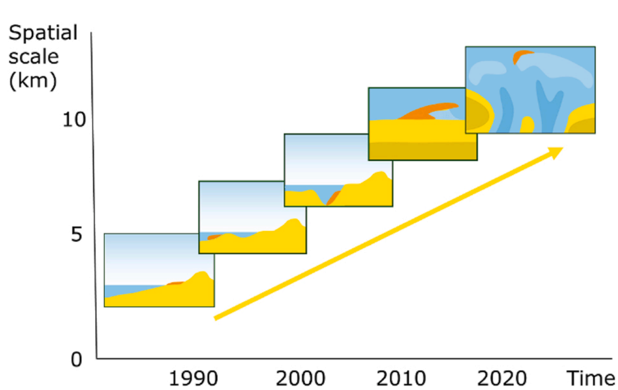


Fig. 19. The evolution of nourishments from beach, shoreface, channel wall, mega, to ebb-tidal delta nourishments.

2. **The effect of the most common types of nourishments, shoreface, beach, and channel wall nourishments, are very differently.** Beach nourishments have the shortest lifespan (~3 years), but the sand is placed directly where it is needed the most for the dynamic conservation of the coastline. Shoreface nourishments have a longer lifespan (4–10 years), but it takes a few years before they have an effect on the shoreline position. Channel wall nourishments have the longest lifespan (at least 10–15 years) but their effect on the coastline is highly variable and depends on the design of nourishment and the regional setting. All nourishments contribute directly to the operational objective to nourish 12 mln. m^3/year to feed the coastal zone with the sediment it needs to rise with sea level.
3. **The nourishment type strongly depends on the location.** Shoreface nourishments are common along the central Dutch coast and the central barrier island coasts, where the morphology of the shoreface, which is often characterized by breaker bars, allows for such nourishments. Deep tidal channels are typically present near the shore at the southwestern delta and the outer ends of the barrier islands, which renders the execution of shoreface nourishments impossible. At these locations, channel wall nourishments are more common, often in combination with beach nourishments. It is preferred to nourish underwater because shoreface nourishments are more cost-effective, but beach nourishments are still common along the entire Dutch coast, because they are sometimes needed for fast recovery, for flood safety purposes, or because it is not possible to nourish underwater. Not only the type of nourishment, but also the nourishment effort varies alongshore with hotspots that require a lot of maintenance and locations that have never been nourished.
4. **Design parameters of beach and shoreface nourishments are rather constant over time, but they are adjusted to the local setting for each nourishment.** In general, beach nourishments are placed at the dune foot, with a gentle slope similar to the natural slope of the beach, a volume of 200 m^3/m, and a length of 2.3 km, on average. Shoreface nourishments are usually placed against the outer bar or on the location where the outer bars fade out. This either results in the nourishment feeding the existing bar preventing it from fading away or slowing down the offshore movement of the inner bars. The volume of shoreface nourishments is typically 450 m^3/m and the average length is 4 km. Along the Dutch coast, it appears that shoreface nourishments are generally most effective when they are placed around NAP -5 m.
5. **Channel wall nourishments allow to add large volumes of sediment to the coastal zone, while also potentially slowing down the landward migration of tidal channels.** The first channel wall nourishment was placed in 2003 and since there have been thirteen of these nourishments at the southwestern delta and at the outer ends of the barrier islands where the nearshore is characterized by tidal channels. Channel wall nourishments can have a positive effect on the coastline when the flow through the channel decreases, when the channel wall becomes less steep, or when the nourished volume serves as a buffer for erosion. They may have a negative effect when they decrease the flow through the channel while no other channel can take over. When placed on the bottom of the channel they may not influence the coastline at all, except when they are significantly decreasing the tidal flow through a channel. The effect of channel wall nourishments not only depends on the design, but also on e.g. the local wave climate, the tidal flow through the channel, and geological layers.

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

Sand supplies are not endless and nourishment efforts likely have to increase in the future due to accelerated sea level rise and increased storminess. Therefore the feasibility of dynamically conserving the shoreline with sand nourishments in the future is uncertain. However, it is expected that sand nourishments will remain the preferred strategy and that they will remain successful in maintaining the Dutch coastline in the coming decades (Rijkswaterstaat, 2021b). The development of new types of nourishments, such as mega or ebb tidal delta nourishments, might benefit the feasibility of sand nourishments in the future. Besides, new nourishment techniques are being developed and these may increase the efficiency or decrease the environmental impact or costs of nourishments in the future.

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

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.

Acknowledgements

We would like to thank all our colleagues and predecessors at Rijkswaterstaat who have contributed to the data collection over the past 70 years and the continuous building of knowledge: without them, this overview would not have been possible. Specifically, we would like to thank Rena Hoogland and Stefan Pluis for reading the manuscript and for discussion and Marga Rommel as the project leader of the research program B&O kust of which this paper is a part. For data collection we are especially grateful to Wim Visser, Gert Jan Harpe, Tinus de Ruiter, and Emiel Olink.

Appendix. nourishments for regular coastline maintenance

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

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

Beach nourishments

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Delfland	1990	11775	11875	183000	Zeeuws-Vlaanderen	2001	1045	1130	123000
Walcheren	1990	1481	1583	245517	Vlieland	2001	5455	5485	20478
Walcheren	1990	1000	1030	20000	Rijnland	2001	6150	6450	603630
Walcheren	1990	2365	2494	105000	Rijnland	2001	6625	6750	248093
Zeeuws-Vlaanderen	1990	1350	1470	388000	Noord-Holland	2001	2832	3000	511127
Noord-Holland	1990	3225	3375	60000	Noord-Holland	2001	150	568	1290240
Noord-Holland	1990	3225	3375	385774	Walcheren	2001	2190	2380	393000
Noord-Holland	1990	3700	3850	323318	Walcheren	2002	2380	2550	462000
Texel	1990	2560	3061	2543022	Walcheren	2002	2940	3475	1130000
Rijnland	1990	6200	6325	261682	Noord-Holland	2002	1827	2035	500561
Zeeuws-Vlaanderen	1990	1330	1430	200000	Delfland	2003	11750	11850	213606
Zeeuws-Vlaanderen	1990	1040	1110	168000	Noord-Holland	2003	150	588	1305458
Delfland	1991	11775	11875	223000	Schouwen	2003	116	210	61912
Walcheren	1991	2180	2590	788000	Schouwen	2003	327	477	201847
Delfland	1991	9781	10139	1005699	Schouwen	2003	1598	1728	125220
Texel	1991	1813	2340	2008898	Schouwen	2003	994	1533	870237
Noord-Holland	1991	1100	1400	538404	Noord-Holland	2003	1110	1375	438155
Schouwen	1991	1184	1727	2672983	Noord-Holland	2003	1983	2058	230577
Noord-Holland	1991	1800	2018	371418	Noord-Holland	2003	2565	2641	357788
Delfland	1992	11775	11875	560000	Delfland	2003	10773	11319	1252797
Walcheren	1992	1280	1742	637000	Delfland	2004	11750	11850	231323
Walcheren	1992	3160	3463	169000	Noord-Beveland	2004	135	405	502353
Walcheren	1992	2593	2783	192000	Walcheren	2004	3315	3375	67117
Noord-Holland	1992	2620	3850	1472640	Walcheren	2004	880	1070	399164
Ameland	1992	1150	1960	1442000	Walcheren	2004	1465	1885	777565
Noord-Holland	1992	100	750	615527	Ameland	2004	200	320	403636

(*continued on next page*)

(*continued*)

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Zeeuws-Vlaanderen	1992	1354	1487	67000	Delfland	2004	10773	11319	1155951
Walcheren	1993	1430	1585	318000	Noord-Holland	2004	1983	2058	133783
Delfland	1993	11400	11875	463000	Noord-Holland	2004	1110	1374	263972
Walcheren	1993	2763	3168	619000	Noord-Holland	2004	2565	2641	219500
Texel	1993	1210	1813	2245231	Delfland	2004	9925	9965	100000
Noord-Holland	1993	328	568	280000	Delfland	2004	9970	10110	682500
Noord-Beveland	1993	220	365	411000	Vlieland	2005	5460	5485	20000
Walcheren	1993	485	550	225000	Goeree	2005	1550	1875	1000552
Zeeuws-Vlaanderen	1993	240	312	90000	Zeeuws-Vlaanderen	2005	31	77	123917
Delfland	1993	10623	11221	1143000	Zeeuws-Vlaanderen	2005	1041	1340	304810
Walcheren	1993	935	1040	287000	Zeeuws-Vlaanderen	2005	1360	1467	105906
Rijnland	1993	6050	6335	255076	Zeeuws-Vlaanderen	2005	251	360	141927
Rijnland	1994	9425	9625	700000	Noord-Holland	2005	3225	3375	300436
Delfland	1994	11775	11875	200000	Noord-Holland	2005	3700	3925	486023
Goeree	1994	1025	1200	505678	Noord-Holland	2005	4650	4850	519850
Schouwen	1994	159	190	40000	Voorne	2005	960	1620	691403
Schouwen	1994	259	293	49000	Zeeuws-Vlaanderen	2005	786	936	252416
Walcheren	1994	1433	1605	453000	Noord-Holland	2005	4450	4500	6000
Zeeuws-Vlaanderen	1994	806	918	348000	Texel	2005	880	1063	301384
Zeeuws-Vlaanderen	1994	1057	1346	560400	Walcheren	2006	2180	3470	1438693
Texel	1994	930	1210	761204	Ameland	2006	1100	1600	1001372
Texel	1994	2540	2820	1331225	Texel	2006	1440	1690	1012481
Rijnland	1994	6500	6730	334147	Delfland	2007	11725	11870	744124
Noord-Holland	1994	3290	3350	100683	Schouwen	2007	377	469	169643
Noord-Holland	1994	3785	3820	106343	Schouwen	2007	106	197	161689
Ameland	1994	4860	4960	190000	Schouwen	2007	1024	1742	994023
Zeeuws-Vlaanderen	1994	1363	1417	91000	Ameland	2007	200	320	303444
Texel	1995	3000	3060	300000	Noord-Holland	2007	150	590	1350448
Delfland	1995	11775	11875	200000	Walcheren	2008	1406	1633	369565
Schouwen	1995	367	643	818000	Walcheren	2008	880	1070	371217
Walcheren	1995	2550	2602	54000	Noord-Beveland	2008	140	400	461043
Walcheren	1995	1686	1889	550000	Walcheren	2008	1653	1735	110435
Walcheren	1995	2983	3306	463000	Walcheren	2008	1755	1970	1022609
Texel	1995	2820	2960	810000	Vlieland	2009	5460	5485	20000
Noord-Holland	1995	3263	3363	306000	Zeeuws-Vlaanderen	2009	30	71	126956
Noord-Holland	1995	3725	3875	306000	Zeeuws-Vlaanderen	2009	979	1046	1514783
Delfland	1995	11221	11450	300000	Zeeuws-Vlaanderen	2009	1068	1112	191304
Vlieland	1995	5370	5440	80000	Texel	2009	900	1070	400000
Vlieland	1995	5370	5440	111000	Zeeuws-Vlaanderen	2009	802	904	230435
Noord-Holland	1995	1880	2040	361740	Zeeuws-Vlaanderen	2009	1136	1335	526957
Noord-Holland	1995	1624	1760	306840	Zeeuws-Vlaanderen	2009	1353	1467	240000
Rijnland	1996	9100	9350	500000	Voorne	2010	1320	1600	561478
Delfland	1996	11775	11875	200000	Zeeuws-Vlaanderen	2010	171	421	429565
Delfland	1996	9700	10100	800000	Ameland	2010	1140	1600	925376
Schouwen	1996	1158	1732	733000	Ameland	2010	200	400	1888934
Noord-Beveland	1996	210	380	435000	Noord-Holland	2010	3150	3400	500000
Walcheren	1996	890	1050	464000	Noord-Holland	2011	3700	3900	400000
Noord-Holland	1996	1001	1410	459000	Walcheren	2011	2950	3460	653519
Ameland	1996	720	1120	1554514	Ameland	2011	1620	2000	909565
Texel	1996	1526	1873	1490561	Noord-Holland	2011	289	628	652020
Texel	1996	2211	2340	493317	Walcheren	2011	2195	2660	701693
Noord-Holland	1996	150	750	400000	Texel	2011	1410	1763	713256
Noord-Holland	1996	5043	5100	180050	Schouwen	2011	106	469	592299
Texel	1997	1878	2091	658846	Texel	2012	2780	3001	700477
Texel	1997	1038	1143	340038	Walcheren	2012	1489	1632	250399
Rijnland	1997	9400	9650	552800	Schouwen	2012	1044	1719	1824901
Delfland	1997	11775	11875	200000	Texel	2012	900	1210	751589
Delfland	1997	10750	11250	834000	Vlieland	2013	5460	5480	20000
Zeeuws-Vlaanderen	1997	1353	1460	95000	Vlieland	2013	4663	5005	1000000
Noord-Holland	1997	4965	5120	304450	Zeeuws-Vlaanderen	2013	1435	1470	12000
Walcheren	1997	3393	3470	125000	Noord-Beveland	2013	180	320	360000
Walcheren	1997	2185	2707	700000	Noord-Holland	2013	1940	2041	360000
Ameland	1997	120	300	510804	Rijnland	2013	8075	8325	410000
Noord-Holland	1997	3450	3575	158000	Zeeuws-Vlaanderen	2014	1372	1467	180000
Noord-Holland	1997	3625	3880	314000	Zeeuws-Vlaanderen	2014	985	1282	600000
Vlieland	1997	4672	4844	279621	Walcheren	2014	1469	1612	350000
Noord-Holland	1997	3105	3350	352000	Zeeuws-Vlaanderen	2014	461	877	650000
Noord-Holland	1997	2600	3005	547000	Delfland	2015	9925	10125	700000
Zeeuws-Vlaanderen	1997	290	352	185000	Walcheren	2015	1755	1948	600000
Goeree	1998	925	1075	745376	Ameland	2015	140	402	1300000
Walcheren	1998	2820	3395	563550	Noord-Holland	2015	3125	3400	605000
Zeeuws-Vlaanderen	1998	1037	1178	314045	Noord-Holland	2015	3700	3900	432500
Noord-Holland	1998	3750	3875	244442	Noord-Holland	2015	150	628	1000000
Rijnland	1998	6600	6750	253000	Ameland	2015	1240	1700	1000000
Rijnland	1998	6150	6350	193378	Goeree	2015	2240	2320	500000
Noord-Holland	1998	1925	2050	228901	Walcheren	2016	2950	3458	650000

(*continued on next page*)

(*continued*)

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Noord-Holland	1999	395	628	287480	Walcheren	2016	2195	2694	805000
Delfland	1999	11775	11850	200680	Goeree	2016	1525	1725	500000
Schouwen	1999	1620	1720	105000	Schouwen	2016	319	469	246750
Schouwen	1999	95	642	560000	Noord-Holland	2017	1213	1421	400000
Noord-Holland	1999	3250	3375	205793	Texel	2017	900	1190	895000
Noord-Holland	1999	3725	3875	214515	Noord-Holland	2017	4575	5075	1000000
Noord-Holland	1999	1320	1400	144000	Schouwen	2017	1044	1228	370000
Texel	1999	2600	2860	1219174	Schouwen	2017	1375	1719	800000
Noord-Holland	2000	1626	1688	120000	Noord-Holland	2017	1213	1401	1000000
Delfland	2000	11750	11850	200000	Vlieland	2018	5410	5420	20000
Noord-Beveland	2000	200	360	524470	Vlieland	2018	5440	5480	20000
Walcheren	2000	1406	1883	886127	Vlieland	2018	4663	5059	1000000
Walcheren	2000	880	1086	322529	Vlieland	2018	5059	5077	20000
Ameland	2000	100	260	401002	Texel	2018	1490	2131	1000000
Texel	2000	1703	1833	245223	Noord-Beveland	2018	160	320	250000
Texel	2000	1001	1190	357020	Ameland	2019	120	420	2542000
Texel	2000	1298	1644	701731	Walcheren	2019	1448	1632	500000
Noord-Holland	2000	3275	3325	225000	Rijnland	2019	8650	8825	400000
Noord-Holland	2000	3800	3900	207445	Walcheren	2019	1735	1948	600000
Texel	2000	2550	2780	883683	Zeeuws-Vlaanderen	2019	1354	1467	150000
Walcheren	2001	2540	2710	354000	Zeeuws-Vlaanderen	2019	985	1335	600000
Vlieland	2001	4890	5010	499579	Schouwen	2019	319	469	418660
Delfland	2001	10800	11200	801178	Schouwen	2019	106	148	81500
Zeeuws-Vlaanderen	2001	800	920	132000	Delfland	2019	9925	10140	400000
Zeeuws-Vlaanderen	2001	17	87	197000	Zeeuws-Vlaanderen	2019	461	877	600000
Zeeuws-Vlaanderen	2001	260	420	168000	Noord-Holland	2019	1213	1421	400000
Zeeuws-Vlaanderen	2001	1200	1340	258000	Walcheren	2020	3165	3239	210000
Zeeuws-Vlaanderen	2001	507	570	52000					

Shoreface nourishments

Location	Year	Start transect	End transect	Volume (m^3)	Location	Year	Start transect	End transect	Volume (m^3)
Zeeuws-Vlaanderen	1990	1330	1430	119000	Texel	2007	900	1392	2000970
Zeeuws-Vlaanderen	1990	1040	1110	200000	Delfland	2007	11300	11800	753277
Terschelling	1993	1370	1810	2000000	Noord-Holland	2007	200	710	3239103
Delfland	1997	11315	11485	882605	Rijnland	2008	6100	6300	1002957
Rijnland	1998	8050	8350	1266028	Rijnland	2008	6775	7025	509913
Ameland	1998	1300	2100	2030510	Walcheren	2008	1755	1970	1392722
Rijnland	1998	8750	8950	753338	Vlieland	2009	4700	5000	1780870
Delfland	1999	9773	10050	1425780	Noord-Holland	2009	700	1000	1301565
Noord-Holland	1999	3690	3910	880100	Texel	2009	2600	2880	1304348
Noord-Holland	2000	3225	3425	994000	Ameland	2010	1100	1460	1941304
Delfland	2001	10740	11250	2970879	Ameland	2010	1480	1680	1123913
Vlieland	2001	4600	4880	831892	Noord-Holland	2010	3400	3900	1713913
Noord-Holland	2001	1108	1401	1499940	Ameland	2010	1700	2000	1634783
Rijnland	2002	9100	9700	2508887	Noord-Holland	2010	3100	3400	1124348
Texel	2002	1700	2300	4593493	Noord-Holland	2011	4575	4750	719656
Rijnland	2002	7300	8000	2645601	Noord-Holland	2011	4800	5000	880344
Noord-Holland	2002	2650	3000	1972272	Noord-Holland	2011	3900	4000	360870
Noord-Holland	2003	1000	1600	2315360	Texel	2012	1332	1778	1800000
Ameland	2003	940	1370	1432000	Texel	2012	1793	2111	1350000
Noord-Holland	2003	913	943	12243	Texel	2012	1200	1312	500000
Texel	2004	2520	2780	2401361	Noord-Holland	2013	1000	1421	2000000
Noord-Holland	2004	3620	4020	1800699	Delfland	2013	11400	11800	1500000
Rijnland	2004	6575	6775	1001095	Rijnland	2014	8000	8850	2200000
Rijnland	2004	6275	6575	1202332	Ameland	2015	1240	1700	2000000
Vlieland	2005	4860	5020	1008032	Noord-Holland	2015	3100	4000	2500000
Texel	2005	1352	1690	2263950	Texel	2015	1210	2111	4004000
Noord-Holland	2005	3150	3620	1306114	Rijnland	2016	6100	6850	2400000
Delfland	2005	10860	11300	882056	Walcheren	2017	1448	1632	800000
Noord-Holland	2006	1000	1520	1651965	Walcheren	2017	1735	2215	2400000
Rijnland	2006	8150	8900	1055035	Walcheren	2017	700	1025	1500000
Ameland	2006	1200	1700	1501510	Ameland	2018	1300	2300	4460000
Texel	2006	1700	2300	1500335	Noord-Holland	2019	3100	4000	2500000
Rijnland	2006	8900	9700	800400	Noord-Holland	2019	328	708	1800000
Ameland	2007	195	302	1201234					

Channel wall nourishments

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

References

Alkyon, 2005. Effectiviteit van vooroeversuppleties langs de Waddenkust. Aanzet tot ontwerprichtlijnen voor het ontwerp van vooroeversuppleties. Alkyon rapport A1539R1r2.

Armstrong, S.B., Lazarus, E.D., Limber, P.W., Goldstein, E.B., Thorpe, C., Ballinger, R.C., 2016. Indications of a positive feedback between coastal development and beach nourishment. Earth's Future 4, 626–635.

Beets, D.J., van der Spek, A.J.F., 2000. The Holocene evolution of the barrier and the back-barrier basin of Belgium and The Netherlands as a function of Late Weichselian morphology, relative sea-level rise and sediment supply. Neth. J. Geosci. 79, 3–16.

Bitan, M., Zviely, D., 2020. Sand beach nourishment: experience from the mediterranean coast of Israel. J. Mar. Sci. Eng. 8, 1–18.

Brakenhoff, L., Ruessink, G., van der Vegt, M., 2019. Characteristics of saw-tooth bars on the ebb-tidal deltas of the Wadden Islands. Ocean Dynam. 69, 1273–1285.

Bruins, R.J., 2016. Morphological Behavior of Shoreface Nourishments along the Dutch Coast. MSc thesis, TUDelft.

Chang, J.I., Yoon, S., 2016. The economic benefit of coastal erosion control in Korea. J. Coast Res. 1, 1317–1321.

Dean, R.G., 1991. Equilibrium beach profiles: characteristics and applications. J. Coast Res. 7, 53–84.

De Schipper, M.A., de Vries, S., Ruessink, G., de Zeeuw, R.C., Rutten, J., van Gelder-Maas, C., Stive, M.J.F., 2016. Initial spreading of a mega feeder nourishment: observaions of the Sand Engine pilot project. Coast. Eng. 111, 23–38.

De Schipper, M., Ludka, B.C., Raubenheimer, B., Luijendijk, A.P., Schlacher, T.A., 2020. Beach nourishment has complex implications for the future of sandy shores. Nat. Rev. Earth & Environ. 1–15.

Ducrotoy, J.-P., Elliott, M., de Jonge, V.N., 2000. the North sea. Mar. Pollut. Bull. 41, 5–23.

Elias, E., Vonhögen-Peeters, L., Bruens, A., 2013. Ontwikkeling suppletie tussen Den Helder en Julianadorp 2007. Deltares rapport 1206171-000.

Elias, 2016. Verkenning Morfologische Effecten (Geulwand)suppletie Paal 10, Texel. Deltares Rapport 1230043-001.

Elias, E.P.L., Van der Spek, A.J.F., Pearson, S.G., Cleveringa, J., 2019. Understanding sediment bypassing processes through analysis of high-frequency observations of Ameland Inlet, The Netherlands. Mar. Geol. 415, 1–19.

Elias, E., Pearson, S., van der Spek, A., 2020. Understanding the Morphological Processes at Ameland Inlet – Kustgenese 2.0 Synthesis of the Tidal Inlet Research. Deltares Rapport 1220339-008.

Ettinger, H.D., de Zeeuw, R.C., 2010. Monitoring Strandsuppletie Scheveningen. Rapport TUDelft.

Führböter, A., 1991. Eine theoretische Betrachtung über Sandvorspülungen mit Wiederholungsintervallen. Kuste 52, 241–254.

Grunnet, N.M., Ruessink, B.G., 2005. Morphodynamic response of nearshore bars to a shoreface nourishment. Coast. Eng. 52, 119–137.

Hallie, F.P., 2018. Basiskustlijn 2017 – Herziening van de ligging van de basiskustlijn. Ministerie van Infrastructuur en waterstaat, Den Haag, 2018.

Hanson, H., Brampton, A., Capobianco, M., Dette, H.H., Hamm, L., Laustrup, C., Lechuga, A., Spanhoff, R., 2002. Beach nourishment projects, practices, and objectives – a European overview. Coast. Eng. 47, 81–111.

Haverkate, S.M., 2020. Nearshore Dynamics of a Nourished Coast with Respect to a Neighbouring Natural Coast. Utrecht University, p. 113.

Hillen, R., de Ruig, J.H.M., Roelse, P., Hallie, F.P., 1991. De Basiskustlijn, Een Technisch/morfologische Uitwerking. Nota GWWS 91.006; RWS Dienst Getijdewateren. Den Haag.

Hoogwaterbeschermingsprogramma, 2019. Een Sterke Alliantie Voor Sterke Dijken. Programmanplan Hoogwaterbeschermingsprogramma 2019-2023. Hoogwaterbeschermingsprogramma, p. 56.

Huisman, B.J.A., Walstra, D.-J.R., Radermacher, M., de Schipper, M.A., Ruessink, B.G., 2019. Observations and modelling of shoreface nourishment behaviour. Mar. Sci. Eng. 7, 1–26.

Jackson, A., Hill, P., McGrath, J., 2013. A History of the Implementation and Evolution of Sand Nourishment Methods on the Gold Coast, Australia. Coasts Ports, pp. 418–423.

Kohsiek, L.H.M., 1984. De korrelgrootte karakteristiek van de zeereep (stuifdijk) langs de Nederlandse kust. Rijkswaterstaat directie waterhuishouding en waterbeweging district kust en zee.

Kroon, A., Hoekstra, P., Houwman, K.T., Ruessink, B.G., 1994. Morphological monitoring of a shoreface nourishment-NOURTEC experiment at Terschelling, Netherlands. In: Edge, B.L. (Ed.), Proc. 24th Int. Conf. On Coastal Engineering. ASCE, New York, pp. 2222–2236.

Leonard, L., Clayton, T., Pilkey, O.H., 1990. An analysis of replenished beach design parameters on U.S. east coast barrier islands. J. Coast Res. 6, 1041–1045.

Lodder, Q.J., Slinger, J.H., 2022. The 'Research for Policy' Cycle in Dutch Coastal Flood Risk Management: the Coastal Genesis 2 Research Programme (this issue).

Luijendijk, A.P., Ranasinghe, R., de Schipper, M.A., Huisman, B.A., Swinkels, C.M., Walstra, D.J.R., Stive, M.J.F., 2017. The initial morphological response of the Sand Engine: a process-based modelling study. Coast. Eng. 119, 1–14.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S., 2018. The state of the world's beaches. Sci. Rep. 8, 1–11.

Ludka, B.C., Guza, R.T., O'Reilly, W.C., 2018. Nourishment evolution and impacts at four southern California beaches: a sand volume analysis. Coast. Eng. 136, 96–105.

Ministerie van Infrastructuur en Milieu, 2015. Ons Water in Nederland, Nieuw Nationaal Waterplan 2016-2021. Ministerie van Infrastructuur en Milieu, p. 24.

Ministerie van Verkeer en Waterstaat, 1988. Handboek Zandsuppleties. Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, p. 310.

Ministerie van Verkeer en Waterstaat, 1990. Kustverdediging na 1990: beleidskeuze voor de Kustlijnzorg. Tweede Kamer 5–6, 1989-1990, 21 136.

Ministerie van Verkeer en Waterstaat, 1991. Regionaal Ontgrondingenplan Noordzee. Deel A Beleidsnota, p. 82.

Ministerie van Verkeer en Waterstaat, 1996. Kustbalans 1995. De Tweede Kustnota. Ministerie van Verkeer en Waterstaat, p. 59.

Ministerie van Verkeer en Waterstaat, 2000. 3[e] Kustnota, Traditie, Trends en Toekomst. Ministerie van Verkeer en Waterstaat, p. 124.

Mulder, J.P.M., 2000. Zandverliezen in Het Nederlandse Kustsysteem. RIKZ rapport, 2000.36.

Mulder, J.P.M., Hommes, S., Horstman, E.M., 2011. Implementation of coastal erosion management in The Netherlands. Ocean Coast Manag. 54, 888–897.

Nordstrom, K.F., 2008. Beach and Dune Restoration. Rutgers University: New Brunswick, NJ, USA. Cambridge University Press, Cambridge, UK.

NOURTEC, 1994. Design Report of the Three NOURTEC Sites. NOURTEC Report No. 1. RWS-RIKZ, The Hague, p. 62.

Pinto, C.A., Silveira, T.M., Teixeira, S.B., 2020. Beach nourishment practice in mainland Portugal (1950-2017): overview and retrospective. Ocean Coast Manag. 192, 1–13.

Pranzini, E., Wetzel, L., Williams, A.T., 2015. Aspects of coastal erosion and protection in Europe. J. Coast Conserv. 19, 445–459.

Rijkswaterstaat, 1987. Evaluaties Strandsuppleties. Rijkswaterstaat Dienst Getijdewateren, Nota DGW-GWWS 87.006. RIKZ Den Haag.

Rijkswaterstaat, 2020. Kustlijnkaarten 2021. Ministerie van Infrastructuur en Waterstaat, Rijkswaterstaat, p. 131.

Rijkswaterstaat, 2021a. Suppletieprogramma Kustlijnzorg – Uitgangspunten Totstandkoming Programma. Rijkswaterstaat, 2021.

Rijkswaterstaat, 2021b. Kustgenese 2.0: Kennis Voor Een Veilige Kust. Rijkswaterstaat, 2021, p. 108.

Roelse, P., 1996. Evaluatie van zandsuppleties aan de Nederlandse kust 1975-1994, een morfologische beschouwing. RIKZ Rapport 96, 28.

Schrijvershof, R., 2017. Evaluatie Geulwandsuppletie Onrust. Deltares memo, p. 44.

Steijn, R., 2004. Ontwikkeling Geulwandsuppletie ZW-Texel (Molengat). Alkyon Rapport Nr, p. A135R1r2.

Stive, M.J.F., Roelvink, D.A., De Vriend, H.J., 1990. Large-scale coastal evolution concept. In: Proceedings of the Twenty-Second Coastal Engineering Conference, July 2-6, 1990, Delft, The Netherlands, pp. 1962–1974.

Stive, M.J.F., de Schipper, M.A., Luijendijk, A.P., Aarninkhof, S.G.J., van Gelder-Maas, C., van Thiel de Vries, J.S.M., de Vries, S., Henriquez, M., Marx, S., Ranasinghe, R., 2013. A new alternative to saving our beaches from sea-level rise: the sand engine. J. Coast Res. 29, 1001–1008.

Stolk, A., 1989. Zandsysteem kust: een morfologische karakterisering. Technisch rapport kustverdediging na 1990 (1), 97.

Spanhoff, R., van de Graaff, J., 2007. Towards a better understanding and design of shoreface nourishments. In: Coastal Engineering 2006 – 30[th] International Conference, San Diego, 2-8 September 2006, pp. 1–13.

Tonnon, P.K., van der Werf, J.J., 2014. Geulopdringing Zuidwest Walcheren. Deltares Rapport Nr. 1208921-000.

USAID, 2009. Adaptation to Coastal Climate Change - A Guidebook for Development Planners. U.S. Agency for International Development (USAID), Washington DC, USA, p. 147.

Valverde, H.R., Trembanis, A.C., Pilkey, O.H., 1999. Summary of beach nourishment episodes on the U.S. East Coast barrier islands. J. Coast Res. 15, 1100–1118.

Van Bemmelen, C.W.T., de Schipper, M.A., Darnall, J., Aarninkhof, S.G.J., 2020. Beach scarp dynamics at nourished beaches. Coast. Eng. 160, 1–10.

Van der Grinten, R.M., Ruessink, B.G., 2012. Evaluatie van de kustversterking bij Noordwijk aan Zee – De invloed van de versterking op de zandbanken. Universiteit Utrecht, p. 53.

Van der Ham, W., 2018. Modern wereldwonder – Geschiedenis van de Deltawerken. Boom uitgevers Amsterdam, Amsterdam, p. 400, 2018.
Van der Meulen, M.J., van der Spek, A.J.F., de Lange, G., Gruijters, S.H.L.L., van Gessel, S.F., Nguyen, B.L., Maljers, D., Schokker, J., Mulder, J.P.M., van der Krogt, R.A.A., 2007. Regional sediment deficits in the Dutch lowlands: implications for long-term land-use options. J. Soils Sediments 7, 9–16.
Van der Spek, A.J.F., de Kruif, A.C., Spanhoff, R., 2007. Richtlijnen Onderwatersuppleties. RIKZ Rapport 2007.012.
Van der Spek, A., Elias, E., 2013. The effects of nourishments on autonomous coastal behaviour. Coastal Dynamics. Proc. 7th Int. Conf. Coast. Dyn. 1753–1763.
van der Spek, A.J.F., Lodder, Q.J., 2015. A new sediment budget for The Netherlands; the effects of 15 years of nourishing (1991-2005). In: Proceedings of Coastal Sediments 2015; Word Scientific Publishing: Singapore, 2015.
van der Werf, J.J., Doornenbal, P.J., McCall, R., 2010. Verkenning van strategieën voor het kustonderhoud bij de Onrustpolder, Zeeland. Deltares rapport nr. 1202349-000.
van Koningsveld, M., Mulder, J.P.M., 2004. Sustainable coastal policy developments in The Netherlands. A systematic approach revealed. J. Coast Res. 20, 375–385.
van Onselen, E., Vermaas, T., 2020. Analyse Geulwandsuppletie Ameland Zuidwest. Deltares Rapport Nr. 11205236-002.
Vermaas, T., Elias, E., Vonhögen-Peeters, L., 2013. Ontwikkeling Gefaseerde Suppletie Ameland 2010-2011. Deltares Rapport Nr. 1207724-002.
Vermaas, T., Elias, E., 2014. Evaluatie Verlegging Krabbengat 1987/1991/1996. Deltares Rapport Nr. 1209381-008.
Vermaas, T., de Bruijn, R., Vonhögen-Peeters, L., 2017. Ontwikkeling Suppletie Heemskerk 2011-2016. Deltares Rapport Nr. 1230043-001.
Vermaas, T., Mastbergen, D., Schrijvershof, R., Mesdag, C., Gaida, T., 2018. Geologie, bestorting en strandvallen bij Ameland zuidwest. Deltares rapport nr. 11200538-004.
van Rijn, L.C., 1995. Sand Budget and Coastline Changes of the Central Dutch Coast between Den Helder and Hoek Van Holland. Delft Hydraulics, Report H2129.
Vermaas, T., Boersen, S., Wilmink, R., Lodder, Q., 2019. National Analysis of Nourishments; Coastal State Indicators and Driving Forces for Bergen-Egmond, the Netherlands. Rijkswaterstaat and Deltares, 2019.
Wijnberg, K.M., 1995. Morphologic Behaviour of a Barred Coast over a Period of Decades. Proefschrift Universiteit Utrecht.
Wijnberg, K.M., 2002. Environmental controls on decadal morphologic behaviour of the Holland coast. Mar. Geol. 189, 227–247. https://doi.org/10.1016/S0025-3227(02)00480-2.
Witteveen+Bos, 2006. Evaluatie onderwatersuppleties Noord- en Zuid-Holland. Eindrapport. Witteveen+Bos rapport Rw1472-2.