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Sustainable coastline management - the cumulative effects of 30 years of nourishments in the Netherlands

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ABSTRACT

Coastal erosion threatens flood safety and other uses of beaches and dunes globally. In the Netherlands a coastline maintenance policy was implemented in the 1990's to address the negative effects of erosion, with sand nourishments as the primary means. In this study, the cumulative effects of these nourishments are evaluated against the strategic goal of sustainable preservation of the uses and values of the coast. This research aims to inform national and international policy makers, practitioners, and scientist about the possible long-term effects of coastal management with structural sand nourishments. Coastal indicators were analysed to quantify the morphological evolution of the coast before and since coastline maintenance. It is observed that regular nourishments serve to halt structural coastline retreat. The coastline built out, on average, which was necessary to achieve maintenance of the most erosive areas. Additionally, strong dune growth is observed since the start of coastline maintenance, thanks to wind-driven transport of nourished sand and more dynamic dune management. Nourishments thus contribute positively to flood safety, although flood safety is not an automatic benefit of coastline maintenance. Space for recreation and nature is maintained or improved: the dry beach width was unaffected, and dune areas have grown. Further, it is reported that the impact of nourishments on the coastal ecosystem is local and temporary, leading to the inference that uses and values of the coast are being maintained sustainably through regular nourishments. Overall, the approach of coastline maintenance with regular pro-active nourishments has thus proven to be successful.

1. Introduction

For centuries, large parts of the Dutch coast have suffered structural erosion with several towns lost to the sea (Dillingh and Stolk, 1989, Ministerie van Verkeer en Waterstaat, 1990a; Groenendijk, 1997; Mulder, 2000). In the hope of combatting the negative effects of such erosion, a national research program termed Coastal Genesis ("Kustgenese" in Dutch) was conducted in the 1980's. This program delivered the key insight that the sediment budget of the entire Dutch coastal system was not in balance (Stive et al., 1987). Subsequently, a heavy storm in 1989 was instrumental in triggering national level policy making, aimed at counteracting coastal erosion by adding sand to the system. The aim was to halt the structural retreat of the coastline and so sustain flood safety levels and the uses (functions) and values of the dunes, such as their ecological value, space for recreation, and fresh water supply (Fig. 1, Ministerie van Verkeer en Waterstaat, 1990b). A dynamic coastline maintenance policy was thus implemented in 1990 and since then the coastline is maintained with regular sand nourishments (Brand et al., 2022).

Globally, coastal erosion is a threat faced by many countries (Luijendijk et al., 2018). Different strategies are adopted in dealing with coastal erosion (Hallin et al., 2021), varying from acceptance (Luijendijk et al., 2018) to the construction of protective infrastructures, such as storm surge barriers and dikes, although the downsides of these infrastructures are increasingly acknowledged (Pranzini, 2018; Rangel-Buitrago et al., 2018; Abeykoon et al., 2021; Hofstede, 2024). Instead of persisting with the construction of hard coastal defence infrastructures, the Netherlands and several other countries have opted for 'soft'

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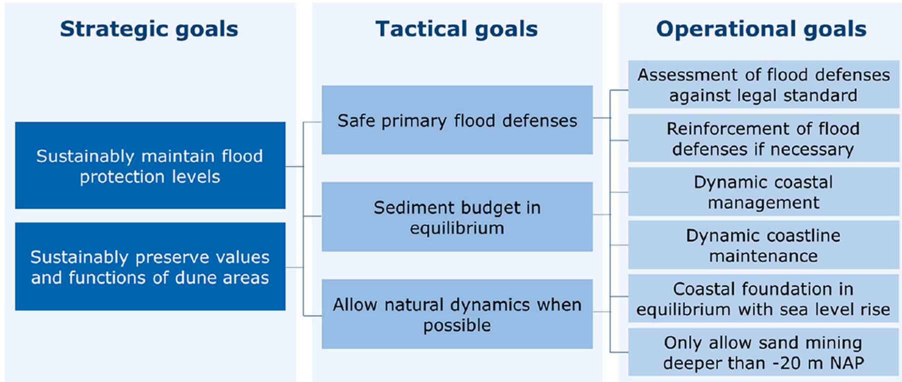

Fig. 1. The current Dutch coastal policy objectives (Rijkswaterstaat, 2020; Lodder and Slinger, 2022).

strategies, meaning that sandy or other nature-based solutions are implemented in preference to 'hard' or concrete infrastructures, where possible (Hanson et al., 2002; Kaufmann et al., 2022; Rauwoens et al., 2023). The Dutch coast is naturally sediment-rich, so a sediment-based approach was chosen to work along with the natural processes.

Soft strategies can be reactive, but the Dutch approach may be characterized as proactive: the coastline is nourished with sand to counteract the anticipated and chronic loss of land with its associated negative consequences. Sand is added to the coastal zone to maintain the position of the coastline, while allowing for natural dynamics as far as coastal uses allow. Since the 2000's, an additional aim of the Dutch coastal policy is to keep the sediment budget of the coastal foundation (i.e. the zone from 20 m below mean sea level up to the inner dune row) in equilibrium with sea level rise to ensure sustainable management and use of the coastal zone (Rijksoverheid, 2022). This is done firstly by regular adjustments of the nourishment volumes to accommodate current sea level rise rates (e.g. Rijkswaterstaat, 2020; Tweede Kamer der Staten-Generaal, 2021). Secondly, the coastline that is maintained is adjusted periodically to align with the current sea level (Ministerie van Infrastructuur en Waterstaat, 2023).

Previously, sand nourishments were viewed as an effective solution to coastline retreat in the Netherlands (e.g. Roelse, 2002; Santinelli et al., 2012; Stronkhorst et al., 2018). Indeed, they provide a cost-efficient way to maintain the coastline (RebelGroup en Witteveen+Bos, 2007; Coelho et al., 2022) and a variety of uses benefit from this maintenance (Stronkhorst et al., 2012, Geukes et al., 2024). Nourishments have also proven effective in other countries, mainly in western Europe, Australia and the USA (e.g. Bitan and Zviely, 2020; Kok et al., 2020; Pinto et al., 2020; Staudt et al., 2021), where it is also observed that physical conditions should allow for coastal maintenance with nourishments (Teixeira et al., 2022). Although nourishments are generally viewed as an effective way to compensate coastal erosion, there are still knowledge gaps regarding their cumulative, long-term effect at a regional scale (Staudt et al., 2021). It is necessary to understand this aspect of nourishments, especially as increasing volumes of sand may have to be added to cope with accelerated sea level rise in the future (Haasnoot et al., 2021; IPCC, 2023; Taal et al., 2023).

There are multiple studies investigating nourishments and other mitigation strategies implemented along the Dutch coast over the last three decades (Vermaas et al., 2018; Huisman et al., 2019). However, no paper has yet specifically evaluated the cumulative effect of all efforts, along the entire coast, for this entire period. Previous publications have evaluated only certain locations, specific nourishments, smaller windows of time, or leveraged modelling to forecast future changes under rising seas (Vermaas et al., 2019; Ribas et al., 2023). In Brand et al. (2022) we elaborated on the Dutch experience with sand nourishments, but we focused on the nourishment approach and less on the impact of nourishments. This paper is unique in evaluating the entirety of all efforts over the last 30 years and specifically relating results to the strategic goals of the Netherlands' coastal policy.

Here, we evaluate the effects of repeated nourishments along the Dutch coast in relation to the strategic goals of the Dutch coastal policy (Fig. 1). We persist in the focus on morphological effects that accompanies the focus of Dutch coastal policy and practice, which carries with it the assumption that sufficient sand availability provides the necessary space for flood safety, ecosystem health, and the continued recreational use of the beach and dunes (Mulder, 2000; Lodder and Slinger, 2022). We focus on the morphological effects, giving less attention to the underlying processes. Notify that sediment transport processes are previously studied (Grasmeijer et al., 2022; Huisman, 2024). We acknowledge that nourishments may have other long-term effects as well; they may harm the ecosystem, both at the nourished locations and in the mining areas, and they involve high emissions, for example (Staudt et al., 2021; Saengsupavanich et al., 2023), and that the assumption that sufficient sandy coastal area will continue to support all desired uses requires investigation. However, we limit the scope of this study to the evaluation of the cumulative morphological effects of nourishments in achieving the tactical goals and the strategic goals of long-term flood safety and preservation of uses and values of the coast, focusing on coastal morphology.

The approach adopted in this study in determining the cumulative effects of the Dutch nourishment strategy is described next. After presentation of the findings, these are then discussed in terms of three themes, namely: (1) the cumulative effect of nourishments on the coastline and dunes; (2) coastline maintenance under a rising sea level; and (3) the effect of coastline maintenance on coastal uses. Conclusions are drawn in relation to the strategic, tactical, and operational goals (Fig. 1). In the synthesis we highlight the implications of this study for coastal management in the Netherlands and elsewhere.

2. Approach

In this study, the beach and nearshore morphology is analysed to understand the cumulative effects of nourishments along the Dutch coast. For this purpose, annual topographic measurements over the past 60 years are converted into indicators for coastal development. The extent of this topographic dataset allows for a comparison of morphological developments before and after implementation of the 1990 dynamic coastline maintenance policy. In this study we primarily focus on morphological developments as indicators for coastal change to evaluate the coastal management goals. Less attention is given to the underlying hydrodynamic processes co-governing the morphological developments.

2.1. Topographic and bathymetric data

Beach topography and nearshore bathymetry are measured annually since 1965 along transects located at 200–250 m intervals along the

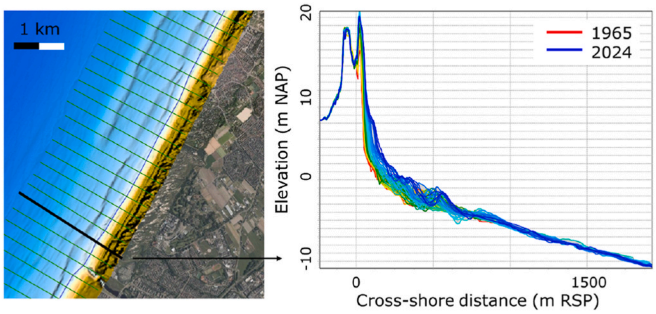

Fig. 2. Illustration of the data availability along a part of the central coast (right: transect 8550). Left: transects are indicated in green, the BKL is displayed in blue. Right: Colors indicate different years, 1965 and 2024 are highlighted. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

entire coast of the Netherlands (Fig. 2, Rijkswaterstaat, 2023a). The topography is measured from the inner dunes to approximately 2 km offshore. Elevations are reported in meters relative to Normaal Amsterdams Peil (NAP), i.e. roughly mean sea level. The cross-shore distance is expressed relative to a fixed line (RSP, i.e. Dutch Beach Poles), which was established in the 19th century to monitor coastal evolution.

2.2. Indicators for coastal development

Five coastal indicators are calculated from these measurements to analyse morphological development, namely: coastline position, beach volume, beach width, dune volume, and coastal zone volume. More indicators exist, but Santinelli et al. (2012) established that indicators of coastal morphology on the Dutch coast are generally well correlated. These indicators capture the morphological development of the Dutch coast at different spatial scales and cover the entire profile from the dunes to the shoreface. The selected indicators are strongly related to the operational goals of the Dutch coastline maintenance policy (Fig. 1). The coastal indicators are only computed for transects where a reference coastline, a BKL (BasisKustLijn), has been established. The BKL approximately corresponds to the coastline of 1990, which is the position of the coastline that is maintained dynamically to ensure that the strategic goals are satisfied (Hillen et al., 1991; Rijkswaterstaat, 2024a, Figs. 2 and 4).

Coastline position: The MKL-position (Momentane KustLijn, i.e. current coastline) is used as a proxy to determine the coastline position

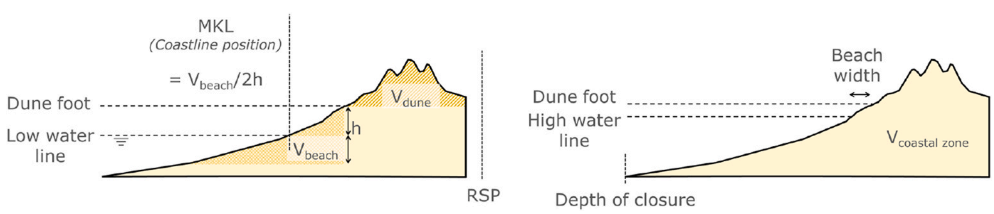

Fig. 3. The determination of the indicators for coastal development.

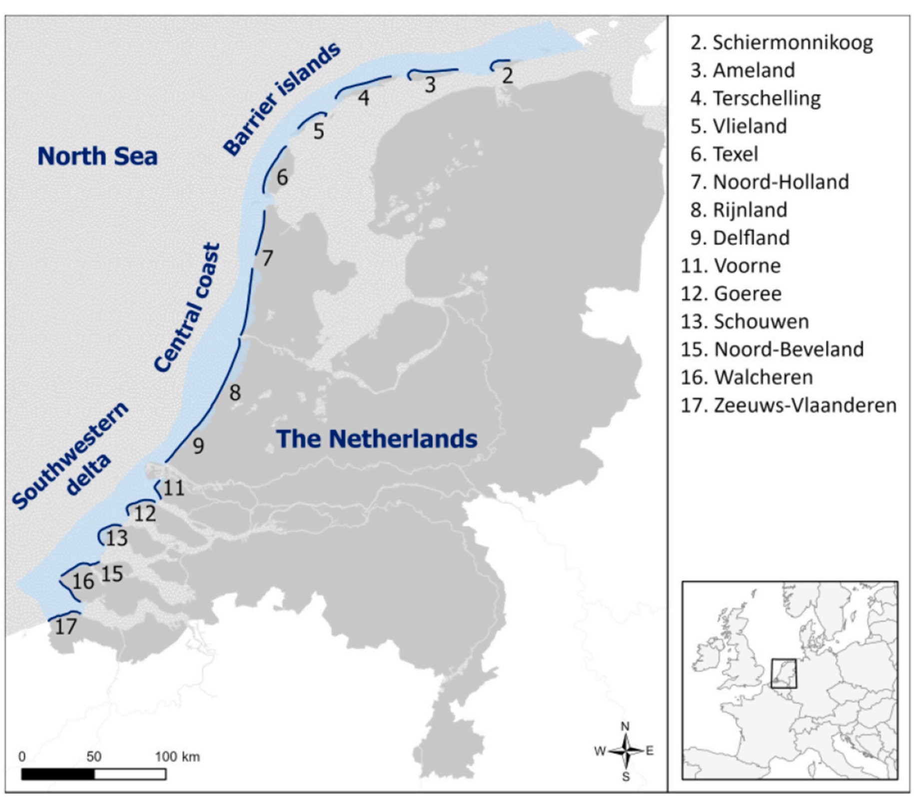

Fig. 4. Overview of the Dutch coast with the formal coastal regions and their numbering indicated. The reference coastline (BKL) is in dark blue and the coastal foundation in light blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(MKL in Fig. 3). The MKL is a weighted average of the sand volume between the dune foot and the low water line and the same elevation below the low water line. This corresponds to roughly 3 m above to 5 m below mean sea level in most regions. The coastline position is expressed as a horizontal distance (m) relative to a fixed line (RSP).

Beach volume: Beach volumes are defined here as the total sand volume (m^2/m) in the MKL-zone (V_{beach} in Fig. 3).

Beach width: The beach width (m) is the width of the area between the dune foot and the mean high water line (based on Rijkswaterstaat, 2013). The dune foot is historically set at +3 m NAP along most of the coast, which is an approximation of the dune foot, but is often not the exact location of the actual dune foot.

Dune volumes: The dune volume (m^2/m) is the volume above the dune foot, which corresponds to the upper boundary of the MKL-zone (V_{dune} in Fig. 3). The landward boundary of this volume calculation is a fixed point with low dune dynamics (based on Elias et al., 2024).

Coastal zone volumes and coastal zone elevation changes: One of the operational goals is to keep the sediment budget of the coastal foundation in equilibrium with sea level rise. Recently, it was observed that the majority of the nourished volume disperses within the coastal zone, consisting of the dunes, beach, and shallow shoreface (Elias et al., 2024). It is concluded that this zone should keep pace with sea level rise to ensure dynamic coastal maintenance (Taal et al., 2023). Therefore, the volume (m^2/m) in this zone is considered here as a proxy for the evolution of the coastal foundation ($V_{coastal\ zone}$ in Fig. 3). The seaward boundary of this coastal zone is here defined as approximately the depth of closure, which varies alongshore but is approximately −8 m NAP. The landward boundary of the coastal zone is defined landward of the foredune at a cross-shore location with low dune dynamics. In total, the cross-shore width of this zone varies between 1.5 and 2 km (Elias et al., 2024). Elevation changes of the coastal zone (m) were determined by dividing the volume changes of the coastal zone over the (transect-specific) cross-shore width of this zone.

2.3. Analysis

The development of the coastal indicators is analysed by means of descriptive or summary statistics, using histograms and boxplots, for example. Information at a transect level is accumulated for the entire Dutch coast to obtain a national overview. Additionally, developments at a transect level are analysed in more detail to understand the alongshore variability in morphological developments. Changes in coastal indicators are mostly analysed in decadal time intervals, which matches the investigated medium scale topographic changes. To minimize disturbance by short-term deviations, owing to individual nourishments, for example, a five-year running average is used to assign a value to a coastal indicator. For instance, the average from 1968 to 1972 is used to determine the indicator value assigned to 1970. Where the topographical data is incomplete or not full representative, this is noted.

2.4. Regional setting

The Netherlands is located on the southeastern edge of the North Sea basin (Fig. 4). 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 along the central Holland coast. The tidal range is larger in the southwestern delta (2.8 m on average) and along the barrier island coast (2.0 m on average). The flood currents to the north are dominant over the ebb currents to the south. The average wave height increases from south to north. Waves are coming predominantly from the southwest to northwest direction. The longshore current is predominantly from south to north and the net sediment transport in this direction is 0.1–1.0 × 10^6 m^3/year. Sea surges develop during strong winds from west and NW direction (van Rijn, 1995; Brand et al., 2022; Huisman, 2024).

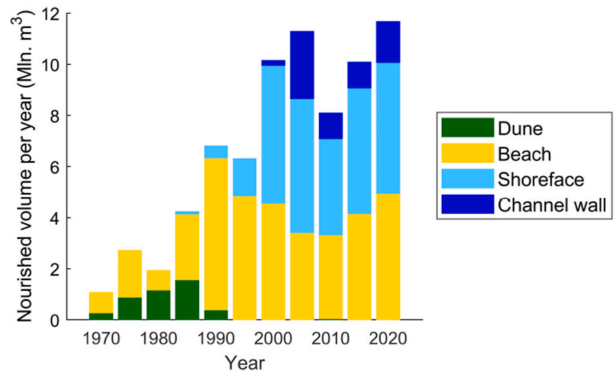

Fig. 5. Annually nourished volume per type of nourishment per period of 5 years.

The Dutch coast is 432 km long and can roughly be divided into three distinct morphological 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 (Elias et al., 2024). The majority of the coast (75 %) consists of sandy shores and dunes, but there are also hard structures (15 %), and tidal flats (10 %). Several local features in the three regions influence the coastal evolution, such as harbours, sluices, groins, and dikes (Brand et al., 2025). Along the central coast, two very distinctive protrusions of the coastline are the Hondsbossche Dunes, a large-scale coastal reinforcement (approximately transect 2000–2600 in Fig. 9, in the middle of Noord-Holland in Fig. 4), and the mega-nourishment of the "Sand Motor" (located at transect 10903 in Fig. 9, at the southern end of Delfland in Fig. 4). Sediment cells can be distinguished within the three morphological regions as a result of natural and man-made local features (Elias et al., 2024).

3. Results

3.1. Nourishment activities

The Dutch coast is intensively nourished. Small-scale nourishments were already undertaken in the 1970's and 1980's through which a total of 50 mln. m^3 of sand was added to the coast (Groenendijk, 1997). In the 1990s, the nourishment efforts increased when coastline maintenance was adopted in policy. Between 1990 and 2000 the coastline was maintained with an average of 6.4 mln. m^3 per year via beach and shoreface nourishments. In 2001, the volume of sand used for nourishments increased to an average of 10–12 mln. m^3 per year to allow the coastal zone to keep pace with sea level rise (Brand et al., 2022, Fig. 5). In total, 267 mln. m^3 was added to the coast through regular nourishments between 1990 and 2020. Additionally, 46 mln. m^3 was added to the coast through reinforcements, of which 21–42 mln. m^3 was added to the beach and 2–24 mln. m^3 to the dunes (it is not always evident what volume is added to which layer). Nourishment efforts are variable alongshore, with parts of the coast that have never been nourished and hotspots where volumes up to 130 m^3/m/year is added to the coast (Brand et al., 2022).

3.2. Coastline and beach volume development

Changes in coastline position were analysed for all transects and summarized (Fig. 6). The coastline maintained a stable position, on average, before 1990. The ratio of transects that showed retreat versus

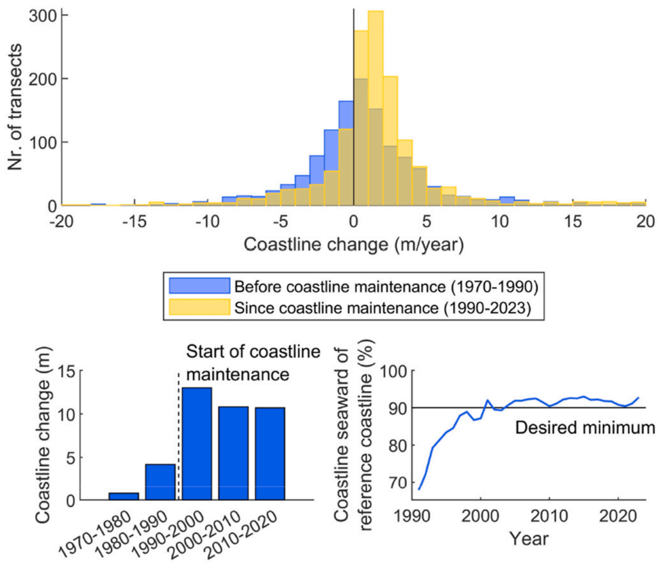

Fig. 6. Top: histogram of coastline evolution before and since coastline maintenance. Bottom left: national median change in coastline position over 10-year periods. Bottom right: Percentage of transects where the reference coastline is achieved over time.

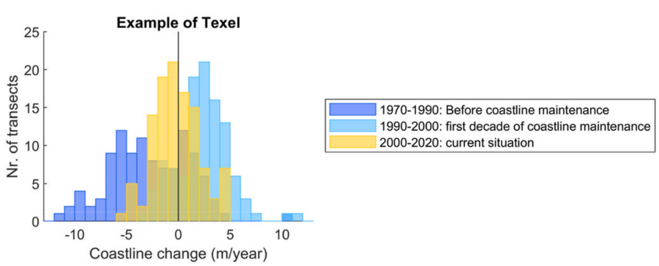

Fig. 7. Histogram of the change in coastline position at Texel for three periods.

expansion was 50:50 (Fig. 6, top). Groenendijk (1997) asserts that the coastline would have retreated without the small-scale nourishments from the 1970s and 1980s. Nevertheless, in 25 % of the transects, portions of the coast exhibited significant coastline retreat of 1.4 m/year or more.

Since the initiation of regular coastline maintenance in the 1990s, the coastline is expanding with 1.1 m/year, on average. The ratio of transects showing retreat versus expansion decreased to 25:75. The percentage of transects where the BKL is exceeded decreased sharply in the first decade of coastline maintenance and thereafter remained stable with 8–10 % exceedance (Fig. 6, bottom right). It should be noted that the reference coastline (BKL) was revised multiple times (Fig. 7) and that this figure shows the coastline position compared to the prevailing reference coastline at the time. Expansion of the coastline was most noticeable between 1990 and 2000. This is especially visible at Walcheren (with an average change in coastline position of 1.8 m/year between 1990 and 2000 and 0.9 m/year after 2000), Texel (2.5 to −0.4 m/year, Fig. 7) and Ameland (2.1 to −0.2 m/year). Nowadays, the coastline is still expanding seawards on average, however at a slightly slower rate (13.0 vs. 10.8 m per decade, Fig. 6, bottom left), while nourishment efforts have increased.

The beach volume analysis for all transects indicates that in total, 143 mln. m^3 of sediment has accumulated in the beach zone since 1990. This includes 21 to 42 mln. m^3 that was added through reinforcements, of which it was the purpose to increase the local volume of sand within the coastal zone to improve local flood protection, and the Sand Motor, a recent mega nourishment. This means that between 38 and 46 % of the

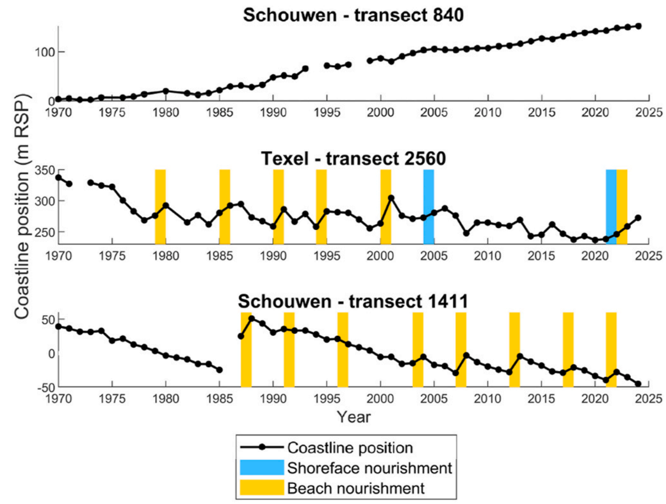

Fig. 8. Examples of the effect of nourishments on the coastline position (positive = seaward, negative = landward movement) for 3 transects. Yellow and blue bars represent nourishments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

nourished sand is still present in the beach zone of the beaches that are maintained.

At a national level, there is evidence of a relationship between the start of regular nourishments and maintenance or even expansion of the coastline (Fig. 6). However, when nourishment efforts per transect are compared to the coastline change at that location, a clear relationship cannot always be established. Some transects exhibit coastal expansion without nourishments (Schouwen, transect 840, Figs. 8 and 9). Other transects show a clear stabilization after the initiation of nourishments (large parts of Texel, Figs. 7–9). Some transects, however, are experiencing some coastal retreat despite nourishments (Schouwen, transect 1411, Figs. 8 and 9). Around 25 % of the coastal transects exhibit coastal retreat despite regular nourishments at the (surrounding) coastline. The strongest linear relationship between nourishment efforts and coastline change at the transect level (not presented here) is observed along the central coast, but the r^2 value is still only 0.4. The lack of a relationship between nourishment efforts and coastline changes at a transect level may be explained by large-scale morphodynamic developments, the influence of hard structures, and alongshore transport of nourished sediment. The coastline evolution is described at a regional level below, to better understand the alongshore variability (Fig. 9).

3.2.1. *Barrier islands*

The evolution of the coastline position is highly variable along the barrier islands enclosing the Wadden Sea. Along these islands the coastline is affected by large-scale morphological developments, such as the migration of the shoals and channels of ebb-tidal deltas, resulting in periodic shoal attachments (visible as a strong expansion of the coastline in Fig. 9). Nationally, the transects that exhibit most retreat and expansion (Fig. 6, top) are mostly located at the outer edges of the barrier islands. Terschelling and Schiermonnikoog are the only sites exhibiting large-scale retreat of the coastline since 1990. These are also the only regions that have not, or have barely, been nourished to allow for natural dynamics, which is considered possible here thanks to limited socio-economic activities along the coast. The islands of Texel and Ameland, on the other hand, are among the most intensively nourished stretches of the Dutch coast (Brand et al., 2022). At Texel, the coastline is maintained in position through these nourishments, while at Ameland the coastline has largely expanded. In the northern part of Texel, the coastline has expanded as a groin has captured approximately 5 mln. m^3 of sand in this area (Brand et al., 2025). Along the remainder of the island the coastline position is relatively stable with changes in the

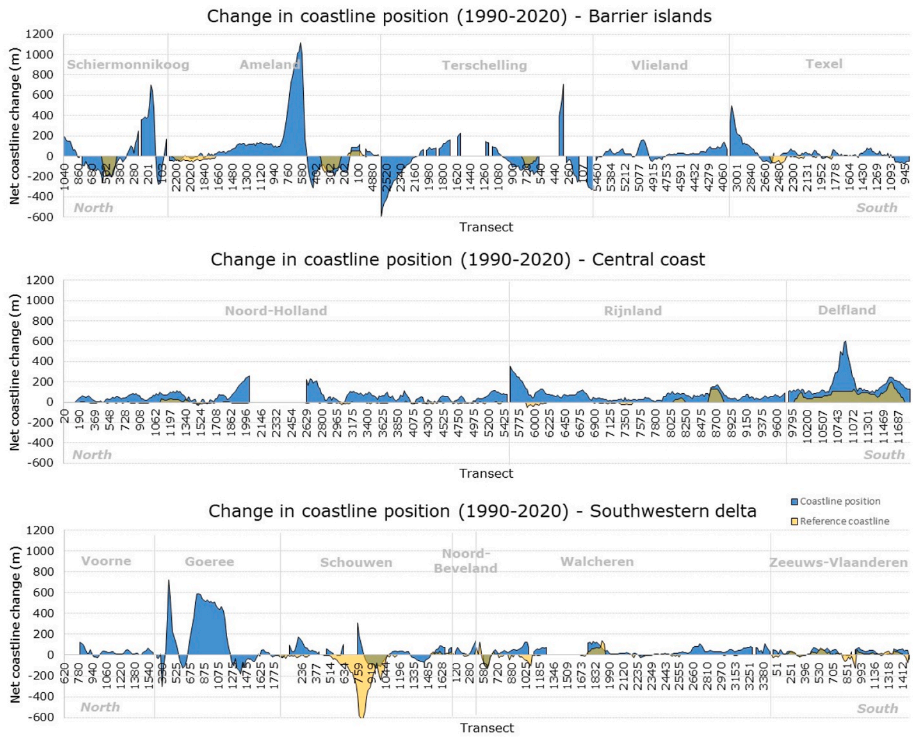

Fig. 9. Change in coastline position since the start of the policy of coastline maintenance (blue) at a transect level. Changes in the reference coastline (BKL) are indicated in yellow since these often correspond to reinforcements of the shoreline where an extension of the coastline was intentional. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

order of tens of meters. The coastline evolution at Ameland is heavily affected by the neighbouring tidal inlet. The coastline expansion between transects 500 and 900, for example, occurs because a shoal of the ebb-tidal delta merged with the island in 2017 (Elias et al., 2019).

3.2.2. *Central coast*

The coastline has built out along most of the central coast. Expansion occurred in 96 % of the transects, with an average of 71 m at Rijnland and 58 m at Noord-Holland. At Delfland, the coastline migrated even more seaward, but this is ascribed to reinforcements and the mega-nourishment of the "Sand Motor". Significant expansion of the coastline is also observed between Rijnland and Noord-Holland, where a harbour breakwater has captured approximately 5 mln. m^3 of sediment, and on either side of the Hondsbossche Dunes (transect 2000–2600). Along the central coast there are several coastal towns where coastal flood protection reinforcements occurred. Here, coastline expansion was needed to ensure flood safety and the reference coastline was revised to a more seaward position to ensure maintenance of the reinforcement (e.g. Ministerie van Infrastructuur en Waterstaat, 2023). Revisions of the reference coastline (BKL) are indicated in yellow in Fig. 9. Landward revisions of the reference coastline are illustrated with negative yellow areas, while positive numbers correspond to a seaward revision of the reference line. These are adjustments in the coastline position that is to be maintained, which do not necessarily correspond to actual coastline changes. However, at Delfland for example, the seaward revision of the reference coastline indicates that the measured expansion of the coastline was intentional.

3.2.3. *Southwestern delta*

At the southwestern delta most transects manifest expansion, albeit to a smaller extent than along the central coast, with an average of 36 m for Walcheren and Zeeuws-Vlaanderen, for example. Parts of the southwestern delta, such as Goeree and Schouwen, are highly dynamic. Here, the coastline position is still being affected by the closure of some of the estuaries as part of the Deltaworks (Elias et al., 2016) Shoals and channels of (former) ebb-tidal deltas have migrated in response to these closures. Like the situation in the central coastal region, there have been multiple reinforcements in the southwestern delta, particularly near

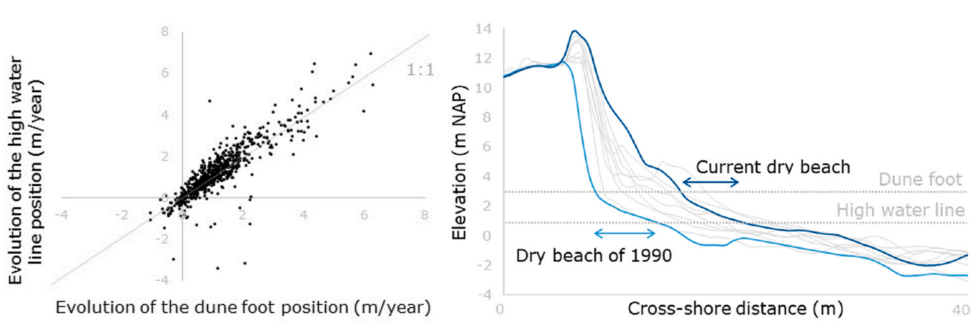

Fig. 10. Left: Trend in dune foot position between 1990 and now, compared to the trend in the high water line position. Each point represents a transect along the coast. Right: example of the evolution of the beach profile development since 1990 at Schouwen.

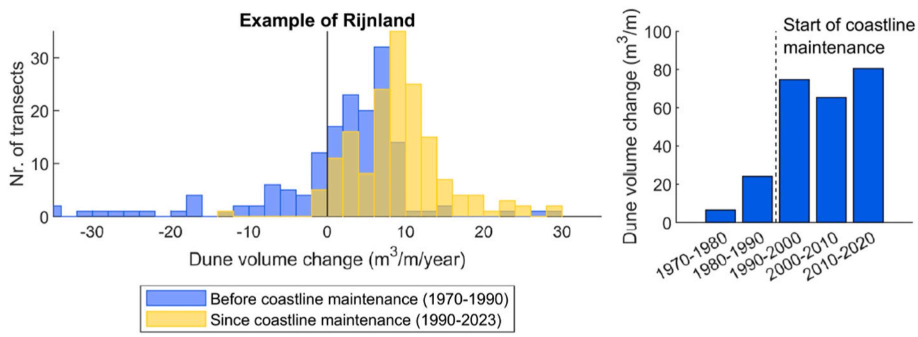

Fig. 11. Left: histogram of dune volume changes before and after coastline maintenance was initiated in 1990 for the relatively undisturbed dunes of Rijnland. Right: national median dune volume changes in 10-year periods.

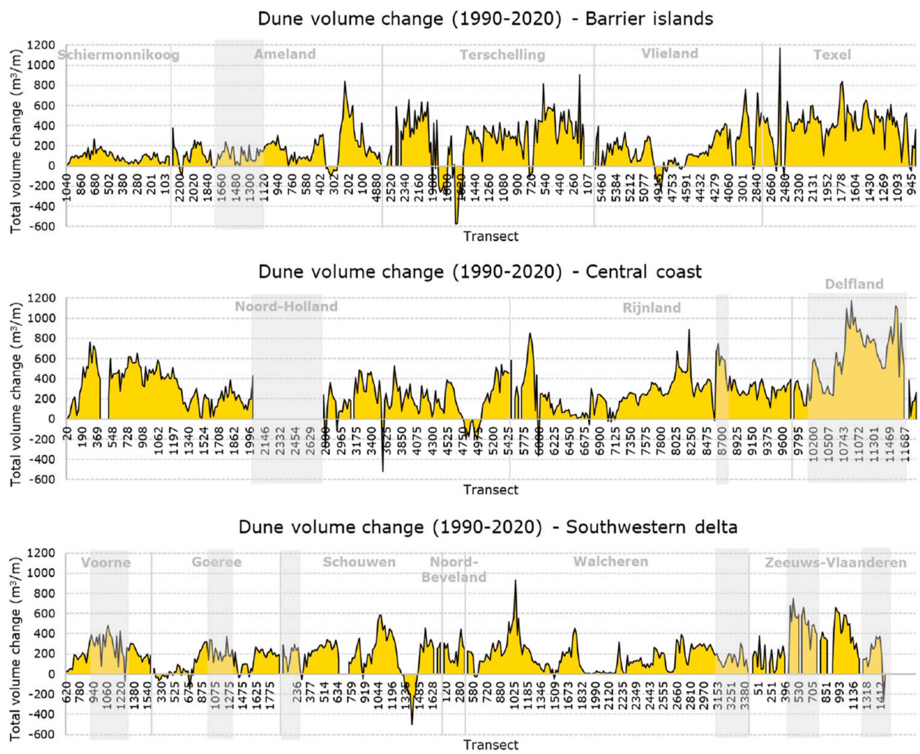

Fig. 12. Change in dune volume since the start of coastline maintenance (yellow) at a transect level. Areas with large-scale dune reinforcements are marked in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

coastal towns. The coastline that is to be maintained was revised to a more seaward position at these locations.

3.3. Beach width

The evolution of the beach width since 1990 is investigated to understand the effects of repeated nourishments on the beach profile. In Fig. 10, the evolution of the dune foot position and the mean high water line are compared for representative transects (i.e. excluding transects where the morphology has changed dramatically, such as at the highly dynamic outer ends of the barrier islands). No changes in beach width are observed since the 1990's: the coastline expands seawards, but the dune foot and the high water line expand at the same rate. This is illustrated in Fig. 10, using the beach profile development at Schouwen as an example.

3.4. Dune development

Generally, the dunes were eroding before the start of regular coastline maintenance, but in the 1970's and 1980's local dune nourishments served to compensate (Groenendijk, 1997). This allowed for a small net dune growth at the national scale (Fig. 11, right). Dune erosion decreased strongly in the 1990's when coastline maintenance started. The proportion of the coast exhibiting eroding dunes over a 10-year period decreased from 32 % to 13 % (illustrated by Fig. 11, left). The policy of coastline maintenance resulted not only in a decrease in dune erosion, but in stronger growth of the dunes (Fig. 11, left). On average, the dunes grew by 7.5 m^3/m per year, in the locations with limited human interference in the dunes, such as large-scale reinforcements. The growth of the dunes has been steady since the 1990's (Fig. 11, right), and the increase in yearly nourishment volume in 2000 did not result in enhanced dune growth. The total net sediment accumulation in the dunes since the 1990's is approximately 70 mln. m^3, a component of which was added directly to the dunes through dune nourishments and reinforcements (between 2 and 24 mln. m^3). This means that between 17 % and 25 % of the total nourished volume was transported by natural forces towards the dunes.

Dune growth occurs along the entire coast but exhibits high

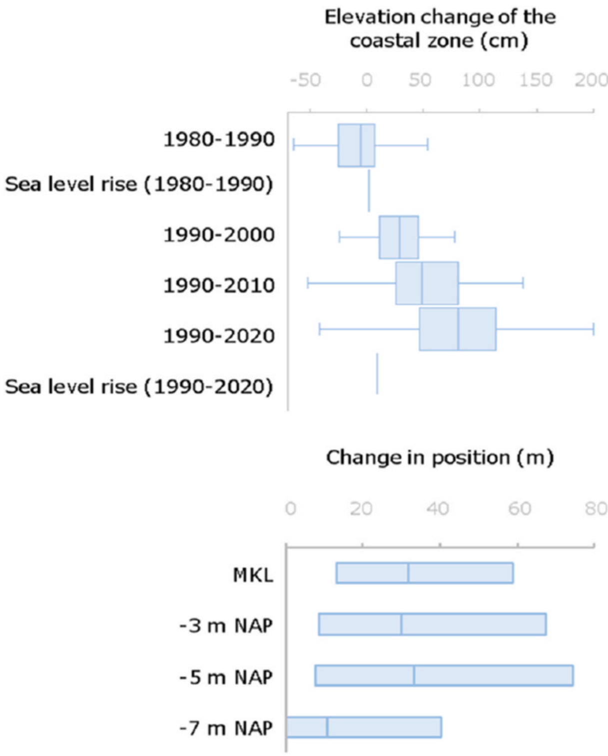

Fig. 13. Top: Boxplot of the transect-averaged elevation change of the coastal zone compared to sea level rise for Texel, Noord-Holland and Rijnland. Bottom: Boxplot of the evolution of shoreface contours at the southwestern coast of Walcheren between 1990 and 2020.

alongshore variability (Fig. 12). There are few locations where the dune volume is smaller nowadays than in 1990. This occurs in 9 % of the transects at the barrier islands, 4 % at the central coast and 8 % in the Southwestern Delta. A clear positive relationship exists between nourishment volumes and dune growth on a national scale (Fig. 11, right). However, similar to the coastline development, the relation between nourishment efforts and dune development is not always evident. The linear relationship between dune volume changes and nourishment efforts at a transect level has a corresponding $r^2 < 0.1$. This implies that more coastline expansion does not necessarily accord with stronger local dune growth.

3.5. The coastal zone

The Dutch coastal policy and practice aims to ensure that the coastal foundation is in equilibrium with sea level rise. Recently, Elias et al. (2024) concluded that the volume of the coastal zone has increased for most of the sandy coast. Here, we investigate elevation and volume changes of the coastal zone in more detail alongshore, to understand local variations in this equilibrium between the coastal foundation and sea level rise, especially since we observe large variations in coastline and dune volume development within sub areas (e.g. Fig. 9). This is done for the relatively undisturbed coastal compartments of Texel, Noord-Holland, and Rijnland. For this purpose, the coastal zone volume and mean elevation change of the coastal zone were considered per transect.

The development of the coastal zone seems to be more uniform along the shore than that of the coastline. The coastal zone volume changes (per transect) have a low standard deviation alongshore. The coefficient of variation, a measure to describe the variation in a dataset (i.e. the ratio of the standard deviation to the mean), is 0.7, while it is 1.1 for coastline development. This is ascribed to the robust development of the dunes, with a coefficient of variation of 0.7, and the lower shoreface, which is not specifically investigated here but is known to be more robust (e.g. Elias et al., 2024).

Elevation changes of the coastal zone were compared to the actual sea level rise that has occurred since 1990 (Stolte et al., 2023). Fig. 13 (top) shows the median, first and third quartile, and minimum and maximum elevation change of all transects before coastline maintenance (1980–1990) and since coastline maintenance (1990–2020). For only 4 % of the investigated transects elevation changes of the coastal zone did not keep pace with the rising sea level. The average elevation change (80 cm over 30 years) is even an order of magnitude greater than the sea level rise (8.7 cm over 30 years, see Stolte et al., 2023). This is in stark contrast to the situation before the start of regular nourishments when the coastal zone eroded in approximately 60 % of the transects. The median elevation change of the coastal zone over this period was −5 cm, while sea level rose 1.8 cm.

A concern regarding the policy and practice of coastline maintenance is the possibility of (undetected) shoreface steepening, which might render coastline maintenance unsustainable (Roelse, 2002). This is especially of concern for steeper shorefaces, for example at shores with channels, such as the southwestern coast of Walcheren. The measurements of the shallow shoreface of Walcheren (up to 1 km offshore) reveal that this steeping is not (yet) happening at a scale that would influence the coastline position on the considered timescale. In this area, the coastline has built out seawards since the initiation of coastline maintenance (Fig. 9, transect 2195–3458). The deeper contours also built out, albeit to a lesser extent, so the considered part of the shoreface has not retreated as was feared (Fig. 13, bottom).

4. Concluding discussions

The aim of this study is to understand the cumulative effect of nourishments along the Dutch coast, with the intention to evaluate the nourishment strategy in relation to the strategic goals of the Dutch coastal policy. For this purpose, the coastal morphology was analysed prior to and since the implementation of the dynamic coastline maintenance policy. Here the connections are discussed in terms of the following three themes 1) cumulative effect of nourishments on the coastline and dunes 2) coastline maintenance under a rising sea level, and 3) coastline maintenance and coastal uses. The results are discussed in relation to findings by other authors and conclusions are drawn in relation to the strategic, tactical, and operational goals (Fig. 1).

4.1. The cumulative effect of nourishments on the coastline and dunes

Since the 1990's, regular nourishments have resulted in an overall stabilization and even local expansion of the coastline of The Netherlands. This expansion was strongest between 1990 and 2000 (Figs. 6 and 7). The coastline faced significant amounts of erosion immediately prior to 1990 (Ministerie van Verkeer en Waterstaat, 1989), so in the first years of the coastline maintenance program, the shoreline was intentionally built out in a seaward direction. Nowadays, the coastline still expands seawards locally, but this is often unrelated to nourishment efforts at the specific locations. This is attributed to the spreading of nourished sand along the coast via natural dynamic processes and the alongshore variability in morphological developments, from natural and anthropogenic causes (Brand et al., 2025). This is illustrated by the fact that the annual nourishment volume is an order of magnitude larger than the average net longshore sediment transport (van Rijn, 1995; Brand et al., 2022; Huisman, 2024): local gradients in longshore transport, cross-shore transport, and sea level rise all contribute to the nourishment demand of the coast (Rijkswaterstaat, 2020). The regions that were identified as the most erosive in the past are generally still the most intensely nourished sections (Groenendijk, 1997; Brand et al., 2022). At these locations, the shoreline is now maintained in position. It thus appears that the operational goal of dynamic coastline maintenance is achieved.

Fig. 14. Beach and dunes of Bergen (Noord-Holland) in 1990, 2002, and the current situation (photo credits: Rijkswaterstaat photo archive Waterdienst and Marinka Kiezebrink).

It is observed that the policy of coastline maintenance also resulted in dune growth (Fig. 11), which confirms previous observations (de Vries et al., 2025). The total dune growth is likely underestimated here, since only transects with a reference coastline were analysed (around 90 % of the sandy coastline). Arens (2010) investigated the total dune growth over a 10-year period in more detail and estimated an increase of 34 mln. m^3 in dune volume, compared to the growth of 46–68 mln. m^3 (70 mln. m^3 minus 2–24 mln. m^3 of reinforcements) over the 30-year period found in this study. Like the coastline position, dune growth cannot be related to nourishment volumes at a transect level. Local dune volume changes could be influenced more by local features such as the presence of beach pavilions (Pourteimouri et al., 2023) and changes in dune management at the locality. The policy of coastline maintenance meant that dune management could accommodate more natural dynamics, as erosion was compensated and therefore formed less of a contribution to flood risk (Löffler and Veer, 1999). So contrary to what might have been expected, the dynamics in the dunes could increase as the coastline position was maintained. The more dynamic dune environment has resulted in enhanced aeolian transport of sand landward into the dunes (IJff et al., 2019). The observed growth of the dunes contributes to the tactical goals of a sediment budget in equilibrium and safe primary flood defences. Furthermore, coastline maintenance facilitates the tactical goal of allowing natural dynamics when possible, regarding the dunes.

4.2. Coastline maintenance under a rising sea level

Maintaining the coastal foundation in equilibrium with sea level rise is one of the operational goals of the Dutch policy since 2000. The increased annual nourishment volume from 2000 onwards for this purpose, did not result in increased coastline and dune expansion (Figs. 6 and 11). However, Elias et al. (2024) investigated the sediment budget of the entire coastal zone, including a larger area of the shoreface and parts of the coast without a reference coastline, and concluded that almost all the nourished sand is still present in this zone. The increase in nourishment volume thus likely resulted in sedimentation in parts of the coast that are not investigated here. Sediment is "lost" for example due to transport through tidal channels, over ebb-tidal deltas, to the lower shoreface, or import into the Wadden Sea (Elias et al., 2024).

For the coastal transects investigated in this study (Fig. 13), the average height of the coastal zone increased more than sea level rise over the considered period. Elias et al. (2024) observed that not all parts of the coastal zone accumulate sediment though; some ebb-tidal deltas and parts of the lower shoreface are losing sediment. There are also sediment sinks, for example near harbour breakwaters, where sediment accumulates (Carvalho et al., 2023; Brand et al., 2025). It is questionable whether sediment that accumulates in these sinks can become available for adjustments of the coastal profile elsewhere, in response to a rising sea level. It can thus be concluded that even though the coastal zone is relatively robust, it does not rise evenly with sea level.

It should be noted that any observations on coastline maintenance under a rising sea level in this study apply to the current rate of sea level rise. They may no longer be true for accelerated sea level rise rates and the associated nourishment efforts that are predicted for the future (Taal et al., 2023). For the current sea level rise though, it appears that the tactical goal of a sediment budget in equilibrium and the operational goal of a coastal foundation in equilibrium with sea level rise are overall achieved, although issues may exist at the locality.

With the increase in annual nourishment volume in 2000, the percentage of this volume that is nourished on the shoreface also increased. It remains difficult to quantify the effects of shoreface nourishments (Brand et al., 2022; van der Werf et al., 2025), however it can be concluded that they are effective overall. Indeed, the coastline is maintained in position with the current relative high proportion of shoreface nourishments (Fig. 6), and shoreface nourishments are known to contribute to the sediment budget of the coastal zone. As shoreface nourishments are cheaper than beach nourishments, the 40 % increase in annual nourishment volume in 2000 only resulted in a 10 % increase in annual costs (Brand et al., 2022). Although it is not an explicit operational goal, maintenance of the coastal foundation can thus be characterized as cost-efficient.

4.3. Coastline maintenance and coastal uses

4.3.1. Flood safety

To maintain flood safety levels under sea level rise it is vital that the dunes grow apace. Although the dunes are indeed growing strongly, it cannot be concluded directly that flood safety levels are maintained as the distribution of the dune volume also matters for flood safety. It is known that the dunes mainly grow on the seaward side (Rijkswaterstaat, 2023b) with the dune foot rising faster than sea level (van IJzendoorn et al., 2021). Although dune growth mainly occurs on the seaward side of the dunes, it appears that the dunes as a whole are largely growing sufficiently to keep pace with sea level rise given the current nourishment strategy (Rijkswaterstaat and HKV, 2024). Santinelli et al. (2012) concluded that the probability of breaching of the first dune row due to dune erosion during extreme storm surges has decreased by one order of magnitude for the Noord-Holland coast owing to regular nourishments, because of a resulting beach-dune system that is more resilient to extreme events. However, that coastline maintenance does not automatically guarantee maintenance of flood safety levels is illustrated by multiple coastal protection reinforcements that have become necessary in the Netherlands over the past decades (Fig. 12, grey area's). These reinforcements were mainly carried out on the seaward side of the dunes. In most of these cases, the reference coastline was subsequently adjusted to include the reinforcements within the policy of coastline maintenance (Ministerie van Infrastructuur en Waterstaat, 2023; Fig. 9). Overall, it can be concluded that the tactical goal of safe primary flood defences is achieved with the current strategy. Rijkswaterstaat (2023b) also concluded that the current strategy is effective for long-term maintenance of flood safety levels under a rising sea level, rendering the maintenance of flood protection levels sustainable. However, issues may arise when the dunes cannot grow further landward owing to anthropogenic land uses.

4.3.2. Socio-economic development

An important socio-economic use of the beaches and dunes lies in the opportunities they provide for leisure and recreation. Erosion of the dunes was one of the triggers for the policy of dynamic coastline maintenance. It can be assumed that the preconditions for dune recreation have improved, or have at the least been maintained, as the majority of the dunes have grown since the policy was initiated (Fig. 11). The appearance of the dunes may have changed owing to coastline maintenance practices and the accompanying dynamic dune management strategies, this has not been investigated here. In general, the preconditions for the socio-economic use of the coast do appear to have been maintained, or even improved, as substantiated by studies of beach visitor experiences (e.g. Bakhshianlamouki et al., 2024). This is illustrated in Fig. 14, showing the dune and beach infrastructure at Bergen in North-Holland (around transect 3275) from before the start of coastline maintenance to the current situation.

The dry beach width is especially important for recreation on the beach. This is the zone where recreational facilities such as beach bars and restaurants can be built and the zone that can be used for sunbathing, for example. It is observed that sand nourishments do not affect the beach width in the long term (Fig. 10). This confirms previous studies, which observed that beach nourishments result in an initial widening of the beach, but that waves, tide, and wind reshape the profile to an equilibrium profile (Den Heijer and Vonhögen-Peters, 2016). The beach width starts decreasing directly after completion of a nourishment and after several years the beach returns to its original width (van Eijsbergen, 2017). Larger nourishment volumes (m^3/m) may result in a larger effect on the beach width (Van Balen et al., 2011). Apart from the short-term effect of nourishments overall, the dry beach width was not affected structurally by the policy of dynamic coastline maintenance. However, nourishments still benefit the recreational socio-economic use of the beach as they stabilize the cross-shore position of the dry beach. The strategic goal of sustainable preservation of values and uses of dune areas is thus generally achieved for the socio-economic use.

Although the preconditions for recreational use of the beach and dunes have been maintained or even improved in places, socio-economic uses of the coast appear to be under pressure. The socio-economic pressure on the coast is increasing and an increase in recreational occupation is observed (e.g. Stiemer and Tillema, 2023). This may be a result of coastline maintenance, as the risk of damage to buildings in the coastal zone has decreased, comparable to observations elsewhere (Armstrong et al., 2016). It may also be an autonomous trend though, as coastal squeeze is observed globally (Lansu et al., 2024).

The increasing socio-economic pressure may in turn affect dynamic coastline maintenance. At its core, the policy is based on utilizing physical processes to re-distribute sediment. However, there is a tension between the socio-economic use of the coast and the degree of dynamics that can be allowed. For example, it may be considered undesirable to allow coastline retreat for multiple years, even if natural restoration would occur thereafter, particularly when a beach is occupied by pavilions and other users. Furthermore, occupation in or near the dunes hinders growth of the dunes and thus impacts the operational goal of a coastal foundation in equilibrium with sea level rise (Rijkswaterstaat, 2023b). Two decades ago, this tension between (natural) dynamics and coastal maintenance was already identified as an ongoing point of concern (Roelse, 2002).

4.3.3. Ecological impacts

Besides the socio-economic use of beaches and dunes, they also provide valuable habitats. Nourishments may benefit the preservation of these habitats, but their direct impact can be damaging. Generally, beaches and dunes provide habitats for species adapted to highly dynamic conditions, but they are vulnerable to human activities such as nourishments (de Schipper et al., 2021). Nourishments are especially harmful to the littoral ecology as they cause burial and crushing of benthos, temporarily reducing the foraging for birds. Nourishment activities can result in increased turbidity, which may negatively impact the underwater ecology (de Schipper et al., 2021). However, along the Dutch coast, it is observed that these effects are local and temporary and that the long-term effects of repeated nourishments are limited (Herman et al., 2022).

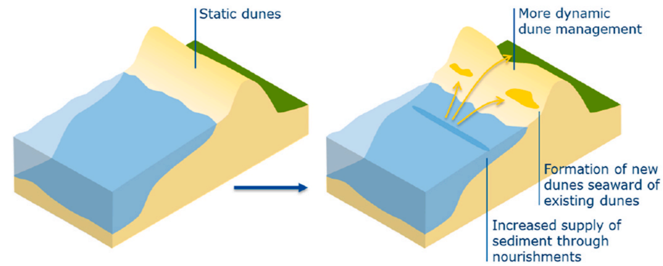

Fig. 15. Conceptual summary of the effect of coastline maintenance on the dunes.

In an effort to limit the local ecological impacts, the Dutch government actively collaborates with nature conservation organizations in designing the nourishment strategy and in ecological monitoring. First the nourished sand is selected based on the grain size to avoid mismatches with the nourishment locations. Next, the number of disturbances by nourishment activities is kept as low as possible to allow for recovery of the benthos. Natural dynamics are used in distributing the sand from the nourishment location, meaning that there are benefits for the sediment budget of a larger area. Nourishments are placed in the most dynamic areas where species are better adapted to disruptions. During the nourishment activities measures are taken to avoid disruption of species such as breeding birds and resting seals (Rijkswaterstaat, 2024b).

Besides temporary disturbances to ecosystems, nourishments may also benefit nature. Valuable dune areas are preserved thanks to regular nourishments (Fig. 12) and the dunes have become more dynamic (IJff et al., 2019). Arens (2010) observed an enhanced availability of sediment, increased aeolian transport, and a greater distribution of dynamic dunes since coastline maintenance with nourishments, which means that the abiotic boundary conditions for the development of relevant habitat types has improved (Fig. 15). Overall, the strategic goal of sustainable preservation of values and uses of dune areas is thus also achieved in terms of ecology, although there are local and temporary negative impacts associated with nourishments.

4.4. Future research

Sediment accumulates in sinks, such as the down drift side of dams, both sides of nourishment hotspots, and parts of the shoreface. Although it is frequently observed that the sediment budget of the Dutch coast is (more or less) in equilibrium with sea level rise thanks to nourishments, sediment transport gradients and the resulting distribution of sediment over the coastal zone deserves particular attention.

The underlying thought of the Dutch coastal policy and practice is that maintaining the physical basis of the coast serves to guarantee coastal uses in the long term. Socio-economic developments of the coast, also in relation to dynamic maintenance, are less well understood. Likewise, studies to the cumulative ecological and environmental effects of nourishments are limited. Such studies would be beneficial for an integral evaluation of the Dutch coastal maintenance strategy.

Synthesis

With the current strategy of pro-active nourishments, structural erosion has been halted and the coastline position has been maintained over the past 30+ years, achieving the goal of the 1990 policy. The coastline has even extended seaward on average, which proved

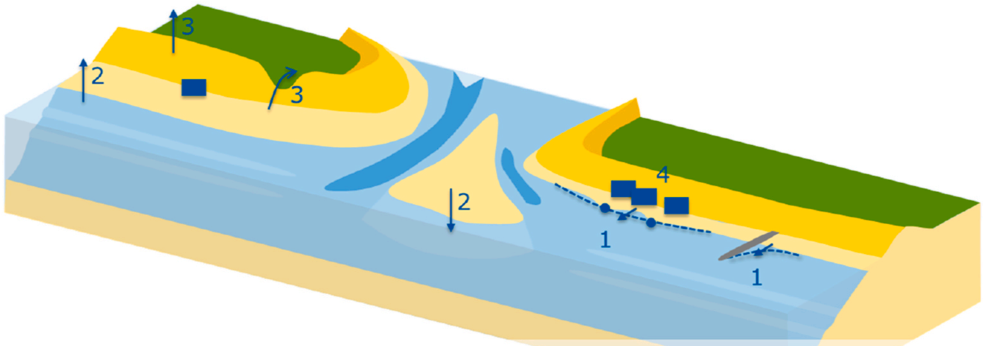

Fig. 16. The cumulative effect of nourishments on the Dutch coast.

necessary to maintain the most erosive parts of the coast. The dunes grew in volume with a significant portion of the nourished sand ending up in the dunes. However, the dunes did not only grow because of an enhanced supply of sediment. The dunes also grew because dune management adapted to the promise of coastline maintenance, allowing more natural dynamics to occur. As a whole, the coastal zone has risen along with the sea level, however the distribution of sediment over the coastal zone in response to nourishments is uneven.

The nourishment strategy for coastline maintenance is primarily based on the multi-annual evolution of the momentary coastline (MKL) in relation to the desired coastline position (BKL). It can be questioned whether the operational goal of coastline maintenance and its corresponding indicators are appropriate for reaching the strategic goals. This study affirms that other coastal morphology indicators, such as beach width and dune volume, are stable or increasing, respectively. With the current approach, the available space for coastal uses is generally maintained or even increased, indicating that the choice of the coastline position as primary indicator for policy and practice seems to be appropriate.

Thanks to the cumulative effect of nourishments, the coastline and dunes were thus maintained and the strategic goals of sustainable maintenance of uses and values of the beaches and dunes, including flood safety, appear to have been achieved to date (Fig. 16). The chosen strategy of nourishments to maintain the coastline in position has proven adaptable with the nourishment volumes and locations being adjusted to match the sea level rise rate and the coastline position being revised to protect newly reinforced coastal locations. The success of this nourishment strategy, applied since 1990, means that it can likely be sustained in the (near) future.

The Dutch dynamic coastline maintenance approach has proved effective, however implementing it elsewhere requires caution. Biophysically, the Netherlands benefits from the large availability of sand within a short distance of the shore, while administratively the flood-prone Dutch prioritize finances for coastline maintenance at a national level. Practically, the efficacy of the nourishment strategy rests on an extensive, annual coastline monitoring program. Coastal management organizations with similar biophysical, administrative and monitoring conditions may benefit from implementing aspects of this study, while others may simply draw inspiration from the cumulative effects of long term, sustained coastal nourishment.

CRediT authorship contribution statement

Evelien Brand: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Quirijn Lodder:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ellen Quataert:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Jill Slinger:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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