Intertidal area in the Dutch Southwest Delta: Changes in the past century, and strategies for conservation

Internship report - World Wide Fund for Nature NL

Tessa Deggeller
Utrecht University
July 2021

Supervision:
Irma Melse (WWF-NL)
Bas Roels (WWF-NL)
Elisabeth Addink (UU)

MSc programme Earth Surface and Water
Utrecht University
Department of Physical Geography

Abstract

Tidal nature in deltas is declining. This report quantifies the historic decline of intertidal area in the Dutch Southwest Delta, and explores the possibilities for nature restoration interventions for the estuaries and tidal basins. Estuaries and tidal basins are partly enclosed coastal bodies of water, with an open connection to the sea, and with minimal (tidal basins) or significant riverine influence (estuaries). These waters have highly productive ecosystems and substantial socio-economic value for society. Worldwide, estuaries and tidal basins are altered by humans to improve water safety, stressing the tidal ecotopes. In the Netherlands, impoldering, damming and diking have reduced the surface area and hydrodynamics of the tidal waters. The Dutch Southwest Delta has a long history of human impact and interventions. Most of the land area has been created by land reclamation of accreted salt marshes. Furthermore, the Delta Works have been constructed in the 1960's – 1980's with the aim to shorten the coastline and improve flood protection. This series of dams and barriers has changed the estuarine landscape of the Rhine-Meuse-Scheldt delta into (partly) disengaged lakes with stagnant fresh-, brackish-, or salt water. When tidal dynamics and sediment supply are blocked by dams, the linear correlation between tidal prism and channel cross section is disturbed, causing sedimentation to occur in the channels. As no new sediment can enter the system, a sediment deficit arises in the basin and former intertidal shoals and banks erode.

In this study, the environmental drawbacks of the Delta Works and other human interventions are examined. It identifies historical and future changes in intertidal surface area of the Southwest Delta. A 51% decline was observed between 1915 and 2015. Future development will depend on policy decisions and the amount of sea level rise (SLR). In a scenario with increased SLR and a continuation of delta strategies as usual, more intertidal area will be lost in 2050, especially behind (partly) closed dams. On the contrary, interventions such as opening dams, applying new sediment through suppletion, and creating exchange polders, much of the intertidal area can be maintained or even restored, despite SLR.

Furthermore, estimations are made on the necessary volume of sediment suppletions as a means to compensate for the sediment shortage that arises through SLR. Assuming the shortage is directly proportional to the rising rate of the sea level, the volume was determined for the whole Dutch coast (currently 12 million m^3/yr), and the relative share of the Delta basins. For sea level rise according to the delta scenario, a yearly 37 million m^3 of sediment is necessary in 2050, of which 3 million m^3 is for the Southwest Delta. The climate scenario RCP8.5 will result in an 81 million m^3/yr deficit in 2050, with 6.6 million m^3 for the delta.

Accreting exchange polders located between double dikes is a second measure for restoring tidal nature that is investigated in this study, focusing on the sediment-poor Haringvliet-Hollands Diep basin. A total of 1580 hectares on 15 different sites was assessed to have the most potential, considering criteria amongst which elevation, absence of buildings, and presence of a sleeper dike. Possibilities for optimizing the accretion speed of the exchange polders were explored. Extra suppletion of silt/mud in the polder accelerate the sedimentation rate, as well as optimized inlet opening times.

Future research should focus on optimizing the sustainability of and extraction and transport, minimizing greenhouse gas emissions and seabed disruption. Also, more knowledge is needed on future soil salinization in the Southwest Delta, and its impact on agricultural yield loss. The potential of exchange polders for reducing this loss must be researched in more detail in a pilot. For accreting polders to be efficient, it is important to start implementing them in the immediate future to enable them to timely grow with the rising sea level, as well as to create empirical understanding of the effects on local hydrology and on the tidal dynamics on the large scale.

Context

This report is the result of internship at World Wide Fund for Nature NL, as part of the masters Earth Surface and Water at Utrecht University.

Human-induced planetary change has resulted in a biodiversity loss, nearing a mass extinction. This trend is also taking place in the Dutch delta. WWF-NL is aiming at development of insight in the consequences of human impact and sea level rise on tidal nature and land use in the Netherlands with the purpose of bending the curve of biodiversity loss. The ambition is to embed nature restoration goals in the Dutch Water Law and in the National Climate Adaptation Strategies.

Within the context of this framework, the central question in report is (1) how the area of tidal nature has changed in the Netherlands, and (2) how we can conserve and restore tidal nature. Focus is laid on whether sediment suppletion and accretion polders can aid with restoring the total intertidal surface area and improve farmland quality. Supplementary to this report, this knowledge is presented in the form of an article and an infographic in order to distribute the insights under professionals.

Table of Contents

1. Introduction

Humans have caused widespread planetary change starting in the last millennia and intensifying in the last centuries, ushering a new geological area: the Anthropocene (Tickner et al., 2020). The consequence of human impact is that biodiversity has declined to the extent that we are facing a sixth mass extinction (Ceballos et al., 2017). To bend the curve of biodiversity loss, interventions are necessary. The threats that anthropogenic influence poses on nature are very evident in the world's deltas and estuaries – where rivers reach the sea. These regions have various functions for humans and nature. They rank among the most ecologically and (socio-)economically valuable environments on earth (Nienhuis et al., 2020). In the Netherlands, important tidal ecotopes are declining due to damming, impoldering and sea level rise. In this report, historical changes in the Dutch delta are researched and future development is explored, focusing on the surface area of the intertidal ecotopes. Three intervention practices are researched: opening of dams, sediment suppletion and establishment of exchange polders.

Economic and ecological functions of deltas are diverse, due to their dynamic qualities. Important environmental factors in estuaries are water movements (vertically and horizontally), salinity, sediment transport and turbidity, and nutrients (Ysebaert et al., 2016). These make up the heterogeneity of the ecosystem habitats. Due to this variety, many species thrive in this productive system. The intertidal areas – submerged during flood and dry during ebb – are especially important for benthic animals such as shellfish and worms, and therefore for wading birds (Saeijs & Bannink, 1978). As the delta is an entrance from the sea to the river, they are essential for fish migration as a corridor to their spawning areas (Ysebaert et al., 2016). Due to their high productivity, the intertidal flats are a large carbon capturer, as they sequester 6500 kg of Carbon per hectare per year (rate for the Scheldt, NL, from Chmura et al., 2003). Also, estuaries and deltas are highly important to societies, due to their role in fishing, agriculture, shipping, ports and urban building (de Haas et al., 2018), as well as for recreation. Finally, the intertidal banks and shoals function as a buffer, breaking and blocking waves before they reach the shoreline. They therefore act as a natural water protecting structure, ensuring better water safety (van Belzen et al., 2021).

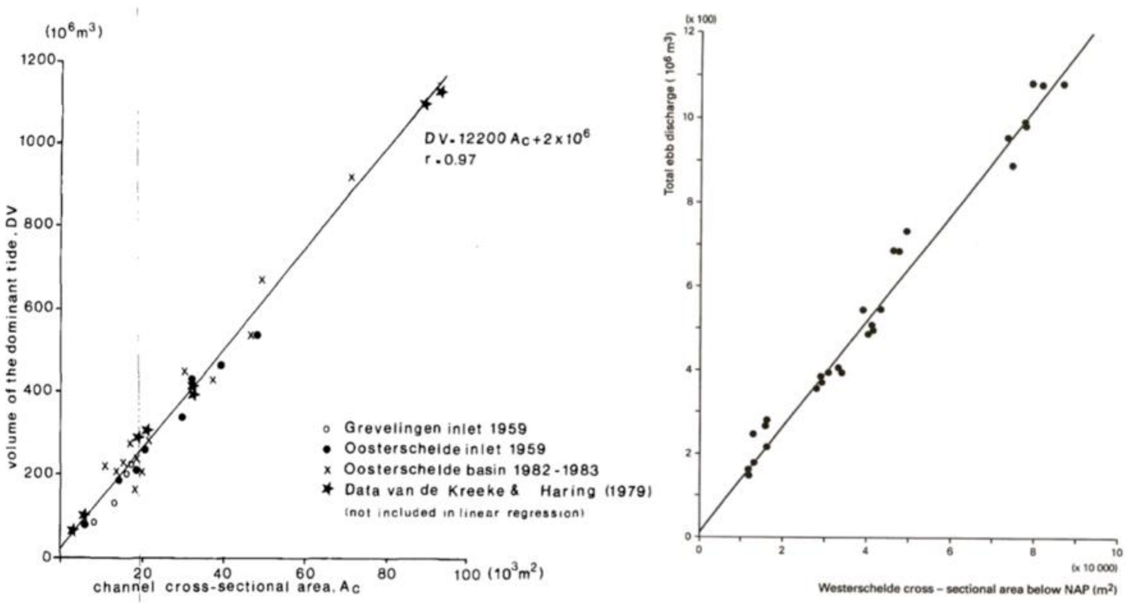


Figure 1. Equilibrium relations for tidal inlets between the tidal volume and its cross-sectional area below mean sea level. Left shows dominant tidal volume to the cross-sectional area of the Eastern Scheldt and Grevelingen. Right shows total ebb discharge to the cross- sectional area for the Western Scheldt (from Louters et al., 1998; van den Berg et al., 1996).

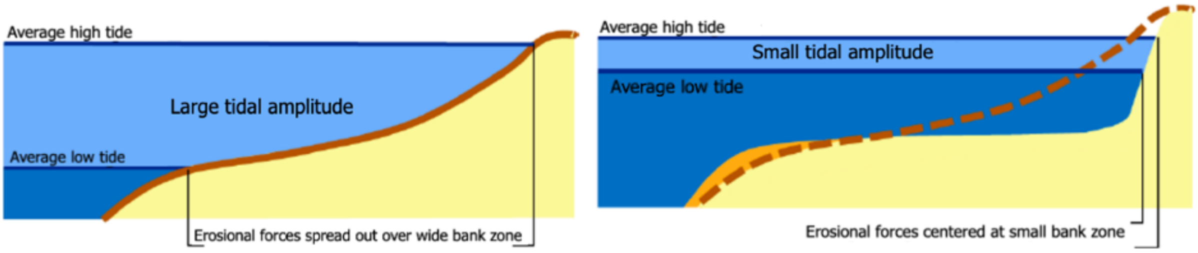


Figure 2. Illustration of the effect of tidal amplitude on wave erosion and the consequential bank- or shoal morphology. Left: large tidal range with mildly sloping banks (natural system in Haringvliet). Right: small tidal range causes steeper slopes on intertidal elevations (situation behind partly closed dams). (translated from Wijsman et al. 2018)

1.1 Dynamics and morphology

With every tide a large volume of water flows in and out of a tidal basin or estuary; this volume is referred to as the tidal prism. Due to their connection to the sea and rivers, deltas and estuaries can interchange sediment. These dynamic systems can therefore adapt to new hydrodynamic circumstances such as a changing tidal prism or changing sea level. A channel's/inlet's tidal prism and cross-sectional area show a linear relationship when in equilibrium state – meaning when the morphology is fully adapted to the dynamics (Figure 1). A larger tidal prism will therefore result in larger channels. When the tidal prism decreases, extra sediment is deposited in the "oversized" channels, restoring the equilibrium situation (Louters et al., 1998). Furthermore, the tidal prism influences the morphology of a basin. When the tidal range is large, wave erosion is spread over a large surface, creating gentle sloping banks (Figure 2). A small tidal range causes very localized wave erosion and thus steeper slopes. The intertidal area will therefore become smaller.

The current rate of relative sea level rise (SLR) in the Netherlands is 1,86 mm/yr (Baart et al., 2019). Under natural circumstances, tidal flats can rise with SLR. Water from the sea and rivers bring in new sediments. As waves break on the shallow shoals, the energy in the water is reduced and sediment is deposited as it drops from the water column. Yet with the construction of dams, this supply is blocked, and a sediment shortage occurs when the water level increases (Ysebaert et al., 2016). Another implication which is enhanced by sea level rise is seepage of saline water from the basins to the low-lying farmlands in the polders. Salinization pressure on the crops will increase with sea level rise (van Belzen et al., 2021).

1.2 Study Area - The Dutch Southwest Delta

In the Netherlands, the boundaries between land and sea have changed from wide natural transition zones to narrower, solid boundaries. Embankments, dikes and dams have reduced the total surface area of tidal basins. This happened in the north through the impoldering of Flevoland and around the Eems-Dollard, and through damming of the former Zuiderzee and Lauwersmeer. Another region where the coastal system is significantly altered is the Southwest Delta, where the Scheldt, Meuse and Rhine rivers converge. Most of its land is formed by impoldering, and most of the tidal dynamics and sediment input are blocked by dams.

The early historical development of the Southwest Netherlands is shown in Figure 3. Around 350 AD, the Southwestern Delta was an extensive tidal flat landscape formed by excavation and flooding of former peat areas (Vos, 2015). From 800 AD onwards, sedimentation of sand and clay led to the silting up of tidal areas, forming salt marshes. During the 12th and 13th century, systemic impoldering of the major part of the saltmarshes took place through accretion polders ("opwaspolders" and "aanwaspolders" in Dutch). Land reclamation continued until far into the

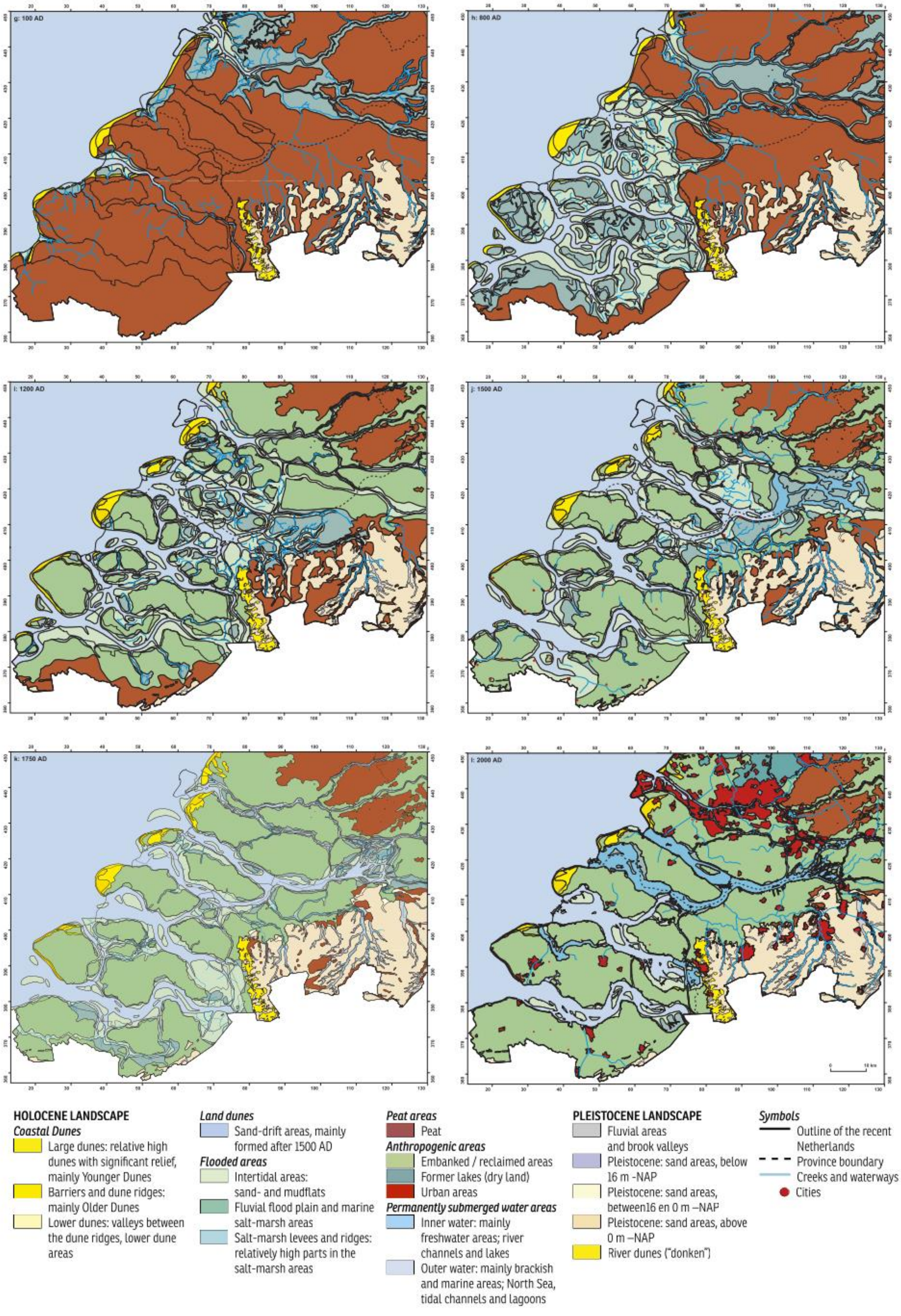


Figure 3. Holocene development of the Dutch Southwest delta between 100AD and present (from Vos, 2015)

Figure 4. Names and construction dates of the different Delta Works (from Rijkswaterstaat).

20th century (Spijker, 2005). Furthermore, in the last 100 years the Dutch coast has been altered by barriers on a large scale. Tidal waters have been dammed as protection against high water, blocking the sea from influencing the basin. Water levels could thus be kept more constant, so dikes around the basins needed to be less high and less strong.

Despite initial advantages for water safety, the environmental drawbacks of the Delta Works have become increasingly evident. For example, ecological quality and ecosystem functioning had severely degraded. The quality of water and sediment has become problematic, and fish migration routes are disrupted (Ysebaert et al., 2016). Furthermore, the dynamics that make the region resilient to climate change have been reduced, making it vulnerable to sea level rise.

A map indicating the different delta works and their construction date is given in Figure 4. Three main areas can be distinguished in de Southwest delta nowadays. The northern area includes the Rhine and Meuse River mouths (with discharges of resp. 1960 m^3/s and 230 m^3/s), via the Nieuwe Waterweg and Haringvliet-Hollands Diep. The latter is closed off from the North Sea by the Haringvlietdam. Since the closing of the Haringvlietdam, the sediment shortage has grown to 1000 million m^3. Transforming the dam to a storm surge barrier will decrease this shortage as the tidal prism will increase; it will then amount to 400 million m^3 (Hanon et al., 2020). Since 2018, the sluices in the dam are set ajar more frequently, with the strict requirement that salt water can not

Table 1. The main water basins in the Southwest Delta, their current characteristics and issues in relation to water quality and ecology, values for ca. 2016. (from Ysebaert et al., 2016)

Basin	Average tide[a] (m)	Salinity range[a] (psu)	Surface (ha)[b]	Issues in relation to water quality or ecology[c]
Northern rivers[d]	1.7–0.8	30–<0.5	7158	Salt intrusion
Biesbosch	0.3	<0.5	8278	Siltation, polluted river sediments
Hollands Diep	0.3	<0.5	4656	polluted river sediments
Haringvliet	0.3	<0.5	10,382	polluted river sediments, connection loss
Volkerak-Zoom	Non-tidal	0.6	7734	Extreme eutrophication, blue–green algae blooms, connection loss
Grevelingen	Non-tidal	28	13,446	Stratification, Oxygen problems, habitat loss
Lake Veere	0.1	25	2437	Oxygen depletion, macro-algae blooms
Oosterschelde	2.5–3.5	30–28	34,856	Morphological imbalance, habitat loss, erosion, invasive species, carrying capacity issues
Westerschelde	3.9–4.8	30–10	31,144	Eutrophication/oxygen, polluted sediments, habitat loss, dredging

[a] The first number in a range is the seaward average, the second number the landward average.
[b] Based on model calculations done in this study.
[c] Adapted from van Wesenbeeck et al., 2014.
[d] Northern rivers include Oude Maas, Nieuwe Maas and Nieuwe Waterweg.

intrude further than the Spui river branch. Secondly, the central area consists of four basins: Volkerak-Zoom, Grevelingen, Eastern Scheldt, and Lake Veere. They are largely independent from each other, and they all have their own water quality problems (Table 1). Volkerak-Zoom (fresh water) and Grevelingen (salt water) have only very limited water exchange through in- and outlets, and they are non-tidal. Lake Veere was non-tidal for 44 years, until a 10 cm microtidal range was facilitated in 2004. The Eastern Scheldt has a storm surge barrier rather than a dam, and a daily 2.5-3.5 m tidal amplitude. The morphology of the basin is still adapting to the reduced tidal prism, which results in erosion of banks and shoals (Figure 1). Lastly, the southern part is the Western Scheldt, which is the only remaining true estuary in the Delta (Ysebaert et al., 2016). It has a small fresh water supply of the Scheldt (105 m^3/s), and is extensively used for navigation by cargo ships for which regular dredging and dumping takes place to maintain the channel.

1.3 Double Dikes

To combat the problems for water safety and farmland deterioration that come with sea level rise, an accretion polder between "double dikes" is a potential mitigating solution (Figure 5). The concept of exchange polders is that a temporary inlet is created in the outer dike, and an inland sleeper dike is used to retain the water. Each tidal cycle – or artificially managed period of opening and closing the inlets – water flows into the confined polder, bringing in sediments. Therefore, accretion is taking place, and the elevation of the land will increase. In sediment rich places such as the Western Scheldt, this can be an elevation difference of several meters in 50 years (van Belzen et al., 2021). The elevated land forms a water safety buffer for the area behind the accretion polder. Also, saline seepage is reduced thanks to the increased elevation. In combination with the additional fertile marine clays, agricultural productivity can be enhanced. The period of accretion, in which it is not yet suitable as farmland, the polder can be used for tidal nature and recreation, and aquaculture and saline cultivation. In the Southwest Delta, this concept is not yet put into practice. However, in the northwestern Netherlands, a pilot location is built adjacent to the Eems estuary, starting 2018 and targeted end date 2022. This will contain two compartments, one of which is designated for pioneer saltmarsh formation, and the other for various aqua- and saline cultivations

1.4 Objective and approach

It is important to make the delta future proof. This includes ensuring tidal nature to persist despite historic damming and future sea level rise, to bend the curve of biodiversity decline. Also, water safety must be secured in the low-lying polders. The risks for agricultural yield should be minimized.

Figure 5. Phases of an exchange polder cycle (From WWF Netherlands)

In this study, the environmental drawbacks of the Delta Works and supplementary alterations are examined. This is done by researching the changes in the surface area of intertidal ecotopes between 1910/1920 and 2010/2020. Next, future scenarios are compared, in which the future development of intertidal nature under influence of sea level rise is hypothesized when no measures are taken and delta strategies are continued as usual, versus when measures are taken including opening of dams, suppletion of sediments, and creating exchange polders.

Then, sediment suppletions are explored in more detail. It is estimated what volumes of sand and mud are necessary to enable intertidal shoals and banks to keep up with sea level rise through accretion. Costs of these suppletions are approximated and the options for sand mining and mud resources are explored.

Furthermore, a case study about exchange polders is conducted to determine the potential of this measure for creating new intertidal nature as well as elevated, high-quality farmland. A spatial examination is done around the Haringvliet-Hollands Diep basin, identifying polders with the highest potential to create exchange polders. Local criteria are defined and applied.

Finally, the goal of this project is to create awareness on the ecological downsides of the delta works, and on the possible interventions for conserving and restoring delta functionalities. For this purpose, an infographic and an article are produced on these topics, informing professionals so they can incorporate the knowlegde in policies and visions for the future delta.

2. Methods

2.1 Changes in intertidal area

For a general impression of the effects of recent human interventions on the coast of the Netherlands, it was assessed how the tidal dynamics and salinity have changed in the last century. This was done for all basins along the Dutch Coast, and this resulted in a map describing the dams, impoldered areas, and changes in conditions since 1900.

To identify the historical changes in intertidal area in the Southwest Delta, a comparison was made between the historical situation dating ±1910-1920, and the recent situation between 2010 and 2020 (hereafter referred to as "current"). Furthermore, two future scenarios where sketched. An overview of the data sources can be found in Table 2. This research focuses especially on the saline intertidal area, as fresh water intertidal area does not provide the same ecotopes.

For the historical changes, georeferenced military maps were used (Figure 6A). These map sheets each cover 10 km by 6.2 km, and together cover the whole Netherlands. Example close-ups are shown in Figure 6B. The maps distinguish unvegetated intertidal shoals and banks. Vegetated salt marshes in the supratidal zone are also indicated, but the boundary between supratidal zones and permanently dry zones is not always indicated so it had to be approximated. The military maps were manually digitized to polygons in ArcGIS.

The current situation was based on various digital maps. The intertidal area in the Western Scheldt and Eastern Scheldt was derived from the salt-ecotope map by Rijkswaterstaat, dating from 2015 and 2016 respectively. For the Haringvliet-Hollands Diep, the distinction between intertidal area is not fully incorporated in the RWS ecotope maps. Therefore, polygons for this intertidal area were created based on model output created by Wijsman et al. (2018) for the situation after the Haringvliet Sluices Ajar Decree. From this model output, three ecotopes where selected and classified as intertidal area: (1) Permanent intertidal area, (2) Summer dry, which has daily tide in winter, and is dry in summer, and (3) High intertidal area. This was combined with the Ecotope map cycle 3, which is the most recent version dating from 2008-2012. In the Grevelingen and Volkerak no tide is present, so these waters do not have intertidal flats. In Lake Veere, a minor tidal amplitude of 10cm is introduced in 2004, but no maps are available identifying the area between the tidal water levels. Lake Veere is therefore assumed to have no intertidal area in the current situation.

2.2 Future Scenarios

Furthermore, two future scenarios were explored for 2050, without and with additional measures. The data sources are listed in Table 2. The first one, "2050 business as usual" assumes sea level rise but no additional measures for dams and intertidal areas. The development of shoals and banks in the Western Scheldt and Eastern Scheldt has been predicted by Holzhauer & Twisk (2009) for a SLR of 0.5m. In this scenario, Lake Veere, Grevelingen and Volkerak are assumed to still have closed dams, so these still do not include tidal flats when sea level rises. For the Haringvliet-Hollands Diep, 40 cm SLR is assumed compared to 2018, which is the Deltascenario "Warm" for the year 2050 (Wijsman et al., 2018).

The other scenario, "2050 dynamics and sediment", also assumes sea level rise, but includes additional measures to maintain the intertidal area. Dams of the Haringvliet, Grevelingen and Veerse Meer are (partly) opened to facilitate tidal range and sediment transport to the basins. Furthermore, sediment suppletions (sand and mud) take place in this scenario, to conserve the intertidal locations where erosion is taking place. Regarding the maps for this scenario, the

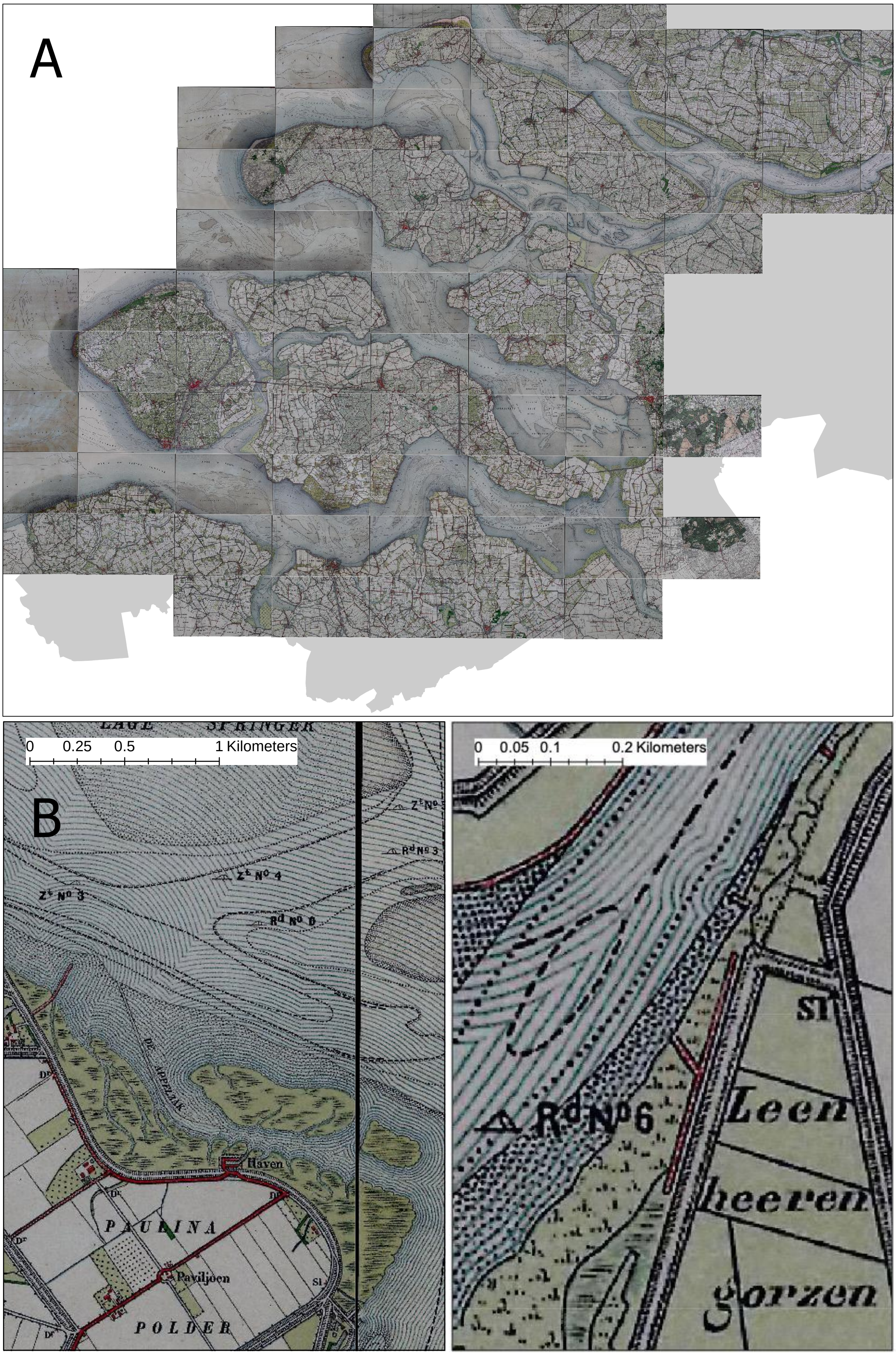


Figure 6. Overview (top) and zoom-in (bottom) of the military maps, "Bonnekaarten", used for the reconstruction of intertidal areas in 1915.

Table 2. Description of sources for the different stages and scenarios

Stage	Source[a]
1915	Bonnekaarten: Military maps ranging from 1910 to 1920
2020	Westerschelde: ecotope map Rijkswaterstaat (2015). Oosterschelde: ecotope map Rijkswaterstaat (2016). Grevelingen: non-tidal. Volkerak: non-tidal. Haringvliet-Hollands Diep: combination of model output from Wijsman et al. (2018). and Ecotope map cycle 3, from Rijkswaterstaat (2008).
2050 Business as usual	Westerschelde: Prognosis by Holzhauer & Twisk (2009), Deltares. Oosterschelde: Prognosis by Holzhauer & Twisk (2009), Deltares. Grevelingen non-tidal. Volkerak: non-tidal. Haringvliet-Hollands Diep: empty, due to erosion, SLR, no salinity gradient.
2050 Dynamics and Sediment	Westerschelde: assumed to be conserved at constant level through suppletions: ecotope map Rijkswaterstaat (2015). Oosterschelde: assumed to be conserved at constant level through suppletions: ecotope map Rijkswaterstaat (2016). Grevelingen: model output from Tangelder et al. (2019) for 50 cm tidal range. Volkerak: excluded from this scenario: unknown. Haringvliet-Hollands Diep: model output from Wijsman et al. (2018) who assume 40 cm SLR, 1,40 m tidal range and no erosion.

[a] Biesbosch is excluded from this timeline

intertidal area in the Western Scheldt and Eastern Scheldt is assumed to be kept at constant level as the current situation, so this is based on the salt-ecotope map by Rijkswaterstaat. For the Grevelingen, model output from Tangelder et al. (2019) is used, which assumes a SLR of 10 cm between the years 1995 and 2025, and 50 cm tidal range in the Grevelingen water level. For the Haringvliet-Hollands Diep, model output from Wijsman et al. (2018) was used, which is based on a situation with 40 cm SLR (Deltascenario "Warm" between 2018 and 2050), and the Haringvlietdam to be implemented as a storm surge barrier, resulting in a tidal range of 1,40m. In this specific scenario, the sluices are constantly open at their maximum of 0.5 m, apart from sea water levels of >2m occurring once every ±10 years. Nonetheless, the dam construction will still be present in the mouth of the Haringvliet, so sediment and flow volumes will still be reduced.

2.3 Sediment shortage due to SLR

The sediment shortages in the different tidal basins and estuaries, which develop as a consequence of sea level rise, were calculated for the different sub-systems along the Dutch coast. This was done using:

$$sediment\ shortage = sea\ level\ rise\ \times\ surface\ area$$

which gives the shortage in m^3/year for a certain rising rate (m/yr) of the local sea level and the size of the basin/estuary (m^2) (Mulder, 2019). The approximation was done for different climate scenarios: Deltascenario, RCP 4.5 and RCP 8.5, for the years 2000, 2050, 2075 and 2100.

As it allows a linear relationship between sea level rise and the volume of the shortage, it is a simplified approach that does not include local processes and changes in dynamics of the tide. When the sea level rises, tidal amplitudes at an estuary/basin mouth are likely to change due to a shift in amphidromic points (zero tidal amplitude) (Leuven et al., 2019). This changes the local distribution of sediment. The linear approach most likely provides a minimum value for the actual shortage.

The estimated volumes of sediments were compared to the current suppletion volume, and to future suppletion volumes for the entire Dutch coast. Costs of these suppletions was estimated using an average price of €5/m^3. It was then explored how the shortage-volume related to the reservation area for sand mining in the North Sea, to see whether the current reservation area suffices when extraction depths of 2 and 8m are used.

2.4 Exchange polder location Haringvliet-Hollands Diep

The second potential measure for nature conservation – exchange polders – is assessed for polders around the Haringvliet-Hollands Diep. First, a list of criteria was formulated (Table 3), with requirements that can be judged using remote (map) data. The maximum elevation of the polder is a fundamental requirement. It must be below the maximum water level to periodically flood and be under influence of sedimentation processes. It was chosen to lower the maximum accepted elevation to an elevation where it can initially be submerged for >50% of the time, as arbitrary threshold of when it is worth transforming an area, compared to the potential land level rise. The elevation corresponding to a 50% submergence time was analyzed by deducting the cumulative temporal distribution from local water level data between May 2017 and May 2021.

The Haringvliet-Hollands Diep area was assessed in ArcGIS based on those criteria, to select locations with potential to be used as an exchange polder with double dikes, It was calculated how much water volume will have to flow in and out through the openings with every tide to give an indication for the amount of natural sediment supply (when combined with suspended sediment concentration) and the hydrodynamic forces to spread out possible artificial sediment suppletions. This is the same volume as the amount of sediment that is necessary to elevate the polders to their maximum level in the first exchange polder cycle, after which it can be closed off again and be used for freshwater agriculture.

Lastly, experts on morphological processes in estuaries and exchange polders were interviewed to assemble different ideas about the implementation and optimalization of exchange polders in the Southwest Delta. These experts are Peter van Veelen (director of Buro Waterfront and involved with Proeftuin Sediment Rijnmond), Jim van Velzen (researcher at NIOZ, a.o. on exchange polders), and Gerard Litjens (director of Bureau Stroming and designer of pilots for exchange polders).

Table 3. List of criteria applied to the Haringvliet-Hollands Diep area to identify the most suitable locations for accretion polders between double dikes.

Criterium	**Data/Method**
An elevation below the mean Haringvliet waterlevel	Water level data from 01/05/2017 to 01/05/2021 with 10 min interval (Rijkswaterstaat), combined with Digital terrain model AHN3 (resolution 5m)
Limited housing and company buildings	Visual assessment of satellite imagery & Kadaster dataset
Sleeper dike present behind the current dike. This can be partly or fully around the exchange polder site.	Digital terrain model AHN3 (resolution 5m)
Between 200 and 2000 m perpendicular to the dike.	GIS
At least 200m length along the dike.	GIS
Tidal amplitude is at least 30 cm.	Water level data from 01/05/2017 to 01/05/2021 with 10 min interval (Rijkswaterstaat)

2.5 Salinization and agriculture

To sketch the effects of optimal exchange polder implementation compared to autonomous (scenario Business as usual) developments, a hypothesis was formulated about future sea level rise, salinization, and consequential crop loss. The available knowledge on this process and region was assembled. Data on this topic is scarce, so different assumptions have been made. It is assumed that continued sea level rise will intensify the salt-pressure on ground water and soil moisture in low lying polders, and that this will surpass salt tolerance levels of part of the crops in the Southwest Delta. Furthermore, in the case of exchange polders, is it suggested that this can form fresh water lenses below the elevated land (ExpeditieWaddenkust, 2021). An exchange polder is assumed to be used partly for intertidal nature, and partly for aquaculture and subsequently for saline and freshwater agriculture once high enough.

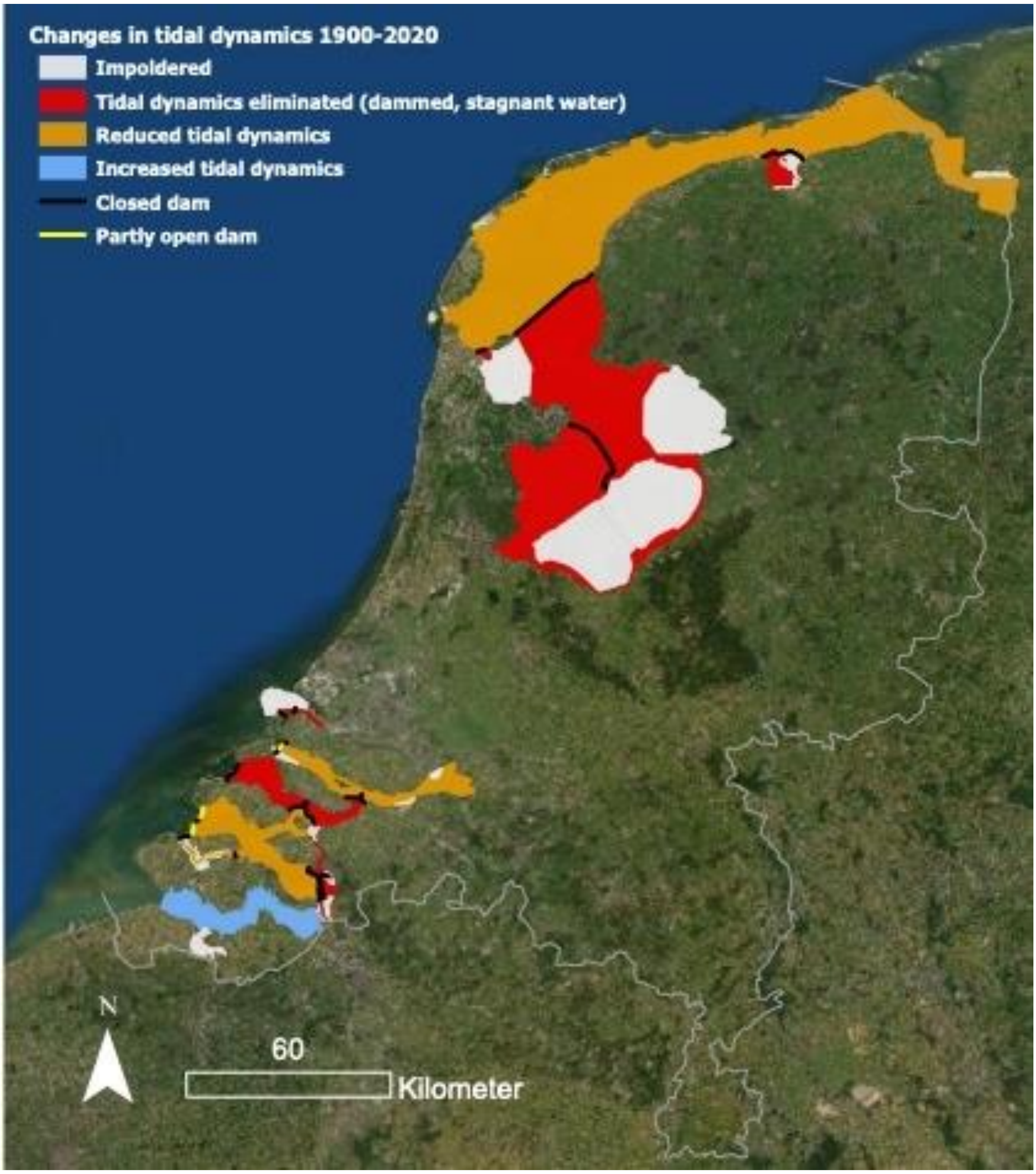


Figure 7. Changes in tidal dynamics since 1900, and location of different dams and storm surges.

3. Results

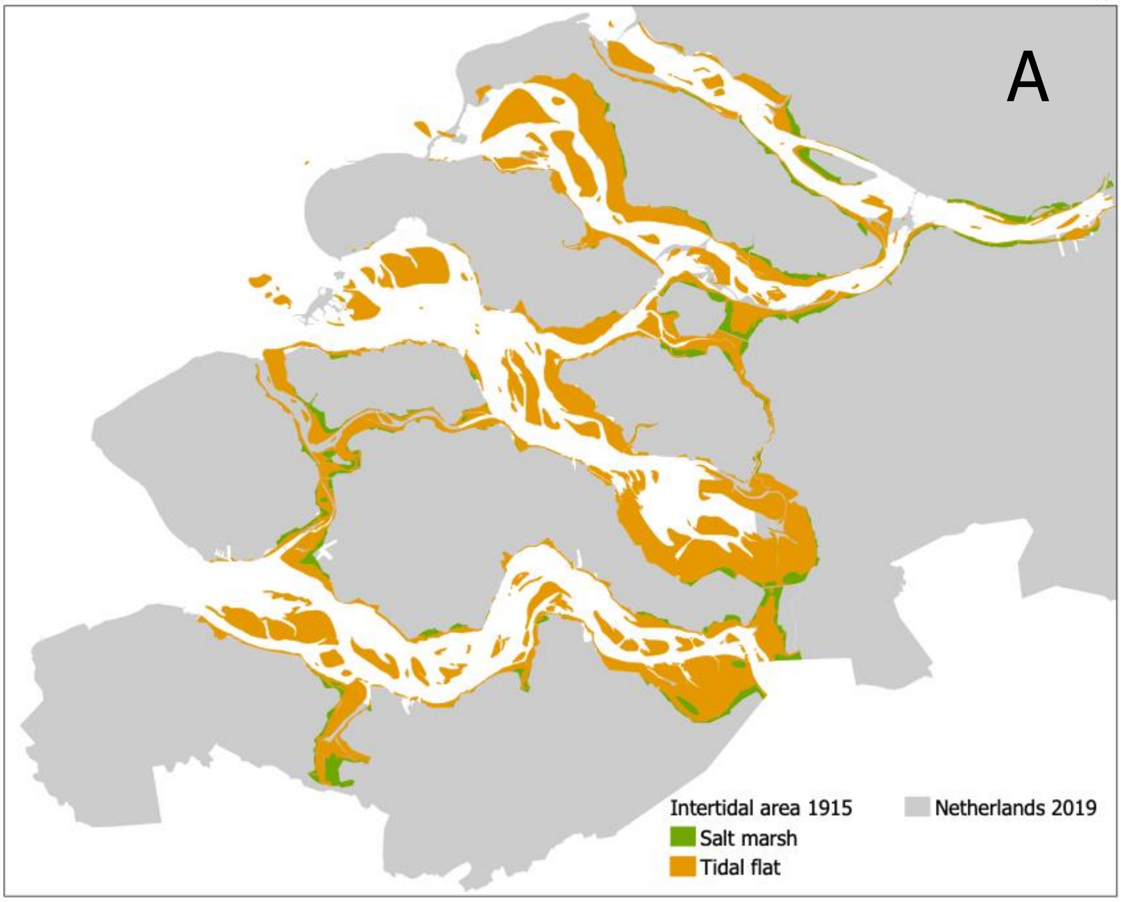
3.1 Changes in intertidal area 1915-2020

Figure 7 shows a map of the changes in tidal dynamics in the Dutch waters. It shows that nearly all former tidal waters have reduced or eliminated tidal dynamics due to damming. The former Zuiderzee (now Ijsselmeer and Markermeer) has been dammed, which reduces the tidal prism in the Wadden Sea. The Western Scheldt is an exception. Due to the intense dredging activities, the estuary is streamlined – the flow of water is subject to less friction. This allows for more water to flow in and out during each tidal cycle.

The digitalization of the historical situation (ca. 1915) of intertidal area in the Southwest Delta can be seen in Figure 8A. A total area of 486 km^2 was within intertidal range. Intertidal area has been divided in tidal flats (unvegetated) and salt marshes (vegetated). Every basin and estuary had large intertidal areas, especially in the smaller side branches, and in the locations where the basins are relatively wide. The vegetated salt marshes are found mostly in the smaller side branches as well, and on the landward (eastern) side of the basins. Figure 8B shows the recent situation. The total intertidal surface area in the study area in 2015/2020 is 211 km^2, which is excluding the freshwater intertidal area in the Haringvliet basin (25 km^2). The differences between 1915 and 2015/2020 are indicated in Figure 9 as a map, as well as the areas per basin. A loss of 56.4% is found compared to 100 years previous.

In the Haringvliet-Hollands Diep, no saline intertidal area is left (Figure 9A), as the construction of the Haringvlietdam in 1971 has caused the basin to become fresh. Due to its connection to the Nieuwe Waterweg, there is still a tidal range in the Haringvliet-Hollands Diep. Thanks to the sluices Ajar Decree, the connectivity of the basin with the sea is partly restored. Yet the tidal range has not significantly increased, and no significant fresh-salt water gradients have been re-introduced. The changes in the (type of) intertidal area for the Haringvliet-Hollands Diep are provided in Appendix 1. Large parts of the intertidal area have disappeared. At the banks, most declines are on the waterside, and some new areas have developed on the landward side: the intertidal area has shifted closer to the dikes. On the island of Tiengemeten, new area has developed due to the creation of a breach in the dike in 2007, allowing a new fresh water tidal area to develop in the former polder. Currently, the Grevelingen (salt water) and Volkerak (fresh water) are enclosed by dams on both sides, and no tidal influence is left. Even though some former shoals are maintained with bank reinforcement, the water level does not change with eb and flood, hence these islands cannot be classified as intertidal ecotopes.

In the Eastern Scheldt, the intertidal flats on shoals and banks have shrunk (Figure 9A). The net loss is 70 km^2 of the initial 174 km^2. At the eastern end, the Oesterdam has created a no-tide zone behind the dam. This has caused the largest decline in intertidal area in the Eastern Scheldt. Lake Veere has lost nearly all of its intertidal nature due to the two dams on either end of the lake. Since 2004, there is a water passage in the Zandkreekdam on the east side. This creates a tidal amplitude of ±12 cm. The small portion of intertidal area that has been recovered because of this is not included in this map. The Western Scheldt has a net loss of 40 km^2 compared to 148 km^2 in 1915. It shows significant amounts of new intertidal area on the shoals in the middle of the estuary, despite also having lost areas. The shoals have moved and changed shape, but did not shrink as much as in the other basins. Yet, large losses in intertidal area happened by land reclamation in the former *Sloe*, which connected Lake Veere with the Western Scheldt. The same happened with the *Braakman* on the south side of the Western Scheldt, and the *Slikken van Hinkelenoord* in the northeast.



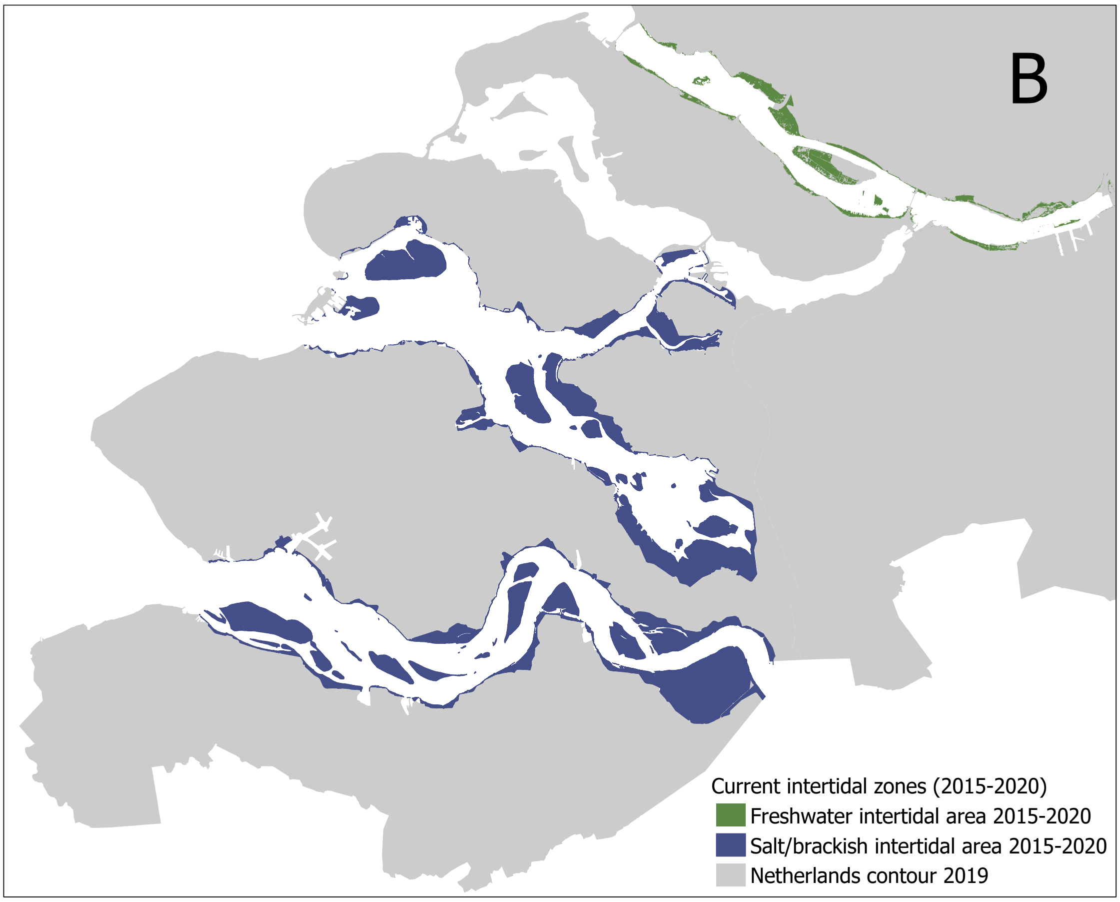
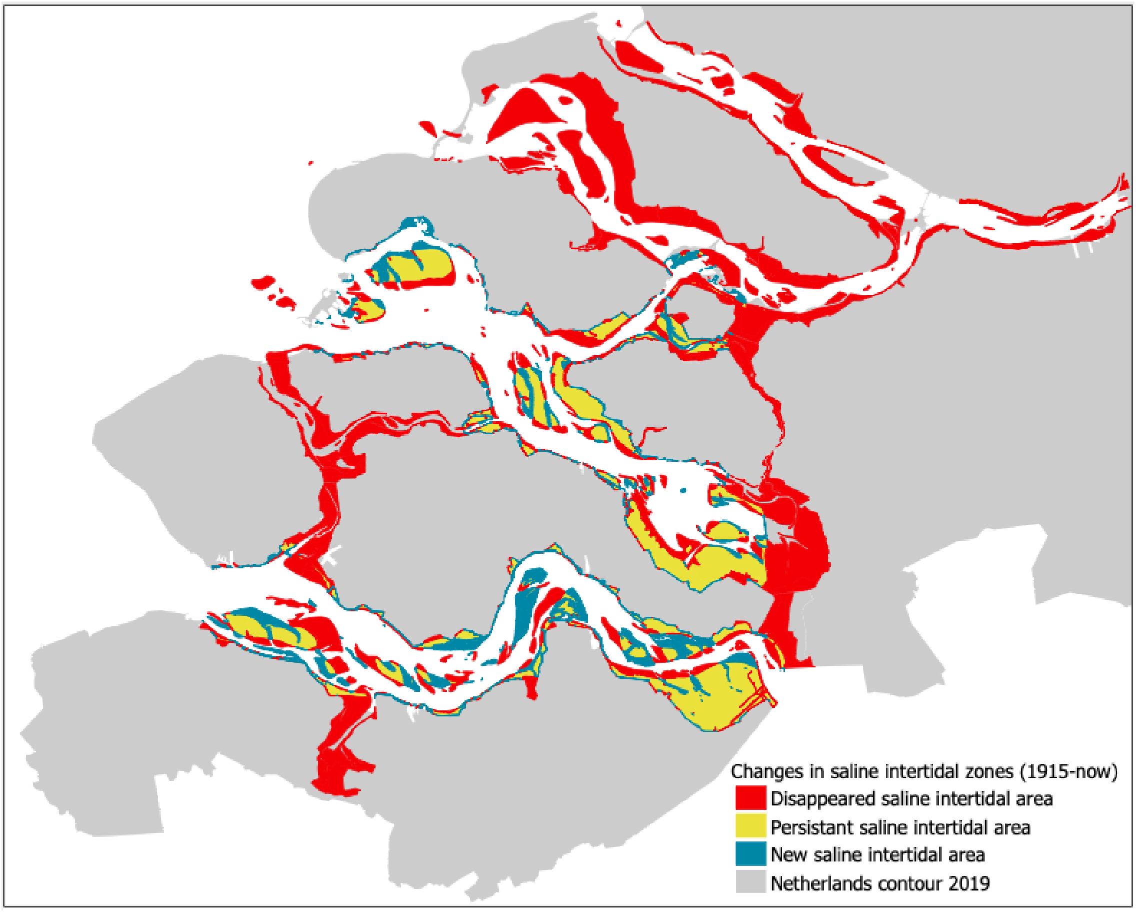


Figure 8. Intertidal area in the Southwest delta in 1915 (A) and 2015-2020 (B).



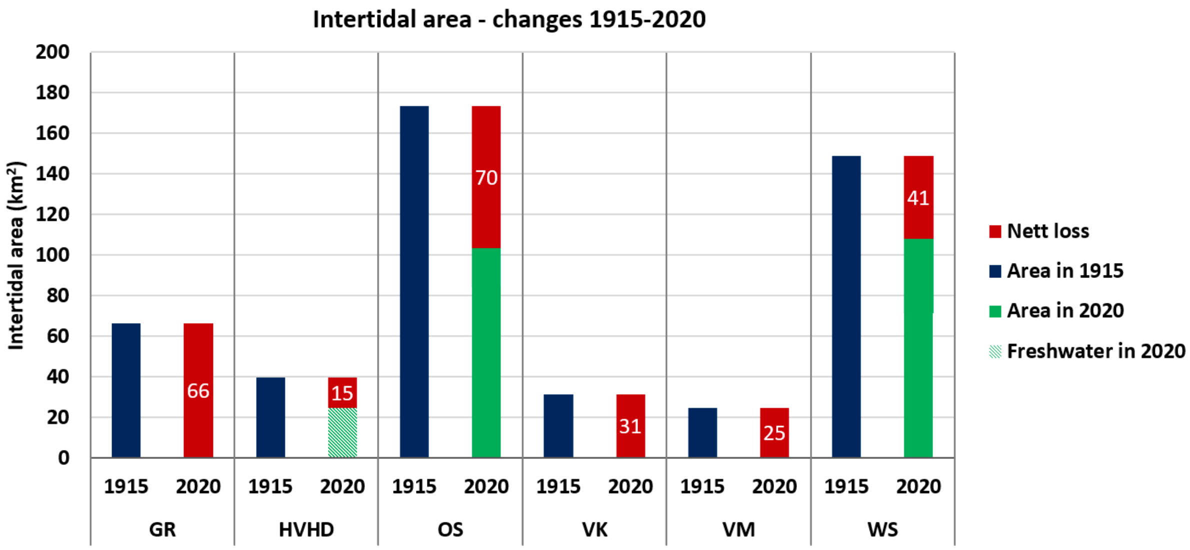


Figure 9. Differences in saline intertidal area between 1915 and the current state. In the map, intertidal area that has become freshwater influenced is marked "disappeared". In the dammed and embanked areas, all saline intertidal area is gone. The majority of the new intertidal area developed in the Western Scheldt estuary.

3.2 Future scenarios

The expected intertidal area is sketched for two future scenarios. In the first scenario current policy is continued: “Business as usual”. The second scenario includes allowing more tidal dynamics into the basins by (partly) opening the dams, and sediment suppletions to compensate for the shortage of sand and mud caused by sea level rise: “Dynamics and Sediment”.

Intertidal area for the scenario “Business as Usual” is shown in Figure 10A. No intertidal area will be restored in the Grevelingen and Volkerak as their dams remain closed. Policy choices for the Haringvlietdam and mouth of the Nieuwe Waterweg will determine if the water level in the Haringvliet-Hollands Diep will rise with sea level. Either way, no or negligible intertidal area will be left: if the water level rises, too little sediment is available for the intertidal areas to grow as well, so they will drown. If the water level is kept artificially low, minimal practice in line with the Sluices Ajar Decree can take place due to the large water level difference inside and outside the dam. Sluices will therefore be permanently closed. The tidal range will thus be reduced to ±0m, leaving no intertidal area. In the Eastern Scheldt, the banks and shoals will shrink due to sea level rise of 50 cm. It is currently already under influence of so called “sand starvation”, as the reduced tidal prism causes shoals to erode and sediment to be deposited in the channels, as too little new sediment is supplied. This sediment shortage will deteriorate when the sea level rises. In the Western Scheldt, the total intertidal area will slightly decrease for a SLR of 50 cm, yet this estuary can largely keep growing with sea level rise due to its open connection with the sea.

Results for the scenario “Dynamics and Sediment” are given in in Figure 10B. Intertidal area is restored in the Haringvliet by opening the sluices permanently (storm surge barrier policy). This allows saline water to enter the estuary, creating a salt-gradient from sea to river and increasing the tidal range. This scenario’s saline intertidal area will therefore be larger than the current fresh water intertidal area. For the Grevelingen, the intertidal area for a tidal range of 50 cm is shown. This causes part of the intertidal area to be restored. Geographically, the Volkerak also has potential for connectivity restoration for salinity gradients and tidal range, yet this is not included in this scenario. For the Eastern Scheldt it is assumed that the current intertidal area is conserved by adding extra sediment to the system. This is also the case for the Western Scheldt, yet the volume of sediment suppletion that is necessary in this estuary is negligible.

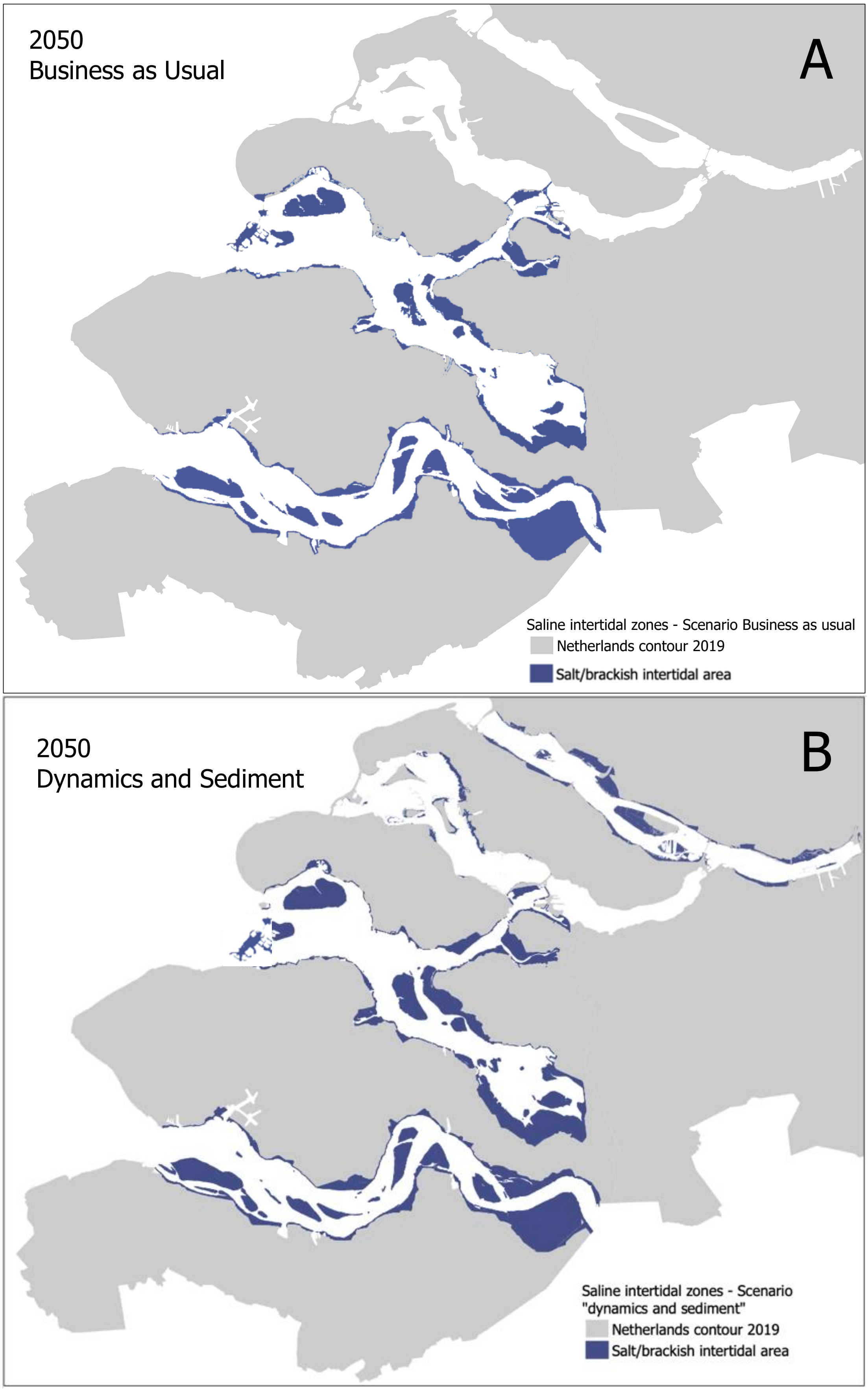


Figure 10. Estimated intertidal areas in 2050 for two scenarios: (A) Business as usual with sea level rise and unchanged dams, and (B) Dynamics and Sediment with sea level rise, increased tidal dynamics through opened dams, and sediment suppletions.

3.3 Sediment shortages due to sea level rise

The sediment shortage that occurs when sea level rises are given below in Table 4 and Figure 11, for the range of SLR rates for RCP4.5 (Mulder, 2019). These are the volumes that will have to be added to the systems to enable the system to grow with sea level rise, assuming that the shortage (m^3) is described by sea level rise (m/year) × surface area (m^2). The coastal fundament can supply a maximum of 15 million m^3 of sediment per year to the Wadden Sea. Shortages above this level, which occur when sea level rise exceeds 6 mm/year, must be compensated by local suppletions. The maximum transport from the coastal fundament to the Western Scheldt is not yet surpassed with the sea level rising rates used below, so no local sediment suppletions are necessary. The share of the Southwest Delta compared to the total sediment shortage is 8.5%.

Table 4. Sediment shortages per sub-system, given for different sea level rise rates for RCP 4.5

		Current	RCP 4.5 lower-value 2020-2050	RCP 4.5 upper-value 2020-2050	RCP 4.5 lower - value 2050-2100	RCP 4.5 upper-value 2050-2100
SLR (mm/year)		2	6	12	17	30
Sediment shortage ($\times 10^6$ m^3)	Coastal fundament	13.6	40.8	66.6	88.1	144.0
	Wadden Sea	0.0	0.0	15.0	27.5	60.0
	Western Scheldt	0	0	0	0	0
	Eastern Scheldt	0.7	2.1	4.2	6.0	10.5
	Lake Veere	0.1	0.2	0.5	0.7	1.2
	Grevelingen	0.3	0.8	1.7	2.4	4.2
	Haringv.-Hollands D.	0.2	0.6	1.2	1.7	3.0
Southwest Delta total ($\times 10^6$ m^3)		1.3	3.8	7.6	10.7	18.9
Total ($\times 10^6$ m^3)		14.9	44.6	89.2	126.3	222.9

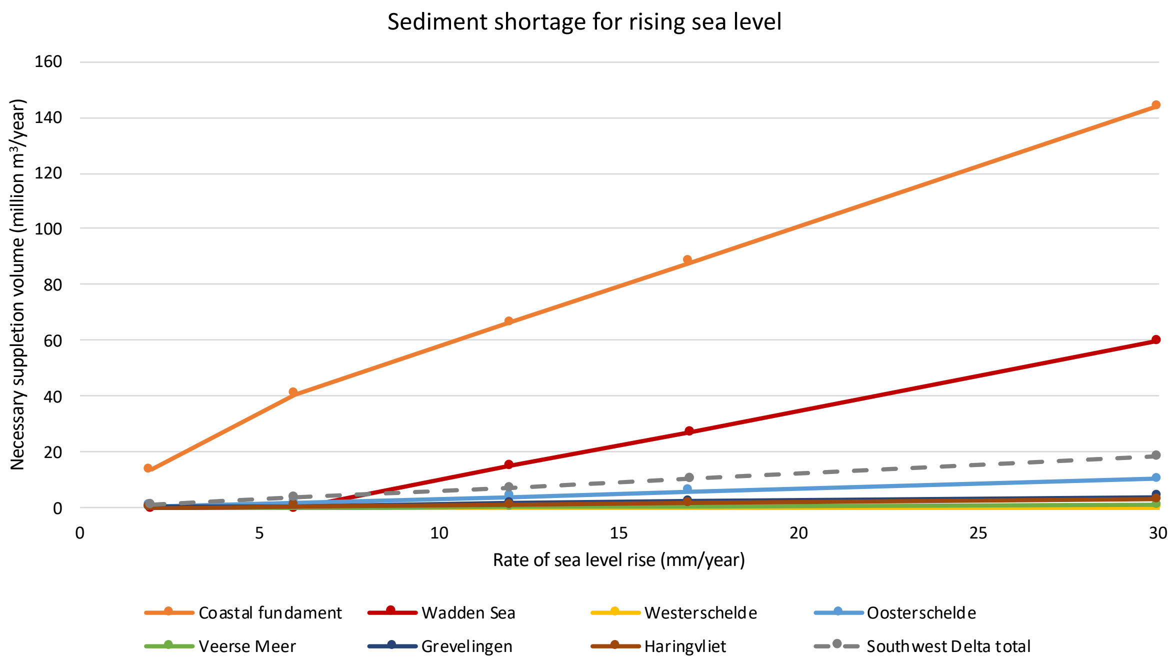


Figure 11. Sediment suppletion volumes that are necessary to compensate for sea level rise, per sub-system.

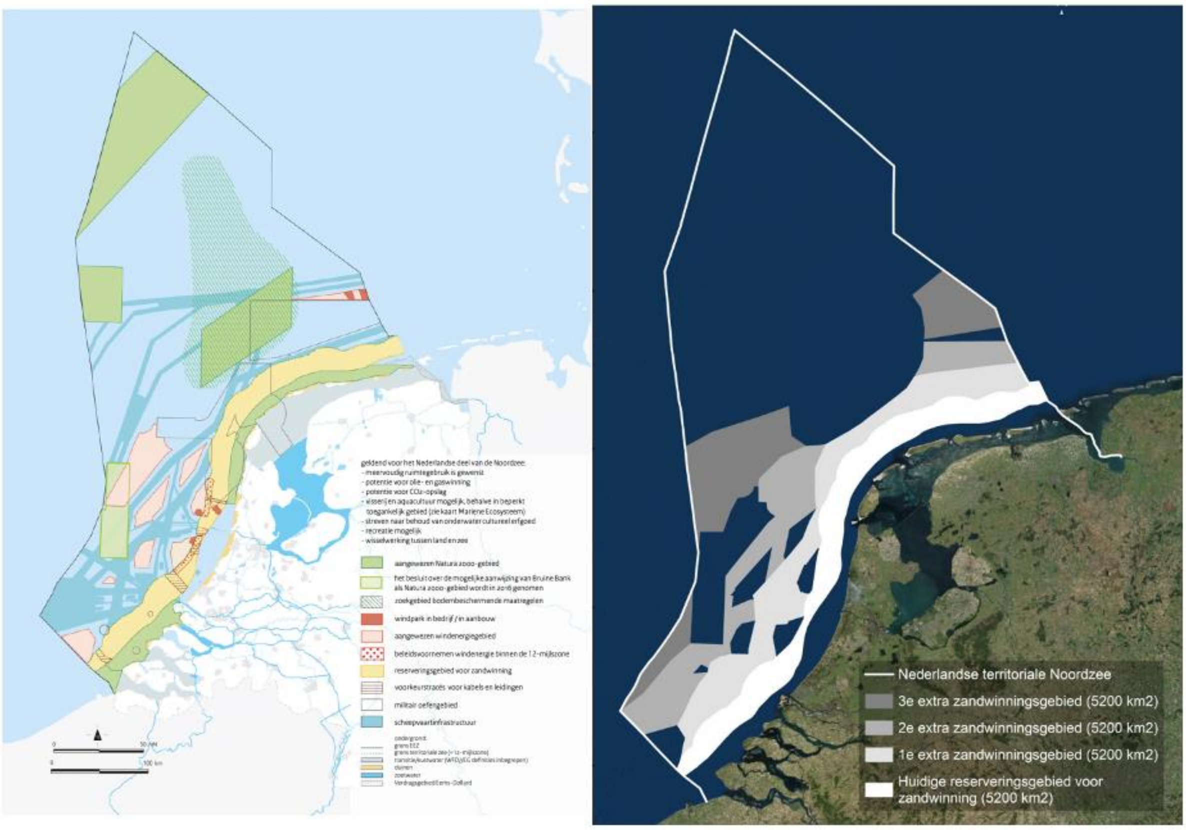


Figure 12. Left: Structure Vision North Sea with the area reserved for sand extraction in yellow (Beleidsnota Noordzee 2016-2021). Right: possible extra regions for sand extraction (Haasnoot et al., 2018). The primary reservation area is likely to suffice for RCP4.5.

The sand volumes in the North Sea are sufficient to provide the volumes necessary for sand suppletion. Sand extraction currently takes place in a designated 5200 km^2 area nearby the coastal fundament (Figure 12). The true availability and usability of the sediment depends on sand quality, space occupied by other functions, and extraction depth (Haasnoot et al., 2018). A yearly average of 25 million m^3 is currently extracted from the North Sea, of which 50% is used as suppletion sand and 50% as construction sand. The usual extraction depth in the most recent years was 2 meters, and the space used amounted to 12-18 km^2 per year. In the Policy Paper North Sea 2016-2021, it is expressed that the preference is to extend the maximum extraction depth to 6-8 m. The total space necessary for extraction was calculated by Mulder et al., (2019) for RCP4.5. With an extraction depth of 2m, this scenario will result in a necessary space of 70-128% (lower boundary to upper boundary of RCP4.5) of the designated area in the 80 years between 2020 and 2100. Thus, some areas will need to be extracted multiple times when the upper limit of sea level rise according to RCP4.5 takes place. This changes for an extraction depth of 8m, which results in 20-36% space use of the total 5200 km^2.

The costs of the suppletions are shown in Figure 13. Costs per cubic meter range between €3.50 and €5.00, and in the graph the upper range limit is assumed. Costs will rise slowly until ±2050, after which the sea level rise will accelerate according to RCP4.5 and RCP8.5, and therefore also the suppletion costs.

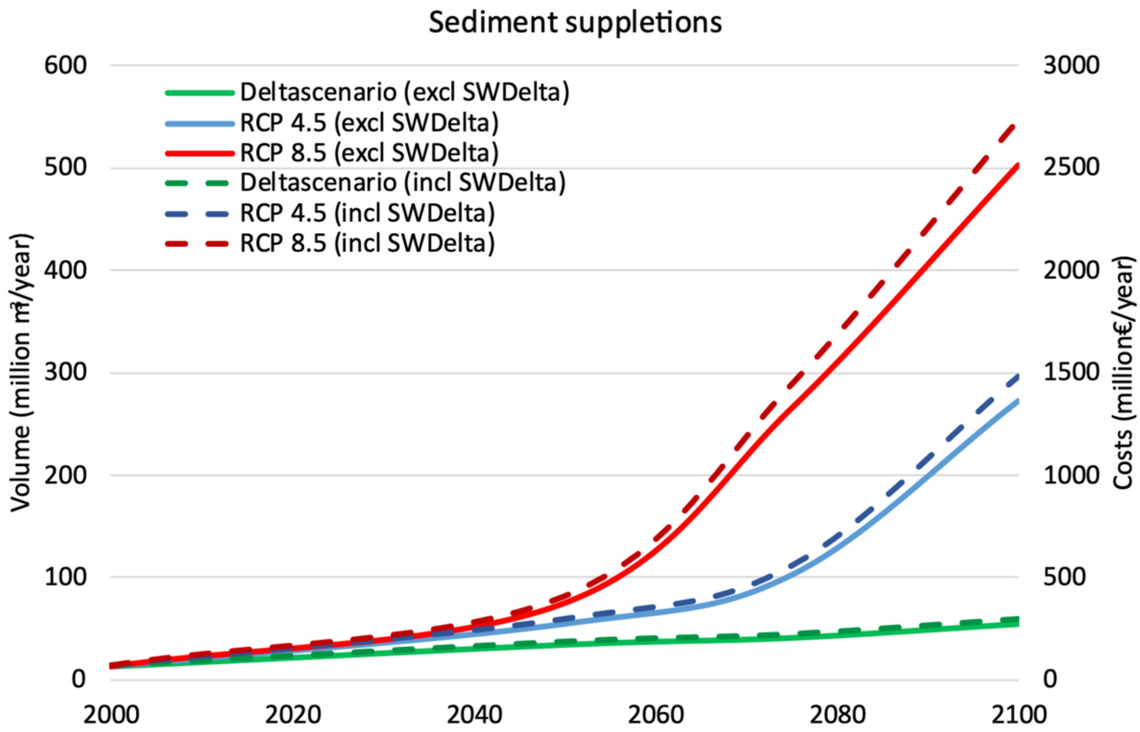


Figure 13. Sediment suppletion volumes and their associated costs for the different sea level rise scenarios. Dashed lines include the Southwest Delta, continued lines do not include the Delta. Considering the amount of sand in the North Sea, this is hypothetically possible, even in the extreme SLR scenario.

3.4 Exchange polders locations Haringvliet-Hollands Diep

A selection of locations was made to identify where double dikes will have the most potential for implementation. The selection was based on size, sleeper dike, elevation, and buildings (see Table 3 in Methods). The criterium for elevation is dependent on the tidal range, as preference was given to polders which would initially have a <50% submergence time. The cumulative water level occurrence (Figure 14A) is given for Rak Noord, located next to the Haringvlietbrug between Haringvliet and Hollands Diep. Water levels are mostly between 10cm and 100cm above NAP. For an initial <50% submergence time, polders must be below 45cm. It can then be subject to enough tidal in and outflow to silt up, although this is not an exact limit. Still, if a polder has a higher elevation, less land level rise is possible and it gives less potential for intertidal nature, so the balance between investment and benefits of this measure are less favourable. If the Haringvliet dams are opened further, the tidal amplitude will change. At Stellendam Buiten (Figure 14B) at the seaward side of the dam, a polder should be lower than -10 cm NAP to be >50% submerged. However, as the tidal range is larger, a larger volume of water will flow in and out every tide.

The selection of potential exchange polder sites are depicted in Figure 15. Enlarged versions op the maps can be found in Appendix 2 and 3. Sizes and remarks for every site is given in Table 5 with corresponding numbering. A total of 1580 hectares is selected. For every selected potential polder, the volume of sediment is calculated that is necessary to enable accretion of the polder to an elevation of 90% de-submergence. A total of 17.89 million m^3 of sediment is needed to raise all selected areas to an elevation of 80cm.

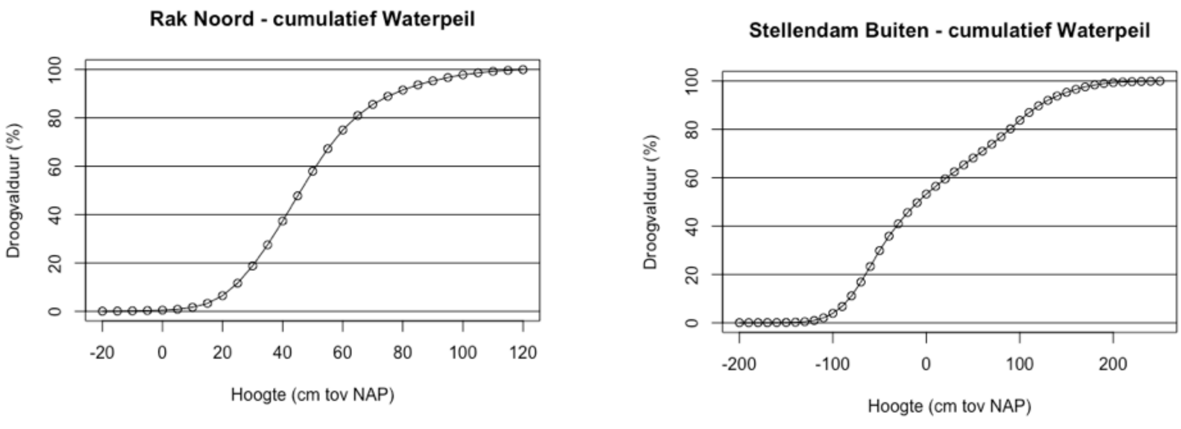


Figure 14. Cumulative water level occurrence given as de-submergence time (%) for Rak Noord at the center south of the Haringvliet-Hollands Diep (A) and for Stellendam Buiten at the seaside of the dam (B). Values are based on water level records from May 2017 to May 2021 with a 10-minute interval (Rijkswaterstaat). Submergence time = 100(%) – de-submergence time(%).

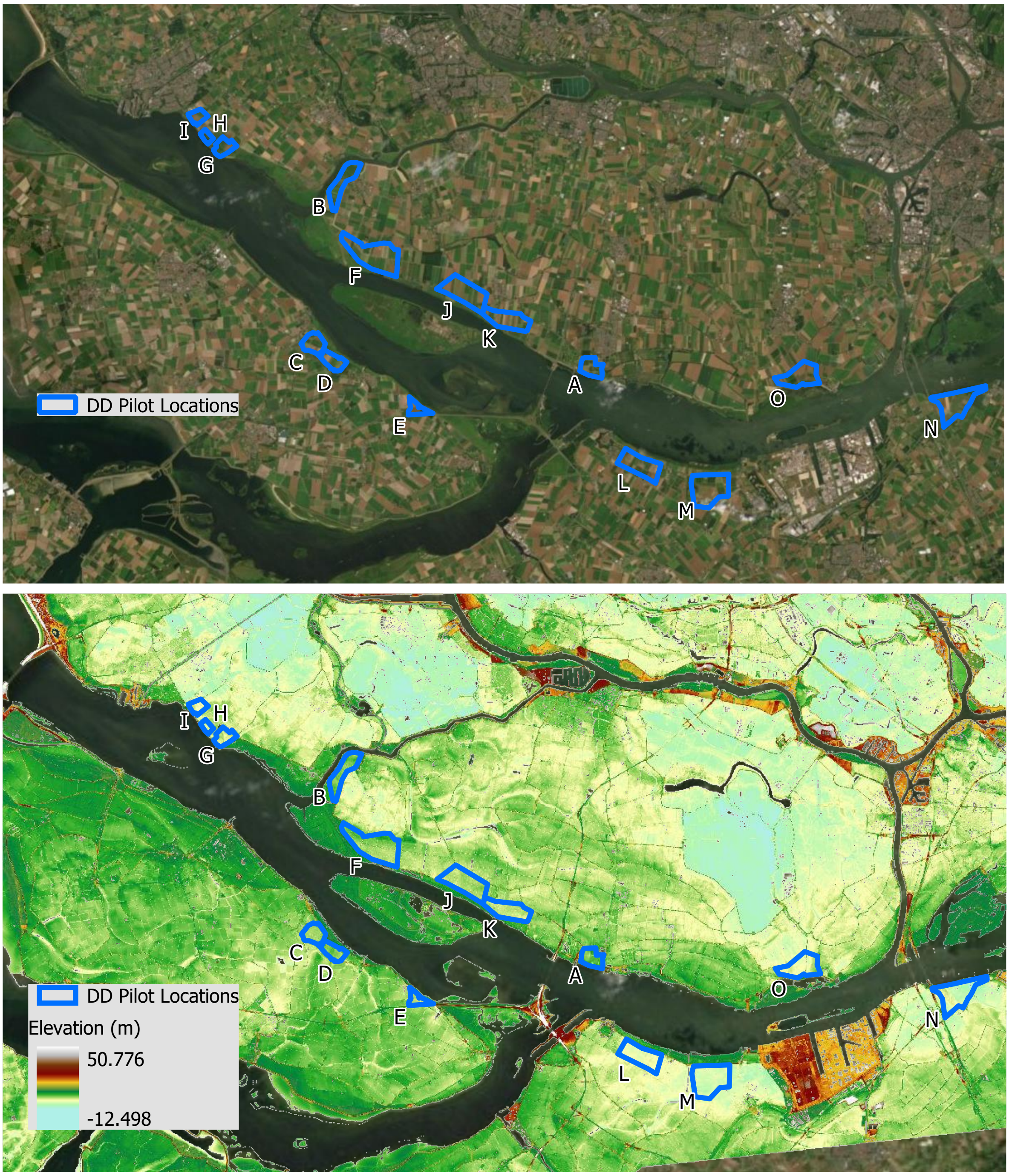


Figure 15. Selection of locations that have potential for double dike accretion polders. Top: selected locations on arial imagery background. Bottom: selected locations on elevation map background.

Table 5. Details per potential double dike location

Site [c]	**Area** *(ha)*	**Elevation** *(m)* [d]	**×10⁶ m³ until max water level (80cm)** [b]	**Diked perimeter** *(km of (sleeper)dike out of circumference)* [e]	**Width (perpendicular)** *(m)*	**Length (along dike)** *(m)*	**Construction** *(number of compounds)* [f]	**Remarks**
A	66	0.396	0.27	3.8 / 3.8	0.84	1.0	None	Leenheerenpolder
B	110	0.236	0.62	5.7 / 5.7	0.63	3.5	Minimal (2)	Molenpolder
C	70	-0.002	0.56	2.4 / 3.5	0.85	1.0	Minimal (2)	Next to stream
D	51	0.091	0.36	2.7 / 3.3	1.00	1.6	Minimal	
E	37	-0.067	0.32	2.6 / 3.5	0.40	0.9	None	Partly forest. Adjacent highway (-)
F	247	0.130	1.65	6.4 / 7.6	1.00	2.8	Significant (>10)	Housing on sleeper dike (-)
G	51	-0.287	0.55	1.5 / 3.1	0.60	1.0	Minimal (3)	Saline potential (+)[a]
H	19	-0.409	0.23	0.6 / 1.8	0.39	0.6	None-minimal	Saline potential (+)[a]
I	36	-0.507	0.47	0.7 / 2.5	0.70	0.6	Minimal	Saline potential (+)[a]
J	175	-0.058	1.50	4.0 / 6.0	0.87	2.1	Significant (>10)	Housing on sleeper dike (-)
K	132	-0.474	1.68	2.3 / 5.4	0.80	1.8	Minimal (3 and road)	
L	130	-0.418	1.58	3.4 / 5.4	0.74	2.1	Significant (>10)	Stream crossing through. Housing on sleeper dike (-)
M	143	-0.700	2.15	1.8 / 5.5	0.75	1.8	Minimal (4)	
N	206	-0.988	2.61	3.1 / 5.9	1.00	1.5	Significant (4-8)	Small stream crossing through
O	173	-1.007	3.13	2.7 / 7.1	1.00	2.0	Minimal (3)	(rail)roads nearby (-)
Total	1586.2		17.69	± 43.8 / 70.0		24.2		

[a] Potential for saline nature, because of its location west of the Spui-Middelharnis-line

[b] This volume indicates both the tidal volume that can flow in and out the exchange polder each tidal cycle, as well as the volume of sediment necessary to raise the land to the maximum elevation.

Colour categories:

[c] Suitability estimation based on characteristics	Sufficient	Good	High
[d] Elevation	>0 m	-0.5-0m	<-0.5 m
[e] Percentage of perimeter with existing dike	25-50%	50-75%	75-100%
[f] Construction (nr of compounds)	>4	3-4	0-2

Lessons from Experts

Below, a summary is provided from the lessons learned from experts on the topic and the region.

Jim van Belzen:

An exchange polder needs to be under influence of enough tidal dynamics to facilitate it to silt up. The initial elevation of the exchange polder influences the possibilities for aquaculture, and nature. If a polder lies below -0.5 m, it will be permanently submerged although the water depth varies with tide. It is possible to create an exchange polder where initially only subtidal nature is present. Lower lying polders can eventually reach a larger elevation difference through sedimentation. Sedimentation speeds are asymptotically related to the difference between the polder level and the maximum water level. A low polder will first silt up fast, but this rate decreases when it grows higher and reaches the maximum water level.

Optimizing the inlet and outlet of the exchange polders can increase the sedimentation rate. The aim is to bring as in as much sediment as possible, and to let out only water. Possibilities are:

- Timing the moment of water inflow to occur when suspended sediment concentrations in the water are high. This is often the case when wind speeds are high, or during specific river discharge periods.
- Manipulating the speeds of inflow and outflow. Water with higher energy can carry more sediment. Increasing the speed of the inflow could bring in more sediment. Reducing the outflow speed can prevent too much sediment from leaving the exchange polder.
- Making the water stagnant for a period, to enable the smallest sediment particles to deposit. If the inlets are open during flood, and the water is retained for another tidal cycle until it is allowed to flow out, this can optimize the sedimentation rate.
- Adapting to neap tide and spring tide cycles. This cycle determines the bottom shear stress experienced by plants and sediments. During neap tide, shear stress is lower, making it easier for new plants to settle than during spring tide. The same is true for sediment deposition, as reduced shear stress causes reduced erosion.
- Artificial suppletion of sediments. This can be done by spraying sand on the exchange polders or by depositing it locally and allowing the water to distribute it.

Peter van Veelen:

We need to know if exchange polders are a concept that are suitable for the Haringvliet-Hollands Diep, as it is relatively sediment poor. Most of the sediment is supplied from the rivers: mostly from the Merwedes and Biesbosch. The sediment concentration reduces in western direction. The largest particles deposit immediately when the flow velocity is reduced. This happens near Moerdijk. Crossing the Hollands Diep from Moerdijk to the Dordtsche Kil, a navigation channel is maintained for accessibility to the port of Moerdijk. It is regularly dredged, and filled up due to new sediment deposition. The dredged material is mostly deposited in a large depot. This mud has large potential to be applied on the shoals and banks of the Haringvliet-Hollands Diep.

An aspect that is relevant to the selection of a location for an exchange polder, is the presence of very deep channels directly adjacent to a dike. In such situations, there is a risk of "zettingsvloeiing", when the dike stability is too poor and the dike slides into the channel. On locations where this risk is high, water safety measures through expanding in seaward direction is impossible, and measures in landward direction become more likely.

The Leenheerenpolder is a location that seems to be suitable as an exchange polder. Also, public support is already high for this polder. A possibility for sediment suppletion is to release it in the Spui river, which can distribute it over the polder. The location and characteristics of the inlet then need to be aimed at receiving as much sediment as possible. It is important to know the local dynamics to estimate the sediment carrying capacity of the water: currently the largest erosive forces are from wind-driven waves, rather than from tide

Gerard Litjens
To research the potential sedimentation rates around the Haringvliet, we need to monitor the salt marshes that are currently under influence of tide. For example, it would be useful to know how the elevation of the Korendijkse Slikken has changed in the last years. Also, there are some farmers that will retire in the coming years, and that do not have a successor. It is important to get insight into such situations, and to maintain in contact with local people.

Exchange polders can very well be combined with housing projects.

Different locations in Hoeksche Waard:
Leenheerenpolder

- This is a very suitable location as it is surrounded by dikes, and has minimal housing. For the houses that are there, a mound can be built to protect them from the water.
- The outer dike next to the Spui can be lowered, so that the Spui is visible when standing on the primary dike.

Polder at Oudendijk

- This polder has the ideal size for an exchange polder
- There is a lot of housing on the dike edge. This makes it difficult to create public support, and it increases the costs.

Polders east and west of Nieuwendijk:

- Too much housing on the dike to be turned into an exchange polder in the near future.

Molenpolder:

- This location is completely surrounded by dikes, which makes it suitable as an exchange polder.
- These is a long-term plan for housing on this location. It can benefit both interests (housing and nature) to combine this.
- Part of the housing in this polder is already prepared for sea level rise by building it on a mount.

West of the A29 highway:

- High potential area. There are some large farms, so relocating them will be expensive.
- Windmills present, and there are plans for a solar panel site. When built on poles, this can very well be combined with letting in tide.

.

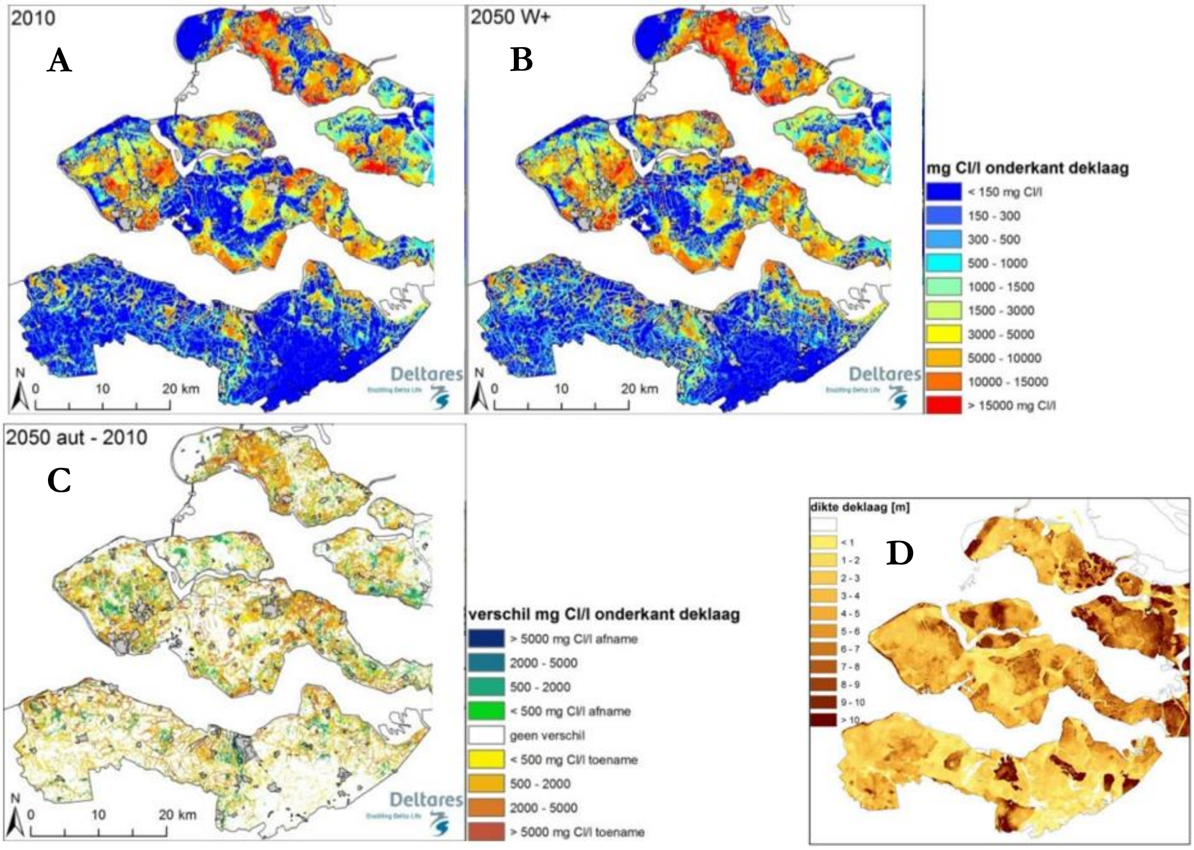


Figure 16. Top: chloride concentration at the bottom of the Holocene top layer (deklaag) in 2010 (A) and 2050 "W+" scenario with 40-80cm SLR (B), for the province of Zeeland. (C) Gives the change in chloride concentration between the 2010 and 2050 W+, and (D) shows the depth of the values (from Van Baaren et al., 2016).

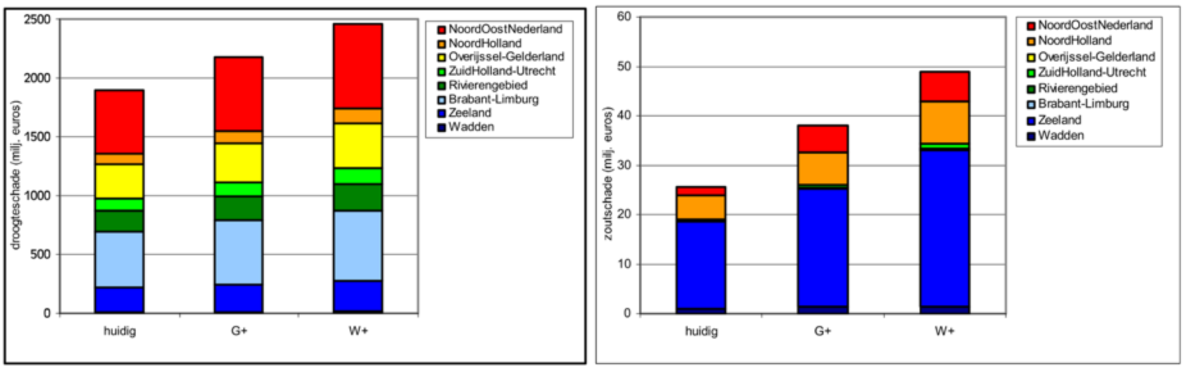


Figure 17. Yield loss due to drought (left) and salinization (right) in million euros for different regions in the Netherlands in a hypothetical extremely dry year for the current situation, G+ and W+ (from van Beek et al., 2008).

3.5 Salinization and agriculture

With sea level rise, salinization will increase in the polders behind the dikes. Regarding the question how much the salinity in the soil and groundwater will change, some processes are still not fully understood but (model) predictions have been made by Van Baaren et al. (2016), shown in Figure 16. To estimate resulting yield loss, this has to be combined with the locations and salt tolerance of crops. In the Southwest Delta, the most important crops are winter wheat, consumer potatoes and sugar beets (CBS, 2014), which have salt tolerance thresholds of respectively 4831, 756 and 4831 mg/l Cl (Roest et al., 2004). Above this threshold, yield loss starts, which increases with increasing salt concentrations. These crops have a crop reduction of 0.0058 % (grains), 0.0163 % (potatoes), and 0.0057 % (sugar beets) per exceeding mg/l Cl (Roest et al., 2004).

Van Beek et al. (2008) have created a prognosis for crop loss with SLR in a future climate, both for damage due to drought, and damage due to salt. Figure 17 shows the monetized loss for the current situation and different climate scenarios, for an extremely dry year. Salt damage is highest in Zeeland, although it is much smaller than drought damage (currently: €18 million compared to ± €200 million). In the future, the salt damage in Zeeland increases from 18 million to €23 million in the scenario G+, and to €31 million in the scenario W+(van Beek et al., 2008).

Figure 19. Impression of the developments in two scenarios: in "Business ar Usual", dikes are reinforced and salinizaition of farmland increases. In “Land level rise with accretion polders”, low lying polders area alternatively allowed to silt up, creating a strip of fertile, elevated soil behind the sea dikes.

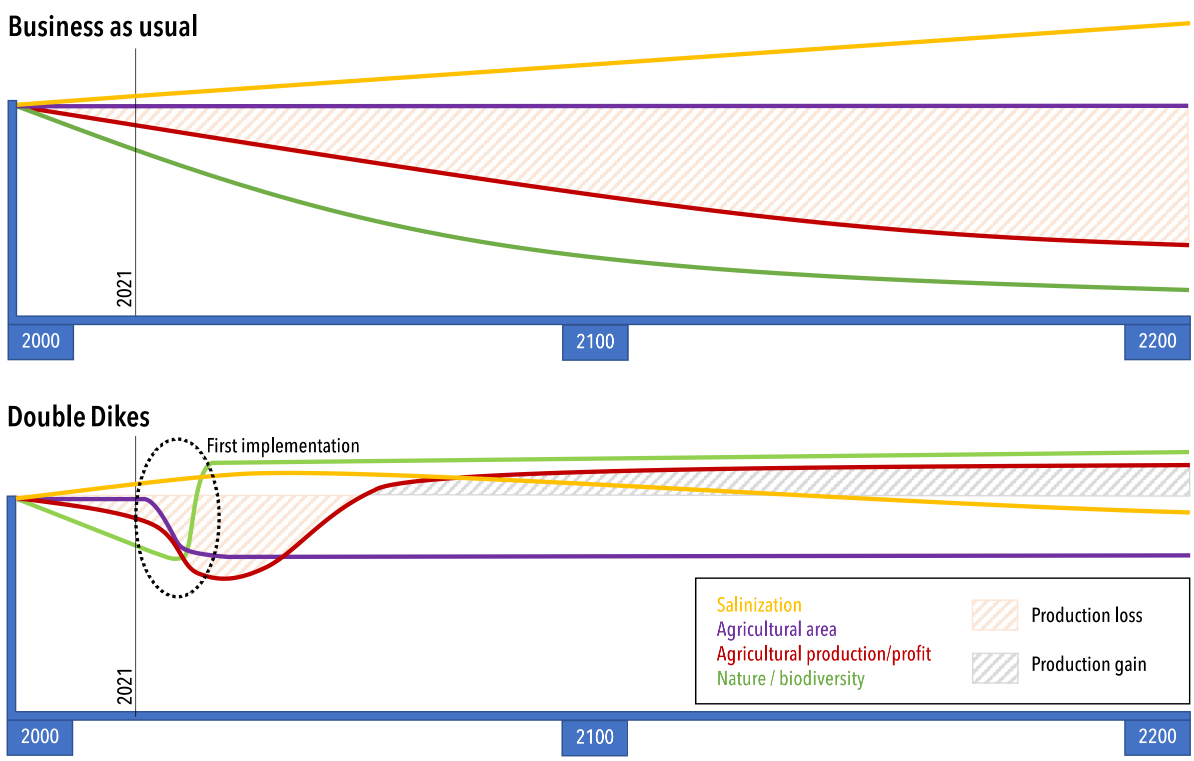


Figure 18. Hypothesis on the development of salinization due to increased SLR, and the expected changes in agricultural area and yield, and the biodiversity in the Delta. The top gives the hypothesis fort he “Business as usual scenario. Salinization will increase in low-lying polders due to saline seepage. The bottom figure shows the hypothesis for exchange polders between double dikes, where development of a freshwater lens below the raised polder is assumed.

Figure 18 shows the hypothesis that was developed based on the data above and the assumptions described in section 2.5. An impression of the two scenarios is shown in Figure 19. In the scenario "Business as Usual" (Figure 18A), sea level rise causes an increase in saline seepage into the low elevated polders. The total farmland area will remain constant, but yields will reduce when salt tolerance of crops is increasingly surpassed. Biodiversity will continue its decline as nature areas cannot grow with sea level rise. Figure 18B shows the hypothesis for a scenario with large scale implementation of exchange polders between double dikes, with the initial implementation between 2021-2025. In the exchange polder, part of the area (±20-50%) is reserved for tidal nature and recreation, and the rest of the area is used for food production. First, profitable aquaculture can take place, and when land raise has taken place, a fresh water lense is potentially developed below the polder, increasing the yield of freshwater crops, despite that the area of farmland will decrease.

3.6 Article and infographic

This project resulted in the findings described above, and in an article and an infographic. The article, "Restoring the delta functions: suppletions and dynamics with a rising sea level", can be found in the supplementary document. The infographic is shown in Figure 20, and an enlarged version is attached in Appendix 4.

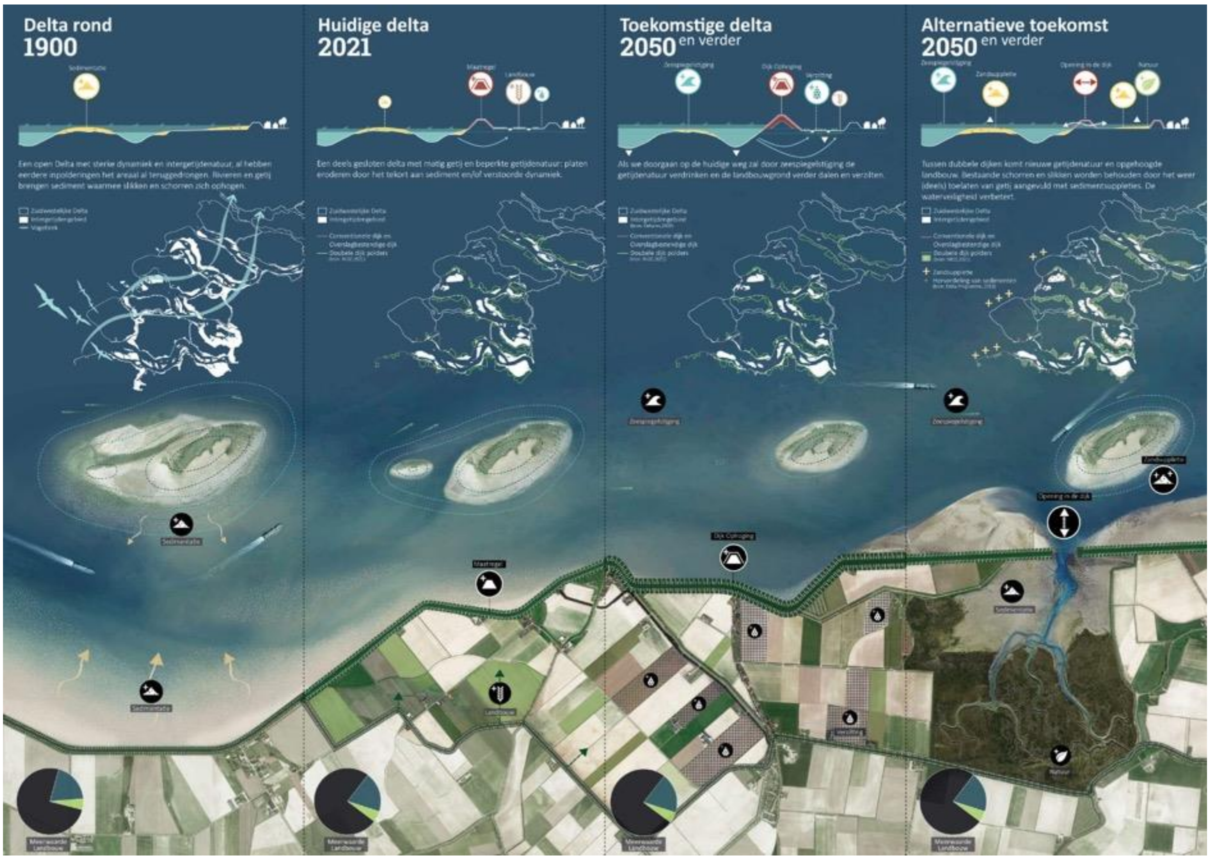


Figure 20. Impression of the infographic about development of intertidal area. The four panels show different stages in time. (CONCEPT)

4. Discussion

4.1 Intertidal area

This report has shown that tidal areas and dynamics along the Dutch Coast are threatened by impoldering, damming and sea level rise. The timeline for intertidal area in the Southwest Delta showed a 56% reduction, for which damming was the leading cause, followed by embankment. Erosion of shoals due to the imbalance between tidal prism and channel size is another contributor; it caused a relatively small loss compared to the previous two drivers, but will increase with sea level rise as sediment shortage will increase. The consequences of intertidal surface area reduction on delta flora and fauna will be negative, yet further research is necessary to quantitatively assess the consequences on specie populations for this specific region. It is then necessary to distinguish between types of habitats for the different scenarios and measures, which Tangelder et al. (2019) have done for the Grevelingen. It will be helpful to explore this for the entire Southwest Delta, and to combine it with the connectivity of the various basins through the dams, and with water quality and salinity in different scenarios.

4.2 Sediment shortage

The results of the estimations about the sediment shortage for different SLR scenarios show that the volume and costs of suppletions necessary for shoal and bank conservation will significantly increase. Suppletions will benefit both nature and water safety. Furthermore, it was shown that the area and volume of sand in the North Sea will be sufficient to satisfy the demand for the coastal suppletions on the Dutch Coast, assuming that sand quality and size do not significantly reduce the area of suitable locations. As sand extraction on the North Sea bed will disturb the local benthic ecology (Mulder, 2019), attention should be paid to the optimal balance between extraction depth and extraction frequency, as well as to the question of how much disruption of the seabed is acceptable compared to the nature restoration in the delta.

Costs for the Southwest Delta can stay within reasonable limits in the context of the national budget for water safety measures. Out of the total suppletion volumes needed to compensate for SLR for the entire Dutch coast, the share of the Southwest Delta will be 8.5%. It is necessary to investigate the most (cost-)effective approach for these suppletions. Additionally, possibilities for CO_2 neutral extraction practices should be pursued; current transports take place with fossil fuel driven boats, which aggravates the sea level rise that is at the root of this sediment shortage.

The calculations for sand shortage in this report were bases on a linear relationship between sea level rise and sand shortage. This is presumably an underestimation of the actual sediments necessary, so it is advised to determine the shortage for every basin using a more elaborate procedure developed by Leuven et al., 2019.

Furthermore, from the total sediment shortage, it should be distinguished what fraction should be supplied as sand, and what fraction should be supplied as mud/silt. Silt is an important component of intertidal flats and salt marshes. When rivers are dredged and when land has to be excavated for construction projects, large volumes of mud are extracted. However, it is often regarded as residual product and dumped at sea. When this extracted mud is not contaminated, it is very valuable if supplied in the Delta.

4.3 Exchange polders

The assessment of the suitability of polders surrounding the Haringvliet-Hollands Diep has resulted in a selection of 1580 ha divided over 13 locations that have the most potential to serve as a pilot location, considering amongst others the potential sedimentation rate (dependent on elevation) and minimizing costs for implementation (absence of buildings, presence of sleeper dike). In general, many bordering polders meet the essential requirement of being below the Haringvliet water level. In lower lying polders, a larger volume of sediment loaded water will flow onto the soil, increasing the accretion rate. On the other hand, lower elevation polders take longer to be raised, which will create a longer period for tidal nature and aquaculture rather than fast restoration of freshwater farmland. The optimal balance between these two advantages depends on the specific objectives for nature and economy.

For the selection of the most suitable location for a pilot, the criterium that only few housing is present is weighed more heavily than the other criteria, as this will simplify creating broad societal support as less people need to be relocated. Societal support is an important success factor, largely determining the opportunities to implement exchange polders on a large scale. Especially when this concept of exchange polders is still new, it might be regarded as "guilty until proven innocent" because the resistance to initial restoration of the tidal dynamics can overshadow the immediate improvements for water safety and long-term economic profit. In that context, it is important to create thorough scientific understanding and substantiation of the concept. This can initially be done with empirical data about the pilot location at the Eems-Dollard and with modelling of salinity and sedimentation rates for exchange polders at different locations in the delta. Furthermore, the developments of salinity and water safety for a future without double dikes have to be forecasted to weigh the different advantages and disadvantages of exchange polders versus no intervention. In this context, attention has to be paid to the possibilities of saline crops, both in the case of exchange polders as well as Business as Usual.

There is an expiry date to storm surge barriers when sea level rises. Due to accelerating sea level rise, the Oosterscheldekering is estimated to "last" until 2050, while it was built with the aim to last 200 years (until 2186). With rising sea level, it will have to close more regularly. It currently closes on average once per year. With a sea level rise of 1 meter, this will increase to 100 times per year. This will reduce the tidal dynamics and thus intertidal area in the basin, but also raises a question for the long term: "business as usual" might not be an option considering water safety. The water inflow from rivers will still need to exit the Southwest Delta, which requires large pumping installations if the water level in the basins is kept artificially low. It should be researched whether exchange polders can provide a solution to this problem. If a continuous strip of exchange polders is implemented around (e.g.) the Eastern Scheldt, this creates a wide elevated barrier. This could potentially provide more opportunities for opening the storm surge barrier during high tide, even with moderate sea level rise. Lastly, it is important to note that all adaptation strategies have higher potential to provide more nature and higher water safety when sea level rise is minimized. Focus should therefore not only be on climate adaptation, but also on climate mitigation. Extensive efforts and investments need to be made to prevent accelerated sea level rise.

5. Conclusion

In the Southwest Delta in the Netherlands, the total area of intertidal ecotopes has strongly declined. This is unfavorable for nature, recreation and water safety. Since 1915, intertidal area has shrunk with 56% due to damming and impoldering. In the Grevelingen and Volkerak, no tidal nature is left due to the non-tidal circumstances. In the Haringvliet-Hollands Diep, the areas have lost their salinity gradient as this basin has become fresh. The Eastern Scheldt shows strong declines in intertidal area due to sediment shortage. In the Western Scheldt, intertidal area of embanked side branches is lost. Other banks and shoals have largely remained due to dredging and regular suppletion of this dredged material on shoals and banks. In the future, further development depends on the rate of sea level rise (SLR) and on policy plans for (opening) dams and sediment suppletions. Business as usual will result in a further loss of intertidal nature in the Scheldts, and a deterioration of the environments in the closed basins. The scenario "Dynamics and Sediment" has shown that letting in more tide into the basins by opening dams will increase intertidal area, and the system's resilience to SLR in 2050. Restored tidal dynamics enable shoals and banks to grow with sea level rise, especially is extra sediments are added to the system by suppletion. This will improve nature, but also creates foreshores in front of the dikes that dampen the waves, thus improving the reliability of the dikes.

Estimations about the sediment shortage arising through SLR show that for every millimeter of sea level rise, 0.63 million m^3 of sediment must be added to the delta basins to enable them to grow with sea level rise. Plainly regarding volumes, it is possible to extract the sand from the reservation zone in the North Sea, although it has to be researched how the disturbance of nature is kept to a minimum by optimizing the frequency, location and depth of extractions. Furthermore, silt/sludge which is the residual product from dredging and large construction projects can be used as valuable material for intertidal ecosystem restoration.

Accretion polders between double dikes are a potential new measure that creates an elevated zone that can be alternately used for nature, aquaculture, saline cultivation, and conventional agriculture. This concept can even improve water safety, increase nature value of the area, and restore farmland. This report indicated potential areas around the Haringvliet-Hollands Diep that are most appropriate for implementing accretion polders. 1500 hectares divided over 15 locations is assessed to have the highest potential A combination of modelling research and empirical research in pilot locations is necessary to determine the effects and possible optimization measures in more detail, focusing on (optimizing) sedimentation rates and water safety levels. This report shows the substantiation for starting an exchange polder pilot in the Molenpolder, Leenheerenpolder, or south of Tiengemeten.

References

Baart, F., Rongen, G., Hijma, M., Kooi, H., De Winter, R., & Nicolai, R. (2019). *Zeespiegelmonitor 2018. De stand van zaken rond de zeespiegelstijging langs de Nederlandse kust*. https://www.deltares.nl/app/uploads/2019/03/Zeespiegelmonitor-2018-final.pdf

Ceballos, G., Ehrlich, P. R., & Dirzo, R. (2017). Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(30), E6089–E6096. https://doi.org/10.1073/pnas.1704949114

Chmura, G. L., Anisfeld, S. C., Cahoon, D. R., & Lynch, J. C. (2003). Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles*, *17*(4). https://doi.org/10.1029/2002gb001917

de Haas, T., Pierik, H. J., Spek, A. J. F. Van Der, Cohen, K. M., & Maanen, B. Van. (2018). Earth-Science Reviews Holocene evolution of tidal systems in The Netherlands : E ff ects of rivers , coastal boundary conditions , eco-engineering species , inherited relief and human interference. *Earth-Science Reviews*, *177*(December 2016), 139–163. https://doi.org/10.1016/j.earscirev.2017.10.006

ExpeditieWaddenkust. (2021). *Van dijk naar dynamische dijkzone*. https://expeditiewaddenkust.nl/eems-dollard/

Haasnoot, M., Bouwer, L., Diermanse, F., Kwadijk, J., Spek, A. van der, Essink, G. O., Delsman, J., Weiler, O., Mens, M., Maat, J. ter, Huismans, Y., Sloff, K., & Mosselman, E. (2018). *Mogelijke gevolgen van versnelde zeespiegelstijging voor het Deltaprogramma. Een verkenning*. Deltares rapport 11202230-005-0002.

Hanon, G. T. M., Roels, B., Winden, A. van, & Litjens, G. (2020). *Kennisdocument Voorbij de Kier*.

Holzhauer, H., & Twisk, F. (2009). *Effecten van klimaatmaatregelen op de estuariene natuur*.

Leuven, J. R. F. W., Pierik, H. J., van der Vegt, M., Bouma, T. J., & Kleinhans, M. G. (2019). Sea-level-rise-induced threats depend on the size of tide-influenced estuaries worldwide. *Nature Climate Change*, *9*(12), 986–992. https://doi.org/10.1038/s41558-019-0608-4

Louters, T., Van Den Berg, J. H., & Mulder, J. P. M. (1998). Geomorphological changes of the oosterschelde tidal system during and after the implementation of the Delta project. *Journal of Coastal Research*, *14*(3), 1134–1151.

Mulder, J. P. M. (2019). *Zandsuppletie en zandwinning bij een versnelde zeespiegelstijging*.

Nienhuis, J. H., Ashton, A. D., Edmonds, D. A., Hoitink, A. J. F., Kettner, A. J., Rowland, J. C., & Törnqvist, T. E. (2020). Global-scale human impact on delta morphology has led to net land area gain. *Nature*, *577*(7791), 514–518. https://doi.org/10.1038/s41586-019-1905-9

Roest, C. W. J., Van Bakel, P. J. T., & Smit, A. A. M. F. R. (2004). *Actualisering van de zouttolerantie van land- en tuinbouwgewassen ten behoeve van de berekening van de zoutschade in Nederland met het RIZA-instrumentarium*. 1–16.

Saeijs, H. L. F., & Bannink, B. A. (1978). Environmental consideration in a coastal engineering project the Delta Project in the south-western Netherlands. *Hydrobiological Bulletin*, *12*(3–4), 180–202. https://doi.org/10.1007/BF02259182

Spijker, J. (2005). Geochemical patterns in the soils of Zeeland. In *Nederlandse Geografische Studies 330*.

Tangelder, M., Ysebaert, T., Wijsman, J., Janssen, J., Mulder, I., Nolte, A., Stolte, W., van Rooijen, N., & van den Bogaart, L. (2019). *Ecologisch onderzoek Getij Grevelingen Ecologisch onderzoek Getij Grevelingen* (Issue C089/19). https://library.wur.nl/WebQuery/wurpubs/fulltext/506617

Tickner, D., Opperman, J. J., Abell, R., Acreman, M., Arthington, A. H., Bunn, S. E., Cooke, S. J., Dalton, J., Darwall, W., Edwards, G., Harrison, I., Hughes, K., Jones, T., Leclère, D., Lynch, A. J., Leonard, P., McClain, M. E., Muruven, D., Olden, J. D., … Young, L. (2020). Bending the Curve of Global Freshwater Biodiversity Loss: An Emergency Recovery Plan. *BioScience*, *70*(4), 330–342. https://doi.org/10.1093/biosci/biaa002

Van Baaren, E. S., Oude Essink, G. H. P., Janssen, G. M. C. M., de Louw, P. G. B., Heerdink, R., & Goes, B. J. M. (2016). Verzoeting en verzilting freatisch grondwater in de Provincie Zeeland. In *Deltares rapport 1220185-000*.

van Beek, E., Haasnoot, M., Meijer, K., Delsman, J. R., Snepvangers, J. J. J. C., Baarse, G., van Ek, R., Prinsen, G. F., Kwadijk, J. C. J., & van Zetten, J. W. (2008). Verkenning kosteneffectiviteit van grootschalige maatregelen tegen droogteschade als gevolg van de G+ en W+ klimaatscenario's. In *Deltares rapport T2498* (p. 144).

van Belzen, J., Rienstra, G., & Bouma, T. (2021). Dubbele dijken als robuuste waterkerende landschappen voor een welvarende Zuidwestelijke Delta. *NIOZ Report 2021-01*, *01*, 99.

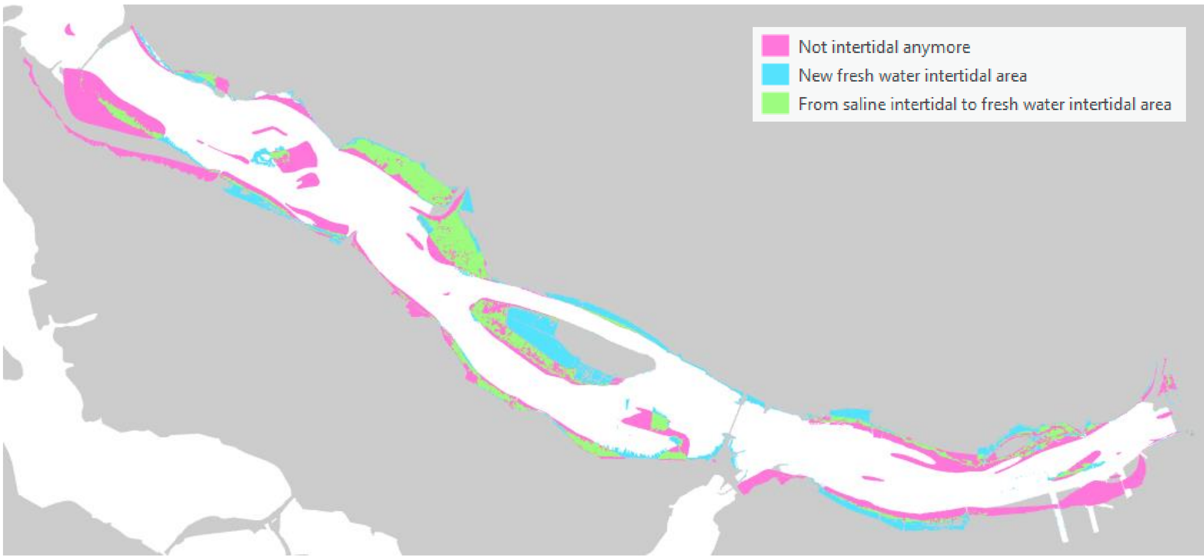
van den Berg, J. H., Jeuken, M. C. J. L., & van der Spek, A. J. F. (1996). Hydraulic processes affecting the morphology and evelotion of the Westerschelde estuary. *Estuarine Shores: Evolution, Environments and Human Alterations*, 157–183.

Vos, P. (2015). Origin of the Dutch Coastal Landscape – Long-Term Landscape Evolution of the Netherlands during the Holocene, Described and Visualized in National, Regional and Local Map Series. In *Deltares* (Vol. 26, Issue 4). https://doi.org/10.1177/0959683616629882

Wijsman, J., Escaravage, V., Huismans, Y., Nolte, A., van der Wijk, R., Wang, Z. B., & Tom Ysebaert, T. (2018). *Potenties voor herstel getijdenatuur in het Haringvliet, Hollands Diep en de Biesbosch*. http://publications.deltares.nl/11200800.pdf

Ysebaert, T., van der Hoek, D. J., Wortelboer, R., Wijsman, J. W. M., Tangelder, M., & Nolte, A. (2016). Management options for restoring estuarine dynamics and implications for ecosystems: A quantitative approach for the Southwest Delta in the Netherlands. *Ocean and Coastal Management*, *121*, 33–48. https://doi.org/10.1016/j.ocecoaman.2015.11.005

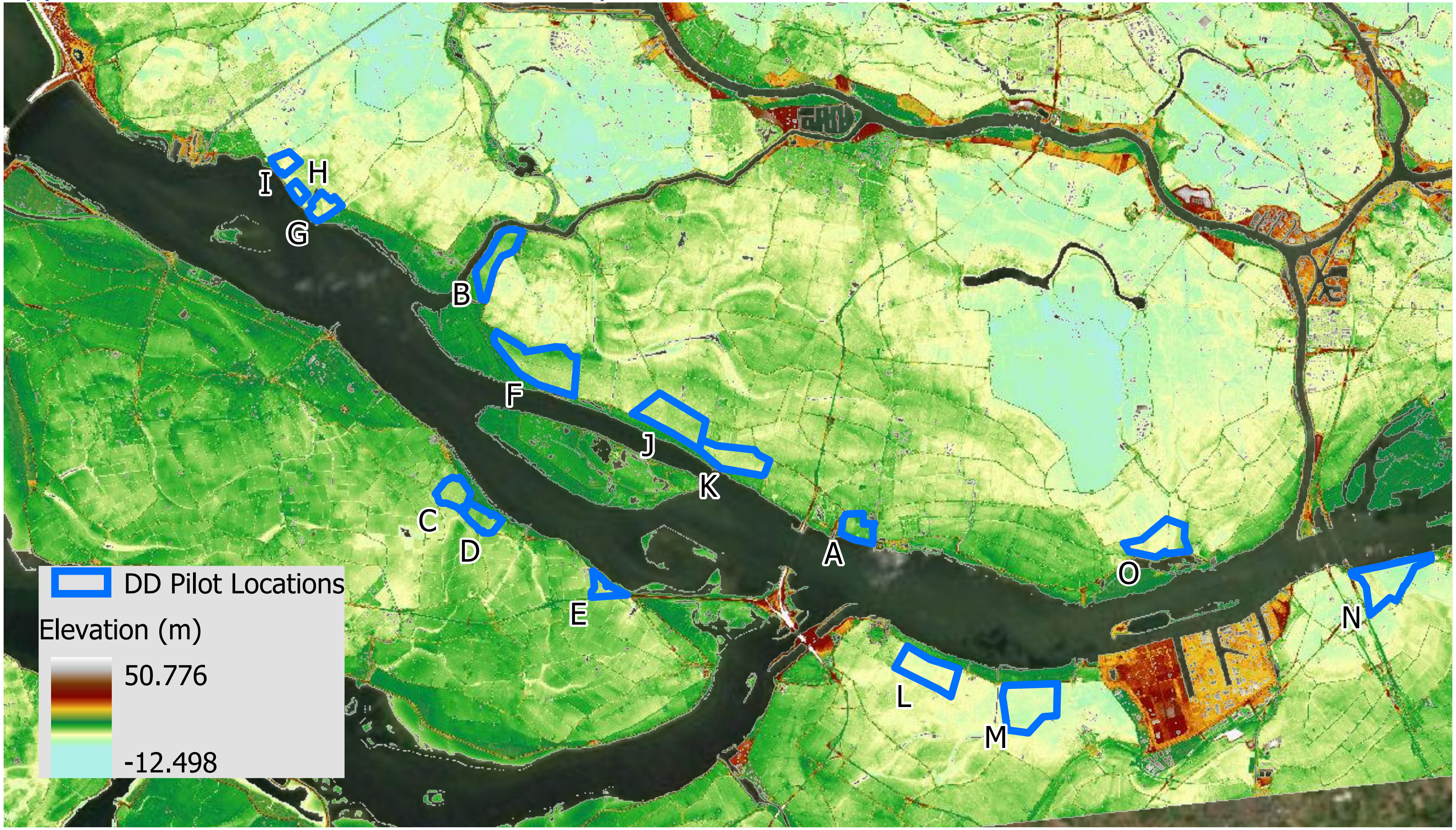
Appendix 1. Changes in the Haringvliet estuary between 1915 and 2020.



The estuary was closed by the dam in 1971, after which the continued water supply from the rivers turned the basin to fresh water. As this provides a different ecotope, it is classified as a loss of the saline intertidal ecotopes in this research.

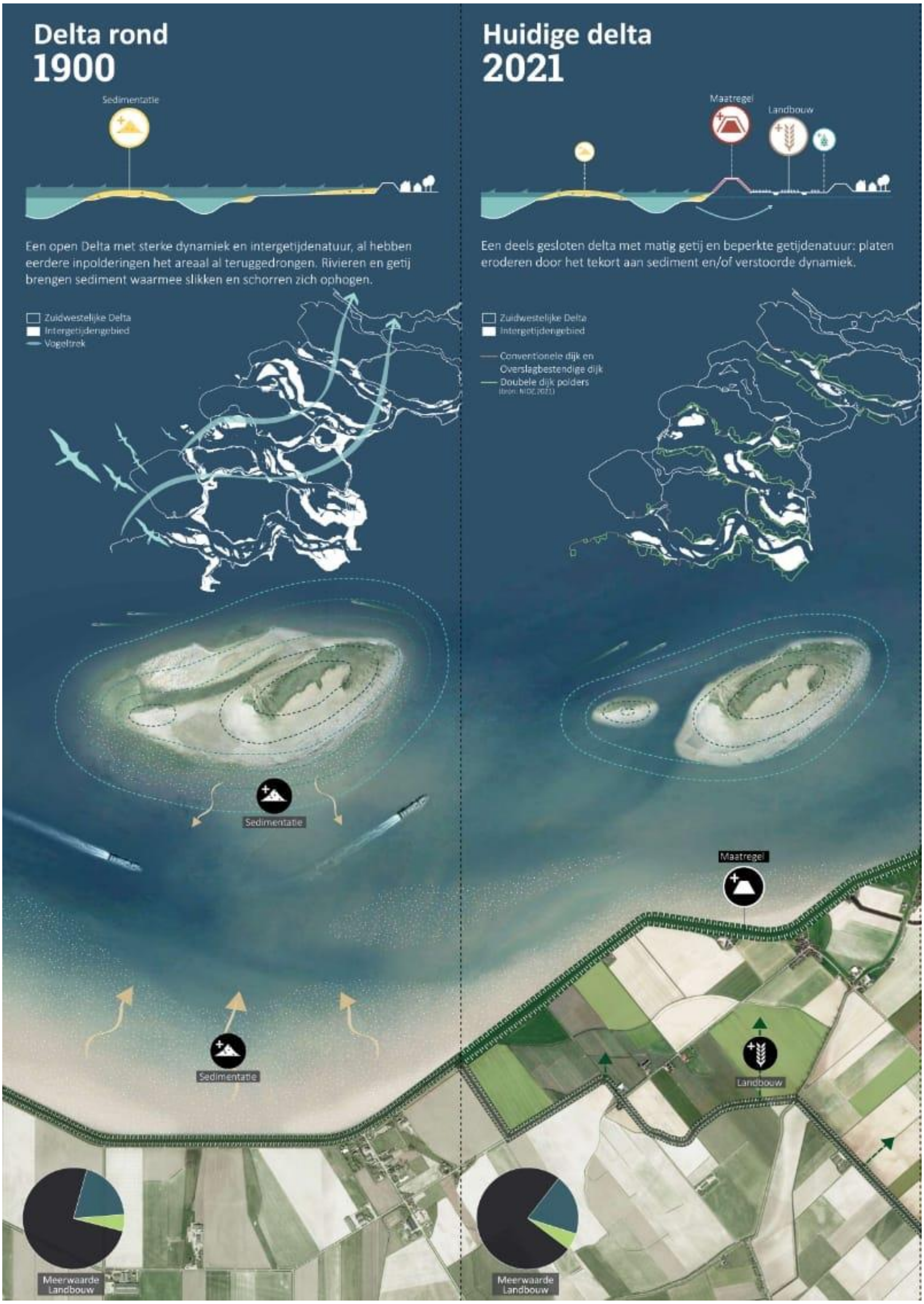
Appendix 2. Selected sites for double dike pilots, on aerial imagery map

Appendix 3. Selected sites for double dike pilots, on elevation map

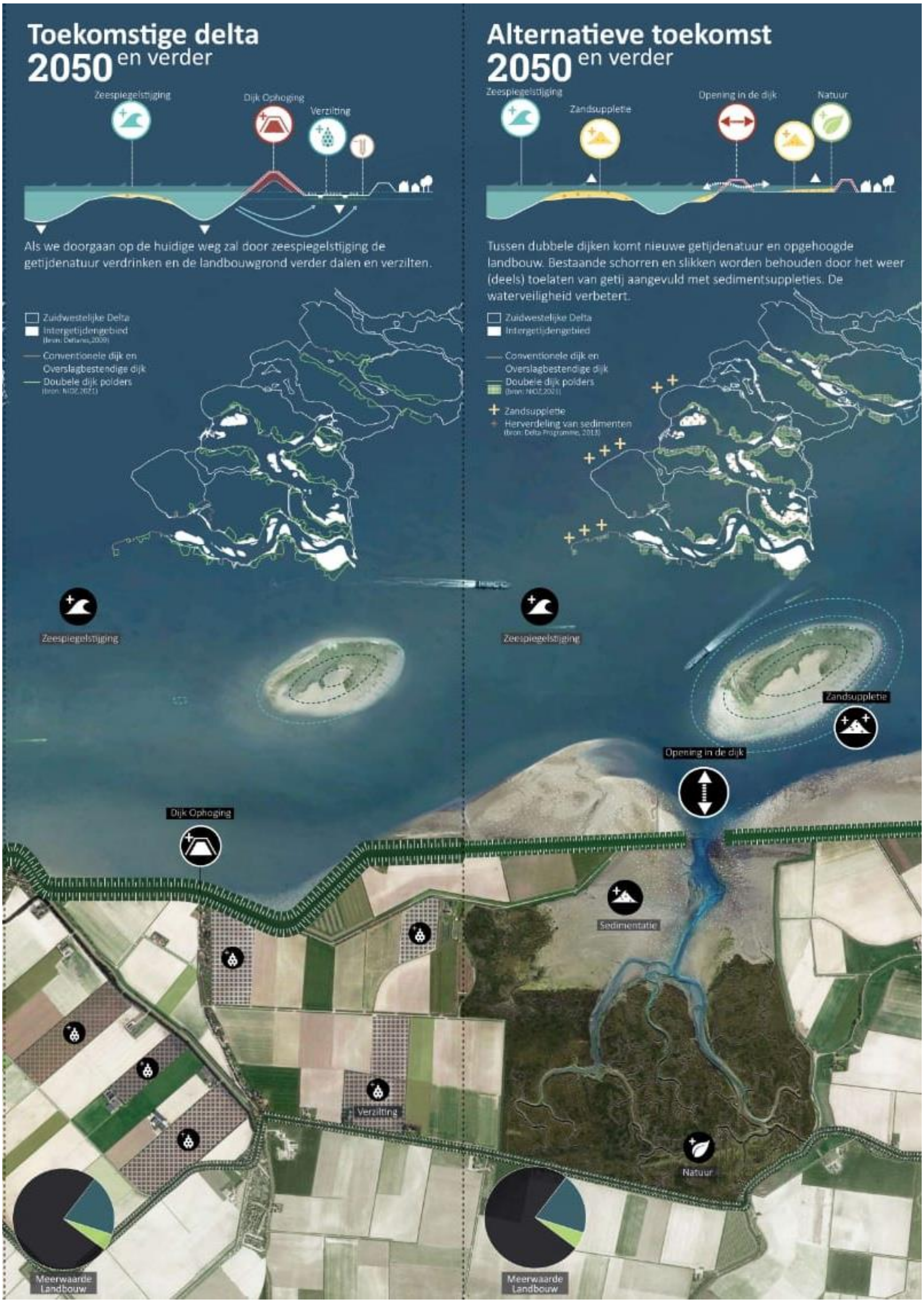


Appendix 4. Infographic Tidal Nature

Infographic Front side 1 / 2 (CONCEPT VERSION)



Infographic Front side 2/2 (CONCEPT VERSION)



Infographic back side (CONCEPT VERSION)

Tidal nature under pressure

The Dutch coast is a dynamic area with a large variety in habitats. Especially the Wadden Sea and tidal basins of the Southwest Delta are highly important for all sorts of plants and animals. With every tidal cycle, ebb and flood create different environments with gradients in salinity, depth, flow speeds, sediment types and nutrients. Tidal flats and salt marshes are the most productive ecosystems on earth: they even surpass tropical rainforests with carbon sequestration[1]. They capture nutritious mud, and facilitate high biodiversity. They are home to many fish species, benthic animals, and therefore a crucial "roadside restaurant" for millions of migratory birds. In addition, they function as a wave breaker in front of the coast: without this buffer zone, our dikes will need to be stronger and higher. Intertidal areas under pressure due to embankments, dams and sea level rise. Pursuing business as usual, little will be left of these valuable areas by 2100[2].

Land elevation between double dikes

The future will bring more sea level rise on the outside of the dike, and more subsidence of the farmland inside the dike. Seepage of salt water will increasingly find its way to the polders, so salinization will increase. Crops loss will therefore aggravate, causing profits to decline.

By reviving the long Dutch tradition of accretion polders – yet now between double dikes – we can create elevated land[3]. Through an alternation of accreting tidal nature, aquaculture, and freshwater farming, new sediments are deposited and soil quality will be restored. At the same time, a broad water-retaining zone is formed, protecting the lowlands against sea level rise.

This approach is cheaper than holding on to continued dike reinforcements. Furthermore, profits from the different saline and freshwater crops, as well as recreation, are higher than if the current cultivation is continued.

A climate-proof delta demands quick action: by starting now, we enable the land to keep pace with the rising sea level.

Restoring tidal dynamics & sediment supply

On the front side, you can observe how the intertidal area has largely reduced by embankments and dams in the last century, and how this process will proceed further if we do not intervene. Due to the dams, tidal dynamics and sediment supply is blocked. Yet erosion of the shoals continues, but these sediments remain in the channels. There is too little energy to replenish this, so the balance is disturbed. Flats and marshes drown. This is happening in the Haringvliet-Hollands Diep, Grevelingen, Volkerak and the Oosterschelde: nature disappears. In the Westerschelde, dredging and streamlining of the channels also induces loss of tidal ecotopes.

We have to prevent further deterioration of the valuable habitats by restoring the tidal functions in the basins. By (partly) reopening the dams, the dynamic, nature building power of the water can conserve intertidal areas. Provided that we build a sediment strategy around this. With sand suppletions and useful application of dredged **sludge**, these tidal flats and salt marshes are prevented from drowning.

The simplified approach of multiplying the basin area with sea level rise gives an indication of the sediment volumes needed: ±1.3 million cubic meters of sediment per year allows the Southwest Delta to keep pace with the current sea level rise of 2 mm/yr.[2]

Sources

The maps on the front page are based on a combination of sources. The intertidal area in 1900 is based on *Bonnekaarten* dating from that period. For the current delta, ecotope-maps from Rijkswaterstaat (2016) are used for the Oosterschelde and Westerschelde. Maps for the Haringvliet-Hollands Diep and Grevelingen in 2021, "2050 hard borders" and "2050 dynamic" are adapted from model output of Wijsman (2018)[4] and Tangelder (2019)[5], using scenario's with 10-40cm sea level rise. Areas in the Oosterschelde and Westerschelde for "2050 hard borders" are computed by Holzhauer (2009)[6] for 50 cm SLR. For these two basins in "2050 dynamic" it is assumed that current areas are preserved. The potential locations for double dikes that are displayed in "2050 dynamic" are researched by Van Belzen (2021)[3].

[1] Teunis, M. & Didderen, K. (2018). Blue Carbon in Nederlandse kwelders. Resultaten van vier kwelders in beheergebieden van Natuurmonumenten. Bureau Waardenburg Rapportnr. 18-301.

[2] Mulder, J. (2019). Zandsuppletie en zandwinning bij een versnelde zeespiegelstijging.

[3] van Belzen, J.; Rienstra, G.U. & Bouma, T.J., (2021). Dubbele dijken als robuuste waterkerende landschappen voor een welvarende Zuidwestelijke Delta. NIOZ Report 2021-01.

[4] Wijsman, J.; Escaravage, V.; Huismans, Y.; Nolte, A.; Van der Wijk, R; Wang, Z.B. & Ysebaert, T., Potenties voor herstel getijdenatuur in het Haringvliet, Hollands Diep en de Biesbosch. Wageningen Marine Research Wageningen UR (University & Research centre),

[5] Tangelder, M., T. Ysebaert, J. Wijsman, J. Janssen, I. Mulder, N. van Rooijen & L. van den Bogaart, 2019. Ecologisch onderzoek Getij Grevelingen: effecten Natura 2000 en autonome ontwikkeling watersysteem vergeleken met getij scenario's, WMR rapport.

[6] Holzhauer, H. & Twisk, F. (2009). Effecten van klimaatmaatregelen op de estuariene natuur, Deltares.