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Ecological consequences of sea level rise and flood protection strategies in shallow coastal systems: A quick-scan barcoding approach

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ABSTRACT

Shallow coastal ecosystems have high ecological value and contribute to flood protection. Their stability is, however, sensitive to the amount and rate of future sea level rise (SLR), their ability to trap sediment which allows them to grow with rising sea level, and human response to SLR. So far, studies have focused on assessing SLR impacts using resource-intensive tools. Here, we present an approach for a first-order assessment and easily accessible 'barcode' visualization to rapidly assess potential impacts of both SLR and adaptation strategies on coastal ecosystems in a spatially explicit way. Our approach relates habitat types (ecotopes) to water level, morphology and salinity, allowing users to determine shifts in spatial arrangements of ecological zones under different SLR rates and strategies. We illustrate this approach for a transect in the Dutch Wadden Sea. We find that beyond a critical rate of SLR, major changes in ecotope distribution are projected to occur as this part of the Wadden Sea starts to drown due to insufficient sediment import. Even larger impacts arise from adaptation strategies. Closing the barrier islands will turn the Wadden Sea into a freshwater lake-system with the absence of intertidal areas, infilling of channels and bank erosion. A strategy that allows for inland migration of the shoreline, results in a deep tidal basin with large subtidal habitats, and a shifted intertidal zone. Our case study shows that the barcoding approach provides a rapid, quantitative and spatially explicit overview of the potential implications for coastal ecosystems under different SLR scenarios, adaptation strategies and time horizons. This can then be used to screen adaptation strategies before going into a more comprehensive analysis. The barcode visualization allows for easy dissemination of potential ecological impacts to a broad community.

1. Introduction

Global mean sea level is rising at an accelerating rate and will continue to rise in the future. Recent sea level rise (SLR) projections of the IPCC show a rise of 0.43 m (0.26–0.59 m, likely range) under RCP2.6 and 0.84 m (0.61–1.10 m, likely range) under RCP8.5 by 2100 (IPCC, 2019), with high-end scenarios indicating a possible rise of 2 m in 2100 (Bamber et al., 2018). Higher sea levels increase the occurrence of sea-level extremes and will expose coastal communities and infrastructure to coastal flooding and erosion (Kirezci et al., 2020). Adaptation strategies to mitigate adverse impacts for coastal communities are thus needed. Shallow coastal ecosystems will also be affected by SLR, together with other climate-associated impacts, such as salinization, warming surface waters and extreme weather conditions (Nicholls and Cazenave, 2010; Wong et al., 2014; FitzGerald et al., 2008). At the same time, these shallow coastal ecosystems are also threatened by anthropogenic activities such as pollution, land use change and anthropogenic subsidence (Adam, 2002). Overall, this forms a threat to the functioning of coastal ecosystems worldwide, being areas of high biodiversity, important for wave attenuation, erosion control and a 'blue carbon' sink (Li et al., 2018).

SLR affects coastal ecosystems in two main ways: directly through SLR itself and indirectly through measures implemented to protect the land from flooding. Coastal ecosystems can only be maintained within narrow ranges of SLR rates; if the rates are too low, the tidal system may turn into land and if the rates are too high the intertidal area will

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gradually reduce, and the system will drown (Baarse, 2014). Their vulnerability to SLR strongly depends on their ability to adapt through enhanced sediment trapping to grow upward with SLR (Kirwan and Temmerman, 2009). To realize this eco-morphodynamic feedback, a sufficient amount of sediment is required. For some marshes and mangrove systems this critical vertical accretion has been observed or modelled (Kirwan et al., 2016; Woodroffe et al., 2016), but for many coastal ecosystems, sediment import is or will not be sufficient to keep up with SLR, which will drown these systems (Blum and Roberts, 2009; Voss et al., 2013; Wang et al., 2018).

Increasing SLR may require adaptation strategies in addition to natural accretion, in particular in densely populated coastal lowlands, and where SLR cannot be compensated by natural accretion of the coastal zone. Such strategies may involve either measures to protect the hinterland with, for example with flood defences and sand nourishments (i.e., keeping the water out), or measures to retreat to higher areas to accommodate the water (i.e., living with water) (IPCC, 2019). Such large-scale management interventions may in turn have a major impact on coastal ecosystems (Esteves, 2013). The magnitude of such indirect effects of SLR on ecosystems thus depends on how humans respond, which can vary from hard protection such as strengthening or constructing new dikes and sea walls, sediment-based protection such as beach and shore nourishment to ecosystem-based adaptation such as wetland restoration (IPCC, 2019).

One of the shallow coastal ecosystems that will be affected by both SLR and adaptation responses is the Dutch Wadden Sea, one of the largest intertidal sand and mud flat systems in the world, and a UNESCO heritage site. The Dutch Wadden Sea is part of a large tidal basin along the south east North Sea coast. Stretching from the Netherlands to Denmark, it forms a large dynamic ecosystem that acts as a natural flood protection for the Dutch low-lying areas by reducing wave-heights reaching the mainland coast. Here, impacts of human-induced sediment disturbances, such as dredging, nourishments to maintain coastline and subsidence as a consequence of gas extraction, are already observed (Piersma et al., 2001; Reise, 2005; Eriksson et al., 2010). Several studies projected future morphodynamic changes arising under rising sea level (Van Maanen et al., 2013; Van Goor et al., 2003; Dissanayake et al., 2012). Wang et al. (2018) identified critical rates of SLR for all tidal basins, ranging from ~6 to 30 mm/year, at which the sediment supply into the Wadden Sea area will become insufficient to keep up with SLR. Large-scale measures of coastal adaptation, such as sand nourishments and flood defences will likely further affect this area. Yet, assessments of both direct and indirect impacts of SLR, including large-scale adaptation strategies and modelling long-term morphological development, remain to be undertaken (Oost et al., 2014; Wang et al., 2012). Moreover, most existing modelling studies so far only indicate a potential ecological impact, caused by for example dredging and sand nourishment, without further explanation or quantitative assessment of this impact on ecology.

Being a low-lying country, the Dutch government has designed a plan to prepare for SLR ranging from 0.35 to 1 m of SLR in 2100, with a rate up to 14 mm/year by the end the century, within a nation-wide program called the Delta Programme (Delta Programme 2018; Bloemen et al., 2019). Currently the country is considering alternative strategies to cope with higher amounts of SLR outside the boundary conditions of the current flood protection program, with possibly 2 m in 2100 and rates of more than 20 mm/year by the end of the century (Haasnoot et al., 2020). The Dutch Wadden Sea is of vital importance to the Netherlands for its ecology, flood protection and tourism. It is therefore important to assess impacts of both SLR and adaptation strategies to SLR on the Wadden Sea.

This study presents a first-order assessment and visualization approach to quantify impacts of SLR and related flood protection adaptation strategies on shallow coastal ecosystems. We demonstrate this approach by means of an application along a transect across the central part of the Dutch Wadden Sea, the tidal basin Borndiep. Our approach is based on a model that relates the distribution of so-called 'ecotopes' to changing critical habitat boundary conditions such as water level, bathymetry and salinity. Ecotopes are defined as ecological units (such as pioneer zone, saltmarsh or deep sublittoral) that can be spatially marked off in a landscape, determined by their abiotic conditions like salinity, depth-range in the intertidal, substrate type, etc. (Bouma et al., 2005). Ecotopes thus describe the main hydro-morphological characteristics and vegetation of an area. The ecotope map of the present-day Dutch Wadden Sea area is shown in Fig. 1. For given transects and locations, these abiotic conditions may change under SLR and flood protection measures. Critical changes in these boundary conditions are based on expert judgement, literature review and reference cases in the Netherlands. We use the distribution of ecotopes as key indicator of ecological change and to quantify potential impacts for coastal ecosystems. This allows for comparison between different SLR scenarios and flood protection measures. For visualizing these potential impacts, we were inspired by the climate warming stripes that originate from Hawkins (2018). Instead of using a pie chart which gives only quantitative information, we introduce a 'barcode' visualization which presents the potential impacts in a quantitative, spatially explicit way. In this way, our approach allows for a first-order assessment that requires limited time and relatively simple data and can be easily communicated with non-experts.

In this paper, we first describe the case study, present-day situation, SLR scenarios and adaptation strategies that are currently considered in the Netherlands. Subsequently, we assess the potential impacts of three SLR scenarios and two 'extreme' adaptation strategies on the spatial distribution of ecotopes to provide a first-order quantitative estimate of the ecological impact. We end with a discussion and describe the applicability of this approach in other areas.

2. Wadden Sea and adaptation strategies to high-end sea level rise

2.1. Study area

The Wadden Sea (hereafter referred to as WS) area in the north of the Netherlands serves as an important coastal flood defence mechanism, by providing a 'shield' of barrier islands, tidal flats and shallow waters that act as a buffer to reduce the hydraulic forces from the North Sea on coastal protection structures (Baarse, 2014). The Dutch WS area comprises a chain of barrier islands that shelter six tidal basins (Fig. 1). These tidal basins contain channels dividing tidal flats and salt marshes along the fringes which support a wide diversity of life, especially in the intertidal areas (Reise et al., 2010). Both tides and waves play an important role in shaping the WS system. The mean tidal range increases from 1.4 m in the southwest to 2.5 m in the east. Wave conditions in the North Sea mainly results from locally generated wind waves with an average significant wave height of 1.37 m (Wang et al., 2018).

2.2. Sea level rise and the Wadden Sea

In the past 80 years, the global mean SLR was about 2.4 mm/year. Over the past 27 years, this rise has accelerated to 3.24 ± 0.3 mm/year (IPCC, 2019). Over the period 2014–2019 it was 5 mm/year (WMO, 2019). Along the Dutch coast the observed sea level rise is ~2 mm/year (Baart et al., 2019). Differences between the global and regional SLR have been attributed to large natural variability as a result of weather events and the SLR contribution of Greenland ice sheet, which is small for the Wadden Sea (Van den Hurk and Geertsema, 2020).

In the future, sea level will continue to rise (IPCC, 2019). The rate and amount of SLR are uncertain and depend on the extent of global warming and underlying greenhouse gas emissions, as well as the response of the earth system to this global warming. Large uncertainty exists in the contributions from the Antarctic and Greenland ice sheets (IPCC, 2019; Pattyn and Morlighem, 2020), which could result in rapid

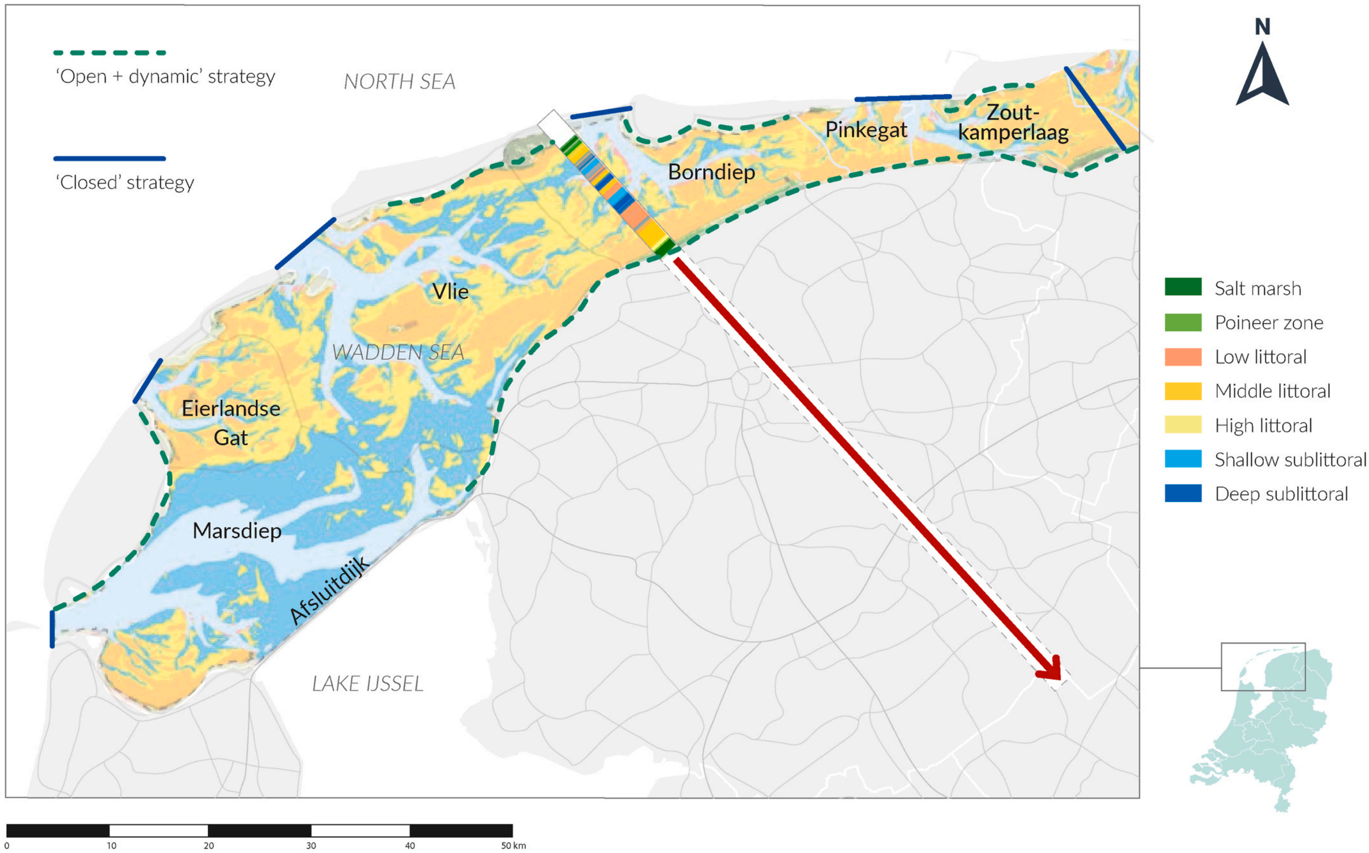

Fig. 1. Overview of the Dutch Wadden area, the present-day ecotopes (derived from Baptist et al., 2016) and the tidal basins (Marsdiep, Eierlandse Gat, Vlie, Borndiep, Pinkegat and Zoutkamperlaag) together with a graphic visualization of the two strategies: the 'Open + dynamic' strategy (dashed line) and the 'Closed' strategy (solid line). In addition, the location of the transect is shown in tidal basin Borndiep with an extension into the mainland.

and high SLR in the future (DeConto and Pollard, 2016; Kopp et al., 2017; Bamber et al., 2018).

Projections for the WS show a potential drowning of the tidal basins due to rapid SLR and local sea-floor subsidence (both natural and anthropogenic) (Elias et al., 2012; Van Der Spek et al., 2018; Wang et al., 2018; Lodder et al., 2019; Haasnoot et al., 2020). Drowning of the WS has major consequences for the biodiversity and flood risk on the mainland and raises concerns about whether the intertidal areas and the unique character of the WS can be preserved in the future.

2.3. Adaptation strategies

In this research we evaluate two potential adaptation strategies for flood protection under rising sea levels that affect the WS: 1) a 'closed' strategy that closes off the WS tidal basins with a chain of barriers between the Wadden islands and the mainland, and 2) a 'open + dynamic' strategy that removes the existing flood defences of the mainland, enabling the inland migration of the WS (Fig. 1). Both strategies are further explained below.

2.3.1. 'Closed' strategy

Plans to (partly) close-off the WS from the North Sea already go back to the 17th century, when Hendrik Stevin suggested closing the entire WS to reduce the total coastline length and hereby the length of dikes exposed to the sea (VVOF, 1983). Other objectives of closing the WS were land reclamation for agriculture and a permanent connection between the islands and the mainland. In 1872, a plan was realized when a 7 km long dam between Holwerd and Ameland in the Borndiep tidal basin was constructed. However, the dam was broken by storms and has never been rebuilt (Van Kuik, 1965). Plans like these were resurveyed in the 1960s in relation to the construction of the Delta works in the Scheldt delta. In view of scenarios with potential accelerated and high-end SLR, this strategy of massive coastal defence and closing tidal inlets has recently returned. By shortening the coastline in this 'closed' strategy, the number of defences needed to assure flood safety for the mainland is reduced, and defence against rising sea level might remain feasible. However, this will have serious implications for the WS and its ecological functioning: after closure, a freshwater lake will remain without tidal influence, and the water level dynamics will dramatically decrease with wind remaining the main driving force.

2.3.2. 'Open + dynamic' strategy

The present-day strategy aims to maintain the coastline at its position based in 1990 (Wang et al., 2018). These fixed basin dimensions make it impossible for the current system to retreat inland (coastal squeeze), in case the system would drown due to a lack of sediment supply. An 'open + dynamic' strategy, that is implemented once the critical SLR rate is exceeded, considers the removal of the existing hard flood defences along the southern border of the WS. This strategy will lead to an inland shift of the Wadden system. Along with this change, the current population and agriculture in the area have to give way to the extended WS, and should be moved to higher ground.

3. Method

To assess ecological impacts of SLR and adaptation strategies for the Wadden Sea we considered their effects on the spatial arrangement of ecotopes. These ecotopes represent the main hydro-morphological characteristics and vegetation of an area, which can be spatially delineated. Ecotopes thereby indicate the spatial arrangement of the main habitats for plant and animal species, and changes in ecotopes thus provide primary measures for ecological change or impact. Using the ecotope system allows for consistent comparison of the impacts of different scenarios. The assessment was done using a simplified version of the Dutch Ecotope System for Coastal Waters (ZES.1; Bouma et al., 2005) for the 'open + dynamic' strategy and the freshwater ecosystem (Noordhuis, 2010) for the 'closed' adaptation strategy (Tables 1 and 2). The ecotope map of the present-day WS using the simplified classification is shown in Fig. 1.

SLR and flood protection strategies will lead to changes in water levels, morphodynamics and salinity, which in turn are key boundary conditions for the occurrence and distribution of ecotopes that will change accordingly. The relation between critical boundary conditions (water level, bathymetry and salinity) that define the occurrence of ecotopes, forms the core of a model that we developed to predict the shift in ecotopes from present day to scenario conditions (see Fig. 2 for an overview of the approach).

Deriving data on these boundary conditions for the entire WS area under different SLR scenarios and resulting from internal system response is a complicated task. As a feasible alternative approach for a first-order estimate of impacts, we assessed changes in ecotope distribution along a transect across the WS from barrier island Terschelling to the mainland across the tidal basin Borndiep (Fig. 1). This location was selected because both ends of the transect are not (completely) dammed, which gives the opportunity to observe a possible inland migration of habitats in case of SLR. For the 'open + dynamic' strategy, the transect was extended into the mainland to show the inland shift of the WS.

We quantitatively documented the ecological implications of SLR and adaptation strategies by mapping ecotope distributions along the transect based on an assessment of the water depth derived from bathymetry (yellow boxes in Fig. 2) and water level (blue boxes) under different SLR scenarios and adaptation strategies (Table 3). We adopted a critical SLR rate of 10.4 mm/year for this basin based on Wang et al. (2018). Below this rate, the influx of sediment into the system is sufficiently large for the natural system to aggregate the tidal flats. Following predictions by Fokker et al. (2018), we neglected future subsidence rates in the Borndiep. Future bathymetry was determined based on whether critical rates are exceeded in the SLR scenarios, using expert judgement and reference cases in the Netherlands. From these, we determined the changes in hydro-morphological boundary conditions for ecotopes in the Wadden Sea under the two adaptation strategies as follows:

When the 'closed' adaptation strategy is implemented, tides will disappear, salinity will decrease and there is no longer sediment import from the North Sea into the WS. The potential consequences of the 'closed' strategy are estimated based on literature on the morphological changes that occurred in a similar situation in the former Zuiderzee area, following its enclosure by the Afsluitdijk barrier (Fig. 1) that turned it into the freshwater lake IJssel in 1932. Additionally, the situation in the Eastern Scheldt was used as a reference of how the intertidal flats may develop after the closing (De Vet et al., 2017). After the construction of the Afsluitdijk barrier, the tidal currents that had scoured deep channels in the shallow and flat bottom of the northern part of the Zuiderzee, were replaced with an approximately fixed water level. The absence of the tides in the present-day lake IJssel has caused these channels to be filled up with silt that is stirred up during windy periods, whereas the shallow parts in the lake remained almost unchanged (Havinga, 1954; De Vet et al., 2017). Assuming a similar transition in the WS for the 'closed' strategy, the absence of tides will result in a near-constant water level, with water level variations only driven by wind drag and variations in discharge of the feeding rivers. This will cause a large part of the Wadden Sea to be permanently submerged, and the intertidal areas will no longer exist. Similar to lake IJssel, tidal channels will gradually fill in and become shallower. Due to the fixed water level, the waves will constantly hit the same places, leading to bank erosion. The disappearance of salt-water input from the North Sea after the construction of the Afsluitdijk caused a gradual reduction in salinity in the new lake IJssel between the years 1932–1937 (Havinga, 1954). By the year 1935 the salinity already dropped to 535 mg Cl/l, at which point freshwater species started to develop. In 1937 the salinity reached a more or less constant value of 165 mg Cl/l. Similarly, after closing off the WS in the 'closed' strategy, there will be no water exchange with the North Sea anymore, which will turn the WS in a freshwater basin, as the WS is fed by a river Rhine branch, and assuming limited saltwater intrusion.

By removing the flood defences in the 'open + dynamic' strategy, natural dynamics of the WS, such as the landward roll-over mechanism of the barrier islands and the inland migration of salt marshes, will be restored. Hereby also undoing the former coastal squeeze and allow ecological zones to migrate landward. From literature it is known that salt marshes are an important sink for muddy sediment and fine sand (Oost et al., 2014). This accumulation might be a way to compensate for SLR on the islands through enhanced sedimentation.

Combining water levels from the SLR scenarios with future bathymetry, we plotted the occurrence of ecotopes along the transect, using a coloured 'barcode' that allows for quick comparison of the differences in ecotope area and spatial arrangement. A more extensive overview of the method is given in Appendix A.

Table 1
Description of ecotopes considered in this research, including their flooding frequency, based on the simplified ZES.1 ecotope system (Bouma et al., 2005). MLWS = mean low water spring tide; MHWN = mean high water neap tide.

Ecotope	Flooding frequency	Description
Salt marsh	50 - 150 x/year	The salt marsh is flooded a few times per year, which makes it possible for vegetation patches to expand in bare sediment (Bouma et al, 2005). Salt marshes occupy a narrow vertical range of less than a meter to 2 m (Hladik et al., 2013).
Pioneer zone	MHWN to > 300x/year	Open vegetation that has adapted to high flooding frequencies, with bare sediment between the pioneer vegetation.
High littoral	25% - MHWN	The benthic biomass and biodiversity in the lower littoral zone are often smaller than in the middle and high littoral zone because of the lower survival chance due to the more intensive predation by fish, crabs and shrimps. In the high littoral zone, no filter feeders are present because of the short period of submergence. The present of benthic biomass creates a foraging area for waders.
Middle littoral	25%-75%	
Low littoral	MLWS to 75%	
Shallow sublittoral	100%	Large benthic population, owing to the absence of high energy conditions.
Deep sublittoral	100%	Because of the high energy in the deeper tidal channels, the benthic density, biomass and biodiversity are very low. Only a few benthic animals can live in such conditions.

Table 2
Freshwater ecotopes considered in the ‘closed’ strategy including their occurrence range (with respect to the fixed water level) and description (Peters and Lodge, 2009).

Ecotope	Water depth	Description
Land	>0.5 m	Zone with terrestrial ecosystems.
Reeds	0 – 0.5 m	Important interface between the terrestrial ecosystem and the water zones. During periods of high water discharge, this zone is flooded, which prevents the transition to a terrestrial ecosystem.
Marsh	-0.5 – 0 m	Hosts many vertebrates (such as mammals and waterfowl); invertebrate (snakes, insects, etc.) that use both the deeper zones as well as the terrestrial ecosystem for food and habitat.
Aquatic plants	-4 – -0.5 m	Close to the shore where sunlight penetrates all the way to the sediment and allows aquatic plants to grow. The presence of aquatic plants is both a protective and nourishing component of the lake ecosystem, which results in a high biodiversity. Whether aquatic plants will be present depends on the turbidity of the water.
Deep	<-4 m	In deeper parts, where no light can reach the sediment, water plants do not grow. Biota in this deeper zone, including zooplankton and fish, often rely heavily on resources from the shallower zone. If there is not much mixing in the system, this zone will be anoxic, rendering life impossible.
Other		Area that is not considered part of the WS.

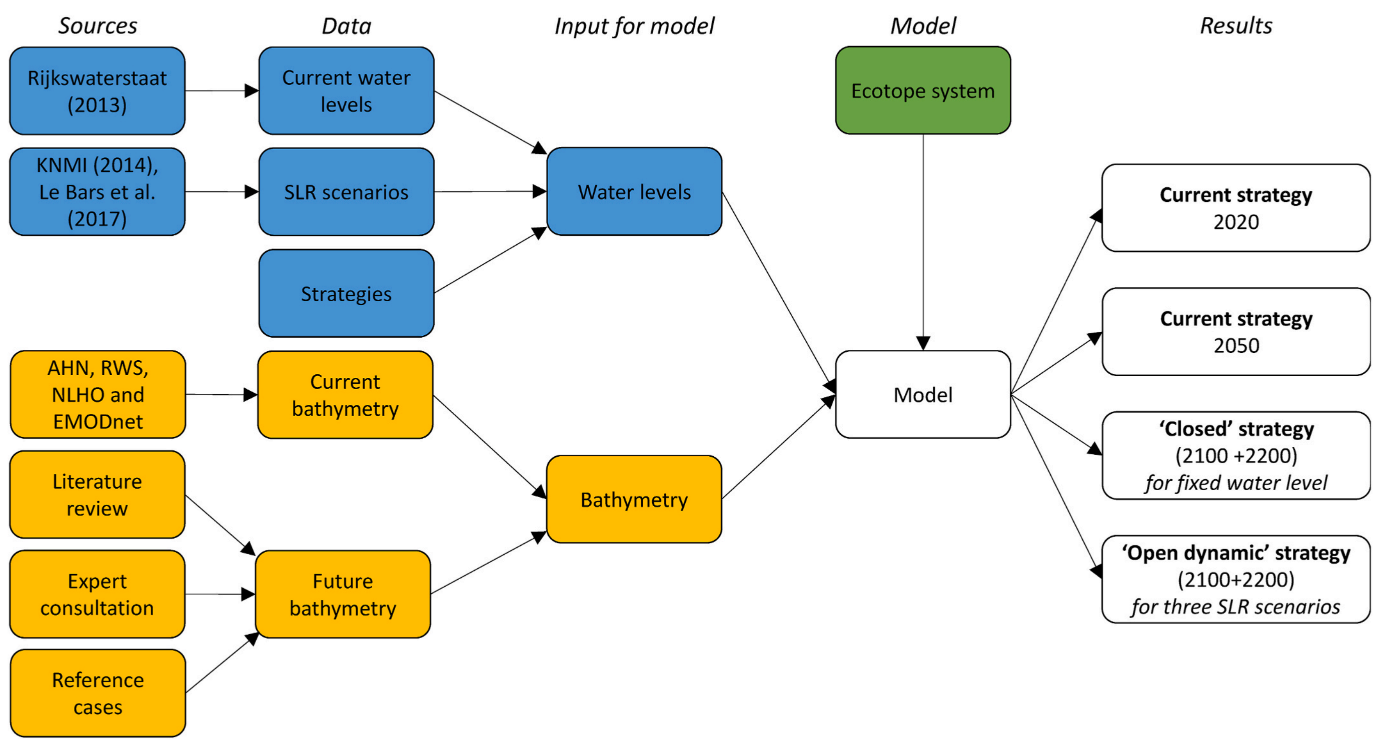

Fig. 2. Scheme of the approach to assess and visualize impacts and SLR and adaptation strategies on ecotope distribution. We considered following situations: the years 2020 and 2050 with the current strategy, 2100 and 2200 under the ‘closed’ adaptation strategy with a fixed fresh-water level and 2100 and 2200 for the ‘open + dynamic’ adaptation strategy, with three SLR scenarios.

4. Results

In this section, bathymetry changes, as result of different SLR scenarios and adaptation strategies, are used to determine ecotope distributions in the transect and visualized as barcode below the transect. First the present-day situation and the situation in 2050 is shown, hereafter the results for the ‘closed’ and ‘open + dynamic’ strategies in 2100 and 2200.

4.1. Situation in 2020 and 2050

4.1.1. Present-day situation: 2020

In the present-day situation, the North Sea and the dunes of barrier island Terschelling are located at the north-western end of the transect and the dike protecting the mainland at the south-east end (elevation peaks in Fig. 3). There is significant spatial variation in ecotopes due to the wide diversity in elevation going from deep channels to tidal flats and elevated salt marshes. The salt marsh, including its pioneer zone, occurs along the northern and southern borders of the WS, at the water-land transition. On both sides of the transect the salt marshes are approximately the same size, with, in the northern part, a few

Table 3
Used combinations of SLR scenarios and adaptation strategies in the assessments for the periods 2020 until 2200. For 2050 and 2100, we used the high estimate SLR scenarios from the Delta Programme (referred to as 'Low SLR'; KNMI, 2014), and two high-end estimates that include a potential accelerated mass-loss from Antarctica (referred to as 'Mid SLR' and 'High SLR' respectively; Le Bars et al., 2017). As the lower estimates of the Delta Programme do not exceed the critical rate for the transect, these scenarios were not considered further for analysis. For SLR beyond 2100 we considered a range of potential SLR in 2200 (3 m, 5 m and 8 m) and associated rates of SLR based on literature (DeConto and Pollard, 2016; Le Bars et al., 2017; Haasnoot et al., 2018; IPCC, 2019). The adaptation strategies 'closed' and 'open + dynamic' are described in section 2.3.

	2020	2050	2100	2200
SLR SCENARIOS	No SLR scenarios used	0.2 m with 9.1 mm/y (combination of 'Low, Mid and High SLR')	0.8 m with 16.0 mm/y ('Low SLR')	3 m with 28.6 mm/y
			0.95 m with 36.9 mm/y ('Mid SLR')	5 m with 44.5 mm/y
			1.8 m with 69.0 mm/y ('High SLR')	8 m with 49.3 mm/y
ADAPTATION STRATEGIES	Current adaptation strategy	Current adaptation strategy	'Closed' strategy 'Open + dynamic' strategy	'Closed' strategy 'Open + dynamic' strategy

interruptions caused by local higher spots. In between the two salt marshes, an irregular pattern of littoral and sublittoral areas can be observed. This pattern is caused by the spatial differences in water depth and is therefore highly variable in space.

4.1.2. Situation in 2050

By the year 2050, the critical SLR rate of 10.4 mm/year is not exceeded in any of our scenarios. Therefore, we assume that the sediment supply is sufficient for the WS bottom to rise along with the SLR. Accordingly, the 2050 bathymetry has risen by the same amount as the SLR (=0.2 m). The combination of equally changed bathymetry and water levels results in the same distribution of ecotopes as in the present-day situation (Fig. 3). This situation serves as baseline for the development in the ecotope distribution under the condition that there are no adaptation strategies implemented yet and the SLR rate does not exceed the critical rate.

4.2. 'Closed' WS

If we assume similar conditions in the WS as in lake IJssel after construction of the Afsluitdijk, our results suggest a large change in ecotopes for the situations in 2100 and 2200 (Fig. 4). The effects of the two most important changes, the absence of tides and drop in salinity, are clearly visible: the ecotopes changed from saline water to freshwater types and there are no longer intertidal ecotopes. Moreover, whereas the ecotopes in the 2050 situation show considerable spatial variation, the ecotopes after the closure are distributed more evenly along the transect: the deep and aquatic plant zones occur in the middle of the transect, while the salt marsh, reeds and land zones are located closer to the shore. The salt marsh and pioneer zone have been converted into land because they no longer experience flooding. As for the bathymetry, the channels and other deeper parts are filled in by sediment and due to bank erosion, there is a narrower and less gradual transition zone from land to water.

4.3. 'Open + dynamic'

4.3.1. Situation in 2100

The first thing that stands out in the ecotope distribution for the 'open + dynamic' strategy in 2100 (Fig. 5) is the loss of intertidal area; the proportion of littoral zones decreases and the proportion of the deep sublittoral ecotope increases for all three SLR scenarios. These are both consequences of the increasing water levels and the sediment deficit, which prevents the intertidal areas to rise along with SLR.

All SLR scenarios in 2100 clearly show coastal squeeze; decreasing area or even disappearance of the salt marshes and their pioneer zone. This is caused by the elevated area around km-23 that prevents the inland shift of the ecotopes. Only for highest SLR scenario the water level is high enough to flood the land behind the elevated area and expand the WS. The current WS area has almost entirely drowned, only a few intertidal areas are left near the flanks, and a new intertidal area with salt marshes is formed inland.

4.3.2. Situation in 2200

By the year 2200, the ecotope distribution under the 'open + dynamic' strategy, shows that the deeper sublittoral zone is dominantly present in all SLR scenarios (Fig. 5); the current WS has turned into a drowning state as (almost) no intertidal areas are left. Because the WS has expanded inland in all SLR scenarios, the characteristic ecotopes of the current WS (channels, tidal flats, salt marshes) have shifted inland.

5. Discussion

Previous studies on the response of coastal ecosystems to SLR have focused on changes in total area of wetlands or other ecosystem types, rather than separating the area into different ecological zones (Glick et al., 2013; Jankowski et al., 2017; Schuerch et al., 2018). Consequences of changes in area for the ecosystem services (the goods and services provided by ecosystems that generate benefits to people; Granek et al., 2010) are therefore generalized for the whole area rather than based on separate analyses for the different habitats. Other studies focus on a specific ecological zone only, such as the salt marsh (Feagin et al., 2010; Yoskowitz et al., 2017; Mehvar et al., 2018). They therefore do not give a full overview of the consequences for the whole coastal ecosystem. Studies that do make a distinction between different ecological zones do often not include the effect of human adaptation strategies to SLR (Craft et al., 2009; Geselbracht et al., 2015). Our approach complements these studies by allowing an assessment of both direct and indirect effects of SLR for all habitat types in coastal ecosystems, allowing a more comprehensive interpretation of impacts. Our rather straight-forward approach provides a rapid first-order assessment of future spatial distribution of all habitats present in coastal ecosystems, including the effect of adaptation strategies to SLR.

In this approach, the development of the bathymetry is based on expert judgement on morphological development of the Wadden Sea under different future boundary conditions and reference cases instead of quantitative modelling. We therefore acknowledge that the projected changes in bathymetry have been simplified in our assessments. Still, significant uncertainties also exist in detailed morphodynamic models, and these substantially increase for long time horizons (Fortunato et al., 2009; Amoudry and Souza, 2011). Moreover, at the large time scales for which our approach has been designed, these inaccuracies are small when compared to the large differences in the water levels between various SLR scenarios (IPCC, 2019). Water levels are thus a more important factor in determining the ecotope distribution than bathymetry, suggesting that the results will not be drastically different if a detailed modelling approach is used.

Using the current simplified approach enables rapid analyses that can be used as a first order assessment for screening of impacts and adaptation strategies. In the approach, the water levels used to determine the ecotope distribution are based on SLR scenarios. Since water

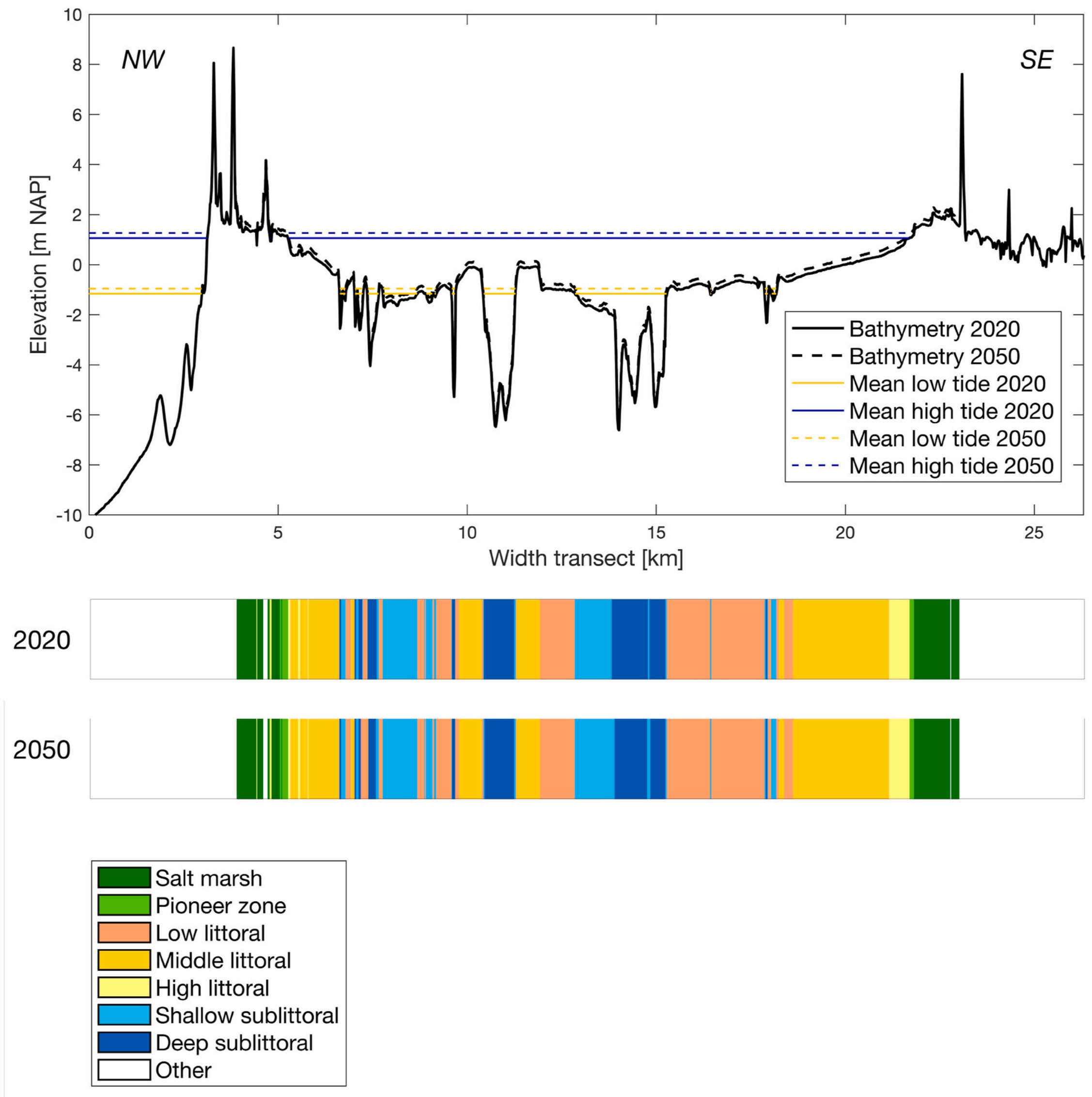

Fig. 3. Transect of the bathymetry with corresponding ecotopes in 2020 (mean high water level: 1.06 m, mean low water level: −1.16 m) and 2050 (bathymetry and water levels 2020 + 0.2 m).

levels are relatively more important in determining the ecotope distribution than bathymetry, this is an important input parameter which depends on the considered scenario, strategy, and time horizon. Exploring multiple scenarios can inform decision makers on whether or within what timespan a critical rate will be exceeded. Although the analysis strongly depends on whether the critical rate is exceeded, this first-order assessment can inform about the sensitivity of this exceedance under multiple scenarios. For example, under the lower SLR estimates of the scenarios of the Dutch Delta Programme that assume the Paris Agreement is reached, the SLR rate remains well below the critical rate in this part of the WS (N.B. in other parts of the Dutch WS such as the Vlie and Marsdiep basin, this critical rate is also exceeded in these low SLR scenarios).

The case study of the WS shows that both SLR and implementation of adaptation strategies have potentially large implications for the ecotope distribution in the WS. Not only the water depth, but also water quality will determine its future state. The 'closed' strategy will turn the WS into a freshwater lake. As the lake will be only 1–1.5 m deep, there are two alternative stable states (Scheffer et al., 1993; Faafeng and Mjelde, 1998): it may turn into a turbid lake due to sediment resuspension without any aquatic plants (Dokulil, 1994; Kelderman et al., 2012), or it may become a clear freshwater system with aquatic plants (Noordhuis, 2010; La Toya et al., 2013). The state of the freshwater lake will depend on climate, nutrients, depth and lake size (Scheffer et al., 2007). A shift between the two alternative states can occur as a result of occasional disturbances such as water level fluctuations or droughts (Blindow et al., 1998; Beklioglu et al., 2006; Ibelings et al., 2007). Management strategy of the area may also influence the future state by, for example, implementing a sediment trap, compartmentalizing the lake, or introducing water plants (Ledden et al., 2006). The 'open + dynamic' strategy will enable the WS to expand inland, while the current WS area will drown under future scenarios in which the SLR rate exceeds a critical value and cannot be counteracted by sedimentation. The disappearance of intertidal areas and salt marshes will result in a loss of food and habitat availability for example for migratory birds (IPCC, 2019). Drowning and reduction in coastal wetland area have already been observed in other parts of the world and is projected to continue in the future (Blum and Roberts, 2009; Li et al., 2018). However, to allow for inland migration of the WS ecotopes, large parts of the northern Netherlands must be given back to the sea. Due to social and economic implications of planned retreat, this is generally considered as last option for adaptation to SLR (Niven et al., 2013). Nevertheless, strategic planned retreat is now

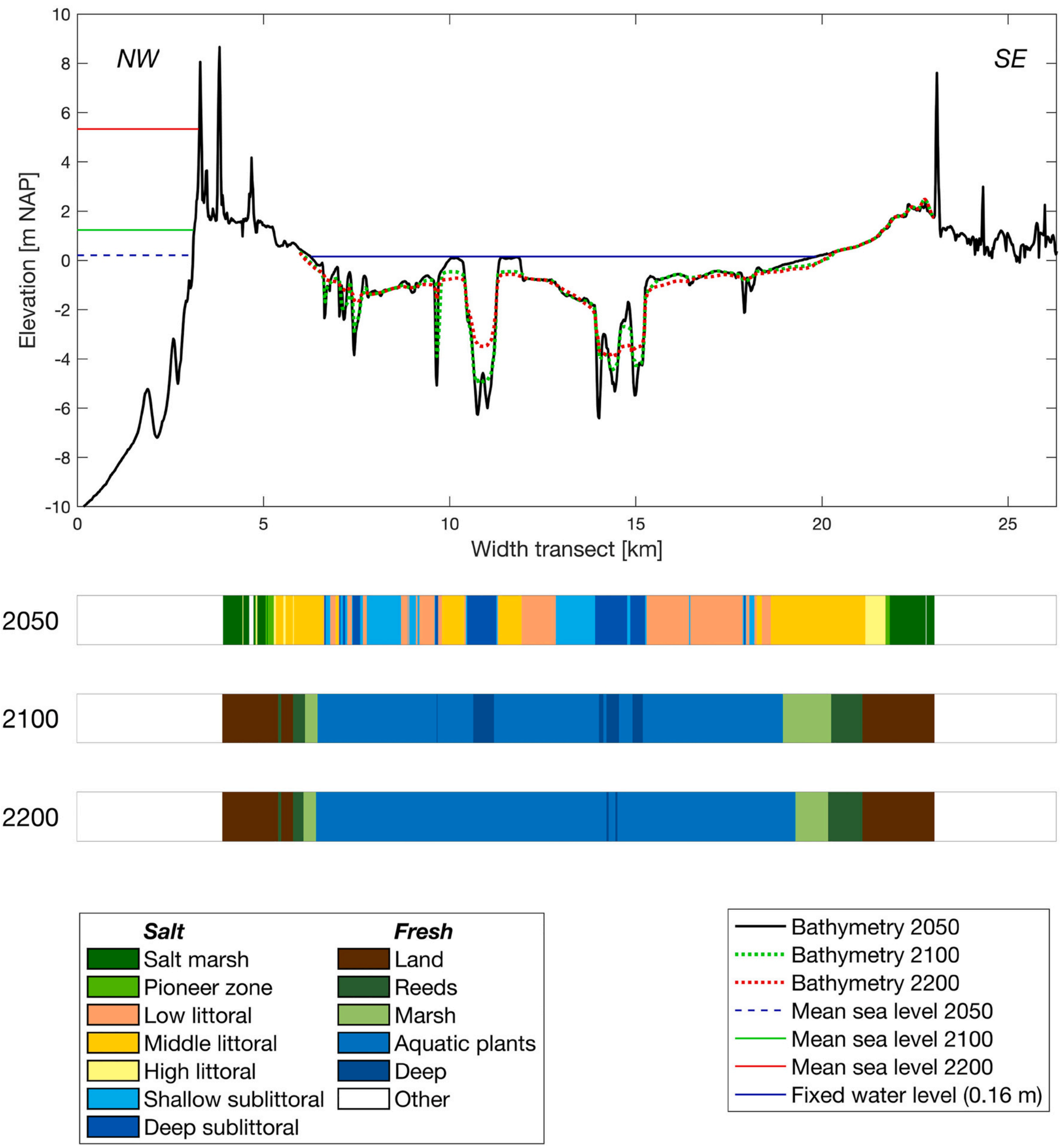

Fig. 4. Transect of the bathymetry with corresponding ecotopes in 2050, 2100 and 2200 for the 'closed' strategy with a fixed water level (0.16 m). The water levels on the North Sea side are mean values of the three climate scenarios.

increasingly suggested as sustainable long-term solution to reduce future risk for coastal communities and ecosystems (Rogers et al., 2014; Dannenberg et al., 2019).

The case study of the WS shows that our approach provides a rapid insight into shifts in ecotope distributions for different adaptation strategies, SLR scenarios and time horizons, and in this way supports assessments of ecological impacts. As the approach requires limited time and relatively simple data, the assessment can be done reasonably easy in other shallow coastal regions vulnerable to SLR, such as iconic sites Banc d'Arguin (Mauritania), Everglades (Florida), Ebro delta (Spain), and San Francisco Bay area (USA). Studies assessing the vulnerability of local ecosystems (Teck et al., 2010; Newton et al., 2014; Myers et al., 2019), could thus be complemented with our approach to include the potential future spatial distribution of habitats.

6. Conclusion

Using simple relations between habitats and their hydro-morphological boundary conditions, we have developed a first-order assessment approach to assess and easily visualize impacts of SLR scenarios and adaptation strategies on coastal ecosystems. Using a simple ecotope-habitat system, we determined to what extent future changes in bathymetry and water levels together with salinity may result in shifts in the ecotope distribution. The latter is visualized in a spatially explicit way using a barcode schematization, to provide an easy to understand first-order estimate of the potential spatial distribution of habitats. This information can be used to inform further research, decision making and for communication with local communities and non-expert stakeholders.

Applying the approach to a transect in the Dutch Wadden Sea, we assess potential ecological impacts of two adaptation strategies under different SLR scenarios and time horizons. The results show two extreme future states of the Wadden Sea once the critical rate of SLR is exceeded: the 'closed strategy' will turn the Wadden Sea into a freshwater lake, and the 'open + dynamic' strategy will allow the Wadden Sea to migrate inland while its current location will drown.

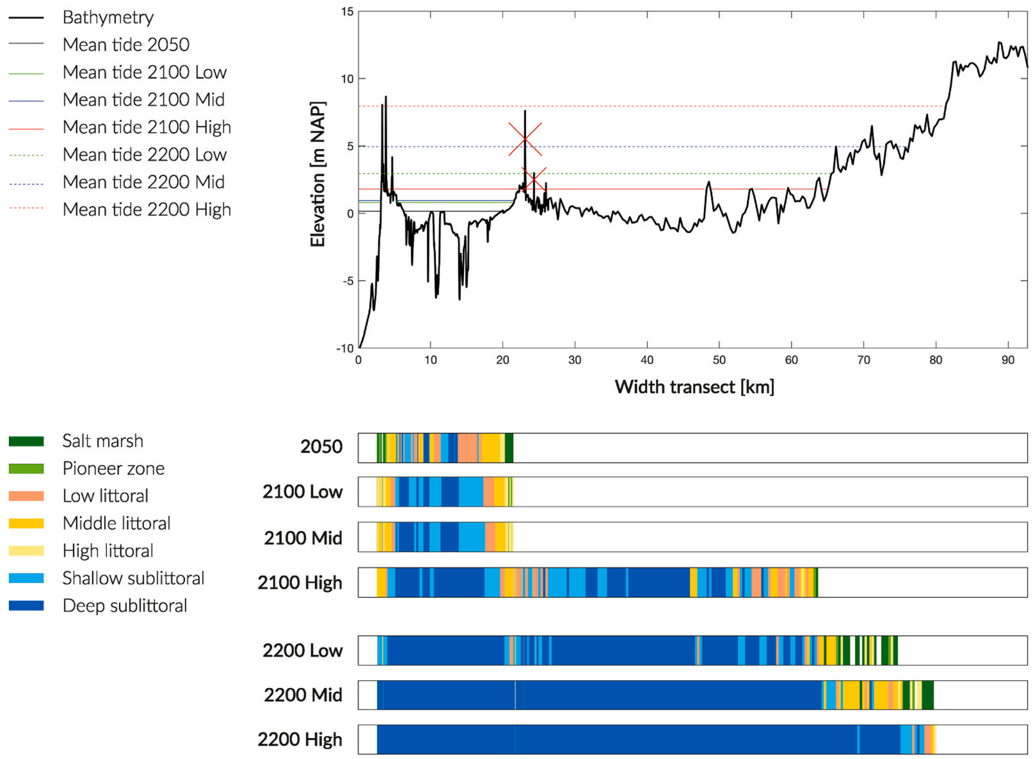

Fig. 5. Transect of the bathymetry with corresponding ecotopes for the 'open + dynamic' adaptation strategy in 2100 and 2200. The mean water levels for the Low, Mid and High SLR scenarios are respectively 0.8 m, 0.95 m and 1.8 m with SLR rates of 16.0 mm/y, 36.9 mm/y and 69.0 mm/y in 2100 and 3.0 m, 5.0 m and 8.0 m with SLR rates of 28.6 mm/y, 44.5 mm/y and 49.3 mm/y in 2200.

As our approach requires limited time and relatively simple data, it can easily be used in other regions to assess vulnerability of local ecosystems to SLR and different adaptation strategies. Our approach also allows for comparison between different time horizons, SLR rates and adaptation strategies, but should be considered as a first assessment because of its limitations. Current studies focusing on impacts of SLR on morphology could be complemented with this first-order ecological assessment. This can be used for communicating with non-experts about impacts and to quickly explore and make sensitivity assessments for coastal ecosystems as a starting point for a more comprehensive analysis.

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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Appendix A. Overview of the method

ZES.1

The Dutch Ecotope System for Coastal Waters (ZES.1) assumes that the occurrence of habitats and ecological communities is mainly determined by physical environmental factors. In this research, the determination of the ecotopes was done using a simplified version of ZES.1. This simplified version is based on the method of Baptist et al. (2019) which consists of two salt marsh types (salt marsh and pioneer), three low dynamic littoral zones (low, middle and high), one high dynamic littoral zone, two high- and low-dynamic sublittoral zones, one hard substrate type and one 'other'. Our approach, however, does not consider differences in low/high dynamics and sediment type because providing reliable estimates of hydrodynamics and sediment composition under scenario conditions in this dynamic system is problematic. Moreover, the WS is a mainly saline intertidal area, with locally some brackish sites near freshwater outlet sluices. As these brackish sites are not present in the transect, it can be assumed that the salinity is constant. Under the 'closed' strategy, the WS will turn into a freshwater lake. A similar change occurred in the 1930s after the closure of the Zuiderzee separating the new lake IJssel from the WS by the Afsluitdijk barrier. Fed by river water, lake IJssel became a freshwater lake already after 5 years (Havinga, 1954). Finally, the ecotope 'Hard substrate' is not included as the type of substratum near the location of the transect is soft (Bouma et al., 2005). Consequently, ecotope determination is only based on water depth. The water depth was determined by water level and bathymetry, which is affected by morphodynamic changes. The ecotopes considered in our simplified ZES.1 ecotope system with their occurrence range are described in Table 1.

Sea level rise projections and water levels

The water levels used to determine the ecotopes are based on three SLR scenarios. We considered the following scenarios for the period 2020 until 2100: 1) the upper estimate from the Delta Scenarios ('Warm' and 'Stoom') used in the current Delta Programme (KNMI, 2014), and two scenarios considering accelerated mass-loss from Antarctica: 2) one with a moderate global warming level (RCP 4.5) and 3) one with a high global warming level (RCP 8.5) (Le Bars et al., 2017) (Fig. A.1). The used SLR scenarios are referred to as Low, Mid and High SLR respectively. The lower Delta Scenarios ('Rust' and 'Druk') were not used in this research, as the rate of SLR in these scenarios does not exceed the critical rate for the WS, so no drastic change in ecotope distribution was expected.

Because no accurate projections for SLR in 2100–2200 are available for the Netherlands, three potential heights of the sea level in 2200 (3 m, 5 m and 8 m) were considered to determine the impacts of the adaptation strategies in the long-term. The sea levels used for 2200 are based on literature (Haasnoot et al., 2018).

For the situation in 2050 the rates of the considered scenarios do not exceed the critical SLR rate and are all similar, so no separate analysis was done for the individual scenarios (Fig. A.1). Beyond 2050 the SLR scenarios start to deviate strongly (Fig. A.1), which does require a separate analysis. For other tidal basins in the WS, for example the Vlie basin with a critical rate of 6.3 mm/year (Wang et al., 2018), the rate is already exceeded earlier and also in the lower SLR scenarios. The SLR values for 2200 based on the available literature at the time of our analysis (3, 5 and 8 m) are higher than the projections of the latest Special Report on the Ocean and Cryosphere in a Changing Climate report (SROCC), which presents a likely global mean SLR range for RCP8.5 of 1.4–2.9 m in 2200 (IPCC, 2019). However, SROCC also states that there is large uncertainty and that SLR beyond the likely range is possible. Although the probability of a high SLR scenario is currently low, plausible high-end scenarios are vital for regions with a low uncertainty tolerance (Hinkel et al., 2019); for example when there is a large value at risk, irreversible impacts and for decisions with a long lead and functional lifespan (Haasnoot et al., 2020). This is thus typically relevant for the WS.

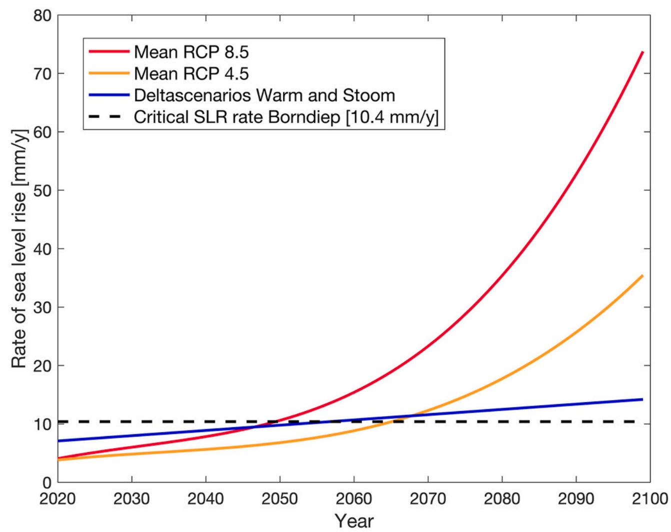

Fig. A.1. Sea level rise rates scenarios that were used for the period 2020–2100: the upper estimate from the Delta Scenarios (Warm and Stoom) and two scenarios considering accelerated mass-loss from Antarctica with a low warming levels (RCP 4.5) and with high warming levels (RCP 8.5) (Le Bars et al., 2017; Haasnoot et al., 2018) .

Bathymetry

Current bathymetry of the WS was derived from a combination of Actueel Hoogtebestand Nederland (AHN), Rijkswaterstaat (RWS), Netherlands Hydrographic Office (NLHO) and European Marine Observation and Data Network (EMODnet) data. This was done in meters relative to NAP with the profile graph tool of the 3D Analyst interactive toolbar in ArcMap. To predict the long-term development of this bathymetry under different SLR scenarios and implemented adaptation strategies, experts from different disciplines were interviewed. In total, 5 experts from the Netherlands were interviewed for roughly 1 h each. Their disciplines included physical geology and ecology. In addition to these interviews, literature was reviewed on the (historic) characteristics and functioning of the WS. Moreover, reference cases from the Netherlands, such as Eastern Scheldt, lake IJssel and lake Marker were reviewed to provide insight into the morphodynamic changes after closing off. Using this information, future changes to the bathymetry of the transect were estimated and drawn manually using the WebPlotDigitizer of Rohatgi (2019), assuming that local morphological changes (aggregation, channel infilling) occur, without large-scale morphodynamic changes in the entire WS. From these new transects, combined with the water levels, ecotope distributions were derived using conditional statements in Matlab and illustrated using a colour-bar, as presented in Section 4. In this way it is possible to visualize the redistribution of the ecotopes and comparing the proportions of the ecotopes in time and space and among the different SLR scenarios.

Ecotope assessment

Using the two input variables, water level and bathymetry, an ecotope assessment was done for four situations: the situation in 2020 and 2050 with the current strategy, the situation in 2100 and 2200 for the 'closed' strategy and the situation in 2100 and 2200 for the 'open + dynamic' strategy. A detailed explanation of these assessment is given below.

Current strategy (2020)

To derive the current ecotope distribution, we used the current bathymetry and water levels. The mean water levels for high and low tide were obtained from Rijkswaterstaat (2013). Rijkswaterstaat is part of the Dutch Ministry of Infrastructure and Water Management. To distinguish between supralittoral and littoral, mean high and low tide during spring tide were used. The present-day situation was used as reference for creating future states in the next steps.

Current strategy (2050)

The situation in 2050 is based on a mean SLR of the three climate scenarios (Delta Scenarios Warm and Stoom, the mean RCP4.5 and the mean RCP8.5) which is 9.1 mm/y. At this point no change in strategy is implemented yet, the current strategy is still in place. The morphodynamic changes are therefore a result of SLR only. Because the SLR rate at this point does not exceed the critical rate (Wang et al., 2018), it was assumed that the bathymetry is able to rise with the same amount as the sea level. Thus, water depths along the transect remain unchanged.

After 2050

After 2050 the rate of SLR will exceed the critical rate in every SLR scenario and the sediment supply is no longer sufficient to maintain the current system in the WS (Wang et al., 2018). To adapt the WS to these higher SLR rates to assure flood safety for the Dutch mainland and preserve the unique character of the WS, a new adaptation strategy will be implemented after 2050. The two strategies are a 'closed' strategy (see Section 2.3.1) and an 'open + dynamic' strategy (see Section 2.3.2). It is assumed that the strategy will be implemented immediately after 2050 and it therefore influences the morphology of the WS during the whole period until 2200. From this point onward, both the morphodynamic changes that are a result of the implementation of a strategy and the SLR feedback on the morphology are included. To develop the intertidal areas in line with rising sea levels and to assure flood safety for the Dutch mainland, the unique character of the WS can be preserved.

'Closed' strategy (2100 & 2200)

To assess the consequences of the 'closed' strategy, morphodynamic changes that occurred in lake IJssel after the Zuiderzee was closed off from the North Sea were used as reference. Additionally, the situation in the Eastern Scheldt was used as a reference of how the intertidal flats may develop after the closing (De Vet et al., 2017). Together, these references gave a first indication of the consequences for the WS if it were closed off.

Within a 'closed' strategy for the WS, more than one situation is imaginable. In this research it is assumed that the water level in the WS will be fixed between the current mean high water and mean low water (0.16 m NAP) This is the same method that was used after the closure of the Zuiderzee (Noordhuis, 2010). This means that during most of the low water period, discharge of excess water into the North Sea by gravity is possible. Considering that this period of discharge by gravity will be shortened as a result of SLR, it can be chosen to increase the fixed level. However, this will cause an even larger loss of shoals, and Rijkswaterstaat (2019) showed that the ability to discharge by gravity only has a small effect in reducing the costs of drainage.

'Open + dynamic' strategy (2100 & 2200)

The 'open + dynamic' strategy, which can be implemented once the critical rates are exceeded, will restore the natural dynamics in the WS by removing the current flood defences on the mainland and the barrier islands. As the size of the WS is now not fixed by dikes anymore, it is expected that the WS will migrate inland and the current location of the WS will drown as a result of insufficient sediment supply.

In the situation for 2100, the water levels used correspond to the three SLR scenarios explained earlier. To be able to determine the impacts of this strategy on the long-term development of the WS, the consequences of three potential water levels in 2200 were assessed: 3 m, 5 m and 8 m.

References

Adam, P., 2002. Saltmarshes in a time of change. Environ. Conserv. 29 (1), 39–61.

Amoudry, L.O., Souza, A.J., 2011. Deterministic coastal morphological and sediment transport modeling: a review and discussion. Rev. Geophys. 49 (2).

Baarse, G., 2014. Natural solutions to cope with accelerated sea level rise in the Wadden Sea region. Towards an integrated long term adaptation strategy framework. Knowledge for Climate report number KfC 132/2014.

Baart, F., et al., 2019. Zeespiegelmonitor 2018; De stand van zaken rond de zeespiegelstijging langs de Nederlandse kust. https://deltares.nl/app/uploads/2019/03/Zeespiegelmonitor-2018-final.pdf.

Bamber, J.L., Westaway, R.M., Marzeion, B., Wouters, B., 2018. The land ice contribution to sea level during the satellite era. Environ. Res. Lett. 13 (6), 063008.

Baptist, M.J., van der Wal, J.T., de Groot, A.V., Ysebaert, T.J.W., 2016. Ecotopenkaart Waddenzee volgens de ZES.1 typologie (Wageningen University & Research rapport; No. C103/16). Den Helder: Wageningen Marine Research.

Baptist, M.J., Van Der Wal, J.T., Folmer, E.O., Gräwe, U., Elschot, K., 2019. An ecotope map of the trilateral Wadden Sea. J. Sea Res. 152, 101761.

Beklioglu, M., Altinayar, G., Tan, C.O., 2006. Water level control over submerged macrophyte development in five shallow lakes of Mediterranean Turkey. Arch. Hydrobiol. 166 (4), 535–556.

Blindow, I., Hargeby, A., Andersson, G., 1998. Alternative stable states in shallow lakes: what causes a shift?. In: The Structuring Role of Submerged Macrophytes in Lakes. Springer, New York, NY, pp. 353–360.

Bloemen, P.J., Hammer, F., van der Vlist, M.J., Grinwis, P., van Alphen, J., 2019. DMDU into practice: adaptive delta management in The Netherlands. In: Decision Making under Deep Uncertainty. Springer, Cham, pp. 321–351.

Blum, M.D., Roberts, H.H., 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nat. Geosci. 2 (7), 488.

Bouma, H., de Jong, D.J., Twisk, F., Wolfstein, K., 2005. A Dutch ecotope system for coastal waters. Report RIKZ 1–115.

Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., Machmuller, M., 2009. Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. Front. Ecol. Environ. 7 (2), 73–78.

Dannenberg, A.L., Frumkin, H., Hess, J.J., Ebi, K.L., 2019. Managed retreat as a strategy for climate change adaptation in small communities: public health implications. Climatic Change 153 (1–2), 1–14.

De Vet, P.L.M., Van Prooijen, B.C., Wang, Z.B., 2017. The differences in morphological development between the intertidal flats of the Eastern and Western Scheldt. Geomorphology 281, 31–42.

DeConto, R.M., Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531 (7596), 591–597.

Delta Programme, 2018. Delta Programme 2019. Continuing the work on the delta: adapting The Netherlands to climate change in time. https://english.deltacommissaris.nl/deltaprogramme/documents/publications/2018/09/18/dp2019-en-printversie.

Dissanayake, D.M.P.K., Ranasinghe, R., Roelvink, J.A., 2012. The morphological response of large tidal inlet/basin systems to relative sea level rise. Climatic Change 113 (2), 253–276.

Dokulil, M.T., 1994. Environmental control of phytoplankton productivity in turbulent turbid systems. In: Phytoplankton in Turbid Environments: Rivers and Shallow Lakes. Springer, Dordrecht, pp. 65–72.

Elias, E.P.L., Van der Spek, A.J.F., Wang, Z.B., De Ronde, J., 2012. Morphodynamic development and sediment budget of the Dutch Wadden Sea over the last century. Neth. J. Geosci. 91 (3), 293–310.

Eriksson, B.K., van der Heide, T., van de Koppel, J., Piersma, T., van der Veer, H.W., Olff, H., 2010. Major changes in the ecology of the Wadden Sea: human impacts, ecosystem engineering and sediment dynamics. Ecosystems 13 (5), 752–764.

Esteves, L.S., 2013. Is managed realignment a sustainable long-term coastal management approach? J. Coast Res. 65 (sp1), 933–939.

Faafeng, B.A., Mjelde, M., 1998. Clear and turbid water in shallow Norwegian lakes related to submerged vegetation. In: The Structuring Role of Submerged Macrophytes in Lakes. Springer, New York, NY, pp. 361–368.

Feagin, R.A., Martinez, M.L., Mendoza-Gonzalez, G., Costanza, R., 2010. Salt marsh zonal migration and ecosystem service change in response to global sea level rise: a case study from an urban region. Ecol. Soc. 15 (4).

FitzGerald, D.M., Fenster, M.S., Argow, B.A., Buynevich, I.V., 2008. Coastal impacts due to sea-level rise. Annu. Rev. Earth Planet Sci. 36.

Fokker, P.A., van Leijen, F.J., Orlic, B., van der Marel, H., Hanssen, R.F., 2018. Subsidence in the Dutch Wadden Sea. Neth. J. Geosci. 97 (3), 129–181.

Fortunato, A.B., Bertin, X., Oliveira, A., 2009. Space and time variability of uncertainty in morphodynamic simulations. Coast. Eng. 56 (8), 886–894.

Geselbracht, L.L., Freeman, K., Birch, A.P., Brenner, J., Gordon, D.R., 2015. Modeled sea level rise impacts on coastal ecosystems at six major estuaries on Florida's gulf coast: implications for adaptation planning. PloS One 10 (7), e0132079.

Glick, P., Clough, J., Polaczyk, A., Couvillion, B., Nunley, B., 2013. Potential effects of sea-level rise on coastal wetlands in southeastern Louisiana. J. Coast Res. 63, 211–233.

Granek, E.F., Polasky, S., Kappel, C.V., Reed, D.J., Stoms, D.M., Koch, E.W., Aswani, S., 2010. Ecosystem services as a common language for coastal ecosystem-based management. Conserv. Biol. 24 (1), 207–216.

Haasnoot, M., Bouwer, L., Diermanse, F., Kwadijk, J., van der Spek, A., Essink, G.O., Delsman, J., Weiler, O., Mens, M., ter Maat, J., Huismans, Y., 2018. Mogelijke gevolgen van versnelde zeespiegelstijging voor het Deltaprogramma. Een verkenning. Deltares rapport, 11202230–005.

Haasnoot, M., Kwadijk, J., Van Alphen, J., Le Bars, D., van den Hurk, B., Diermanse, F., Mens, M., 2020. Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of The Netherlands. Environ. Res. Lett. 15 (3), 034007.

Havinga, B., 1954. Hydrografie van het IJsselmeer. In: De Beaufort, L.F. (Ed.), Veranderingen in de flora en fauna van de Zuiderzee (thans IJsselmeer) na de afsluiting in 1932: Verslag van de onderzoekingen, ingesteld door de Zuiderzee-Commissie der Nederlandse Dierkundige Vereniging, pp. 1–24.

Hawkins, E., 2018. Warming stripes. https://www.climate-lab-book.ac.uk/2018/warming-stripes/ (last accessed March 2021).

Hinkel, J., Church, J.A., Gregory, J.M., Lambert, E., Le Cozannet, G., Lowe, J., van de Wal, R., 2019. Meeting user needs for sea level rise information: a decision analysis perspective. Earth's Future 7 (3), 320–337.

Ibelings, B.W., Portielje, R., Lammens, E.H., Noordhuis, R., van den Berg, M.S., Joosse, W., Meijer, M.L., 2007. Resilience of alternative stable states during the recovery of shallow lakes from eutrophication: lake Veluwe as a case study. Ecosystems 10 (1), 4–16.

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. M. Weyer (in press).

Jankowski, K.L., Törnqvist, T.E., Fernandes, A.M., 2017. Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. Nat. Commun. 8 (1), 1–7.

Kelderman, P., Ang'Weya, R.O., De Rozari, P., Vijverberg, T., 2012. Sediment characteristics and wind-induced sediment dynamics in shallow Lake Markermeer, The Netherlands. Aquat. Sci. 74 (2), 301–313.

Kirezci, E., Young, I.R., Ranasinghe, R., Muis, S., Nicholls, R.J., Lincke, D., Hinkel, J., 2020. Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. Sci. Rep. 10 (1), 1–12.

Kirwan, M., Temmerman, S., 2009. Coastal marsh response to historical and future sea-level acceleration. Quat. Sci. Rev. 28 (17–18), 1801–1808.

Kirwan, M.L., Temmerman, S., Skeehan, E.E., Guntenspergen, G.R., Fagherazzi, S., 2016. Overestimation of marsh vulnerability to sea level rise. Nat. Clim. Change 6 (3), 253–260.

KNMI, 2014. KNMI'14: climate change scenarios for the 21st century – a Netherlands perspective; by Bart van den Hurk, Peter Siegmund, Albert Klein tank. In: Jisk Attema, Alexander Bakker, Jules Beersma, Janette Bessembinder, Reinout Boers, Theo Brandsma, Henk van den Brink, Sybren Drijfhout, Henk Eskes, Rein Haarsma, Wilco Hazeleger, Rudmer Jilderda, Caroline Katsman, Geert Lenderink, Jessica Loriaux, Erik van Meijgaard, Twan van Noije, Geert Jan van Oldenborgh, Frank Selten, Pier Siebesma, Andreas Sterl, Hylke de Vries, Michiel van Weele, Renske de Winter and Gerd-Jan van Zadelhoff. Scientific Report WR2014–01, KNMI. De Bilt, The Netherlands.

Kopp, R.E., DeConto, R.M., Bader, D.A., Hay, C.C., Horton, R.M., Kulp, S., Strauss, B.H., 2017. Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. Earth's Future 5 (12), 1217–1233.

La Toya, T.K., Jacob, D.L., Hanson, M.A., Herwig, B.R., Bowe, S.E., Otte, M.L., 2013. Macrophytes in shallow lakes: relationships with water, sediment and watershed characteristics. Aquat. Bot. 109, 39–48.

Le Bars, D., Drijfhout, S., de Vries, H., 2017. A high-end sea level rise probabilistic projection including rapid Antarctic ice sheet mass loss. Environ. Res. Lett. 12 (4), 044013.

Ledden, Van, et al., 2006. Verdiepingsslag en maatregelen slibproblematiek Markermeer–Analyse kennisleemten en inventarisatie maatregelen. Royal Haskoning and WL Delft Hydraulics. Report 9R3456.A0.

Li, X., Bellerby, R., Craft, C., Widney, S.E., 2018. Coastal wetland loss, consequences, and challenges for restoration. Anthropocene Coasts 1 (1), 1–15.

Lodder, Q.J., Wang, Z.B., Elias, E.P., van der Spek, A.J., de Looff, H., Townend, I.H., 2019. Future response of the Wadden Sea tidal basins to relative sea-level rise—an aggregated modelling approach. Water 11 (10), 2198.

Mehvar, S., Filatova, T., Syukri, I., Dastgheib, A., Ranasinghe, R., 2018. Developing a framework to quantify potential sea level rise-driven environmental losses: a case study in Semarang coastal area, Indonesia. Environ. Sci. Pol. 89, 216–230.

Myers, M.R., Barnard, P.L., Beighley, E., Cayan, D.R., Dugan, J.E., Feng, D., Page, H.M., 2019. A multidisciplinary coastal vulnerability assessment for local government focused on ecosystems, Santa Barbara area, California. Ocean Coast Manag. 182, 104921.

Newton, A., Icely, J., Cristina, S., Brito, A., Cardoso, A.C., Colijn, F., Ivanova, K., 2014. An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal systems, lagoons and transitional waters. Estuar. Coast Shelf Sci. 140, 95–122.

Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science 328 (5985), 1517–1520.

Niven, R.J., Bardsley, D.K., 2013. Planned retreat as a management response to coastal risk: a case study from the Fleurieu Peninsula, South Australia. Reg. Environ. Change 13 (1), 193–209.

Noordhuis, R., 2010. Ecosysteem IJsselmeergebied: nog altijd in ontwikkeling. Trends en ontwikkelingen in water en natuur van het Natte Hart van Nederland. Rijkswaterstaat Waterdienst. Lelystad.

Oost, A.P., Wang, Z.B., de Groot, A.V., Duren, L.A., van der Valk, L., 2014. Preparing for Climate Change: a Research Framework on the Sediment-Sharing Systems of the Dutch, German and Danish Wadden Sea for the Development of an Adaptive Strategy for Flood Safety (No. 1209152–000). Deltares, Delft.

Pattyn, F., Morlighem, M., 2020. The uncertain future of the Antarctic ice sheet. Science 367 (6484), 1331–1335.

Peters, J.A., Lodge, D.M., 2009. Littoral zone. In: Likens, G.E. (Ed.), Ency- Clopedia of Inland Waters, vol. 1. Elsevier, Oxford, pp. 79–87.

Piersma, T., Koolhaas, A., Dekinga, A., Beukema, J.J., Dekker, R., Essink, K., 2001. Long-term indirect effects of mechanical cockle-dredging on intertidal bivalve stocks in the Wadden Sea. J. Appl. Ecol. 38 (5), 976–990.

Reise, K., 2005. Coast of change: habitat loss and transformations in the Wadden Sea. Helgol. Mar. Res. 59 (1), 9–21.

Reise, K., Baptist, M., Burbridge, P., Dankers, N.M.J.A., Fischer, L., Flemming, B., Smit, C., 2010. The Wadden Sea-a universally outstanding tidal wetland. In: The Wadden Sea 2010. Common Wadden Sea Secretariat (CWSS); Trilateral Monitoring and Assessment Group: Wilhelmshaven. (Wadden Sea Ecosystem; 29/editors, Harald Marencic and Jaap de Vlas, vol. 7.

Rijkswaterstaat, 2013. Kenmerkende Waarden Getijdegebied 2011.

Rijkswaterstaat, 2019. Beleidsaanbevelingen voor het langetermijn peilbeheer in het IJsselmeergebied. Eindrapport Integrale Studie Waterveiligheid en Peilbeheer IJsselmeergebied, 2019D25786. https://www.rijksoverheid.nl/documenten/rapporten/2019/06/18/eindrapport-integrale-studie-waterveiligheid-en-peilbeheer-IJsselmeergebied.

Rogers, K., Saintilan, N., Copeland, C., 2014. Managed retreat of saline coastal wetlands: challenges and opportunities identified from the Hunter River Estuary, Australia. Estuar. Coast 37 (1), 67–78.

Rohatgi, A., 2019. WebPlotDigitizer. http://arohatgi.info/WebPlotDigitizer/. (Accessed July 2019).

Scheffer, M., Hosper, S.H., Meijer, M.L., Moss, B., Jeppesen, E., 1993. Alternative equilibria in shallow lakes. Trends Ecol. Evol. 8 (8), 275–279.

Scheffer, M., van Nes, E.H., 2007. Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients, depth and lake size. In: Shallow Lakes in a Changing World. Springer, Dordrecht, pp. 455–466.

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D., Hinkel, J., 2018. Future response of global coastal wetlands to sea-level rise. Nature 561 (7722), 231–234.

Teck, S.J., Halpern, B.S., Kappel, C.V., Micheli, F., Selkoe, K.A., Crain, C.M., Murray, G., 2010. Using expert judgment to estimate marine ecosystem vulnerability in the California Current. Ecol. Appl. 20 (5), 1402–1416.

Van den Hurk, B., Geertsema, T., 2020. An assessment of present day and future sea level rise at the Dutch coast; Zeespiegelstijging langs de Nederlandse kust en de regionale bestuurlijke consequenties. https://www.waddenacademie.nl/fileadmin/inhoud/pdf/04-bibliotheek/2020-05_An_assessment_of_present_day_and_future_sea_level_rise_at_the_Dutch_coast.pdf.

Van der Spek, A.J., 2018. The development of the tidal basins in the Dutch Wadden Sea until 2100: the impact of accelerated sea-level rise and subsidence on their sediment budget–a synthesis. Neth. J. Geosci. 97 (3), 71–78.

Van Goor, M.A., Zitman, T.J., Wang, Z.B., Stive, M.J.F., 2003. Impact of sea-level rise on the morphological equilibrium state of tidal inlets. Mar. Geol. 202 (3–4), 211–227.

Van Kuik, P.H., 1965. Amelanderdam. Master Thesis, Civil Engineering and Geosciences, Hydraulic Engineering. TU Delft, Delft, The Netherlands. http://resolver.tudelft.nl/uuid:ee3ffb3b-8799-4049-82db-58c521045e79.

Van Maanen, B., Coco, G., Bryan, K.R., Friedrichs, C.T., 2013. Modeling the morphodynamic response of tidal embayments to sea-level rise. Ocean Dynam. 63 (11–12), 1249–1262.

Vereniging van Verzamelaars van Oude Fondsen (VVOF), 1983. Mededelingenblad. http://www.scripophily.nl/scripophily/VVOF-Mededelingenbladen/1983-juli.pdf. (Accessed October 2019).
Voss, C.M., Christian, R.R., Morris, J.T., 2013. Marsh macrophyte responses to inundation anticipate impacts of sea-level rise and indicate ongoing drowning of North Carolina marshes. Mar. Biol. 160 (1), 181–194.
Wang, Z.B., Hoekstra, P., Burchard, H., Ridderinkhof, H., De Swart, H.E., Stive, M.J.F., 2012. Morphodynamics of the Wadden Sea and its barrier island system. Ocean Coast Manag. 68, 39–57.
Wang, Z.B., Elias, E.P., van der Spek, A.J., Lodder, Q.J., 2018. Sediment budget and morphological development of the Dutch Wadden Sea: impact of accelerated sea-level rise and subsidence until 2100. Neth. J. Geosci. 97 (3), 183–214.
Wong, P.P., Losada, I.J., Gattuso, J.P., Hinkel, J., Khattabi, A., McInnes, K.L., Sallenger, A., 2014. Coastal systems and low-lying areas. Climate change 2104, 361–409.
Woodroffe, C.D., Rogers, K., McKee, K.L., Lovelock, C.E., Mendelssohn, I.A., Saintilan, N., 2016. Mangrove sedimentation and response to relative sea-level rise. Annual Review of Marine Science 8, 243–266.
World Meteorological Organization (WMO), 2019. The Global Climate in 2015–2019. WMO, Geneva, Switserland, p. 21. https://library.wmo.int/doc_num.php?explnum_id=9936.
Yoskowitz, D., Carollo, C., Pollack, J.B., Santos, C., Welder, K., 2017. Integrated ecosystem services assessment: Valuation of changes due to sea level rise in Galveston Bay, Texas, USA. Integrated Environ. Assess. Manag. 13 (2), 431–443.