MEETING DOCUMENT

**Expert group Climate Change Adaptation**

**(EG-C)**

21 October 2021

**Subject: Single integrated management plan (SIMP) – Assessment of (potential) impacts of Coastal Flood Defence and Protection activities on the Outstanding Universal Value (OUV) of the Wadden Sea World Heritage**

**Date:** 15 October 2021

**Submitted by: CWSS and Ingrid van Beek**

The Leeuwarden Declaration 2018 includes the task to develop a single integrated management plan for the Wadden Sea World Heritage (SIMP) as requested by the WH Committee in 2014. The content of the SIMP, based on the preliminary structure endorsed by the WSB 30 ([*WSB30 5.1-2 SIMP status report.pdf*](https://www.waddensea-worldheritage.org/system/files/WSB30%205.1-2%20simp%20status%20report.pdf)), aims to provide a clear overarching description of the nature conservation management systems at the national and trilateral levels. The SIMP also aims to address key topics presenting concrete threats to the OUV and takes into consideration the influence of climate change adaptation. The five key topics in the SIMP are coastal flood defence and protection measures, fisheries, shipping, tourism and energy.

The referential structure for the single integrated management plan (SIMP) key topics was agreed by Task Groups World Heritage (TG-WH) and Management (TG-M) in their joint meeting in January 2020. Part of the content identified as wanted and needed is an assessment of the threats and opportunities of each of the five key topics related activities on the OUV key values.

The EG-C, in their meetings 6,7 and 8 produced a preliminary list of the existing coastal protection activities that have a (potential) impact on the OUV and opportunities. EG-C 7 agreed to seek support from outside EG-C to add to the list of activities and to define the impact on key values of the OUV. The engaged consultant Ingrid Van Beek produced a first draft of the rapid expert assessment based on the preliminary list developed by EG-C. The draft was reviewed and commented by EG-C (June 2021).

This document contains the updated expert rapid assessment incorporating all comments received regarding content and structure, as well as additions from consultations with experts from the three countries. The expert assessments of the five key topics in the SIMP are being reviewed, discussed, and enriched. These, together with the site managers input, will support the definition of activities for the key topics in the SIMP seeking ambition and articulating policy and site management. Ambitious policy priorities should be taken up in the Ministerial Declaration (WSB 33 Draft Summary Record).

**Proposal:** to review the updated expert assessment and send written comments by 28 October 2021.

Assessment of (potential) impacts of Coastal Flood Defence and Protection activities on the Outstanding Universal Value (OUV)

Introduction

Sea level rise, temperature increase, and extreme heat events could be the key stressors of climate change to affect the Wadden Sea World Heritage (Heron et al 2020). This was the outcome of a rapid assessment in February 2020, using the Climate Vulnerability Index (CVI). The CVI has been applied in multiple World Heritage sites to assess their vulnerability to climate change pressures.

The report of Heron et al (2020) states that the vulnerability of the Wadden Sea to impacts from sea level rise escalates from low in 2050 to high in 2100. Sea level rise may seriously impact the structure, functions and characteristic biodiversity of the Wadden Sea ecosystem, and the safety of the inhabitants of the region. Sea level rise especially influences the geomorphological developments of the area, which shape future habitats upon which species are highly dependent, especially in the long-term perspective beyond 2050.

Adaptation strategies associated with sea level rise might also have significant influence on the Outstanding Universal Value (OUV). Coastal protection interventions and management response may be stressors that have consequences. Further in-depth research for more profound evidence on the severity of their impacts was suggested in the report.

Flood risk reduction in coastal areas is traditionally approached from a conventional engineering perspective, where dikes and dams are built to withstand the forces of tides, surges, and waves. This approach has often resulted in negative or unforeseen impacts on local ecology or even surrounding ecosystems on larger scales (Borsjes et al 2011). Nature-based approaches to flood risk reduction is increasingly promoted, by utilizing the benefits of coastal ecosystems for reducing impact of extreme weather events. Ecosystems such as salt marshes and sand dunes are preserved, enhanced, or even created, in order to reduce flood risk in coastal areas. Nature-based flood defences can work stand-alone, like sand dunes, but can also function in combination with engineered defences, for example when vegetated foreshores reduce wave loads on dikes or dams. The utilization of ecosystem engineering species to achieve civil-engineering objectives, either by trapping sediment or reducing wave energy is another nature-based approach (Borsjes et al 2011).

Consequences of climate change, especially sea level rise, for the Wadden Sea ecosystem entered the political agenda of the trilateral Wadden Sea cooperation in 1997, at the 8th trilateral Conference in Stade, Germany. In 1998, a trilateral expert group, the Coastal Protection and Sea Level Group (CPSL) was installed. A first screening of sustainable coastal defence strategies with minimal impacts on the ecosystem was conducted. The following sustainable coastal defence instruments and measures were investigated further: spatial planning, sand nourishment, dune management, salt marsh management, mussel and sea grass beds, outbanking of summer polders, and sea dikes (CPSL 2005).

This document presents an expert assessment including a description of identified coastal flood defence and protection measures activities and their (potential) impacts on the OUV key values. It also includes recommendations to reduce or eliminate negative effects on the OUV or to leverage positive effects. The underlying method, percentages and definitions are provided by the World Heritage Committee in the Periodic Reporting, Chapter 4 designed to assess the factors affecting a property.

The expert assessment is visualised in figure 1, where each impact is assessed across each of the ten OUV key values (defined for the Climate Vulnerability Index workshop, enriched and endorsed by TG-WH), by checking if the impact is positive and/or negative, current and/or potential, the origin of the impact (inside and/or outside of the property), the temporal scale (one off or rare, intermittent or sporadic, frequent or on-going), the spatial scale (restricted, localised, extensive or widespread), and the trend of the overall impact (stable, increasing, decreasing). The degree of concern of the impact or the degree of benefit, if the impact is positive, can be ranked from insignificant, minor, significant, to major. The standardized method and visualisation are being used for the expert assessment of all five key topics of the SIMP.

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| --- | --- | --- | --- | --- |
|  |  | **Criterion (viii): Outstanding geological processes** | **Criterion (ix): Ongoing ecological and biological processes** | **Criterion (x): Vital habitats for in-situ biodiversity conservation** |
| **Possible areas of interaction** |  | 1Unbroken tidal flat and barrier system | 2Typical geomorphological diversity | 3Ongoing natural geomorphological processes | 4Intact natural intertidal ecosystems | 5Linked geomorphological, biophysical and biological processes | 6High biomass production typical for the Wadden Sea | 7Key site for sustaining abundant wildlife beyond its borders | 8High typical biodiversity  | 9Staging, moulting and wintering area for migratory birds | 10Essential stopover for the East Atlantic Flyway |
| 1. Coastal Flood Defence: Dikes and closure dams | Pfeil nach rechts mit einfarbiger Füllung | Harvey Balls 90% mit einfarbiger Füllung |  |  |  |  |  |  |  |  |  |
| 2. Coastal Flood Defence: Dike maintenance and strengthening | Pfeil nach rechts mit einfarbiger Füllung |  |  |  |  |  |  |  |  |  |  |
| 3. Coastal Flood Defence: Dune management | Pfeil nach rechts mit einfarbiger Füllung |  |  |  |  |  |  |  |  | scale?  | scale?  |
| 4. Coastal Flood Defence & Coastal Protection: Salt marsh management | Pfeil nach rechts mit einfarbiger Füllung |  |  |  |  |  |  |  |  |  |  |
| 5. Coastal Protection: Shoreline protection | Pfeil nach rechts mit einfarbiger Füllung |  |  |  |  |  |  |  |  |  | degree/scale? |
| 6. Coastal Protection: Sand nourishment | Pfeil nach rechts mit einfarbiger Füllung |  | Harvey Balls 35% mit einfarbiger Füllung | Harvey Balls 35% mit einfarbiger Füllung |  |  |  |  | Harvey Balls 35% mit einfarbiger Füllung | ? | Harvey Balls 35% mit einfarbiger Füllung |

**Legend**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Impact** |  | **Origin** |  | **Trend** |  | **Temporal scale** |  | **Spatial scale** |
|  | positive |  |  | inside  |  |  | stable |  |  | one off or rare  |  |  | **Widespread** affecting between 91-100% of the property’s area at any one time |  | **Localised** affecting between 11 and 50% of the property’s area at any one time |
|  | negative  |  |  | outside |  |  | increasing |  |  | intermittent or sporadic |  |
|  | current  |  |  |  |  |  | decreasing |  |  | frequent or on-going |  |  | **Extensive** affecting between 51-90% of the property’s area at any one time |  | **Restricted** affecting less than 10% of the property’s area at any one time |
|  | potential  |  |  |  |  |  |  |  |  |  |  |

|  |  |  |
| --- | --- | --- |
| **Degree of concern (negative)** |  | **Degree of benefit (positive)** |
|  | Insignificant | The (potential) impact has no effect on the OUV key value.  |  |  | Insignificant | The (potential) benefit has no effect on the OUV key value. |
|  | Minor | The (potential) impact produces/can produce a minor disturbance of the OUV key value.  |  |  | Minor | The (potential) benefit has/can have a minor effect on the OUV key value.  |
|  | Significant | The (potential) impact produces/can produce a significant disturbance of the OUV key value. |  |  | Significant | The (potential) benefit has/can have a significant effect on the OUV key value. |
|  | Major | The (potential) impact is/can be a major cause of disturbance of the OUV key value.  |  |  | Major | The (potential) benefit has/can have a major effect on the OUV key value.  |
|  | Range | The (potential) impact is/can be from insignificant to a major cause of disturbance of the OUV key value depending on the conditions. |  |  | Range | The (potential) impact is/can be from insignificant to a major cause of disturbance of the OUV key value depending on the conditions. |

**Figure 1.** Assessment of (potential) impacts of Coastal Flood Defence and Protection activities on the Outstanding Universal Value (OUV).

# Possible IMPACTS of coastal protection activities

## Coastal Flood defence: dikes and closure dams

From a historical perspective, the construction of dikes and closure dams had a major impact on the geomorphology of the Wadden Sea. The spatial scale of all impacts is considered widespread, as almost the entire coastline of the Wadden Sea has been artificially fixed with hard structural flood defences, and closure dams have separated most of the coastal inlets from the sea. These rigid separations of land and sea shortened the coastal zone to a 500-km straight shoreline and changed the once highly dynamic coastline.

Sea level rise and sediment supply used to be the main drivers that shaped the geomorphological diversity of islands, ebb-tidal deltas, tidal inlets, and back-barrier tidal basins with channels, sand shoals and mud flats. Landward of the tidal area, similar sized salt marshes and reed marshes provided periodically flooded plains. The shoreline between tidal area and salt marsh was highly dynamic and shifted with sea level and sediment supply (Reise 2005).

About 1000 years ago diking became a key anthropogenic driver of change in geomorphological processes, affecting hydrodynamics, sediment dynamics, habitat dynamics and habitat diversity. Sea walls were built for the purpose of land reclamation and flood prevention. Periodical flooding during storm surges still occurred due to breaching of dikes. This and subsidence of the land due to draining and mining of peat contributed to the formation of large coastal inlets and major losses of land. Since the 17th century dike building intensified, technology improved and embankments became permanent. In the 19th century large tidal areas were embanked or dammed and transformed mainland marshes and deltas into arable land, polders and freshwater reservoirs. Ongoing subsidence of reclaimed marshland due to drainage and soil compaction, with the oldest marsh sinking below sea level, continued to require coastal protection for the strongly increasing population in the lowlands (Reise 2005).

Crucial for understanding historic long-term trends in shoreline development is the relation between sea level rise and sediment availability under natural conditions or with coastal protection structures. Tidal area development is largely determined by the ratio between increase in water volume associated with sea level rise, sediment demand due to sea level rise, and sediment supply from external sources. With an excess of sediment supply, shoreline accretion can keep up with sea level rise. With low sediment supply, tidal areas are expanding by shoreline erosion. Erosion is a source of sediment to raise the level of the nearshore zone. The effect of dikes in tidal areas with sediment hunger arising from sea level rise is downshore and offshore erosion. Downshore, dikes cause coastal squeeze of upper shoreline habitats until they are lost. Increased hydrodynamics prevent settlement of fine sediment particles, and salt marshes and tidal flats will disappear. Offshore, size reduction of tidal areas by dikes causes a corresponding reduction in sediment volume of ebb tidal deltas. The sediment in ebb tidal deltas is needed to adjust the tidal basins to sea level rise, the remainder may contribute to island dunes and high sandy shoals (Reise 2005).

**Geomorphological impacts**

Most severe geomorphological impacts are the major size reduction of the tidal flat and barrier system (affecting key value 1) and (key value 3) long-term and large-scale changes in dynamic geomorphological processes such as hydrodynamic sedimentation and erosion patterns.

The Wadden Sea is still one of the largest tidal flat and barrier systems, but it decreased in size more than 60% compared to about 1000 years ago, by the separation of mainland habitats from the sea by dikes and closure dams. Of the mainland coastal plain of 24.000 km2, measured from the 15-m depth contour offshore to the tidal area including wetlands and estuaries, nowadays 15.000 km2 consists of embanked salt marshes, brackish reed marshes and inlets. The remaining tidal flat area consists of 4.000 km2 subtidal zone, 4.000 km2 intertidal flats, 200 km2 mainland and 1oo km2 island salt marshes, and 1.000 km2 of islands and high sandy shoals (Reise 2005). Geomorphological diversity is preserved (key value 2) with the continuous transformation of mudflats, beaches, dunes and saltmarshes by natural dynamics of tides, wind and waves. However, dikes and closure dams altered the natural dynamics of water and sediment movements.

Closure of coastal inlets shortened the distance between barrier islands and mainland. In general, high-water levels went up and low water levels hardly changed. After closure of the brackish Zuiderzee in 1932, the largest coastal inlet with 3.600 km2, the tidal range in the Marsdiep tidal basin increased up to 0.5 meter. Shorter width, steeper slopes, and increased high water levels enhanced hydrodynamics. This resulted in decreasing fine particle deposition and less muddy sediments. Fine particles were also removed from the sediment budget due to embankment of muddy coastal inlets and nearshore mudflats.

The functions of coastal morphology and habitats to dissipate energy from waves and tides, retain imports of deposits and substances, and provide enough space and dynamics to support biodiversity have changed. The transformation is highest in marshes and estuaries, moderate in the tidal area and relatively minor on the barrier islands (Reise 2005).

**Ecological impacts**

Major ecological impacts are the size reduction of natural intertidal habitats and typical species in marshes and estuaries (key values 4 and 8), and loss of connectivity between marine and freshwater habitats, resulting in loss of migrating species like diadromous fish depending on this functioning link between habitats during part of their life cycle (key values 7 and 8) (Swimway 2019).

Due to impermeable dikes and closure dams, connectivity between salt marshes and inland brackish and freshwater habitats got lost. Sluices, pumps, culverts, and ship locks in coastal defence structures discharge freshwater, but with a few exceptions do not let seawater in. They are all causing abrupt salinity gradients. Dikes and dams block migration routes for fish to freshwater spawning sites, and discharge facilities can cause damage to small fish if they manage to migrate to the sea. Since the early 19th century populations of sturgeon (*Acipenser sturio*), salmon (*Salmo salar*), trout (*Salmo trutta*), alis shad (*Alosa alosa*) and houting (*Coregonus oxyrhynchus*) became extinct or critically endangered. This was besides loss of connectivity, also caused by overexploitation, habitat destruction and water quality degradation (von Nordheim et al. 1996 in Lotze 2005). When strong salinity gradients were still present, marine fish species used to favour estuarine recruitment (Schlacher & Wooldridge 1996 in Phillipaert and Baptist 2016). Anchovy (*Engraulis encrasicolus*), herring (*Clupea harengus*), smelt (*Osmerus eperlanus*) and flounder (*Platichthys flesus*) used the large open brackish inlets with tidal influence to spawn, grow and mature (Redeke 1939 in Phillipaert and Baptist 2016).

Subtidal seagrass (*Zostera marina*) all along the northern Atlantic coasts suffered from a wasting disease in 1932-1934. At two sites with subtidal sea grass beds, construction of the Zuiderzee closure dam and the dam at Sylt happened around the same time. The increased hydrodynamics, water turbidity and sediment mobility adjacent to the dams, in combination with the loss of the positive feedback mechanism of seagrass to reduce turbidity (Van der Heide et al 2007), may all have contributed to a lack of seagrass recovery (Reise 2005). In Germany, subtidal seagrass did partially recover in the 1970s to the 1980s (Reise et al 1989 in Lozte 2005). Widespread loss of European flat oyster (*Ostrea edulis*) beds in the Wadden Sea due to overexploitation resulted in a collapse of this commercial fisheries in the 1870s (Lotze 2005). One of the reasons of poor recruitment, recovery and recolonization of oyster beds is arguably increased siltation as impact from coastal engineering, which buries shells and smothers spat (Berghahn and Ruth 2004). The decrease in red and brown algae is also attributed to increased water turbidity and loss of solid surfaces for attachment, such as seagrass beds and oyster reefs. Oyster banks once supported rich communities of sponges, sea anemones, hydroids, worms, sea urchins and other species (Lotze 2005). Lack of recovery of flat oysters and seagrass has a significant impact on (OUV 5&8) biophysical processes like flow reduction and sediment entrapment and on biogeomorphological interaction between these three-dimensional structures and their environment, shaping bedforms and providing habitat for settlement, shelter and food to a variety of species (key values 5 and 8).

The extensive shoreline zone, rich in marsh plants, seagrass and microphytobenthos on mudflats, had a high number of primary producers. High productivity provided carrying capacity for grazers, surface deposit feeders and higher trophic levels. With the size reduction of seagrass and marsh habitats and a transformation from an area dominated by mud flats into an area dominated by sandy tidal flats, productivity is depending primarily on external plankton supply (Reise 2005). This is considered to have a significant impact on biomass production (key value 6). Due to changes in sediment composition, benthos composition changed from mud dwelling surface deposit feeders and diatom grazers to sand dwelling subsurface deposit feeders (Reise 2005). These changes can have a significant impact on biogeomorphological interactions (key value 5) as the benthos composition determines the bioturbation potential. This process of biogenic modification of sediments through particle reworking and burrow ventilator is a key mediator of important geochemical processes in the seabed, changing sedimentary conditions. Changes in sediment reworking functional types, from regenerators that excavate holes and transfer sediment at depth to the surface, to surficial modifiers that bioturbate at the sediment-water interface, reduce the bioturbation potential (Quierós et al 2013).

Habitat transformations of peatlands, salt marshes and mudflats also affected breeding and migratory birds. Since the Middle Ages (500-1500 AD) it caused strong declines in benthivorous (36% decrease), piscivorous (45%) and planktivorous (55%) birds. Embankments in the past 1000 years are considered to have a significant impact to these declining bird populations (key values 9 and 10). Herbivorous birds depending on salt marshes and seagrass beds, such as the brent goose (*Branta bernicla*) and teal (*Anas crecca*), have declined two- to threefold since the Middle Ages. In contrast, those which adapted to new food sources available on agricultural fields such as graylag goose (*Anser anser*) and white-fronted goose (*A. albifrons*) strongly increased, especially during winter (van Eerden 1997 in Lotze 2005).

**Trend**

The situation is not stable, and changes are ongoing, because habitats will continue to change by fixed coastal morphology that is not in line with hydrodynamic morphology, and by continued sea level rise (Reise 2005). Hard structural flood defences are no ecologically sustainable solution as long as the sediment hunger from sea level rise continues, because the process of downshore and offshore erosion will continue. This ongoing influence on the morphological development of the Wadden Sea will also continue to have an impact on ecological and biological processes.

**Opportunities**

Mitigation of the ongoing process of coastal erosion is possible by giving space to the seawater or by artificial sediment supply from an external source.

Giving the tidal area space during storm surges can be achieved by converting unpopulated polders which are below mean sea level into reservoirs, using sluices and drainage canals in reversed direction (Reise 1996 in Reise 2005). There are several managed retreat initiatives in the Wadden Sea, to increase resilience to sea level rise by enhancing natural sedimentation processes, and to counteract habitat loss due to coastal squeeze by creating new marine or brackish habitats in polders (Hofstede 2019, WWF 2015). De-embankment of summer polders by opening low summer dikes in salt marshes is a managed retreat measure which is addressed in chapter 4. Removing or opening seaward primary embankments is possible in polders with a double embankment system. About half of the Schleswig- Holstein coastal lowlands and the majority of the Dutch Wadden Sea coast are protected by multiple embankments with polders behind each other. In Schleswig Holstein, three salt-water nature reserves with reduced tides have been implemented behind primary embankments. In the Dutch Ems-Dollart estuary initiatives include creation of a secondary dike and polder with tidal water inlet in the primary dike, with pilots to establish ecosystem services such as marine aquaculture, saline agriculture, brackish natural habitats, as well as clay production from high concentrations of silt in the estuary (Hofstede 2019, Van Loon 2021).

Opening of populated polders may require additional flood risk management measures such as strengthening of secondary dikes (Hofstede 2019). Although low lying polders are significant and effective sediment sinks, accumulation in opened polders would lead to sediment deficits in fronting tidal areas, making the measure counterproductive for the sediment budget (Hofstede 2015).

To balance sediment hunger, sand nourishment by means of islets, bars, and spits in sheltered embayments can help to restore transitional habitats in the upper shore, such as salt marsh and mud flat development by natural accretion (Reise 2003 in Reise 2005). Such sediment supplementation should be concentrated at locations where natural forces organize redistribution most efficiently (Hofstede and Stock 2018). Sandy solutions for coastal defence reinforcement can also mitigate coastal erosion and have positive ecological impacts by mitigation of intertidal habitat loss, which is further discussed in chapter 2.

Other opportunities include improvement of estuarine gradients and restoration of connectivity between marine and freshwater systems and within freshwater systems for fish migration (Van der Veer and Tulp 2015 in Philippart and Baptist 2016). The construction of brackish zones in freshwater bodies or more permanent freshwater discharges in tidal basins are other potential solutions to create estuarine gradients. Natural estuarine gradients include saltwater inlets, freshwater seepages, creeks and estuaries. Man-made estuarine gradients in coastal defence structures include sluices, pumps, culverts, and locks. The amount of freshwater discharge is an indication of the size of the potential inland habitat available. Some of them are already equipped with facilities for (anadromous) fish migration to freshwater or prevention of damage to (catadromous) fish migrating to the sea. Due to more extremes in riverine water levels and rainfall patterns discharge facilities will require more capacity, which is an opportunity to include fish passages by a number of technical solutions.

Relatively simple are fish-friendly discharge sluice and ship lock management, tide gates or tidal flaps in culverts and openings or slots in locks. More expensive are fish-friendly pumps or pumps with fish bypasses, and fish ladders, siphon spillways or eel gutters. Most expensive and complex are fish passage constructions that include collection and upstream return flow for the inflow of saltwater with the incoming flood tide (Phillipaert and Baptist 2016). The Fish Migration River in the Afsluitdijk is such a permanent open connection between the Wadden Sea and the freshwater IJsselmeer, with a 4-km long salinity gradient and fish passage solutions for strong and weak swimmers.

## Coastal flood defence: dike maintenance and strenghtening

Dikes should be continuously maintained, heightened, and strengthened to preserve their protection levels, due to sea level rise and degradation of materials after extreme storm surge events. Higher water levels lead to decreasing wave height reduction over the foreshore, and subsequently, to higher probabilities of dike failure by wave overtopping (Vuik et al. 2019). Dike reinforcement includes raising and widening the dike crest or strengthening the inner or outer slope revetment.

Sea dikes and revetments are designed and constructed according to guidelines for coastal structures, such as the International Levee Handbook (CIRIA 2013). Dike form and building materials used vary depending on the boundary conditions, like hydraulic loads, soil properties, locally available materials, and spatial restrictions. The hydraulic load is determined by water level and flow, wind direction and speed, wave run-up and height, and local bathymetry. In the Wadden Sea, dikes usually consist of soil constructions with a sand core, an outer protective layer of clay and grass, toe protection and a maintenance road. Stone and asphalt are used at sites with higher hydraulic loads (Van Loon 2015).

Dike slopes are designed as a compromise between mild slopes, with optimal dike stability, and steep slopes, with minimal material consumption and dike footprint (Scheres and Schüttrumpf 2019). The traditional dike in the Netherlands is a dike with a steep slope (around 1:3) and grey revetment. The traditional dike concept in Germany and Denmark is a wide green dike, with a grass covered shallow seaward slope (around 1:7) that merges smoothly into the adjacent salt marshes. A smooth transition is only possible with salt marshes in front of a dike, while tidal flats require a concrete foot protection to avoid erosion at the foot during storm surges. In Schleswig-Holstein dikes are 8 to 9.5m high and up to 80m wide (Hofstede 2019).

**Geomorphological impacts**

The impact on geomorphological sedimentation and erosion processes (key values 3) and on the tidal flat and barrier system (key value 1) due to changes in sediment dynamics and habitat loss depend on dike maintenance measures and methods applied, which vary, depending on the location and traditional approach in each country. On a widespread scale, as elaborated in the previous chapter, there are ongoing changes, because habitats will continue to change by fixed coastal morphology that is not in line with hydrodynamic morphology, and by continued sea level rise (Reise 2005).

Construction materials like sand and gravel are extracted from the North Sea or from inland sources. Clay can be extracted locally, although this can have an impact on the sediment budget in the Wadden Sea. In Germany, clay extraction from salt marsh pits to strengthen dikes used to be possible under strict rules, but it was a growing source of conflict (Karle and Bartholomae 2008). In Lower Saxony, this clay extraction stopped recently (J. Fröhlich, pers. comm.) and in Schleswig-Holstein, clay for dike strengthening is taken from terrestrial sources (J. Hofstede, pers. comm.). In the Netherlands, clay mining for a nearby wide green dike resulted in a project in polder Breebaart, where between double dikes, dredged material from the Ems-Dollard estuary is used to ripen and dry silt and produce a solid clay. This would have positive effects on the water quality and the ecological quality of the estuary (Van Loon and Vellinga 2019). This option is excluded in Schleswig-Holstein, because of negative effects, as the extracted material can function as a buffer against drowning of tidal flats, beaches, primary dunes and salt marshes due to sea level rise (Hofstede and Stock 2018).

**Ecological impacts**

The ecological impacts also depend on dike maintenance measures and methods applied, which vary per location and country. Wide green dikes are assumed to have positive effects on nature compared to steep grey or black dikes. Waves do not reach the dike during normal conditions and are damped by the foreshore. Wave energy dispersion along the slope is more distributed and wave run up is reduced, in comparison to steep grey dikes. This makes a thick clay layer covered in grass sufficient to protect the dike against erosion (Van Loon and Schelfhout 2017). However, as the dike footprint increases linear with the slope inclination, loss of original habitat increases accordingly. Hence, in Germany, dike strengthening occurs, wherever possible, to the inland side. A larger dike footprint may have a negative impact on habitat connectivity. At the same time alternative habitat is created, like grass meadows, which may have an ecological value.

Meadow birds species foraging on open agricultural areas bordering the Wadden Sea are the black-tailed godwit (*Limosa limosa*), oystercatcher (*Haematopus ostralegus*) and barnacle goose (*Branta leucopsis*). However, most meadow birds require wet permanent grassland and reduced grazing pressure for their conservation. Barnacle geese prefer short-grazed agricultural and livestock grasslands and started to breed along their flyways, nowadays in the entire Wadden Sea (Tentij et al 2009).

Connectivity beyond the inland borders of the Wadden Sea remains an issue and impact for species migrating between habitats (key value 7). If dike widening is carried out inland instead of seaward, at least size reduction of intertidal habitats is limited (key value 4). The ecological value of green dikes is not considered to contribute to typical biomass production (key value 6) or typical biodiversity (key value 8) in the Wadden Sea. It may increase food availability to certain migratory bird species (key value 10), but this will be at the expense of species foraging in intertidal habitats that got lost.

**Trend**

Material needs for coastal protection works are expected to increase due to sea level rise, which is not a concern for the Wadden Sea as long as it is taken from external sources.

Latest developments in coastal engineering use ecosystem-based engineering solutions and build with natural processes, for more sustainable and adaptive designs. Nature-based flood defences like sand dunes and salt marshes, that function stand-alone or in combination with engineered defences, are addressed in chapter 3 and 4. On Texel, an artificial sand dune has been constructed seaward from the existing Wadden Sea dike. The higher and broader sandy dike is fixed with marram grass and sand fences, has added natural elements such as a beachfront, embayment, sand spit and transplanted salt marsh (Perk et al 2019). Two measures were taken to ensure minimal erosion: the coarsest (400 μm) sand was used, and the seaward slopes approach a natural slope for the given grainsize (Fordeyn et al 2020). The sand dune has improved the naturalness of the dike and created new beach and dune habitat. However, due to the seaward expansion it reduced naturally occurring tidal flat habitat, and in terms of principle, it is against the uniqueness of a natural world heritage site to introduce habitat on a location where it is not naturally occurring.

**Opportunities**

According to Scheres and Schüttrumpf (2019) knowledge on ecologically valuable dikes is available, for example on the erosion resistance of vegetated dike covers, the use of vegetated revetments, and other methods to enhance the ecological value of dikes.

Dike strengthening projects can become more environmentally sustainable and reduce the global climate change footprint by using and generating renewable energy, applying innovations and new technologies for collecting renewable energy. At the Afsluitdijk closure dam, ‘blue’ energy is generated by differences in salt concentration of salt and freshwater, and a solar energy generating road will be integrated in the design.

## Coastal flood defence: Dune management

Dunes are natural flood defences, and since a long time the aim of dune management is to maintain this ecosystem service. Measures today include dune restoration, dune relocation, natural dune dynamics and wash-overs defences (CPSL 2005). Dune restoration encompasses the catching of wind driven sand to promote dune growth, by planting marram grass or building (brushwood) sand fences. Dune relocation is the establishment of a new dune line at an eroding coastline, where the outer dune will gradually retreat. Natural dune dynamics is applied as measure when dunes have no immediate coastal defence function. It is a long-term coastal defence measure to stimulate vertical accretion of the inner part of the islands due to Aeolic sand transport. Wash-overs also is a way to use natural dynamic processes to help barrier islands keep up with sea level rise. It allows transportation of water and sand across the island through wash-over channels. These channels are not created but are allowed to occur naturally.

The choice of a measure depends on hydro-morphological boundary conditions: the sediment budgets of the interdependent foreshore, beach, and dunes. Insufficient sediment supply at the foreshore causes a narrow beach, which causes dune foot erosion due to storm surges and wave energy dissipation (CPSL 2005). Three types of dunes are distinguished, with a positive, neutral, or negative sand balance. The first type requires little restoration, for example if blow outs occur. The second type requires strengthening of temporary sand loss, often at the dune foot after storms. Occasional beach or foreshore nourishments may be suitable measures as well. The negative sand balance dune type, with a coastal protection function, often got shoreline protection structures like groynes and seawalls to stop beach and dune erosion. Nourishment is often needed in addition, with or without structures being present. Relocation can be a good measure as well.

Natural dynamics and wash-overs have ecological benefits as they add to the naturalness. Wash-overs can create habitat change or gradients from freshwater to brackish or saline environments. However, these positive impacts are not considered in this assessment, as the measures are not applied in dunes with coastal protection function. Dune restoration and relocation, possibly in combination with sand nourishments, do interfere with nature, yet are still preferred above hard constructions (CPSL 2005).

**Geomorphological impacts**

Dune systems with natural dynamic processes of wind, water and sand are important components of the geomorphological processes that enable young dunes to wander freely. Artificial dune fixation as coastal flood defence measure hampers this cycle of succession and renewal of dune habitat. This has a significant impact on biogeomorphological diversity (key value 2) of different dune habitats. Accelerated succession in mobile dunes that are fixed with marram grass, results in climax vegetation instead of allowing complex habitat succession (Reise 2005, Oost et al 2012). This results in the loss of shifting young (white) dunes. There are other factors which stabilize dunes and accelerate succession, such as the invasion of native grasses due to nitrogen deposition, lack of grazers and dehydration.

A significant geomorphological impact from dune fixation and artificial closure of dune breaches is that dynamic sediment patterns by the process of Aeolic sand transport (key value 3) across the islands, from the North Sea to the inner island and southern parts, are prevented (CPSL 2005, Oost et al 2017). This impact is not restricted to the dune system alone, the spatial scale of the impact is on the island development as a whole.

**Ecological impacts**

Accelerated succession has consequences for flora and fauna communities when typical pioneer vegetation and habitat disappear (key value 8). Massive stabilization reduces the opportunities for pioneer vegetation (Oost et al. 2012). This has significant impact on the positive feedback mechanisms of pioneer species (key value 5). The dynamics in dune landscapes are controlled by biophysical landscape-forming feedback mechanisms between dominant plant species and physical processes, ameliorating stressful conditions to improve their own growth conditions. Loss of pioneer species as sand couch (*Elytrigia juncea*) and marram grass (*Ammophila arenaria*) has impact on the dune ecosystem, because they have a high resilience to physical stress in all succession gradients in the beach and embryonic dune system and colonize bare unmodified environments and stimulate vegetation (Reijers et al. 2020).

Sand drift dikes have a similar ecological impact as dune fixation. These artificial dune ridges were built in the past, and still exist today. As a result, openings in dune arcs and washovers disappeared, ending natural sand dynamics. This prevented transport of water, sediment, and nutrients to the inner island or even to the Wadden coast. The sand drift dikes were also intensively maintained by planting marram grass and placing sand fences to limit Aeolian transport across the island. The lack of natural dynamics led to fast development and succession of the vegetation. It was decided that the sand drift dikes on the uninhabited island tails would no longer be maintained. New openings formed in the sand drift dikes on some locations, but this has not seriously improved the situation. There where large sand drift dikes are absent, there is much more natural environment with highly dynamic ecosystems (Oost et al 2012).

Dunes provide good nesting opportunities and food for wintering, migrating and breeding bird species. Pioneer habitats with wandering dunes, wet dune valleys and sea inlets should be preserved (Tentui et al 2009) as staging, breeding, moulting, and wintering area for migratory birds (key value 9) and for food availability (key value 10).

**Trend**

Sediment budgets will develop negatively with increasing sea level. This means there is a need for natural dune dynamics so islands can accrete vertically and keep up with sea level rise. However, due to sea level rise the flood defence function of dunes becomes more important. It is likely that dune fixation measures will increase, for the above-mentioned reasons: negative sediment budgets require more management, and flood defence gets priority in dune management. These measures have a negative impact on natural dune dynamics and on complex habitat succession.

In addition, foreshore and beach nourishment will become increasingly important to increase the sand budget and stabilize dunes. Dune relocation or dune nourishments may become necessary as well (CPSL 2005).

**Opportunities**

Dune management includes two measures with geomorphological, ecological, and biophysical benefits: natural dune dynamics and wash-overs. They both are long-term coastal defence measures that allow islands to keep up with sea level rise. In addition, wash-overs can create habitat gradients by changing freshwater to brackish or saline environments which increases diversity on the islands.

It is an opportunity to restore dune dynamics at a large scale where possible, at least on uninhabited island tails. Also on inhabited land, dunes are preferred above hard constructions, even though dune restoration and relocation measures do interfere with nature (CPSL 2005) as it has less negative impacts than hard constructions.

Since sediment budgets of dunes are interconnected with beaches and foreshore, sand nourishments are a good supporting coastal defence. It contributes directly to erosion prevention and stabilization of dunes, natural dune-foot, and outer dune slope protection, and it is serves as a sand source for natural dune dynamics.

## Coastal flood defence & coastal protection: Salt Marsh management

In the Wadden Sea, three salt marsh types are distinguished: foreland marshes, back-barrier marshes and Hallig salt marshes. A Hallig is a salt marsh island originating from mainland high-marsh zones. The Hallingen are surrounded by revetments and have dwelling mounds and ditches on the island to protect inhabitants. Sandy back-barrier marshes are mainly natural, although natural dynamics in some marshes has been reduced due to artificial drainage or sand drift dikes. Clayey foreland marshes on the mainland make up over 50% of the Wadden Sea marshes and were mostly developed in the salt marsh works by the construction of sedimentation fields (Esselink et al. 2017).

The salt marsh works started about 150 years ago with the aim to establish new marshes that could be reclaimed. Important management practices were digging drainage ditches and the construction of brushwood groyne fields to enhance vegetation establishment and increase livestock grazing capacity and prevent formation of unvegetated salt depressions. The effect of drainage was a vertical descent of the pioneer and low-marsh zones, while vertical accretion rates were not affected, and sedimentation continued to late-succession vegetation (Esselink et al. 2017).

Salt marsh works developed marshland in areas with hydrodynamics conditions that are naturally not suitable for establishment of pioneer vegetation and sedimentation. The naturally low incidence of salt marshes in the western Wadden Sea may be caused by large-scale coastline fixation with dikes and closure dams (Dijkema 1987 in Esselink et al. 2017). In exposed environments, low stone dams on salt marshes create a broader foreshore and salt marsh habitat and are effectively reducing retreat of the salt marsh edge and increasing sedimentation on mudflats between dams and the former salt marsh cliff. Under favourable conditions for sedimentation, erosion protection by low stone dams reduces retreat of edge and helps to restore an ecological attractive foreshore zone with pioneer salt marsh vegetation (Van Loon and Slim 2013). However, stones are not natural in the Wadden Sea and, thus, this measure presents an ecological interference.

Since the last quarter of the 20th century salt marsh management in the Wadden Sea shifted from land reclamation and agricultural exploitation to recognition of nature values and coastal protection. This shift led to a change in management measures that varied from minimum intervention to strategic upkeep of the drainage and groyne system.

In the Netherlands, maintenance of artificial drainage systems in the salt marsh works stopped by 2001. Only ditching by local farmers to facilitate livestock grazing continued. To protect salt marsh habitat and avoid erosion, brushwood groynes are well maintained. Only nearshore groynes are not maintained, so the outer fields are mudflats and a gradient between intertidal and salt marsh habitats. Although there is still a strong human influence due to the presence of livestock and the contours of old drainage systems, the salt marshes are slowly shifting towards a state of naturalness. Elements of a natural foreland salt marsh are visible by development of creeks in the pioneer zone, build-up of levees, development of poorly drained depressions, and new creeks in these depressions. To enhance naturalness, restoration experiments have been carried out as well, such as filling up parts of the drainage system, removing topsoil or digging deep clay pits (Esselink et al. 2017).

Salt marshes are recognized for their coastal protection function, as they can keep up with certain rates of sea level rise by their sediment trapping vegetation. In Germany, salt marshes have a coastal flood defence function in front of dikes as well. Under moderate storm surges, salt marshes effectively limit the amount of water that flows through a dike breach. It functions as a barrier in front of the breach, thereby limiting the damage expectations (Thorenz et al. 2017).

**Geomorphological impacts**

Salt marsh management aims to enhance sediment accretion processes and prevent erosion processes in hydrodynamic locations where salt marshes would otherwise not have established. As such it had an impact on natural geomorphological processes. Minimal management measures, by not maintaining nearshore groynes and drainage systems, allow for more natural stages of mudflat and salt marsh diversity (key value 2) and more natural sedimentation and erosion patterns (key value 3). Erosion of high marshes allows for pioneer vegetation to re-establish, and positive feedback mechanisms between vegetation, water flow and marsh morphology can re-establish a natural drainage network of creeks (Temmerman et al. 2007).

Therefore, salt marsh management is considered to have minor positive impact on geomorphology, although it is acknowledged that natural development of salt marshes is preferred if hydrodynamic conditions are favourable. There is proof of substantial natural growth of salt marshes in Schleswig-Holstein (Hofstede, pers. comm.).

**Ecological impacts**

As mentioned above, due to changes in salt marsh management, vegetation succession slows down and at eroded marsh zones primary pioneer vegetation can re-establish. By removing topsoil or digging deep clay pits on high marsh zones, secondary pioneer vegetation can replace succession vegetation. This results in complex succession stages with high plant diversity (key value 8). Limited ditching by farmers to facilitate livestock grazing contributes to the local diversity of the salt marshes (Esselink et al 2017).

Other ecological benefits of salt marshes are improved water quality by trapping suspended sediment (key value 5), which is beneficial to intertidal seagrass beds adjacent to salt marshes. Seagrass also benefits from degradation of nearshore brushwood groynes, as there is no more risk of mechanical damage during maintenance work or suffocation by green drift algae that can get trapped in the groynes. On the long run nearshore groynes are also disadvantageous as sedimentation rates exceed the ability of small eelgrass (*Zostera Noltii*) to cope with burial (Reise and Kohlus 2008). Formation of a natural network of creeks connected to the intertidal ecosystems creates nursery habitat for juvenile fish species including marine and diadromous species that use the Wadden Sea for part of their life cycle (key values 4 and 7). Salt marshes are important for high primary production (key value 6) and are home to about 25 species of typical vegetation adapted to different gradients of salinity and periodic inundation (key value 8). The flora and associated fauna of insects, spiders and invertebrates ensure food availability and provide habitat for foraging, resting, breeding, and wintering birds (key values 9 and 10). They will benefit from more natural and diverse salt marsh habitats that retain water and have high plant diversity.

**Trend**

Salt marshes are ecosystem engineers as they create their own growth conditions. Positive feedbacks between the vegetation and hydrodynamic forces are the ability to reduce wave heights, limit erosion, trap nutrient-rich sediment, retain water and influence flow velocity and the formation of creeks (Olff et al 1997, Ford et al 2016). Engineering drainage by digging channels to help establishment of pioneer vegetation should not be necessary. With current salt marsh management measures, they will continue to shift to more natural processes and high primary production, plant diversity and habitat provisioning. To keep up with sea level rise suspended sediment concentrations in the tidal flow must be sufficient (Kirwan et al 2010).

Hallig salt marshes have the lowest surface elevation change of all salt marsh types, because of impeded sediment supply to these marshes due to the surrounding revetments and summer dikes (Esselink et al 2017).

**Opportunities**

Salt marshes provide multiple ecosystem services to deal with global climate change. The vegetation captures and stores carbon, thereby reducing atmospheric carbon dioxide. As mentioned above they can keep up with certain rates of sea level rise due to sediment trapping vegetation. The vegetation of salt marshes in front of dikes dissipates wave energy under moderate storm surges. If a heavier, so-called design storm surge occurs, water depths over the salt marsh are too high to effectively reduce wave height and period on the outer dike slope. The flood risk management function of salt marshes in front of sea dikes is that they effectively limit the amount of water that flows through a dike breach (as a barrier in front of the breach), thereby limiting the damage expectations (Thorenz et al. 2017).

In ecosystem-based coastal flood protection in Germany, salt marshes function effectively as dike foot protection compared to artificial structures such as revetments and are preferred because of their outstanding ecological value. To secure dike-foot drainage, natural drainage by creeks can effectively provide the same function as artificial drainage furrows. Where natural dynamics allow, new salt marshes should be developed in front of dikes as an ecosystem-based measure, and the functionality of existing salt marshes should be secured by solid management techniques.

Sometimes summer polders are mentioned as an artificial salt marsh type. However, they cannot be considered a salt marsh as they flood less frequent, mostly less than once a year. Sediment supply is disturbed due to the height of the enclosing summer dikes, and surface elevation change is negligible. A salt marsh management measure to restore accretion processes is the de-embankment of summer polders. Successful examples of salt marsh restoration by de-embankment of a summer polder are on the island Langeoog in Germany (Hofstede 2019) and in the Netherlands, where in Noord-Friesland Buitendijks the surface elevation changes exceeded sea level rise with more than 300% (Esselink et al 2015, in Esselink et al. 2017).

## Coastal protection: groynes and revetments

To prevent shoreline erosion various protective structures are used, such as revetments, walls and groynes. Stone or concrete groynes on beaches are built perpendicular to the shore to reduce shore parallel sediment transport (littoral drift). Shore parallel groynes are constructed to limit wave energy impact and erosion on the beaches. Stone or concrete revetments and walls are built to protect against erosion of island coasts.

Not addressed here are groynes and low dams in salt marshes and revetments surrounding Hallingen, which are considered as protective structures in the salt marsh management chapter. Hard revetments used on dike slopes with high hydraulic loads are considered as part of the coastal flood defence system in the first chapters. Dams on tidal divides of Sylt and Rømø are elevated roads to connect the islands with the coast, without coastal protection function, and therefore excluded in this assessment.

**Geomorphological impacts**

Successful attempts to stabilize coasts of barrier islands resulted in a reduction of sand transport from and along the shoreface to the beach and onto the islands. Due to hard shoreline protection structures, vertical accretion of the islands is largely impossible, thus reducing the morphological development of the islands (Oost et al 2012). Erosion of the islands due to sediment demands in the back-barrier area may be prevented to some extent by groynes and revetments, but they do not prevent erosion of the ebb-tidal delta. With the retreat of ebb-tidal deltas there is less shelter and sediment supply to the islands and greater difficulty to maintain coastal safety (Elias et al. 2012 in Oost et al 2012). Groynes do only partly prevent beach erosion and often cause heavy lee-side and downstream erosion at sections of the coast which are undefended (Vinther et al. 2004). To compensate erosion and stabilize and avoid damage to groynes, regular beach and foreshore nourishments have been necessary (Reise 2005).

**Ecological impacts**

Stones are not natural in the Wadden Sea and present an ecological interference. The Wadden Sea used to be free of rock. This has changed with stone or concrete dikes and dams, as well as other shoreline protective structures such as also breakwaters, groynes and revetments. A rough estimate is that the length of petrified shorelines below mean high tide is about 730 km and stretching almost continuously through the entire Wadden Sea. The rocky shore habitats account for the widespread occurrence of species otherwise rare or absent in a sedimentary environment, ranging from the isopod *Ligia oceanica* in the supratidal to the kelp *Laminaria saccharina* in the subtidal zone (Reise 2005).

Along natural dynamic coasts ground-nesting bird species like the little tern (*Sternula albifrons*) and Kentish plover (*Anarhynchus alexandrinus*) breed on pioneer coastal habitats. Sandy beaches which are almost free of vegetation appear and disappear and provide undisturbed breeding sites before they are found by predators. In more static coasts birds are losing such beach habitat (Tentij et al 2009).

The ecological interference of stone groynes and revetments with ecological processes and productivity of the ecosystem is considered insignificant (key values 5 and 6) but at a local level there are changes compared to the typical biodiversity of soft-sediment ecosystem (key value 8). Reduced natural dynamics of water and sand transport may have an impact on the breeding success of migratory bird species (key value 10).

**Trend**

On the long run sedimentary dynamics are essential for the Wadden Sea to accrete vertically with sea level rise and contribute to a robust and sustainable strategy to stabilize shorelines and guarantee safety. The existing shoreline protective structures will continue to reduce the mobility of sediment (Oost et al 2012). Revetments and groynes do not mitigate sediment deficiency caused by sea level rise, because despite reduced shore erosion, at undefended shores they initiate downstream erosion (Reise 2005).

## Coastal protection: Sand nourishment

The main objective of sand nourishment at beaches and foreshores of barrier islands is to compensate for sand losses due to coastal erosion by storm surges. Coastal erosion also occurs due to downstream erosion under influence of hard protective structures, and due to nearshore underwater erosion.

A beach can be divided into three zones: nearshore, foreshore and backshore. The nearshore zone is always underwater and extends from the mean low tide line to a depth where wave motion does not affect the sea floor. The foreshore is extending from the mean low water line to the highest elevation reached by waves at normal high tide and the backshore is the area from the normal high tide line to the maximum uprush during storms (Brenninkmeyer 1982). The shoreface is part of the nearshore zone where transport of sediment by wave action is substantial.

Sand loss in the beach zone can either be restored by sand nourishment at the foreshore or shoreface. The efficiency strongly depends on sediment transport processes in the foreshore and shoreface area. Generally, the closer to shore the nourishment, the better is the effect (Hillen 1991 in CPSL 2005).

In the Wadden Sea each tidal inlet, ebb-tidal delta, adjacent barrier islands and back-barrier tidal basin forms a sediment sharing system. Sand deposited in a back-barrier area is mainly derived from the North Sea coast of the barrier island and the ebb-tidal delta. The sand balance of a barrier island is thus directly linked to the tidal inlet system development (Oost et al 2012). A long-term objective of sand nourishment, apart from stabilizing the shorelines, is maintaining a dynamic quasi-equilibrium in the sediment sharing system to be able to adapt to sea level rise. For this, sand needs to be extracted from outside the system (CPSL 2005).

Sand nourishment volumes are highest in the Netherlands, followed by Denmark and Germany, and vary between years (OSPAR [[1]](#footnote-1)). Sand extraction mainly takes place in the North Sea and extraction pits along the Dutch coast are located between the -20m depth contour and 12 miles zone, which is outside the sediment sharing system of the Wadden Sea. Impacts on the sand extraction location itself are not considered in this assessment.

**Geomorphological impacts**

Beach and foreshore nourishment has positive impacts on the geomorphological diversity (key value 2) as it contributes directly to the prevention of dune erosion. It helps to stabilize dunes, as natural dune-foot protection, and as a sand source for natural dune dynamics. Sand nourishment is preferred compared to hard structures to stabilize shorelines, because it does not interfere as much with natural processes and does not reduce the mobility of sediment (CPSL 2005).

Beach and shoreface nourishment allow for sand transport along and perpendicular to the island coasts and into the back-barrier and to the ebb-tidal deltas. This has a positive impact on sediment accretion processes (key value 3) and the integrity of the sediment sharing system, which can to some extent be restored (Oost et al 2012). The ecological effects are however still unclear (CPSL 2005).

**Ecological impacts**

Sand extraction on the North Sea may have an effect on suspended matter content and turbidity in the Wadden Sea. This is considered to have insignificant ecological impacts, based on a modelled outcome that silt- and nutrient concentrations increase 1-2%, while primary production showed variable results (Brinkman 2012).

The scale of ecological impacts will be restricted to where sand deposition covers benthic fauna. Some cannot survive 1 cm, while others can cope with up to 50 cm sediment cover. Foreshore nourishment effects are debated. The effect can be either limited to species covered by thick layers of sand, while the effect to benthic fauna may also be similar to those in the extraction pit (CPSL 2005). The effect on biodiversity (key value 8) is therefore considered minor. Food availability for fish and bird species may reduce and have a minor impact as well, especially affecting waders and coastal breeders (key value 10). Recovery can last less than a year upto several years, depending on season and sediment composition of the sand nourishment. Ecological impacts are minimized when nourishment takes place in winter, and the grain size and organic content of the sediment composition is comparable (Peterson et al 2000 in CPSL 2005).

**Trend**

Due to storm surges and sea level rise both beach erosion and sediment deficits will increase. It is expected that nourishments will increase, both in frequency and volumes of sand needed (CPSL 2005). Also, the current approach of fixation of inhabited barrier islands, which will most likely result in de-alignment of the barrier chain, will lead to increased erosion and a reduction of sand transport from and along the shoreface to the beach and onto the islands (Oost et al 2012).

**Opportunities**

Sand nourishment is considered as the best practice to compensate for beach erosion, as it is the most sustainable solution compared to hard protective structures (CPSL 2005). Sand nourishments can make existing protective structures unnecessary.

Sand nourishment and dune management can be combined successfully as the sand to compensate beach erosion is a natural dune-foot protection and a source of sand for natural dune dynamics.

Sand nourishment on strategic locations in the Wadden Sea may help to balance the sand-deficit resulting from sea level rise. To balance sediment deficits in the upper shore of mainland transitional habitats, sand nourishment by means of islets, bars, and spits in sheltered embayments can help to restore salt marsh and mud flat development by natural accretion (Reise 2003 in Reise 2005). Beach and foreshore nourishments could be partially shifted to the ebb-tidal deltas or given a different shape, although knowledge on system behaviour over time is insufficient (Oost et al 2017). To design effective strategies the KustGenese 2.0 programme programme (RWS [[2]](#footnote-2)) started a pilot nourishment in the ebb-tidal delta and lower shoreface of Ameland inlet, to gain knowledge on processes driving sediment transport and interactions between sediment and hydrodynamics, morphology, benthos and fish. First steps have been taken to develop and calibrate models to describe interactions between biotic and abiotic processes, aimed at designing effective nourishment strategies to keep up with sea level rise (Van Prooijen et al 2020). Conclusions are that the ebb-tidal delta has a buffer function with large quantities of sand to meet sediment demands of the Wadden Sea tidal basin and has a function in local sediment dynamics along island coasts. If the ebb-tidal delta sediment buffer is not sufficient, island coasts will be a sediment source resulting in coastal erosion. Ebb-tidal delta nourishment may become a vital part of the strategy to keep up with increased rates of sea level rise, because it is a good solution to work with hydrodynamic and geomorphological processes and sedimentation patterns (Deltares 2020).

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