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Update of the Schleswig-Holstein State master plan for coastal flood defense and coastal protection with a focus on climate change adaptation

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Summary

In 1963, under the impression of a catastrophic storm surge that hit the North Sea coast of Germany in 1962, Schleswig-Holsteins State Government released its first master plan for coastal flood defense and coastal protection. This paper presents the fifth update of 2022. The focus is on the adaptation strategy to climate change, with which the state of Schleswig-Holstein wants to ensure the long-term safety of the coastal population from coastal flooding and erosion despite stronger rising sea levels. Based upon a description of the actual coastal flood and erosion risk situation, this paper aims to inform about this coastal adaptation strategy.

Without coastal flood defenses, about one quarter of Schleswig-Holstein with 333,000 inhabitants and 60 billion euro of real assets could flood during severe storm surges. Further, the 1,110 km long coastline almost completely consists of non-cohesive easily erodible sediments. These figures show the high vulnerability of Schleswig-Holstein to coastal flooding and erosion and, thus, substantiate the socio-economic significance of coastal flood and erosion management as well as the need for sustainable climate change adaptation. In all, about 567 km of dikes, dams and other coastal flood defenses protect the lowlands from flooding. Coastal protection constructions such as groins and revetments exist to limit or prevent coastal retreat and erosion. Regular sand replenishments stabilize the shorelines of sandy islands along the North Sea coast, especially Sylt.

The adaptation strategy contained in the master plan consists of three components: technical measures, regional planning and the use of ecosystem services. In order to consider future sea level rise, the dimensioning of all technical flood defense measures includes a safety allowance of 0.5 m on top of the design height. The strengthening of state dikes, being the cornerstones of coastal flood defense in Schleswig-Holstein, further includes a flattening of the outer dike slope in order to reduce storm wave run up and to create building reserves for further adaptation as necessary. Safety allowance, flat outer dike slopes and building reserves can together compensate for a sea level rise of up to two meters. In regional plans, priority areas for coastal flood defense, coastal protection and climate change adaptation secure the availability of space needed for technical reinforcements as well as utility-free buffer zones landward of cliffs, dunes and beach ridges to allow for coastal retreat. Finally, the application of ecosystem-based measures, for example salt marsh enhancement techniques, acknowledges and uses the high natural resilience or adaptability of coastal ecosystems to sea level rise.

Keywords

Schleswig-Holstein, coastal flood defense, coastal protection, climate change adaptation, sea-level rise

Zusammenfassung

Im Jahre 1963 verabschiedete die schleswig-holsteinische Landesregierung unter dem Eindruck einer katastrophalen Sturmflut, die 1962 die Nordseeküste Deutschlands traf, den ersten Generalplan Küstenschutz. In dieser Abhandlung wird die fünfte Fortschreibung von 2022 vorgestellt. Schwerpunkt dieser Fortschreibung ist die Klimaanpassungsstrategie, mit der das Land Schleswig-Holstein die Sicherheit der Küstenbevölkerung vor Meerwasserüberflutungen und Küstenabbruch bei verstärkt ansteigendem Meeresspiegel langfristig gewährleisten möchte. Basierend auf einer Beschreibung der aktuellen Küstenhochwasser- und Erosionsrisikosituation zielt dieses Papier darauf ab, über diese Strategie zu informieren.
Ohne Küstenhochwasserschutz könnte etwa ein Viertel Schleswig-Holsteins mit 333.000 Einwohnern und 60 Milliarden Euro an Sachwerten bei sehr schweren Sturmfluten überfluten. Darüber hinaus besteht die 1.110 km lange Küstenlinie fast ausschließlich aus nicht-kohäsiven leicht zu erodierenden Sedimenten. Diese Zahlen zeigen die hohe Vulnerabilität Schleswig-Holsteins gegenüber Meerwasserüberflutungen und Küstenabbruch auf und belegen die große gesellschaftliche Bedeutung des Küstenschutzes sowie die Notwendigkeit einer nachhaltigen Klimaanpassung. Aktuell schützen etwa 567 km Deiche, Dämme und sonstige Hochwasserschutzanlagen die Küstenniederungen vor Überschwemmungen. Weiterhin sind vielerorts Küstensicherungsanlagen wie Buhnen und Deckwerke zur Begrenzung oder Verhinderung von Küstenrückgang und -erosion vorhanden. Die im Generalplan Küstenschutz enthaltene Anpassungsstrategie besteht aus drei Elementen: technische Maßnahmen, Raumordnung und die Nutzung von Ökosystemleistungen. Bei der Bemessung von technischen Hochwasserschutzmaßnahmen wird auf die Soll-Höhe der Anlage generell ein Klimazuschlag von 0,5 m zur Berücksichtigung des künftigen Meeresspiegelanstiegs aufgeschlagen. Die Verstärkung von Landesschutzdeichen beinhaltet darüber hinaus die Abflachung der äußeren Deichböschung, um den Wellenauflauf zu reduzieren und Baureserven für weitere Anpassungen zu schaffen. Klimazuschlag, flache Außenböschung und Baureserven können insgesamt einen Meeresspiegelanstieg von bis zu zwei Metern ausgleichen. In Regionalplänen ausgewiesene Vorranggebiete für Küstenschutz und Klimafolgenanpassung an den Küsten sichern die Verfügbarkeit von Platz für Verstärkungen sowie von nutzungsfreien Pufferzonen hinter Steilufer, Dünen und Strandwällen für den zu erwartenden Küstenrückgang. Schließlich wird durch die Anwendung ökosystembasierter Maßnahmen wie das integrierte Vorlandmanagement die hohe natürliche Resilienz bzw. die Anpassungsfähigkeit von Küstenökosystemen an einen beschleunigten Meeresspiegelanstieg anerkannt und im Sinne eines nachhaltigen Küstenschutzes eingesetzt.

Schlagwörter

Schleswig-Holstein, Küstenschutz, Klimaanpassung, Meeresspiegelanstieg

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1 Introduction

Figure 1: Dike breach in the polder Dockkoog near Husum after the 1962 storm surge (source: MELFF 1962). The inset shows a destroyed house on the Hallig Langeneß (source: Wohlenberg 1962).

In 1962, a catastrophic storm surge hit the German North Sea coast. In the federal states of Hamburg, Lower Saxony and Bremen, 340 people lost their lives. In Schleswig-Holstein, no one died but the storm surge severely damaged 270 of 560 km of sea dikes (MELFF 1962). On five locations, dike breaching occurred (Figure 1) and large areas flooded. On the dwelling mounds on the Halligen, unprotected marsh islands in the Wadden Sea, the storm surge destroyed or severely damaged almost all the houses (Figure 1 inset). Under the impression of the catastrophe, Schleswig-Holsteins State Government decided to draw up a master plan for coastal flood defense and coastal protection (MELFF 1963). The plan contains the governmental strategy for coastal flood and erosion risk management. The plans are not legally binding. As so-called self-binding governmental documents, they regulate administrative action. Subsequent Governments updated the original master plan from 1963 in the years 1977, 1986, 2001 and 2012 in order to consider socio-economic and natural developments as well as technical and scientific progress. The actual fifth update from 2022 (MELUND 2022) contains an integral strategy for climate change adaptation in coastal flood defense and coastal protection in Schleswig-Holstein.

Based upon a description of the actual coastal flood and erosion risk situation, this paper aims to inform about this adaptation strategy. The actual master plan is publicly available, but so-called gray literature and in German. The paper starts in chapter 2 with a description of the current coastal flood and erosion risk situation in Schleswig-Holstein. For coastal flooding and for coastal erosion, this chapter presents the existing vulnerabilities as well as the protective measures taken. In chapter 3, a description of the main coastal impacts of climate change and the three components of climate change adaptation as included in the master plan follows. After defining monitoring and research needs, the paper closes with an outlook.

2 Coastal flood and erosion risk situation

2.1 Coastal flood vulnerabilities and defense measures

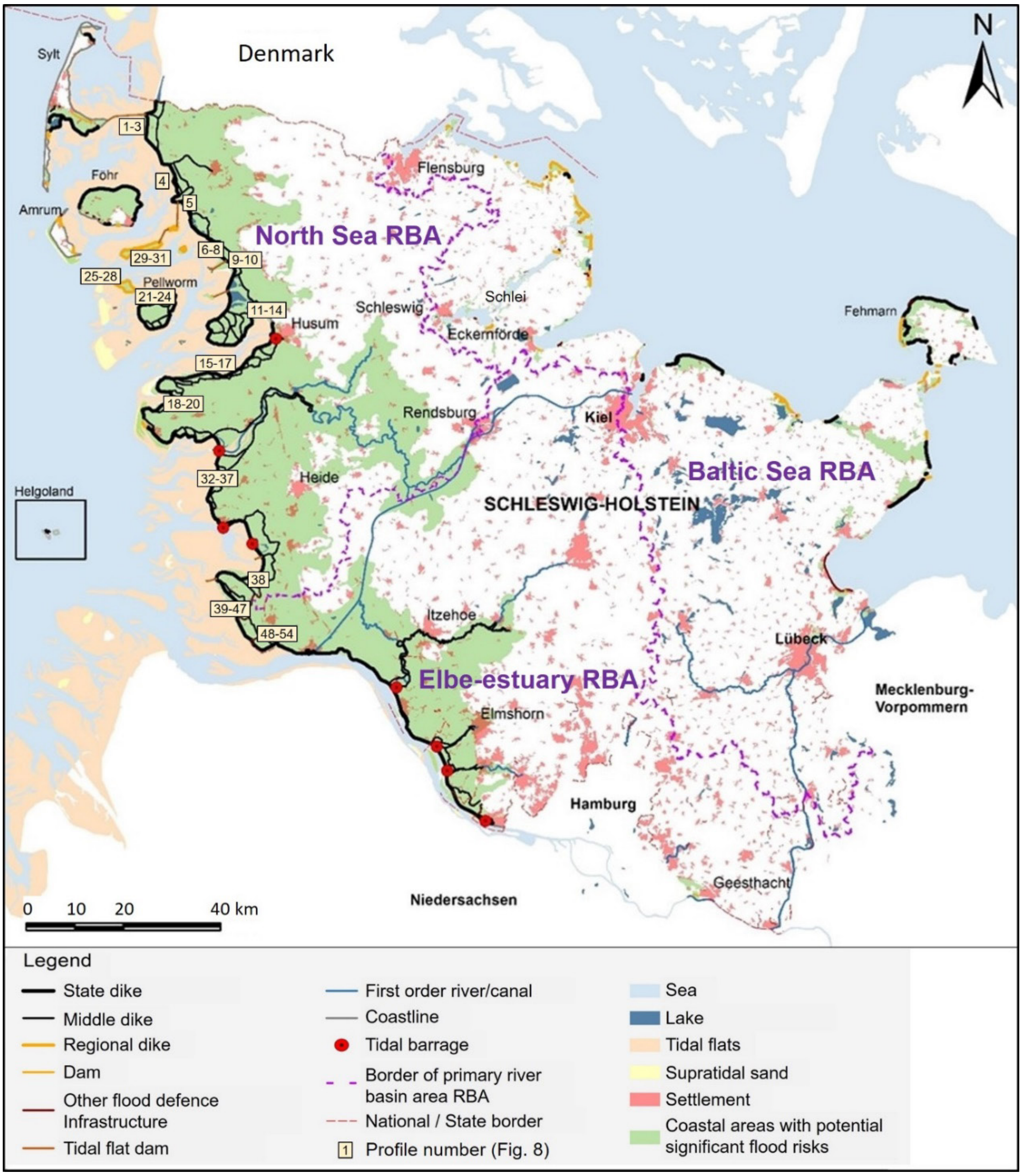

Figure 2: Areas of potential significant coastal flood risk (in green) and coastal flood defense infrastructures in Schleswig-Holstein (MELUND 2022).

Without flood defenses, about one quarter of Schleswig-Holstein could flood during extreme storm surges (Figure 2, Table 1). In these so-called areas of potential significant flood risk (APSFR), about 333,000 people live. Almost 60 billion euro of real assets as well as many critical infrastructures and significant cultural heritage are present. Finally, several fresh water nature reserves in the APSFR depend on coastal flood defenses with respect to their preservation goals.

Table 1: Inhabitants and assets in the coastal areas of potentially significant flood risk (APSFR) in Schleswig-Holstein (borders of the river basin districts North Sea, Elbe-estuary and Baltic Sea are in Figure 2).

	APSFR (km^2)	Inhabitants	Assets (billion Euro)
North Sea	2,515	140,037	28.5
Elbe-estuary	1,157	162,172	24.4
Baltic Sea	315	30,533	6.9
Schleswig-Holstein	**3,987**	**332,742**	**59.9**

Coastal flood defense in the coastal marshes along the North Sea coast of Schleswig-Holstein started about 2,000 years ago with the erection of artificial dwelling mounds. Around 50 AD, the Roman chronicler Plinius wrote in his encyclopedia *Naturalis Historia*: "There a pitiable people dwell in high mounds of earth raised with their hands according to the measure of the highest flood" (https://de.wikipedia.org/wiki/Warft). A few centuries later, first ring dike systems protected agricultural areas from summer floods (Meier 2000). Winter dike construction along the North Sea coast began around 1,000 years ago. In the Middle Ages, severe storm surges like the first and second "Grote Mandränke" (great men-drowning) in 1362 and 1634 led to numerous dike breaches, great loss of lives and major losses of coastal marshland (Scherenberg 1992).

Figure 3: Aerial photograph of the Hallig Hooge in the North-Frisian Wadden Sea (photo: Jacobus Hofstede). The inset shows a dwelling mound on the Hallig Südfall during flood (©: Martin Stock/ LKN.SH).

The Halligen in the North-Frisian Wadden Sea (see example in Figure 3) are remainders of this former coastal landscape. Along the Baltic Sea coast of Schleswig-Holstein, a catastrophic storm surge in 1872 with 31 fatalities led to the initiation of the first large dike construction program by the Prussian Government (Eiben 1992, Hofstede and Hamann 2022). DVWK (1992) gives a comprehensive overview of the history of coastal flood defense and protection in Schleswig-Holstein.

Today, about 433 km of so-called state dikes protect more than 90% of the APSFR in Schleswig-Holstein from flooding during storm surges (Figure 2, Table 2). Along the North Sea coast and in the Elbe-estuary, they have a crest height among 6.5 and 9.5 m above German ordnance datum NHN (≈ mean sea level), depending on tidal range, surge levels and wave set up. Along the Baltic Sea coast, where there is almost no tidal range, the heights vary among 3.0 and 6.0 m above NHN. State dikes are in the responsibility of the State and have a fixed safety standard as defined in the master plan. Accordingly, the maximum permissible wave-overtopping rate per running meter of dike crest for a defined (reference) storm surge with an annual probability of 0.005 is two liters per second. The last safety check showed that 74 km of state dikes do not meet this standard and need strengthening (MELUND 2022).

Table 2: Main coastal flood defenses in Schleswig-Holstein (borders of the river basin districts North Sea, Elbe-estuary and Baltic Sea are in Figure 1).

	North Sea	Elbe-estuary	Baltic Sea	**Schleswig-Holstein**
State dikes (km)	266.7	94.8	71.0	**432.5**
Middle dikes (km)	340.0	208.0	0.0	**548.0**
Regional dikes (km)	50.8	0.0	47,0	**97.8**
Dwelling mounds	39	0	0	**39**
Dams (km)	4,7	0,0	7,1	**11,8**
Other flood defenses (km)	3,8	0,2	23,4	**27,4**

Almost 98 km of regional dikes exist in Schleswig-Holstein (Figure 2, Table 2). In contrast to state dikes, they do not have a uniform safety standard and vary considerably in height and design. Most lowlands protected by regional dikes are predominantly in agricultural use and have a lower safety standard than state dikes. The 44 km long regional dikes along the mainland coast are in the responsibility of dike and water boards, whereas the 54 km long regional dikes on the islands (13 km) and Halligen (41 km) are in state responsibility. On the Halligen (Figure 3), the regional dikes function only to avoid flooding during summer. In consequence, flooding of these highly exposed marsh-islands in the Wadden Sea occurs several times every winter. The about 260 inhabitants of the Halligen then remain on 32 artificial dwelling mounds (in German: "Warften"; see example in Figure 3 and Table 2).

Situated behind the state dikes, 548 km of middle dikes function as a second flood defense line along the North Sea coast and in the Elbe-estuary (Figure 2, Table 2). If a breach in a state dike occurs, the middle dikes function to limit the flood extent. Lockable passages in the middle dikes guarantee access to the polders between the first and second dike line. These dikes are former sea dikes that have moved into the second line due to land reclamation activities in the last centuries. Age, height and design vary strongly. The middle dikes are in the responsibility of dike and water boards. The share of APSFR that has a double protection by a staggered system of state and middle dikes amounts to 1,726 km^2 (43% of total APSFR in Schleswig-Holstein). A safety check showed that, especially on the islands and along the Elbe-tributaries, a number of middle dikes perform their intended function only to a limited extent (MELUR 2012).

On several locations, about 12 km of dams provide flood protection for the APSFR in Schleswig-Holstein (Figure 2, Table 2). Constructed for other purposes, these dams function as coastal flood defenses as well. One example is the railroad dam on the island of Sylt, which protects the 18.7 km² large APSFR Nössekoog with 2,270 inhabitants from flooding. It has a comparable safety standard as state dikes. More than 27 km of so-called "other flood defenses", which are neither dikes nor dams, exist in Schleswig-Holstein (Figure 2, Table 2). One example is the 4.7 km long coastal flood defense wall in the inner Lübeck Bight (Figure 4). Hidden in a semi-natural beach ridge, this wall protects the about 2.7 km² large APSFR of Scharbeutz along the Baltic Sea with 1,080 inhabitants from flooding. It has a comparable safety standard as state dikes. Finally, state administration is responsible for 147 constructions like tidal barrages, sluices, pumping stations and lockable passages in the sea dikes in Schleswig-Holstein (Figure 2, Table 2). Of these, 110 structures primarily drain the coastal lowlands; the rest is traffic infrastructure.

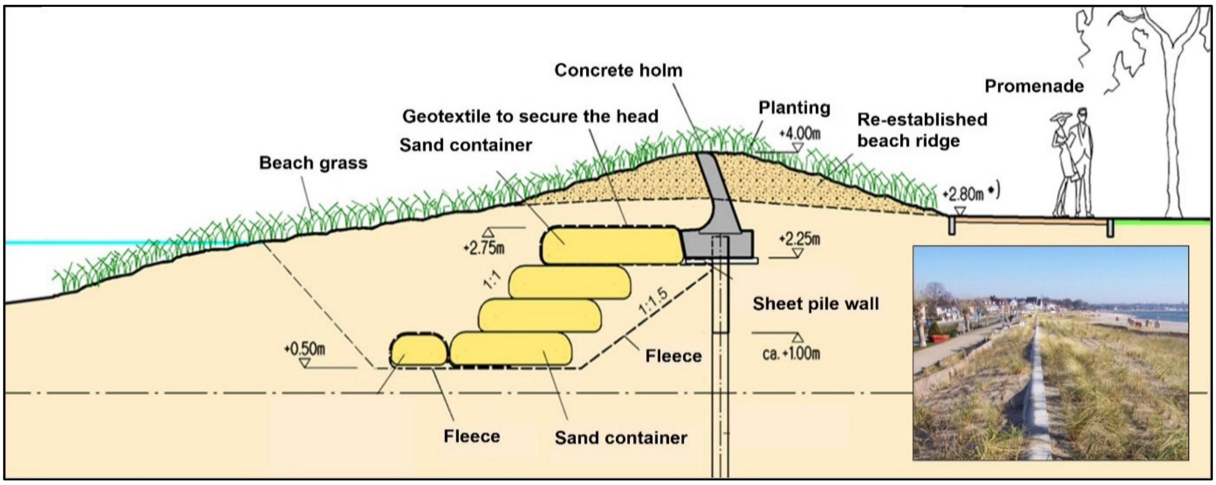

Figure 4: Technical sketch of the coastal flood defense at Scharbeutz (source: WTM Engineers Hamburg). The inset shows the concrete holm "hidden" in the vegetated beach ridge after construction (photo: Jacobus Hofstede).

2.2 Coastal erosion vulnerabilities and protection measures

Schleswig-Holstein has 1,110 km of coastlines along the North Sea and the Baltic Sea (Table 3). With the exception of Helgoland, the shorelines consist of non-cohesive easily erodible sediments.

Table 3: Length of coastlines in Schleswig-Holstein.

North Sea		Baltic Sea	
Mainland	195	Mainland	328
Islands and Halligen	271	Islands	76
Elbe-estuary	103	Schlei-firth	137
Sum	**569**	**Sum**	**541**

Along the Baltic Sea coastline, 122 km (58 cliffs) underlie structural erosion (Averes et al. 2021). Over the last decades, these cliffs show a yearly mean retreat among 0.10 and 0.73 m with an average rate of 0.24 m/a. Along the North Sea mainland coast, at the islands Pellworm and Föhr as well as in the Elbe-estuary, state dikes fix most of the coastlines. Whereas the barrier island Amrum is rather stable, strong structural erosion occurs along the about 38 km long North Sea coastline of the barrier island Sylt (location in Figure 2).

Long-term monitoring by the responsible State Agency LKN.SH shows that natural coastal retreat amounts to about 1.0 m per year with significantly higher values at the northern and southern tips of the island. Off the North Sea mainland coast lies the about 2,750 km² large Wadden Sea with extensive intertidal flats and subtidal gullies, salt marshes, islands and Halligen (Figure 2). In the last decades, most intertidal flats were accreting, whereas most subtidal gullies deepened (Benninghoff and Winter 2019).

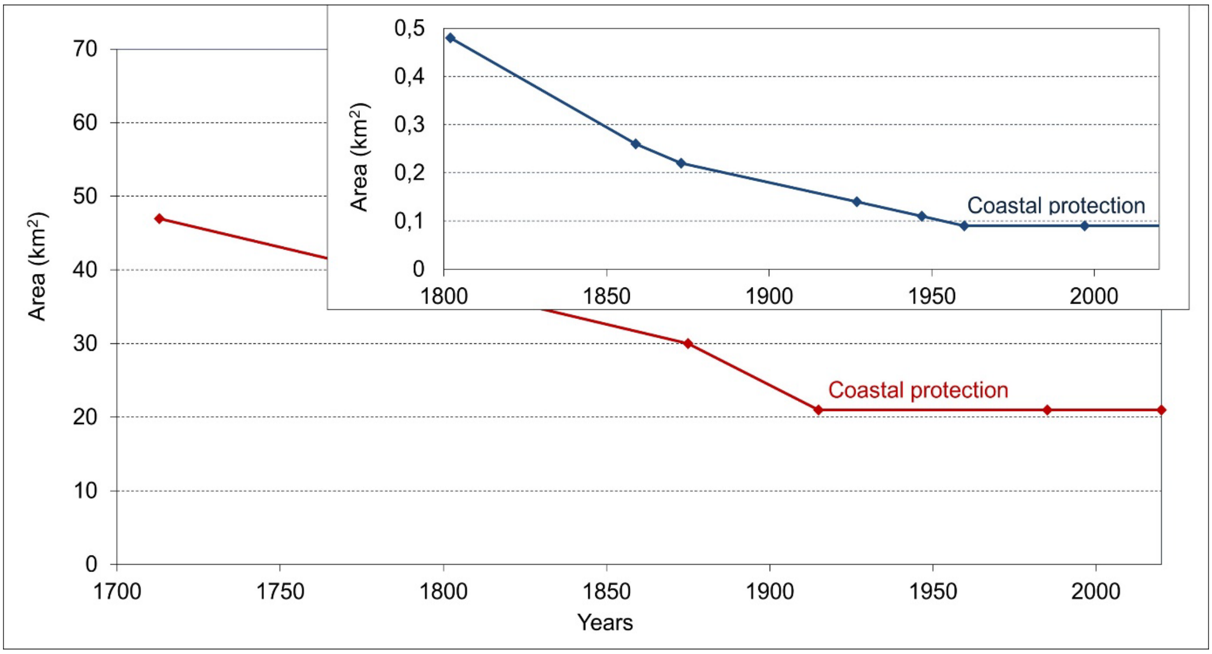

Figure 5: Development of the Halligen size since 1713. The inset shows the respective development of the nature reserve Hallig Norderoog since 1800 (source: Levsen 2013), where coastal protection started in 1947 with the construction of brushwood groin fields.

The erection of coastal protection structures like stone groins and revetments started in Schleswig-Holstein near the end of the 19th century (DVWK 1992). Today, numerous constructions protect against local erosion. Detailed descriptions are available in internet-based regional technical plans (www.schleswig-holstein.de/lkn). Prominent example for strongly protected coastlines are the 10 Halligen in the North-Frisian Wadden Sea. From the beginning of the 18th until the beginning of the 20th century, these exposed marsh islands lost more than half of their size due to storm surge erosion (Figure 5). Since then, stone revetments in combination with stone groins prevent further shoreline retreat (Figure 3). Without coastal protection, erosion of the exposed Hallig coasts would probably have continued, as hydraulic loads did not subside after 1900. If so, most if not all Halligen would have disappeared by today.

Along the 38 km long North Sea coast of Sylt, artificial sand replenishment on the beach and in the foreshore balance the natural erosion since the early 1980ies. The first sand suppletion occurred in 1972; regular replenishment started in 1983. Figure 6 shows the yearly replenishment volumes from 1972 to 2021. In all, the supply of sand since 1972 amounts to 56.3 million m³. Focal points for suppletion are the center of the island and the island tips. Here, total sand supply locally exceeds 6,000 m³ per running meter coastline. Over the last years, supply of sand into the foreshore instead of on the beach gains more importance. Dumping of sand in the foreshore is significantly cheaper than pumping sand on the beach. Monitoring data, evaluated by the responsible state administration, show that this method effectively stabilizes the shorelines behind it. Since 1983, sand suppletion successfully prevents further retreat of the North Sea coastline of Sylt. Only along the highly dynamic southern spit of Sylt and in front of the city of Westerland, hard constructions provide extra protection. In Westerland, a wall protects the promenade behind it. Natural erosion at the southern tip of Sylt is so high that hard constructions, in addition to sand replenishment, are indispensable. The supply of sand also presents a flexible measure concerning accelerated sea level rise, as the amounts are easily adjustable as required. In contrast to the Baltic Sea of Schleswig-Holstein, where no significant sand volumes exist, sufficient volumes of sand are available in the approved extraction site in the North Sea, even in the case of stronger sea level rise.

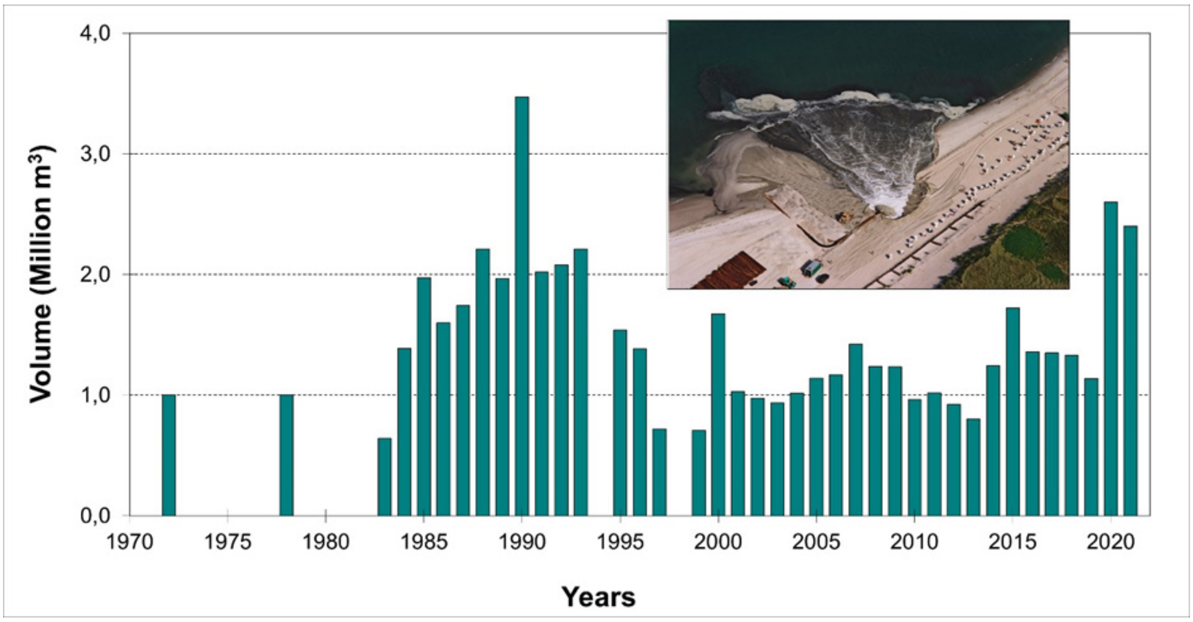

Figure 6: Yearly sand suppletion volumes on the island of Sylt since 1972. The inset displays an aerial photograph of a beach suppletion on Sylt (photo: Rohde Nielsen A/S).

According to Staudt et al. (2021), sand extraction and suppletion interfere with nature and need reconsideration as "soft" coastal protection measures. In their global review study, they did not consider the implications of alternatives. According to the Schleswig-Holstein State Water Act (GVOBL 2019), the protection of islands is a state obligation if public interests are affected. At Sylt with its more than 18,000 inhabitants, this is the case. Hence, the alternative of retreat, as recommended by Parkinson and Ogurcak (2018) is neither legally not feasible. The alternative to avoid coastal retreat and maintain the island is fortification, e.g., by walls and revetments. Environmental impact assessments in the plan approval procedures for these "hard" measures carried out at other locations show that they lead to significant and continuous interferences with nature. Accordingly, after environmental evaluation of several beach nourishments on Sylt, Menn et al. (2003) concluded that sand suppletion constitutes an acceptable method of coastal protection. According to Bridges et al. (2021), sand replenishment constitutes a nature-based approach to stabilize sandy coasts. Finally, the expected high maintenance and overhaul costs of "hard" measures are a relevant aspect to consider. The current overhaul of the protective wall in front of Westerland (see above) costs about 15 million euros per kilometer. Without regular sand replenishment in front of the wall, additional massive foot protection would become necessary.

Figure 7: Brushwood groin fields in front of a state dike in Schleswig-Holstein. The inset shows a close-up of a brushwood groin. Note the newly developed vegetation cover behind the groin. (photos: Jacobus Hofstede).

A special type of coastal protection along the North Sea coast of Schleswig-Holstein are brushwood groin fields (Hofstede 2003; Figure 7). The erection of these fields started at the beginning of the 20th century in the Wadden Sea of Schleswig-Holstein and originally mainly aimed at land reclamation (Probst 1996). Situated in front of state dikes, they enhance new salt marsh development and reduce lateral erosion of existing salt marshes during storm surges (Dijkema et al. 1990). High salt marshes in front of dikes limit the cross-section of the breach, thereby significantly reducing the volume of water that flows through the breach and, in consequence, the water depths and damage expectations in the flooded polder (Thorenz et al. 2017). Another ecosystem service provided by salt marshes for coastal flood defense is that they dissipate storm wave energy, thereby reducing wave load and run-up on the outer dike slopes during storm surges (Möller et al. 2014). Since 1995, Schleswig-Holstein implements an ecosystem-based salt marsh management that aims at maintenance and enhancement of these ecosystem services (Hofstede 2003). Also through this program, the salt marsh area along the mainland coast in the Wadden Sea of Schleswig-Holstein grew by 28% from 73.0 to 93.5 km² between 1988 and 2015 (MELUND 2022). The mean yearly accumulation rate on the salt marshes for the period 1996 to 2018, as monitored by the responsible state agency LKN.SH, amounted to 0.90 ± 0.55 mm/a. As shown in Figure 8, mean accumulation rates between the monitoring profiles vary strongly depending on wave and current exposure as well as on sediment availability. Further, the mean accumulation rate along the mainland coast is significantly higher than along the more exposed islands and Halligen. Both mean values are, however, significantly higher than the regional rise in mean sea level of about 0.22 mm/a and in mean high tide of about 0.28 mm/a observed over the same period.

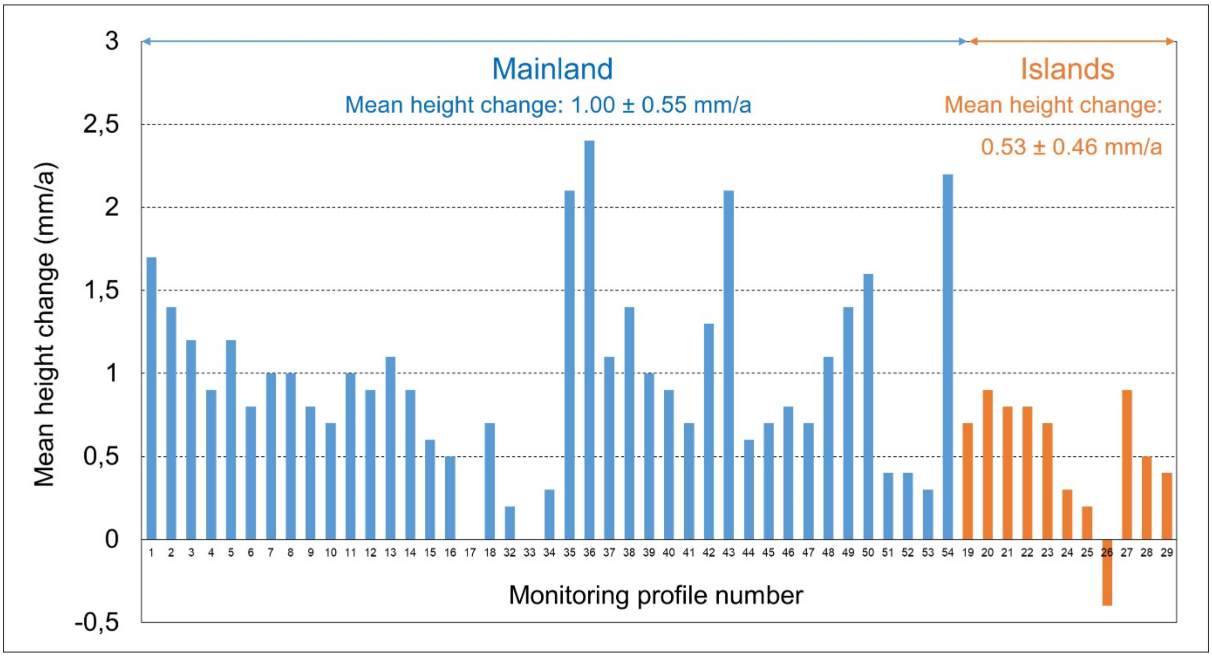

Figure 8: Mean yearly height changes on 54 monitoring profiles along the Schleswig-Holstein Wadden Sea coast for the period 1996–2018 (data: LKN.SH; location of profiles in Figure 2; profiles 30 and 31 are sub profiles not shown in this diagram).

3 Climate change: coastal impacts and adaptation

3.1 Coastal impacts of climate change

Determinants for planning in coastal flood defense and coastal protection are mean sea level and storm climate as well as their changes through time. According to IPCC (in press), global mean sea level rise will further accelerate in future. The German coastal states and Federal Government have agreed to use the IPCC-scenario with the highest adaptation needs for long-term precautionary planning along the coasts. For this SSP5-8.5 scenario, projections for mean sea level rise from 2020 to 2150 along the German North Sea and Baltic Sea coast are among about 0.9 and 1.9 m (likely range) with an average value of 1.3 m (Figure 9). For the period 2020 to 2120, the projected mean sea level rise amounts to about 1.0 m. Even higher values are not impossible but have a low confidence due to the large uncertainties associated with the underlying processes in the ice shields on Greenland and in the West-Antarctic (IPCC in press).

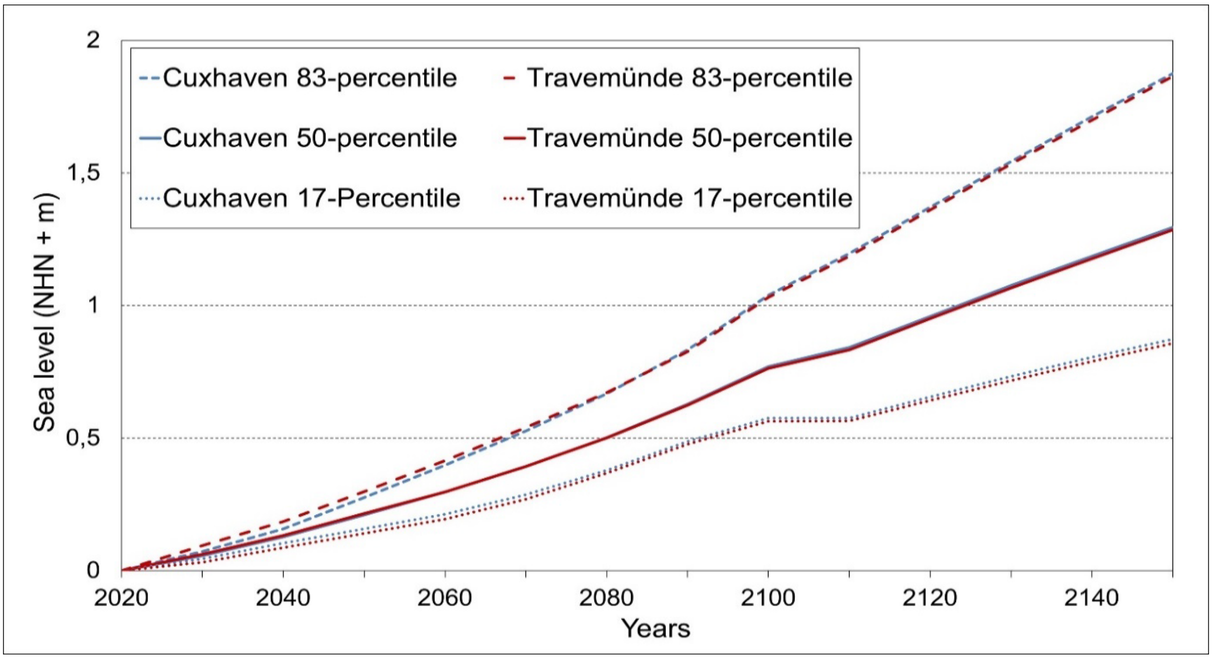

Figure 9: Projected sea level rise at Cuxhaven (North Sea) and Travemünde (Baltic Sea) gauges for the period 2020 to 2150 and the SSP5-8.5 scenario. Depicted are mean values (50-percentile) as well as 17 and 83 percentiles (data: https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool).

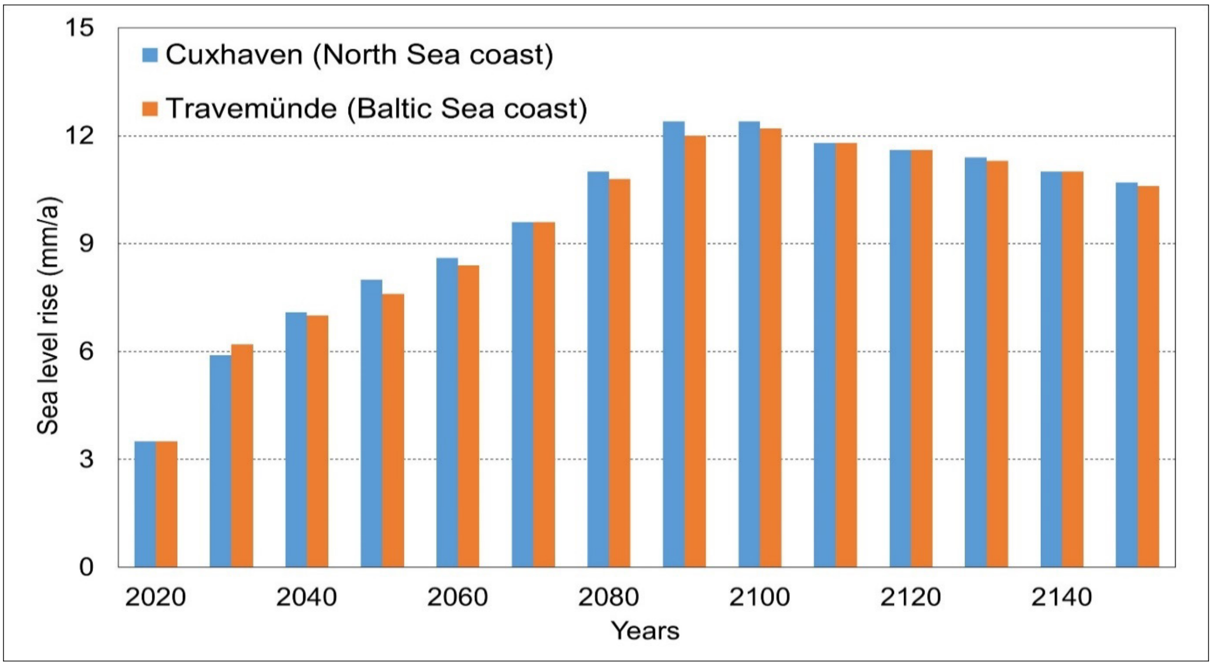

Figure 10: Projected yearly rate of sea level rise at Cuxhaven (North Sea) and Travemünde (Baltic Sea) gauges for the period 2020 to 2150 and the scenario SSP5-8.5. Depicted are 50-percentiles of the decadal mean values (data: https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool).

Further, the average rate of sea level rise by the end of this century may reach about 12 mm/a along the North Sea and Baltic Sea coasts of Schleswig-Holstein for the SSP5-8.5 scenario (Figure 10). This is more than six times as high as observed over the last century and four times as high as today (Dangendorf et al. 2022). It is interesting to note that, even for the SSP5-8.5 scenario, the yearly rate of sea level rise in the next century will slowly decrease to about 10.5 mm/a in 2050. This is, however, still more than five times as high as observed over the last century.

As stated above, storm climate and its future development is the second key factor in the planning of coastal flood defense and protection measures. Depending on the fetch and in interaction with the underwater topography, storm climate determines the intensity of local storm setup and storm waves. Based on a comprehensive evaluation of scientific literature, Klein et al. (2018) found that storm surge water levels on the German North and Baltic Sea coasts will probably rise in the same order of magnitude as mean sea level. Hence, they expect no significant changes in storm setup. With respect to storm waves, Klein et al. (2018) further state that recent studies do not show a clear signal or pattern for changes along the Baltic Sea coast of Germany. For the North Sea, respective studies consistently project an increase in the 99th percentile of the significant wave height in front of the Wadden Sea of Schleswig-Holstein by the end of this century. Within the shallow Wadden Sea, water depths determine or, rather, limit the height of storm waves.

3.2 Adaptation to climate change

From the elaborations above, it becomes clear that in future hydraulic loads from storm surges and storm waves will increasingly strain the sandy coasts as well as the coastal flood defense and coastal protection structures in Schleswig-Holstein. In order to keep adverse effects on human health, the environment, cultural heritage and economic activities at a socially acceptable level, climate change adaptation becomes indispensable (as does climate change mitigation). For the period 2015 to 2100, Vousdoukas et al. (2020) estimated the benefit to cost ratio (BCR) of adaptation in coastal flood defense, amongst others in Schleswig-Holstein, for two IPCC-scenarios RCP4.5 and RCP8.5. For scenario RCP4.5, the BCR amounts to about 3.5, for RCP8.5 to about 5.5. Without any future adaptation measures, the direct damages and the number of people flooded would, for both scenarios, increase by at least one order of magnitude until the end of this century. In recognition of this, the new Schleswig-Holstein State master plan for coastal flood defense and coastal protection contains technical and non-technical options and criteria for adaptation, as described in the next sections.

3.2.1 Ecosystem services for adaptation

Coastal ecosystems are robust or, rather, have a high natural adaptability to climate-related changes (CPSL 2005). A general adaptation strategy contained in the master plan is to mobilize these natural potentials as ecosystem services for coastal flood defense and coastal protection. Salt marshes, for example, accrete faster with higher rates of sea level rise, as the resulting higher flooding frequency brings in more sediment (Dijkema et al. 1990). By this mechanism, salt marshes may balance (up to a certain threshold) an accelerated sea level rise through increased accretion. This secures the functionalities or, rather, ecosystem-service, of salt marshes for coastal flood defense and risk management (Ch. 2.2) despite stronger sea level rise. Thus, brushwood groin fields (Figure 7) also present an ecosystem-based adaptation measure, because they support sediment accretion. Another ecosystem-based measure taken up in the master plan is the requirement to keep cliffs along the Baltic Sea coast free from coastal protection wherever possible, i.e., a zero-solution. Active cliffs and their foreshores along the Baltic Sea coast of Schleswig-Holstein are, in contrast to the North Sea coast (see below), the only significant and sustainable sand sources to stabilize shorelines. Averes et al. (2021) estimated the yearly sand input from the cliffs into the coastal system among 39,000 and 161,000 m^3. The large difference between minimum and maximum estimates results mainly from large uncertainties with respect to carbonate and sand content in the highly heterogeneous morainic cliffs. It can be expected that cliff erosion and, therewith, the supply of sand to the shores increase with stronger sea level rise. In this case, the zero-solution also presents an ecosystem-based adaptation measure. Only where public interests are at stake and where high vulnerabilities like settlements on the cliff are present and in danger, protective measures are permissible.

The Schleswig-Holsteins state strategy for climate change adaptation in the Wadden Sea (Hofstede and Stock 2018) evaluates the supply of sand on strategic locations as an ecosystem-based adaptation measure in a long-term perspective. This measure aims to prevent intertidal flats and salt marshes from submerging due to disproportionate strong sea level rise (CPSL 2005). Asymmetrical natural processes redistribute the supplied material onto the intertidal flats and salt marshes, thus securing their storm wave attenuation functionality as an ecosystem service for coastal flood defense under rising sea levels. The sand replenishments on Sylt (Figure 6) have, in this context, a double functionality. The supplied sand that originates from an extraction site in the North Sea not only stabilizes the North Sea coast of Sylt, but can also help to compensate for an accelerated sea level rise in the Wadden Sea tidal basins. After erosion during storm surges, the supplied sand drifts towards and through the tidal inlets into the tidal basins and partly accumulates here on the intertidal flats and salt marshes (BAW 2020, LKN.SH 2020).

3.2.2 Technical adaptation measures

Based on the sea level projections for the SSP5-8.5 scenario (Figure 9), the coastal states agreed to consider a climate surcharge of 1.0 m per century when planning coastal flood defense measures. This climate surcharge is intended to ensure that today's standard of protection is guaranteed even in the event of a storm surge that is one meter higher than the actual reference storm surge (Ch. 2.1). For the SSP5-8.5 scenario, this would be the case in about 100 years.

State dikes are the cornerstone of coastal flood defense in Schleswig-Holstein (Ch. 2.1). The last check showed that 74 of 433 km of state dikes do not meet the safety standard and need strengthening (MELUND 2022). Already since 2001, reinforcements of state dikes in Schleswig-Holstein include a safety allowance of 0.5 m to account for equivalent sea level rise (MLR 2001). Since 2012, the design procedure also considers building reserves as adaptation pathway to climate change (MELUR 2012). In addition to the safety allowance of 0.5 m, the outer dike slope becomes a constant lower gradient of about 1:10 (instead of the traditional upward steepening slope) and a doubled dike crest width of 5.0 m (Figure 11a). Since wave run-up is inversely proportional to slope gradient (e.g., EurOtop 2018), an equivalent sea level rise is compensated. In result and assuming that storm waves do not change significantly (Klein et al. 2018), this profile should be able to withstand up to 1.0 m higher storm surge water levels, i.e. 0.5 m safety allowance plus approx. 0.5 m reduced wave run up due to the lower gradient. The flat outer dike slope is a typical no-regret solution, as it enables further adjustment measures if or when sea level rise exceeds one meter.

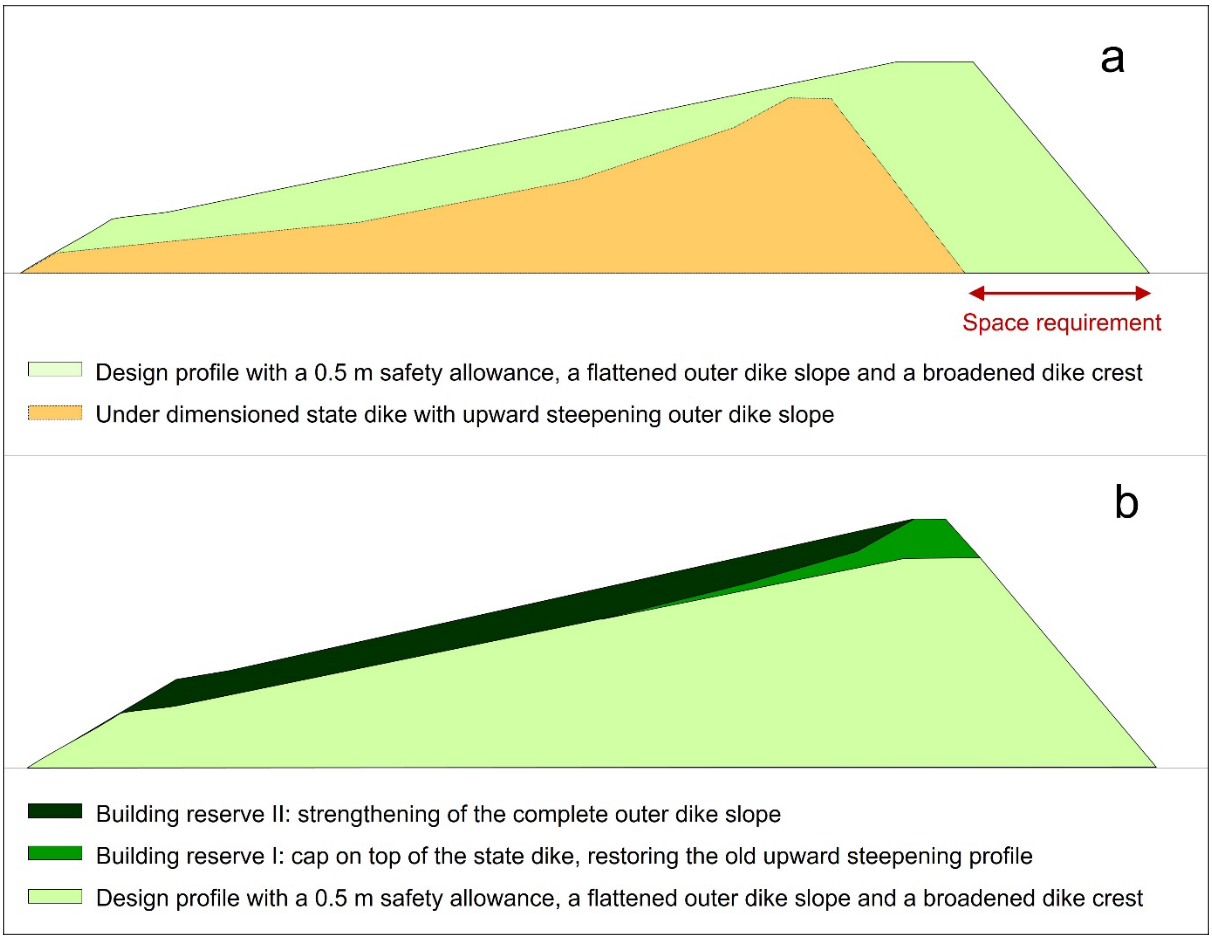

Figure 11: Schleswig-Holsteins adaptation pathway for state dikes, consisting of design criteria to withstand one meter higher storm surge water levels (a) and two building reserves to account for further rising sea levels (b).

The two building reserves, shown in Figure 11b, are the installment of a dike cap on the dike crest and the strengthening of the complete outer dike slope. These measures do not need additional space. This considerably simplifies and shortens the planning phase, as it requires no formal plan approval procedure. Further, implementing the building reserves needs relatively little technical and financial efforts. Hence, the concept of building reserves may also constitute a form of intergenerational justice, as future generations are not responsible for today's anthropogenic climate change. After implementation of the dike cap reinforcement, the dike can withstand storm surge water levels up to 1.5 m higher, and up to 2.0 m higher water levels after complete heightening of the outer dike slope. This means that the current safety standard still applies when mean sea level is about two meters higher. With respect to the carrying capacity of the subsoil, the design of the first building phase should already consider the resulting total load after the third building phase. If technical structures such as tidal barrages are part of a dike strengthening campaign, their reinforcement also includes a safety allowance of 0.5 m. In addition, the building statics allow for a further heightening of 0.5 m and storage basins behind the structures allow larger wave overtopping rates. Regional dikes and other coastal flood defenses normally have a shorter lifetime than state dikes and are mostly not in state responsibility. As a precondition for state co-financing (90% of total eligible costs), reinforcements of these flood defenses should at least include the safety allowance of 0.5 m.

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Figure 12 shows the completed dike reinforcement in front of the coastal resort Büsum along the Wadden Sea coast. It was the first measure that implemented the design procedure described above (Figure 9). Squeezed between dense tourist infrastructure on the landside and the Wadden Sea National Park on the seaside, it was nevertheless possible to implement the dike concept describe above, including a safety allowance, a flattened outer dike slope and a broadened crest. As a positive side effect, tourist uses of the green and flat outer dike slope, such as setting up beach chairs in summer, are possible. A special feature of the measure was the tourist development work carried out in combination with the dike reinforcement. Examples are the paved promenade on the dike crest, a paved event area on the outer dike slope and pedestrian bridges to the city (Figure 12). It is worthwhile to note that, after completion of the measures in 2015, hotel investments in the city as well as the number of overnight stays strongly increased. According to inter alia Van Loon-Steensma and Cleveringa (2019), this design with a flat and vegetated inner and outer dike slope, fronted by a salt marsh, represents the so-called Wide Green Dike concept that has high potential as nature-based adaptation innovation, particularly due to its "green" and "adaptability" characteristics.

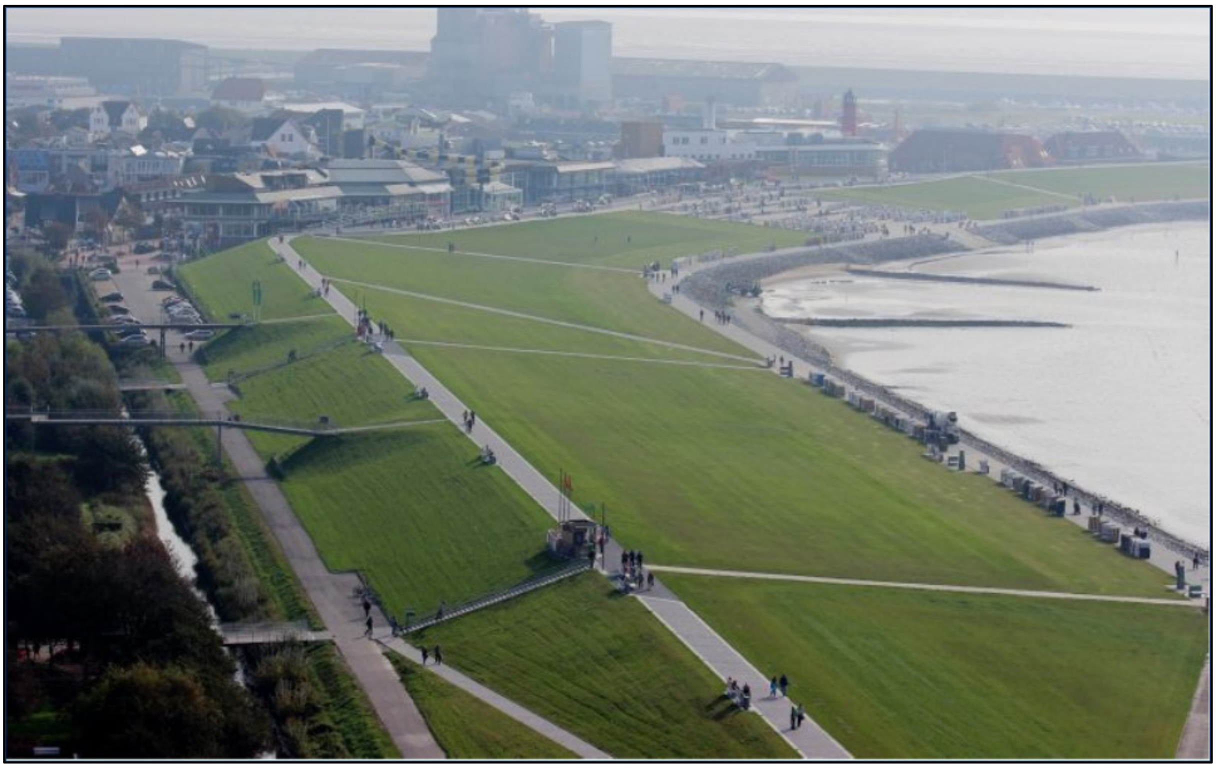

Figure 12: Strengthened dike in front of the tourist resort Büsum with a flat outer dike slope, a broad dike crest and a safety allowance of 0.5 m (Photo: LKN.SH).

Situated in a highly exposed tidal environment with regular winter flooding, the dwelling mounds on the Halligen (Figure 3) are a special case. In 2015, the State Government acknowledged the Halligen as cultural and natural heritage and adopted a strengthening and development program for the dwelling mounds (MELUND 2022). A security check revealed that 18 inhabited dwelling mounds have larger flood safety deficits and need reinforcement. As with state dikes, the design criteria for strengthening include a safety allowance of 0.5 m as well as flat slope gradients in the windward (north- to southwest) direction to reduce wave run up and to allow for further reinforcement (Figure 13).

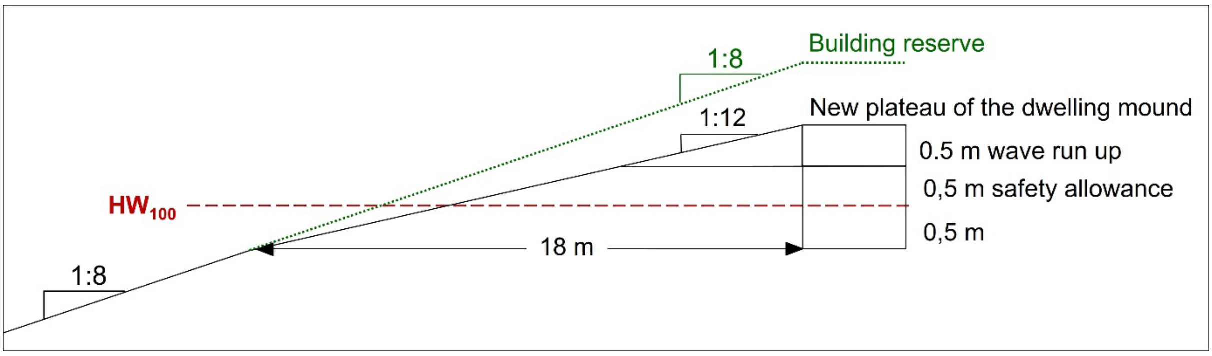

Figure 13: Design profile for the strengthening of a dwelling mound, including a safety allowance of 0.5 m and a building reserve to balance a further sea level rise (HW_{100} stands for a storm surge water level with a yearly probability of 0.01).

In consideration of existing buildings on the mounds (which have a right of continuance) and in order to create space for socioeconomic developments, the strengthening campaigns normally occur as so-called plateau-reinforcements, meaning the erection of an elevated plateau along the windward side of the existing dwelling mound (Figure 14). This new plateau provides adequate flood safety for new buildings and acts as a wave breaker in extreme storm surges, protecting the lower-lying buildings on the old plateau.

Figure 14: Plateau-reinforcement on the Hallig Nordstrandischmoor. The height difference among the existing mound with the house and the new plateau is about 1.5 m. (©: Thore Siefert).

3.2.3 Regional planning for adaptation

The strengthening of dikes requires space (Figure 11a). In recognition of this requirement, the state development plan (MILIG 2021) identifies priority areas for coastal flood defense and climate change adaptation behind dikes. In these priority areas (50 m behind state dikes and 25 m behind regional dikes), the interests of coastal flood defense have priority over competing land use claims. Accordingly, the priority areas must remain free of new, spatially significant plans and measures that do not serve coastal flood defense as well as from other uses that are difficult to revise and that conflict with interests of coastal flood defense.

On the sandy coasts of the islands and along the mainland coast of the Baltic Sea, the accelerated sea level rise and the resulting increasing hydraulic loads during storm surges will generally lead to an intensification of the erosion processes and coastal retreat. Sections of the coast that are still stable or even growing today may also erode and recede. In recognition of this fact and the need to keep the cliffs free from coastal protection wherever possible (Ch. 3.2.1), the state development plan (MILIG 2021) identifies priority areas for coastal protection and climate change adaptation behind cliffs, dunes and beach walls. In these 150 m wide priority areas, the interests of coastal protection have priority over competing land use claims. Accordingly, the priority areas must remain free of new, spatially significant plans and measures that do not serve coastal protection as well as from other uses that are difficult to revise and that conflict with interests of coastal protection.

4 Monitoring, research needs and outlook

For the development, examination and updating of adaptation strategies for coastal flood defense and coastal protection, early detection and quantification of the hydro-morphological impacts of climate change on the coasts is essential. For this purpose, responsible State administration further develops its monitoring program (MELUND 2022). This includes the collection of relevant hydrological and morphological data as well as the establishment of meaningful impact indicators (e.g., mean yearly change of coastline position over a five-year period). Figure 15 depicts a preliminary example for hydrological data and a possible impact indicator: the 19-year running mean of yearly highest water levels.

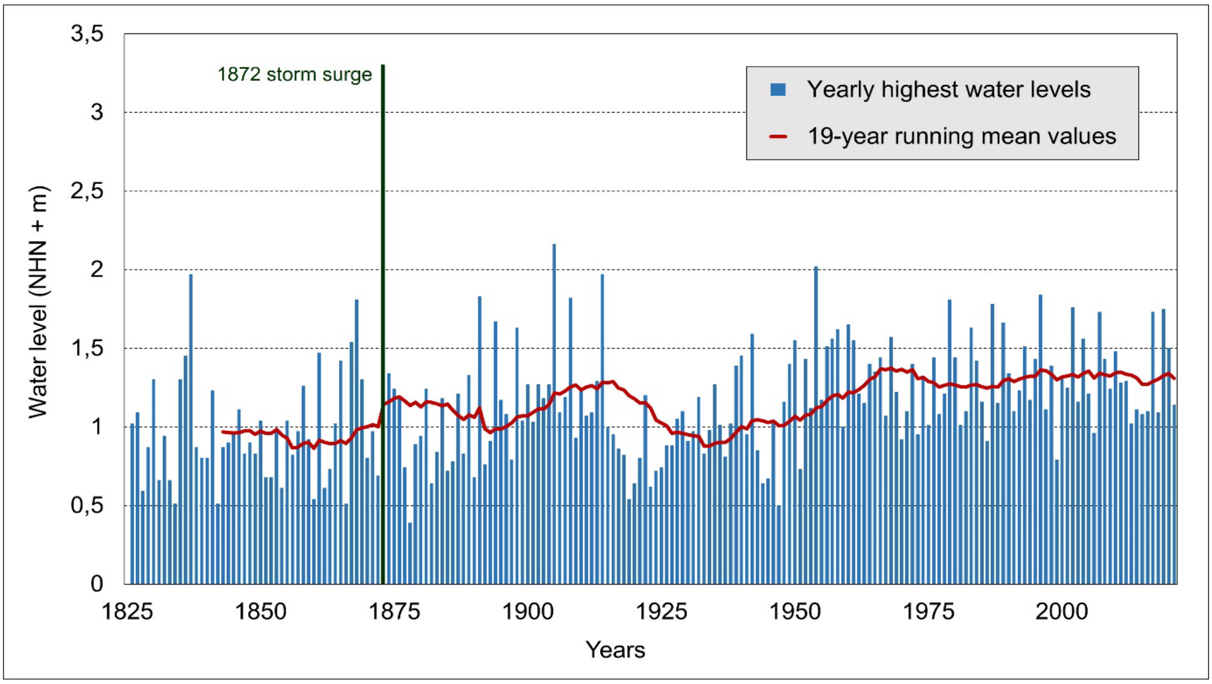

Figure 15: Development of the yearly highest water levels at Travemünde gauge near Lübeck from 1826 until 2021 (not corrected for mean sea level rise of about 0.2 m). Shown in red is the development of the 19-year running mean values as an optional impact indicator for climate change.

In this indicator, a tipping point or shift in trend due to anthropogenic climate change is not (yet) detectable. Further, to inform the public and for controlling purposes, monitoring of the adaptation efforts will occur by so-called response indicators (e.g., the 12-year running mean of strengthened state dikes with "climate-proof" design). Every six years, State administration will compile a monitoring report that flows into the regular updating of the master plan for coastal flood defense and coastal protection.

Investigations into the future development of mean sea level and storm surge intensity under climate change represent international research foci and plausible results are available (IPCC in press, Klein et al. 2018, Figure 9 and 10). For sustainable coastal flood and erosion risk management, scientific information on the future morphological behavior of Schleswig-Holsteins sandy coasts is of high importance as well. A cooperation with a national research institute delivered first morphological projections for different sea level rise scenarios for the Wadden Sea (Hofstede et al. 2019). The projections imply that the Wadden Sea tidal basins are rather robust or adaptable to stronger rising sea levels. However, the modelling results indicate that the applied wave model needs further adjustments with respect to long-term morphodynamic simulations (Hofstede et al. 2019). For the Baltic Sea coast, the new master plan contains a research cooperation with universities, which has one focus on morphological projections for different sea level rise scenarios (MELUND 2022). One of the intended outcomes is a web-based waves and transport atlas, indicating so called "hot spots" of future coastal retreat under accelerated sea level rise. The master plan further defines research needs with respect to ecosystem-based protection of the Halligen as cultural and natural heritage. Without sustainable protection, the Halligen would erode and in the end disintegrate (Figure 5). The traditional way to reinforce the revetments has, with respect to accelerated sea level rise, negative side effects like the reduction of sediment accumulation on the Halligen (Hache et al. 2020). Another research need is the development of alternative technical adaptation solutions that needs less space (Figure 11a). Due to competing spatial requirements, the challenge of finding legally compliant and publicly acceptable solutions that work in the long term will grow as the need for adaptation increases.

Despite the strong rise in population density since then, the 1872 storm surge along the Baltic Sea coast (Figure 15) was the last flood event that caused fatalities in Schleswig-Holstein (Kiecksee 1972, Hofstede and Hamann 2022). This is also a success of coastal flood and erosion risk management in Schleswig-Holstein, as laid down in the successive master plans. Against the background of men-made climate change and its hydro-morphological consequences, safeguarding the people in Schleswig-Holstein from storm surges in the long-term is the main challenge and constitutes a generational task. It will not always be possible to find a consensus solution for all measures. Due to stronger sea level rise, a rethink towards more sustainable utilization forms may become necessary in highly affected areas. With regards to an assumed human tendency to forget bad experiences and disregard or fade out hazards (Hofstede and Hamann 2022), this represents another challenge for modern coastal flood and erosion risk management.

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