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# The 1872 catastrophic storm surge at the Baltic Sea coast of Schleswig-Holstein; lessons learned?

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## Summary

November 13, 2022 marks the 150<sup>th</sup> anniversary of the most severe storm surge to date along the Baltic Sea coast of the German Federal State of Schleswig-Holstein. Thirty-one people died in the floods and about 15,000 became homeless. It was the last storm surge in Schleswig-Holstein, in which human lives were lost. Given this and in the face of strongly increasing mean and extreme sea levels in future, the 1872 storm surge constitutes an admonition or rather a plea for sustainable coastal flood risk management.

Along the Baltic Sea coast of Schleswig-Holstein, peak water levels of the 1872 storm surge probably varied among about NHN +2.4 and +3.4 meter. The highest local wind speeds and waves occurred four to 10 hours earlier than peak water levels in Schleswig-Holstein. The unprecedented height of the 1872 storm surge in Schleswig-Holstein resulted from an external surge that propagated into the area from the central Baltic Sea region and piled up here on top of already prevailing very high storm surge water levels. The 1872 storm surge represents a singular event in Schleswig-Holstein, which makes it scientifically challenging to assess its probability of occurrence. Present-day coastal flood defense, spatial planning and disaster management, as cornerstones of public coastal flood risk management in Schleswig-Holstein, generally and in combination consider the lessons learned after the 1872 flood calamity. In the light of intensifying utilizations, the need to improve the status of the environment and with regard to stronger rising sea levels in future, implementing sustainable coastal flood risk management remains a challenge.

## Keywords

Schleswig-Holstein, Baltic Sea, storm surge, flood catastrophe 1872, coastal flood defense

## Zusammenfassung

*Am 13. November 2022 jährt sich zum 150sten Mal die bisher schwerste Katastrophenflut in der westlichen Ostsee, bei der allein in Schleswig-Holstein 31 Menschen umkamen und etwa 15.000 obdachlos wurden. Es war das letzte Sturmflutereignis in Schleswig-Holstein, bei dem Menschenleben zu beklagen waren. Aus diesem Grund und vor dem Hintergrund stark steigender mittlerer und Extremwasserstände in der Zukunft, stellt diese Flutkatastrophe eine Mahnung und einen Appell für ein nachhaltiges Management von Hochwasserrisiken an den Küsten dar.*

*Diese Abhandlung beginnt mit einer Beschreibung der Sturmflut des Jahres 1872 und ihrer Folgen in Schleswig-Holstein. Der Fokus liegt dabei auf den besonders betroffenen Orten Dahme und Eckernförde. Anschließend wird dargestellt, wie die während der Sturmflut gewonnenen Erkenntnisse in den Jahrzehnten nach der Sturmflut und heute in der Planung und Umsetzung von Küstenschutzmaßnahmen und des Hochwasserrisikomanagements generell umgesetzt wurden und werden. Nach einer Ausarbeitung der Komponenten des integrierten Hochwasserrisikomanagements wird die Abhandlung mit einer Diskussion über die Lehren aus der Sturmflut fortgesetzt. Sie endet mit den nachfolgenden Schlussfolgerungen.*

*Die Sturmflut von 1872 erreichte an der Ostseeküste von Schleswig-Holstein wahrscheinlich maximale Wasserstände zwischen NHN +2,4 und 3,4 m. Die höchsten lokalen Windgeschwindigkeiten und Wellen traten in Schleswig-Holstein vier bis 10 Stunden früher auf als die Höchstwasserstände. Die einzigartige Höhe der Sturmflut vom 13. November 1872 in Schleswig-Holstein wurde durch eine externe Flutwelle aus dem zentralen Ostseeraum verursacht, die sich auf bereits vorherrschende sehr hohe Sturmflutwasserstände aufstürmte. Entsprechend stellt die Sturmflut in Schleswig-Holstein ein singuläres Ereignis dar, weshalb seine statistische Einordnung eine wissenschaftliche Herausforderung darstellt. Als Hauptbestandteile eines integrierten Hochwasserrisikomanagements an den Küsten berücksichtigen Küstenschutz, Raumordnung und Katastrophenschutz in Schleswig-Holstein generell und in Kombination die nach der Flutkatastrophe gesammelten Erfahrungen. Vor dem Hintergrund intensiver Nutzungen und die Notwendigkeit einer ökologischen Zustandsverbesserung sowie im Hinblick auf den beschleunigten Meeresspiegelanstieg bleibt die Umsetzung eines nachhaltigen Küstenhochwasserrisikomanagements eine Herausforderung.*

## Schlagwörter

*Schleswig-Holstein, Ostsee, Sturmflut, Flutkatastrophe 1872, Küstenschutz*

## 1 Introduction

November 13, 2022 marks the 150<sup>th</sup> anniversary of a catastrophic storm surge that hit the coastlines of the western Baltic Sea region. In Germany, Denmark and Sweden, about 300 people died, 127 of them at sea (Fredriksson et al. 2017, Kiecksee 1972). In the German Federal State of Schleswig-Holstein (Figure 1), 31 people died in the floods, about 2,850 houses were destroyed or uninhabitable and more than 15,000 persons became homeless and needy (Kiecksee 1972). It was the last storm surge in Schleswig-Holstein, in which human lives were lost. Since 1872, the number of inhabitants and physical assets or, rather, tangible damage potentials have multiplied.

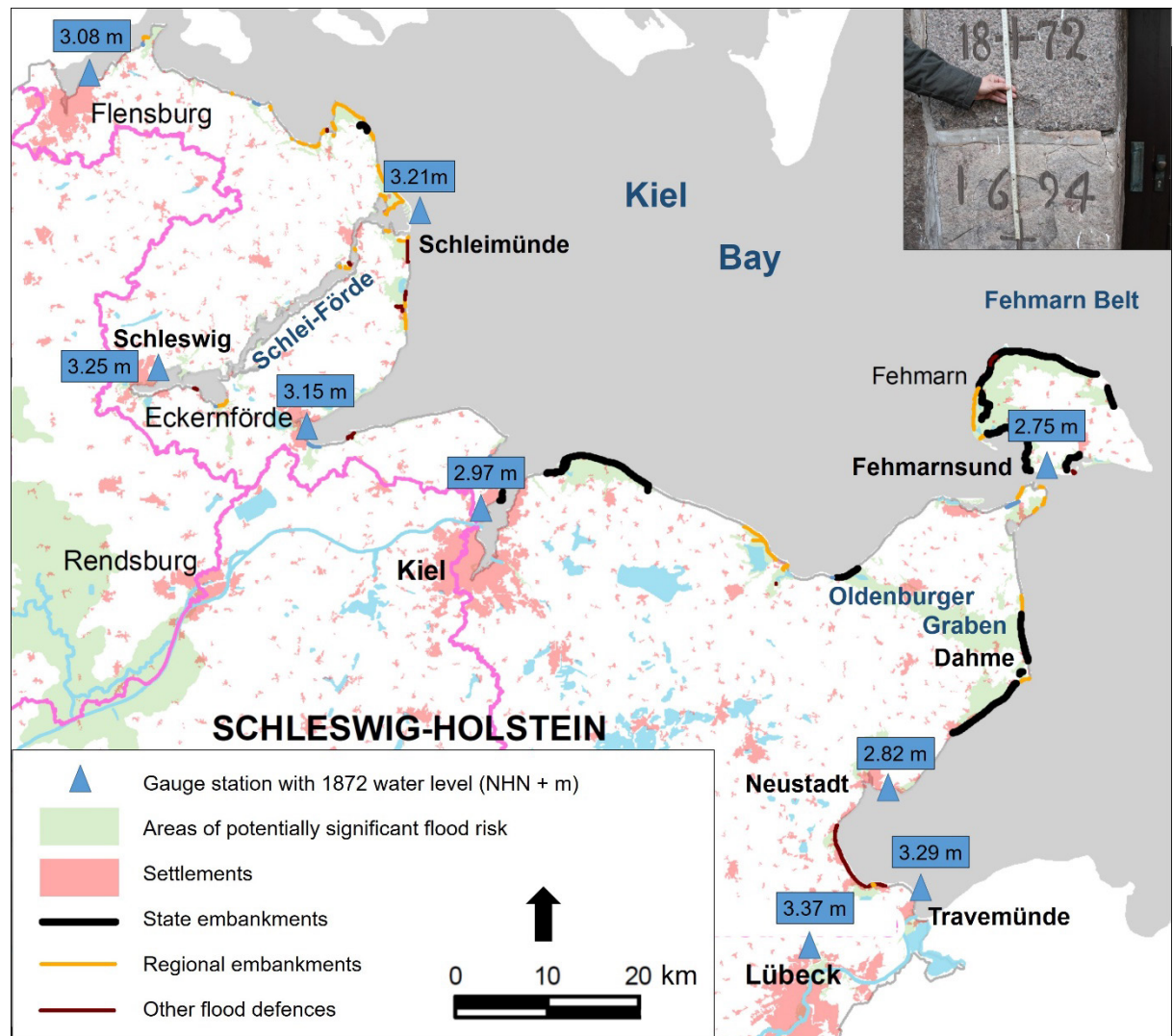


Figure 1: overview of the Baltic Sea coast of Schleswig-Holstein with coastal lowlands (in green), coastal flood defenses and 1872 storm surge water levels (gauge data: NHN = “Normalhöhennull” = German ordnance datum). The inset at the top right of the figure shows high water marks from the storm surges 1694 and 1872 at the former Gottorf water mill in Schleswig (photo: J. L. A. Hofstede).

Today, more than 30,000 people live and damage potentials of almost seven billion Euros are present in the about 315 km<sup>2</sup> large coastal lowlands along the Baltic Sea of Schleswig-Holstein. MELUND (in press) defines these lowlands as the areas situated less than 2.5 m above German Ordnance Datum NHN ( $\approx$  mean sea level). This is the area that could potentially, i.e., without coastal flood defenses, flood during a storm surge with a yearly probability of 0.005. Although the flood defense standards have strongly improved since 1872, a comparable storm surge could still have disastrous impacts due to the multiplied population density and damage potentials. Given this and in the face of strongly rising mean and extreme sea levels in future (IPCC in Press), the 1872 storm surge in Schleswig-Holstein constitutes an admonition or rather a plea for sustainable coastal flood risk management.

This paper starts with descriptions of the storm surge and of its impacts with a focus on two severely affected municipalities in Schleswig-Holstein: Eckernförde and Dahme. The next section describes the implementation of the findings, gained during and directly

after the 1872 surge, in the planning and execution of coastal flood defense measures and coastal flood risk management in the following decades and today. After an elaboration of the components of integrated flood risk management, the paper continues with a discussion about the lessons learned from the storm surge and ends with some conclusions.

## 2 The 1872 storm surge in Schleswig-Holstein

### 2.1 Meteorology and hydrology

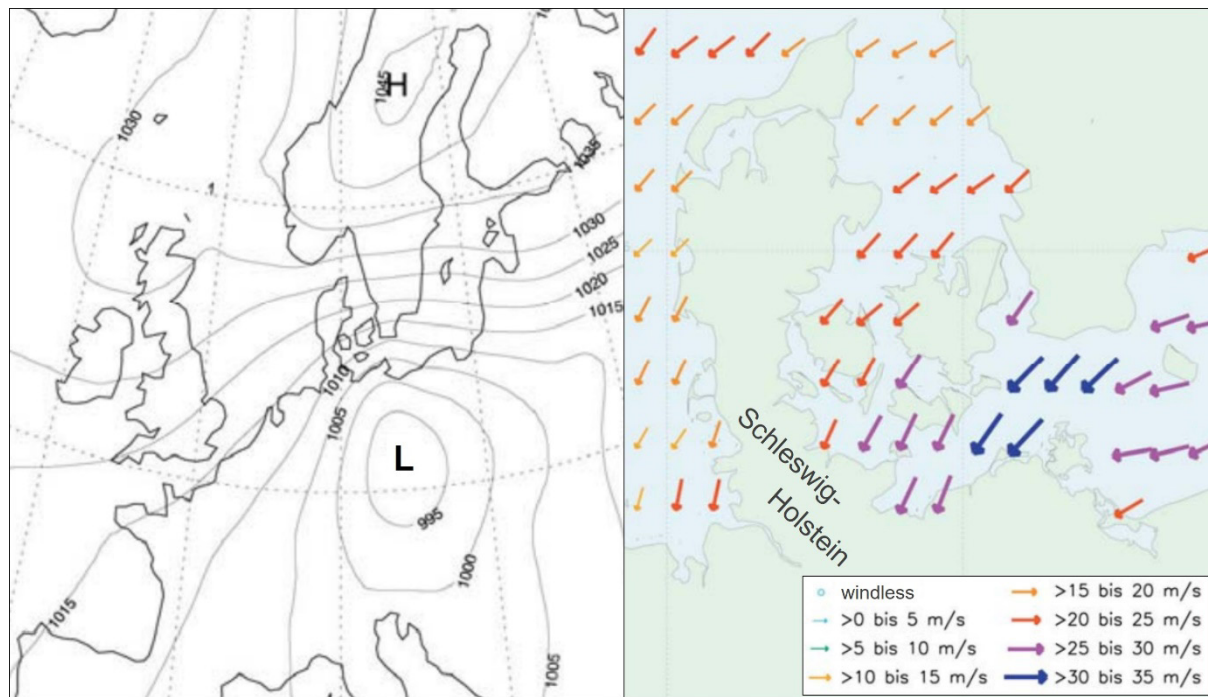


Figure 2: reconstructed air pressure fields and wind velocities in the western Baltic Sea region on November 13, 6 a.m. (source: Rosenhagen und Bork 2009).

Although the 1872 storm surge reached its maximum water levels on November 13, the causative weather situation started already two weeks before (Rodloff 1972, Rosenhagen und Bork 2009). From November 1 to 10, a strong and stable low-pressure system over Scandinavia induced strong westerly winds that “pushed” seawater away from the German Baltic Sea coasts towards the east. This resulted in falling water levels in the western Baltic Sea and, in compensation, water inflow from the North Sea via the Kattegat. In effect, the Baltic Sea filled up with water. Around November 10, the weather situation changed, the westerly winds waned and water started to flow back from the east. A high-pressure system evolved over Scandinavia, accompanied by a low-pressure system in central Europe. Both weather systems continually intensified until November 13, when extreme air pressure gradients induced a northeasterly hurricane (Figure 2). Peak wind velocities in Schleswig-Holstein occurred in the late morning. In Kiel, the hurricane reached a maximum of about 31 m/s around 10 a.m. (Baensch 1875).

Baensch (1875) comprehensively described the hydrology of the 1872 event, including the establishment of 23 storm surge curves recorded at Prussian gauges in the Baltic Sea. Figure 3 depicts coastal flood hydrographs from the gauges Travemünde, Fehmarnsund (positions in Figure 1) and Stralsund (situated about 135 km to the east of Travemünde)



from November 11 to 14. The curves show that water levels continuously rose for more than two days. Such a long and strong rise of sea levels as well as the resulting maximum storm water levels were and are unprecedented in the region. Further, the gauge stations Fehmarnsund and Travemünde visualize the well-known effect of increasing surge levels from the outer towards the inner parts of bights.

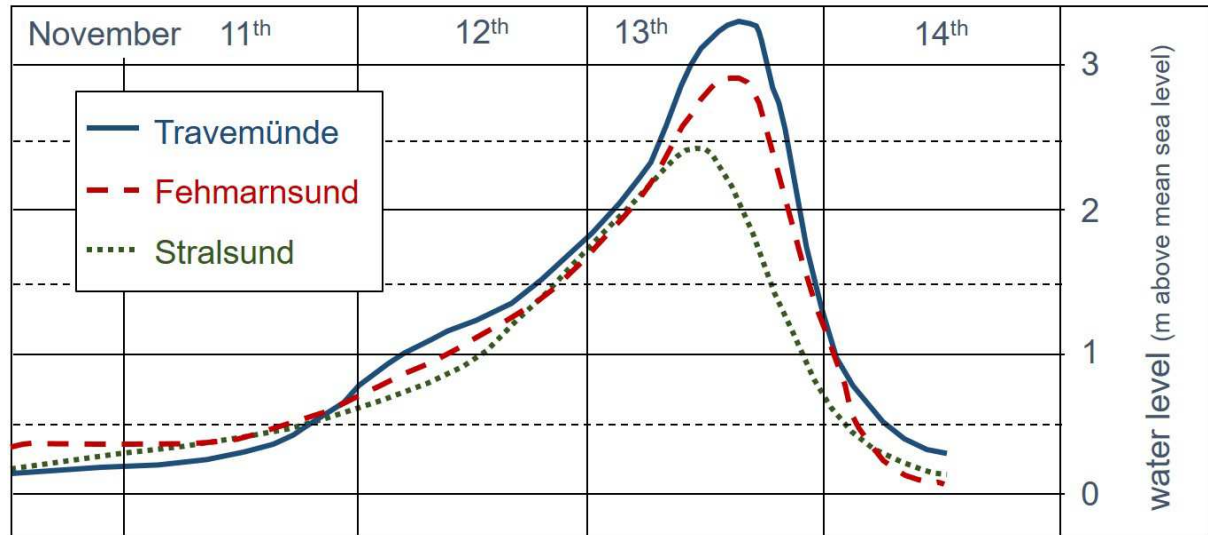


Figure 3: Storm surge curves at Travemünde, Fehmarnsund and Stralsund gauge stations from November 11 to 14 (adapted from Baensch 1875).

Figure 1 depicts known maximum water levels of the 1872 storm surge at gauge stations in Schleswig-Holstein. Lübeck gauge station recorded the highest water level in Schleswig-Holstein with 3.38 m above mean water level (NHN +3.37 m). At the former “Blue Tower” in Lübeck, high water marks existed of two earlier extreme floods that occurred in the years 1625 and 1694. A regional railway company dismantled the Blue Tower in the late 19<sup>th</sup> century to make room for a new railway line. Based on these marks, Baensch (1875) established maximum water levels of 2.80 m (1625) and 2.82 m (1694) above mean water level, i.e., 0.58 resp. 0.56 m lower than the flood from 1872. Baensch applied the mean water level of his time, thus assuming that no secular mean sea level changes occurred among 1625 and 1872. According to Baensch (1875), no reliable height information exists of older storm surges, whereas the storm surges that occurred among 1694 and 1872 were significantly lower. Based on historical data, Jensen et al. (2022) reassessed the heights of storm surge water levels in Travemünde over the last 1,000 years and concluded that a comparable surge height as in 1872 may have occurred in 1320. At the former Gottorf water mill in Schleswig, high water marks exist from the storm surges in 1694, 1836 and 1872 (inset in Figure 1). According to these marks, the peak water level in Schleswig in 1694 was about 0.6 m lower than in 1872, as the water level reached NHN +3.25 m at the local gauge station (Figure 1).

Figure 4 depicts the yearly highest water levels (HW) at gauge station Travemünde from 1826 to 2020, one of the world’s longest continuous HW time series. Here, the 1872 water level reached NHN +3.29 m. The second highest storm surge water level was recorded in 1904 with NHN +2.15 m, i.e., 1.15 m lower than the 1872 peak water level.

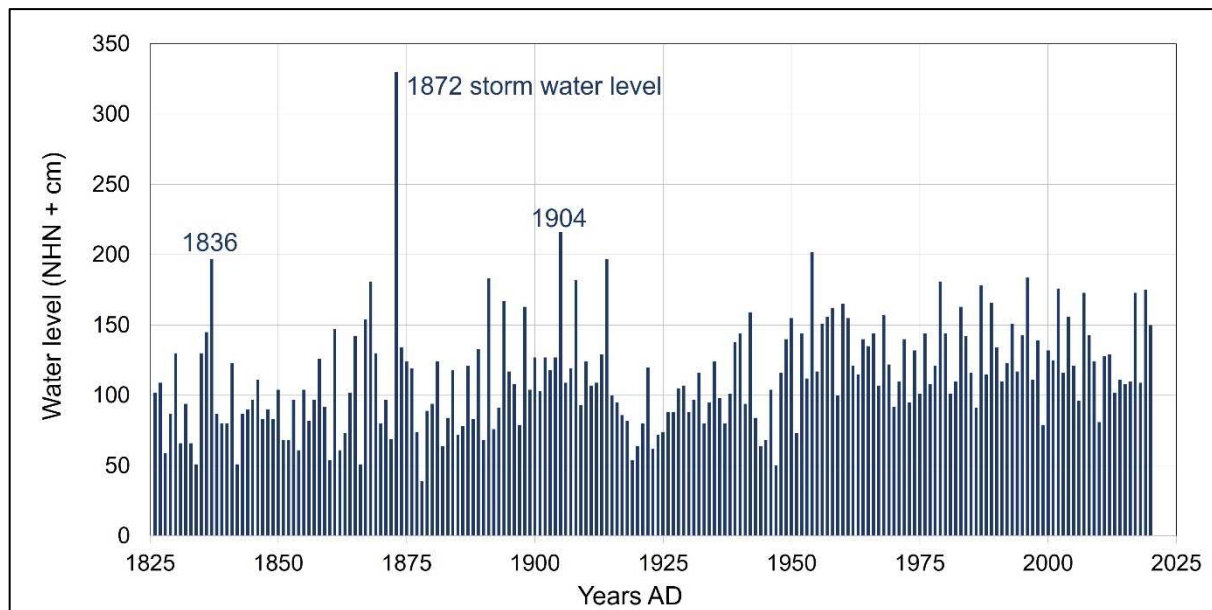


Figure 4: the yearly highest water levels at gauge station Travemünde from 1826 to 2020 (data from LKN.SH; data not corrected for mean sea level rise).

An internal report from the State Water Management Authority Lübeck (WWA Lübeck 1946) lists, for each of the Dike and Drainage Boards on the island of Fehmarn (location in Figure 1), maximum water levels for the 1872 storm surge. The values vary among 2.37 and 2.68 m above mean sea level. The data stem from local inquiries after the storm surge and do not have the same accuracy as gauge data. The lowest water levels appeared expectedly along the downwind-side western shorelines, the highest to the northeast and in the Fehmarnsund. The listed water levels are lower than along the mainland coast, which seems physically plausible. In synthesis, maximum water levels along the Baltic Sea coast of Schleswig-Holstein probably varied among about NHN +2.4 and +3.4 m.

Based on reported peak water levels and their occurrence times in the Schlei firth (location in Figure 1), Baensch (1875) established a mean progression velocity of the surge wave in this firth with about seven km per hour. The lowest speeds occurred at the mouth and in the broader inner part of the firth, the highest velocities in the narrow central part. At the mouth, in Schleimünde, maximum water level (NHN +3.21 m) occurred around 3:30 p.m. At the inner end, in Schleswig, water level reached its maximum (NHN +3.25 m) around 9:30 p.m., i.e., almost 10 hours later than the maximum wind velocities in the region (see above). Baensch (1875) reported that peak water levels within the Schlei decreased from the mouth towards the inner parts. At the broader inner end of the firth, however, local surge levels increased again and even exceeded the values observed at the mouth (Figure 1). This kind of surge progression is typical for the Schlei and probably relates to its particular shape.

## 2.2 Impacts

In 1872, large parts of the coastal lowlands along the Baltic Sea coast of Schleswig-Holstein were still unprotected. Only some lowlands like the Oldenburger Graben (Figure 5) already featured coastal flood defenses. As these under dimensioned defenses all collapsed during the storm surge, the impacts in Schleswig-Holstein were disastrous. More than 300 km<sup>2</sup> of

coastal lowlands with numerous settlements as well as harbor areas of larger towns like Flensburg and Lübeck flooded. According to Kiecksee (1872), the floods damaged or ruined about 2,850 houses, 31 people died and more than 15,000 persons became homeless and needy. Kiecksee (1972) gives a comprehensive and regionalized overview of the flood impacts and of the recovery measures after the flood in the western Baltic Sea region. With numerous data and facts, he documents that not only the surge and its impacts, but also the public and private readiness to help after the catastrophe were unprecedented. This subchapter contains a description of the catastrophic impacts in two particularly affected villages in Schleswig-Holstein: Dahme and Eckernförde.

Dahme is a small coastal municipality with about 1,250 inhabitants (Figure 1 and 5). With almost one million overnight stays per year, seaside tourism dominates local economy. Parts of Dahme lie in the about 43 km<sup>2</sup> large coastal lowland Oldenburger Graben. In this lowland, about 1,900 people live and 366 million Euros of capital assets exist (Fachplan Küstenschutz Ostseeküste 2022).

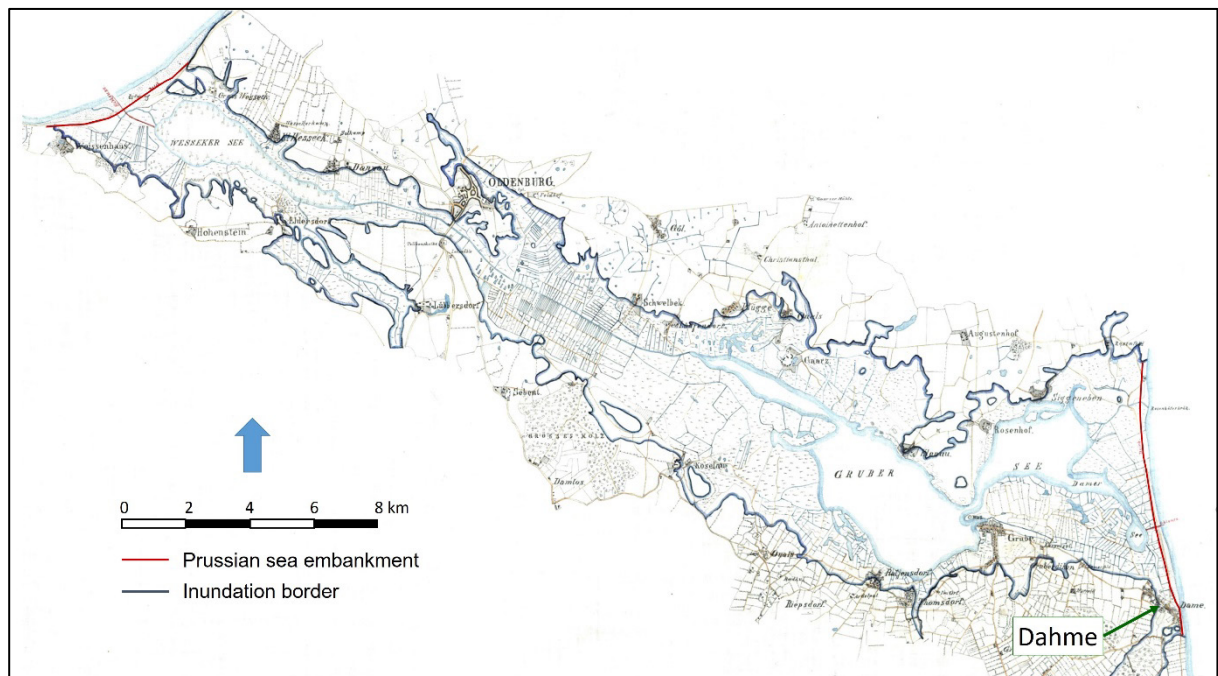


Figure 5: historical map from 1878 showing embankments and inundated area in the coastal lowland “Oldenburger Graben” (location in Figure 1) during the 1872 storm surge (source: LASH Abt. 402 A 24 Nr. 36).

In the late 1860ies, as part of a socio-cultural aid for the newly established province of Schleswig-Holstein, the Prussian Government initiated a comprehensive coastal flood defense program (Kannenberg 1958). One of the first larger measures was, in 1868 and 1869, the erection of an about 5.5 km long sea embankment in front of Dahme and the Oldenburger Graben (Figure 5). It was probably designed based on observations from the last severe storm surge that had occurred in the region in 1836 (Figure 4). This storm surge resulted in maximum water levels of about 2.0 m. In all, the embankment was about 3.0 m high, considering a local wave run up of about 1.0 m. The embankment, that consisted of sandy material and had relatively steep slopes, lay on top of dunes and beach ridges. November 1872, three years after finalization of the flood defense, storm surge water levels in the area rose to about 2.8 m above normal. Unsurprisingly, the embankment collapsed,



amongst others directly in front of Dahme (Kiecksee 1972). After breaching of the defenses, the floodwaters swiftly inundated not only large parts of the village, but also the Oldenburger Graben (Figure 5). Ten persons died in the floods in Dahme, more than in any other municipality in Schleswig-Holstein. According to Reher (1931), only 20 from 80 to 90 houses that originally existed in the village were still inhabitable after the flood. The strong flood currents ruined 40 to 50 houses and washed 20 other houses away. In all, 51 families with about 300 persons (i.e., more than half of the total population) became homeless. Most of the livestock drowned.

Eckernförde is a coastal city with about 21,700 inhabitants (Figure 1). It is situated in the inner part of Eckernförde Bight that faces towards the northeast, i.e., that is directly exposed to northeasterly storms and waves. Major parts of the inner city are flood prone coastal lowland (Figure 6). Here, about 1,250 people live and 130 million Euros of capital assets exist (Fachplan Küstenschutz Ostseeküste 2020). In contrast to Dahme, there are no technical flood defenses in Eckernförde. An elevated promenade on former beach ridges, partly protected by revetments, and an elevated harbor area protect the low-lying inner city from flooding. Responsible city authorities are planning a comprehensive flood defense scheme (PROKOM 2017).



Figure 6: Maps of the city of Eckernförde. The left image displays a historical map from 1864 (source: PROKOM 2017). The right image shows the present situation; including hypsometric layers; note that the green and yellow areas are flood prone (source: KIS-SH).

As no flood defenses existed in 1872, the rising waters more or less steadily inundated the city. Most of the damages to buildings occurred along the “Jungfernstieg” road (Figure 6) and resulted from wave impacts. Flood marks on both sides of this road, however, show that some of them withstood the flood (Figure 7).



Figure 7: Flood marks in the historical town center of Eckernförde (photos: M. Hamann).

The devastation in Jungfernstieg actually furthered the upcoming fish industry. In the “cleared” space, it was easy to raise e.g. new smokehouses, which contributed to following decades of economic prosperity (Schinkel 2001). Despite of the 1872 calamity, new buildings arose even at the seaward (eastern) side of the road. As shown in Figure 6 (left image), first developments on existing beach ridges had only started here after 1864. Until the mid-1970s, commercial uses prevailed along the seaward side of the Jungfernstieg. Afterwards, the area converted into a residential area. In all, waves and currents destroyed 78 houses and damaged 138 in the 1872 storm flood (Kiecksee 1972). After the catastrophe, 112 families were homeless and 150 to 160 families with about 400 persons needy. Although the numbers of damaged houses and needy persons after the flood were significantly higher in Eckernförde than in Dahme, nobody died here in the floods.

### 2.3 Statistical appraisal of the 1872 storm surge

From Figure 4, it becomes clear that the 1872 water level clearly stands out. In relation to NHN, the peak water level in 1872 is more than 50% higher than the second highest recorded water level. From a statistical point of view, this is an indication that, in Schleswig-Holstein, the event is an outlier that does not belong to the population. This makes it scientifically challenging to assess its probability of occurrence. The German joint research project MUSTOK (Jensen 2009) investigated meteorology and hydrology of the 1872 event. Mudersbach and Jensen (2009) corrected the 1872 value at gauge station Travemünde (Figure 4) for mean sea level rise until 2006. With a newly established distribution function, they calculated a recurrence interval of 10,000 years for the 1872 storm surge water level if it would reoccur in 2006. They concluded that the statistical population used could not describe the storm surge. Extending the population with historical data (inter alia, the 1625 and 1694 peak water levels) and modelling results on hydro-meteorologically possible extreme water levels in the region (Bork and Müller-Navarra 2009) reduced the

recurrence interval of the event to about 3,400 years. Based on numerical modelling of the 1872 event, Bruss et al. (2009) stated that the extreme peak water levels in Schleswig-Holstein resulted mainly from a combined water transport into the area from the central Baltic Sea and the Kattegat, driven by an extraordinary supra-regional meteorological situation rather than by local weather.

The fact that peak water levels in Schleswig-Holstein occurred four to 10 hours later than the observed maximum local wind velocities (Baensch 1875), supports this hypothesis. In Kiel, for example, after a maximum of 31 m/s around 10:00 a.m., local wind velocity was in the order of 17 m/s during peak water level around 3:30 p.m. (Figure 8). Although the local wind already decreased, the water level in Kiel still rose by more than 0.5 m. In Schleswig, local wind velocity was probably less than 10 m/s during peak water level. Hence, highest wind velocities and peak water levels did not coincide in Schleswig-Holstein. This indicates that an external surge wave, caused by a northeasterly hurricane in the central Baltic Sea region, entered Kiel Bay via the Fehmarn Belt and approached the coastline of Schleswig-Holstein. Here, it piled up on top of already raised storm water levels. Without the external surge wave, peak water levels may have resembled those of the 1625 and 1694 storm water levels in Schleswig-Holstein (see Ch. 2.1). This extraordinary multi-causal emergence of local peak water levels supports the hypothesis that the 1872 storm surge represents a singular event in Schleswig-Holstein. Further, the time lag among highest wind velocities and peak water levels indicates that, fortunately, maximum wind waves probably occurred several hours before peak water levels in Schleswig-Holstein.

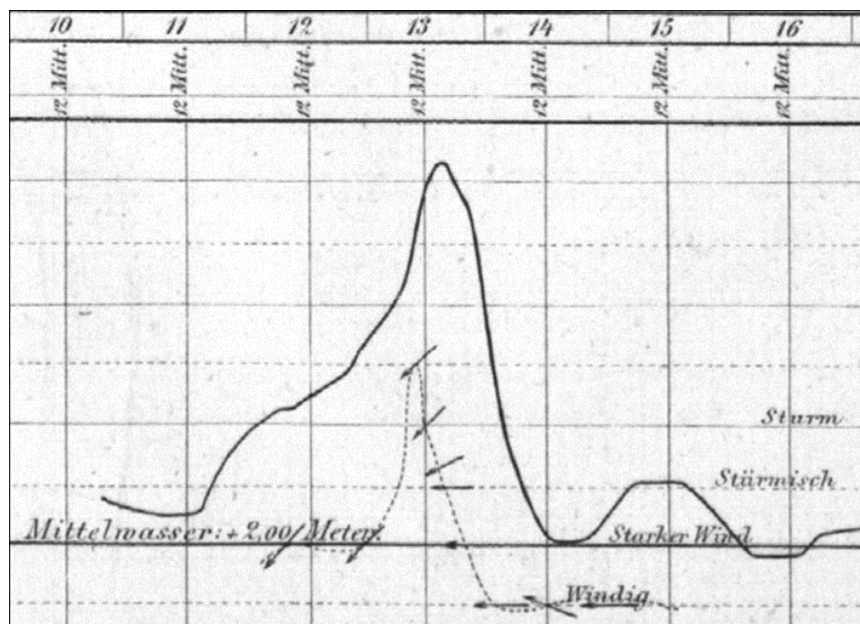


Figure 8: wind curve (dotted line) and flood hydrograph of the 1872 storm surge at Kiel gauge station (taken from Baensch 1875).

### 3 Coastal flood defense after the 1872 storm surge

Less than one month after the catastrophic flood, Prussian Government passed a decree for a comprehensive coastal flood defense program, including design criteria (Kannenbergs 1958). One forward-looking criteria was that new sea embankments should be erected

sufficiently landward of dunes and beach ridges, instead of on top of them. Based on observations made during the storm surge (Baensch 1875), this measure envisaged a reduction in hydraulic loads on the outer slope of the embankments as well as the creation of a buffer zone for coastal erosion during storm surges. After evaluation of the 1872 hydraulic loads, it was further stipulated that:

- the height of the new embankments should be about 5.0 m above mean sea level,
- the crest width should be about 3 to 4 m,
- the outer slope should have a gradient of 1:6, the inner slope 1:2,
- the embankment should have a cover of at least 0.6 m of erosion resistant material like clay.

Figure 9a visualizes the Prussian standard design for sea embankments (Eiben 1992). In the building campaigns after 1872, one-to-one implementation of this design did not occur (Kannenbergh 1958). Although the erection of new embankments normally took place behind natural dunes and beach ridges, mean height of the embankments was normally up to about four meter above mean sea level. The outer slopes had gradients among 1:3 and 1:6; the inner slopes were normally steeper than 1:2. For most embankments, no information exists about their composition. Figure 9b displays the profile of the sea embankment in the Probstei near Kiel from 1882. With a maximum height of NHN +4.0 m, it lies directly behind the beach and partly on top of a pre-existing consolidated beach ridge.

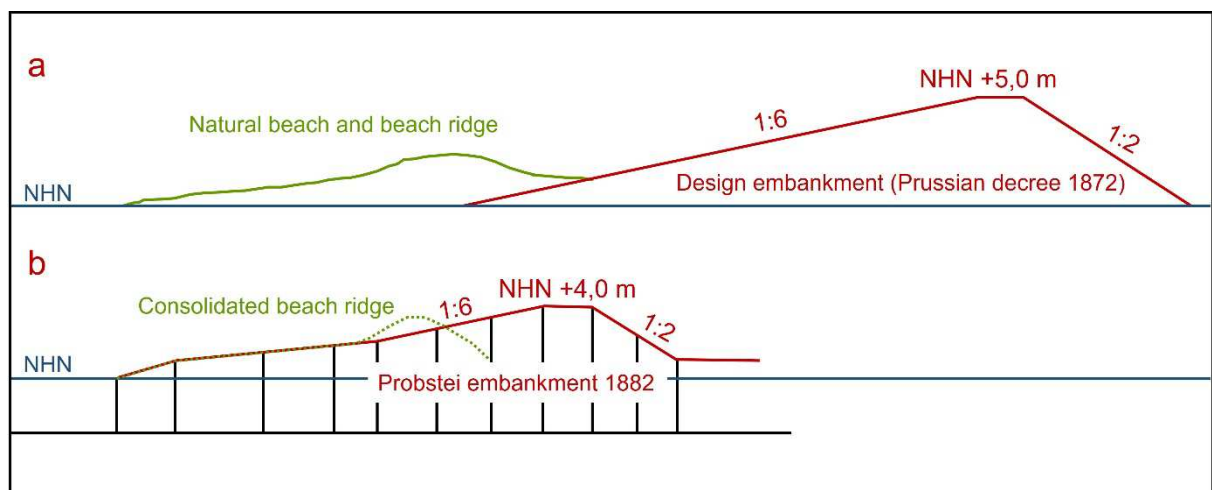


Figure 9: design profile of a sea embankment according to the Prussian design criteria (Figure 9a) and of the 1882 sea embankment in the Probstei near Kiel (Figure 9b) (adapted from Eiben 1992).

Until 1882, with technical and financial support from the Prussian Government, about 70 km of sea embankments arose along the Baltic Sea coast of Schleswig-Holstein (Kannenbergh 1958). These defenses protect about 145 km<sup>2</sup> of coastal lowlands. Newly founded Dike and Water Boards became the task to maintain the embankments and secure the drainage of the lowlands. In these boards, all potentially affected landowners were member (with the power of co-decision according to landholding). In the year 1972, upon request of the boards, Schleswig-Holstein State Government took over technical and financial responsibility for the sea embankments. Conform the Schleswig-Holstein State Water Act, these coastal flood defenses passed as rededicated state embankments into state ownership.



One of the first measures after 1872 was the erection of a 5.5 km long new embankment in front of Oldenburger Graben near Dahme (Kannenberg 1958). The new crest height was about 4.2 m above mean sea level. Outside of Dahme, the new embankment ran behind the dunes and beach ridges, as stipulated in the Prussian decree. In front of Dahme, due to limited space, the new embankment lay again in an exposed situation directly behind the beach and featured relatively steep paved slopes. The expectation was that a paved outer dike slope should be able to withstand the higher hydraulic loads. The embankment and its foreland came into the possession of the newly founded local Dike and Water Board. It was governmental intention that the foreland should remain free from utilizations (Runde 1883). However, the upcoming of seaside tourism thwarted this specification. In 1920, local community erected a swimming pool in front of the embankment (Reher 1931). A concrete walking trail (promenade) on the foreland of the embankment followed, protected by a low flood defense wall situated directly on the beach. Based upon a public beach building plan from 1921, the area behind the wall but in front of the sea embankment increasingly filled up with touristic infrastructures (Kannenberg 1958). Today, dense touristic utilizations prevail in front of the embankment (Figure 10).



Figure 10: Aerial photo of Dahme seaside (Photo: LKN.SH / VPS).

After taking over the responsibility in 1972 (see above), state administration checked and listed the state embankment in front of Dahme as unsafe (i.e., not able to withstand the 1872 storm surge). Planning of a strengthening campaign started around the year 2,000. Achieving formal approval for public coastal flood defense measures may take 10 years or more in Germany, due to comprehensive state, national and EU legislation as well as the challenge of achieving local acceptance. The strengthening campaign went from 2010 to 2013 (Hofstede 2011). The design height based on the 1872 storm water level and included an additional margin of 0.5 m to account for sea level rise. Considering local wave run up, the existing about 5.5 km long embankment became a new crest height of NHN +4.8 m. A layer of clay covers a sandy core. Outside of Dahme, about 3.7 km was constructed with



a seaward gradient of 1:8 and an inside gradient of 1:3. In Dahme, the challenge was to consider the existing touristic infrastructure on the foreland as well as dense housing and public infrastructure behind the embankment (Figure 10). Existing buildings and uses have a legal right of continuance and local community would not have accepted their removal. In consequence, the seaward gradient remains steeper and, over a stretch of about 0.7 km, a flood defense wall on top of the sea embankment secures the prescribed flood safety standard. Three passages through the embankment that are lockable in case of flood emergency enable easy access to the seaside facilities. In order to secure coherence for overbuilt NATURA 2000 sites, a specialized company removed moist dune habitats from the construction site and relocated them on prepared new dunes (Hofstede 2011). In synthesis, the new sea embankment fulfills the Prussian design criteria from 1872.

#### 4 Integrated flood risk management

In order to minimize the risks of coastal flooding, building flood defenses is only one brick in the wall. Hofstede (2007, 2011b) describes a holistic and integrated approach that combines technical and non-technical measures in a coastal flood risk management cycle (Figure 11).

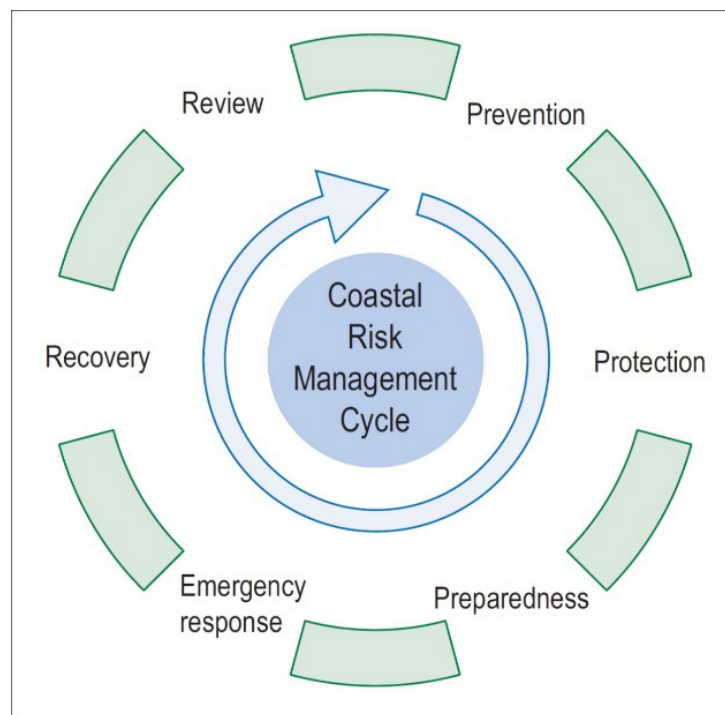


Figure 11: The cycle of integrated coastal flood risk management (source: Hofstede 2007).

Starting point in the cycle is prevention that aims at avoided or minimized flood risks, e.g., by stipulating building ban zones in flood hazard areas. The objective of protection is a minimized probability of a harmful flood event to occur, e.g., by building sea embankments. Preparedness has much to do with flood risk awareness of the affected population and the responsible decision makers (i.e., politicians). An important instrument to achieve this is appropriate risk communication. Informed people are more willing to take responsible preparatory actions (including evacuation). Further, they accept the high costs and other possible constraints associated with coastal flood risk management (Hallin et al.

2021). Emergency response manages the “worst case” scenario, i.e., the possibility of flooding. Flood warning and evacuation are two well-known measures. Recovery comprises aftercare measures, such as provisional repair of collapsed defenses and medical attendance for the injured. Finally, review stands for learning from new information and research outcomes as well as from disasters. It aims at an optimized next control loop (cycle) and monitoring and research programs are an important aspect of this element.

Main actors in the field of coastal flood risk management are spatial planning, coastal flood defense and disaster management. Whereas spatial planning focusses on prevention, flood defense aims mainly at protection but also deals with prevention and preparedness. Finally but evenly important, disaster management has a focus on emergency response but also deals with preparedness and recovery. All sectors consider review and should have a holistic view. The Dutch multi-layer safety approach from 2009 (van Herk et al. 2014), which defines three so called safety layers to reduce flood risk: protection, spatial planning and disaster management, closely resembles the cycle. The Floods Directive of the European Union (2007) sets a focus on prevention, protection and preparedness (including flood forecasts and early warning systems), i.e., on measures before the flood occurs.

## 4.1 Prevention

With respect to prevention, Schleswig-Holstein State Government updated in 2018 the State water Act and included building ban zones of 150 m behind the seaward edges of dunes, beach ridges and cliffs as well as in coastal lowlands that are not adequately protected by state embankments or other flood defenses with comparable safety standards. This in order to avoid and reduce damage expectations as well as to create a buffer zone for intensifying coastal retreat due to stronger sea level rise. The new state development plan for Schleswig-Holstein (MILIG 2021) considers these land use requirements by the definition of congruent areas of preference for coastal flood defense and for climate change adaptation along coasts. If implemented appropriately, these restrictions prevent rising damage expectations in future due to coastal floods in Schleswig-Holstein.

## 4.2 Protection

With respect to protection, state administration regularly performs safety checks of the State embankments. According to the last check in 2020, four State embankments along the Baltic Sea coast (i.e., 20 out of 70 km) need strengthening in order to meet the safety standards (MELUND in press). The design of these schemes base upon a statistically derived storm surge water level with a yearly probability of 0.005 and contains several extra safety factors:

- broadened crest width of 5.0 m (previously 2.5 m),
- low outer slope gradient of 1:10 (previously upward steepening profile),
- reduced allowable wave overtopping of 0.5 l/(s\*m) (previously 2.0 l/(s\*m)), and
- safety margin to account for future sea level rise of 0.5 m.

The low gradient significantly reduces wave run up and allows for a further heightening of the embankment if stronger sea level rise should make this necessary. With this staggered procedure or climate change adaptation pathway, a total sea level rise of approximately

2.0 m can be balanced (Hofstede 2019). In synthesis, after strengthening, the State embankments should be able to withstand the 1872 storm surge if it would reappear in this century. State embankments and other coastal flood defenses with a similar safety standard protect about half of the coastal lowlands and the affected population along the Baltic Sea coast of Schleswig-Holstein. This highlights the significance of prevention, preparedness and emergency response in an integrated and holistic flood risk management.

### 4.3 Preparedness

With respect to preparedness, nowadays the conditions for early warning are much better as in 1872. Operational models of the German Federal maritime and Hydrographic Agency (BSH) allow first indications of storm water levels up to six days before the event. Eight to 15 hours before a storm surge occurs, BSH starts with issuing regionalized flood warnings with expected maximum water levels. This gives disaster management authorities enough time to prepare appropriate measures and to inform the local population. BSH directs flood warnings to all regional disaster management authorities and to the public. While authorities use official communication structures, the public is warned e.g. by the smartphone app NINA, which is part of the Modular Warning System MoWaS (BBK 2021). The Federal Office of Civil Protection and Disaster Assistance (BBK) established MoWaS, since the civil protection siren network was dismantled after the end of the cold war in the 1990s. End devices triggered by MoWaS include all warning media e.g. radio, television, Internet, mobile apps.

However, warning of the affected population can only be effective when accompanied by an appropriate risk communication. People have to know what to do in case of warning. Risk communication comprises clear and honest information about possible hazards in the peoples own residential and working environments, how to prepare individually and, related to that, clear advice how to react if a warning is issued. The BBK provides information for emergency preparedness and emergency actions for a number of hazards e.g. severe weather, fire, floods and industrial disasters. Nonetheless, the need to prepare is not evident for many inhabitants of coastal lowlands. This could be a side effect of the high coastal defense standard and very few real events in the past decades.

### 4.4 Emergency response

With respect to emergency response, the present situation differs completely from 1872. As laid down in the German Constitution (Grundgesetz) from 1949, emergency response in Germany is in the responsibility of the Federal States (Länder). The states maintain disaster management authorities on state and county level as well as procedures for this purpose. These are laid down in state specific disaster management acts, e.g. in the Schleswig-Holstein State Disaster Management Act (Landeskatastrophenschutzgesetz Schleswig-Holstein) and in specific disaster management plans on different levels. On the state level, the responsibility is broken down to regional administrative levels. In Schleswig-Holstein, the Chief Administrative Officer of the County is in charge of disaster management and takes over the command in case of a disaster in his county. If the emergency event occurs in more than one county, the Schleswig-Holstein State Ministry of the Interior becomes responsible and takes over the entire command of operations. On the local level, the fire

brigades play a major role in hazard control and therefore as well in disaster management. In the majority of Schleswig-Holstein's municipalities, firefighters work as volunteers, only the four major cities maintain a professional fire brigade. However, all local fire brigades have the legal status of a municipal authority, and so they are the main instrument of the mayor, who is in charge of local hazard control. So today the capacities for hazard control are much better than 1872, when the first volunteer fire brigades just had been founded (e.g., in Eckernförde in 1871).

In view of the lack of real events, responsible authorities together with local fire brigades and voluntary associations like the Red Cross conduct storm surge exercises to test their preparedness (availability of personnel, equipment, material and infrastructures) as well as to optimize disaster management plans and procedures. These plans provide for the successive actions taken with increasing predicted and observed storm water levels, from the establishment of a flood-monitoring center and an operational headquarters to emergency measures like placing sandbags or evacuation of endangered areas.

## 5 Discussion

### 5.1 Lessons learned

The 1872 storm surge with its catastrophic consequences was a turning point in coastal flood defense along the German Baltic Sea coast. Responsible administration reacted promptly with the establishment and issuing of design criteria for stronger sea embankments. At this time, when anthropogenic climate change and stronger sea level rise were not relevant, these criteria were certainly forward-looking and sustainable. The implementation of a buffer zone with natural dunes and/or beach ridges in front of the new embankments considered coastal erosion during storm surges. The flatter outer slope guaranteed optimal dissipation of incoming waves. Crest height and width considered both still water level and wave run up. A thick cover of clay prevented erosion of the outer and inner slopes by wave breaking resp. wave overtopping. Finally, as a non-technical flood risk measure to avoid damage expectations, Prussian policy already aimed at avoiding utilization of the forelands of the new embankments.

Already with the first measures, financial constraints resulted in deviations from the original design criteria. The local decision to erect the Probsteier embankment partly on top of an existing fortified beach ridge directly behind the beach (Figure 8b) mainly aimed at cost reduction (Runde 1883). In this respect, it is worthwhile to note that only 10 years after the catastrophe, the responsible local public construction officer stated that, due to the extenuated design, the newly erected embankment would probably not withstand the 1872 event (Runde 1883). The allocation of public financial means has, at least in part, to do with setting of political priorities and their changes through time. One month after the 1872 event, Prussian Government issued design criteria that would avoid a replication of the calamity. It was certainly realized that the application of these criteria imply huge efforts and costs, but the catastrophe was still visible and in the minds. The necessity (priority) of using private and public means for recovery was widely accepted. For example, Schleswig-Holstein civilians donated about 700,000 Taler in the months after the event as aid for needy people, 150 years ago an enormous amount of money (Kiecksee 1972). In 1874, only two years after the storm surge, concrete flood defense measures in Dahme started with

already extenuated design criteria. Less than three generations after the calamity, the foreland of the sea embankment was increasingly overbuilt with touristic facilities (Reher 1931). In Eckernförde, directly after the calamity, new commercial buildings arose along the “Jungfernstieg”, even at the seaward (eastern) side of the road. In the mid-1970s, the area converted into a residential area. Accordingly, damage expectations due to flooding and, thus, the flood risk increased. It may be discussed whether these examples are indicative for a general human aptitude to forget bad experiences and to ignore or suppress hazards, especially when an apparent possibility of creating income or other short-term benefits exists. According to Hallin et al. (2021), collective forgetting of disasters constitutes a threat with respect to robust flood risk assessment and sustainable urban planning. This pinpoints the relevance of raising awareness for coastal flood risks by the responsible authorities, especially in the light of men-induced strongly rising sea levels in future (IPCC in Press). It further emphasizes the need for restrictive spatial planning that avoids further increasing damage potentials in coastal lowlands.

From a coastal flood risk management perspective, it is of high relevance to realize that the under dimensioned embankment from 1869 may be one reason why people died in Dahme. Based on eyewitness accounts, Reher (1931) reports: *“people in Dahme relied on the new sea embankment, which brought the people no safety but harm. Without the embankment, the water would have come in steadily, giving the people time to react and bring themselves and their belongings into safety. Instead, after breaching of the embankment, the impounded waters swiftly expanded into the village and forced the people to flee on the lofts. Many of the frame houses collapsed under the massive hydraulic loads.”* In the unprotected city of Eckernförde, more damages to houses occurred than in Dahme but nobody died. Here, the rising waters more or less gradually inundated the city; giving the inhabitants the time to react that was missing in Dahme. Further, the inhabitants of Dahme seemingly over trusted their new embankment and were, thus, not adequately aware of the remaining flood hazard. This underlines the importance of appropriate risk awareness in the potentially affected population (see above) as well as the need for effective disaster management in protected areas; including flood warning and evacuation in time before breaching of the embankments occurs.

## 5.2 Integrated flood risk management in Dahme and Eckernförde

As described above, the flood protection status differs greatly between Dahme and Eckernförde. Hence, also the elements of the risk management cycle (Figure 11) each need a different emphasis.

### 5.2.1 Dahme

A state embankment protects Dahme from flooding through storm surges. According to the Schleswig-Holstein State Water Act, state embankments provide adequate protection against coastal flood. In consequence, the Schleswig-Holstein State Development Plan (MILIG 2021) does not provide for flood-related land use restrictions in coastal lowlands protected by state embankments. The plan only states that in these lowlands, local building plans should consider the interests of coastal flood defense. Building planning is in the responsibility of the municipalities. Hence, it seems realistic that in Dahme, where tourism constitutes the dominant economic factor, further development behind the embankment



will occur. The fact that it was not possible to relocate existing touristic infrastructure seaward of the embankment in the course of the last strengthening campaign, underpins this expectation.

According to the State Master Plan Coastal Flood and Erosion Management (MELUND in press), a coastal flood defense structure provides adequate protection if it can withstand a storm surge with a yearly probability of 0.005. This automatically implies that a residual hazard for breaching and flooding remains. As in the disaster of 1872, the people in Dahme feel safe behind the state embankment (which provides “adequate” protection). This may lead to an underestimation of the remaining hazard and underlines the need for constant risk communication in order to raise awareness of the flood risk. Implementing an effective risk communication strategy still poses a challenge for the state, county and municipal disaster management authorities, although well elaborated disaster management plans and appropriate local emergency provisions are available.

### 5.2.2 Eckernförde

Because Eckernförde has, in contrast to Dahme, no adequate protection against coastal flooding, the focus is more on prevention and preparedness. In not adequately protected lowlands, the Schleswig-Holstein State Water Act stipulates a general building ban. New developments in these areas are allowable only after implementation of appropriate measures to secure adequate protection. The State Master Plan Flood and Erosion Management (MELUND in press) defines respective measures like coastal raising the area. Accordingly, a local building plan in Eckernförde from 2017 specifies the minimum height for the ground floor in living rooms with 2.95 m and in commercial rooms with 2.45 m above NHN (Stadt Eckernförde 2017). Most buildings in the flood prone historical town center lie between 1.8 m and 2.5 m above NHN. As stated above, these buildings have a legal right of continuance. However, this right ends with the implementation of changes in use or structural alterations of the building. Strict implementation of the new regulations could impede the preservation of historic buildings and have a massive impact on local merchants, restaurants and other touristic infrastructures. For these reasons, the local building plan stipulates that exceptions are acceptable if individual measures like waterproof doors and windows, backflow flaps and/or protection of heating, ventilation and other relevant utilities provide adequate flood protection.

In order to enhance flood safety in the historical town center, the local parliament has adopted a coastal masterplan (PROKOM 2017), which comprises technical flood defense measures. Although economic efficiency, technical feasibility and ecological impacts needs consideration (Roggesack 2006), the aim is to achieve adequate flood safety for the city center. Finally, as in Dahme, there is the need to raise the awareness and preparedness of the inhabitants. The last critical flood event is probably too long ago to remain in the personal and common memories. However, some almost-critical floods in the last decade brought back this topic into the local public discussion, as newspaper articles show. To be prepared for the worst case, the town administration is preparing evacuation plans for the historical town center including information leaflets for the local residents. Further, the local public services have prepared an emergency power supply system (Stadt Eckernförde 2017).

## 6 Conclusions

Based on the descriptions and the discussion, the following conclusions are drawn:

- Along the Baltic Sea coast of Schleswig-Holstein, peak water levels of the 1872 storm surge probably varied among about NHN +2.4 and +3.4 m.
- The highest local wind speeds and waves occurred four to 10 hours earlier than peak water levels in Schleswig-Holstein.
- The unprecedented height of the 1872 storm surge in Schleswig-Holstein resulted from an external surge that propagated into the area from the central Baltic Sea region and piled up here on top of already prevailing very high storm surge water levels.
- The 1872 event was a singular event in Schleswig-Holstein, which makes it scientifically challenging to assess its probability of occurrence.
- Present-day coastal flood defense, spatial planning and disaster management, as cornerstones of public coastal flood risk management in Schleswig-Holstein, generally and in combination consider the lessons learned after the 1872 flood calamity.

In the light of intensifying utilizations, the need for ecological recovery and with regard to stronger rising sea levels in future, implementing sustainable coastal flood risk management remains a challenge.

## 7 Literature

Baensch, O.: Die Sturmfluth von 12./13. November 1872 an den Ostseeküsten des Preussischen Staates. In: *Zeitschrift für Bauwesen*, Ausgabe XXV, 155–220, 1875.

Bork, I.; Müller-Navarra, S. H.: Modellierung von extremen Sturmhochwassern an der deutschen Ostseeküste. In: *Die Küste*, 75, 71–130, 2009.

Bruss, G.; Jimenez, N.; Eiben, H.; Mayerle, R.: Bestimmung von Bemessungsparametern für Küstenschutzanlagen an der deutschen Ostseeküste aufbauend auf Szenariosimulationen. In: *Die Küste*, 75, 163–189, 2009.

Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (BBK): The Modular Warning System MoWas, [www.bbk.bund.de/EN/Topics/Crisis\\_management/Warning/MoWas/MoWas\\_node.html](http://www.bbk.bund.de/EN/Topics/Crisis_management/Warning/MoWas/MoWas_node.html), zuletzt geprüft am: 4.5.2021.

Eiben, H.: Schutz der Ostseeküste von Schleswig-Holstein. In: DVWK (Hg.): *Historischer Küstenschutz, Deichbau, Inselschutz und Binnenentwässerung an Nord- und Ostsee*. Verlag Konrad Wittwer, Stuttgart, 517–534, 1992.

European Union: Directive 2007/60/EC of the European Parliament and the Council of 23. October 2007 on the assessment and management of flood risks. In: *Official Journal of the European Union*, L 288, 27–34, 2007.

Fachplan Küstenschutz Ostseeküste. Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein, [www.schleswig-holstein.de/DE/Fachinhalte/K/kuestenschutz\\_fachplaene/Dossier/\\_functions/teaser\\_tabelle\\_Ostsee.html](http://www.schleswig-holstein.de/DE/Fachinhalte/K/kuestenschutz_fachplaene/Dossier/_functions/teaser_tabelle_Ostsee.html), zuletzt geprüft am: 18.12.2020.

Fredriksson, C.; Feldmann Eellend, B.; Larson, M.; Martinez, G.: The role of historical storm events in risk analysis - A study of the coastal flood events in 1872 and 1904 along

the south and east coast of Scania, Sweden. In: VATTEN – Journal of Water Management Research 73, 93–108, 2017.

Hallin, C.; Hofstede, J. L. A.; Martinez, G.; Jensen, J.; Baron, N.; Heimann, T.; Kroon, A.; Arns, A.; Almström, B.; Sørensen, P.; Larson, M.: A comparative study of the effects of the 1872 storm and coastal flood risk management in Denmark, Germany, and Sweden. In: Water, 13, 1697. <https://doi.org/10.3390/w13121697>, 2021.

Hofstede, J. L. A.: Küstenschutz im Küstenrisikomanagement. In: HANSA Int. Maritime Journal, Nr. 6, 103–105, 2007.

Hofstede, J. L. A.: Küstenschutz in Schleswig-Holstein – Trutz, Blanke Hans: Deichverstärkungen Brunsbüttel und Dahme-Rosenfelde. In: Bauen und Wirtschaft, Landesausgabe Schleswig-Holstein, 44–47, 2011a.

Hofstede, J. L. A.: Climate change and the need for integrated coastal risk management in the Baltic Sea. In: Schernewsky, G.; Hofstede, J. L. A.; Neumann, T. (Eds.): Global change and Baltic coastal zones. Coastal Research Library, Vol. 1, Springer, Dordrecht, 93–102, 2011b.

Hofstede, J. L. A.: On the feasibility of managed retreat in the Wadden Sea of Schleswig-Holstein. In: Journal of Coast Conservation, DOI 10.1007/s11852-019-00714-x, 2019.

IPCC: Summary for Policymakers. In: Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S. L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M. I.; Huang, M.; Leitzell, K.; Lonnoy, E.; Matthews, J. B. R.; Maycock, T. K.; Waterfield, T.; Yelekçi, O.; Yu, R.; Zhou, B. (Eds.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.

Jensen, J.: MUSTOK – Modellgestützte Untersuchungen zu extremen Sturmflutereignissen an der deutschen Ostseeküste: Eine Einführung. In: Die Küste, 75, 1–7, 2009

Jensen, J.; Habib, M.; Beckmann, S.: Best estimates for historical storm surge water level and MSL development at the Travemünde/Baltic Sea gauge over the last 1000 years. In: Die Küste, 92, 2022.

Kannenbergh, E. G.: Schutz und Entwässerung der Niederungsgebiete an der schleswig-holsteinischen Ostseeküste. In: Die Küste, 7, 47–106, 1958.

Kiecksee, H.: Die Ostseesturmflut 1872. Schriften des Deutschen Schiffahrtsmuseums Bremerhaven, Heft 2. Westholsteinische Verlagsanstalt Boyens & Co., Heide in Holstein, 1972.

MELUND: Generalplan Küstenschutz des Landes Schleswig-Holstein – Fortschreibung 2022. Ministerium für Energiewende, Landwirtschaft, Umwelt, Natur und Digitalisierung, Kiel, in Press.

MILIG: Landesentwicklungsplan Schleswig-Holstein – Fortschreibung 2021. Ministerium für Inneres, ländliche Räume, Integration und Gleichstellung, Kiel, 2021.

Mudersbach, C.; Jensen, J.: Extremwertstatistische Analyse von historischen, beobachteten und modellierten Wasserständen an der deutschen Ostseeküste. In: Die Küste, 75, 131–161, 2009.

PROKOM: Masterplan Eckernförder Bucht. Gutachten im Auftrag der Stadt Eckernförde (unveröffentlicht), 2017.

Reher, F.: Festschrift 50 Jahre Ostseebad Dahme. Ostholsteinische Zeitung, Neustadt in Holstein, 1931, [www.wirliedendahme.de/archiv/dokumente](http://www.wirliedendahme.de/archiv/dokumente), zuletzt geprüft am: 19.12.2020.

Rodloff, W.: Hydrologische Betrachtungen zur Ostseesturmflut vom 12./13. November 1872. In: Deutsche Gewässerkundliche Mitteilungen, 16/6, 153–159, 1972.

Roggesack, C.: Überlegungen zum Hochwasserschutz der Altstadt von Eckernförde. In: HANSA, 6, 75–78, 2006.

Rosenhagen, G.; Bork, I.: Rekonstruktion der Sturmflutwetterlage vom 13. November 1872. In: Die Küste, 75, 51–70, 2009.

Runde: Deichanlagen an der Ostsee in der Provinz Schleswig-Holstein. In: Zeitschrift des Archäologie- und Ingenieur-Vereins zu Hannover, Heft 6, 1883.

Schinkel, K. F.: Eckernförde – ein Spaziergang durch die Stadtgeschichte. Eckernförde 2001.

Stadt Eckernförde: Begründung zur 1. Änderung des Bebauungsplans Nr. 4/9 „Nördliche Altstadt, zugleich 6. Änderung des Bebauungsplanes Nr. 4 „Innenstadt“. Eckernförde 2017.

Van Herk, S.; Zevenbergen, C.; Gersonius, B.; Waals, H.; Kelder, E.: Process design and management for integrated flood risk management: exploring the multi-layer safety approach for Dordrecht, The Netherlands. In: Journal of Water and Climate Change, 05.1, 100–115, 2014.