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On the feasibility of managed retreat in the Wadden Sea of Schleswig-Holstein

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Abstract
Sea embankments along the mainland coastline in the Schleswig-Holstein Wadden Sea safeguard 130,000 people and 19 billion € of capital assets from flooding during storm surges. Due to climate change induced sea-level rise, these defences will become exposed to higher storm surges and adaptation becomes inevitable. As an alternative to strengthening, managed retreat is discussed in literature as a coastal risk management option for climate change adaptation. Based on an evaluation of examples from the Wadden Sea, this paper elaborates managed retreat as alternative climate change adaptation from a coastal risk management perspective. This paper concludes that, conform the principles of integrated coastal zone management, one precondition for successful implementation of managed retreat is local acceptance. With respect to natural resilience to sea-level rise, managed retreat may counteract the loss of Wadden Sea structures and habitats due to coastal squeeze. However, the effectiveness depends on the surface elevation in the opened polder. If large volumes of sediment are needed to restore a natural elevation, regional resilience against SLR-induced drowning may deteriorate. With respect to coastal flood risk management in Schleswig-Holstein, opened polders have no significance as flood retention rooms and managed retreat does not reduce the hazard of flooding in surrounding polders. Further, removal of primary embankments requires large efforts to secure flood safety in adjacent polders. Under certain conditions, removal or opening of embankments may constitute sustainable coastal risk management, e.g., if retreat leads to a shorter line of defence or if other win-win-situations like securing of NATURA 2000 coherence arise.

Keywords Wadden Sea · Schleswig-Holstein · Sea-level rise · Managed retreat · Coastal risk management · Climate change adaptation pathways

Abbreviations

CCA	Climate change adaptation
CRM	Coastal risk management
LKN.SH	Schleswig-Holstein State Agency for Coastal Flood Defence and Protection, the National Park and Marine Protection
MHW	Mean tidal high water level
SLR	Sea-level rise

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Introduction

In the Schleswig-Holstein sector of the Wadden Sea, more than 1000 years of land reclamation through embankments has led to the detachment of about 2400 km^2 of coastal marshes from marine influences (Fig. 1). Today, the mainland coastline is almost completely occupied by 190 km of primary embankments in the responsibility of the State. The 8 to 9.5 m high and up to 80 m broad embankments protect about 130,000 inhabitants and 19 billion € of capital assets in the reclaimed lowlands from flooding (MELUR 2013). Due to the long history of land reclamation, in many places, several embankments and polders exist behind each other; the oldest ones lying the farthest from the sea. In result, more than half of the coastal lowlands are protected by a so-called second embankment-line. These secondary (backward) embankments are regulated by the Schleswig-Holstein State Water Act and serve to limit the flooded areas in case of breaching of a

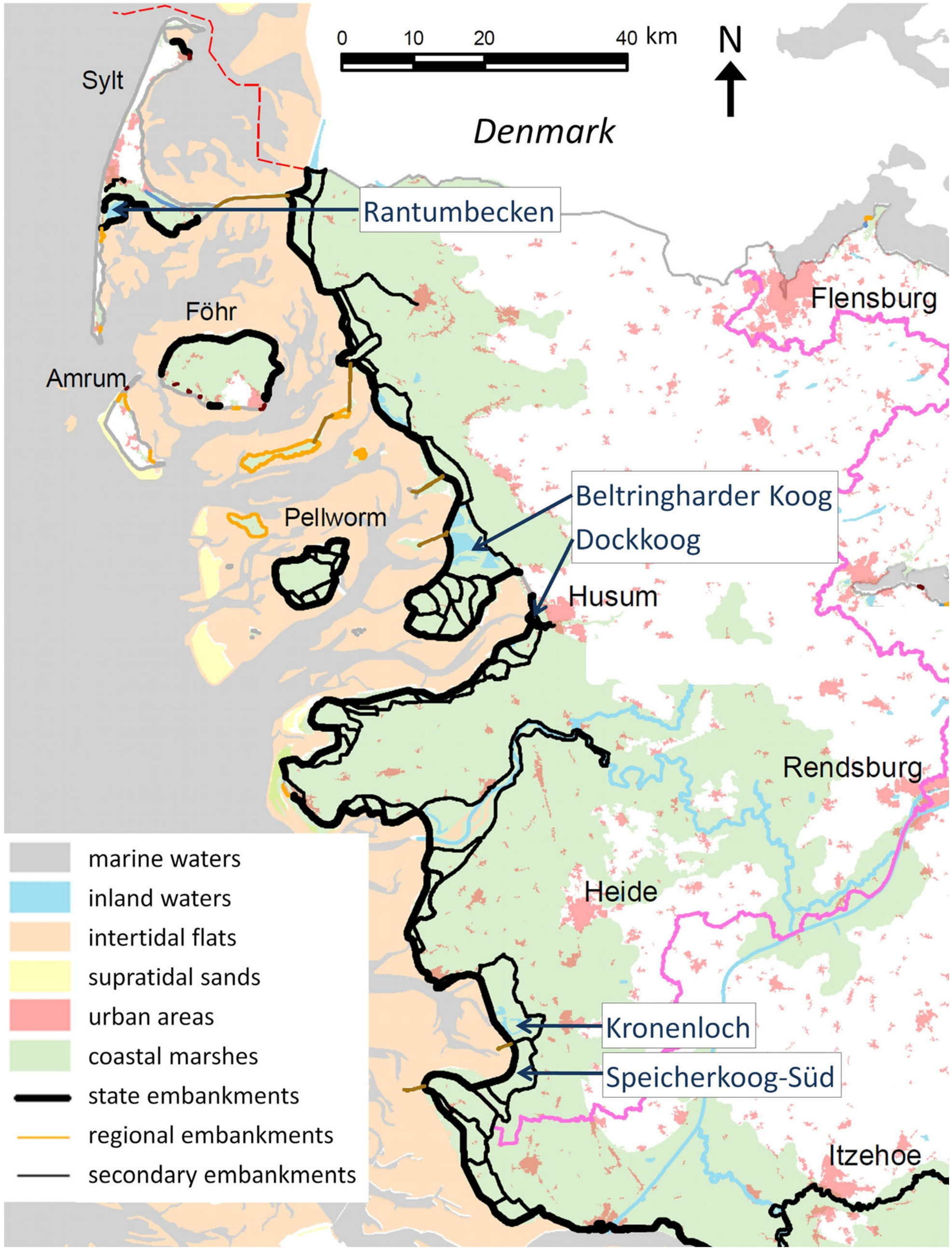

Fig. 1 Overview of the Wadden Sea region of Schleswig-Holstein (Germany)

primary embankment. As such, the so-called twin-dike concept (van Loon-Steensma et al. 2014, see below) has a long tradition in Schleswig-Holstein. Responsible for the second embankment-line are the embankment and water boards.

Schleswig-Holstein State Government adopted a first master plan coastal flood defence and coastal protection in 1963. Since then, this plan is updated every 10 to 15 years; the next (sixth) plan is scheduled for 2022. One key issue will be climate change adaptation (CCA). In its fifth assessment report, IPCC (2014) projects a global sea-level rise (SLR) among about 0.3 and 1.0 m for this century. Recent studies indicate that even stronger SLR may occur in future (e.g., Grinsted et al. 2015). Over the last century, SLR in the Wadden Sea amounted to about 0.16 m (Hofstede 2007, Wahl et al. 2011). Hence, a strong acceleration in SLR in the Wadden Sea in this century will occur and, correspondingly, storm surge water levels will increase significantly. Higher storm surges lead to stronger hydrological loads on embankments. In order to guarantee flood safety in the polders, more efforts become necessary to maintain and adapt these defences. If a sea embankment in Schleswig-Holstein needs strengthening, the actual geo-technical design already considers a SLR of about 2.0 m in up to three building phases (Fig. 2, see below). As a possible alternative to strengthening, managed retreat is discussed

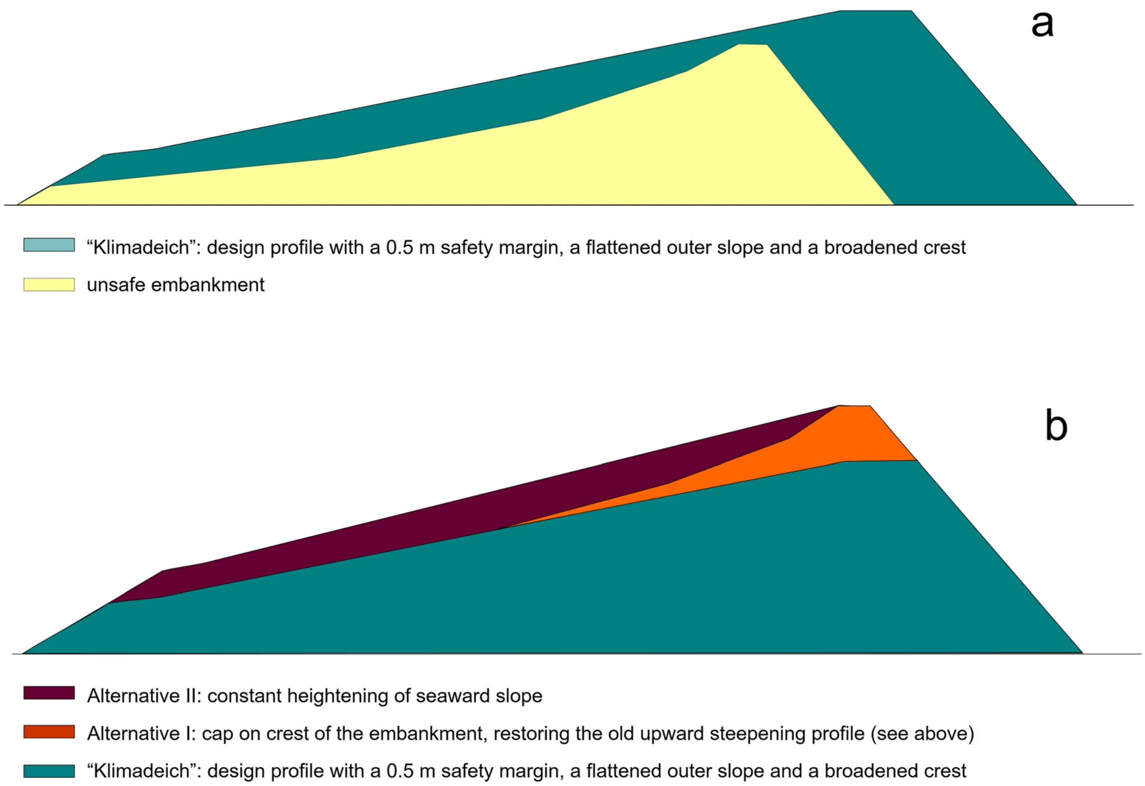

Fig. 2 Schleswig-Holsteins climate change adaptation pathway: "Klimadeich" for primary State embankments

as a sustainable CCA option (Temmerman et al. 2013, WWF Deutschland 2015). Apart from cost-effectiveness, it is argued that, by restoring the natural sedimentation processes, an increased resilience to SLR may be achieved. Further, nature-oriented tourism and recreation benefit from managed retreat. Reise (2015, 2017) argues that re-establishing sedimentation in polders by creating passages in embankments, i.e., letting the tide into the polder, may represent a sustainable form of CRM, in that alternative forms of living (with the sea) in the opened polders could be developed.

From a conservational point of view, it is clear that removing or opening embankments mitigates intertidal habitat loss resulting from coastal squeeze and from earlier embankments. Natural Wadden Sea processes (i.e., functions, structures and resources) in the opened polders are restored. In its present state, the Wadden Sea is one of the last remaining near-natural large-scale ecosystems in central Europe. One main criterion for the establishment of the UNESCO world natural heritage site Wadden Sea was the unique scale of unbroken intertidal sand and mud flats with its highly specialized habitats and flora and fauna (CWSS and World Heritage Nomination Project Group 2008). This outstanding ecological significance is, at least in the long-term, challenged by the impacts of accelerated SLR. If no countermeasures are undertaken, coastal squeeze and drowning of inter- and supratidal habitats are anticipated (CPSL 2001, Hofstede 2015, Hofstede and Stock 2016). Re-establishing Wadden Sea habitats along the mainland coastlines by managed retreat may thus be an appropriate ecological CCA measure.

Managed retreat by removing or opening embankments is a form of managed realignment. Managed realignment includes various methods of implementation like complete or in-part removal of embankments, controlled tidal restoration in polders by culverts as well as seaward realignment of defences and habitats like the so-called sand engine in the Netherlands (Stive et al. 2013). Most examples of managed retreat in tidal environments exist in the UK. Here, it is mainly seen as a viable concept to restore coastal habitats (Pethick 2002, ABPmer 2017), thereby mitigating the loss of intertidal habitats due to coastal squeeze (Morris, 2012). English Nature (1992) describes the concept of managed retreat as a cost-effective solution to the twin problems of biodiversity loss and coastal risk management (CRM). According to DEFRA (2004), removal or opening of embankments may present feasible CRM, if there is insufficient economic justification and/or no legal obligation (e.g., nature conservation) for continuing to maintain the defences. In Germany, coastal flood defence measures that are of public interest are stipulated and regulated in State laws, i.e., economic justification is not the only argument for decisions (Hofstede et al. 2009).

This paper elaborates pros and cons of different forms of managed retreat as an alternative CCA measure in the Schleswig-Holstein sector of the Wadden Sea region from a CRM perspective. The paper starts with a description of how

CCA is currently considered in CRM in Schleswig-Holstein. Next, some examples of managed retreat measures in the Wadden Sea are described and discussed. This paper ends with some conclusions.

Integrated coastal risk management and climate change adaptation

The concept of integrated CRM was formally introduced in the German Federal State of Schleswig-Holstein with the adoption of the fourth master plan coastal flood defence and coastal protection in 2000 (MLR 2001, Hofstede and Hamann 2002). In accordance with the principles of integrated coastal zone management; integrated CRM was defined as a continuous and dynamic planning process to protect human lives and assets from coastal flooding and erosion. It understands coastal flood defence and coastal protection as a spatial task on the land-sea interface (i.e., not only focussing on the technical line of defence like an embankment or a shoreline). Further, it integrates other interests in the coastal zone and actively involves the affected population in the planning process. Finally, it considers climate change, its consequences and the uncertainties inherent to the projections. Correspondingly, in the State master plan 2000, 10 goals and conditions for integrated CRM were included, one of them focussing on managed retreat (MLR 2001): "only as an exemption, the removal or abandonment of primary embankments may be possible." Probst (1998) stipulated three preconditions for possible exemptions:

- persistence of existing regional flood safety standards (including a second embankment-line),
- local acceptance of the measure, and
- cost-neutrality (or reduced costs) for CRM administration.

In response to the high uncertainties with respect to future SLR, Schleswig-Holstein adopted a staggered CCA pathway "Klimadeich" (climate-change-proof-embankments) for primary State embankments in its 2012 master plan (Fig. 2). Every 10 years, all primary State embankments are checked with respect to their safety. If a section fails to meet the prescribed safety criteria, strengthening becomes necessary. In the design of this strengthening, an extra safety margin of 0.5 m on top of the embankment-crest is included to account for future SLR. Further, the seaward slope becomes a constant flatter gradient of 1:10 (instead of the traditional upward steepening slope) and the width of the crest is enlarged from 2.5 to 5.0 m. If a revetment (rip-rap) is necessary at the tow of the embankment, the same safety margin as on the crest is added. With this new profile (Fig. 2a), a SLR of up to about 1.0 m can be balanced (0.5 m safety margin + about 0.5 m reduced wave run up due to the flatter seaward slope). When SLR approaches 1.0 m, in a second building phase, a cap can be installed on the embankment-crest with relatively little costs and efforts (Fig. 2b). A seaward profile with upwards steepening gradients is re-established and a total SLR of about 1.5 m can be balanced. If this is still insufficient, alternatively or as a third building phase, the complete seaward embankment-slope may be heightened (Fig. 2b).

With this staggered procedure or CCA pathway, a total SLR of approximately 2.0 m can be balanced. With respect to the carrying capacity of the subsoil, it is important that the design of the first building phase already consider the resulting total load after the third building phase. It should further be noted that this staggered procedure cannot invariably be repeated due to the limited width of the seaward slope. In addition, the revetment would increasingly protrude from the fronting tidal flats or salt marshes, leading to stronger hydraulic turbulences and erosion at and near the foot of the construction. Further, although the safety standard of the embankment can be maintained for a SLR of up to 2 m, it should be stated that, after breaching of the embankments, the water depths in the polders and, therewith, the damage expectations increase with rising sea levels.

Apart from SLR, possible future changes in tides and waves should be considered in the planning of embankment strengthening. In the Wadden Sea of Schleswig-Holstein, design storm wave run-up on the outer slopes of embankments may locally reach more than 3.5 m. Based upon a hydro-numerical modelling study with constant topography for the Schleswig-Holstein sector of the Wadden Sea, Arns et al. (2017) stated that, with SLR, shallow water wave dissipation decreases, resulting in waves with larger periods and greater amplitudes and, correspondingly, higher wave run-up on embankments. In their model, sea level driven changes in wave characteristics, and to a lesser extent, tides, amplified the resulting design heights by an average of 48–56%, relative to design changes caused by SLR alone. Becherer et al. (2017) performed a morphodynamical modelling study in the same area for different SLR scenarios. From this study, it appears that intertidal flats and salt marshes near the coast show strong accumulation tendencies in response to SLR. In consequence, the amplification in design heights hypothesized by Arns et al. (2017) based on a constant topography (increasing water depths) is probably significantly too high and needs concretisation by coupled hydro-morphodynamical modelling.

Managed retreat measures in the Wadden Sea

In the Wadden Sea region, a number of managed retreat initiatives exist. Some of them have been implemented; some are being planned whilst others have been aborted. In the following, examples of each category are described. Further examples for implemented managed retreat measures along the

Wadden Sea coast of Germany are Langwarder Groden and Wurster Küste (NPV 2016).

Langeoog summer polder (Lower-Saxony, Germany)

About 5.5 km of relatively lower embankments were erected in 1934/35 on the German barrier island Langeoog in order to protect cattle from flooding during summer (WWF Deutschland 2015, NPV 2016). This resulted in reduced flooding frequencies in the protected summer polder (< 25 times per year), lower sediment accumulation rates and changes in vegetation. In 2002/03, as compensation for the construction of a natural gas pipeline through the Wadden Sea and after a comprehensive public participation procedure, about 3 km of the summer embankment were removed and natural dynamics and development in a 218 ha large marsh area were restored (Fig. 3).

From a CRM point of view, the damage expectations in the former polder were low (i.e., a few livestock and an unpaved path to the eastern part of the island). The project was planned and conducted by the Lower-Saxony State Agency for Water Management, Coastal Protection and Nature Conservation. Due to the higher flooding frequency after removal of the summer embankment, the expected succession from higher to lower salt marsh vegetation started and accumulation of fine sediments increased (Barkowski et al. 2009). In the new pioneer zone, a maximal sedimentation rate of 19 mm per year was recorded in the first two years after the measure. In the higher marsh areas, mean accumulation amounted to 3.4 mm/y. In total, about 18,000 m^3 of sediments accumulated in the first two years (WWF Deutschland 2015). The strong increase in surface elevation (compared to the actual SLR of about 1.6 mm/y) will lead to a reduction in flooding frequency and accumulation rate until a new steady state among SLR and accretion is reached. The (re-)establishment of this steady state improves the natural resilience of the area to SLR. Restoration of natural processes is achieved. Before removal of the summer embankment, the unpaved path was elevated and fortified as road dam to avoid flooding of the northern section of the polder and as contingency route during storm floods. This was one prerequisite for achieving local acceptance, as the island had been flooded in this location during medieval storm floods. The new road is intensively used by bicyclists and hikers, i.e., turned into a touristic asset.

Twin-dike Ems-Dollart-estuary (Netherlands)

A safety check by the Dutch CRM authorities revealed that the primary embankment between Delfzijl and Eemshaven in the Dutch sector of the Wadden Sea is deficient and needs to be strengthened. As a pilot project, a double-embankment system (twin-dike) is being implemented along a part of this defence line (Kwakernaak and Lenselink 2015). Instead of strengthening the primary embankment, a 3 km long secondary embankment, consisting of clay, is being erected behind the primary embankment (Van Loon et al., 2015). The new polder between the primary and secondary sea defences will consist of an about 25 ha large southern and an about 33 ha large northern section. In the primary embankment, a culvert will be constructed to let tidal water into the southern polder. Here, it is intended that the suspended fines may settle and, after ripening, be used as raw material for varying purposes like strengthening of embankments or improvement of peaty soils in the hinterland. Today, clay for strengthening of embankments in the Dutch Wadden Sea is, at least partly, imported from Estonia, implying high carbon footprints and costs. A

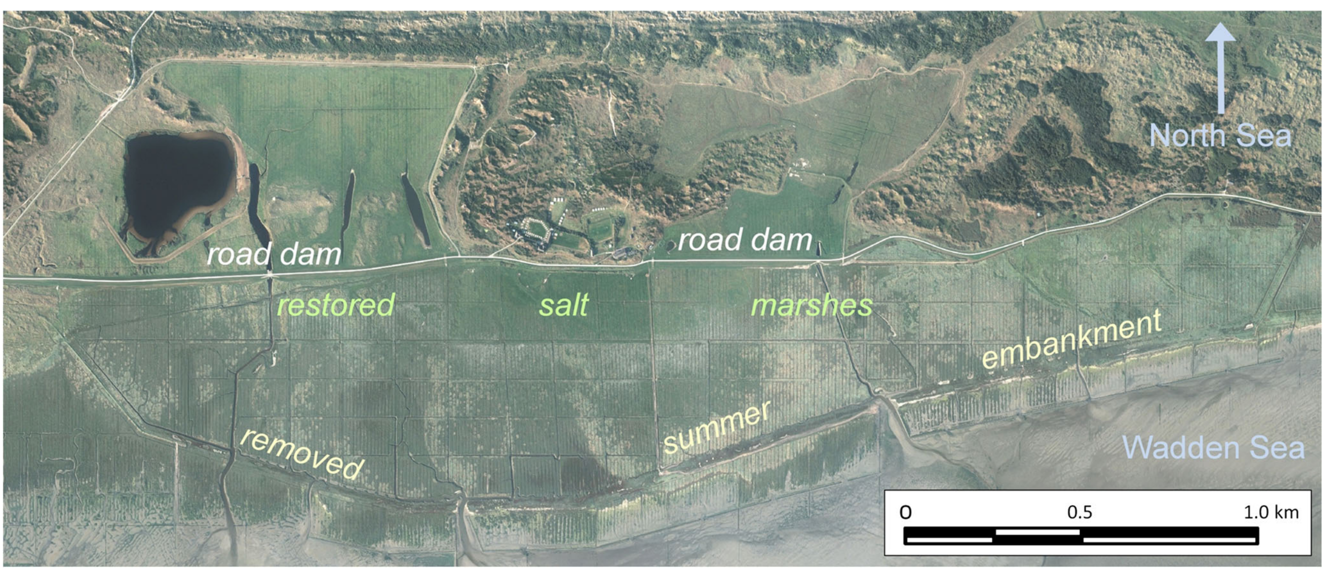

Fig. 3 Managed retreat scheme: "Langeoog Sommerdeich" (Langeoog, Lower-Saxony, Germany; © NLWKN / NLPV)

relatively high accretion rate of about 60 mm/y in the new polder is expected, which is caused by the (extremely) high silt concentration in the tidal waters and the relatively low surface elevation in the polder. It is stated, however, that accumulation will probably diminish with elapsing time and artificial ways of increasing the sediment content of the incoming tidal waters are considered. The northern polder section will be used to test marine and brackish aquacultures. Added ecological values are expected due to the increased (brackish) biodiversity in the southern polder section. Further, the overload of fine silts and, thus, the turbidity in the Ems-Dollart-estuary will be slightly reduced, thereby increasing primary production and ecological capacities of the ecosystem. The new polder was formerly used for agricultural purposes. Hence, as one main boundary condition, the land owners had to be won over this project, amongst others, by appropriate subsidies for "green" farming. From a CRM point of view, the combined defence system will secure national flood safety standards behind the double-embankment system. Further, the so called clay-engine may produce up to 7000 m^3 of clay per year for strengthening campaigns, which brings cost savings of about 88,000 €/y compared to traditional procurement costs (Kwakernaak and Lenselink 2015). It should be noted that this "extracted" material is no longer available for balancing stronger SLR in the Wadden Sea ecosystem.

Dockkoog Hallig-concept (Schleswig-Holstein, Germany)

A safety check by the Schleswig-Holstein CRM authorities revealed that the 2.3 km long primary embankment in front of the 78 ha large polder Dockkoog to the west of the city of Husum is deficient and needs to be strengthened (Fig. 1). Apart from a small hotel and a camping ground, no capital assets are present in the unpopulated polder. The polder is used extensively for grazing. A part of the city of Husum lies in an adjacent, backward situated polder. The southern stretch of the embankment co-functions as longitudinal embankment for the access channel to the harbour of Husum. Responsible for the primary embankment is the Schleswig-Holstein State Agency for coastal flood defence, coastal protection, national park and marine conservation (LKN.SH). Over the last decades and with support from the city of Husum, considerations about economic developments in the polder have been taking place. Touristic upgrading of the area is aimed for. Landward strengthening of the existing embankment as "Klimadeich" (Fig. 2) could interfere with the location of the envisaged touristic infrastructure. Strengthening to the seaward side would strongly interfere with nature. A secondary embankment exists behind the primary embankment, implying that the city of Husum is at least partly protected by a double-embankment system. As pilot project on integrated coastal zone management, WWF Germany initiated and coordinated an integrated planning process with the aim of ecologically sustainable CRM solutions that would meet the various social and economic needs in the region (WWF Deutschland 2016). Partners in the planning process were, amongst others, a local action group "Dockkoog", the city of Husum (partly as guest, see below), the regional chamber of industry and commerce as well as the LKN.SH. The project received comprehensive public and political attention as well as press coverage.

In 12 externally moderated meetings, the partners developed three so called preferred CRM alternatives; two classical approaches (strengthening of the primary embankment) and one managed retreat solution by removing the about 600 m long north-western section of the primary embankment and by strengthening of the secondary embankment (Fig. 4). The retreat solution incorporates a so-called "Hallig-concept", in that a dwelling mound with a new hotel would be erected at the western spit of the remaining (southern) section of the primary embankment. In the rest of the area, natural Wadden Sea processes with opportunities for careful nature recreation would be re-established. In the project group, there was general agreement that the three established CRM alternatives would secure socio-economic development perspectives as well as adequate flood safety for the city of Husum in times of climate change. Before the agreed project term was finished, parts of the city political representatives argued, though, that the retreat solution would lead to increased flood risks for Husum, amongst others by the partial loss of the so-called double embankment system. In other parts of the local population and in politics, there was a lively interest in the "Hallig-concept". In May 2016, the city board for environment and planning argued in favour of the two classical approaches. Since then, the city of Husum continued its participation in the WWF-project as guest (not as active partner). In May 2017, the board's recommendation that a classical strengthening of the primary embankment should be pursued by responsible State authorities was confirmed by a decision of the city council.

Beltringharder Koog salt-water biotope (Schleswig-Holstein, Germany)

The Beltringharder Koog is a 3345 ha large polder in the Schleswig-Holstein sector of the Wadden Sea (Fig. 1), established in 1987 by the construction of a 9 km long new primary State embankment in front of an existing embankment (Scherenberg und Saggau 1988, Fig. 5). Although it is clearly not a managed retreat (but a realignment) measure, it is considered here because about 860 ha of the new polder have been developed into a salt-water biotope as a compensation for nature losses. Via two tidal gates (Holmer Siel, Lüttmoor Siel) in the new embankment, salt water enters and leaves part of the polder during flood- resp. ebb-tidal phases. Thus, this

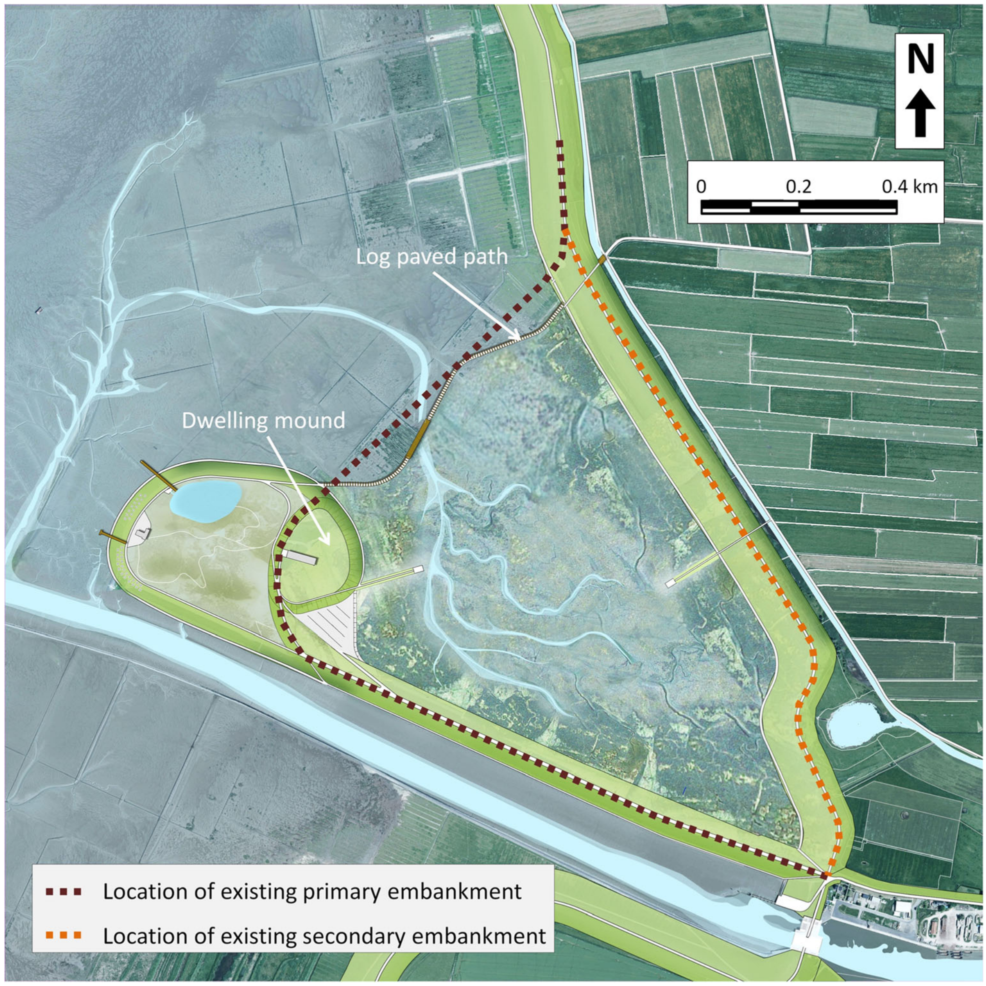

Fig. 4 Managed retreat concept: "Husumer Hallig" (Husum, Schleswig-Holstein, Germany. Source: WWF Deutschland (2016), studio urbane landschaften)

measure may be evaluated as an example of creating free passages in embankments, i.e., letting the tide into the polder (Reise 2015, 2017). The CRM measure was implemented in the 1980ies in order to:

1. shorten the line of defence from about 17 to 9 km (i.e., reducing the statistical hazard of breaching),
2. create a double embankment system by turning the existing primary into a secondary embankment,
3. improve the drainage of about 320 km2 coastal lowlands by creating storage basins in the new polder, and
4. reduce the structural erosion on the surrounding intertidal flats by reducing the tidal basin area (i.e., reducing tidal prism and tidal currents).

The reclaimed polder was originally intended to be used for agricultural purposes. With the measure, about 2450 ha of intertidal flats, 845 ha of salt marshes and 140 ha of tidal gullies were embanked, which caused intense and controversial discussions during the plan approval procedure. For example, about 3500 written objections were submitted, mainly by NGO's (Stadelmann 2008). As compromise, it was determined in the formally approved plan that the reclaimed area should become a nature reserve with fresh and salt-water biotopes. Also, the size of the reclaimed area became smaller as originally planned (3345 instead of ca. 5500 ha).

Water levels and discharges in the established 860 ha large salt-water biotope are regulated by two tidal gates with a total discharge cross-section of about 48 m^2. Maximum current velocities of 5.5 m/s have been recorded in the gates. The drainage storage basin (SP in Fig. 5) is separated from the salt-water biotope by a dam. In the salt-water biotope, a tidal range amounting to about 0.4 m (tidal prism 1.75 million m3) is strived for in the breeding season (Hagge et al. 1998), which is less than 15% of tidal range in the fronting Wadden Sea. During the rest of the year, depending on wind climate, tidal range may vary among 0.1 and 0.8 m (sluice custodian H. Krön, pers. comm.). In winter, with strong westerly winds, the complete biotope may remain inundated over several tides, reflecting natural storm surge conditions. About 380 ha of the salt-water biotope are permanently water covered, 170 ha are occupied by intertidal flats, 215 ha by salt marshes and about 95 ha by supratidal environments (artificially created bird

Fig. 5 Managed realignment scheme: "Beltringharder Koog" (Nordstrand, Schleswig-Holstein, Germany)

islands, Fig. 5). Ten years after construction of the embankment, all characteristic Wadden Sea animal species and vegetation types and distributions reappeared in the salt-water biotope (Hagge et al. 1998). Even common seals and, sporadically, harbour porpoises have been observed (H. Krön, pers. comm.). From a morphological or, rather, climate change resilience point of view, the question of sedimentation in the biotope is relevant. According to Hagge et al. (1998), some sedimentation has been observed in the biotope in the first ten years after construction. For example, two sediment extraction sites in the biotope, that were excavated for the construction of the embankment, silted up from originally 20 m to about 14–15 m of water depths between 1987 and 1996. Most of these very fine sediments probably originate from the Wadden Sea and were imported into the salt-water biotope by flood currents through the gates. Significant sedimentation on the intertidal flats in the inner part of the biotope could, on the other hand, not be observed. Internal sediment redistribution occurs during winter storms, e.g. the bird islands reduced in size due to shoreline erosion. As indication for the, in general, limited net-sedimentation in the biotope, only minor changes have occurred in sediment characteristics and morphological structures (Hagge et al. 1998). Further, there are no indications for a general shift in vegetation towards more brackish or fresh water types as could be expected with increasing surface heights. It must be mentioned, however, that there was no systematic monitoring after 1996. In the Schleswig-Holstein Wadden Sea, two further salt-water nature reserves behind primary State embankments with strongly reduced tides exist: Rantumbecken on the island of Sylt and Kronenloch in the rural district Dithmarschen (Fig. 1). These polders were embanked in 1938 resp. 1978; floodwater enters and leaves the biotopes through gates. As in Beltringharder Koog, there are no indications for significant sedimentation in these salt-water biotopes either.

Discussion

In the described examples, one critical success factor seems to be acceptance of the measure by the local inhabitants and their political representatives. The planned double-embankment system in the Ems-Dollart-estuary will guarantee national flood safety standards for the local population as well as possible new ways of subsistence (brackish "green" farming) for the landowners. Even though the installation of fresh and salt water nature reserves in the Beltringharder Koog was perceived as disadvantageous compared to agricultural uses in parts of the local population, the visible positive effects of the CRM measure (i.e., double-embankment security, optimized drainage of the hinterland) prevailed and resulted in general local acceptance. At Langeoog, local concerns about a possibly reduced flood safety due to the removal of a summer embankment turned into a win-win-situation by heightening and fortification of the unpaved path. For the Dockkoog-project, the perceived loss of coastal flood safety for the city of Husum was probably the main bottleneck. This perception resulted in deprecation of the managed retreat solution by some local politicians and (subsequently) parts of the local population. Thus, in recognition of a thousand year history of struggling with the sea, it is clear that CRM solutions that incorporate an increase in marine influences should not lead to the impression of reduced flood safety. In this respect, it is worth mentioning that the described polders are all unpopulated (and do not contain significant capital assets). The alternative of "living with the sea" by letting the tide into populated Wadden Sea polders (Reise 2017) seems, at least for the directly affected population and under the current political circumstances, not feasible if not the same level of safety can be guaranteed otherwise.

The examples show that, by removing embankments or letting the tide in through tidal gates or culverts, sedimentation in the opened polders is re-established. Whether the accumulation is sufficient to balance (accelerated) SLR mainly depends on the volume of tidal waters that flood the area and sediment concentration in the flood-tidal waters. In the Ems-Dollart-estuary, despite limited discharge cross-sections in the culverts, accumulation rates of up to 60 mm/y are anticipated. In the nearby and comparable Breebaartpolder, strong sediment import through culverts and siltation in the polder has been observed (Het Groninger Landschap 2013). These high accumulation values, however, are the result of excessive mud contents of the tidal waters in the Ems-Dollart-Estuary. In the Beltringharder Koog, Rantumbecken and Kronenloch salt water biotopes, no signs of significant sedimentation that could balance (stronger) SLR has been observed (geodetic surveys have not been carried out though). On Langeoog, finally, a height-dependant significant increase in accumulation rates was observed in the first years after the removal of the summer embankment. From the examples it can be deduced that, under normal conditions, a real opening of a polder by removing (parts of) the primary embankment seems most suitable to reach an adequate increase in accumulation and, thus, a higher geomorphological resilience of the restored natural area.

As natural sedimentation terminates after land-reclamation, surface elevation in polders is normally lower than in the fronting tidal areas and sediment is imported to restore a natural (equilibrium) surface elevation. Managed retreat thus normally induces a sediment deficit in the surrounding Wadden Sea area. For example, mean surface elevation in the (small) Dockkoog polder amounts to about NHN +0.9 m, whereas local mean tidal high water level (MHW) is in the order of NHN +1.7 m. In order to regain a more natural surface elevation (on average slightly below MHW), it can be estimated that accumulation of about 0.5 million m^3 of sediment would be needed. The larger and older the polder, the more sediment becomes necessary. For example, opening of the about 1900 ha large unpopulated Speicherkoog-Süd polder in the rural district Dithmarschen (Fig. 1) would induce a sediment hunger of up to five million m^3. This would exacerbate the expected SLR-induced sediment deficit in the Wadden Sea (Hofstede and Stock 2016). Hence, although restoration of natural processes in the opened polder effectively compensates the loss of habitats by coastal squeeze, the natural resilience of the ecosystem against SLR-induced drowning of intertidal flats and salt marshes may diminish (Hofstede 2015, Hofstede and Stock 2016).

Opened coastal polders have, in contrast to opened polders along rivers, no significance as flood retention room. Along rivers, flood retention rooms function as (temporary) storage basins for floodwater volumes, thereby reducing the flood heights downstream. For hydraulic reasons, opening of a coastal polder would only lead to an equivalent net-increase in surge water volumes in the Wadden Sea. In this case, the North Sea would function as an endless source for floodwater. Reduction of storm surge water levels in the vicinity would be negligible. As such, managed retreat does not reduce the hazard of breaching and flooding in surrounding polders.

Temmerman et al. (2013) argue that storm surges attenuate in coastal marshes due to bottom friction. Thus, managed retreat that leads to broader marshes in front of the mainland has the potential to reduce surge heights and thus the hydraulic loads on backward sea defences. They report surge attenuation rates of 0.05 to 0.1 m per km marshland in the Mississippi region. Based on modelling studies, Wamsley et al. (2010) give a range of attenuation rates among 0.02 and 0.17 m per km, depending on the surrounding coastal landscape and the strength and duration of the relevant forcing. From these values, it becomes clear that a strong landward retreat in the order of several km is required to reduce storm surge heights significantly. For a densely populated area like the Wadden Sea region, this seems unrealistic. Further, surge attenuation only occurs on vegetated marshes with high frictional resistance. In the Wadden Sea with its large bare sand flats (low frictional resistance), surge heights normally increase from the North Sea towards the mainland coast. Hence, only if salt marshes occupy the opened polder, surge attenuation may prevail. This, however, would imply accumulation of large volumes of sediment in the opened polders (see above). Temmerman et al. (2013) further argue that coastal marshes dissipate storm wave energy, which they interpret as another potential CRM functionality of managed retreat. In the shallow Wadden Sea, storm waves are predominantly of local origin and their heights show a strong positive correlation with water depths (Siefert 1974, Niemeyer 1983). Thus, as surface elevation in opened polders is lower than in the fronting tidal area, managed retreat by completely removing primary embankments does not lead to reduced wave loads on the backward embankments. In contrast, it may even lead to increased wave heights and loads. If the primary embankment is only dismantled over a short section, however, the remaining parts can still function as wave breaker. A significant reduction in storm wave energy would still occur and the necessary height of the backward embankments could be significantly lower. The single line of defence would evolve into a staggered defence zone.

The statistical hazard of breaching during storm surges relates positively to the length of an embankment. Removal of a primary embankment in the Schleswig-Holstein sector of the Wadden Sea normally results in a significant increase in the line of defence (i.e., backward embankment length) and, thus, in the statistical hazards of breaching and flooding. In the example of Speicherkoog-Süd (Fig. 1), the embankment length that would directly face the sea after managed retreat would more than double. Further, the secondary embankments that are reconverted into primary defences normally need significant strengthening in order to meet the safety standards of modern primary embankments (unless a staggered defence zone is being implemented, see above). Temmerman et al. (2013) did not consider these critical CRM-factors. Finally, as partly the case in Dockkoog, a second line of defence may be lost (Probst 1998). These considerations indicate that a complete removal of embankments is, from a CRM point of view, highly problematic and may only be justified in exceptional circumstances. In the Dockkoog (peninsula) case, as a positive example, the primary embankment has a length of 2.3 km, whereas the secondary embankment is 1.6 km long (Fig. 4). For this reason, the LKN.SH as competent CRM authority did not reject the managed retreat alternative. Another benefit (win-win-situation) of managed retreat in the Dockkoog case would have been that the restored natural area could have secured coherence for this and other CRM measures according to NATURA 2000 regulations.

Conclusions

Based on the described examples and the discussion, the following conclusions about the feasibility of managed retreat in the Schleswig-Holstein sector of the Wadden Sea are formulated:

- In accordance with the principles of integrated coastal zone management; one main precondition for successful implementation of managed retreat is local acceptance. In this respect, CRM solutions that incorporate an increase in marine influences should not lead to the impression of reduced flood safety.
- With respect to natural resilience to stronger SLR:
- managed retreat counteracts the loss of Wadden Sea structures and habitats due to coastal squeeze and earlier embankments,
- only the removal of (parts of) a primary embankment may lead to significant accumulation in the restored natural area, and
- the effectiveness of the removal depends on the surface elevation in the area. If large volumes of sediment are needed to restore a natural elevation, regional resilience against SLR-induced drowning may deteriorate.
- With respect to CRM:
- opened coastal polders have no significance as flood retention rooms and, thus, managed retreat does not reduce the hazard of breaching and flooding in surrounding polders,
- in opened polders, attenuation of storm surges and waves does not occur and, thus, hydraulic loads on the backward embankments during storm surges are not lower than on the (former) primary embankments,
- depending on the length of the section, removal of primary embankments requires extra efforts to secure flood safety standards in the backward and adjacent polders,
- removal of primary embankments normally results in a longer line of defence (backward embankments) and, thus, to higher statistical hazards of breaching and flooding, and
- under certain conditions, removal or opening of embankments may constitute sustainable CRM in the Schleswig-Holstein sector of the Wadden Sea, e.g., if the retreat leads to a shorter line of defence, or if other win-win-situations like securing of NATURA 2000 coherence arise.

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