communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-023-01100-0 OPEN

Raising dikes and managed realignment may be insufficient for maintaining current flood risk along the German Baltic Sea coast

Joshua Kiesel[1,2✉], Lars E. Honsel[1,3], Marvin Lorenz[4], Ulf Gräwe[4] & Athanasios T. Vafeidis[1]

Without upgrading existing adaptation, Germany is projected to be among those European countries that will suffer severe flood damages in 2100. Here we use a validated modeling framework to explore the effectiveness of two hypothetical upgrades to existing dike lines in reducing flood extent and population exposure along the German Baltic Sea coast. We perform a number of model runs where we increase the heights of existing dikes by 1.5 m, implement managed realignment as a nature-based solution, where physically plausible, and run a 200-year surge under two sea-level rise scenarios (1 and 1.5 m). We show that managed realignment is more effective in reducing future population exposure to coastal flooding compared to increasing dike heights. However, the maximum reduction in population exposure compared to a do-nothing approach amounts to only 26%, suggesting that even managed realignment is insufficient to maintain flood risk at today´s levels. The greatest potential for protecting people and property from future flooding lies in developing adaptation strategies for currently unprotected coastal sections.

[1] Department of Geography, Kiel University, 24118 Kiel, Germany. [2] Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, 1081 HV Amsterdam, The Netherlands. [3] Global Climate Forum (GCF), 10178 Berlin, Germany. [4] Leibniz Institute for Baltic Sea Research Warnemünde, 18119 Rostock, Germany. ✉email: j.kiesel@vu.nl

Across Europe, the North- and the Baltic Sea are projected to experience the highest increase in extreme sea levels (ESL) until the end of the century, primarily due to relative sea-level rise (SLR)[1]. This has serious implications for coastal flooding and adaptation planning as, without upgrading adaptation in Europe, the population exposed to coastal flooding annually is expected to increase from 102,000 to between 1.52 and 3.65 million by 2100 and projected annual flood damages are expected to increase by two to three orders of magnitude[2]. This is particularly true for Germany, which, without adjusted adaptation, may be among those European countries that will suffer the largest absolute flood damages in 2100[3].

Studies have shown that protecting people and assets from coastal flooding is more economically beneficial than the expected costs of flood damages without adaptation[3,4]. However, effective adaptation, including maintenance and upgrading of existing coastal protection systems, requires extensive knowledge on how risk varies spatially along the coast. Understanding and managing risk requires detailed inundation maps that consider information such as friction induced by various land cover types, the temporal evolution of storm surges, and coastal protection measures such as dikes.

Recent advances in coastal flood mapping involve reduced-form hydrodynamic models that allow simulations at local to continental scales[5–9]. These models can provide improved estimates of flood characteristics compared to the simpler bathtub approach that has been extensively used in the past[6–8]. This is due to the fact that these models consider the temporal evolution (e.g. duration and intensity) of storm surges as well as the effects of drag exerted by variably "rough" land cover types (e.g. forest as opposed to concrete). In addition, state-of-the-art hydrodynamic models are able to capture biogeomorphic feedbacks between coastal vegetation, shallow-water bathymetry and water flows on local scales[10–12]. However, at regional to continental scales, the combination of limited computational capacity and coarser data resolution or lack of data makes it difficult to predict the response of shallow-water bathymetry to long-term trends in mean sea level or wave dynamics[6]. Broad-scale studies have therefore neglected future shoreline morphodynamics when simulating exposure to sea-level rise[6,13,14]. It is important to note that regional scale field observations and local scale hydrodynamic modeling have demonstrated the importance of nearshore bathymetry and topography for coastal peak water levels and flooding[15,16]. Thus, disregarding these processes can introduce bias in broad-scale flood simulations[17]. Given the challenges in projecting shallow-water bathymetry across extensive spatio-temporal scales outlined above, we have disregarded this aspect in our study.

The calibration and validation of hydrodynamic models remain a major concern, as information on flooding characteristics is difficult to obtain in the field during an event. Satellite data could help address this limitation but they can only provide a snapshot of the flooding during the passage of the satellite[18–20]. Other problems include the fact that high-quality elevation data are seldom available and that coastal protection structures are often not represented in the elevation data due to coarse resolutions[21,22]. Studies on local scales can implement information on coastal protection structures on a subgrid level using high-resolution topographic data sources[7,23]. On the other hand, broad scale assessments must rely on global datasets as consistent high-resolution data on large spatial scales are mostly non existent[24]. An example of a global dataset is the FLOPROS database[25], which provides information on generalized adaptation standards along the full length of the global coastline.

Yet, the incorporation of detailed and spatially explicit information on coastal protection infrastructure is one of the main sources of uncertainty in large scale simulations of coastal flooding[17,24]. While FLOPROS constitutes an important step towards the consistent incorporation of protection standards on continental or global scale for flood modeling, it fails to accurately represent the spatially highly variable protection standards of dikes along the German Baltic Sea coast. For instance, approximately one third of the German Baltic Sea coast is protected by dikes[26]. While the protection standard given in FLOPROS equals the 100-year return water level for the whole region, state authority data indicate that protection standards are varying between below the 5-year and up to the 200-year return water level, the latter including a provision for SLR[27,28]. Therefore, studies that have used FLOPROS for coastal flood modeling[3,6] are likely to over- or underestimate flood extents and the affected population along the German Baltic Sea coast. Using hydrodynamic modeling and the FLOPROS database to incorporate coastal protection measures, Vousdoukas et al., (2020)[3] estimated that Germany requires dike height increases up to 1.38 m in a high-emissions scenario to protect their coastal communities. State authorities in Germany have already planned for dike height increases (and new dike constructions[29]) along the German Baltic Sea coast and have introduced the climate dike concept, which involves dikes with a wider base that allow for increases of up to 1.5 m in height[28]. This increase, however, is currently only intended for dikes in the responsibility of the state (state dikes), while regional dikes are taken care of by water and soil associations and are characterized by variable and lower protection standards[27,28]. Along the German Baltic Sea coast, 57% (438 km) of the total dike length corresponds to regional dikes, while 43% (326 km) are state dikes (calculated based on state authority dike data listed in Kiesel et al., 2023[23]).

The conventional type of hard coastal protection poses several environmental problems, such as land subsidence and coastal squeeze[30]. The latter refers to the loss of coastal wetlands in front of sea defenses due to SLR[31]. In contrast, summer dikes are designed to allow overflow during high tides or storm surges, thus enabling the preservation of upper saltmarsh vegetation behind them[32]. The raising of the regional or the summer dikes across the country implies that along many coastal stretches, the shoreline may become disconnected from the hinterland[3]. This would lead to an increased loss of coastal wetlands fostering subsiding hinterlands[30,33,34], and higher dike maintenance costs[35,36]. The presence of a vegetated foreshore reduces wave loads on dikes and thus influences the likelihood of dike breaching due to wave overtopping[35]. The coastal protection function of wetlands such as salt marshes, even under storm surge conditions, has been shown for various environmental settings, including natural and restored habitats as well as locations at the open coast and along estuaries[37–43]. Therefore, nature-based solutions for improving and complementing conventional coastal protection and adapting to SLR have received increased scientific attention in recent years[30,44,45].

Managed Realignment (MR) is an example of a nature-based solution that aims to restore coastal ecosystems, such as salt marshes, on formerly reclaimed land. MR involves breaching or removing seaward dikes and constructing new dike lines further inland[46,47]. Thus, MR constitutes a hybrid approach taking advantage of the wave and surge attenuation function of (restored) coastal vegetation, while still relying on dikes that ultimately prevent flooding of adjacent low-lying lands[44,45]. The effectiveness of MR with respect to coastal protection under a range of hydrodynamic forcings and environmental settings is yet to be explored, which arguably constitutes one of the reasons why the large-scale implementation of MR is still hampered[45,48]. Yet, in the German federal state of Mecklenburg-Western Pomerania (MP), 24 MR schemes have already been implemented covering an area of 5,790 ha[49]. While previous work in MP has suggested a strong additional potential for more MR sites along outer coastal sections (excluding the lagoon areas)[50], the full potential across both German federal states with Baltic Sea coastlines remains uncertain. This uncertainty is particularly true for the low-lying lagoon system of MP and includes lacking information and concepts to identify spatially explicit boundaries for MR.

Here we explore the effectiveness of a hypothetical large-scale implementation of MR and dike height increases along the German Baltic Sea coast in reducing flood extent and exposed population for a 200-year storm-surge event and two scenarios of the same event with 1 and 1.5 m of SLR. In this study, we use the term "exposure" as defined by the IPCC[51], which, for instance, encompasses infrastructure and population potentially affected by flooding. Consequently, we consistently use the terms "exposure" and "potentially affected" throughout the manuscript. In this study, we first identify potential areas and perimeters for MR sites along the German Baltic Sea coast using a fully automated detection approach. Second, we integrate MR and dike height increases into a hydrodynamic modeling framework covering the German Baltic Sea[23]. The applied modeling framework does not account for morphological responses to rising water levels, such as the potential of dune collapse, dike breaching and changes in nearshore morphology and bathymetry.

We develop an automated detection approach to identify the physically plausible potential for MR along the German Baltic coast, based on the extent of built-up areas, existing infrastructure, and elevation. Further, we use a new modeling framework for the study region to simulate coastal flooding along the German Baltic Sea coast (see Kiesel et al., 2023)[23]. The modeling framework consists of two offline-coupled hydrodynamic models: a coastal ocean model (200 m resolution) and a coastal inundation model (50 m resolution). We use extreme value analysis to extrapolate 200-year events for 32 stations along the German Baltic Sea coast and additionally model two SLR scenarios (1 and 1.5 m). The two SLR scenarios correspond to the regional-scale medium-confidence projections of the Shared Socio-economic Pathway (SSP) scenario SSP5-8.5 (between the 50th and 83rd percentiles) of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) for the tide gauges in Lübeck-Travemünde and Wismar[23,52]. The modeling framework addresses existing uncertainties around the incorporation of dikes in the study region, accounts for the temporal evolution of the surge, and includes the effects of surface roughness on flood propagation. All components of the modeling framework, including the coastal ocean model, the coastal inundation model, the extreme value analysis, and the incorporation of dikes in the region, have been validated. The methods are described in detail in Section 5.

We use the modeling framework to run the following three adaptation scenarios for the 200-year event and the two SLR scenarios mentioned above: 1) we increase the height of all dikes in the study region by 1.5 m; 2) we only increase the height of state dikes by 1.5 m; 3) we implement MR in identified potential locations and increase the height of state dikes by 1.5 m.

We find that MR constitutes the most effective adaptation measure to reduce the population potentially affected by a 200-year event, under 1 and 1.5 m of SLR. Specifically, MR reduces affected population by 26% for both SLR-scenarios, while increasing all dikes by 1.5 m reduces affected population by 21%. The least effective measure is increasing only state embankments by 1.5 m, which reduces affected population by 17% and 11% for 1 and 1.5 m SLR, respectively. In contrast, differences in maximum flood depth in populated areas are negligible among all tested adaptation options. We conclude that redesigning existing coastal protection by dike height increases or MR is insufficient to maintain current flood risk along the German Baltic Sea coast. Our results indicate that under the employed SLR scenarios, most of the exposed population in the future will be located in regions currently not protected by the existing dike lines, which needs to be considered when planning future coastal adaptation.

Results

The potential for managed realignment along the German Baltic Sea coast. The German Baltic Sea coast has a total length of 2538 km (based on the coastline used in van der Pol et al., (2021)[53] and consists of the federal states of Schleswig-Holstein (SH) and Mecklenburg-Western Pomerania (MP) (Fig. 1). Across both federal states, we find a high potential for implementing MR. Our results show that the physically plausible potential area for MR amounts to 60,750.42 ha, whereas the largest part (77%) of this area lies in MP (Table 1, Fig. 1). Based on our MR detection approach, we find that 87% of the German Baltic Sea dike line has the potential to be realigned. 58% of the dikes that fall inside the detected potential MR sites are regional dikes, while 42% are state dikes. In MP, only 12% of the full MR potential as identified in this study are currently exploited (compare La Vega-Leinert et al., 2023[49]).

The land use in the potential MR areas is predominantly agricultural, as 31% of the total area is classified as farmland. Other main land use types include meadows (25%), forests (14%), nature reserves (8%), and to a lesser extent grassland (4%) (Fig. 2) and scrubs (2%). 16% of the land within the potential MR sites is unclassified (i.e. no land use class found in Open Street Map). Land use areas with a share smaller than 1% are commercial (0.01%), farmyards (0.01%), heath lands (0.26%), orchards (0.01%), parks (0.01%), and residential (0.03%) (Table S1 in the supplementary material). The low proportion (less than 1%) of residential and commercial areas within the potential MR sites indicates that the detection approach by excluding built up areas is robust.

We find differences in the share of land uses between both federal states. While farmland is the dominant land use inside potential MR areas in SH (44%), the percentage of farmland in MP is lower and equal to meadows (both 27%). On the other hand, forests make up a larger share in MP (17%) compared to SH (5%) and nature reserves hold a larger share of potential MR areas in SH (14%) compared to MP (6%).

Flood extent and exposed population under dike height increases and managed realignment. Our results show that improvements to existing dike lines are insufficient for effectively reducing flood extent and exposed population along the German Baltic Sea coast. For instance, the flood extent along the German Baltic Sea coast caused by a storm surge event with a return water level of 200 years (without SLR and without increasing dike heights) amounts to 217 km^2 [23]. For a 200-year event in the case of 1.5 m SLR, and if all dikes are raised by the same amount, the floodplain increases almost fourfold (Fig. 3). An efficient reduction in flood extent or population exposure cannot be achieved by increasing dike heights or by implementing MR on a large scale. However, among the tested adaptation options (raising the height of all dikes by 1.5 m, raising only state dikes by 1.5 m and implementing MR wherever physically plausible including raising state dikes by 1.5 m), MR is the most effective measure to reduce the exposed population (Fig. 3c, d) and the most effective in reducing the flood extent of a 200-year event under a SLR of 1.5 m (Fig. 3a, b). The smaller inundation area in the case of MR is particularly noteworthy because the large-scale opening of dikes in the context of MR deliberately exposes a substantially

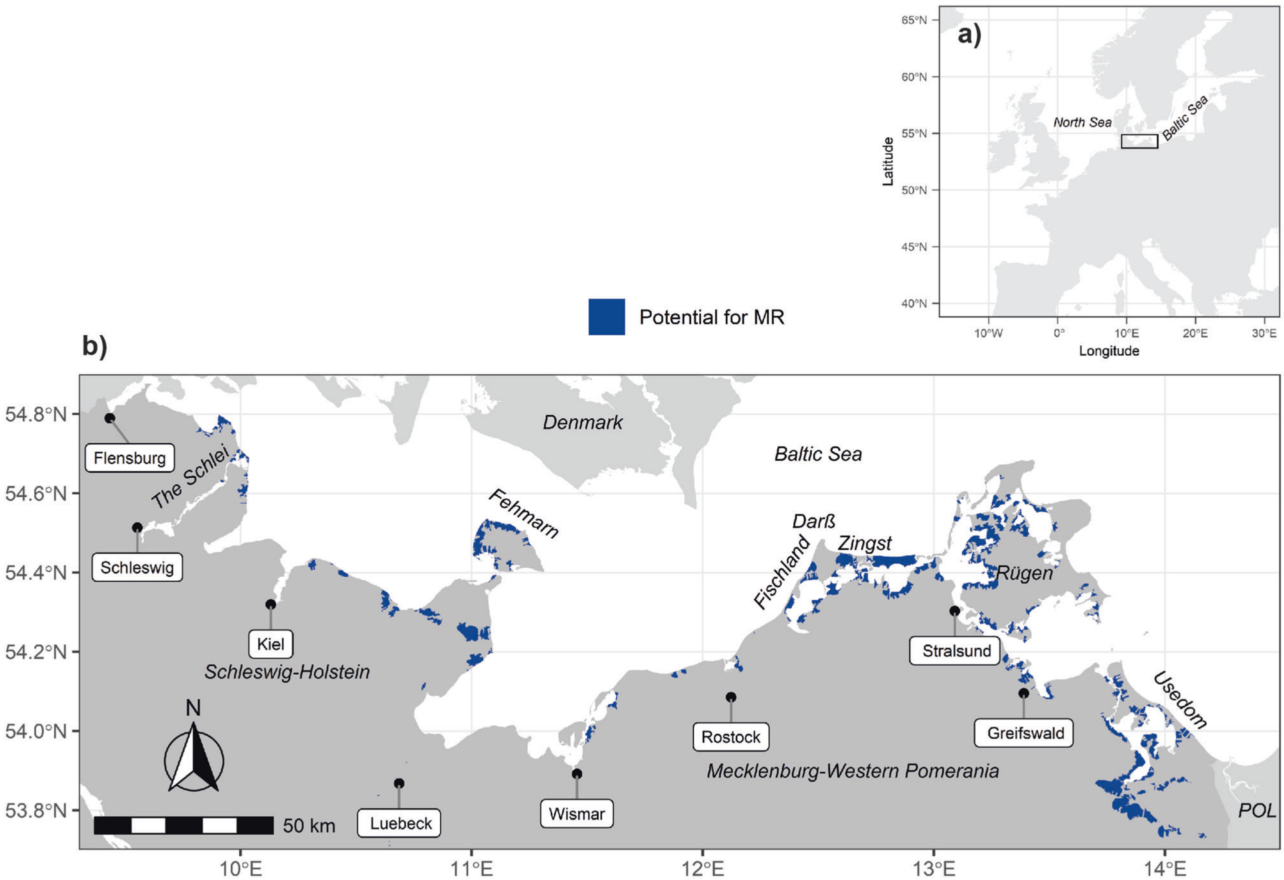

Fig. 1 Study area and potential MR sites across the German Baltic Sea coast. a Location of the study region in Europe. **b** Overview of the German Baltic Sea coast and physically plausible locations for managed realignment (MR).

Table 1 The potential for MR along the German Baltic Sea coast.

	total area (ha)	max area (ha)	min area (ha)	mean area (ha)	count
MP	46,850.39	3,267.83	1	323.11	145
SH	13,900.04	2,041.22	1.17	257.41	54
Total	60,750.42	3,267.83	1	305.28	199

larger area to inundation than envisaged by conventional coastal protection.

We find that flood extent and potentially affected population depend more on the SLR-scenario than on the selected adaptation measure. For instance, the population affected by an extreme sea level (ESL) of a 200-year event plus 1.5 m SLR under the most effective adaptation scenario (i.e. MR) (Fig. 3c) is 43% higher compared to the 1 m SLR and no improved adaptation (status quo) scenario.

The reason for the relatively low effectiveness of all tested adaptation options to reduce the inundation area lies more in the length and position of the dikes than in the dike height. The inundation maps show that the water does not overflow the dikes but rather bypasses them (Fig. 4b) or floods low-lying areas of the coast that are not currently protected by dikes (Fig. 4b, c, d, e; see also Supplementary Figs. S1–S3 for full-page maps showing the flood extents for each adaptation scenario).

Our results further indicate that the coastal protection function of MR is realized through the new, longer dike lines rather than by the restored shallow-water habitats. Under an ESL of the 200-year event plus 1.5 m, water floods most potential MR sites and is often stopped at the new, landward dike line (Fig. 4c, e). In addition, the increased flow resistance caused by the (re)created shallow-water habitats does not result in lower inundation depths. For the 1 m and the 1.5 m SLR scenario, maximum inundation depths are highest for the large-scale implementation of MR (Table 2). However, this is not the case when comparing maximum flood depths throughout the model domain in areas (cells) where people are living. The latter reveals that differences in flood depths between adaptation scenarios amount to a maximum of only 5 cm (Table 2).

Discussion

The limited effectiveness of raising dikes demonstrates the need for protecting currently unprotected coastal sections. We find that upgrading existing dikes by increasing their heights or MR may be insufficient to maintain current flood risk levels. This finding is not in agreement with the findings of previous global- and continental-scale studies. Here we show that water does not overflow dikes but bypasses them or floods unprotected areas (Fig. 4b, c, d, e and Figs. S1–S3 in Supplementary Material). On the other hand, global or continental-scale studies consistently demonstrate the effectiveness of raising dike heights in reducing population exposure and expected annual damages[3,4,54]. However, due to their scale, these studies address adaptation in a more stylized way, for instance by assuming uniform coastal protection standards along the full length of the coastline, including areas where currently no dikes are present. In this case, dikes of a defined protection standard are assumed along the entire coast, thus not allowing water to bypass them and leading to higher efficiency when dike height is increased.

Further, assumed protection standards are often based on existing global databases, which may introduce errors in local or regional assessments. For our study area, FLOPROS assumes a 100-year return water level protection standard for SH and MP[25], which underestimates the height of state embankments that are generally designed based on the 200-year return water level[27,28]. As a result, the baseline population exposure simulated using FLOPROS for the German Baltic Sea coast is overestimated, thus leading to an overestimation of the effectiveness of dike height increases in reducing affected population.

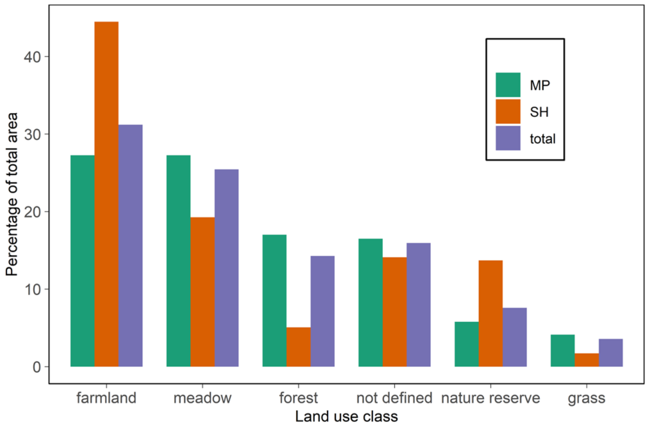

Fig. 2 Share of land use class on total MR area for SH, MP, and the entire study region. This figure only shows those land uses which cover more than 4% of the MR area in either SH, MP, or the entire study region.

Our study demonstrates the importance of incorporating spatially explicit information on coastal protection heights in coastal flood modeling, calling for new, comprehensive datasets that contain geographically referenced dike lines and associated heights. The latter are necessary in order to understand the effectiveness of dike height increases and to identify coastal sections where new protection structures are needed. Such coastal protection data are arguably one of the main bottlenecks for improving the accuracy of coastal flood risk assessments[24]. This is particularly true for studies extending beyond the national scale. Recent advances address this critical knowledge gap by providing spatially explicit data on dikes and associated design standards for river deltas on a global scale[55].

We argue that debates on how to protect currently unprotected (or insufficiently protected) areas from flooding should consider new adaptation approaches such as setback zones (exposed areas where no further development is allowed)[56] and/or nature-based solutions. Such discussions will become necessary, as our findings suggest that it is important to develop adaptation solutions for those coastal sections that are currently without any, or with insufficient adaptation measures. While plans to construct new

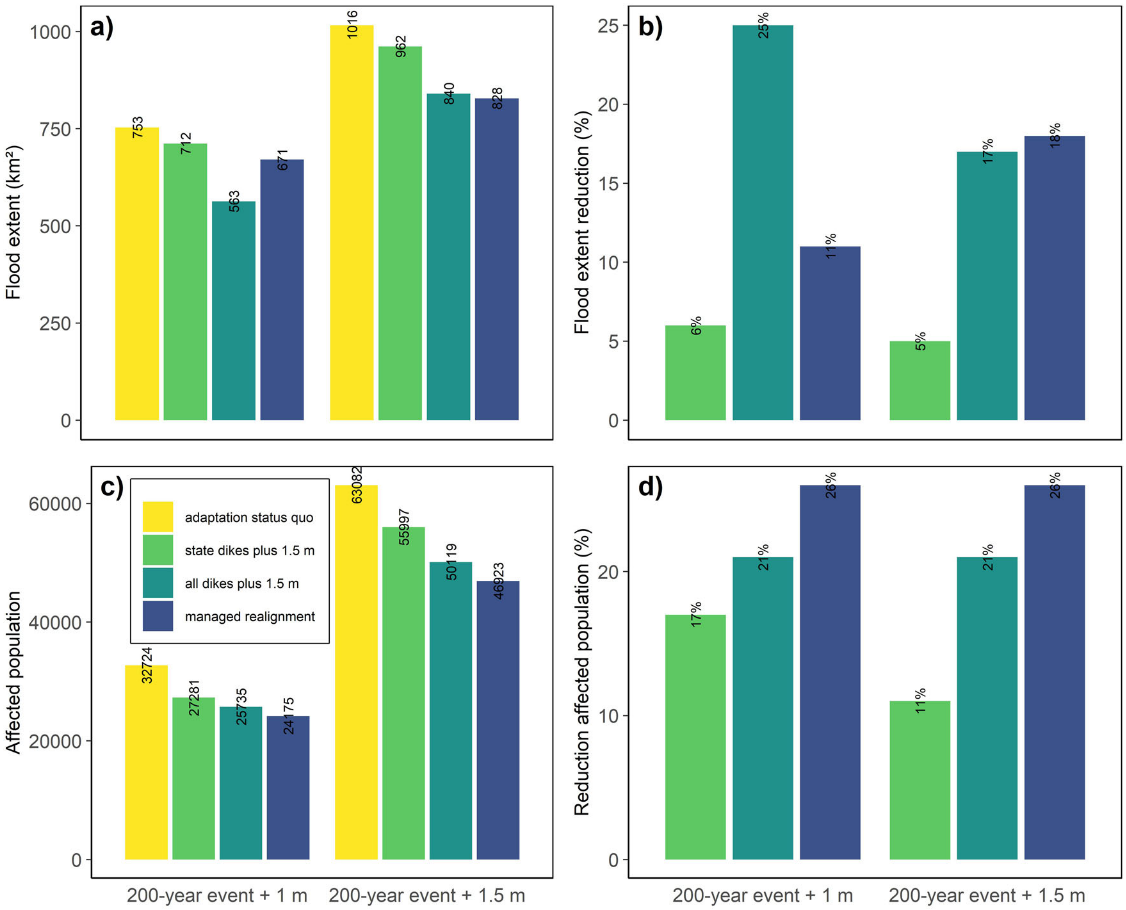

Fig. 3 Flood extent and potentially affected population for both SLR and the three adaptation scenarios. a Flood extent for the three adaptation scenarios and status quo adaptation. **b** Flood extent reduction in percent compared to status quo adaptation. **c** Potentially affected population as calculated from Census 2011 data for all three adaptation scenarios and status quo adaptation. **d** Reduction of potentially affected population in percent compared to status quo adaptation.

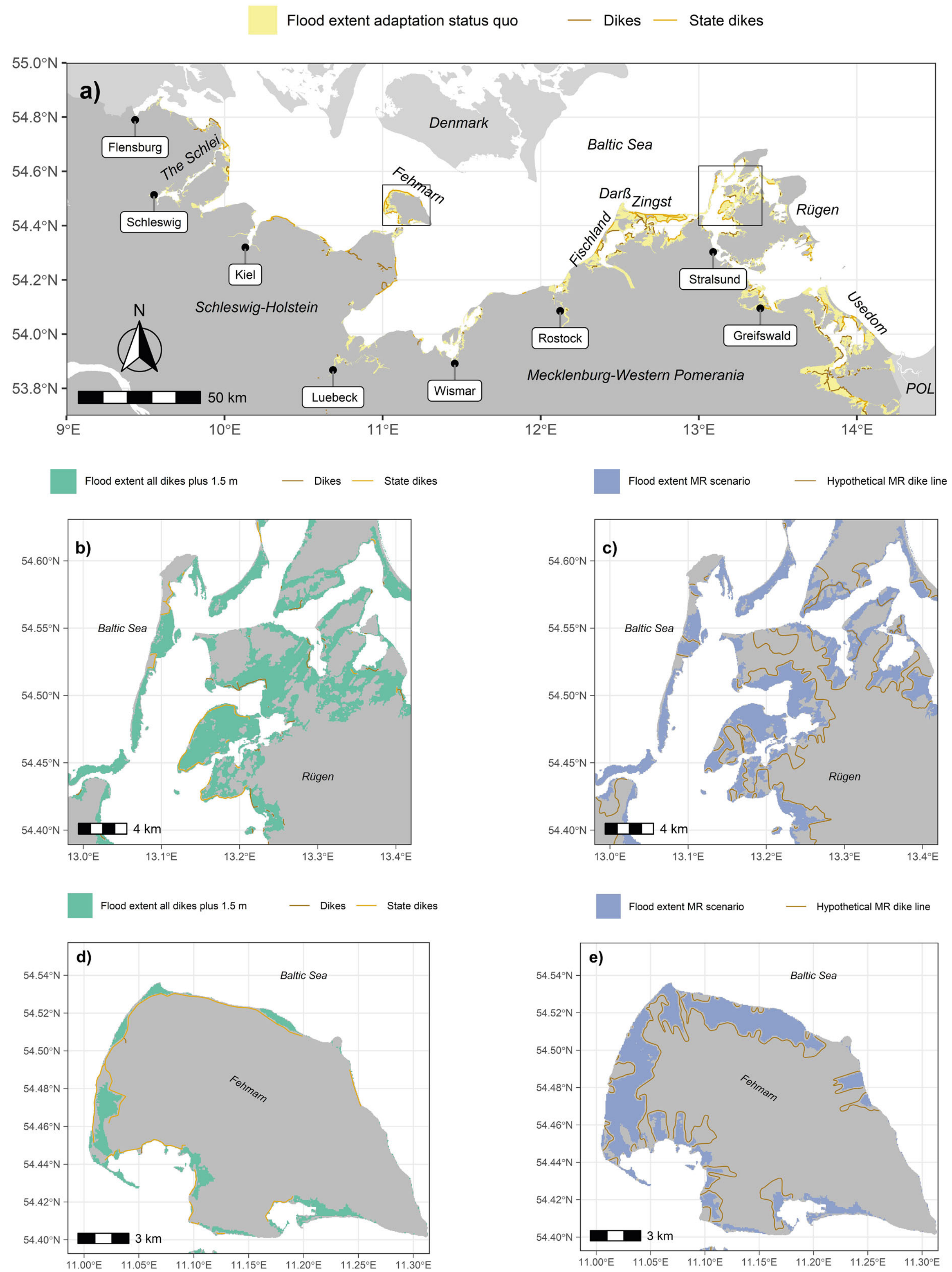

Fig. 4 Flood extent for the 200-year event plus 1.5 m SLR and two adaptation scenarios. a Flood extent adaptation status quo. **b** Flood extent for western Rügen when all dikes are increased in height by 1.5 m. **c** Flood extent for western Rügen under the implementation of hypothetic MR sites (including state dikes plus 1.5 m). **d** Flood extent for Fehmarn when all dikes are increased in height by 1.5 m. **e** Flood extent for Fehmarn under the implementation of hypothetic MR sites (including state dikes plus 1.5 m).

Table 2 Maximum inundation depth (m) for both SLR and all adaptation scenarios.

		MP	SH	Study region	Flood depth in populated areas (study region)
200-year event + 1 m SLR	Adaptation status quo	1.31	1.25	1.31	0.70
	All dikes plus 1.5 m	1.19	1.31	1.21	0.73
	State dikes plus 1.5 m	1.3	1.31	1.3	0.71
	MR and state dikes plus 1.5 m	1.47	1.7	1.52	0.73
200-year event + 1.5 m SLR	Adaptation status quo	1.64	1.5	1.62	0.97
	All dikes plus 1.5 m	1.44	1.53	1.46	0.93
	State dikes plus 1.5 m	1.55	1.55	1.55	0.92
	MR and state dikes plus 1.5 m	1.75	1.92	1.78	0.92

Maximum inundation depth was calculated by extracting each cell's maximum over the simulation period and then averaging these maxima over the model domain for each scenario. Dry cells were excluded.

dikes in the study region until 2030 already exist[29], their construction and maintenance is very costly and they must be upgraded in response to future sea levels that will keep rising well beyond the end of the 21st century[57]. These limitations in combination with the associated environmental costs, such as the loss of coastal ecosystems in front of sea defenses[31,58], loss of hydrological connectivity[59], and land subsidence behind dikes due to drainage and prevented sedimentation[33], make traditional defenses economically, environmentally and socially unsustainable[60]. Moreover, building dikes can lead to increased exposure, a paradox previously described as the "levee effect"[61]. Even though a residual risk for wave overtopping, overflow or breaching remains when dikes are constructed according to a certain design standard[62], the presence of dikes can steer economic development in low-lying coastal areas, leading to a shift from frequent low impact flooding to rare but catastrophic events[63,64]. Such events could however be prevented, for example by implementing setback zones[56].

Because of the known disadvantages of conventional defense systems, alternative adaptation options such as setback zones and nature-based solutions are gaining increasing scientific attention[30,34,35,44–46,56]. Specifically the latter may be particularly effective where restoration success is not yet compromised by land subsidence due to decades of dike constructions[65] and they are also better suited for low-to-medium urgency scenarios, as the restoration of coastal vegetation (e.g. salt marshes) requires time[60].

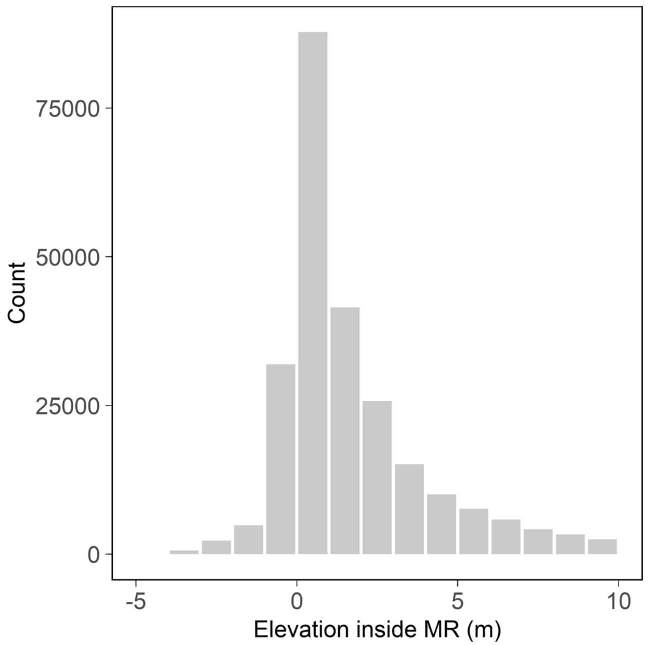

Fig. 5 Histogram showing elevation distribution within potential MR sites along the German Baltic Sea coast. To improve the readability of the figure, the histogram excludes 162 of the total 243,480 MR cells (0.07%) that have elevations higher than 10 m.

Managed realignment as a hybrid adaptation solution. Our results show that MR is the most effective measure for reducing the exposure of the population to flooding along the German Baltic Sea coast (Fig. 3d). We find that the coastal protection function of MR is primarily due to the new and much longer landward dike line rather than the result of the surge attenuating effects of the restored coastal wetlands. First, we see that inundation depths are generally higher in the MR scenario as compared to when dike heights are increased. We note, however, that this is not true for areas where people live (Table 2). Second, the flow of water is often only stopped at the new landward dikes (Fig. 4c, e).

The reason for the comparatively low performance of the restored wetlands in terms of coastal protection may be a result of the combination of the ESL (200-year event plus 1 m and 1.5 m SLR), the comparatively long surge duration and low elevations inside the MR sites, which have led to very high inundation depths. Increased water depth can reduce surge attenuation rates over coastal wetlands, as observed for wetlands restored in the context of MR[40,41] and natural habitats alike[39,43,66]. Further, surge attenuation is low when the surge duration is long compared to the time required to fill the storage area (i.e. the MR site)[67]. Due to the microtidal regime of the Baltic Sea, storm surge water levels can persist for days[68], providing sufficient time to flood extensive MR sites. The flooding (and flood depth) of MR sites is facilitated through the low site internal elevation range. We find that the great majority of the MR internal elevations range between −1 and 2 m above the local reference datum (NHN) (Fig. 5), which is well below the extreme water levels simulated in this study. We note, however, that the surge attenuation capacity of coastal wetlands restored in the context of MR along the German Baltic Sea will be higher during more frequent events with lower peak water levels and shorter durations. Vegetated foreshores can also effectively reduce wave loads on dikes even during storm surge conditions[35], resulting in less damage to the dike and thus, lower maintenance costs and reduced risk of breaching[69]. In addition, higher inundation depths in the MR scenario were not observed in populated areas, where differences between adaptation options do not exceed 5 cm (Table 2).

Our results confirm that MR is most effective as a hybrid solution, where restored coastal wetlands may reduce maintenance costs of realigned dikes through wave and surge attenuation under moderate conditions. However, the ultimate protection during rare extreme events is safeguarded by the new landward dike. The combination of new, landward dike lines and vegetated foreshores is more effective in reducing the potentially affected population compared to dike height increases.

However, critical knowledge gaps remain. Future research should continue to invest in identifying thresholds with respect to the protection function of coastal wetlands. These thresholds are probably exceeded by the surges modeled in this study. In addition, regional-scale studies need to explore sediment accretion in natural and restored coastal wetlands, addressing whether these foreshore systems can keep pace with SLR or drown once a threshold is reached. The long-term resilience of coastal wetlands is one of the most important knowledge gaps hampering their application in coastal defense schemes[48]. This is particularly valid for microtidal wetlands of the Baltic Sea coast, which are more vulnerable to drowning as a consequence of SLR[70].

Limitations. The flood maps presented here are likely to underestimate flood extents. First, our study excludes the effects of waves on the total extreme water levels, which can result in an underestimation of flood extent[6]. The resolution of the coastal ocean model (200 m) is not fine enough to sufficiently resolve the nearshore thus not allowing a reliable approximation of wave setup[23]. Another reason for not considering waves is the limited knowledge regarding potential future changes in wave climate[71]. Even though the inclusion of wave setup in the modeling approach is likely to increase the simulated flood extent, the magnitude is unclear. For example, a more detailed resolution of the nearshore coastal ocean would facilitate the inclusion of wave setup but at the same time allows a better representation of the vegetation-induced friction of the shallow-water area and the coastal foreshore. The latter is likely to contribute to wave energy dissipation thus counteracting the potential for wave-induced increases in flood extent[35,37,72].

Second, the presented results neglect morphological responses to extreme water levels, such as the potential for dune collapse and dike breaching. Waves and very high water levels induce hydraulic loads on dikes, potentially leading to failure and breaching once a threshold water level is exceeded[73,74]. In addition, the long-term response of the nearshore morphology and bathymetry as a consequence of rising sea levels has not been considered. There is an inherent limit to the predictability of nearshore morphology and bathymetry in dynamic coastal settings due to non-linear feedbacks. This has been demonstrated by van Lancker et al., 2004[75], who have shown that meteorological conditions (e.g. fair-weather vs. storm dominated) are important for explaining nearshore morphodynamics. However, future storminess remains uncertain[76] and the time-scales of coastal morphological change are yet to be identified[75]. Thus, the precise prediction of spatiotemporal water level variability over long time scales is particularly challenging, as these parameters strongly depend on coastal morphology[16]. Therefore, the results presented here should be interpreted as representative of future regional trends rather than an accurate prediction at the local level.

Third, representing dike heights in coastal inundation models requires high resolution elevation data due to narrow dike crests. It is therefore not surprising that elevation data with resolutions below 10 m were previously suggested for reliable results[6,21,22]. To address this issue, we extracted the dike heights from a 1 m Light Detection And Ranging (LiDAR) derived digital elevation model and aggregated these values to the 50 m grid of the coastal inundation model by using the maximum values. It is therefore likely that we overestimate the height of the dikes. In order to test the sensitivity of our model with respect to the approximation of dike heights, we ran an additional simulation for the 200-year event in SH, where dike heights were derived based on data from the state´s dike levelling campaign. In this campaign, 9519 high-resolution real time kinematic GPS points of dike heights in SH were acquired. These data were provided by the SH State Agency for Coastal Protection, National Park and Marine Conservation (LKN). We quantified the elevation difference between both dike datasets by calculating the Root Mean Square Error (RMSE) and the mean absolute error (MAE), which amount to 0.65 m and 0.37 m, respectively. The simulated flood extent using the high-resolution GPS data was 9.8% higher than the flood extent produced with the original model setup. A more detailed description of uncertainties associated with the presented modeling approach is provided in Kiesel et al., (2023)[23].

Fourth, we have used data from the 2011 census in order to assess the population potentially affected by coastal flooding in 2100 due to SLR. However, population projections suggest changes in exposure depending on socio-economic development. While strong increases in exposure are expected for Africa and Asia, exposure in Europe increases only slightly and remains relatively stable throughout the century for most socio-economic scenarios[77,78]. Therefore, we assume the uncertainty introduced by overlying population data from 2011 with flood extents simulated for 2100 is comparatively low.

Here we show the potential for MR along the German Baltic Sea coast without accounting for technical, financial and governance barriers[79]. For instance, our data shows that the largest proportion of the potential MR sites is located on agricultural land (Fig. 2) and the societal and economic implications of losing this land for food production and livelihoods remain uncertain and need to be assessed. The potential MR sites presented in this study consequently represent a high-end estimate of what is physically plausible rather than politically and socio-economically realistic. While our study addresses technical and governance barriers by highlighting potential benefits and tradeoffs that can help increase public confidence in MR, involved costs cannot be reliably estimated. This is mostly due to the dike line produced by our MR modeling approach (see Section 5.4), which is not the optimal from a cost-benefit perspective. Calculating the economically optimal dike line in future studies could help address this knowledge gap.

Last, our work assesses changes in risk as a result of hazard and exposure as defined in the IPCC[51] and does not consider changes in vulnerability, which would also affect risk[80]. Consequently, we omit aspects of a comprehensive risk analysis, such as variations in impacts caused by the spatial distribution of health, education or socioeconomically vulnerable groups[81].

Conclusion

There is great potential for MR along the German Baltic Sea coast and in our study, MR constitutes the most effective adaptation measure to reduce the population potentially affected by coastal flooding. However, all adaptation options that we explored were insufficient for maintaining current flood risk levels, as water bypasses dikes or floods low-lying areas of the coast that are currently unprotected. This finding suggests that revisiting adaptation strategies to include currently unprotected coastal stretches is more important for reducing population exposure to coastal flooding compared to upgrading existing dikes by height increases or MR. New dikes are already in the planning stages for certain areas within the study region, but for other parts, decisions regarding adaptation strategies and, consequently, the potential future coastal landscape, remain pending. Due to the known drawbacks of conventional defenses, the effectiveness of MR as a hybrid adaptation solution and the associated multiple environmental benefits, MR and nature-based solutions represent a promising alternative.

Based on our findings, we suggest that future research focuses on the further development of existing coastal protection datasets, including both the protection standards and their spatially explicit representation on continental and global scale. In addition, in order to implement nature-based solutions such as MR, more research is required for understanding and identifying the conditions, under which habitats restored in the context of MR can actually contribute effectively to coastal protection. Such research should include wave and surge attenuation and also assess the wetland´s capacity to accrete sediments and survive even higher rates of SLR.

Methods

The Baltic Sea modeling framework. In order to simulate coastal flooding along the German Baltic Sea coast, we have used a calibrated and validated modeling framework for the region, presented in Kiesel et al., (2023[23]). The modeling framework offline couples a hydrodynamic coastal inundation model (LISFLOOD-FP[82,83]) and a hydrodynamic coastal ocean model (General Estuarine Transport Model (GETM)[84]). The coastal ocean model (200 m resolution) provides spatially varying boundary conditions for the coastal inundation model (50 m resolution). The elevation data for the coastal inundation model was aggregated from a 10 m LiDAR dataset provided by state agencies in SH and MP. Dikes in the region were incorporated by aggregating a 1 m LiDAR derived terrain model within a 100 m buffer around all dikes to 50 m using maximum values. We validated the resulting 50 m dike heights used in the modeling framework by comparing them to 9519 field observation points measured by the SH State Agency for Coastal Protection, National Park and Marine Conservation (LKN) using a Real Time Kinematic (RTK) GPS. The Root Mean Square Error (RMSE) and the mean absolute error between both datasets are 0.65 m and 0.37 m, respectively.

We assessed the sensitivity of the coastal inundation model to five configurations of Manning´s *n* surface roughness coefficients, which we derived from the literature for ten land cover classes. Manning´s *n* coefficients are typically applied in hydrodynamic simulations to approximate drag induced on the water column as a consequence of differently "rough" surfaces[85,86]. First, we reclassified Corine land cover data (© European Union, Copernicus Land Monitoring Service 2018, European Environment Agency (EEA)) to represent the ten classes (see Kiesel et al., 2023[23] for more information on the ten classes and the reclassification scheme). Second, we reviewed the literature for a variety of Manning´s coefficients for each of the ten land cover classes, which we then grouped into five categories (low, medium, high, uniform and land/water). Differences in flood characteristics for the five different sets of Manning´s coefficients reveal that the model is robust against these variations, with maximum differences in flood extent and depth of up to 9.5% and 5.1%, respectively. In addition, we tested the sensitivity of the coastal inundation model against variations in the dike height approximations. Therefore, we used high-resolution field data provided by the LKN to incorporate dike heights into the coastal inundation model. The latter approach resulted in a flood extent that was 9.8% larger than in the original model setup.

The coastal ocean and inundation models were validated by comparing modeled and measured peak water levels and flood extents for the storm surge that occurred in the study region on 2nd January 2019. The peak water levels of this heavy storm surge have a recurrence interval of approximately 50 years[87]. The root mean square error between modeled peak water levels and observations at 28 tide gauges amounts to 15 cm, while on average, the coastal ocean model underestimates peak water levels by 5 cm. Over- and underestimation of peak water levels depend on the geographical setting. For instance, the model overestimates peak water levels in most lagoons and sheltered fjords. For further information, we refer the reader to the publication presenting the modeling framework[23].

We validated the coastal inundation model by comparing simulated flood extents with Sentinel-1 SAR imagery taken on January 2nd, 2019, only a few hours after the peak of the surge. In comparison to other studies that have used LISFLOOD-FP to simulate flooding[5,6,86], we find lower hit-ratios (50%) that we consider an underestimation caused by 1) the pre-processing of the SAR imagery that is required to derive flood maps, 2) difficulties in the contrast-based differentiation between flooded areas and specific land surface covers, and 3) the accuracy and preprocessing of the 50 m elevation data used in the coastal inundation model. For more details and the sources of the data used for this study, the reader is referred to the original publication[23].

Incorporation of dike height increases in the modeling framework. According to the General Plan for Coastal Protection of SH, state dikes can be transformed into so-called climate dikes, which are constructed with a wider base, allowing for comparatively easy dike height increases of up to 1.5 m[28]. For regional dikes, which are not managed by the state and are characterized by variable protection standards, achieving dike height increases of a similar magnitude is more challenging. Therefore, we have implemented two scenarios where 1) all dikes are increased by 1.5 m and 2) only state dikes are increased by 1.5 m (dike line shown in Fig. 4a). In order to implement dike height increases in the coastal inundation model, we added 1.5 m to all cells with values greater than 0.5 m elevation in a 100-m distance buffer around the dike line (including state and regional dikes). We used the buffer to ensure that the targeted dike height was implemented for at least two cells in the model, so that water cannot erroneously flow between the dike cells. The latter would introduce a much greater error compared to the overly wide dikes that are produced by our approach. Furthermore, the buffer accounts for deviations between the actual vectorized dike line and the cells in the digital elevation model actually representing the dike heights. We used the threshold of 0.5 m to ensure that only the elevation of the dikes is increased, not the elevation of adjacent low-lying areas.

The potential for managed realignment along the German Baltic Sea coast. This study explores the physically plausible potential for MR along the German Baltic Sea coast by considering critical infrastructure, which, according to the EU Council Directive involves "an asset, system or part thereof […], which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption and destruction of which would have a significant impact [..] as a result of failure to maintain those functions"[88]. We excluded all areas where critical infrastructure such as residential, industrial, commercial and transportation was present using the GHS Built Up Layer[89] and the Open Street Map Roads and Railways layer. We selected both datasets as they are available on a global scale and are open access, which facilitates the transferability of the approach to other regions. In addition, the GHS Built Up Layer does not differentiate between individual buildings but rather covers continuously sealed surfaces. Otherwise, the space between buildings would have been detected as a potential MR area.

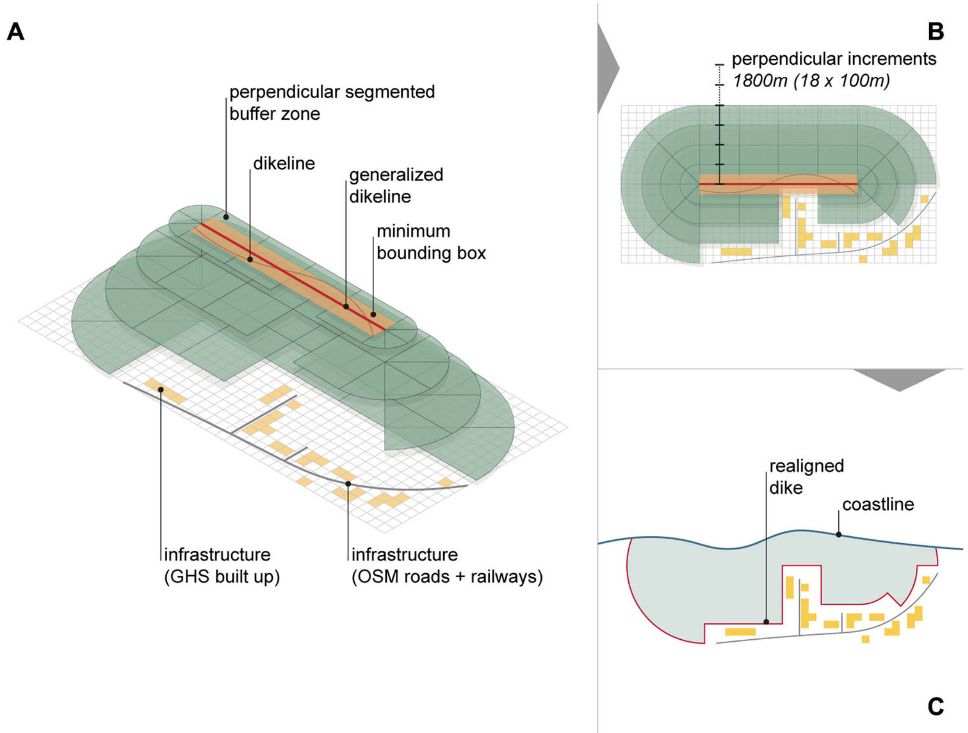

Fig. 6 Schematic drawing showing how we selected physically plausible MR sites along the German Baltic Sea coast. A 3-D view on the stepwise selection process. **B** Birds eye view on the segmented buffer zones and excluded areas due to the presence of infrastructure. **C** Resulting physically plausible MR area.

Data managed realignment model. The GHS built-up area grid (100 m resolution) is a global raster dataset derived from satellite imagery, describing the land surface in two classes: built-up and non-built-up areas. Built-up areas are defined as any permanent constructions, both above and below ground, which are used as a shelter for humans, animals, things, and the production of economic goods or the delivery of services[90]. In order to account for roads and railways that connect the built-up areas, we used Open Street Map. From the road layer, we selected primary roads, secondary roads, tertiary roads, and motorways as we assume that these represent the largest proportion of solid road structures and their potential removal or relocation as part of MR would strongly impact local socio-economic systems.

Data on dikes (regional dikes and state dikes) in the study region are provided by state authorities in SH and MP. In SH, we used ATKIS® data provided by the State Office for Surveying and Geoinformation. In MP, we received the dike shapefiles directly from the Coastal Division of the State Office for Agriculture and the Environment Mittleres Mecklenburg (internal data). However, dike data of similar quality are not freely available for many other regions. The availability of high-quality data on dike positions and heights consequently constitutes a major limitation compromising the transferability of this work to other regions.

The Low Elevation Coastal Zone (LECZ) is the area below 10 m elevation hydrologically connected to the sea[91]. To identify the LECZ within the study region, we used a LiDAR derived digital elevation model with 1 m horizontal resolution (ATKIS DGM1®), which we also used to derive the dike heights in the coastal inundation model (see also Kiesel et al., 2023[23]).

Selection of physically plausible managed realignment sites. MR requires dikes to be breached per definition, which is why all following steps to detect potential areas are exclusively focusing on those coastal sections where currently dikes are present. We used a five-step approach to identify potential MR sites in the study region. First, we determined a maximum inland extent for potential MR areas of up to 1,800 m. This value was defined by calculating the average distance from the coastline to the most landward dike of the ten largest MR sites in Europe recorded in the OMReg database[92]. The OMReg database contains information on completed coastal habitat restoration schemes and other projects related to adaptation[92].

Second, we implemented segmented buffer zones in 100 m increments along the generalized dikeline and 100 m perpendicular increments (Fig. 6A, B). The perpendicular increments were repeated until the maximum width (1,800 m) was reached (Fig. 6B), and the horizontal segments were added along the full length of the generalized dike (Fig. 6A, B). In case the generalized dike length could not be evenly divided into 100 m horizontal increments, we added half of the remainder to the segments at each end of the dike. The triangular segments at the ends of the buffer were created by applying a polar coordinate system to the idealized dike line. We used a polar angle of 15° to define the segments. We kept the side areas to provide for larger water retention areas and connect smaller MR sites.

Third, the resulting grid was clipped to a land mask, overlaid with the critical infrastructure data described above and the LECZ. Cells were retained or deleted accordingly, taking hydrological connectivity into account (Fig. 7).

The fourth step involved cleanup and postprocessing of potential misidentifications as a result of the previous steps. We refer to these misidentifications as island effects and peninsula/bay effects. The island effect refers to the case where the buffer around the idealized dike line is large enough to extend overseas to adjacent islands that have no dike, leading to identifying a potential MR site with no dikes to be breached. This effect was corrected by clipping all potential MR sites with a land layer that excludes all islands without dikes. The peninsula/bay effect is very similar to the island effect but refers to remnants of potential MR

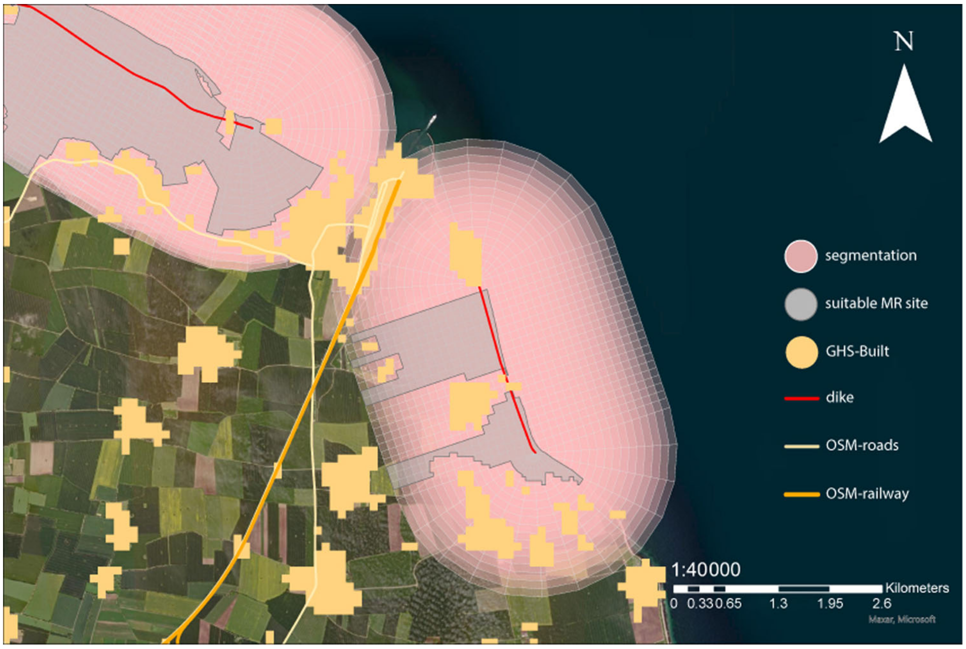

Fig. 7 The gridded buffer zones and the detection of potential MR areas. The detection takes critical infrastructure, roads and railways, hydrological connectivity and elevation into account. OSM refers to the data source of the road layer: Open Street Map.

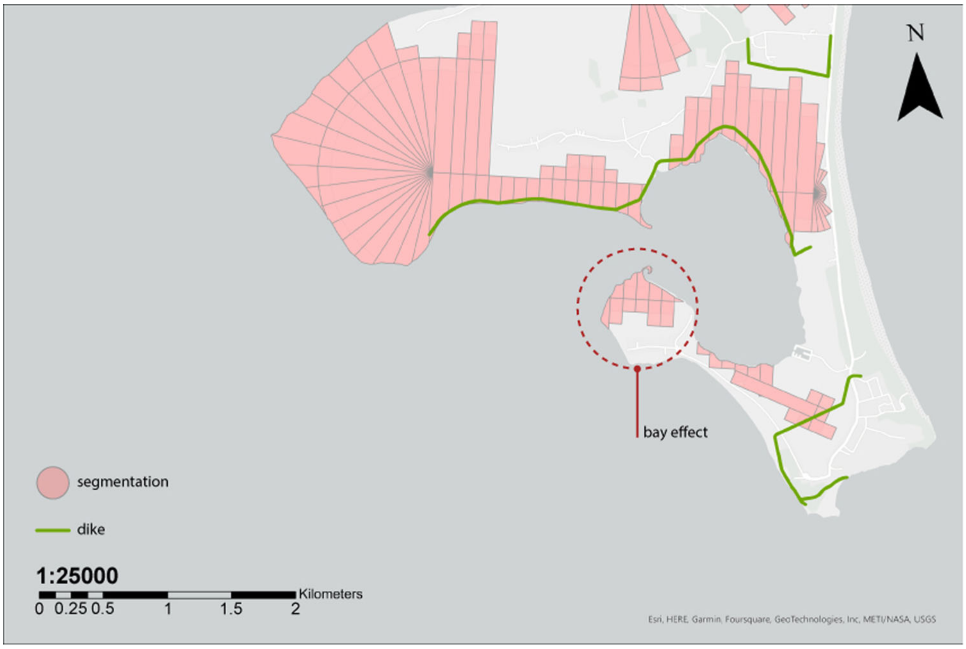

Fig. 8 Depiction of the peninsula/bay effect. The peninsula/bay effect describes a situation where the buffer zones in which we selected potential MR sites extend overseas or overland to areas not protected by dikes, which can consequently not become a MR site.

sites on the opposite side of bays (Fig. 8). The peninsula/bay effect was corrected by intersecting all MR sites with the generalized dike line (see also Fig. 6).

Finally, we excluded all MR sites smaller than 1 ha, as implemented MR sites should cover at least two grid cells in the coastal inundation model. This takes into account that the coastal protection function of wetlands increases with their size[40,41,93,94].

Managed realignment model calibration. We tested the sensitivity of our MR model to variations in horizontal segment-width, side-segmentation angle and side areas. All parameters have comparatively little effect on the potential for MR in the study region. Generally, a finer horizontal segmentation results in a larger total MR area, as areas closer to the next built-up area or infrastructure are considered. For a constant side-segmentation angle, segment widths of 50 m, 100 m and 150 m produced potential MR areas of 62,496 ha, 60,750 ha and 59,084 ha, respectively. The difference in MR area between a segment width of 50 m and 150 m is 5%. The differences in potential MR areas when using varying side-segmentation angles range in the same order of magnitude. With constant segment width (100 m), side-segmentation angles of 5°, 10° and 15° produced potential MR areas of 63,958 ha, 62,118 ha and 60,750 ha. Relative to the 15° side-segmentation angle used in the final model, the 5° angle differs by 5%. In contrast, the potential MR area including the side areas is 20,674 ha (34 %) larger than the results of a model run where side areas are excluded. In addition, keeping the side areas reduces the overall number of potential MR sites from 233 in a model run without side areas to 199. This is mainly due to the connection of smaller potential MR sites through the side areas. The final model setup uses a horizontal segment width of 100 m, a side-segmentation angle of 15° and includes side areas.

Incorporation of potential managed realignment sites in the modeling framework. To incorporate the potential MR sites (see section 5.3) in the coastal inundation model, the modeled MR outlines need to be included in the digital elevation model satisfying three main criteria: 1) The new, landward dike/outline should have the same level of protection as the old, seaward dike plus 1.5 m; 2) the seaward outline of the MR areas should be breached in order to allow flooding of the adjacent low-lying areas and; 3) the old dikes lying within the potential MR area should be removed.

In a first step, we smoothed the outline of the new MR sites created in section 5.3, using the Polynomial Approximation with Exponential Kernel algorithm (smoothing tolerance 500 m) in ArcGIS Desktop (version 10.8.1). Seaward breaches in the outline were created by removing the potential MR dike line, which overlays with a 50 m buffer around the German Baltic Sea coastline (the latter taken from van der Pol et al., 2021[53]). The remaining MR outline already represents the new landward dike and receives the elevation of the nearest existing dike plus 1.5 m. This makes the dike height consistent with the other two adaptation scenarios (state dikes and all dikes plus 1.5 m). All dikes in the original dike dataset that fall within the MR areas are removed by assigning an elevation of 0 m. Finally, this dataset is exported as a raster (50 m horizontal resolution) and merged with the original elevation dataset of the coastal inundation model, including the state dikes plus 1.5 m. We combine both scenarios because we assume that even under large-scale implementation of MR in 2100, state dikes where MR is not possible will still need to be increased in height to prevent damage to people, property and infrastructure.

As we expect the establishment of coastal wetlands such as reed belts and saltmarshes inside the MR sites[46,47,95,96], we adjusted the surface roughness coefficients of the coastal inundation model accordingly. For all coastal wetlands in the study region, including MR internal areas, we used a Manning´s n coefficient of 0.06, as suggested in Bunya et al., (2010)[23,97].

Data availability

Spatial flood characteristics (flood extent and depth) for all SLR and adaptation scenarios and the potential MR sites are publicly available from Zenodo[98] (https://doi.org/10.5281/zenodo.10008225).

Code availability

The Python code used to detect the physically plausible potential for managed realignment is publicly available from https://gitlab.com/larsenno/sumare.

Received: 2 April 2023; Accepted: 10 November 2023;
Published online: 24 November 2023

References

1. Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M. & Feyen, L. Extreme sea levels on the rise along Europe's coasts. *Earth's Fut.* **5**, 304–323 (2017).
2. Vousdoukas, M. I. et al. Climatic and socioeconomic controls of future coastal flood risk in Europe. *Nat. Clim. Change* **8**, 776–780 (2018).
3. Vousdoukas, M. et al. Adapting to rising coastal flood risk in the EU under climate change. *EUR 29969 EN, Publications Office of the European Union, Luxembourg* (2020).
4. Hinkel, J. et al. Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Nat. Acad. Sci. USA* **111**, 3292–3297 (2014).
5. Bates, P. D. et al. Combined Modeling of US Fluvial, Pluvial, and Coastal Flood Hazard Under Current and Future Climates. *Water Resour. Res.* **57**; https://doi.org/10.1029/2020WR028673 (2021).
6. Vousdoukas, M. I. et al. Developments in large-scale coastal flood hazard mapping. *Nat. Hazards Earth Syst. Sci.* **16**, 1841–1853 (2016).
7. Lopes, C. L. et al. Evaluation of future estuarine floods in a sea level rise context. *Sci. Rep.* **12**, 8083 (2022).
8. Didier, D. et al. Multihazard simulation for coastal flood mapping: Bathtub versus numerical modelling in an open estuary, Eastern Canada. *J. Flood Risk Management* **12**; https://doi.org/10.1111/jfr3.12505 (2019).
9. Leijnse, T., van Ormondt, M., Nederhoff, K. & van Dongeren, A. Modeling compound flooding in coastal systems using a computationally efficient reduced-physics solver: Including fluvial, pluvial, tidal, wind- and wave-driven processes. *Coastal Eng.* **163**, 103796 (2021).
10. Gourgue, O. et al. A Convolution Method to Assess Subgrid-Scale Interactions Between Flow and Patchy Vegetation in Biogeomorphic Models. *J. Adv. Model Earth Syst.* **13**; https://doi.org/10.1029/2020MS002116 (2021).
11. Gourgue, O. et al. Biogeomorphic modeling to assess the resilience of tidal-marsh restoration to sea level rise and sediment supply. *Earth Surf. Dynam.* **10**, 531–553 (2022).
12. Duran Vinent, O., Andreotti, B., Claudin, P. & Winter, C. A unified model of ripples and dunes in water and planetary environments. *Nat. Geosci.* **12**, 345–350 (2019).
13. Brown, S. et al. Quantifying Land and People Exposed to Sea-Level Rise with No Mitigation and 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300. *Earth's Future* **6**, 583–600 (2018).
14. Kirezci, E. et al. Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Sci. Rep.* **10**, 11629 (2020).
15. Passeri, D. L., Hagen, S. C., Bilskie, M. V. & Medeiros, S. C. On the significance of incorporating shoreline changes for evaluating coastal hydrodynamics under sea level rise scenarios. *Nat. Hazards* **75**, 1599–1617 (2015).
16. Spencer, T., Brooks, S. M., Möller, I. & Evans, B. R. Where local matters: impacts of a major north sea storm surge. *Eos Trans. AGU* **95**, 269–270 (2014).
17. Hinkel, J. et al. Uncertainty and bias in global to regional scale assessments of current and future coastal flood risk. *Earth's Future* **9**, e2020EF001882 (2021).
18. Molinari, D. et al. Validation of flood risk models: Current practice and possible improvements. *Int. J. Disaster Risk Red.* **33**, 441–448 (2019).
19. Rollason, E., Bracken, L. J., Hardy, R. J. & Large, A. The importance of volunteered geographic information for the validation of flood inundation models. *J. Hydrol.* **562**, 267–280 (2018).
20. Sampson, C. C. et al. A high-resolution global flood hazard model. *Water Resour. Res.* **51**, 7358–7381 (2015).
21. Vousdoukas, M. I., Ferreira, Ó., Almeida, L. P. & Pacheco, A. Toward reliable storm-hazard forecasts: XBeach calibration and its potential application in an operational early-warning system. *Ocean Dyn.* **62**, 1001–1015 (2012).
22. Vousdoukas, M. I., Wziatek, D. & Almeida, L. P. Coastal vulnerability assessment based on video wave run-up observations at a mesotidal, steep-sloped beach. *Ocean Dyn.* **62**, 123–137 (2012).
23. Kiesel, J., Lorenz, M., König, M., Gräwe, U. & Vafeidis, A. T. Regional assessment of extreme sea levels and associated coastal flooding along the German Baltic Sea coast. *Nat. Hazards Earth Syst. Sci.*, 2961–2985; https://doi.org/10.5194/nhess-23-2961-2023 (2023).
24. Vousdoukas, M. I. et al. Understanding epistemic uncertainty in large-scale coastal flood risk assessment for present and future climates. *Nat. Hazards Earth Syst. Sci.*, 2127–2142; https://doi.org/10.5194/nhess-18-2127-2018 (2018).
25. Scussolini, P. et al. FLOPROS: an evolving global database of flood protection standards. *Nat. Hazards Earth Syst. Sci.* **16**, 1049–1061 (2016).
26. Sterr, H. Assessment of vulnerability and adaptation to sea-level rise for the coastal zone of Germany. *J. Coastal Res.* **242**, 380–393 (2008).
27. StALU. *Regelwerk Küstenschutz Mecklenburg-Vorpommern. Küstenraum und Bemessungsgrößen von Küstenschutzanlagen in M-V* (Verlag Redieck & Schade GmbH, Rostock, Schwerin, 2012).
28. Melund. *Generalplan Küstenschutz des Landes Schleswig-Holstein. Fortschreibung 2022* (Kiel, 2022).
29. StALU. *Regelwerk Küstenschutz Mecklenburg-Vorpommern. Küstenschutzanlagen M-V - Bestand und Plan* (Rostock, 2020).
30. Temmerman, S. et al. Ecosystem-based coastal defence in the face of global change. *Nature* **504**, 79–83 (2013).
31. Pontee, N. Defining coastal squeeze: A discussion. *Ocean Coastal Manag.* **84**, 204–207 (2013).

32. Barkowski, J. W., Kolditz, K., Brumsack, H. & Freund, H. The impact of tidal inundation on salt marsh vegetation after de-embankment on Langeoog Island, Germany - six years time series of permanent plots. *J. Coast. Conserv.* **13**, 185–206 (2009).
33. Syvitski, J. P. M. et al. Sinking deltas due to human activities. *Nat. Geosci.* **2**, 681–686 (2009).
34. Weisscher, S. A., Baar, A. W., van Belzen, J., Bouma, T. J. & Kleinhans, M. G. Transitional polders along estuaries: Driving land-level rise and reducing flood propagation. *Nature-Based Sol.* **2**, 100022 (2022).
35. Vuik, V., Jonkman, S. N., Borsje, B. W. & Suzuki, T. Nature-based flood protection: The efficiency of vegetated foreshores for reducing wave loads on coastal dikes. *Coastal Eng.* **116**, 42–56 (2016).
36. Vuik, V., Borsje, B. W., Willemsen, P. W. & Jonkman, S. N. Salt marshes for flood risk reduction: Quantifying long-term effectiveness and life-cycle costs. *Ocean Coastal Manag.* **171**, 96–110 (2019).
37. Möller, I. et al. Wave attenuation over coastal salt marshes under storm surge conditions. *Nat. Geosci.* **7**, 727–731 (2014).
38. Hewageegana, V. H., Bilskie, M. V., Woodson, C. B. & Bledsoe, B. P. The effects of coastal marsh geometry and surge scales on water level attenuation. *Ecol. Eng.* **185**, 106813 (2022).
39. Stark, J., van Oyen, T., Meire, P. & Temmerman, S. Observations of tidal and storm surge attenuation in a large tidal marsh. *Limnol. Oceanogr.* **60**, 1371–1381 (2015).
40. Kiesel, J., MacPherson, L. R., Schuerch, M. & Vafeidis, A. T. Can managed realignment buffer extreme surges? The relationship between marsh width, vegetation cover and surge attenuation. *Estuaries Coasts* **45**, 345–362 (2022).
41. Kiesel, J. et al. Effective design of managed realignment schemes can reduce coastal flood risks. *Estuarine, Coastal Shelf Sci.* **242**, 106844 (2020).
42. Smolders, S., Plancke, Y., Ides, S., Meire, P. & Temmerman, S. Role of intertidal wetlands for tidal and storm tide attenuation along a confined estuary: a model study. *Nat. Hazards Earth Syst. Sci.* **15**, 1659–1675 (2015).
43. Wamsley, T. V., Cialone, M. A., Smith, J. M., Atkinson, J. H. & Rosati, J. D. The potential of wetlands in reducing storm surge. *Ocean Eng.* **37**, 59–68 (2010).
44. Moraes, R. P. L., Reguero, B. G., Mazarrasa, I., Ricker, M. & Juanes, J. A. Nature-Based Solutions in Coastal and Estuarine Areas of Europe. *Front. Environ. Sci.* **10**; https://doi.org/10.3389/fenvs.2022.829526 (2022).
45. Seddon, N. Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. *Science (New York, N.Y.)* **376**, 1410–1416 (2022).
46. French, P. W. Managed realignment – The developing story of a comparatively new approach to soft engineering. *Estuarine, Coastal Shelf Sci.* **67**, 409–423 (2006).
47. Esteves, L. S Managed realignment: A viable long-term coastal management strategy?. (Springer, New York, 2014)..
48. Bouma, T. J. et al. Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: Opportunities & steps to take. *Coastal Eng.* **87**, 147–157 (2014).
49. La Vega-Leinert, A. de, Kaufmann, J., Reinwardt, N., Wermes, M. & Gussmann, G. Managed realignment in Mecklenburg-Western Pomerania, German Baltic Coast — An Inventory. *Zenodo*; https://doi.org/10.5281/zenodo.7736794.
50. Tiede, J., et al. (EUCC-D, Kiel, Rostock, 2022), pp. 7–22.
51. Reisinger, A. et al. *The concept of risk in the IPCC Sixth Assessment Report: a summary of cross-Working Group discussions. Guidance for IPCC authors* (Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2020).
52. Fox-Kemper, B. et al. Ocean, Cryosphere and Sea Level Change. In *Climate Change 2021 – The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. Masson-Delmotte, et al. (Cambridge University Press 2021), pp. 1211–1362.
53. van der Pol, T. et al. Regional economic analysis of flood defence heights at the German Baltic Sea coast: A multi-method cost-benefit approach for flood prevention. *Clim. Risk Manag.* **32**, 100289 (2021).
54. Tiggeloven, T. et al. Global scale benefit-cost analysis of coastal flood adaptation to different flood risk drivers using structural measures. *Nat. Hazards Earth Syst. Sci.*, 1025–1044; https://doi.org/10.5194/nhess-2019-330 (2020).
55. Nienhuis, J. H., Cox, J. R., O'Dell, J., Edmonds, D. A. & Scussolini, P. A global open-source database of flood-protection levees on river deltas (openDELvE). *Nat. Hazards Earth Syst. Sci.* **22**, 4087–4101 (2022).
56. Wolff, C., Bonatz, H. & Vafeidis, A. T. Setback zones can effectively reduce exposure to sea-level rise in Europe. *Sci. Rep.* **13**, 5515 (2023).
57. Horton, B. P. et al. Estimating global mean sea-level rise and its uncertainties by 2100 and 2300 from an expert survey. *npj Clim. Atmos. Sci.* **3**; https://doi.org/10.1038/s41612-020-0121-5 (2020).
58. Schuerch, M. et al. Future response of global coastal wetlands to sea-level rise. *Nature* **561**, 231–234 (2018).
59. Bishop, M. J. et al. Effects of ocean sprawl on ecological connectivity: impacts and solutions. *J. Exp. Marine Biol. Ecol.* **492**, 7–30 (2017).
60. Morris, R. L., Boxshall, A. & Swearer, S. E. Climate-resilient coasts require diverse defence solutions. *Nat. Clim. Change* **10**, 485–487 (2020).
61. Montz, B. E. & Tobin, G. A. Livin' Large with Levees: Lessons Learned and Lost. *Nat. Hazards Rev.* **9**, 150–157 (2008).
62. Serra-Llobet, A., Tourment, R., Montané, A. & Buffin-Belanger, T. Managing residual flood risk behind levees: Comparing USA, France, and Quebec (Canada). *J. Flood Risk Manag.* **15**; https://doi.org/10.1111/jfr3.12785 (2022).
63. Di Baldassarre, G. et al. Debates-Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. *Water Resour. Res.* **51**, 4770–4781 (2015).
64. Kates, R. W., Colten, C. E., Laska, S. & Leatherman, S. P. Reconstruction of New Orleans after Hurricane Katrina: a research perspective. *Proc. Nat. Acad. Sci. USA* **103**, 14653–14660 (2006).
65. Liu, Z., Fagherazzi, S., Li, J. & Cui, B. Mismatch between watershed effects and local efforts constrains the success of coastal salt marsh vegetation restoration. *J. Cleaner Prod.* **292**, 126103 (2021).
66. Temmerman, S., de Vries, M. B. & Bouma, T. J. Coastal marsh die-off and reduced attenuation of coastal floods: A model analysis. *Global Planet. Change* **92-93**, 267–274 (2012).
67. Resio, D. T. & Westerink, J. J. Modeling the physics of storm surges. *Phys. Today* **61**, 33–38 (2008).
68. MacPherson, L. R., Arns, A., Dangendorf, S., Vafeidis, A. T. & Jensen, J. A stochastic extreme sea level model for the German Baltic Sea Coast. *J. Geophys. Res. Oceans* **124**, 2054–2071 (2019).
69. Baker, S., Murphy, E., Cornett, A. & Knox, P. Experimental Study of Wave Attenuation Across an Artificial Salt Marsh. *Front. Built Environ.* **8**; https://doi.org/10.3389/fbuil.2022.893664 (2022).
70. Kirwan, M. L. *et al.* Limits on the adaptability of coastal marshes to rising sea level. *Geophys. Res. Lett.* **37**, n/a-n/a; https://doi.org/10.1029/2010GL045489 (2010).
71. Weisse, R. et al. Sea level dynamics and coastal erosion in the Baltic Sea region. *Earth Syst. Dynam.* **12**, 871–898 (2021).
72. Möller, I. Quantifying saltmarsh vegetation and its effect on wave height dissipation: Results from a UK East coast saltmarsh. *Estuarine, Coastal and Shelf Sci.* **69**, 337–351 (2006).
73. Bomers, A., Schielen, R. M. J. & Hulscher, S. J. M. H. Consequences of dike breaches and dike overflow in a bifurcating river system. *Nat. Hazards* **97**, 309–334 (2019).
74. Marijnissen, R. J., Kok, M., Kroeze, C. & van Loon-Steensma, J. M. Flood risk reduction by parallel flood defences – Case-study of a coastal multifunctional flood protection zone. *Coastal Eng.* **167**, 103903 (2021).
75. van Lancker, V. et al. Coastal and nearshore morphology, bedforms and sediment transport pathways at Teignmouth (UK). *Continental Shelf Res.* **24**, 1171–1202 (2004).
76. Calafat, F. M., Wahl, T., Tadesse, M. G. & Sparrow, S. N. Trends in Europe storm surge extremes match the rate of sea-level rise. *Nature* **603**, 841–845 (2022).
77. Merkens, J.-L., Lincke, D., Hinkel, J., Brown, S. & Vafeidis, A. T. Regionalisation of population growth projections in coastal exposure analysis. *Clim. Change* **151**, 413–426 (2018).
78. Neumann, B., Vafeidis, A. T., Zimmermann, J. & Nicholls, R. J. Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. *PloS one* **10**, e0118571 (2015).
79. Sánchez-Arcilla, A. et al. Barriers and enablers for upscaling coastal restoration. *Nature-Based Solutions*, 100032; https://doi.org/10.1016/j.nbsj.2022.100032 (2022).
80. Cardona, O. D., et al. Determinants of risk: exposure and vulnerability. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (IPCC)., (eds. Field, C. B. et al.) pp. 65–108 (Cambridge University Press, Cambridge, UK & New York, NY, USA, 2012).
81. Piontek, F. et al. Integrated perspective on translating biophysical to economic impacts of climate change. *Nat. Clim Change* **11**, 563–572 (2021).
82. Neal, J. et al. Evaluating a new LISFLOOD-FP formulation with data from the summer 2007 floods in Tewkesbury, UK. *J. Flood Risk Manag.* **4**, 88–95 (2011).
83. Bates, P., Trigg, M., Neal, J. & Dabrowa, A. *LISFLOOD-FP User manual. Code release 5.9.6* (Bristol, 2013).
84. Burchard, H. & Bolding, K. *GETM: A General Estuarine Transport Model. Scientific Documentation* (European Commission, Joint Research Centre, Institute for Environment and Sustainability, 2002).
85. Garzon, J. & Ferreira, C. Storm surge modeling in large estuaries: sensitivity analyses to parameters and physical processes in the chesapeake bay. *JMSE* **4**, 45 (2016).

86. Alfieri, L. et al. Advances in pan-European flood hazard mapping. *Hydrol. Process.* **28**, 4067–4077 (2014).
87. Kaehler, C., Cantré, S., Schweiger, C. & Saathoff, F. Dune Erosion at the German baltic coast—investigation and analysis of a large-scale field experiment compared to life dunes. *JMSE* **10**, 1605 (2022).
88. *European Union Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructure and the assessment of the need to improve their protection* (2008).
89. Pesaresi, M. *et al.* GHS-BUILT R2015B - GHS built-up grid, derived from Landsat, multitemporal (1975, 1990, 2000, 2014) - OBSOLETE RELEASE. European Commission, Joint Research Centre (JRC) [Dataset]. Available at http://data.europa.eu/89h/jrc-ghsl-ghs_built_ldsmt_globe_r2015b (2015).
90. Schiavina, M. *et al. GHSL data package 2022. Public release GHS P2022* (Publications Office of the European Union, Luxembourg, 2022).
91. Lichter, M., Vafeidis, A. T. & Nicholls, R. J. Exploring data-related uncertainties in analyses of land area and population in the "Low-Elevation Coastal Zone" (LECZ). *Journal of Coastal Research* **27**, 757 (2011).
92. ABPmer. The Online Managed Realignment Guide (OMREG). Available at https://doi.org/10.1371/journal.pone.0058715 (2022).
93. Koch, E. W. et al. Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. *Front. Ecol. Environ.* **7**, 29–37 (2009).
94. Barbier, E. B. et al. Coastal ecosystem-based management with nonlinear ecological functions and values. *Science (New York, N.Y.)* **319**, 321–323 (2008).
95. Hughes, R. G., Fletcher, P. W. & Hardy, M. J. Successional development of saltmarsh in two managed realignment areas in SE England, and prospects for saltmarsh restoration. *Mar. Ecol. Prog. Ser.* **384**, 13–22 (2009).
96. Friess, D. A. et al. Remote sensing of geomorphological and ecological change in response to saltmarsh managed realignment, The Wash, UK. *Int. J. Appl. Earth Observ. Geoinform.* **18**, 57–68 (2012).
97. Bunya, S. et al. A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave, and Storm Surge Model for Southern Louisiana and Mississippi. Part I: Model Development and Validation. *Monthly Weather Rev.* **138**, 345–377 (2010).
98. Kiesel, J., Honsel, L. E., Lorenz, M., Gräwe, U. & Vafeidis, A. T. Baltic Sea flood maps under the influence of sea-level rise, dike height increases and managed realignment. Version v2. *Zenodo [data set]* (2023).

Acknowledgements

JK, ML, ATV and UG were supported by the Federal Ministry of Education and Research (BMBF, funding code 03F0860H). This work is a contribution to the ECAS-Baltic project: Strategies of ecosystem-friendly coastal protection and ecosystem-supporting coastal adaptation for the German Baltic Sea Coast. JK would also like to thank Lars Michelsen for his support in the design and preparation of Figs. 1 and 4. All authors would like to acknowledge Eric D. White and two anonymous referees for their thorough and constructive feedback, which greatly contributed to improving this manuscript. Finally, the authors would also like to thank the OpenStreetMap contributors and note that any OpenStreetMap (OSM) data used in our analyses is copyrighted by OpenStreetMap contributors and is available at https://www.openstreetmap.org.

Author contributions

J.K. performed the hydrodynamic modeling, prepared the elevation data, conducted the analysis, wrote the first draft of the paper and contributed to designing an approach for the automated detection of potential managed realignment sites. L.E.H. wrote the Python code for the MR model and performed the automated detection of potential managed realignment sites. M.L., U.G., A.T.V. and L.E.H. participated in the design of the study, the selection of the extreme water-level scenarios and in technical and content discussions. All authors contributed to editing, reviewing and revising the manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-01100-0.

Correspondence and requests for materials should be addressed to Joshua Kiesel.

Peer review information : *Communications Earth & Environment* thanks Eric White and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Claudia Zoccarato, Joe Aslin and Carolina Ortiz Guerrero. A peer review file is available.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.