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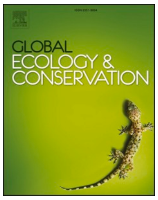

Sea level rise implications on future inland migration of coastal wetlands

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ABSTRACT

Coastal wetlands provide essential ecosystem functions, including coastal protection, improvement in water quality and carbon sequestration, which are threatened due to sea level rise (SLR) – a well-documented aspect of anthropogenic climate change. While there are numerous articles on SLR impacts on wetlands, data about the interactions between natural or human-made barriers and future SLR projections e.g. coastal squeeze are still sparse. If wetlands are bounded by natural formations or human-made structures, coastal wetlands could be permanently lost in a warming climate. Here we delineate impacts of SLR on wetland inland migration under a changing climate in six locations around the world with a particular focus on the consequences of human-made structures along coastlines in Europe, specifically along the largest continuous coastal wetland system in the world, the Wadden Sea. Various locations around the world (North America, South America, Europe, Africa, Asia and Australia) were chosen to analyze the impacts of regional SLR on wetland dynamics under climate change scenario. Our results show that places like Bangladesh, India and Myanmar have much larger areas at risk with nearly 10% of their coastal wetlands, whereas the wetlands in northern Australia seem to have a low area at risk to be lost with not even 1%. For the North Sea coast, wetlands where we had access to data from human-made infrastructure, we show that due to the built infrastructure, the wetland areas do not have the opportunity to evolve landward and hence, are expected to disappear permanently.

1. Introduction

Wetlands are identified as areas of land that are permanently or temporarily covered with water and are considered among the most valuable and productive ecosystems in the world to (Mitsch and Gosselink, 2015). Their importance was particularly emphasized in the 1971 UNESCO Ramsar Convention aimed to enhance international cooperation to foster wetland conservation. To date almost 90% of UN member states have joined and declared over 2400 wetlands “Ramsar Sites”, distributed in all climate zones, covering more than 2.5 million km^2 (Ramsar Convention Secretariat, 2021).

Coastal wetland ecosystems maintain vital functions and provide services that are crucial to humans and nature and include, among others, coastline protection (Chung et al., 2021; Costanza et al., 2014; Perillo et al., 2018; Sun and Carson, 2020), carbon sequestration (Morris et al., 2012; Nahlik and Fennessy, 2016) and biodiversity preservation, as they provide habitats for numerous plant, fish and bird species (Yang et al., 2017; Russi et al., 2013).

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The IPCC's latest Working Group I contribution to the Sixth Assessment Report, highlighted once more the threat that climate change and sea level rise (SLR) impose on coastal wetlands. The studies show that under the different climate scenarios, the projected rising sea levels exceed the levels of SLR reported in previous assessments (Masson-Delmotte et al., 2021). The Wadden Sea, for example, is one of the largest coherent coastal wetland ecosystems, and emerged around 8000 years ago along with the deceleration of the post glacial SLR (Reise et al., 2010). The Wadden Sea ecosystem adapted dynamically during the slow rate of the rising sea level, however, the projected acceleration in future SLR endangers this development (Graph inside Fig. 1).

The adaptive capability of coastal wetlands during rising sea levels can be attributed to sediment accumulation from sediments transported landwards by waves and sea tides (Reise et al., 2010) or from rivers. If the sediment supply is insufficient to make up for the SLR, the landward migration of the ecosystem during marine transgression can help to preserve coastal wetlands (Fig. 2a). However, coastal areas worldwide are home to hundreds of millions of people, and predictions show that the global coastal population will exceed one billion people this century (Hauer et al., 2020). To protect the coast from storms, floods and other SLR related hazards, a variety of structures were installed along coastlines. These structures along with natural barriers, like cliffs, prevent the landward migration of wetlands and can result in permanent disappearance of wetlands (Fig. 2b) this process is also known as coastal squeeze (Borchert et al., 2018; Torio and Chmura, 2013).

This study aims to analyze the impact of future SLR on coastal wetlands around the world with a focus on whether the wetlands have the opportunity to evolve into a new wetland environment. Our analysis includes natural or human-made barriers (Fig. 2), located alongside the North Sea coast in Europe adjacent to the largest coherent coastal wetland system in the world, that can be fatal to the future of some wetlands. In order to achieve this, locations in North America, South America, Europe, Africa, Asia and Australia were chosen (boxes labeled Zone 1 to Zone 6 in Fig. 1), that also have their significance as Ramsar Sites.

2. Methods

We used a geographic information system to assess the vulnerability of coastal wetlands to a 1 m SLR. In order to get information on the area that is at risk to be lost, we combined bathymetry data, digital elevation models as well as a database on the global extent of wetlands (see Figs. 3 and 4).

2.1. Digital elevation models and bathymetry

As a data source for our bathymetric information, we used the GEBCO_2021 Grid data. This global terrain model for ocean and land provides elevation data with a spatial resolution of 15 arc-seconds (GEBCO Compilation Group (2020). However, this data has a relatively coarse resolution, which might be challenging in shallower water depths that are more susceptible to changes in morphology due to tidal and wave action. For the land and terrain elevation information we could use the SRTM 1 Arc-Second Global elevation data offering a much higher resolution than the GEBCO grid data (Earth Resources Observation and Science (EROS) Center, 2017, Farr

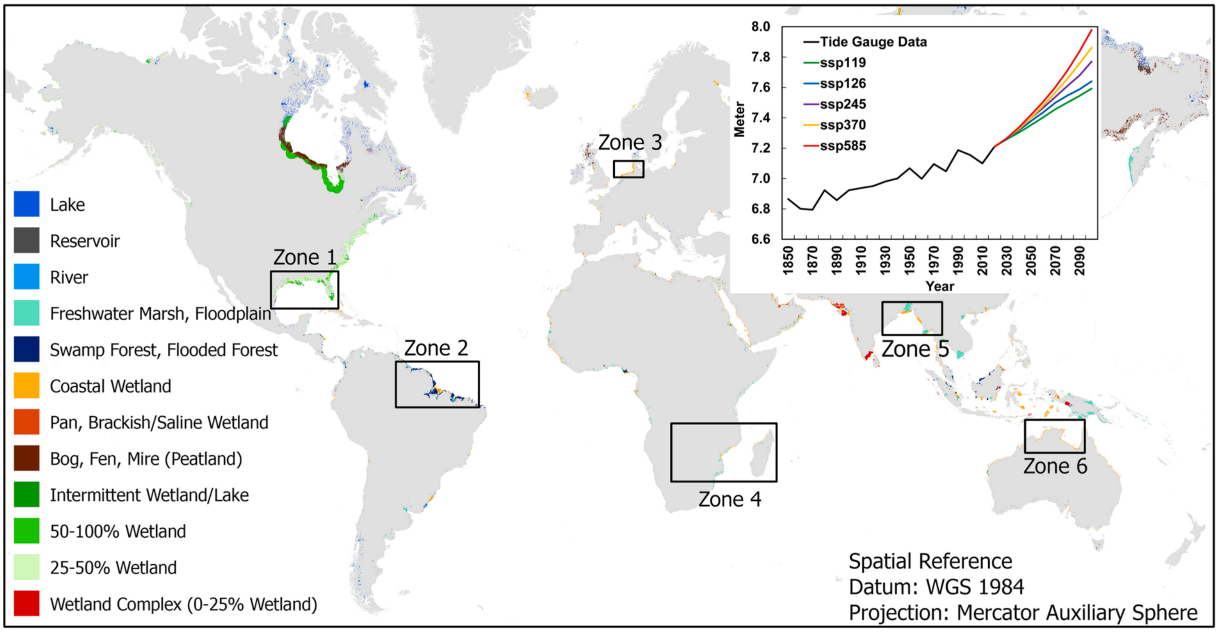

Fig. 1. Global map that shows the different types of wetlands within 100 km of the coast. The graph over Asia shows the measured sea level change over the past 170 years in black and the different projected SLR scenarios in color for the tide gauge station Cuxhaven 2, located in Germany. The black boxes show the six study areas (Zone 1 to Zone 6) that are investigated in this study.

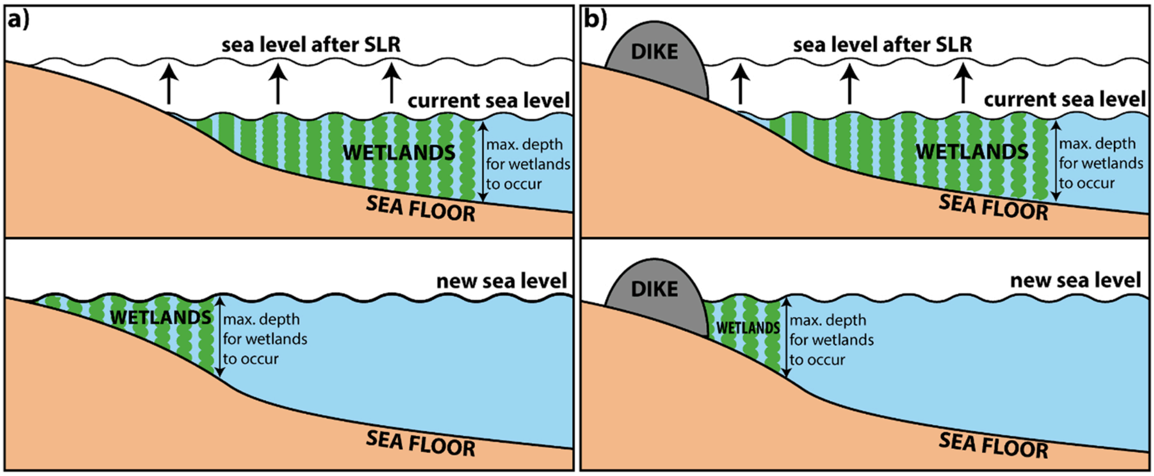

Fig. 2. Illustration of a) wetlands moving landwards due to SLR; b) coastal morphology, natural barriers or human-made structures/cities could prevent the wetlands from naturally migrating inland under SLR.

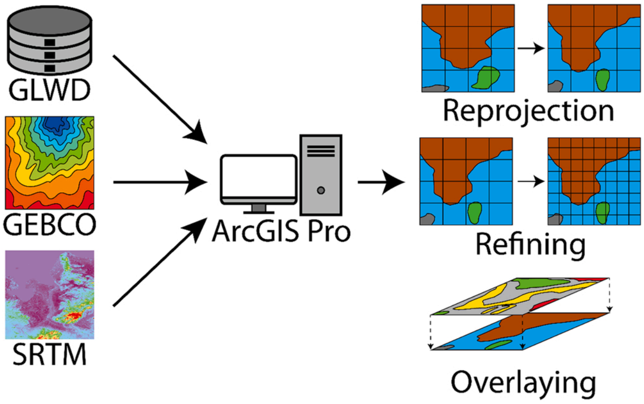

Fig. 3. Flowchart showing an overview of the basic steps of the workflow used in this study.

et al., 2007). The GEBCO_2021 Grid was refined via resampling to the cell size of the SRTM grid.

2.2. Wetland database

The main source for the distribution and classification of the wetlands was the Global Lakes and Wetlands Database (GLWD), which is a combination of several existing datasets and provides a good representation of the maximum extent of global wetlands with a spatial resolution of 30 arc-seconds (Lehner and Döll, 2004). There are various types of coastal wetlands such as salt marshes, freshwater marshes, seagrass beds, mangrove swamps as well as forested swamps. The GLWD contains one layer for coastal wetlands that includes mangroves, estuaries, deltas and lagoons. However, there are also separate layers for freshwater marshes, swamps and flooded forests, saline wetlands and also different layers that are categorized as wetland complexes with varying percentages that can be included as coastal wetlands. To include the different wetland categories appropriately, a coastal zone had to be chosen in which those wetland types that are not clearly classified as coastal wetlands are included. We chose the coastal zone that was defined in the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment (Program), 2005) which includes an area that is closer than 100 km from the sea but that doesn't exceed 50 m elevation. Towards the sea we decided to choose areas that don't exceed water depth of 60 m due to depth limitation of sea grass beds.

2.3. Sea level projections

The data used for the different sea level projections was created by the Working Group 1 contribution to the Intergovernmental Panel on Climate Change's Sixth Assessment Report. We used sea level projections created from CMIP6 models for this assessment (Fox-Kemper et al., in press).

Fig. 3 shows how the various data sources were combined using the ArcGIS Pro 2.7.0 software. To work with the different types of

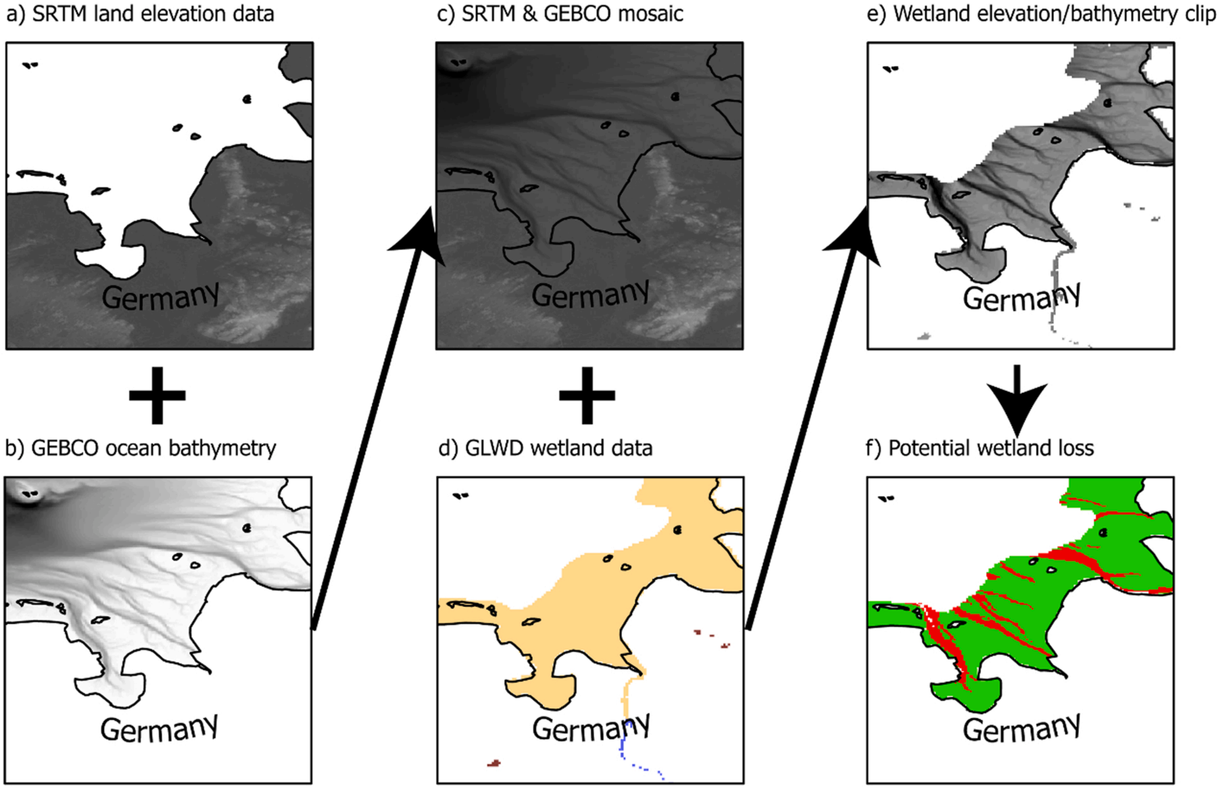

Fig. 4. Flowchart showing detailed steps of the overlaying process used to analyze the data.

data, we had to firstly project the data in appropriate coordinate system for each of the six zones. The second step encompasses refining the data in order to have identical cell sizes throughout our datasets. Once the data is refined, through the method of resampling, we could create mosaic datasets from the SRTM land elevation data and the GEBCO ocean bathymetry (Fig. 4a), b) and c)). The last step in Fig. 3 depicts the overlaying of the data. This is necessary to be able to use different geoprocessing tools such as clipping the data. Once the wetland data from the GLWD (Fig. 4d)) is clipped with the previously created mosaic (Fig. 4c)), more geoprocessing tools, e.g. raster calculator can be applied. An important step is the overlaying of the data to use different geoprocessing tools such as the raster calculator. Fig. 4f) shows how results from calculations of the raster data (Fig. 4e)) might look.

3. Results

In this study, we considered coastal wetlands on all continents, besides Antarctica, categorized into six zones (Fig. 1). Zone 1 is located in North America and comprises nearly the entire southern coast of the USA (Fig. 5). Our analysis showed that the majority of wetlands in this zone were classified as “Intermittent Wetland/Lake”, “50–100% Wetland” and “25–50% Wetland”. The extent of wetlands is nearly 19 million ha and ranges from around 50 m below sea level to 50 m above sea level (Fig. 6).

Located in South America is Zone 2, which includes large parts of the Brazilian coast (Fig. 5). Wetlands in this area were classified as “Coastal Wetland”, “Swamp Forest, Flooded Forest” and “Freshwater Marsh, Flooded Forest” and range from 95 m below sea level to 50 m above sea level (Fig. 6) making up an area of around 16.7 million ha. On the European continent we choose the Wadden Sea for our analysis which makes up Zone 3. As presented in Fig. 5, this entire area was classified as “Coastal Wetland” and spreads over the North Sea Coast of Germany, Netherlands and Denmark. Wetlands were mapped from 40 m below sea level to 50 m above sea level (Fig. 6) and cover an area of around 1.2 million ha.

Zone 4 is located in the southwest of the African continent and spreads mainly along Mozambique and South Africa (Fig. 5). “Coastal Wetland” and “Freshwater Marsh, Floodplain” make up the entirety of the wetland area in this zone covering an area of 1.3 million ha and ranges between 100 m below sea level and 50 m above sea level (Fig. 6). The wetlands in Zone 5 are mainly located in Bangladesh, India and Myanmar (Fig. 5) and were chosen as our study area for Asia. An area of around 10.4 million ha were mapped as “Coastal Wetlands” and “Freshwater Marsh, Floodplain”. The extent of the mapped wetlands in this zone varies from 100 m below sea level to 50 m above sea level (Fig. 6). The coastline of the Northern Territory and some of Queensland, Australia make up our area of interest on the Australian continent, Zone 6. The wetlands along the coastline were classified as “Coastal Wetlands” and have an extent of around 3 million ha (Fig. 5). They range from 85 m below sea level and 50 m above sea level (Fig. 6).

The classification used for the Global Lakes and Wetlands Database (GLWD), shows clear differences in the identification of wetland

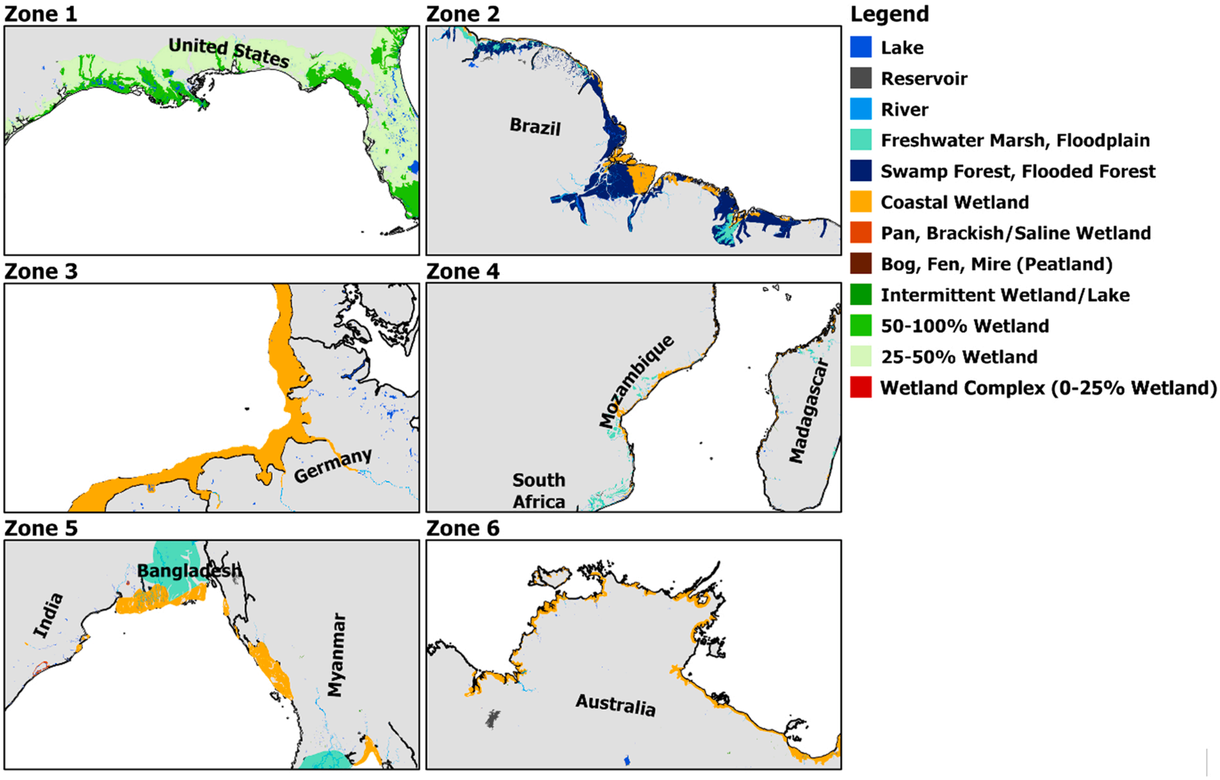

Fig. 5. Close up maps of the six zones highlighted in Fig. 1.

areas in coastal regions. For our analysis, we generated overlays of the wetland data with the bathymetry and land elevation data, allowing us to visualize the impacts of current and future sea levels based on wetlands elevation information (see the Methods section for more details). Fig. 5 shows that Zone 1 has a very large wetland area along the coast, however, it is not classified as "Coastal Wetland" but as a combination of wetlands, virtually a wetland complex. In all other zones the classification includes "Coastal Wetlands". Our data shows that the water depth in which coastal wetlands were mapped is much deeper in all six zones than what would occur naturally. This can be observed, for example in Fig. 6, where it shows depths of coastal wetlands in Zone 2, 4 and 5 of ~100 m below sea level, which is far too deep even for seagrass beds in tropical regions (Durako et al., 2003). This might be due to the coarse resolution of the GLWD. If we look at the distribution of the mapped wetlands over depth of occurrence, we can see in our data that in Zone 1, 2 and 4 (Fig. 6) large areas were mapped above sea level. In all three zones over 90% of the mapped wetlands were between 0 m and 50 m. In order to make better estimates of percentage losses of wetlands by zone, we only looked at wetland regions mapped below sea level up to a depth of 6 m (Fig. 7). The area of coastal wetlands in that range are much smaller than the mapped extent. From our analysis we estimate that only ~630 thousand ha of coastal wetlands are located between 0 m and 6 m water depth in Zone 1 (Fig. 7). Zone 2 has ~400 thousand ha, Zone 3 ~670 thousand ha, Zone 4 only ~22 thousand ha, Zone 5 has nearly 940 thousand ha and Zone 6 has ~770 thousand ha in the range between 0 m and − 6 m (Fig. 7).

Our results indicate that the area of wetland that is at risk of permanent loss due to 1 m SLR is largest in Zone 5 with nearly 10% (see Fig. 7). The second most affected area is Zone 2 with over 6%, followed by Zone 4 with ~5%, and Zone 1 and Zone 3 with both around 2.6%. Zone 6 wetlands appear to show the lowest area at risk with nearly 0.5%.

This study shows that vast areas that are currently classified as "Coastal Wetlands" and also wetlands that are just in coastal areas, are above sea level and a large fraction is not expected to entirely "drown" under 1 m of SLR. However, using a threshold of 6 m water depth for wetland definition, indicates that up to 10% of wetlands in some areas (Fig. 7 Zone 5) are at risk of permanent disappearance. The results indicate that coastal areas most threatened by SLR area in are in Bangladesh, India and Myanmar (Zone 5 in Fig. 7). These results are in line with the concerns discussed in other studies regarding the areas that seem to be greatly vulnerable to SLR (Hooijer and Vernimmen, 2021; Kibria and Yousuf Haroon, 2017). Northern Australia (Zone 6), where the environment is relatively pristine compared to other areas exhibits the lowest risk. However, the results confirm that permanent loss of coastal wetlands are expected globally and in all climate zones due to SLR consistent with other findings though with different rates (Blankespoor et al., 2014; Crosby et al., 2016; Rodríguez et al., 2017; Spencer et al., 2016; Woodruff, 2018). We note that the percentages presented here correspond to fraction of wetlands lost permanently due to 1 m SLR. In practice, a much larger area will be impacted due to the rising baseline that will also affect tidal range and enhance storm future storm surges. For this reason, the estimated loss reported here should be considered as the lower bound of future impacts.

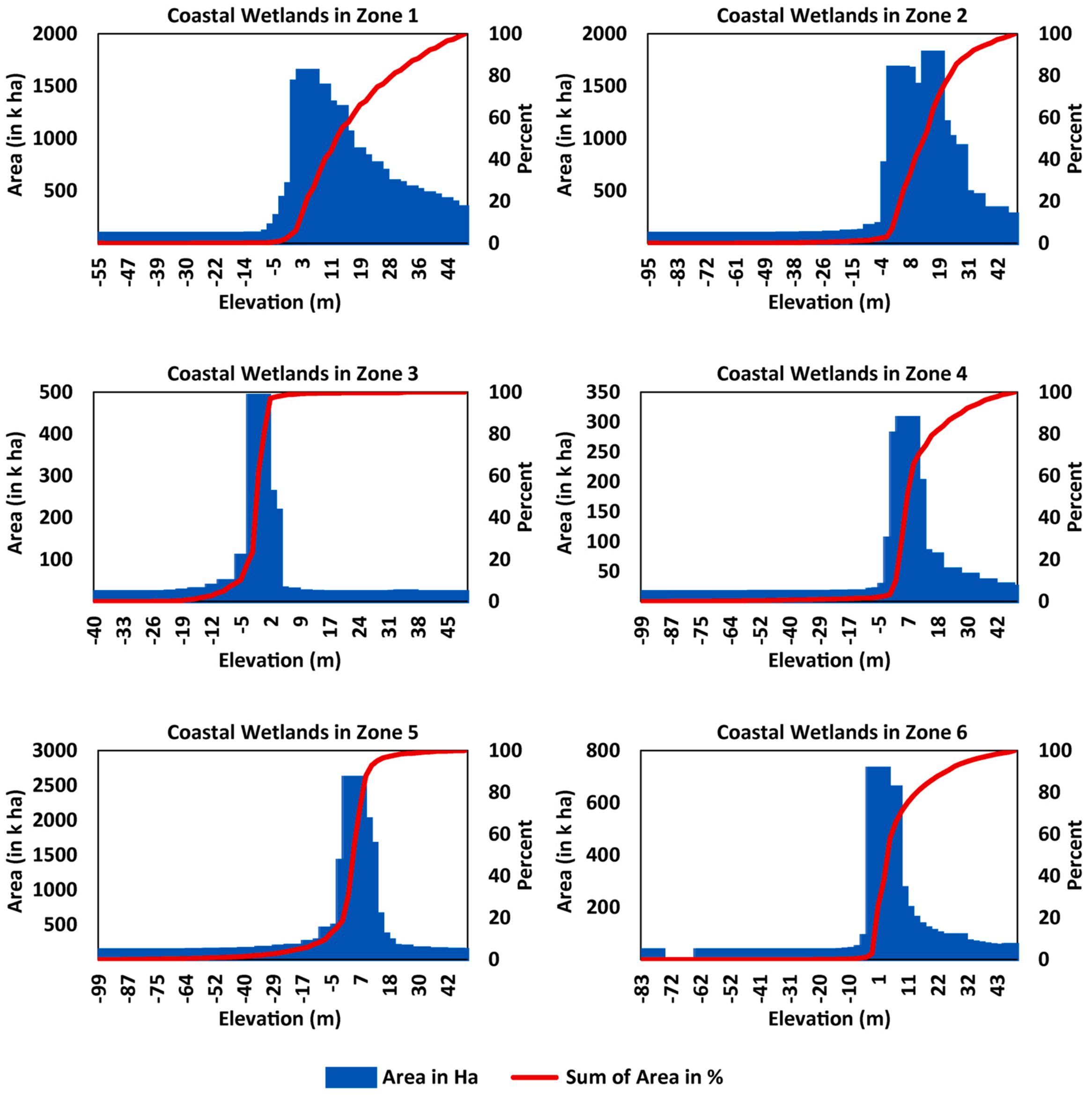

Fig. 6. Area of coastal wetlands plotted over elevation for every zone.

3.1. *Influence of human-made barriers*

The influence of human-made barriers built for coastal protections on the landward migration of the coastal wetlands has been rarely discussed in literature partly due to lack of data. Currently, conducting such analysis for the entire globe considering human-made infrastructure is not possible as there is not such global product. Here, we show the adverse consequence of such built environments on the fate of coastal wetland extending along the entire North Sea coast of Germany, called the Wadden Sea, where such data is available. The Wadden Sea is one of the world's largest intertidal wetlands registered on the UNESCO World Heritage List (Huismans et al., 2022). Fig. 8 shows the expansion of the Wadden Sea along Germany in green, and in red the area of the wetland that is at risk under 1 m SLR. Also shown in this figure is the blue colored area that displays the parts of the mainland that would be flooded at a 1 m SLR. This flooded area is large enough to compensate for the ecosystem at risk of drowning, however, the thick black line shows the location of dams, walls and dikes that are built as protection structures along the entire North Sea coast of Germany. The dikes have a height of around 8 m above the mean sea level and are expected to be elevated to over 9 m due to projected future SLR (D. J. Hofstede, 2008; D. J. (MLUR) Hofstede, 2022.; J. Hofstede and Hamann, 2022).

Since the entire coastline has a protective barrier, the event conceptualized in Fig. 2b is expected to occur. Our analysis reveals that more than 2,5% of the coastal wetlands in Zone 3 (Fig. 7), which mainly comprises of the German North Sea coast, will be under risk of being lost. Due to the presence of the human-made structure along the coast, there will be no opportunity for the wetland to evolve into

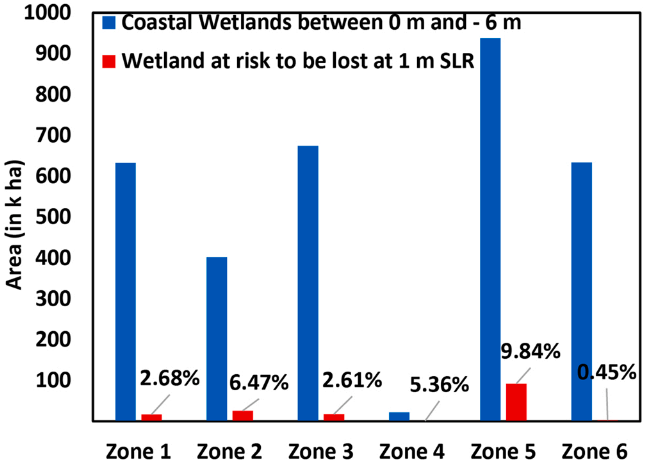

Fig. 7. Area of coastal wetland that lies extents between sea level and 6 m water depth (blue). In red is the area that is at risk at a SLR at 1 m. The locations of the zones were illustrated in Figs. 1 and 5.

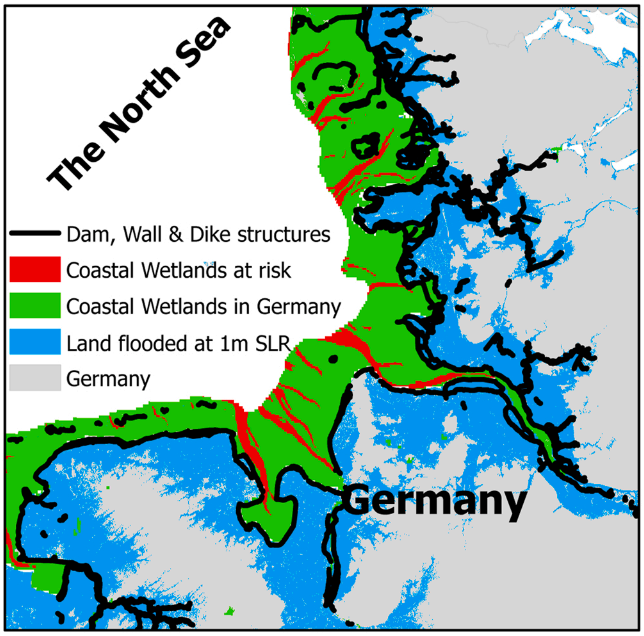

Fig. 8. Map of the German North Sea coast.

a new system by moving landward and thus, these wetlands (facing human-made barriers) may be lost permanently leading to severe consequences on ecosystem. Given that significant populations live close to the coastal areas (Hauer et al., 2020), it can be concluded that wide areas along the shorelines will be protected by structures. An increase in the coastal population will also lead to an increase in the number of protective structures to be constructed and prevent the wetlands from migrating landwards.

4. Summary and Conclusions

In this study, we investigated the implications of climate change and the accompanying SLR on the evolution of coastal wetlands. Our results showed that there are wetlands at risk on all continents, however it is unclear how much of the ecosystem will be lost and how much can adapt through a landward migration. It should be noted that the vertical growth of biomass has not been considered in this analysis that may contribute to the survival of the wetland. Quantifying dynamic changes in wetland ecosystems can be challenging due to several unknown parameters related to driving forces. Under certain conditions involving high sediment influx into coastal areas, there could be even an increase instead of a decrease in coastal wetlands (Schuerch et al., 2018). That being said, in this analysis, we examined only the horizontal shift of wetlands and did not assume any increase in sedimentation. To examine this closer, we analyzed the migration possibilities of one of the world's largest coastal wetland systems. This could be done due to the data availability in Europe. Information on natural or human-made barriers in other locations are not readily available. Such information is vital to have an accurate understanding of the complex coupling between wetland dynamics and human-made structures. This information is needed to devise the necessary action plans for coastal wetland protections.

Digital elevation models have improved greatly over the past decades, however, it is still challenging to obtain global datasets with very fine horizontal and vertical resolutions for studying wetlands. The same applies for global bathymetry datasets, especially close to the coast, as in our study. Coastal wetlands usually occur in water depths too shallow for vessels recording bathymetry. Hence, the accuracy and reliability of the bathymetry data in water depths below 10 m is hard to evaluate. The relatively coarse resolution of datasets, vertical usually 1 m or more, horizontal even more than 100 m, makes it almost impossible to determine fluctuations of sea level changes that are in the centimeter range. Due to those limitations, we assumed a sea level increase of 1 m, which is most likely expected to happen under scenario SSP3–7.0 and SSP5–8.5 in all of our locations by the year 2150 and in Zone 1 even under scenario SSP2–4.5. The changes between the different scenarios are too fine, only several centimeters or decimeters, to make valid predictions using the datasets available to us. Elevation data, obtained by lidar, has substantially improved vertical accuracy over the past decades (Gesch, 2009) however, we could not obtain those fine datasets for the areas of interest in our study. Datasets with a higher spatial resolution could significantly improve the analysis of wetlands in coastal zones. It would allow us to make more accurate statements about the distribution of these ecosystems.

Another limiting factor is the variability of coastal areas, not only on land but also below the water surface. Tidal activity and natural alterations can change the morphology of the area under investigation in a relatively short time. Heavy storms for example, can erode or modify the ground in the order of several centimeters during a single event. Therefore, it is very difficult to make clear statements about long-term changes. Since we did not have fine resolution bathymetry data, we had to exclude tidal activity in this study, although tidal activity has an impact on morphology and the overall ecosystem.

Inundation models, used in this study, for SLR have many advantages but also disadvantages e.g. areas of inundation are often overestimated when the connectivity of water is ignored (Mcleod et al., 2010). In our analysis we only counted areas that had connections to the ocean to counter this problem. Another disadvantage of the inundation model for this analysis is that it does not account for possible feedbacks on wetland accretion. We discounted this in our study due to the rapid increase in SLR, which is expected to be much faster than in previous times where sedimentary accumulation was more likely to happen (Graph inside Fig. 1).

The Global Lakes and Wetlands Database (GLWD), that was used to identify wetland areas in this study, is very comprehensive but it has some limitations. This global dataset was created by combining data from different datasets with various levels of accuracy and resolution. As a result, the information the accuracy is not necessarily consistent across space, primarily because, unlike lakes and rivers, partially under water areas cannot be mapped easily via satellites. In some locations, coastal wetlands were mapped in areas with water depths of more than 100 m. Coastal wetlands cannot even remotely exist at those depths and it is likely that the mapping was done with horizontal resolutions that were too coarse and in areas with deep slopes close to the shore. Another issue with the GLWD is that the classification is not consistent globally. In Zones 2, 3, 4, 5 and 6 the coastal wetlands were classified as "Coastal Wetland", whereas in Zone 1 nearly the entire southern coast of the USA was classified as "25–50% Wetland" or "50–100% Wetland". This makes the analysis very difficult, especially since that area is so large and at a very low elevation. It is likely that wetland types such as coastal wetlands, floodplains, swamps, bogs and others are included in that "25–50% Wetland" or "50–100% Wetland" layer. Although global datasets of wetland types, that also occur in coastal regions, exist in a finer resolution e.g. mangroves and salt marshes (Giri et al., 2011; Mcowen et al., 2017) the GLWD seemed to be the most complete dataset of global coastal wetlands that we could acquire.

Considering the variety of different study areas spread over six continents in different climatic zones, we used a rather simple model for our analysis. We decided not to use the finest datasets available, which are only for certain types of coastal wetlands in certain regions, but instead the datasets that we considered to cover the different areas with a similar accuracy. Another consideration of this assessment is the variety of biota that makes up the coastal wetlands. The six zones looked at in this study are located in different climatic zones, resulting in different plant populations. The location might also be affected by the angle of the sun, e.g. if the wetlands are closer to the equator, the sun might penetrate the water to deeper levels, allowing plant growth at greater water depths. In our analysis, we neglected the effects of such differences on wetland inland migration and we assumed that all types of coastal wetlands behave the same. In reality, different wetlands may react differently to the projected SLR but such an assumption could serve the purpose of our analysis which was to investigate and highlight the extent and possible consequences of built structure or natural barriers on inland migration of coastal wetlands. According to (Mitsch and Gosselink, 2015) coastal wetlands exist to a water depth of 6 m at low tides. The tides can vary, depending on the location, by up to several meters. However, in some regions there are sea grass beds, that are also considered as coastal wetlands, that exist at much greater depths. Sea grass beds can exist up to 50 m water depth (Durako et al., 2003) and some sea grass species (Halophila decipiens) are apparently located even deeper at ~80 m. The reliability of results in areas that contain sea grass beds at such depths is questionable. Therefore, we considered coastal wetlands in our study up to a bathymetry depth of 6 m.

Previous studies have shown that SLR impacts the loss of coastal wetlands much less than direct human modification (Kirwan and Megonigal, 2013). Coastal wetlands have the ability to compensate the "drowning" by transgression and also by geomorphological feedback mechanisms e.g. vertical sediment accretion (Kirwan et al., 2016; Kirwan and Megonigal, 2013; Schuerch et al., 2018). However, wherever humans create urban areas close to the coast it is likely there will be protection infrastructure, constructed to prevent areas from inundation. Those act as barriers and will generate coastal squeezing and that can result in coastal wetland losses (Enwright et al., 2016). The survival of coastal wetlands depends on a number of dynamic factors whose mechanisms of interaction have not been well understood. In this analysis, we only considered the landward migration and the effect of coastal squeeze by human-made structures. Important factors that need further study include the impact of socio-economic pathways or the potential availability of buffer zones for coastal wetland ecosystems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data are already available with the required references provided in the paper.

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