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Sea level rise risk to critical infrastructures: assessment and adaptation using open-access tools and data

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ABSTRACT

Sea level rise is one of the most pressing climate concerns, which is already having an impact on many low-lying islands and coastal communities all over the world. Critical infrastructure and livelihoods in coastal areas are at high risk due to rising sea that increases coastal erosion and flooding. The socioeconomic impact in these areas is expected to increase significantly as a result of global warming based on recent climate projections. Therefore, it is essential to assess the vulnerability and potential damages of the exposed areas and infrastructure, in support of decision-making for risk mitigation and adaptation measures. In this context, a two-level methodology is introduced, to assess the impact of sea level rise on critical coastal infrastructures such as port facilities. Firstly, a physical coastal vulnerability index (PCVI) is adopted, to assess the vulnerability of the study area under current climate change conditions. Secondly, a flood loss assessment approach is employed, to quantify the potential impact of future flood events on infrastructure under various climate change scenarios and return periods using flood depth-damage functions.

This methodology is applied to Harwich, a coastal town in southeast England, and a major port for cross-channel ferry and freight traffic. Open access tools are employed to collect and process the required data, i.e. Google Earth, QGIS and open flood maps with climate projections. The PCVI assessment showed an overall low vulnerability under current climate conditions, while the loss assessment for selected infrastructure (railways, roads, and buildings) under flood events with return periods of 25-, 50-, and 100-years would result in losses ranging from £11M to £15M under RCP scenarios 4.5 and 8.5 in 2030, 2050 and 2080. Adaptation strategies to the rapid and uncertain changing climate are grouped in three categories, including protection, adaptation, and accommodation. The choice of an adaptation measure should consider the economic, social, and environmental impact associated with these strategies. The vulnerability and loss assessments facilitate decision-making, toward minimising negative consequences and increasing the resilience of the exposed infrastructure and communities.

Keywords: sea level rise, critical infrastructure, vulnerability, adaptation measures

INTRODUCTION

Climate change is one of the biggest challenges of our time, while sea level rise is one of the major consequences of the changing climate that threatens coastal infrastructure and communities that live in coastal regions and low-lying islands (Koks et al., 2019). Mean Sea Level (MSL) rise is defined as an increase in the time average height of the sea with respect to the land at a certain place by eliminating short duration fluctuations like waves, surges, and tides. The spatially averaged MSL corresponds to the Global Mean Sea Level (GMSL), which, based on observations, has been increased by about 21–28 cm since 1880, with 8 cm occurring since 1993 (NOAA, 2017). The assessment of the future rise in GMSL due to thermal expansion, melting of glaciers and ice sheets, and changes in terrestrial water storage, is substantially influenced by the emission scenario used in the Representative Concentration Pathway (RCP) (Church et al., 2013). GMSL is projected to rise between 0.43 m (0.29-0.59 m, likely range; RCP 2.6) and 0.84 m (0.61-1.10 m, likely range; RCP 8.5) by 2100 relative to 1986-2005 (Oppenheimer et al., 2019).

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As a result of the rising sea level, a substantial increase is expected in the exposure and vulnerability of the growing population in coastal regions, as well as of the critical infrastructure, e.g., transportation, energy, trade, and coastal ecosystems (Dawson et al., 2016a; Adams and Heidarzadeh, 2021). The sea level rise impact affects infrastructure in different ways (Azevedo de Almeida and Mostafavi, 2016), including (i) accelerated degradation of infrastructure due to chronic and acute weather impacts (e.g., storm surges), (ii) increased exposure of infrastructure to disruptive events, and (iii) greater likelihood of cascading failures due to increased interdependencies between infrastructure. Hence, the impact of sea level rise on critical infrastructure will greatly affect the socio-economic aspects of coastal regions. For example, 15% of the major road network and 4–5% of the railway network and stations in the UK, are in areas with a 'significant' or 'moderate' annual chance of coastal flooding (Dawson et al., 2016b). Also, a recent global analysis concluded that a large number of airports is at risk due to rising sea, and depending on the rate of sea level rise, this risk could increase by a factor of 17 to 69 by 2100 (Yesudian and Dawson, 2021).

A main step in the risk analysis of critical infrastructure is their vulnerability assessment (Argyroudis et al., 2019). Vulnerability of infrastructure refers to the degree to which its assets and systems are susceptible and unable to cope with the adverse impact of external stressors, including diverse climatic conditions (Shen et al., 2016). The coastal vulnerability index (CVI) is a widely used method that is adapted to assess the vulnerability of coastal areas exposed to coastal and climatic hazards, based on various parameters that describe the topography and ecosystem of the study area. Palmer et al. (2011) used the CVI to investigate the relative coastal vulnerability of the Kwazulu-Natal in South Africa, exposed to erosion and extreme weather events, while Islam et al. (2016) adapted the CVI to predict the future recession of the shoreline at the Ganges deltaic Coast, in Bangladesh. Kantamaneni et al. (2018) assessed the vulnerability of coastal infrastructure in the Aberystwyth coast, using the CVI and its associated fiscal factors, while Kantanameni et al. (2019) adapted the PCVI by adding additional weighting parameters relating to the estuarine environment and the physical structure of the port of Southampton, UK.

Quantifying the impact loss for different climate conditions is valuable for improving the understanding of risk and communicating the relative importance of natural hazard risks and other factors such as location, land use, or zoning, contributing to that risk (Scawthorn et al., 2006). Flood impacts are commonly quantified using depth damage functions, which correlate the hazard intensity (e.g., inundation depth) and the average damage percentage of the asset under study. HAZUS is a standardized methodology for estimating potential losses risk from natural hazards developed by the United States Federal Emergency Agency (FEMA, 2020), including depth damage functions for different assets. The flood damage estimator is an alternative GIS-based approach to the HAZUS model used by Karamouz et al. (2016), while Small et al. (2016) assessed the Coastal Environmental Risk Index (CERI), an online GIS-based system, by combining storm surge and wave estimations with erosion maps and damage functions, to assess the impact of different adaptation strategies for individual buildings.

The JRC report (Huizinga et al., 2017) provided a globally consistent database of flood depth-damage curves, representing fractional damage as a function of water depth, as well as appropriate maximum damage values for a range of assets and land use classes. Habermann and Hedel (2019) presented a collection of depth damage curves, which can be used for modelling transport infrastructure, including roads and railways affected by floods. Kellerman et al. (2015) presented an empirical approach to assess the structural flood-induced damage to railways and the associated economic losses, combining previous damage data from Austria and simulated flood parameters such as water levels or flow velocities. More recently, geospatial analytics using open-access tools (Google Earth) and cloud-stored elevation data were employed, to provide rapid floodwater depth estimations during flood events (Peter et al., 2020). Emerging digital technologies such as Artificial Intelligence combined with satellite imagery can further improve rapid flood risk assessments (Argyroudis et al., 2022). Yet, the available flood damage models are limited and further research and damage data are needed to develop reliable models for critical infrastructure exposed to flood events.

This paper introduces a two-level methodology to analyse the vulnerability of a coastal area and to assess the impact of sea level rise to critical infrastructure using open-access tools and data. The first level assesses the vulnerability of a coastal area to sea level rise under the current baseline conditions based on the physical coastal vulnerability index (PCVI) (Kantamaneni et al., 2019). The second level combines flood hazard layers along with flood depth-damage functions to assess the losses that could be caused by coastal floods due to the rising sea level for different return periods and climate projections. Adaptation measures are suggested for port infrastructure with the highest risk, to enhance their resilience to sea level rise.

METHODOLOGY

The proposed framework is shown in Figure 1 and the two levels assessment is explained in the following paragraphs.

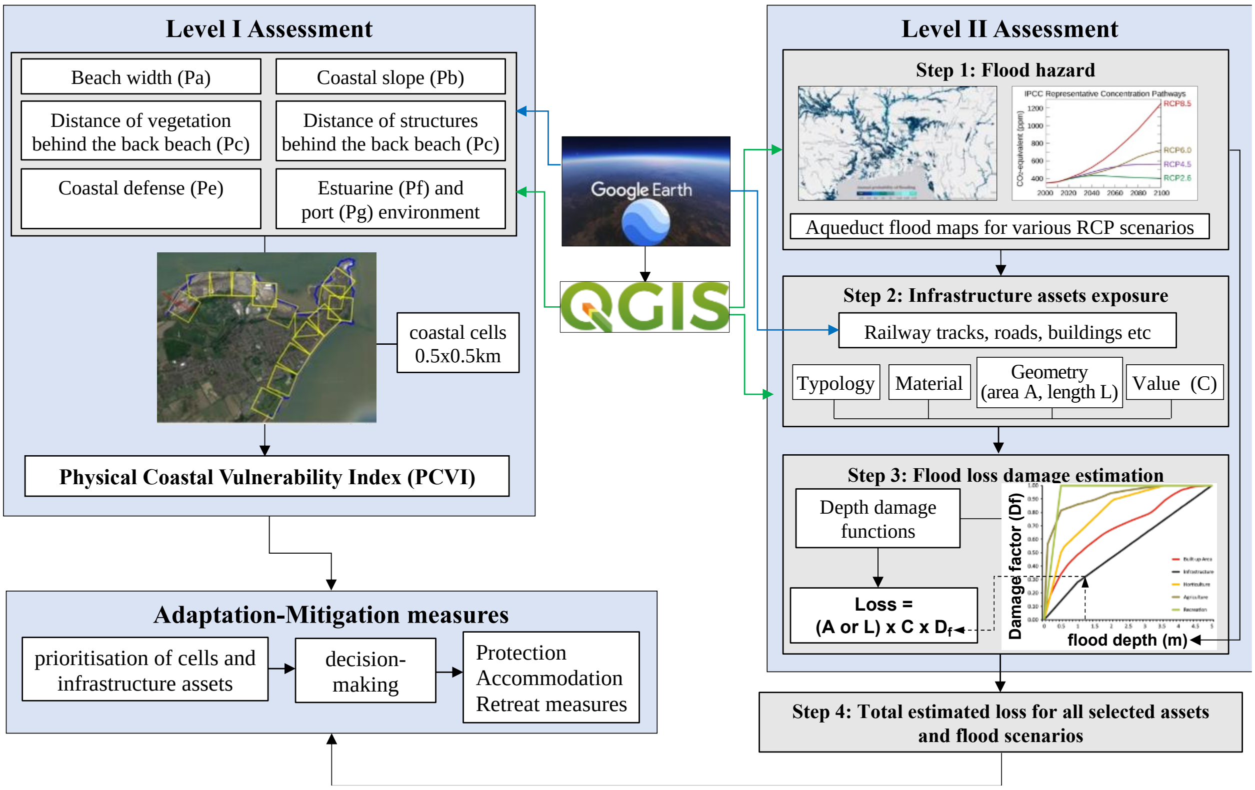

***Figure 1.** Methodology flowchart for vulnerability and loss assessment to coastal flooding to inform decision-making for adaptation measures*

Level I: Physical Coastal Vulnerability Index (PCVI)

The PCVI was introduced by Kantamaneni et al. (2018) to assess the vulnerability of coastal areas, by rating physical parameters associated with the surrounding ecosystem. The parameters and their ranking to different levels of vulnerability, from extremely low (1) to high (4), are described in Table 1. The study area is divided into grid cells (e.g., 0.5x0.5 km) along the coastline, and the physical parameters are ranked into classes of vulnerability for each cell, by retrieving relevant data from open access platforms such as the Google Earth Engine. In this way, the coastal vulnerability is assessed by measuring the five parameters related to the estuarine environment and the infrastructures in the area. In particular, the parameters are integrated into a single PCVI for each cell (Equation 1), which describes the total relative vulnerability score. Based on the resulted value of the PCVI, the vulnerability of each cell is ranked into five classes (Very low, Low, Moderate, High, Very high) according to Table 2.

$$PCVI = Pa + Pb + Pc + Pd + Pe + Pf + Pg \qquad (1)$$

Level II: Flood loss assessment using depth-damage functions

Level I assessment aims at ranking the vulnerability of the study area cells. To quantify the impact of coastal floods on the infrastructure of the study area, a Level II approach is adopted including four steps (Figure 1). In step 1, flood hazard maps are obtained, and flood depths are identified for different scenarios. Flood hazard maps are available from different sources at variable resolution, e.g., at national or global scale. In this paper, Aqueduct open access flood maps are employed, to define the extent and depth of coastal floods. This is an online platform developed by the Water Resources Institute (WRI) in collaboration with other agencies, which helps measure global flood risk based on the current baseline and future projections in 2030, 2050, and 2080

(Ward et al., 2020). Different RCP scenarios and return periods are selected and the corresponding maps are imported into QGIS. Google Earth is used as a base map to retrieve the topology of infrastructure assets at risk and obtain the flood depth at the points of interest. The overlay of the flood maps with the infrastructure layers provides the exposure of infrastructure assets to flood events (step 2). For the study area, port infrastructure assets such as roads, railways and buildings exposed to flood inundation were considered. In step 3, the damage loss for each asset is estimated, using the depth damage factor. The evaluation is based on damage functions, which describe the relationship between the water depth and the damage caused to the infrastructure. Such damage functions are available in the literature and have been produced based on empirical data and/or expert judgment. Finally, the total expected loss for each infrastructure is estimated (step 4) for the selected RCP scenario and return period by adding the losses estimated in step 3. The loss for each infrastructure asset is estimated based on Equation 2.

$$\text{Loss} = (\text{A or L}) \times \text{C} \times \text{D}_f \tag{2}$$

where C is the cost per unit of the given infrastructure, and Df is the depth damage factor. A refers to the total area of buildings and L to the total length of linear infrastructure (e.g., roads, railways) in a zone with a particular flood depth.

The results of Level I and II assessments can facilitate the prioritisation of cells and infrastructure assets and inform decision-making for the allocation of resources toward mitigation measures for adapting to changing climate conditions.

Table 1. *Rating of physical parameters (PCVI) to different levels of vulnerability (Kantamaneni et al., 2019)*

Physical parameter	**Extremely low (1)**	**Low (2)**	**Moderates (3)**	**High (4)**
Beach width (Pa)	> 150 m	100 – 150 m	50 – 100 m	< 50 m
Coastal slope (Pb)	> 12%	12 – 8%	8 – 4%	< 4%
Distance of the vegetation behind the back beach (Pc)	> 600 m	200 – 600 m	100 – 200 m	< 100 m
Distance of the built structures behind the back beach (Pc)	> 600 m	200 – 600 m	100 – 200 m	< 100 m
Coastal defence (Pe)	> 50%	20 – 50%	10 – 20%	< 10%
Pf and Pg are additional weighting score related the estuarine and port environment respectively				

Table 2. *Rating of PCVI to different classes of vulnerability (Kantamaneni et al., 2019)*

PCVI	**Vulnerability**
< 15	Very low
15 – 17	Low
18 – 20	Moderate
21 – 24	High
25 – 28	Very high

CASE STUDY

Harwich is a traditional historic maritime town formed by the union of the Stour and Orwell estuaries located in southeast England in the administrative county of Essex (Figure 2). It is an important major port for cross-channel ferry and freight traffic, the second busiest passenger ferry port in the UK, with the largest harbour between the Humber and the Thames. The study area of Harwich is about 8 sq. km and includes the intensively urbanised peninsula area as well as other rural areas to the south. Its eastern border is formed by the North Sea, hence extreme coastal flooding can be caused by a variety of factors, which include pressure differential, as well as wind and wave action, intense low-pressure system that can artificially raise sea levels and the combined effect known as storm surge (Tendering District, 2008). The north boundary is formed by the river Stour estuary and is connected to the North Sea at the extremity of Harwich, which can be a source of tidal flooding. The Ramsey River discharge is pushed across the railway line and into the North Sea/River Stour Estuary at Harwich International Port.

Figure 1. *Study area: Harwich, Administrative County of Essex, UK (Source: Google earth pro map)*

Level I assessment

The blue line was drawn (Figure 3) to represent the coastline and was used as a proxy baseline for the measurement of physical parameters. Seventeen cells, approximately 0.5 x 0.5 km, were drawn perpendicular to the coastline in a Google Earth pro map, and a detailed measurement of the physical parameters was carried out (Figure 4). All cells have been thoroughly analysed by applying the Physical Coastal Vulnerability Index.

Figure 3*. 0.5 x 0.5 km coastal cells in the study area*

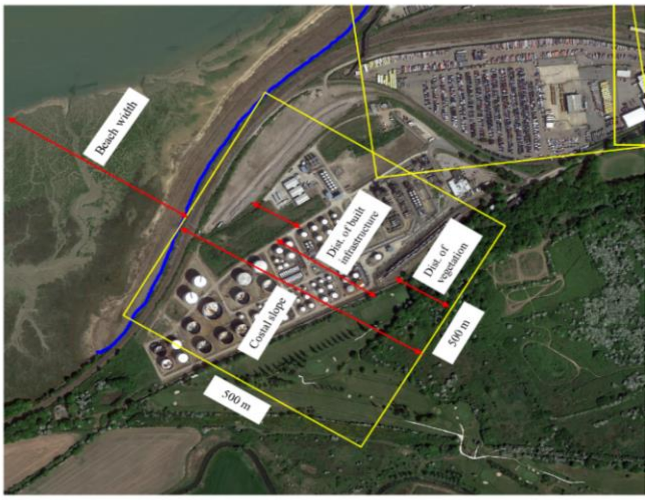

Figure 4*. Coastal cell with parameter marked*

Level II assessment

Level II assessment is performed at the area of Harwich port where critical infrastructures are located. Flood hazard maps for two RCP scenarios (RCP 4.5 and RCP 8.5) and three future projections in 2030, 2050, and 2080 are obtained from WRI online platform. Figure 5 shows an example of a flood hazard map and zonation for the study area. The zones were identified based on the size of the corresponding pixels in the flood raster maps. The exposed port infrastructure includes 3.23 km of railways, 3.07 km of roads, and 3 major buildings (Figure 6). The inundation depth for each zone and each scenario is identified to perform the loss assessment.

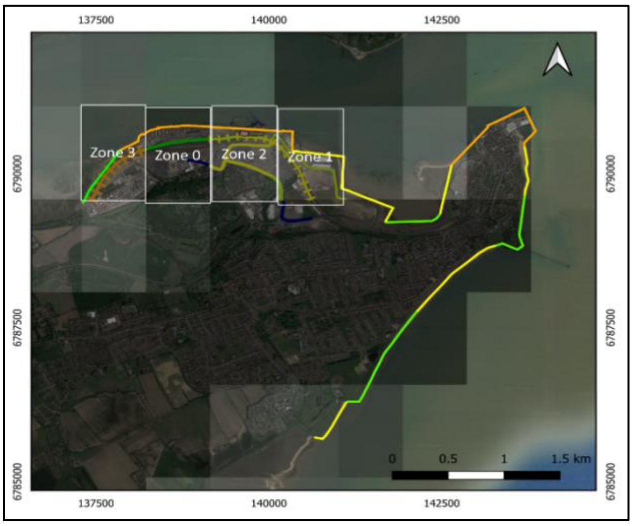

Figure 5. *Flood hazard map with flood zones classification (zone 0: lower water level, zone 3: highest water level)*

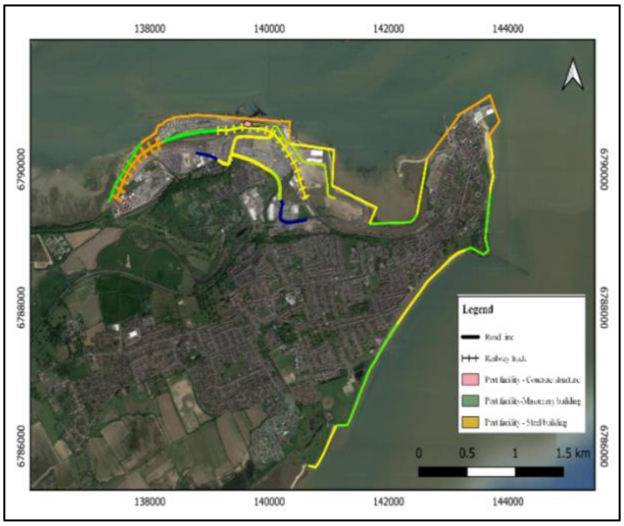

Figure 6. *Map of listed critical assets for loss assessment*

To compute the flood damage loss associated with each SLR scenario, flood depth damage functions, such as the ones shown in Figures 7 and 8, were used to establish the relationship between flood hazard and loss in value of infrastructure. These functions are based on the direct economic cost of flood damage and flood water depth for various infrastructure types and show the extent of damage (percent) of infrastructure at a given depth of flood water.

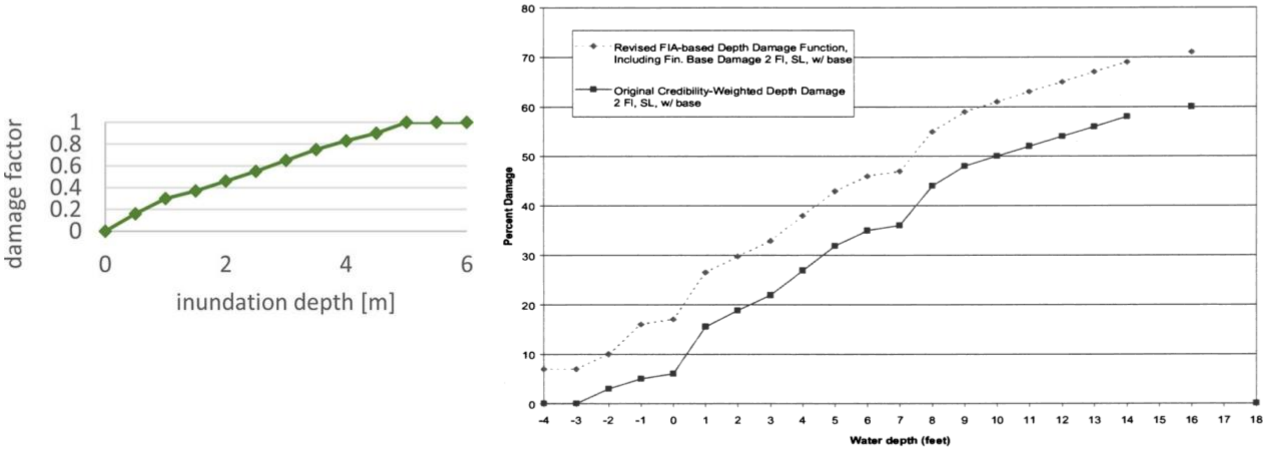

Figure 7. *Flood depth damage curve for roads and railways (Habermann et al., 2016) (left) and for building structural damage (Scawthorn et al., 2006) (right)*

RESULTS

The PCVI was assessed for 17 cells in total (Figure 8). Additional weightage scores (Pf and Pg) were applied to the data after the examination of the five parameters (Pa to Pe) shown in Table 1. The average score was

16, putting it in the moderate range. The highest PCVI value (20) was achieved in cell 9, while the lowest (13) was obtained in cells 15 and 16. Five cells were classified as moderately vulnerable, while five and seven of the cells were classified as very low and low vulnerable, respectively.

The overall Physical Coastal Vulnerability Index (PCVI) scores suggest that 30% of Harwich's coastline has a very low physical coastal vulnerability, 41% low and 29% a moderate vulnerability (Figure 9). Hence, a significant amount of high-value infrastructure, such as port and oil facilities, highways, and houses, located along the coastline stretches of Harwich are currently characterised by low to moderate vulnerability to the actual climate condition scenario.

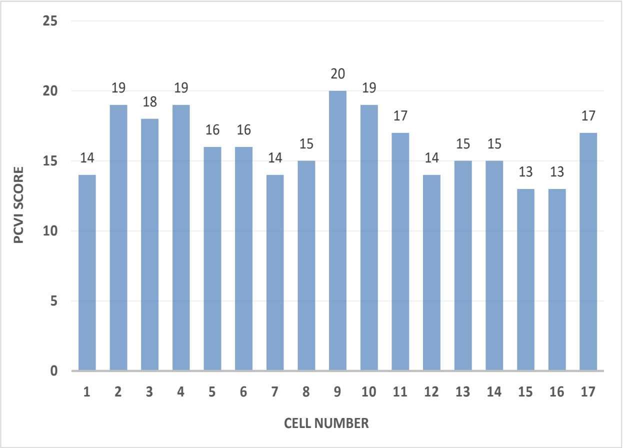

Figure 8. *Graphical representation of cumulative PCVI score*

Figure 9. *Coastal vulnerability map of Harwich*

Based on the data collected for the flood depth and the depth damage factor, flood damage was determined for the 25-years, 50-years, and 100-year flooding scenarios in 2030, 2050, and 2080. Under the RCP 4.5, the estimated losses in value of these infrastructures range from ~£11m for a 25-years flood return period in 2030 to ~£14 for a 100-years flood return periods in 2080. The results show variation between the losses due to the difference in annual flood probability. As the graph shows in Figure 10, direct damage caused by floods of 25, 50 and 100-year return period is nearly the same with an estimated loss of about £14 million. The expected losses for the higher emissions projection (RCP 8.5) are higher, ranging from ~£15.5m to £19m for the 100-years return period in 2030 and 2080, respectively.

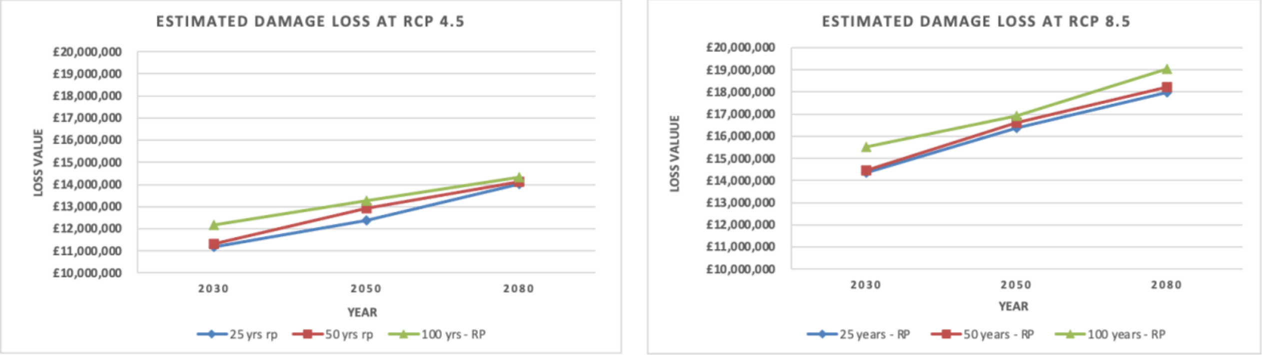

Figure 10. *Estimated damage loss trend under RCP 4.5 (left) and RCP 8.5 scenario (right)*

ADAPTATION MEASURES

Climate change has engendered the need for long-term adaptation strategies to deal with the increasing sea level (Griggs and Reguero, 2021). Adaptation entails taking steps to reduce coastal risks, minimise or avoid potential negative consequences of increasing coastal hazards (e.g. storms, erosion, inundation) caused by the accelerating rise in sea level combined with growth and demographic concentration. Thus, adaptation measures refer to the combination of techniques, practical knowledge and skills that can be used to minimize the impact of coastal hazards and has the benefits of reducing the vulnerability of the coastal community to these hazards (Valente and Veloso-Gomes, 2020). There are various adaptation measures, which are grouped into three categories: protection, accommodation, and retreat (Linham et al., 2010).

Protection measures are defensive approaches used to protect an area from inundation, tidal floods, the impact of waves on infrastructure, coastline erosion, saline intrusion, and the loss of natural resources. Protection measures are further divided into hard and soft protection. Hard protection measures include dikes, sea walls, armour units and breakwater, while soft protection measures include dune rehabilitation or sand nourishment. Accommodation is an adaptation measure to reduce the vulnerability of existing infrastructure against climate change conditions, especially the SLR. This approach allows coastal communities to occupy vulnerable areas by using technology that can physically modify infrastructure to cope with the threat or use information systems to raise awareness of the community to coastal risk to enable them to take appropriate responses to minimise the impact of flood events (Bongarts et al., 2021). Retreat is a proactive or deliberate withdrawal from the coast, as opposed to an unintentional or forced retreat, which might also occur as a result of SLR and climate change (Linham et al., 2010). This adaptation approach to the climate in coastal regions refers to the strategic relocation of private, public infrastructure and/or communities, limiting new developments in coastal regions and allowing only developments that can be abandoned if necessary (Tubridy et al., 2021).

In the Harwich area, considering its current sea defences, measures such as raising the existing defensive structures by prioritising the most vulnerable cells (Figure 8) might be an appropriate measure that can be implemented to adapt to coastal future changes with less significant additional costs. In coastal cells with wider beaches, beach nourishment can be implemented. This is considered an environmentally friendly protective reaction since it allows the coast to respond dynamically to the coastal changes (Bongarts et al., 2021). Regarding railways and roads, their robustness against flood events can be enhanced by implementing drainage systems and bank protection measures such as riprap structures, gabions and vegetation to improve the stability of the most vulnerable sections.

CONCLUSIONS

Admittedly, climate change will have a considerable impact on flood susceptibility of coastal regions, notably as a result of rising sea levels. A better understanding of the extent of climate change and its physical consequences on infrastructure is crucial for designing adaptation measures that could reduce risks in these regions in the future. This research sought to assess the impact of sea level rise on coastal areas with a focus on critical infrastructure. To achieve this, a two-level approach was introduced, based on the physical coastal vulnerability index (PCVI) and the loss assessment for different RCP scenarios and return periods using flood damage functions. The benefits of open-access tools and data were highlighted, for enabling rapid estimations that can inform decision making.

The Harwich area in the southeast coast of England was used as a case study. The estimation of PCVI (Level I) has shown variations in the intensity of vulnerability of coastal cells under the current climate condition. This assessment identified the cells with the highest vulnerability scores, based on the rating of different physical parameters. The flood loss analysis (Level II) was performed using open-access raster hazard maps from the WRI and depth damage functions from the literature, to estimate the cost associated with the damage to critical infrastructure affected by flood using two RCP scenarios and three return periods. Although the Level I analysis shows overall low vulnerabilities of the area under the current climate condition, the vulnerability of the coastal infrastructure will increase due to sea level rise throughout the century, as was identified for the climate projections (Level II). Hence, risk mitigation measures are required to protect communities and increase infrastructure resilience.

The methodology used in this study can be applied in the long-term planning of coastal regions to mitigate sustainably the impact of sea level rise on coastal infrastructure by adopting appropriate measures. Based on the prioritisation of the exposed areas and assets using the two-level assessment, and considering economic, environmental, social, and legal aspects, an appropriate strategy can be decided for increasing the resilience of the coastal infrastructure and communities. Limitations of this study are related to the uncertainties associated with the data used, such as the flood hazard maps (Vousdoukas et al., 2018) and the damage functions. Site-specific flood analysis and case-specific fragility models can further improve the reliability of the assessments.

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