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Assessment of harbour inoperability and adaptation cost due to sea level rise. Application to the port of Tangier-Med (Morocco)

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ABSTRACT

This paper intends to assess the potential impacts of the future SLR on the operability of berthing structures and to estimate in monetary terms the adaptation costs to it. To do this, three scenarios of SLR are considered, two corresponding to the last assessment report of IPCC (RCP4.5 and RCP8.5) and the other being a high-end scenario (HES), with a low probability of occurrence but physically possible. The research is focused on the case study of Tangier-Med port, which is considered as an economic magnet for the northern region of Morocco and the centerpiece of the government strategy for port development. The results show that the operability of the port will be affected only under the HES and from 2090 onwards. However, by 2100, in this scenario all the docks would be affected, especially the service terminal and those dedicated to containers, hydrocarbons, vehicles and general cargo, in which the percentage of inoperability could exceed 30% of the time. This would lead to traffic losses of 1.9 million TEUS and more than 22 million tons of cargo by 2100 while the adaptation costs would exceed 40 million euros (in present monetary units).

1. Introduction

With the observed increase in the air and ocean temperature, the decline of snow covers and ice extent, changes in the rainfall rates and the timing of seasons, and the rise of the sea level, today it is more noticeable than ever that the world's climate is changing as a result of an abnormal increase in the average global temperature, a key indicator that reflects climate (Yan et al., 2016). In its latest Assessment Report (AR6), the Intergovernmental Panel for Climate Change (IPCC, 2021) attests that the current warming is extremely likely (95 percent) due to human activities and that the observed increase in the global temperature is mainly related to the anthropogenic greenhouse gas emissions and other forcing. However, the carbon dioxide generated through the burning of fossil fuels remains by far the major forcing contributor (NAS, 2001). Indeed, the present-day and future concentrations of greenhouse gas emissions from the anthropogenic activities determine the average global temperature, which influence the current and future climate. As noted by Nazarenko et al. (2015) the greater the future forcing, the greater the warming and larger the impacts on other components of the climate system.

Today it is widely recognized that climate change is among the most challenging issues of our time. It is reflected in a number of effects that can lead, in many cases, to devastating environmental, social and economic consequences (Hardy & Hauer, 2018; Nicholls et al., 2008; Oven et al., 2012). However, sea level rise (SLR) remains one of the most noticeable effects of climate change (Chang et al., 2018; Frazier et al., 2010; Sánchez-Arcilla et al., 2011), especially in the coastal areas (e.g. Addo, 2014, 2015; Bon de Sousa et al., 2018; Brown et al., 2016; Grases et al., 2020; Neumann et al., 2010; Nicholls & Cazenave, 2010; Nicholls et al., 2011; Wu et al., 2016). The increase of the sea-level will modify the evolution of the coastal system in a multitude of ways, such as submergence, flooding, erosion, saltwater intrusion, rise in water tables, hindered drainage, changes or losses in wetlands and storm damage (e.g. Bhuiyan & Dutta, 2012; Fraile-Jurado et al., 2017; Ivajnšič et al., 2018; Li et al., 2015; Mehdizadeh et al., 2017; Paprotny & Terefenko, 2017).

Given the importance of harbours as essential contributors to the coastal fringe economy, climate change impacts on ports are one of the major climatic risks in coastal zones (Sánchez-Arcilla et al., 2016;

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Izaguirre et al., 2021). Although several studies have addressed the impacts on ports generated by changes in wave patterns due to climate change (e.g. Casas-Prat & Sierra, 2010, 2012; Mase et al., 2013; Messner et al., 2013; Suh et al., 2013; Sierra et al., 2015; Izaguirre et al., 2020), SLR is considered to be the primary effect of climate change that will affect ports (Messner et al., 2013), increasing the magnitude of the impacts of climate hazards (Becker et al., 2013). Actually, it poses a real threat to the port sector and will undoubtedly continue threatening this sector in the future by increasing the risk of flooding (Wright, 2013; McLeod et al., 2018). Moreover, it can significantly damage the port infrastructure and equipment (Zviely et al., 2015). Besides this, the SLR can decrease the safety of vessels inside the port or interrupt the loading and unloading operations, which can affect negatively the operability and therefore the reputation of the port (Wright, 2013; Hanson & Nicholls, 2020; Verschuur et al., 2020). In addition, SLR will increase the water depth around and inside the harbour, modifying wave propagation patterns (Sierra et al., 2017) that can in turn produce other impacts on ports, affecting processes such as wave agitation (oscillations due to wind waves within the port), siltation, scouring or structure stability (Sierra & Casas-Prat, 2014). However, SLR can also have positive impacts on ports by reducing the dredging maintenance costs, or by enabling the port to receive larger vessels (Chhetri et al., 2016).

Although the potential impacts of SLR have become an increasingly worrying issue for the communities all over the world and according to a recent survey finding (Becker et al., 2012), port authorities believe that SLR is the climate issue that more negatively will affect their operations, very few studies have been carried out addressing SLR impacts on ports (Gracia et al., 2019; Sierra et al., 2016), and almost none of these are centered on African ports (HR Wallingford, 2014, p. 39).

Besides affecting the normal flow of activities inside the port, SLR impacts will be much broader as many economic sectors depend on port services. Thus, any disruption of port activities can be translated into significant economic losses taking into account that more than 80% of the world's trade is transported by the shipping industry (Becker et al., 2013; UNCTAD, 2016a). One of the direct impacts of SLR on ports is reflected in the decrease of the dock's freeboard. Another potential direct impact comes from the rise of the sea level above the elevation of the docks, causing temporary or permanent flooding. Both consequences could lead to the slowing down or the interruption of the operations, and the dock's flooding would result in serious damages to the assets and equipment.

The main aim of this present work is to evaluate the potential impacts of SLR due to climate change (including other permanent or temporary effects as tides and storm surge) on port operability. Besides evaluating the loss of operability in percentage of time, an assessment of the potential loss of traffic that this would entail is also carried out. Finally, a solution is proposed to deal with the problem and its cost is estimated.

Although the used methodology is illustrated by its application to a case study in the coast of Morocco, it could be applied worldwide. The application of this methodology to any port would give very useful information to port stakeholders about the potential areas of their ports that could be susceptible of having disruptions and when this could occur. In this way, port authorities could plan well in advance the necessary works to prevent such disruptions and to allocate the necessary means and funds for this purpose. Other original features of this work are the lack of studies of this type focused on African ports (HR Wallingford, 2014, p. 39) and the use of a probabilistic approach to take into account the combined effects of SLR, tides and storm surge, since similar studies (e.g. Gracia et al., 2019) focus on fixed values of total sea level rise (including climate change, storm surge and tides).

In the following, after the description of the study area (section 2), the description of the methodology used in this study is detailed (section 3). After that, the obtained results are presented (section 4) and discussed (section 5). Finally, a summary of the results and the main conclusions of the work are given (section 6).

2. Study area

The Tangier-Med Port is situated in the northwestern Mediterranean coast of Morocco close to the strait of Gibraltar, around 40 km east of Tangier (35° 54′N, 005°29′W), as illustrated in Fig. 1. It is geographically located in a unique area, where the climate is strongly influenced by the Mediterranean Sea and the Atlantic Ocean. In this zone, winds and waves come from the East and the West (BO, 2016). According to Sogreah (2007), the prevailing winds come from the East and from the North-northwest to Southwest. The directional distribution of waves shows that the dominant waves come essentially from the West and have an average height of 2 m and periods of 9–12 s, while the waves coming from the East have periods of 3–5 s and a height that does not exceed 1.5 m (Benali & El Moutchou, 2016). The area has a semidiurnal tidal cycle, which is characterized by two high and two low tides of approximately the same height (Sogreah, 2007) with an average tidal range of 0.70 m (BO, 2016).

Tangier-Med is an integrated port platform covering an area of about 50 km^2. It is dedicated to transshipment, import-export and value adding logistics and services. Taking advantage of its geographical location on the maritime routes of Europe, America, and Africa, the port is connected to over 170 ports in 67 different countries. However, due to its good performance, strategic location and first class infrastructure, the port is considered as one of the major transshipment hubs in the Mediterranean Sea and the busiest port in Africa for maritime trade (UNCTAD, 2016b), ranking 47th on the Lloyd's (2019) list of the top 100 container ports.

The port complex includes three different ports (The Tangier-Med I, The Tangier-Med II and Tangier-Med Passengers), a Logistic Free Zone and a Port Center (Fig. 2). The Tangier-Med I has 2600 linear meters of docks, two container terminals, one railway terminal, one hydrocarbon terminal, one bulk and break-bulk terminal and one vehicle terminal. The first and second container terminals (TC1 and TC2) have a total berthing length of 1600 m and a total capacity of 3 million TEUs. The railway terminal provides a good link between the Tangier-Med I terminals and the national network. It has an area of 10 ha capable of handling 400,000 TEUs annually. The hydrocarbon terminal is devoted to trading (*trans*-shipment), import of refined products and bunkering, having a storage capacity of 512,000 m^3. The bulk and break-bulk terminal is characterized by a quay 500 m long with a surface of 5 ha, which allows the processing of 800,000 tons of various goods. The vehicle terminal has two docks 240 m long and a total surface of 20 ha, with a nominal capacity of 1 million vehicles per year.

Regarding Tangier-Med II, the port is composed of two container terminals (TC3 and TC4). TC3 has a 800 m long quay, an area of about 32 ha and a total capacity of 1.3 million TEUs. On the other hand, the future terminal TC4, whose construction began in 2019, will consist of a 1600 m linear quay expandable to 1800 m and an area of 76 ha expandable to 94 ha, with a capacity of 5 million TEUs (TMSA, 2016).

Concerning the Tangier-Med Passengers, it mainly handles the TIR and passenger/vehicle traffics. This port has eight berths with a storage area of 35 ha.

3. Material and methods

In many port areas even a small rise in the sea level combined with the height of a storm surge can significantly affect port operations, even producing dock flooding (NRC, 2010). As indicated in the Introduction, the present study is aimed to determine the combined impacts of the permanent (mean sea level and astronomical tides) and the temporary (storm surge) events, to provide useful information to port authorities that can be used to deal with such impacts. Therefore, the probable future rates of SLR were first selected and then the mean climate of sea level variations due to the combined effects of tide and storm surge was calculated.

Due to the lack of a suitable Regional SLR Scenario for Morocco, the

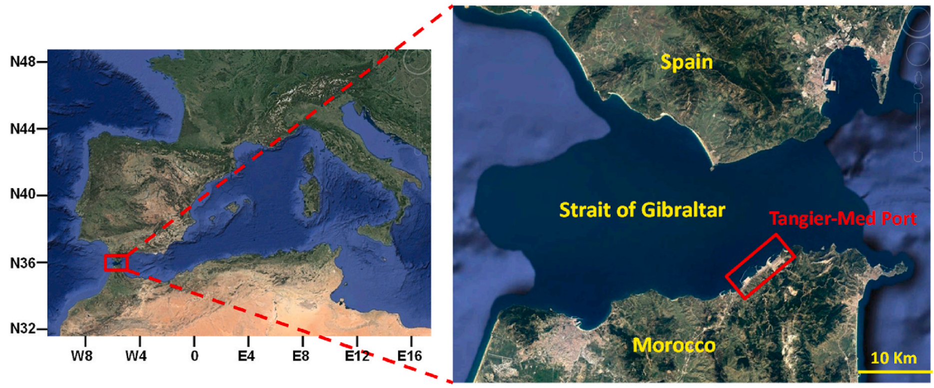

Fig. 1. Location of the port.

Fig. 2. Location of the different terminals. The minimum operability freeboard of each area is indicated.

global average increase with the regional variation projected by the IPCC (2021) for the Mediterranean region is assumed. Given the large uncertainty about SLR and the difficulties to predict it with accuracy, three SLR projections are considered in this study. Two of them are related to IPCC (2021) scenarios from the latest assessment report AR6 (RCP4.5 and RCP8.5), and the third one is a high-end scenario (HES),

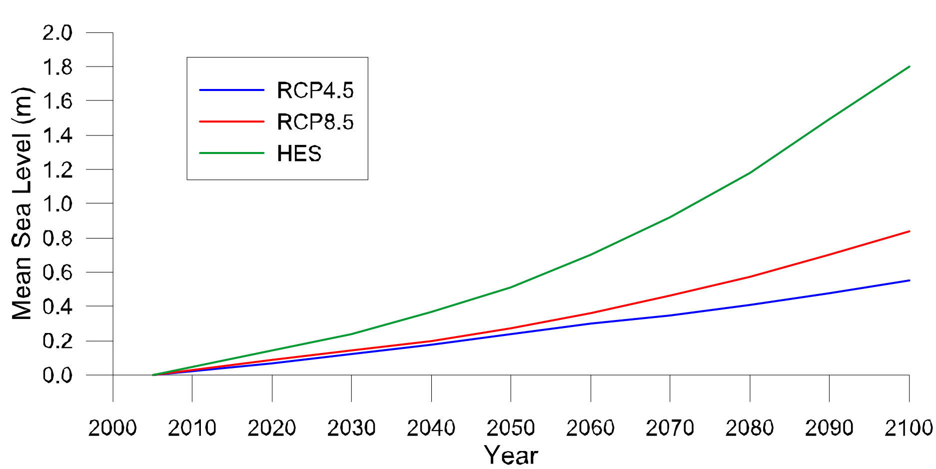

Fig. 3. Sea level rise projections during the 21st century in the three scenarios considered.

physically feasible although with a very low probability of occurrence (<5%, Jevrejeva et al., 2014). Fig. 3, displays the evolution of SLR projections for each scenario during the 21st century.

The mean climate of sea level variations (tide plus storm surge) was determined using hourly sea level records registered at the Tangier-Med tide gauge. The dataset covers the period from September 2015 to December 2016. These data were fitted to a 2-parameter Weibull function (Weibull, 1951), from which the probability of non-exceedance of a certain level can be calculated.

Once the potential sea level variations are known, their impact on port operability has to be assessed. To do this, it has to be taken into account that, depending on their use, each berthing structure of the harbour has a required crest elevation. Indeed, the height of the docks must be sufficient to ensure enough freeboard to allow port operations. In this study, due to the lack of regulations in Morocco, the minimum freeboard height required for the docks of each terminal was determined based on the Spanish ROM 2.0–11 recommendations (Puertos del Estado, 2012), because Spain is the closest country to Morocco in which there are such regulations. These values are shown in Table 1.

Assuming that a dock will be inoperable if its freeboard is less than the minimum freeboard required for its use, the future sea level that could interrupt the functioning of the docks is calculated. Then, taking into account the SLR scenario and the probability of exceedance of a certain sea level (due to the combined effects of tide and storm surge, as shown in Fig. 4), the percentage of inoperability is determined.

On the other hand, the traffic loss due to the disruption of the dock operability was calculated for each terminal. To do this, an estimation of the future traffic was made by assuming that the flow will evolve in the same way as in the preceding years. In addition, trend analysis was used to obtain the best equation representing the past trends and to estimate the future traffic as a function of time. The losses were calculated by multiplying the extrapolated annual traffic volume by the percentage of inoperability.

4. Results

4.1. Assessment of the inoperability time

For the purpose of assessing the inoperability of the docks considering the effects of tide and storm surge, the sea level data recorded by the tidal gauge were analyzed. The probability of non-exceedance of a certain level due to the cumulative effects of tide and storm surge was determined by fitting the sea level data to a Weibull probability function (Weibull, 1951), as indicated in Section 3. Fig. 5 shows the probability of non-exceedance of the positive values (representing 50.72% of the data) that was combined with the projected SLR for each scenario to determine the time at which the docks will remain inoperable under each scenario.

Therefore, the computation of the inoperability time has been done considering the total sea level for the three scenarios, including tide and storm surge, and comparing the reduced dock freeboard with the minimum values given in Table 1. Results show that the docks will only experience inoperability under the high-end scenario (HES), while for RCP4.5 and RCP8.5 all the docks will be fully operative throughout the century. As shown in Fig. 6, the operability of the docks at 4.5 m (the container, vehicle, hydrocarbon and general cargo terminals) and the

Table 1
Freeboard values used to evaluate the dock operability (Puertos del Estado, 2012).

Terminals	Minimum freeboard (m)
Containers, Cereals and General Cargo, Hydrocarbons, Car Carrier	2.5
Passengers, Port service	1.5

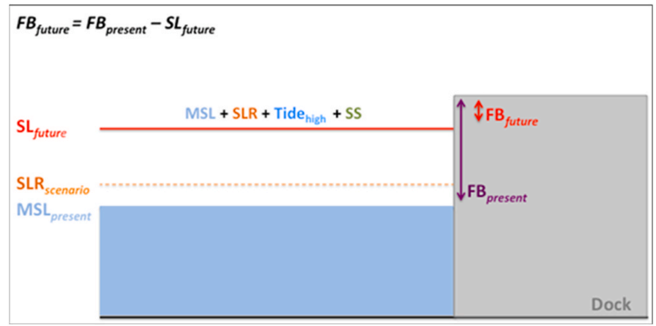

Fig. 4. Schematic representation of the present and future sea level. MSL: mean sea level; FB: freeboard; SL: total sea level; SLR: sea level rise; SS: storm surge.

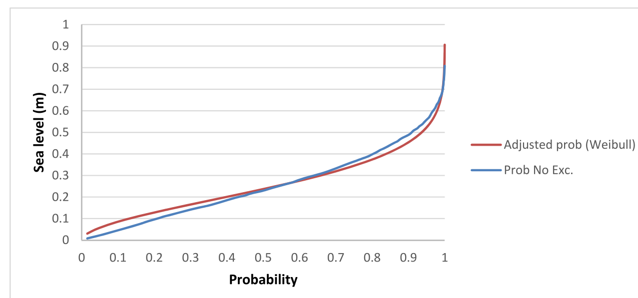

Fig. 5. Weibull function giving the probability of non-exceedance.

docks at 3.5 m (port service) will decrease by almost 0.05%, 3.12% and 30.14% in 2080, 2090 and 2100 respectively. However, the docks at 4 m (passenger terminal) will only be affected in 2100 when their operability is expected to decrease by 0.27%.

The percentage of inoperability can be transformed into time (hours or days) of terminal forced inactivity, as presented in Fig. 7. This shows how the functioning of the docks at 4 m (passengers) could be disrupted for slightly over 1 day in 2100. The docks at 4.5 m (containers, solid bulk, hydrocarbons) and 3.5 m (service port) will be more affected by the end of the century. Indeed, they will remain inoperable some hours (4.6) in 2080, increasing to 11.4 days in 2090 and to more than 110 days in 2100. This could actually result in the reduction of the port performance, entailing serious problems to give service to the future port traffic.

Regarding these results, it must be taken into account that when dealing with issues related to climate change, the used data are based on scenarios and long term projections for such scenarios, which are submitted to a large uncertainty. Therefore, the obtained results cannot be validated due to the large underlying uncertainties, which cannot guarantee that the data being used correspond to the SLR values that will take place in the future.

The presented results should be considered as a picture of what could happen in the event of a certain scenario (and its associated projections). With the potential results corresponding to several scenarios (as in this work), port authorities can have the range of potential impacts on their facilities and, as a consequence, they can design adaptation measures well in advance, that can be applied when the real situation approaches one of the scenarios.

4.2. Assessment of traffic losses

To have an idea of the scope of the negative impact that can result from the disruption of the normal functioning of the docks due to SLR, the traffic losses were calculated for each terminal by multiplying the obtained percentages of inoperability in a given year by the estimated future annual traffic volume in the same year. To estimate this traffic

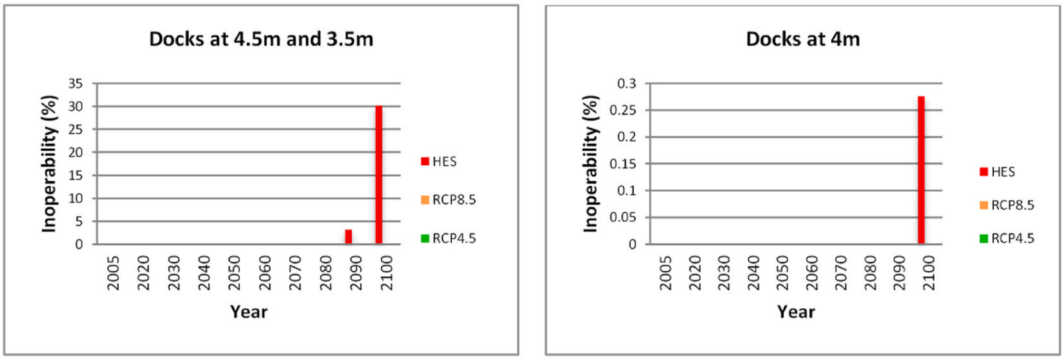

Fig. 6. Percentage of inoperability under RCP4.5, RCP8.5 and the high-end scenario (HES) for docks with a freeboard of 3.5 and 4.5 m (left) and a freeboard of 4 m (right).

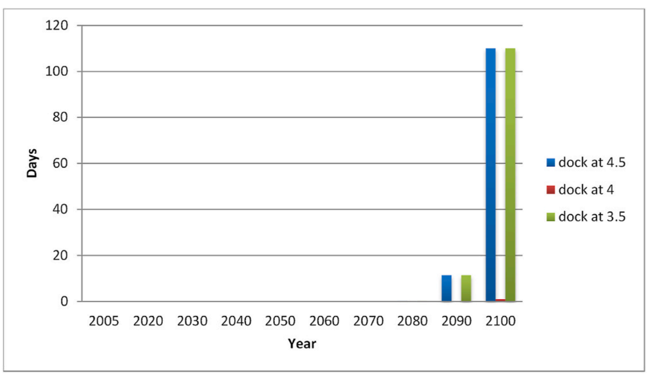

Fig. 7. Number of non-operative days for the HES and the three types of docks.

volume, as indicated in Section 3, the previous annual traffic data for the port were analyzed and a best-fit function was used to predict (by extrapolation) the future traffic for the different terminals. Fig. 8 shows the future annual traffic estimated until 2100. It is worth noting that the traffic predicted for 2100 can be covered by the present (2021) capacity of the terminals, as described in Section 2.

The results of traffic losses for the HES scenario in the last part of the century are summarized in Table 2. As shown, the traffic losses in the future will be especially important in 2100. As can be noticed, the losses will be much higher for containers and hydrocarbons. Indeed, the volume of traffic lost during 2100 for the two sectors is estimated to reach 1.97 million TEUs for containers, and 19.9 million tons for hydrocarbons.

5. Discussion

5.1. Inoperability of docks

As pointed out in the previous section, despite the difference in their height (1 m), the operability of the docks at 3.5 m and 4.5 m for the same period and under the same scenario will be equally affected. Indeed, the difference in the minimum freeboard required for the optimal functioning of each type of dock (1.5 m for the port service docks and 2.5 m for the container, vehicle, hydrocarbon and general cargo docks) explains this result. Therefore, the lower dock elevation is compensated by the lower minimum freeboard required and, as a consequence, the final inoperability time is the same.

Analyzing the inoperability percentages, it is clear that SLR will not affect the functioning of the port terminals during most of the century or even during all the studied period for scenarios RCP4.5 and RCP8.5. Only in the case of the exceptional HES and in the last years of the century (from 2090 to 2100) the negative impact on terminal activity will be significative. To describe those impacts in a simple manner, the degree of vulnerability of each terminal was estimated based on the percentage of inoperability. This criterion was classified in a qualitative scale of three levels:

- Low vulnerability: 0% < inoperability ≤1%
- Medium vulnerability: 1% < inoperability ≤5%
- High vulnerability: inoperability >5%

Fig. 9 shows the vulnerability maps of the port for the high-end scenario (HES) during the last part of the century if no adaptation measure is taken. In this figure it can be seen how, by the end of the century, most of the port terminals will be highly vulnerable to SLR. This is in line with that indicated by Wright (2013) and Sanchez-Arcilla et al. (2016), who pointed out that SLR is one of the main factors generating impacts in ports.

With regard to traffic losses, as presented in Table 2, they will grow by an order of magnitude between 2090 and 2100. Such a large increase can be explained by the percentage of inoperability, which is expected to attain 30% in 2100, in contrast to just over 3% as projected for 2090.

These sudden changes due to SLR beyond 2090 indicate that this year corresponds to a tipping point. According to Kwadijk et al. (2010), adaptation tipping points are defined as points at which the magnitude of the change due to climate change or SLR is such that the current management strategy is no longer able to meet the objectives and, therefore, other strategies are needed. In the case of Tangier-Med port, this indicates that until 2090 no adaptation measures are necessary for any of the scenarios considered. From this year onwards, and for the HES scenario, adaptation measures to face the expected impacts will be indispensable.

5.2. Adaptation measures and associated costs

The main measures proposed to develop better resiliency to inundation and inoperability are to build coastal armouring such as seawalls and dikes, to elevate the entire port area, or to relocate to a nearby area with sufficient elevation to accommodate future commerce (Messner et al., 2013). In this case, taking into account the large investments already made and the additional funds that will be necessary to prepare the new facilities, relocation is not a suitable option. In addition, the building of dikes or revetments to protect the docks from flooding will hinder loading and unloading operations. Therefore, in response to the projected SLR, raising the docks is the best adaptation option to prevent the interruption of any operation and to insure the normal functioning of the terminals.

In order to roughly assess the cost of such adaptation measure, the additional volume of dock (in cubic meters) required for each terminal to prevent inoperability must be computed. This volume can be obtained by multiplying the surface of the affected docks by the necessary

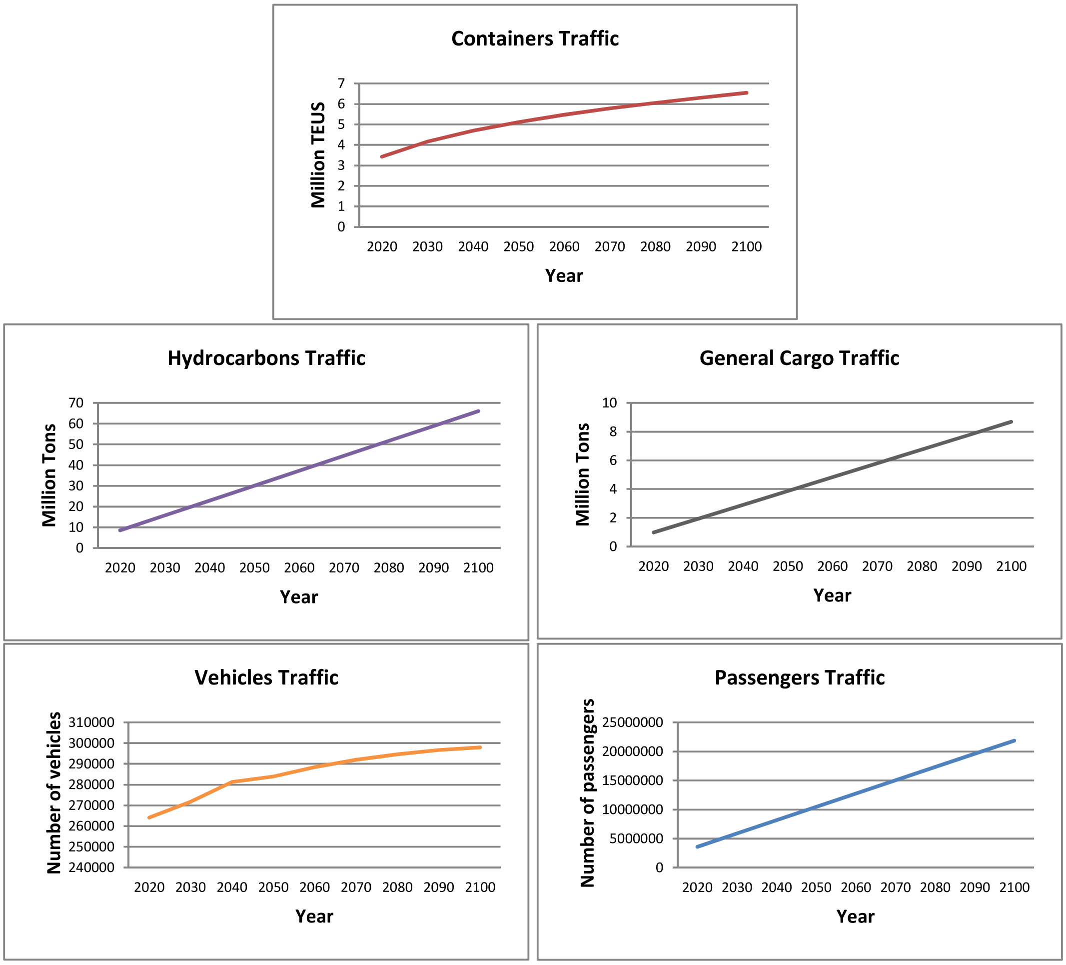

Fig. 8. Extrapolated annual traffic volume.

Table 2
Traffic losses for the HES scenario.

Year	Containers (TEUs)	Vehicles	Hydrocarbons (Tons)	General Cargo (Tons)	Passengers
2080	3183	155	27,140	3552	0
2090	197,187	9276	1,839,703	241,481	0
2100	1,970,448	89,842	19,908,179	2,619,264	60,390

elevation to reach the minimum operability freeboard. It should be noted that the lay-out of the port is assumed unchanged after the building of TC4 terminal, i.e. possible future enlargements are not taken into account. In this case, the surface affected by the potential inoperability will be larger and, therefore, the cost to overcome it will be greater.

Therefore, the adaptation cost of each terminal (in present monetary units) for years 2080, 2090 and 2100 has been estimated as the product of the total surface of each dock, the necessary meters to compensate the projected SLR in that year and the price of constructing one cubic meter. Indeed, the docks requiring an adjustment (the docks at 3.5 m and 4.5 m) should be raised 0.10 m in 2080 and 0.42 m in 2090, whereas in 2100 they should be raised 0.72 m. As mentioned above, the docks at 4 m will only be at risk in 2100. In response to this, they should be heightened by 0.20 m. The cost of construction per cubic meter has been quantified taking into account the total cost of construction of the TC4 dock, its total surface and its height. Thus, the present construction cost was estimated approximately at 25 euros per cubic meter.

Fig. 10 presents the cost (in present monetary units) of elevating the docks of each terminal as a response to the SLR under the high-end scenario (HES). As can be noticed, the total cost of elevation of the container terminals to adapt to the projected sea levels will be the highest. In effect, the total cost of adaptation will depend on the type of docks and mainly on the surface that should be elevated and, hence, on the surface of the docks of each terminal. As indicated in Fig. 11, most of the docks belong to the container terminals. In fact, more than 95% of the dock surface is dedicated to the container sector. On the contrary hydrocarbons, cereals and general cargo, car carrier, passenger and port service docks constitute only 0.13%, 0.27%, 0.38%, 0.35% and 0.07% of the total surface, respectively.

Adding the cost of each terminal for a given year, the total adaptation cost for this year is obtained (see Fig. 12). This total adaptation cost (in present monetary units) would amount to 5.57 million euros in 2080, whereas it would increase to 23.39 million euros in 2090. In 2100, the cost would rise to reach 40.11 million euros. In this last year, the docks of all terminals would need to be elevated, including the passenger terminal, to cope with the expected SLR for the HES.

In summary, although Tangier-Med port has a design that will allow it to cope with the SLR projected by AR6 IPCC scenarios, a greater SLR caused by higher temperatures or an increase in the rate of ice melting could lead the port to a difficult situation, in particular from 2090 onwards. In this case, the port would require costly adaptation measures. Therefore, port authorities should consider this option as possible (although not likely) and prepare response actions in advance.

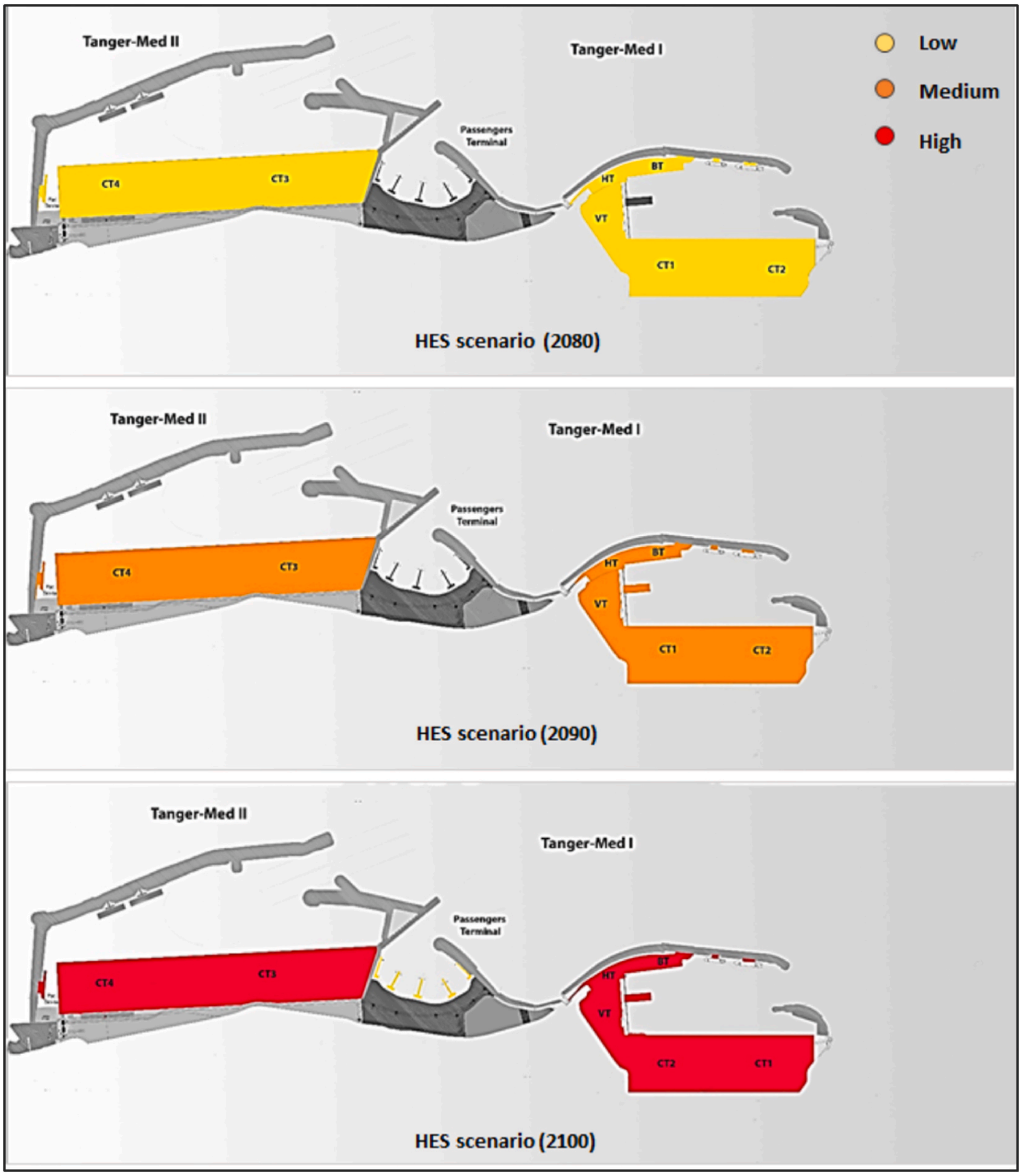

Fig. 9. Vulnerability maps of Tangier-Med port under the high-end scenario (HES) for the last part of the XXI century.

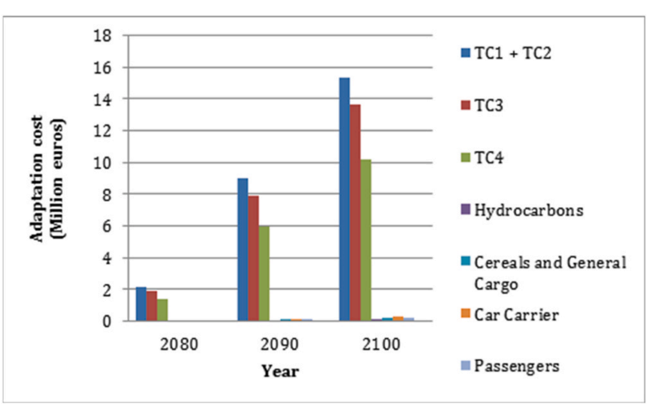

Fig. 10. Adaptation cost of each terminal for years 2080, 2090 and 2100 (in present monetary units).

5.3. *Applicability of the study, limitations and future work*

This study focuses on a problem that will affect most ports during the 21st century: the loss of operability of docks and berthing areas due to the reduction of their freeboard as a consequence of climate change and associated SLR. It proposes a methodology to estimate the port terminals that will be affected, considering the total rise in sea level (due to climate change, tides and storm surges). The effect of tides and storm surges is taken into account using a probabilistic approach, unlike in other previous studies (e.g. Gracia et al., 2019) in which fixed values are considered for these processes. This allows to determine with greater accuracy the inoperability time of a certain terminal and to build vulnerability maps, which will give insight to port authorities about the port areas most likely to be affected by SLR.

Furthermore, the traffic loses have been estimated, a possible adaptation measure has been proposed and its associated costs appraised. In addition, the estimation of inoperability and evaluation of adaptation costs has been carried out every ten years. This allows to build, for each scenario, vulnerability maps on a decadal basis,

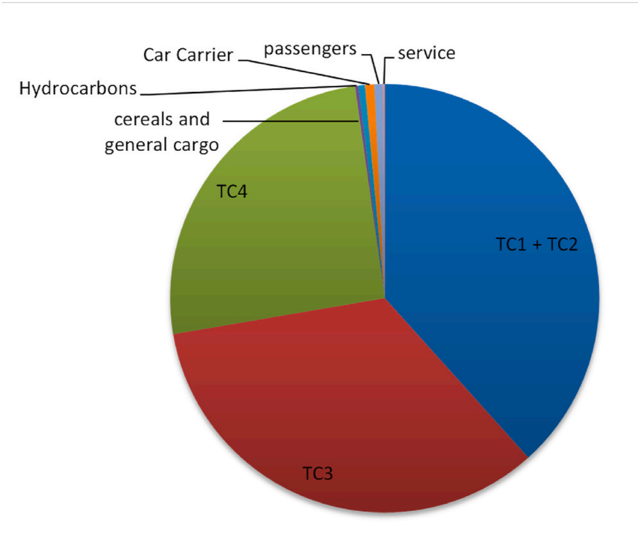

Fig. 11. Distribution of the Tangier-Med docks surface area.

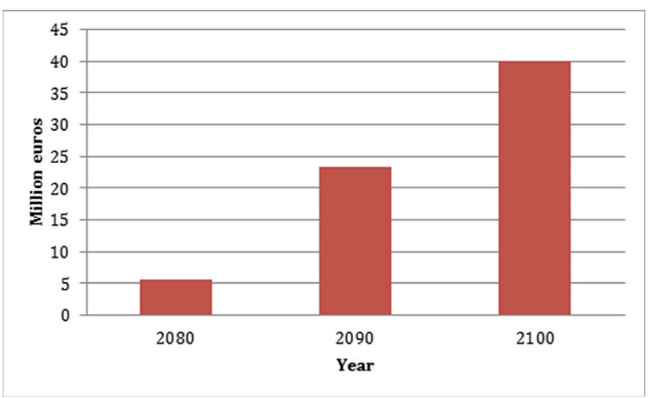

Fig. 12. Total adaptation forecasted cost for years 2080, 2090 and 2100 (in present monetary units).

providing a powerful tool to port authorities to plan well in advance the most suitable responses (for each scenario) to overcome the impacts as well as an estimation of their cost. This is essential in port engineering as the usual planning horizon is 20–25 years, since it involves several stages: diagnosis of the situation, forecast of maritime traffic evolution, evaluation of infrastructure requirements, study of possible alternatives and its compatibility with urban planning, economic and financial analysis, design and project of the selected alternative, environmental impact study, period of public information and discussion, process of obtaining the construction permit, submission of tenders and execution of works (which usually last several years).

The effectiveness of the methodology is illustrated by its application to a case study, the Tangier-Med port, located in the Mediterranean coast of Morocco, although it could be applied to any port worldwide.

Nevertheless, the study presents a number of limitations. In particular, there is great uncertainty associated with the fact that the results are based on scenarios of climate change, not in a real situation, being impossible a priori to know which scenario will be closer to what will happen. In addition, for each scenario, SLR data are obtained from numerical model projections which, in turn, contain more uncertainty. Despite this, as pointed out above, the use of different scenarios depicts a wide range of potential impacts. This information can help port authorities to anticipate and design different levels of response to such impacts.

Another source of uncertainty is related to the estimation of future traffic, which is made based on extrapolations. These extrapolations do not take into account potential changes in maritime transport or events that can have major impacts on the economy, such as the 2008 crisis or Covid'19 in 2020. Moreover, it is assumed that the port configuration will remain the same throughout the 21st century. Obviously, if operational problems arise at any time, the port authorities will react avoiding to reach unacceptable situations.

Finally, another limitation of the study consists of considering only one measure of adaptation and a rough estimate of its cost.

Anyway, the study is useful because it allows to detect the evolution of the berthing inoperability during the studied period. Graphics shown in this study (e.g. Figs. 6, 7, 9 and 12) allow to visualize abrupt changes in the percentage of port inoperability. Such sudden changes are tipping points (Kwadijk et al., 2010; Lenton, 2011; Barrett & Dannenberg, 2014; van Ginkel et al., 2020), which can be considered moments where the magnitude of change due to SLR is so large that the present management strategy is no longer able of meeting its goals and, therefore, if operating conditions have to be maintained, other strategies are necessary. The identification of these tipping points will allow policy makers to establish adaptation pathways (Haasnoot et al., 2013, 2019; Barnett et al., 2019; Kench et al., 2018; de Ruig et al., 2019), to design different strategies to deal with the negative impacts of SLR. Due to the necessary time for port planning, as indicated in the previous Section, the early knowledge of the possible impacts and potential adaptation strategies enables port authorities to allocate the necessary means for undertaking the appropriate measures to overcome the impacts.

To finish this section, some lines of future tasks are proposed that would allow reducing the indicated limitations. The first task consists of including more scenarios and their confidence bands, to limit the uncertainty associated with the SLR. Another action to take would be to analyze more adaptation measures, to increase the options of the port authorities, to design the most appropriate measures to solve the problem. Finally, the definition of adaptation pathways would help to establish the optimal temporal distribution of such measures.

6. Conclusions

In this paper a methodological framework to assess the potential impacts of SLR on port operability is proposed. The methodology is based on SLR projections for different scenarios combined with a probabilistic approach to take into account sea level variations due to tides and storm surges. The probability of having a certain sea level is compared to the minimum freeboard required for the use of each berthing structure. It allows to identify, for each scenario and every ten years, the port areas that will be inoperable and the percentage of inoperability. As a consequence, port vulnerability maps may be plotted and operability tipping points detected. This gives port authorities a powerful tool to design, well in advance, the necessary adaptation measures to overcome the impacts due to SLR.

To illustrate the effectiveness of the method, it was applied to the port of Tangier-Med, being the first study investigating the potential impacts of SLR due to climate change on the operability of the docks in a Moroccan port. It analyzed the effects on this port considering SLR values from RCP4.5, RCP8.5 and HES scenarios during the 21st century and provided, in monetary terms, the cost of a plausible adaptation option. This methodology was applied only to this port but it could be used to assess the effects of SLR on port operability in any port worldwide.

The results showed that the port could cope with the water levels expected during this century under the RCP4.5 and RCP8.5 scenarios proposed by IPCC in its last assessment report (AR6). However, under a HES (with a low probability of occurrence but physically possible) it could be significantly affected, leading, as a consequence, to a decrease in the operability from 2080 onwards, especially in 2100 when all the docks would be affected, with the inoperability of some of them reaching

30% of the time. During this year and for this HES, the loss of traffic would amount to about 1.97 million TEUs for the containers, 19.9 million tons for the hydrocarbons, 2.62 million tons for the general cargo, 90,000 vehicles and 60,000 passengers.

To overcome these negative effects adaptation measures should be taken. The proposed adaptation strategy consisted of elevating the berthing structures to confront the future sea levels in order to ensure the effective functioning of the port. The adaptation cost would mainly depend on the surface to be elevated. The estimations showed that the container terminals were more costly to adapt (due to their larger surface) accounting for a total budget (in present monetary units) of 5.57 million euros in 2080, 23.39 million euros in 2090 and 40.11 million euros in 2100.

The port seems to be designed to withstand the highest sea levels projected by IPCC in AR6, but the results showed that it might potentially be affected in the worst-case scenario, leading to large economic losses due to the disruption in the operability of its docks, particularly the container and hydrocarbon terminals. This situation, for a *trans*-shipment hub such as the Tangier-Med, besides the negative economic impact, would adversely affect the reputation of the port. This paper highlights the need for port authorities to be aware of this possibility despite its low probability of occurrence, so that they have contingency plans prepared in advance to give a suitable response if SLR rates grow more than expected during this century.

Author statement

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