EXPLORING POTENTIAL CLIMATE CHANGE IMPACTS AND ADAPTATION STRATEGIES FOR SEAPORT OPERABILITY

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ABSTRACT

As seaports are located within the coastal zone, they are susceptible to climate change impacts such as changing wave conditions and sea level rise. To secure the operability of seaports under these changing conditions, a deeper understanding of potential local-scale climate change impacts is needed to explore suitable adaptation strategies. Previous studies focused on climate change impacts on seaports at a regional scale. Consequently, there remains a lack of understanding of these impacts on individual seaports and how these seaports can accommodate or adapt to these impacts. This study provides a conceptual framework for (i) quantifying risks for port operability and (ii) exploring adaptation strategies. The framework is tested on a case study of the Port of IJmuiden in the Netherlands. The study demonstrates that in the absence of adaptation measures, climate change may result in significant risks for the operability of this port. While the framework is tested on a single case study site, it is believed to be a promising tool for exploring climate change risks and adaptation strategies for seaports worldwide.

1. INTRODUCTION

Ports are vital within the global economy due to their crucial role in the globalized trading system. Because of an expected increase in the world's merchandise seaborne trade, it is important their role will be maintained in the future (UNCTAD, 2011). The performance of ports depends on the level of operability in terms of the amount of uptime, defined as the extent to which it is possible to continue operations such as berthing, mooring and navigating.

Ports are often located in coastal zones due to strategic considerations, to optimize the accessibility between land and water. Consequently, seaport operations are exposed to specific physical conditions such as storm surges, storm waves and sea water levels. Therefore, seaports are vulnerable to climate change impacts on these conditions. For example, sea level rise causing increased water levels may result in flooding of quay infrastructure and subsequently hinder quay wall operations.

Following a worldwide survey amongst 93 seaports, port authorities are concerned about sea level rise and increased storminess, causing flooding of infrastructure and impacting port operations (Becker et al, 2011). To secure seaport operability under these changing conditions, an understanding of potential climate change effects and possibilities for adaptation is needed. Most port authorities feel uninformed about potential climate change impacts and consider climate change as a topic they should know more about (Becker et al., 2011). The United Nations considers assessing climate change impacts and adaptation options for ports to build their resilience as an urgent imperative (UNCTAD, 2011).

IPCC suggests approaches for assessing climate change impacts on a conceptual level (Lal et al., 2012). Other studies focus on climate change impacts at the scale of a sea basin, for example, the North Sea (Grabemann et al., 2014; Groll et al., 2013). A recent study provides a framework for quantifying local scale climate change impacts on coasts (Ranasinghe, 2016). However, the amount of publications on assessing climate change impacts on individual seaports is limited (Becker et al. 2011; McEvoy et al., 2013). Therefore, there is a lack of understanding of how ports can accommodate or adapt to these impacts.

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In order to improve the understanding of this topic, this paper provides a conceptual framework to assess climate change impacts on port operability and to explore potential adaptation options for individual seaports. The presented framework combines and builds upon existing approaches to assess climate change impacts (Grabemann et al., 2014; Groll et al., 2013; Lal et al., 2012; Ranasinghe, 2016) and is tested on a case study of the Port of IJmuiden in the Netherlands.

Chapter 2 reviews existing assessment approaches and introduces the developed framework. Application of the framework to the case study of the Port of IJmuiden is provided in Chapter 3. Chapter 4 discusses the relevance and suitability of the use of the framework to seaports worldwide and Chapter 5 provides the main conclusions of the study.

2. METHODOLOGY

Section 2.2 presents the framework for quantification of climate change risks for port operability and for exploring adaptation options. It combines and builds upon existing approaches resulting from a literature review described in section 2.1.

2.1 Review of existing approaches for climate change impact assessments

The approaches for assessing climate change impacts in previous studies are conceptual (Lal et al, 2012), but also provide concrete steps for quantification of impacts at regional scale (Grabemann et al., 2014; Groll et al., 2013) and local scale (Ranasinghe, 2016).

IPCC suggests two conceptual approaches. A top-down approach (Figure 1, left part) focuses initially on downscaling of global climate change impacts by modeling, to assess relevant impacts (Kwadijk et al, 2010; Ranger et al., 2010). These results provide the base for designing relevant adaptation options. The second is a bottom-up approach (Figure 1, right part) which suggests studying the context and its vulnerabilities first, to subsequently define the focus for identifying adaptation options. Studies recognize that both approaches are complementary and combining them can be beneficial for the result (Lal et al., 2012).

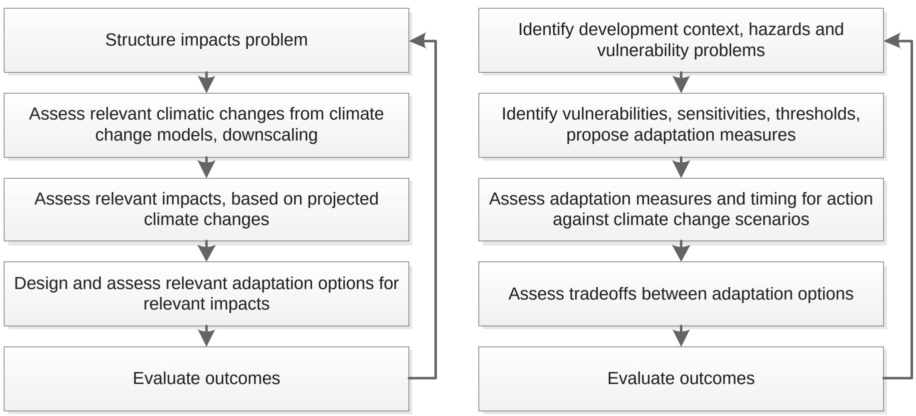

Figure 1: Existing approaches for assessing climate change impacts and for identifying adaptation options. Figures adopted from Lal et al. (2012). Left: the top-down approach, “Climate models, scenarios, impacts-first”. Right: the bottom-up approach, “Vulnerability, threshold-first.

Downscaling global climate change predictions to the local scale is crucial for impact assessments of individual ports. Several studies provide concrete steps for downscaling global climate change impacts to local scale physical conditions (Grabemann et al., 2014; Groll et al., 2013; Ranasinghe, 2016). Following these approaches, a first step is to select global greenhouse gas (GHG) emission scenarios as input for Global Climate Models (GCM’s, e.g. models such as HADCM and GISS). GCM output consists of time series of various climate variables, such as surface temperature, wind and precipitation. As the resolution of GCM output is too coarse for a local scale climate change impact assessment, a next step is to further downscale the result to a regional or local scale. This comprises the use of the coarse grid output of a GCM (typically in the order of 200 x 200 km) as boundary conditions of a model with a finer grid, such as a Regional Climate Model (RCM, e.g. models like CRCM and CCAM with a typical output in the order of 50 x 50 km). In order to obtain corresponding

regional scale climate change predictions on hydraulic conditions which are directly affecting port operations, such as water level or wave conditions, regional forcing models (e.g. WAM) are applied with the RCM output as boundary conditions. Ranasinghe (2016) suggests an additional step for downscaling regional scale impacts to the local scale on coasts, by using the output of the RCM and forcing model as boundary conditions of local scale coastal impact models.
Noted is that instead of dynamic downscaling, statistical downscaling is possible in areas in which data is abundantly available. Furthermore, bias correction of the results (e.g. of the RCM) is conducted to improve the accuracy of the output, by comparing obtained time series of physical conditions with field measurements and by applying correction techniques as required. Also, a range of scenarios is considered, for incorporation of uncertainties due to assumptions of global GHG scenarios. Finally, Ranasinghe (2016) suggests using an ensemble modeling approach to include modeling uncertainties, by using multiple global- and regional climate and forcing models.

2.2 Suggested conceptual framework for climate change impact assessments on port operability

The framework suggested for quantification of climate change risks for port operability and for exploring adaptation strategies is based on specific elements of the existing approaches presented in section 2.1.

Figure 2 displays the framework with its main steps: (1) analyzing the port system and selecting its valuable and vulnerable port operations and related infrastructural assets, (2) selecting global climate change scenarios and downscaling these to the local scale to assess the impacts within the port, (3) quantifying port risks and investigating their relevance and (4) exploring adaptation options for the port.

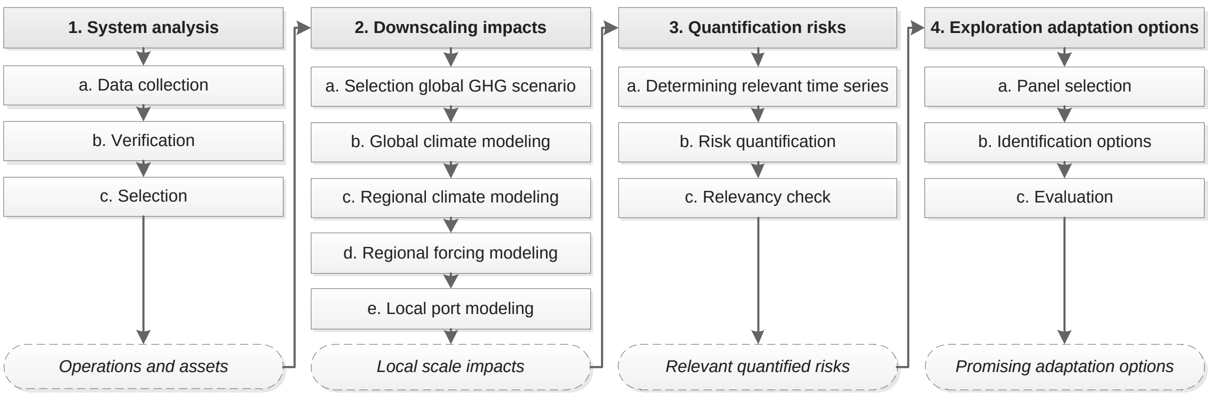

Figure 2: Suggested framework for a climate change impact quantification and adaptation study for ports. The box at the bottom of each of the four steps is describing the main output.

The framework combines the conceptual top-down and bottom-up approach of IPCC (Kwadijk et al, 2010; Ranger et al., 2010). Initially, the context including its vulnerable assets and thresholds are identified according to the bottom-up approach (step 1) and subsequently climate change impacts are assessed by means of downscaling, which is in line with to the top-down approach (step 2). Eventually, exploration of adaptation options (step 4) is following from both IPCC approaches. Specifications for downscaling impacts to the regional scale (step 2a to 2d) are adopted from the existing approaches presented in section 2.1 (Grabemann et al., 2014; Groll et al., 2013; Ranasinghe, 2016). Local port modeling (step 2e) in order to determine impacts within seaports is in line with the final step of the framework of Ranasinghe (2016) in order to determine local scale impacts.

Step 1 of the framework is a system analysis, consisting of selecting port operations and infrastructural assets that are valuable to stakeholders and that may be vulnerable to climate change impacts. These operations and assets form the focus of the subsequent climate change risk assessment. In addition, a focus must be set on specific climate change hazards, such as sea level rise, wind, storm surge or waves. For the specific case study of IJmuiden, climate change impacts on sea levels, storm surge and storm waves are considered.
An inventory is made (step 1a) of (i) operations and infrastructural assets, (ii) physical conditions and (iii) port operability thresholds values: values of physical conditions (e.g. wave height, water level or wind speed) and related variables (e.g. overtopping or flooding discharges) under which a specific port operation cannot take place and which is causing port downtime.

Stakeholders are identified, based on their potential vulnerability to climate change effects and their influence in the area. These actors are contacted in order to verify the collected data (step 1b) and to make a selection of valuable and vulnerable port operations and infrastructural assets (step 1c).

Subsequently, global climate change impacts are downscaled and assessed on the local scale of the port (step 2). Specific steps for determining these global impacts and for downscaling to the regional scale are adopted from the approaches presented in 2.1 (Grabemann et al., 2014; Groll et al., 2013; Ranasinghe, 2016). An ensemble scenario- and modeling approach is suggested to obtain insight in GHG scenario and modeling uncertainties. However, a tradeoff should be considered between computational model effort and the accuracy of the results.
Firstly, global climate change impacts are determined by means of a GCM with the input of a global GHG emission scenario (step 2a and b). The coarse grid GCM output presents a set of time series of climate variables (e.g. air pressure, wind, precipitation) for the present and future time slice. Subsequently (step 2c), regional impacts are determined by dynamic downscaling the GCM results, by using the coarse grid GCM output as boundary conditions of a RCM with a finer grid. To obtain corresponding predictions for hydraulic conditions directly impacting port operations (e.g. water levels, storm surge and waves), the RCM output is used as boundary conditions of a regional forcing model (step 2d).
Eventually (step 2e), local projections within seaports at an appropriate scale (depending on the port, but typically in the order of 10-100 m) are determined by using the RCM output (e.g. wind) and output of regional forcing models (e.g. water levels, storm surge and wave characteristics) as boundary conditions of an appropriate local validated model (e.g. Delft3D). Alternatively, GCM output is used as boundary conditions of the local model directly, but this might lead to a less accurate result.

In order to quantify port risks and to investigate their relevance (step 3), the following three steps are required.
Initially (step 3a), additional data is obtained based on analysis of local scale physical impacts following from step 2 (e.g. time series of mean sea levels, storm surge and wave characteristics). Gathered data are time series of variables related to the defined port operability thresholds (e.g. data on overtopping discharges), which are assessed by means of rules of thumbs with input of the local scale impacts. For example, suggested rules of thumbs for determining overtopping discharges are theories by Allsop (1995) and Franco (1994), applicable depending on the relation between the water depth and significant wave height at a specific moment (van der Meer & Bruce, 2014).
Then, climate change risks are quantified as expected changes of frequencies of port downtime (e.g. in terms of expected amount of days per year) in the future time slice compared to the present time slice (step 3b). Port downtime is defined as the time in which it is not possible to continue port operations, due to exceedance of a port operability threshold value by one of the relevant physical conditions or related variables (e.g. wave heights exceeding the wave height threshold value for navigational operations). By including all relevant physical conditions in the same analysis of a specific port operation, correlations between different types of physical conditions leading to port downtime are taken into account (e.g. correlated high water levels and wave heights during a storm event causing a flooded quay wall and therefore downtime). In case of a lack of data points above the port operability threshold values (e.g. water level heights which are lower than threshold values for flooding in all data points of the time series), return periods are obtained by means of a Peak over Threshold analysis, based on Extreme Value Theory (Caires & van Os, 2012).
Eventually, the relevancy of the risks defined is checked by the input of stakeholders (step 3c).

Due to the uniqueness of most ports and their environment, promising adaptation strategies might differ for each case. In order to explore adaptation options (step 4) and to obtain a Taylor-made solution for a port, a panel is composed (step 4a), consisting of a combination of stakeholders and experts with backgrounds in seaports, policy, management and other relevant subjects to the case, such as specific physical conditions (e.g. hydraulics). Initially, a divergent brainstorm session is conducted (step 4b) in the categories (i) operational: logistic and technological solutions, (ii) institutional: economic, legislative and political options, (iii) social: options in which the influence on the behavior of actors is considered, (iv) grey: physical engineering solutions within the port area and (v) green: win-win solutions which are also benefitting the natural environment. These categories are based on suggestions by IPCC (Wong et al., 2014). In a subsequent convergent part (step 4c), promising alternatives are selected by means of voting and a panel discussion.

3. APPLICATION OF THE FRAMEWORK TO THE PORT OF IJMUIDEN

A case study is conducted to illustrate the application of the framework. Selected is the Port of IJmuiden in the Netherlands, approximately 20 kilometers west of Amsterdam. An overview of the port and the focus locations for this study is displayed in Figure 3.

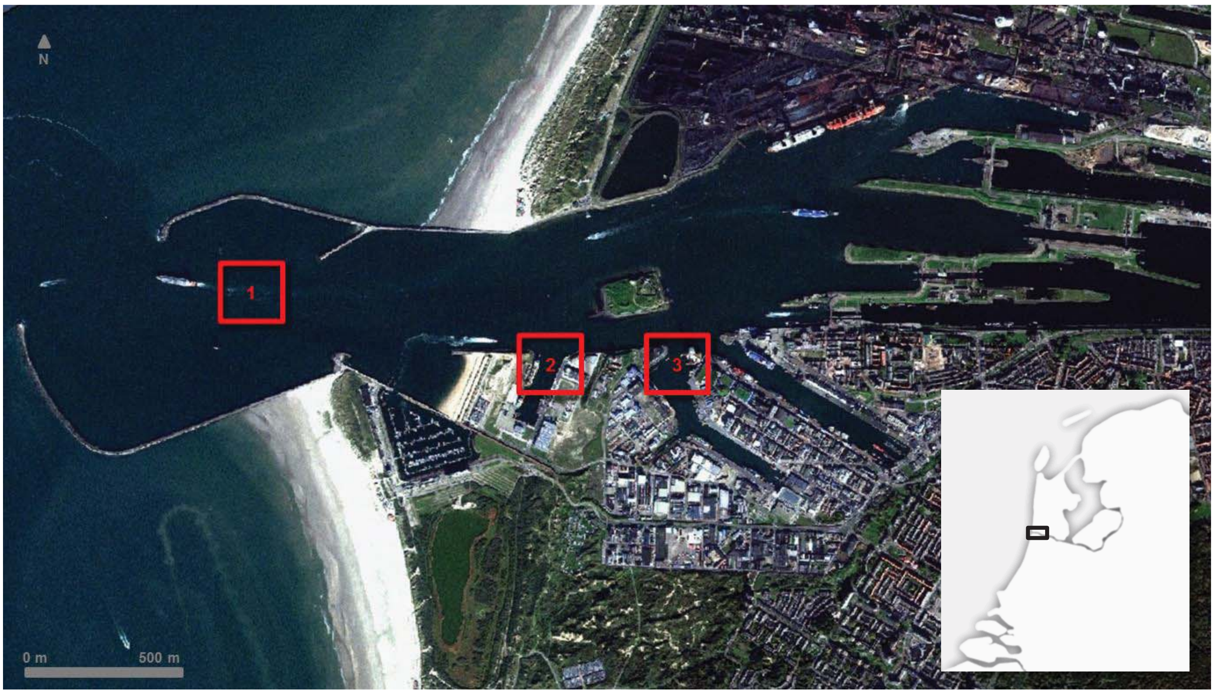

Figure 3: Study locations within the Port of IJmuiden notified in red with (1), (2) and (3). The photo is adopted of the Netherlands Space Office (2015). The location of the port within the Netherlands is displayed in black on the map of the country.

In section 3.1, the results of the system analysis of the Port of IJmuiden are presented. Section 3.2 discusses the downscaled impacts and section 3.3 provides the climate change risks for port operability in terms of changed frequencies of downtime. In section 3.4, promising adaptation options for the case study of the Port of IJmuiden are introduced.

3.1 Port operations and infrastructural assets

Selected port operations and assets in the Port of IJmuiden are (i) navigational activities (Figure 3, location 1), (ii) berthing and mooring of vessels (Figure 3, location 2) and (iii) quay wall operations (Figure 3, location 3). These operations and assets are verified to be valuable to stakeholders. Climate change impacts on sea levels, storm surge, wind waves and overtopping discharges are assessed since the selected assets and operations are sensitive to these physical conditions or related variables.
For each of the types of operations, threshold values for port operability and their specifications are displayed in Table 1.

Table 1: Specifications of port operability thresholds in terms of significant wave height (H_S) and overtopping discharge (q) for the selected operations in the Port of IJmuiden.

Type of operations	Vessel specification	Threshold values for port operability	Criterion angle of incidence waves	Reference
Navigational activities	Tugboat Assistance	**H_s (m) = 2.5**		Svitzer Amsterdam (2016)
Berthing and Mooring	Bulk	**H_s (m) = 1.0**	θ (degrees) = 0-45 (head or stern)	Ligteringen & Velsink (2012)
	General cargo	**H_s (m) = 1.0**	θ (degrees) = 0-45 (head or stern)	
	Offshore and Wind farm	**H_s (m) = 0.8**	θ (degrees) = 45-90 (beam)	

	Fishing	**H_s (m) = 0.8**	θ (degrees) = 45-90 (beam)	
	Transportation and Roro	**H_s (m) = 0.5**	θ (degrees) = 45-90 (beam)	
Quay wall operations		**q (m^3/m/s) = 0.05**		Vrijling et al. (2011)

3.2 Downscaled climate change impacts within the port

As input of the modeling assessment, the Representative Carbon Pathway (RCP) scenario (range) 4.5-6.0 is assumed, an emission scenario range which is in line with the amount of global gasses emitted in case of a climate policy being successfully implemented (Moss et al., 2010). In this study, this scenario will be referred to as the 'moderate emission scenario'. In addition to that, the RCP scenario 8.5 is considered, a higher emission scenario which is referred to as the 'high emission scenario'.
Global and regional climate change predictions for the significant wave height, storm surge height and sea level rise for each of the assumed scenarios are following from an ensemble modeling approach. Previously to this study, numerous other studies are published in which predictions for the region of the Port of IJmuiden (especially the North Sea area) are obtained. This study builds upon these results by taking representative predictions for each of the assumed global GHG scenarios. These predictions for regional scale impacts are downscaled to the local scale, by using them as boundary conditions of the local validated SWAN model for the Port of IJmuiden (Booij et al., 1996).

3.3 Risks port downtime

The resulting quantified risks for the selected operations (i) navigational activities (location 1), (ii) berthing and mooring of ships (location 2) and (iii) quay wall operations (location 3) are displayed in Table 2.

Table 2: Expected frequencies port downtime per time slice due to hinder of selected operations.

Location	Operation	Reference period Time slice 1979-2001	Moderate emission scenario RCP 4.5 – 6.0 Time slice 2070-2100	High emission scenario RCP 8.5 Time slice 2070-2100
1	**Navigating**	*5 days/year*	*7 days/year*	*10 days/year*
2	**Berthing / Mooring**	*1 days/year*	*1.15 days/year*	*2 days/year*
3	**Quay wall operations**	*1 day / few hundred years*	*1 day / few years*	*1 day / 1-2 months*

The risks identified are relevant since the port is operating 24 hours per day and continuity in the operations is required.

3.4 Adaptation options

Based on the expert voting and panel discussion, the following conceptual adaptation options are identified as promising in dealing with sea level rise: (i) increasing quay heights and (ii) construction of a retention basin in combination with a drainage system for quay walls. The first option (i) is considered promising due to its effectiveness in reducing the risk of flooding of quay walls and due to expected low investment costs. The second option (ii) is besides being regarded effective also beneficial to the natural- and social environment. To deal with increased downtime due to changed storminess, the following options are identified as promising: (i) a multi-purpose land reclamation offshore of the port to provide a shelter zone for high waves and (ii) the application of navigable, wave-absorbing vegetation between breakwaters. The land reclamation (i) is stated to be a promising option benefitting the shipping- and airport industry, whilst being risk reductive. Option (ii) is positively influencing the natural environment whilst reducing wave energy. Further studies on the feasibility and effectiveness of all options are still required.

4. DISCUSSION

Regional predictions for sea level rise and increased storminess are more extreme in other regions than the area of the Port of IJmuiden. For example, wave heights are projected to increase more rapidly due to climate change at the German and Norwegian border of the North Sea, in southern and eastern parts of Australia, south-east Asia, west- and east Africa, South-America and the Caribbean (Hemer et al., 2012). This implies that climate change risks for port operability may be even larger for seaports located in these areas, and calls for attention on this issue worldwide.

It is believed that the conceptual framework presented in this paper is useful for assessing climate change impacts on seaport operability in terms of downtime, due to wind waves affecting vessel operations and changed sea levels, storm surge and wave overtopping discharges causing delay of quay operations, as shown in the case study of the Port of IJmuiden. The framework can also be applied to seaports elsewhere for which these hazards are relevant since the suggested sub steps, models and methods are applicable more generically than just for the case study of the Port of IJmuiden. Assumptions made for the case study can be suitable for other ports as well, specifically regarding the global GHG scenarios and port operability threshold values for shipping and quay wall operations (e.g. assumptions regarding wave height conditions in which a ship can navigate sufficiently and safely).
The applicability of the framework for assessing other seaports depends on the availability of data of the port environment and on the specific hazards selected for the assessment. Data of port operations and physical assets to be analyzed (e.g. quay heights and types of vessels operating in the port) and other environmental specifications (e.g. bathymetry) are required. In case of availability of regional climate change predictions, such as for the Port of IJmuiden, at least regional measurements are needed (e.g. water levels, wave and wind characteristics) for downscaling the regional predictions to the local scale. Although the analysis of climate change induced changes in sea levels, storm surge, storm waves and subsequent wave overtopping discharges impacting port operations is illustrated by means of the case study of the Port of IJmuiden, the assessment of other hazards (e.g. changes in precipitation and temperature) and indirect impacts of sea level rise and increased storminess (e.g. changes in currents and sediment transport) is not. However, the framework can be extended by assessing (other) seaports to a larger range of hazards or indirect impacts, by applying appropriate models and vulnerability threshold values related to the relevant hazards and operations selected.

5. CONCLUSIONS

Seaports are located in the coastal zone and hence their operations are exposed to specific physical conditions (e.g. storm surges, storm waves and varying water levels), and therefore they are susceptible to climate change impacts on these conditions. For seaports to still be able to operate under these changing conditions, it is crucial to understand potential climate change impacts and corresponding adaptation options.

This paper provides a conceptual framework to assess climate change impacts on seaport operability and to explore potential adaptation options. An initial step of the framework is (1) analyzing the port system and selecting its valuable and vulnerable port operations and related infrastructural assets, followed by a step (2) to select global climate change scenarios and to downscale these to the local scale to assess the impacts within the port. In a subsequent step (3), port risks are quantified and their relevance is investigated. In a last step (4), options for adaptation of the seaport are explored.

The framework is applied to the Port of IJmuiden illustratively, for which the impacts of climate change on sea levels, storm surge, wind waves and overtopping discharges on the delay of vessel- and quay operations are assessed, according to the first step. The results of the second and third step show that, without adaptation measures, climate change holds significant risks for port operability in the Port of IJmuiden. For each of the identified risks, promising conceptual adaptation options are identified following from the fourth step of the framework, although further studies on their feasibility and effectiveness are still required.

It is believed that the conceptual framework presented in this paper is useful for assessing climate change impacts on seaport operability in terms of downtime, due to wind waves affecting vessel operations and flooding of quays as a consequence of changed sea levels, storm surge and wave overtopping discharges. The suitability of the framework for assessing other seaports depends on the availability of data for a specific seaport environment. The framework can be extended by assessing (other) seaports to a larger range of hazards or indirect impacts (e.g. precipitation, currents and sediment transport). Therefore, the framework is considered promising for exploring climate change risks and adaptation options for seaports worldwide.

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