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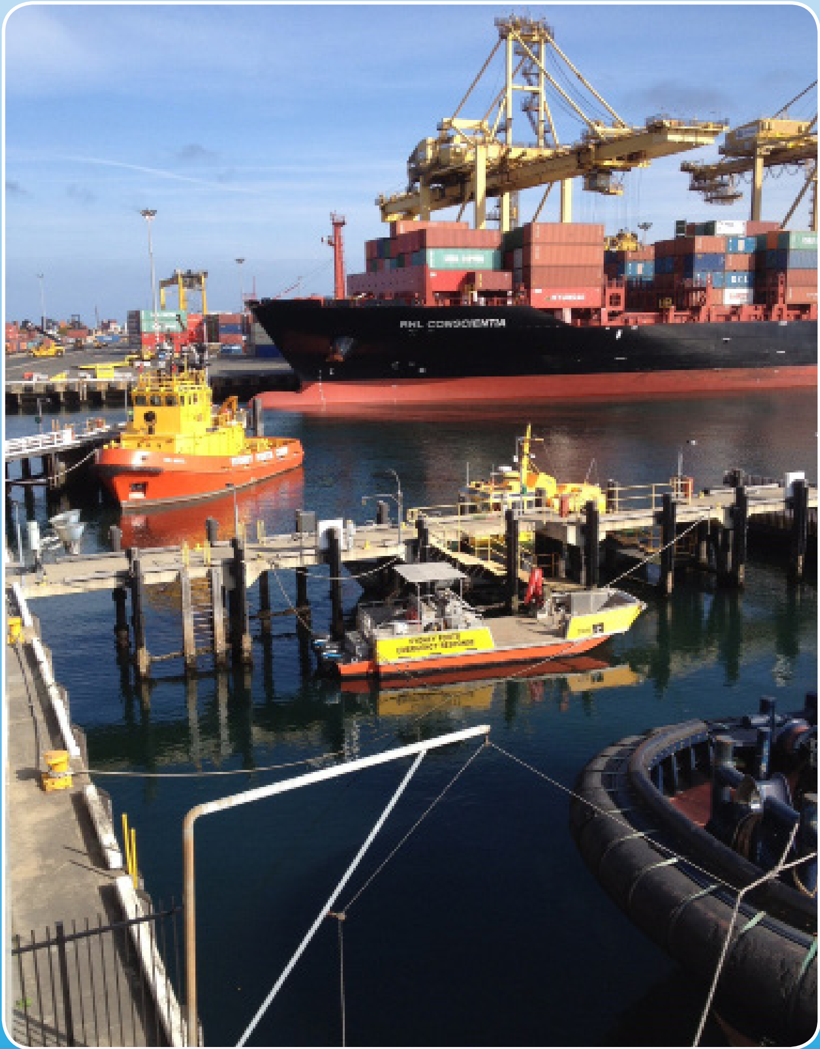

CLIMATE CHANGE ADAPTATION PLANNING FOR PORTS AND INLAND WATERWAYS

The World Association for Waterborne Transport Infrastructure

PIANC

The World Association for Waterborne Transport Infrastructure

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CLIMATE CHANGE ADAPTATION PLANNING FOR PORTS AND INLAND WATERWAYS

2020

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This report has been produced by an international Working Group convened by the Environmental Commission (EnviCom). Members of the Working Group represent several countries and are acknowledged experts in their profession.

The objective of this report is to provide information and recommendations on good practice. Conformity is not obligatory and engineering judgement should be used in its application, especially in special circumstances. This report should be seen as an expert guidance and state-of-the-art on this particular subject. PIANC disclaims all responsibility in the event that this report should be presented as an official standard.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF BOXES

SUMMARY

Ports and waterways around the world are experiencing air and water temperature increases, rising sea levels, and changes in seasonal precipitation, wind and wave conditions. Many are also seeing more frequent and severe extreme events such as storms, heatwaves and droughts.

Climate change represents a significant risk to business, operations, safety and infrastructure – and hence to local, national and global economies. Waterborne transport infrastructure will be adversely affected. Port and waterway operators need to take urgent action to strengthen resilience and adapt.

The guidance prepared by PIANC's technical Working Group 178 provides a brief introduction to the potential consequences of climate change and some of the challenges to be addressed. It then introduces a four-stage methodological framework to help port and waterway operators plan how best to adapt.

- Stage 1 facilitates understanding of the assets, operations and systems that could be affected by climate change; highlights possible interdependencies with other sectors that are also susceptible; encourages engagement with internal and external stakeholders; and enables the setting of climate change adaptation objectives. It also stresses the need for data collection and its effective management.
- Stage 2 identifies the type of information needed to determine baseline conditions and to explore possible future changes in relevant climate-related parameters and processes. It also introduces the use of climate change scenarios to assist in understanding the range of possible future changes, and highlights the importance of monitoring and collecting local data.
- Stage 3 describes how the vulnerability of waterborne transport infrastructure assets, operations and systems can be assessed and, where appropriate, a more detailed risk analysis undertaken to understand the likelihood and potential consequences of the projected changes.
- Stage 4 introduces some of the concepts that need to be considered when deciding how best to address climate risks and hazards. It also presents a 'portfolio' of potential measures (structural, operational and institutional), and provides guidance on how to screen and evaluate options that might be included on an adaptation pathway.

Sixteen international good practice case studies are appended to the guidance, along with various templates to be used for data collection and record keeping.

WORKING GROUP MEMBERSHIP AND ACKNOWLEDMENTS

All PIANC Working Group reports rely on the willingness of individual experts to provide their time and to share their technical expertise. Working Group 178 was no exception, and PIANC therefore expresses its sincere gratitude to the following individuals for their invaluable contributions to this technical guidance on climate change adaptation planning for ports and inland waterways.

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GLOSSARY

Different climate-related publications use the same terminology in different ways. The tables below explain how this guidance document uses these terms. These tables are arranged according to the Stage in which the terminology is used.

Stage 1: Context and Objectives

Term	Description
Climate hazard	The term hazard refers to climate-related physical events or trends or their physical impacts [IPCC, 2014]. A change in a climate parameter that exceeds a certain pre-determined threshold or has the potential to cause damage or disruption or other negative effects is therefore a hazard.
Criticality	Criticality is a measure of the relative importance that enables the identification of assets, systems or operations where disruption or destruction would have a significant adverse impact on the continued functioning of the port or waterway or those that are indispensable in some other way.
Planning horizon	The planning horizon is the length of time into the future that is covered in a climate change adaptation strategy.
Slow onset	Slow onset changes are characterised by gradual and incremental changes that typically occur gradually, evolving over many years. In the context of this guidance, slow onset events include increasing air and water temperatures, sea level rise, ocean acidification, salinisation, glacial retreat and related impacts. [UNFCCC, 2012]
Susceptibility	Susceptibility indicates whether an asset, operation or system is prone to harm, disruption or other adverse effects as a result of changes in meteorological, oceanographic or hydrological characteristics.
Adaptation	A response or a process of adjustment to accommodate the actual or projected climate or the effects of climate change.

Stage 2: Climate Information

Term	Description
Climate driver	A climate driver is a cause of or contributor to climate change. Changes in the atmospheric abundance of greenhouse gases and aerosols (e.g. carbon dioxide, methane, nitrous oxide), in solar radiation and in land surface properties alter the energy balance of (i.e. drive change in) the climate system. These changes are often expressed in terms of radiative forcing. [IPCC, 2007]
Climate-related parameters and processes	Climate is characterised by measurable parameters including atmospheric parameters such as air pressure and temperature, and non-atmospheric parameters such as sea surface temperature. Changes in these parameters in turn drive change in processes such as wind, waves, precipitation and river flow. For this reason, some other publications use the term climate drivers to describe these parameters. To avoid confusion with the above use of the same term, however, this guidance uses 'parameters and processes' to cover this wide range of meteorological, oceanographic or hydrological variables or characteristics.

Climate hazard	See definition in Stage 1.
Impact	The term impact is used to describe an effect of the change in a climate-related parameter or process on an aspect of the human or natural environment (i.e. an impact is the consequence of a climate hazard). The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts. [IPCC, 2014]
Projections	The term 'projection' rather than 'prediction' is used in this guidance. A prediction is a probabilistic statement that something will happen in the future based on what is known today, for example as is used in weather forecasting. Projections of future climate change are not like weather forecasts. It is not possible to make deterministic, definitive predictions of how climate will evolve over the next century and beyond as it is with short- or even medium-term weather forecasts. Projections of climate change are uncertain, both because they depend primarily on scenarios of future anthropogenic and natural forcings that are uncertain, and also because of incomplete understanding and imprecise models of the climate system and the existence of internal climate variability. [Collins et al., 2013]

Stage 3: Vulnerabilities and Risks

Term	Description
Risk	In this guidance, risk describes an uncertain event or condition that, if it occurs, has an effect on at least one objective i.e. uncertainty about future changes in relevant climate parameters and processes that could affect port or inland waterway assets, operations or systems. Risk assessment is an overall process of risk identification, analysis and evaluation. There are various types of risk assessment involving differing levels of detail. Risk analysis is the systematic process employed to understand the likelihood that a climate hazard will occur, and if it does, the magnitude and severity of the consequences.
Vulnerability	Vulnerability indicates the degree to which a system is susceptible to, and unable to cope with, adverse climate change effects, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which an asset, operation or system is exposed, its sensitivity (see criticality) and its adaptive capacity.
Consequence	Outcome of a climate-related event affecting the objectives. Consequences are most likely adverse impacts upon vulnerable assets, operations and systems.
Likelihood	The chance of a consequence or impact occurring, generally described in terms of probability, or frequency, and that can be expressed qualitatively or quantitatively (depending on the type of risk assessment being used).
Redundancy	Redundancy is the duplication or supplementation of critical components or functions of a system with the intention of increasing the reliability of the system.
Residual risk	The remaining risk after all efforts have been made to eliminate, minimise and/or mitigate risks through identifying and implementing adaptation actions and activities. An 'acceptable' residual risk depends on the appetite for risk of the risk taker (e.g. port, inland waterway, owner of maritime infrastructure). Different stakeholders are likely to start with different perceptions of what constitutes an 'acceptable' residual risk, so dialogue will be important.

Stage 4: Adaptation Options

Term	Description
Maladaptation	Failing to adjust adequately or appropriately to an anticipated change, for example by implementing an inflexible solution that cannot be modified if climate-related variables do not change in the manner projected at the time of design provides an example of maladaptation. An asset could ultimately be over-designed or under-designed and (some of) the initial investment may be wasted. Alternatively, the vulnerability of the infrastructure to ongoing future climate change may be increased. Interventions that increase vulnerability at another location or of another sector are also considered as maladaptation. [IPCC, 2014]
Resilience	Resilience refers to the capacity to anticipate and plan for disruption, absorb the impact of disturbance, and rapidly recover afterwards. Resilient assets and operations can adapt to both short- and long-term stressors, and to changing conditions and constraints. Resilience is not only physical; it is also societal, environmental and economic. Accommodating or accepting disturbance (rather than only protecting against it) can be important components of resilience.
Adaptive capacity	Adaptive capacity means having the ability to adjust to change. For example, there may be redundancy or resilience within the system that means a change or impact can be accommodated. Having adequate adaptive capacity can make the difference between an incident or event being inconvenient and potentially catastrophic.
No or low-regret measures	No or low-regret measures refer to solutions that provide benefits under any foreseeable climate scenario including present day climate (i.e. the benefits will be realised irrespective of how climate variables change over time).
Low-hanging fruit	Taking the low-hanging fruit means doing the most obvious and simplest work first; implementing the easiest measures that will contribute to or achieve the climate change adaptation objective. These measures enable some useful early benefits to be realised even if the delivery of a long-term solution takes some time.
Adaptive management	Adaptive management describes an iterative approach to planning, developing, delivering and modifying operations or infrastructure solutions while retaining maximum flexibility in the face of uncertainty through an incremental risk management process. Monitoring is critical to adaptive management because responsive solutions are informed by evidence gathered as conditions evolve.
Adaptation pathway	Adaptation pathways describe a sequence of actions (measures, modifications or other investments) that are implemented as conditions change. Uncertainty is accommodated by allowing the first steps on the pathway to be taken with confidence, while the organisation continues to plan to deal with risks associated with climate change in a flexible way. As future options are kept open, maladaptation can be avoided.

INTRODUCTION

Background

The climate is changing. Ports and waterways around the world are experiencing temperature increases, rising sea levels, and changes in seasonal precipitation, wind and wave conditions. More frequent and severe extreme events such as storms, heatwaves and droughts are also attributable to climate change. Early analysis using sophisticated climate models estimate that global warming made the elevated temperatures experienced in Europe in 2019 at least five times more likely and potentially over 100 times more likely than a century ago [World Weather Attribution Group, 2019].

Extreme events, such as those summarised below, cause direct damage, structural failure, downtime and even the closure of waterborne transport assets, cargo handling activities and operational systems.

- Hurricane Sandy, USA, 2013, completely closed the Port of New York and New Jersey for around a week. The re-opening of numerous cargo terminals and maritime support facilities was delayed further because of power failures and damage to ancillary equipment.
- Severe storm conditions, Port of Durban, South Africa, 2017, blew containers into the Bay, broke mooring lines and left a container ship blocking the entrance to the harbour, one of several vessels grounded as a result of the storm.
- Extreme rainfall and flooding, Itajai Port, Brazil, 2017, resulted in a three-week closure of the port; dangerously strong currents prevented the berthing of 30 vessels leaving temperature-controlled warehousing stretched beyond capacity. A significant dredging requirement to restore safe navigation in the approach channel was another consequence.
- Extended drought conditions, River Rhine, Germany, 2018, due to a combination of prolonged heatwave, low rainfall and reduced supply from shrinking glaciers, led to restrictions on River shipping throughout much of 2018, in some cases making river sections impassable and cutting off freight suppliers from their markets.

Urgent Need for Adaptation Planning

In 2019, extreme weather and climate change policy failures were identified by the World Economic Forum's Global Risk Report as the gravest short to medium-term threats to be dealt with globally. The United Nations Conference on Trade and Development [UNCTAD, 2018] specifically highlighted the urgent need for ports to adapt, along with vital connecting transport infrastructure and global supply-chain networks, if significant trade disruption is to be avoided. In 2018, the European Joint Research Centre [JRC, 2018] published two studies highlighting an unprecedented coastal flood risk unless urgent climate change adaptation measures are taken [Vousdoukas et al., 2018a ; 2018b]. Equivalent reports exist for other regions around the world.

Without timely and effective preparation, climate change will result in increasing incidences of damage or structural failures; lead to downtime, disruption and operational delays; and impact on the safety of personnel, equipment and the environment. Port and waterway operators need to act urgently to strengthen resilience and adapt critical assets, operations and systems.

Identifying and Assessing the Risks

Ports and waterways already have to accommodate a variety of risks associated with a range of meteorological, hydrological and oceanographic parameters and processes. Climate change will impact upon these parameters and processes, exacerbating existing risks and introducing new ones including impacts associated with:

- overwhelmed drainage systems or high groundwater levels resulting in flooding
- overtopping and flooding due to high river flow levels, high tide or storm surge
- high in-channel river flow velocities or sea state changes (agitation, extreme waves)
- low river flow conditions, drought or reduced water supply
- changes in bathymetry or in sediment or debris transport, deposition and accumulation
- river or sea bed or bank erosion

- fog or other reduced visibility, for example due to blizzard conditions or sandstorms
- changes in wind speed/strength, direction, or duration
- extreme cold, ice or icing
- extreme heat or humidity (magnitude, duration or frequency)
- changes in water chemistry (acidity, salinity)
- changes in biological character (vegetation growth rates, species migration, invasive species)

Figure 1 illustrates where changes in climate parameters or processes can lead to such impacts in a representative port.

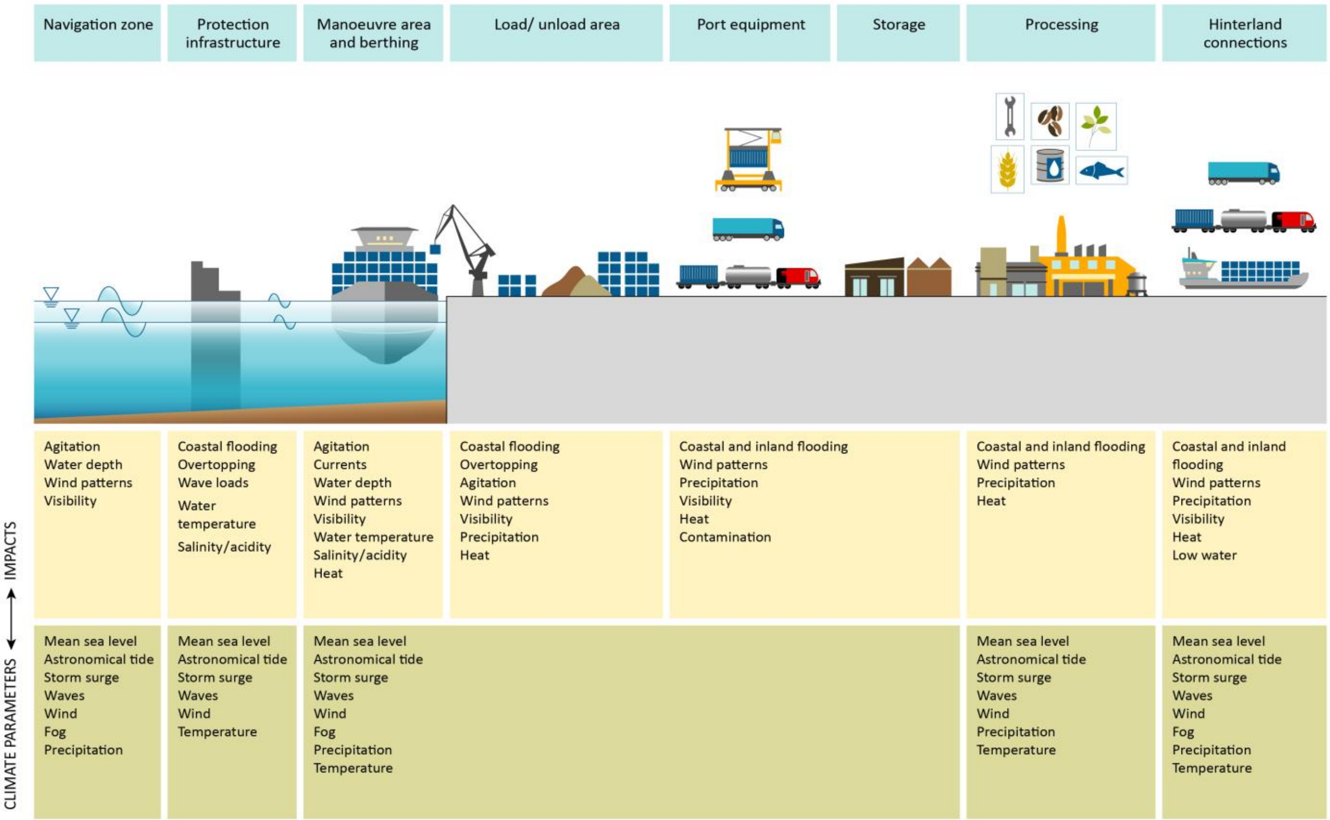


Figure 1: Interactions between climate parameters and processes and representative port assets and operations

In addition to the direct physical effects of climate change dealt with in this guidance, ports and waterways may need to identify and adapt to a number of indirect (economic) impacts. In particular, the effects of climate change on other industry sectors may lead to some ports and waterways experiencing shifts in the nature, quantities or timings of goods being transported, or of passenger traffic. Climate-related changes, in agricultural production or manufacturing activity for example, may result in changes in vessel types using the port or waterway, in changing specifications for berthing or storage facilities, a demand for increased seasonal capacity, a reduction of turnover, or a move from export towards import activities (or vice versa). Modal shift to waterborne transport for goods and passengers to help reduce greenhouse gas emissions from road transport, changes in tourism patterns, and even migration associated with temperature extremes also have the potential to change existing demands on ports and waterways in the short or longer term. Some of these indirect effects will mean that a port or waterway needs to adapt its infrastructure, operations or systems.

Notwithstanding that the focus of this guidance is on the projected direct, physical effects of the changing climate and all of the examples provided reflect this focus, the methodology set out herein is equally applicable to, and can therefore be used to identify and respond to, indirect economic effects.

Understanding How the Climate May Change

In order to prepare for, and appropriately manage, future climate change risks, some form of risk assessment is required.

A fit-for-purpose comparison of current and future risks will help to identify areas where resilience can be improved or where existing assets, operations and systems need to be adapted. In some cases, a high-level assessment based on local experience and expert judgement will suffice. In others, a detailed assessment involving independent advisors or consultants, modellers and other technical specialists may be justified.

This risk assessment should be informed by an understanding of how the climate is expected to change. Many of the climate-related changes that matter most to ports and waterways are driven by changes in temperature. However, for political and economic reasons, there remains a great deal of uncertainty about how quickly temperature will change. Uncertainty about long term changes in temperature therefore means uncertainty about changes in seasonal precipitation; rates of sea level rise; increases in extreme event frequency and severity; and changes in many other potentially relevant parameters and processes.

Levels of uncertainty increase significantly beyond ten years from the present time, so if an organisation is developing a medium to long term adaptation strategy, a range of possible future changes need to be considered. This is done by exploring different climate change scenarios.

Table 1 provides examples of the projected or observed changes being used for climate change planning purposes by the Ports of Antwerp (Belgium) and London (UK) in Europe, Manzanillo (Mexico) and Sydney (Australia). The full version of the case studies mentioned in the table can be found, together with the other case studies referred to throughout this guidance, at the end of the document after References.

Port	Parameter or process	Working projections for adaptation planning
London, UK (Case Study 4)	Temperature	Mean +3ºC to +4ºC by 2080s Summer maximum +4ºC to +5ºC by 2080s
	Sea level	+0.2 m to +0.9 m most likely, but up to +2.7 m by 2100
	Precipitation	Winter +10 % to +20 % by 2080s. Summer -20 % to -30 % by 2080s
	Fog	Winter fog days +20 % by 2080s
Cartagena, Colombia (Case Study 12)	Mean temperature	Global Climate Models project +1.2 to +2.2°C by 2050s; +1.7 to +3.7°C by 2080s Downscaled models suggest +6°C by 2050s
	Sea level	Observed sea level rise suggests +0.5 m by 2100 Accelerated sea level rise scenario +1.3 m by 2100
	Mean precipitation	Continuation of observed trends suggests annual increase of 0.6 % wet days
	Wind	+0.2 m/s by the 2020s and +0.5 m/s by the 2050s and 2080s; winds in the range 3 to 10 m/s could become more frequent
Long Beach, USA (Case Study 2)	Temperature	+0.6 to +6.4°F by 2050 (Long Beach); +4.1 to +8.6°F (California) by 2100. Extremely hot days >95°F increase two- or three-fold by 2050
	Sea level	+0.13 m to +0.61 m by 2050; +0.43 m to 1.68 m by 2100
	Precipitation	-9 % total rainfall at coast; -13 % daily rainfall totals by 2050. +10-25 % total rainfall per storm in California by 2100. 1:20 year storm becomes 1:4 to 1:15 year storm by 2100
	Acidity	-0.5 units pH (California) by 2050
Antwerp, Belgium [1]	Temperature	+3.7ºC to +7.2ºC by 2100, 2 to 9 heatwaves annually
	Sea level	+0.6 m most likely, but up to +2.0 m worst case by 2100
	Waves	Predicted significant wave height +4.0 m per 1.0 m sea level rise
	Precipitation	Winter +3 % by 2030, +12 % by 2100. Summer -4 % by 2030, -15 % by 2100

Table 1: Examples of changes in climate parameters being used for port adaptation planning purposes

[1] Presented at the European Environmental Ports Conference in Antwerp, Belgium on 12-13 June 2019.

Involving Stakeholders and Identifying Actions

Key players from within and beyond the organisation need to be involved in the adaptation planning process: connected operations and businesses will also be affected by climate change. Interdependencies are important. If the site has no power or if personnel cannot get into work because access roads are under water, business will be interrupted. So too will the import and distribution of disaster relief aid. It is, therefore, important to look beyond the boundary of the port or waterway. Engagement with external stakeholders can help to identify win-win opportunities and save money.

Strengthening resilience and adapting an existing port or waterway to the effects of climate change is not only about raising or strengthening physical infrastructure. Depending on the type of risks identified, changes to operations, management or maintenance might be more appropriate or cost-effective. Institutional changes, for example in policy or financing, might also form part of a long-term solution. Delivery of some of these measures will depend upon the effective involvement of external stakeholders.

Four-Stage Approach to Climate Change Adaptation Planning

Ports and navigable waterways play a vital commercial and societal role. Ensuring their resilience to climate change is clearly in the local, national and international interest. This PIANC guidance document therefore introduces a stepwise process to climate change adaptation planning. It builds on local knowledge about the existing susceptibility of the port or waterway, enabling the user to answer the following questions:

- Which assets, operations or systems might be affected by climate change?
- What are the aims and objectives of the adaptation planning exercise?
- Who should be involved in the process?
- What to think about when setting climate change adaptation objectives, agreeing on the planning horizon and selecting scenarios?
- Which climate-related parameters are expected to change and by how much?
- How will critical assets, operations and systems be affected?
- How to deal with uncertainty?
- What other information is needed to inform the assessment?
- How to identify and assess the risks?
- How to identify and evaluate interim and long-term options to strengthen resilience and adapt?
- How to decide when action needs to be taken?

The four stages in this process are summarised in Figure 2. These four stages in the guidance can be followed in their entirety or a particular stage can be used as a standalone reference for the topic in question.

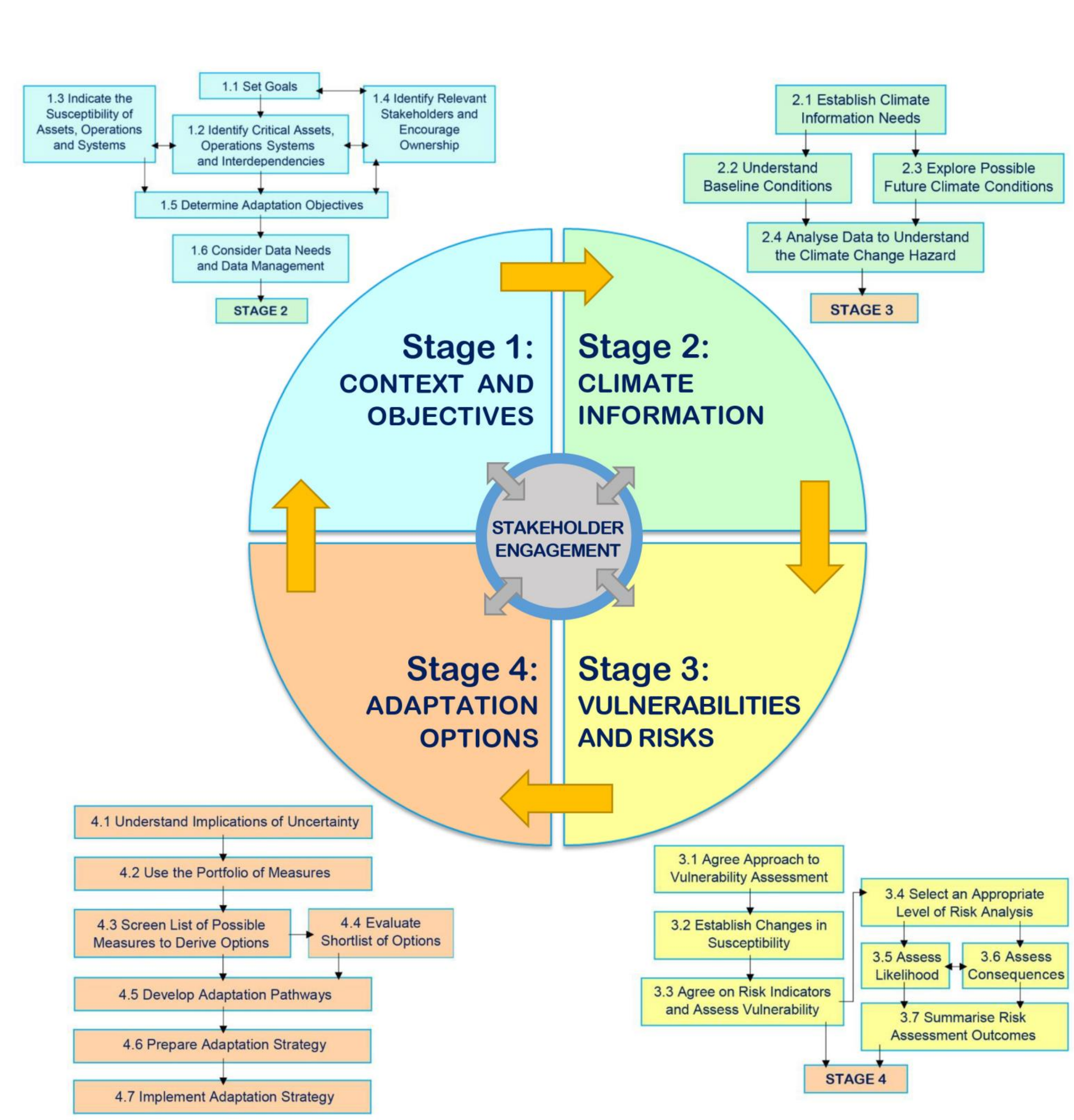


Figure 2: The four stages in the climate adaptation planning process

STAGE 1: CONTEXT AND OBJECTIVES

Stage 1 describes the preparatory steps needed to understand which assets, operations and systems are critical and might be affected by the changing climate, to highlight interdependencies, and to identify relevant stakeholders. This understanding enables climate change adaptation objectives to be agreed.

Step 1.1 Agree High-level Goals

The first step in the adaptation planning process is to set the main goal(s) that represent the expected or desired outcome and describe its high-level, medium- to long-term aims. A typical overarching goal is the example of the Port of Rotterdam where the main goal was to "make the port fully resilient to climate change impacts by 2025 and ensure that it remains one of the safest port cities in the world" (see Case Study 1).

The subsequent steps *(*1.2 to 1.4) then provide information to help define more specific adaption objectives. Objective setting is an iterative process, however, and the initial high-level goals may need to be revisited and revised as indicated in Figure 3.

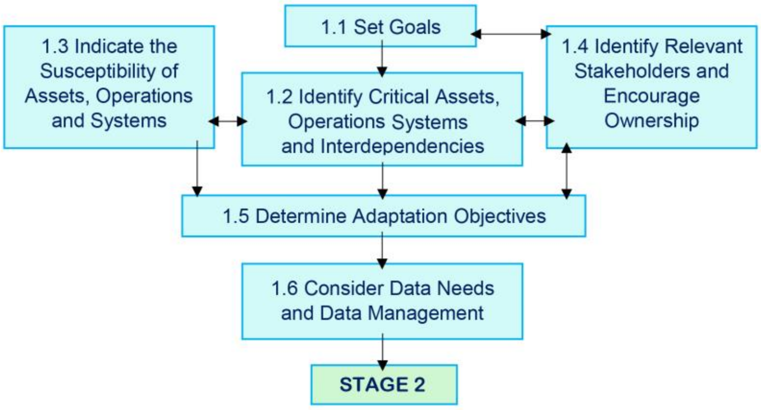


Figure 3: Stage 1 in the climate change adaptation planning process

Step 1.2 Identify Critical Assets, Operations, Systems and Interdependencies

The development of an adaptation plan or strategy needs to be based on a full understanding of which port or waterway assets, operations and systems could be impacted by the changing climate. Understanding both internal and external interdependencies (e.g. energy supply, water, supply chain networks, onward transport modes) is also important in ensuring the resilience of the port or waterway.

1.2.1. Prepare an Inventory

Reference to an inventory of infrastructure assets, operations and systems and associated interdependencies helps to promote understanding and develop ownership of climate change adaptation issues. In this context, infrastructure includes the following:

- Physical assets such as breakwaters, groynes, quays and berths, embankments, docks, locks and other protective or operational structures
- Terrestrial or hinterland assets associated with the port estate or waterway operation (e.g. offices, operations' centres, terminals, equipment and handling, storage or reception facilities)
- Other assets such as port navigation and approach channels, berth pockets and disposal sites for dredged material
- Operations such as maintenance dredging, pilotage, vessel services, scheduling, passage planning, mooring, berthing, cargo handling or recreational use that depend on, or are related to, waterborne transport assets

- Supporting systems such as River Information Services [PIANC, 2019], Vessel Traffic Services, Terminal Operating Systems, Automatic Identification Systems, tracking systems, incident management systems, port security or CCTV, and administrative systems
- Interdependent services or systems including connecting road, rail or other transport infrastructure, power stations or energy supplies, utilities such as water supply and waste water treatment works, and supply chain terminals, distribution and storage centres (see example in Figure 4 [Bles et al., 2016])

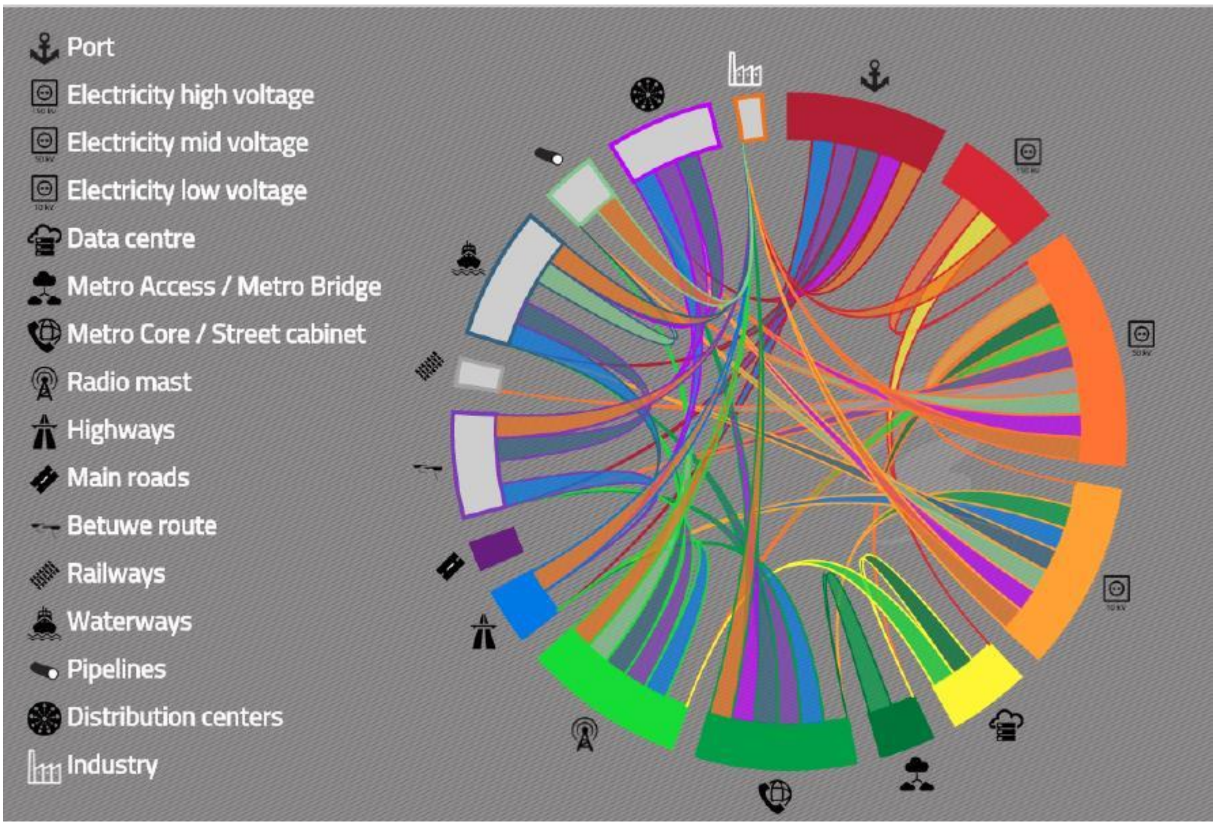


Figure 4: Interdependencies between and within infrastructures within the system of the Port of Rotterdam

Annex 1A provides a comprehensive but not exhaustive list of assets, operations and systems in template format. Using this template as a starting point for the preparation of an inventory helps to ensure that nothing of potential importance is missed out. It also provides a starting point for the risk assessment.

The rows in the template show the assets, operations and systems that should be evaluated for their susceptibility to climate change. Relevant third-party infrastructure, services, etc. should also be added to the template to reflect hinterland assets, interdependencies, supply chains and other interconnected features or activities.

The columns in the template should include the location and details on who is responsible for each asset, operation and system.

A 'snapshot' of such a template (showing only the land-water interface assets and operations by way of an example) is provided in Table 2.

Maritime and inland port and navigation infrastructure				Key facts				
				Geometrical data			Responsible department or organisation	
				Location	Depth (m relative to OD)	Elevation (m relative to OD)	Management	Operation and maintenance
LAND-WATER INTERFACE; INTERTIDAL; RIPARIAN ZONE	Assets	Structures	Quay wall (i)	North quay wall	-15	3	Port Manager	Operations Manager
			Quay wall (ii)	East quay wall	-12	3	"	"
			Fenders	North quay wall	-5	2	"	"
			Ladders	North quay wall	-5	N/A	"	"
			Slipway	Central area	-2	3	"	"
		Physical systems	Cathodic protection	North quay wall	N/A	N/A	"	"
		Resources	Heritage resource (Lighthouse)	East Pier	N/A	10	Local Government	Local Government
			Beach nourishment	South of East quay wall	-1	1	"	"
	Operations		Pilotage	N/A	N/A	N/A	Harbour Master	Pilotage Master
			Dredging / disposal	Inner harbour	N/A	N/A	"	Harbour Master
			Sailing / water sports events	Inner harbour	N/A	N/A	"	"
			Marker buoys navigation aids water sports events	Inner harbour	N/A	N/A	"	"

Table 2: Snapshot of a completed template showing land-water interface assets and operations

1.2.2. Determine Criticality

Critical infrastructure refers to assets or systems and associated operations that are of relatively greater importance because their disruption or destruction would have a significant adverse impact on the continued functioning of the port or waterway, or they are indispensable in some other way.

In order to provide focus to the collection of climate change data (Stage 2) and the scope of the risk assessment (Stage 3), the assets, operations and systems identified in Step 1.2.1 need to be reviewed to determine their relative criticality. This exercise is done in collaboration with relevant stakeholders.

The process of establishing criticality is not climate change-specific. Critical assets, operations or systems could also be affected by structural, mechanical or power failures, by natural catastrophes or emergencies, or by human error. Common considerations in determining criticality relate to the potential consequences if the asset, operation or system is compromised for a given period of time, for example if:

- port or navigation activity or business continuity would be adversely impacted
- there would be health and safety implications
- there would be strategic consequences (e.g. for the regional or national economy or for the distribution of aid, either directly or because of interdependencies or network or supply chain connectivity issues)
- the functioning of the emergency services would be affected
- there would be unacceptable social, socio-economic or environmental implications

The process of determining criticality should be commensurate with the scale of the facility and the level of detail required from the climate change adaptation assessment.

If a corporate method for identifying criticality exists, this should be applied. If there is no corporate method, a simple, subjective exercise based on expert judgement might suffice. For example, 'critical' assets, operations or systems could be highlighted on the completed inventory template using a traffic light system of colour-coding. Table 3 illustrates a qualitative but structured approach to determining whether a particular asset, operation or system is critical [Australian Greenhouse Office, 2006; European Commission 2008/114/EC]. This type of approach encourages the organisation to consider the likely severity of the implications if an asset or system is out of service for whatever reason or if an operation is compromised to the extent that it can no longer take place for, say, a day, a week or a month. The first column on the table qualitatively describes the potential consequence; the final column indicates whether the asset, operation or system concerned might therefore be considered to be critical. The middle columns on the table can be adjusted to reflect site-specific characteristics and the adaptation goal(s).

Implications for: / Scale of impact:	Safety	Economic effects; business continuity	Public effects and local community	Environment sustainability and compliance	Critical?
Catastrophic	Risk of large numbers of serious injuries or loss of life	Loss or degradation would risk long-term viability of business including supply chains	Essential services lost, daily life becomes intolerable, unacceptable physical suffering	Irrecoverable damage, proven breach, prospect of corporate penalty	Yes
Major	Risk of isolated instances of serious injuries or loss of life	Loss or degradation would have serious effects on business requiring significant remedial action	Severe disruption of essential services and hence daily life, high levels of physical suffering	Severe and continuing loss, significant management effort needed to deal with compliance failure	Probably
Moderate	Risk of small numbers of injuries	Intervention needed to protect business continuity	Frequent disruption of essential services; daily life difficult, moderate levels of physical suffering	Minor, reversible damage, action needed on issues of compliance	Unlikely
Minor or insignificant	Risk of near misses or minor injuries	Isolated difficulties (e.g. in supply chain, replacements or alternatives exist)	Intermittent disruption of essential services and daily life, low levels of physical suffering	Negligible damage, minor breaches, easily resolved	Not critical

Table 3: Example considerations for determining criticality

The criteria used to determine criticality will vary between organisations. In addition, if third party activities or services are involved, criticality criteria will also need to be agreed with the responsible owner or operator.

The column with the outcome of the criticality analysis can now be added to the template (see snapshot in Table 4).

Maritime and inland port and navigation infrastructure				Criticality: Not critical	Criticality: Unlikely	Criticality: Probably	Criticality: Yes
LAND-WATER INTERFACE; INTERTIDAL; RIPARIAN ZONE	Assets	Structures	Quay wall (i)				✓
			Quay wall (ii)				✓
			Fenders			✓	
			Ladders			✓	
			Slipway	✓			
		Physical systems	Cathodic protection				✓
		Resources	Heritage resource (Lighthouse)				✓
			Beach nourishment			✓	
	Operations		Pilotage				✓
			Dredging / disposal			✓	
			Sailing / water sports events		✓		
			Marker buoys navigation aids water sports events		✓		

Table 4: Snapshot of the template showing the assessment of the criticality for the different assets and operations

Irrespective of the level of sophistication of the exercise, a record should be kept confirming how criticality was determined and by whom.

Box 1 describes which assets and operations were deemed critical by Port of Long Beach, USA, in preparing their Climate Adaptation and Coastal Resiliency Plan. It also notes which of these assets were subsequently found to be susceptible or vulnerable to the projected changes in sea level and storm surge.

As part of their Climate Adaptation and Coastal Resiliency Plan (Case Study 2), a comprehensive inventory of assets and operations considered important for maintaining business continuity was developed by the **Port of Long Beach, USA**. This process catalogued assets at piers and wharves as well as in the backlands, and included utilities, roads, rail assets, and critical buildings such as those housing security, administration, fire, and life safety functions.

The assets most critical to the Port's business continuity were identified and vulnerability profiles were subsequently developed for these asset types: pier infrastructure, transportation network, critical facilities, utilities, and the breakwater.

- Most critical buildings are located at a sufficiently high elevation to not be susceptible to the modelled levels of sea level rise and storm surge. However, the most vulnerable building is Fire Station #24 (Pier S) because its access route is susceptible to inundation.
- The Foss Maritime mooring of tugboats and barges could be indirectly impacted under storm conditions because the access road is susceptible to inundation.
- Extreme heat may cause electrical outages and area-wide brown-outs unless back-up generators are installed in the building. Building heating and cooling equipment will be disrupted, including all computers and other mechanical and electrical systems, and employee comfort, health, and productivity may be impacted.

Box 1: Critical assets and operations identified by Port of Long Beach, USA

Step 1.3 Indicate the Susceptibility of Assets, Operations and Systems

Port and waterway owners and operators already deal with a variety of existing hazards associated with hydrological, meteorological or oceanographic conditions. Climate change has the potential both to alter these existing climate-related hazards and associated impacts, and to introduce new ones.

Susceptibility is a function of exposure to a risk. Understanding the current or possible future susceptibility of those 'assets, operations and systems identified as being 'critical' or 'probably critical' will help in understanding the type of climate data needed to inform the risk assessment. Critical assets, operations or systems may be susceptible to the following impacts[2].

- Flooding due to **overwhelmed drainage systems** or **high groundwater** levels
- **Overtopping** and flooding due to high river flow levels, **high tide or storm surge**
- High in-channel river **flow velocities** or changes in sea state (**extreme waves**, agitation)
- **Low river flow** conditions, **drought** or reduced water supply
- Changes in **bathymetry** or in **sediment or debris transport**, deposition and accumulation
- River or sea bed or bank **erosion**
- Fog or other **reduced visibility**, for example due to blizzard conditions or sandstorms
- Changes in **wind** speed/strength, direction, or duration
- **Extreme cold**, ice or icing
- **Extreme heat** or humidity (magnitude, duration or frequency)
- Changes in **water chemistry** (acidity, salinity)
- Changes in **biological character** (vegetation growth rates, species migration, invasive species)

In order to indicate susceptibility, records of hydrological, meteorological or oceanographic incidents should be reviewed and the conditions that have caused or contributed to past adverse impacts or near misses should be identified. It may also be helpful to make a note (if known) of whether the impacts were associated with a discrete extreme event or with a longer-term trend in ambient conditions. If these data do not already exist (i.e. information on trends or on the occurrence and consequences of extreme events), a system of monitoring and record keeping will need to be introduced. Effective, targeted monitoring and data management are essential to improving preparedness, informing decisions on how and when to act to strengthen resilience and adapt, and justifying the necessary investment.

The amount of effort dedicated to the initial assessment of susceptibility should be commensurate with the scale of the facility and the level of detail required from the climate change adaptation assessment.

Local knowledge and the expert judgement of responsible individuals will often be sufficient at this stage. Reference might also be made to generic resources such as ThinkHazard! – an initiative of the World Bank and the Global Facility for Disaster Reduction and Recovery, which identifies and classifies different types of hazard at country and local level. However, there may be some situations in which it is necessary to use a more formal or sophisticated, qualitative or quantitative methodology.

Information on the susceptibility of each critical asset, operation or system to each potential impact can now be added to the template columns (Table 5). Key data on critical assets (e.g. design data and current condition, as well as geospatial and geometrical information) can also be added where these are available. Such data will typically be sourced from record keeping associated with existing routine activities such as asset management, condition and performance monitoring or maintenance. If these data are not already available a system of monitoring and record keeping will need to be introduced. Data needs and data management are discussed in Step 1.6.

[2] In addition to the direct physical impacts highlighted above, a port or waterway may also experience indirect, economic effects as a result of climate change, for example associated with changes in agricultural production, manufacturing, tourism, etc. As noted in the introduction, the stepwise methodology set out in this guidance document can equally well be used to identify and assess the adaptation responses needed to address such changes.

A snapshot of the template illustrating which assets, operations, etc. are susceptible to which impacts, and highlighting available data on design and condition, is presented in Table 5.

Maritime and inland port and navigation infrastructure				Criticality				Susceptibility to hazards causing impacts												Key facts					
																				Design data			Asset condition		
				Not critical	Unlikely	Probably	Yes	Flooding	Overtopping	Flow velocities/extreme waves	Low river flow	Changes in bathymetry	Bed or bank erosion	Fog or reduced visibility	Changes in wind	Extreme cold, ice or icing	Extreme heat, also humidity	Changes in water chemistry	Changes in biology	Design life (years)	Date of construction	Residual life	Good	Moderate	Poor
LAND-WATER INTERFACE; INTERTIDAL; RIPARIAN ZONE	Assets	Structures	Quay wall (i)				✓	✓	✓	✓		✓	✓	✓	✓	✓		✓		50	1994	25		✓	
			Quay wall (ii)				✓					✓	✓	✓	✓	✓		✓		50	2014	45	✓		
			Fenders			✓								✓	✓	✓	✓	✓		15	2014	10	✓		
			Ladders			✓								✓	✓	✓	✓	✓		15	2014	10	✓		
			Slipway	✓																					
		Physical systems	Cathodic protection				✓						✓			✓		✓		10	2014	5	✓		
		Resources	Heritage resource (Lighthouse)				✓	✓	✓	✓				✓	✓	✓	✓			N/A	1950	N/A		✓	
			Beach nourishment			✓			✓	✓		✓	✓						✓	15	2018	14	✓		
	Operations		Pilotage				✓			✓	✓	✓		✓	✓	✓				N/A	N/A	N/A	N/A	N/A	N/A
			Dredging / disposal			✓				✓	✓	✓	✓	✓	✓					N/A	N/A	N/A	N/A	N/A	N/A
			Sailing / water sports events		✓																				
			Marker buoys navigation aids water sports events		✓																				

Table 5: Snapshot from completed template illustrating susceptibility of critical assets and operations

An example of how the susceptibility of assets and operations can be determined, and the role stakeholders can play in this process, is provided in Box 2, describing the experience of the Port Authority of New York and New Jersey following Superstorm Sandy.

Following the events and impacts of Superstorm Sandy in 2016, the **Port Authority of New York and New Jersey (PANYNJ, USA)** carried out a study to identify the potential risks of future coastal flood inundation from storms of various scales (Case Study 3). These investigations evaluated the potential impacts of storms, sea level rise and climate change, over a 40-year period, on critical infrastructure, assets and operations at PANYNJ.

Representatives from various departments within the Port Authority worked alongside tenant operations (external stakeholders) in Port Newark South to characterise assets and to identify vulnerabilities to coastal flood hazards. The tenants provided input on potential impacts such as how they would function with loss of electricity, loss of water service, and equipment loss. The fact that Hurricane Sandy was still fresh in the memory of many of the tenant representatives meant that most could recall which assets and infrastructure were impacted and explain how they had adjusted or adapted their operations to meet a future event similar to Sandy.

The most obvious issues involved water damage to buildings, damage to electrical and electronics equipment, and problems associated with power loss. Other issues were the damage to cranes, stackers, and other mobile equipment: these factors significantly slowed many of the tenants' operations for months after the event. Fuel supply was also a critical issue in the region after Hurricane Sandy, both regarding the operation of clean-up/debris removal equipment and in relation to the transportation of staff to and from their homes to assist in the clean-up operation.

Box 2: Port of New York and New Jersey experience in determining susceptibility, USA

Step 1.4 Work with Stakeholders

1.4.1. Identify Relevant Stakeholders

The development of a port or waterway climate change adaptation strategy will typically involve a wide range of stakeholders from both within and outside the organisation. Effective dialogue with external individuals and organisations is vital for a number of reasons, including:

- ensuring that interrelationships and interdependencies between different port and waterway assets, operations and systems as well as with third party interests are identified and properly accommodated
- enabling adverse impacts on others' interests or working practices to be avoided

- reducing the risk of maladaptation (i.e. avoiding making the wrong decision on which measures are adequate and appropriate; see Step 4.1.1)
- identifying cost-effective adaptation pathways (see Step 4.5)
- ensuring that collaborative opportunities are not missed

Climate change adaptation often focuses in the first instance on measures to strengthen the resilience of day-to-day activities or working practices. Maintenance regimes may need to be modified, or contingency plans prepared or updated. This means that internal stakeholders such as the harbour master, pilots, port engineer and berth or terminal operators will need to be involved.

Most ports and waterways cannot operate without power/energy or water and wastewater provision so the security of these third-party services will be of concern. The same applies to the resilience of onward transport infrastructure and the wider supply chain – not only shipping lines, but road, rail and other modes of transport. Engaging with the organisations responsible for such infrastructure and services will therefore be essential.

In cases where incremental physical or operational/management measures prove insufficient and a fundamental or 'disruptive' change is needed, senior management will need to be involved in adaptation decision making. In other cases, changes in local, regional or national policy might be sought.

The template in Annex 1B provides a comprehensive but not exhaustive list of typical port or waterway and external stakeholders and their associated roles and responsibilities. Reference to this template will help ensure that all relevant individuals, organisations and groups are identified and approached. However, the template is not a prescriptive list. Rather it gives examples of different types of organisations. Its intention is to stimulate thinking about who needs to be involved. The preparation of a list of relevant stakeholders, whether based on Annex 1B or using another process, will be an organisation- or site-specific exercise.

Climate change adaptation is an iterative process. The process of engaging stakeholders may lead to the identification of additional critical assets or interdependencies to be added to the inventory and included in the assessment of adaptation requirements. (see Figure 3).

1.4.2 Encourage Ownership of the Climate Change Challenge

Some climate change preparedness measures might be implemented unilaterally by the port or waterway, but others will require the support of, or action by, third party organisations. Efforts therefore need to be made to raise awareness and generate ownership of the challenges that climate change will bring. Having identified relevant stakeholders, an effective way of developing ownership is to organise a facilitated workshop like that used by the Port of London Authority in the UK (see Box 3). This case study also illustrates the value of such workshops in identifying unexpected impacts.

Further guidance on identifying and engaging stakeholders is provided in Annex 1C.

A series of facilitated workshops to discuss the potential implications of climate change formed a key part of the preparation of the **Port of London Authority**'s first climate change adaptation report for the UK Government (Case Study 4). The workshops involved senior personnel from different port departments (harbour masters, navigation systems, civil and marine engineering, hydrographic surveying, corporate affairs, planning and partnerships, finance, environment and marine services) as well as commercial terminal owners and operators, shippers, recreational users, water companies and various public sector and community groups.

These workshops led to a much-improved understanding of climate-related risks. Prior to the workshop most of those attending had assumed that the main issues – and hence the need for adaptation measures – would be associated with sea level rise and would be focused on the Thames Estuary. By the end of the discussion, however, it was clear that although sea level rise is relevant, climate change is likely to bring far greater short to medium term challenges with regard to precipitation and associated freshwater flow rates into port and with vegetation management in the upper reaches.

Projections suggest extreme low and high flows will become much more common, with associated risks for safety of navigation. A potentially significant increase in the number of fog days affecting parts of the river used by both recreational and commercial traffic is also possible, but there is more uncertainty around these projections. The need to identify drought-tolerant species for planting along the upper river banks was identified as another relatively urgent action.

Overall, therefore, the workshop not only raised awareness; it resulted in a significant shift in emphasis within the Authority on where initial climate change adaptation measures would be needed.

Box 3: Role of facilitated workshops in identifying climate change adaptation priorities, UK

Other methods that can be used to improve engagement and encourage ownership include face-to-face meetings, presentations and training initiatives. Where relevant, these should build on existing organisation-specific processes such as risk management, emergency planning, sustainability reporting, etc.

For external stakeholders, the preparation of technical documents; online activities such as webinars, webpages or social media posts, the publication of newsletters, or exhibitions, drop-in events or similar outreach initiatives can all help to raise awareness and generate engagement.

Not being able to assign or encourage ownership might lead to inaction and thus a possible high risk of unacceptable climate change impacts. An example of this is provided by the case of the Port of Providence, summarised in Box 4.

There is no official port authority in Rhode Island. Rather the businesses that make up the **Port of Providence** most closely resemble a private sector port. The State plays no direct role in managing port operations or centralised planning although the Coastal Resources Management Council, the State's coastal agency, regulates land use in the coastal area including the area occupied by the Port.

A pilot project, funded by the Federal Highway Administration and the Rhode Island Department of Transportation, brought together 30 key stakeholders from the Port of Providence to engage in a dialogue around the risks from a major hurricane at the Port (see Case Study 5).

Researchers from the university surveyed the stakeholders to ascertain their preferred strategy and to identify where they felt leadership responsibility should lie for both disaster preparedness and for the delivery of adaptation measures. While all participants agreed there was a need for strong public-private collaboration on disaster preparedness, the study highlighted the different views of stakeholders as to the allocation of responsibility for adapting to climate change impacts.

Although many stakeholders recognise the likelihood of climate change and the increased occurrence of major storm events affecting their port, in this case threats were not perceived as imminent. Little was being done to prepare and the incentives for making investments are still not clear. The private sector puts the leadership burden on the public sector and vice versa to a certain extent. In any case, most agreed that the state needs to play a large role in leading the process and that specific leaders from the private and/or public sectors will need to step forward to initiate actions – through guidance, directive, mandate, self- or altruistic-interest – that make the system, or components thereof, more resilient to climate change and natural disasters.

Box 4: Port of Providence strategic vulnerability and resilience assessment, USA

Step 1.5 Determine Adaptation Objectives

1.5.1. Agree Boundary Conditions, Constraints and Opportunities

Boundary conditions or constraints can significantly influence the objectives of a climate change adaptation strategy. Typical constraints can relate to ownership or jurisdictional limits; reflect environmental, financial, regulatory or policy requirements; or concern the availability of data, budgets or resources.

The examples in Table 6 illustrate on the one hand how legislative requirements and jurisdictional limits might determine the scope of climate change adaptation considerations and on the other, how policy and practical factors might constrain the scope of what is realistically achievable.

Case Study	Examples of boundary conditions or constraints
Harwich Haven Authority, UK (Case Study 6)	Under the UK Climate Change Act (2008) ten major ports were required to report to the DEFRA Secretary of State on how climate change will impact their organisation and what adaptation measures are proposed. Reports were to focus on the port's statutory responsibilities and duties. Harwich Haven Authority on the east coast of England is a statutory UK Harbour Authority established by Act of Parliament in 1863. The scope of the report therefore had to reflect the Authority's duty to conserve, protect and improve the harbour and its approaches for the benefit of all its users; and to cover the services the Authority provides for shipping, pilot boarding and landing as well as for recreational users within its area of jurisdiction.
Tuvalu, South Pacific (Case Study 7)	The early recognition of a number of policy and logistical issues which were likely to constrain options for adaptation or improving infrastructure resilience meant that investigations could focus on realistic options from the outset: • Environmental concerns had led to a Government ban on the use of locally available coral sands and rock. Any construction materials required for adaptation will therefore need to be imported. • The islands' remoteness makes it difficult to source and transport construction materials, plant or machinery to site. • Funds and capacity to undertake ongoing maintenance of the infrastructure are limited.

Table 6: Examples of boundary conditions and constraints on adaptation studies

Climate change adaptation is not only about recognising limitations; it also provides a platform for seeking opportunities, particularly for collaborative initiatives. It may be possible, for example, to:

- Link climate change adaptation to ongoing corporate initiatives such as asset management or Corporate Social Responsibility (CSR) programmes
- Realise cost savings e.g. through collaboration on third party initiatives, shared services
- Deliver social, recreational, socio-economic or environmental co-benefits, or highlight win-win solutions (see Box 5)
- Identify Working with Nature [PIANC, 2018] or other nature-based solutions.

The Mid-Atlantic coast, where many **US Department of Defense** (DoD) critical installations are located, supports a diverse ecological community and provides significant economic benefit to the region (e.g. migratory waterfowl hunting and blue crab shellfishery). Importantly for the DoD, these ecosystems also provide natural storm surge attenuation. Sea level rise (SLR) will affect both built and natural systems, leading to changes in structure and function which could drastically alter the system's capacity to provide such ecosystem benefits and services. Although inundation is a primary concern, other effects of SLR such as increased storm susceptibility, barrier island migration, coastal erosion, wetland drowning, and saltwater intrusion needed to be accounted for to adequately understand the impacts of SLR on coastal installations. Of particular concern, conversion, migration, or loss of beach, marsh, or swamp features could result in loss of critical habitat and change storm surge attenuation. The US Army Corps of Engineers' step-wise risk assessment approach for critical defence assets in Chesapeake Bay therefore considered both the direct and indirect implications of SLR and changes in storm characteristics for these ecosystem services (Case Study 8).

Box 5: Example of socio-economic and environmental co-benefits and the role of ecosystem services, USA

1.5.2. Determine the Planning Horizon

Another important consideration that influences the objectives of the climate change assessment is the period of time (horizon) to be covered by the adaptation plan or strategy.

Much port and waterway infrastructure has a design life of decades. An adaptation strategy for existing assets should therefore cover a similar period if it is to assist owners and operators in understanding the type of changes over the lifetime of their assets. Conversely, if the assessment is intended to inform short-term investment decision making (e.g. about the type of measures needed to prolong the functionality of existing assets until these are replaced with new, climate-resilient infrastructure) a shorter planning horizon may be appropriate. The interests of key stakeholders are also important in deciding on the adaptation planning horizon.

Taking into account the climate change projections and associated uncertainties discussed in Stage 2, there are three broad possibilities:

i. Planning horizon up to 10 years from the present time
ii. Planning horizon between 10 and 30 years from the present
iii. Planning horizon beyond 30 years

The decision on the adaptation planning horizon is critical because it determines the type of climate change data and nature of the analysis required for the assessment.

1.5.3. Set Specific Adaptation and Resilience Objectives

The next step is to draft practicable adaptation objectives in conjunction, or to be discussed with stakeholders. These objectives need to be realistic in terms of the identified boundary conditions, constraints, opportunities and the agreed planning horizon, but they should also relate directly to the critical assets, operations and systems likely to be affected by climate change. Two quite different examples of climate change adaptation objectives taken from the case studies are presented in Table 7.

Port or navigation organisation	Climate change adaptation objectives
Avatiu Port, Rarotonga (Cook Islands) qualitative climate risk assessment (Case Study 9)	• Understand the risks posed by changes to sea level and wave behaviour on coastal infrastructure and communities in the Avarua area, particularly during extreme events. • Identify needs and develop options for responses to the risks. • Build local capacity to understand the science and manage the risk assessment and planning process.
Port of Long Beach (USA) climate adaptation and coastal resiliency plan (Case Study 2)	• A more resilient Port able to continue operations under changed conditions. • A Port prepared and ready to adapt.

Table 7: Examples of climate change adaptation objectives

Ideally, adaptation objectives should be 'SMART' (Specific, Measurable, Attainable, Realistic, Timely). However, in practice, they can only be as SMART as the available information allows.

Climate change adaptation is an iterative process. Discussions with stakeholders and taking a flexible approach to incorporating new sources of information are therefore essential. The objectives are likely to be modified as the adaptation planning process progresses. For example monitoring results or other new information will become available; other organisations may become involved in the planning and delivery process; or understanding of the potential implications of climate change may improve. Initial priorities might be set at this stage to help to provide clarity and focus to the climate change adaptation decision-making process. The roles and responsibilities of the port or waterway operator and other stakeholders, both in the process of developing the strategy and in taking action to achieve the objectives, similarly need to be defined.

Step 1.6 Consider Data Needs

1.6.1. Monitoring and Recording

Effective and efficient climate change adaptation depends on accessible, fit-for-purpose data. Local knowledge is invaluable in informing decisions on climate change adaptation as well as in minimising downtime and managing operations during an event. Data collection and accurate record-keeping play a vital role, both in understanding local trends and hence determining when action is needed; and in documenting the frequency and consequences of extreme events. The significant value of long-term data series in assessing trends in meteorological, oceanographic and hydrological data cannot be overstated when climate change adaptation decisions are being made.

An important early step in climate change adaptation planning is therefore to acquire, store and manage relevant local data. Owners and operators of waterborne transport infrastructure should make provision to collect and manage the following:

- Data on the condition and performance of physical assets and on operational efficiency. Reference to this data set will facilitate understanding of the effects on infrastructure of slow onset, climate-related changes such as increasing air or water temperatures or sea level rise. It will also enable any deterioration caused by climate-related incidents to be highlighted. This information is useful both in determining the susceptibility and vulnerability of critical assets, systems and operations and in understanding how urgently adaptation measures are likely to be needed (relevant to Steps 1.3, 3.2 and 3.3 and 4.5).
- Data on the costs and consequences of extreme events, including damage, disruption and downtime. These data contribute to the assessment of susceptibility and vulnerability and also enable the potential costs of inaction to be quantified, in turn supporting the business case for adaptation and resilience measures (relevant to Steps 1.3, 3.2 and 3.3 and 4.4 to 4.6).
- Local meteorological, oceanographic or hydrological data. Such information is invaluable in determining if local trends are in line with projected rates of change, as well as informing decisions on 'when' an adaptation action or adaptive management response is needed (relevant to Steps 2.2 to 2.4 and 4.5).
- Information on the performance of already implemented adaptation and resilience measures, including their efficiency. This will enable decisions to be made on future modifications, supplementary measures or adaptation pathways (relevant to Step 4.7).

1.6.2 Physical Assets and Operational Efficiency

Data on the status or condition of physical assets and on the efficiency of operations (performance) already informs many activities in ports and waterways. These technical data are equally important to climate change adaptation decision making. If a comprehensive and accessible record of asset condition/status and other factors relating to functionality efficiency does not exist, an appropriate monitoring system needs to be developed, set up and maintained.

Whenever possible, monitoring and recording to be used to inform climate adaptation decisions should be aligned with existing asset management procedures and systems, e.g. for hydrology, hydrographic or other surveying, technical services or infrastructure inspection. In some cases, specialist companies may need to be involved. Local research institutes or universities might provide assistance with measurement and interpretation, including analytical and numerical modelling if appropriate.

Insofar as monitoring the performance and condition of physical assets is concerned, knowing the design life of a structure is useful to adaptation decision making, but it is usually its integrity or actual condition (i.e. its residual life) that will influence whether climate resilience measures can wait until the asset is due to be replaced or whether action needs to be taken in the meantime. The effectiveness of maintenance can similarly be a major factor in determining whether and when additional resilience measures may be needed.

When deciding what to monitor, reference should be made to the inventory of critical infrastructure (Step 1.2) and its susceptibility to climate related impacts (Step 1.3). Depending on the nature of the (critical) assets, the following might be amongst the parameters requiring monitoring and recording:

- structural condition, status, integrity, including condition of foundations
- residual life of structural elements; levels with respect to design or operational functionality
- nature/extent of post-event or weather-related damage, level of damage and any associated consequences (serviceability, reparability, ultimate fate)
- extent to which rates of change in the above (deterioration, damage, etc.) are exceeding those normally expected.

Structural monitoring can be undertaken through routine, special, or post-repair inspections carried out by competent individuals. Inspections can be visual, undertaken through measurements (e.g. designed to identify rates of change), or intrusive. Inspection of underwater constructions can be realised by de-watering or using underwater cameras or professional divers.

Insofar as day-to-day port and waterway operations are concerned, anecdotal information on performance or efficiency should be collated via a regularly completed log used by pilots, harbour masters, maintenance personnel, terminal operators and others. Such a log, whether electronic or paper-based, can be used to record delays or disruptions, operational threshold exceedances, or situations where it is necessary to resort to an alternative operational mode or back-up provision. It may also be useful for recording general asset condition or specific damage (see above).

Whenever a record is logged, the exact time, date and location should be documented alongside information about the prevailing conditions. This will enable the records to be used alongside local meteorological, oceanographic or hydrological data (see Step 2.2) to help understand any changes in frequency, etc. Wherever practicable, key facts collected as a result of the monitoring should be added to the critical assets, operations and systems inventory template.

1.6.3. Implications of Extreme Events

Specifically, in relation to understanding the costs and consequences of extreme events, information on the following needs to be recorded whenever business is disrupted:

- the nature of the event causing the damage or disruption, including details about its magnitude and other key characteristics (e.g. total rainfall over a period of time, duration of drought, strength and direction of wind, maximum wave height, etc.)
- details about disruption and downtime, including which assets or operations were affected, for how long, and with consequential costs (e.g. lost trade)
- direct and indirect losses to the business resulting from such disruption or downtime, including during the post-event recovery period (e.g. increased insurance premium)
- implications for business performance, locally and at system level; this should be recorded against locally-defined and agreed metrics, or as a deviation from agreed targets
- the direct costs of clean up and damage repair
- how stakeholders were affected (terminal operators, others on the port estate, workforce, local community, industry)
- implications for nature and environmental resources

In order to facilitate the collection of information on downtime, disruption or loss of function, a template such as that provided in Annex 1D might be used.

The records of extreme events are somewhat distinct from the day-to-day changes discussed in Step 1.6.2, because they address exceptional incidents. When this type of event occurs, the immediate focus tends to be on cleaning up, repairing damage, replacing assets, reopening facilities, etc. The full cost of the event to the port or waterway business is rarely properly documented. However, an understanding of these costs is vital if the cost of inaction is to be understood and investment in improved resilience justified.

1.6.4. Data Management

A modern data management system enabling the control, protection and efficient use of data and information assets is vital in supporting timely, proportionate and cost-effective adaptation action.

Understanding when to act and what type or how much of a measure is needed to meet the adaptation objective requires targeted monitoring and effective management of the data being collected.

Decision makers not only need information on the status of assets, operations and systems (Step 1.6.2) and how and when these may be affected (i.e. rates of change in key parameters and when thresholds are expected to be exceeded; Step 2.2.1), but also on the costs and consequences of the projected changes, including extreme weather events (Step 1.6.3); and the effectiveness of implemented adaptation measures (see Step 4.7.1).

To be of maximum value, all these data need to be collected in a consistent and compatible manner and stored and managed so as to be readily accessible when needed. This includes retaining existing datasets when a system is upgraded or renewed.

Annex 1E discusses how to set up a fit-for-purpose data management system.

Outcomes of Stage 1

For those working through the climate change adaptation planning process, the following steps should be completed before progressing to Stage 2:

- The goal(s), planning horizon and objectives of the climate change adaptation initiative are agreed (Steps 1.1 and 1.5).
- An inventory of critical assets, operations and systems including interdependencies is complete (Step 1.2) and the climate impacts to which each is susceptible have been confirmed (Step 1.3).
- Relevant internal and external stakeholders have been identified and action taken to ensure they are engaged in the process (Step 1.4).
- Monitoring of physical asset condition, operational performance and the consequences of extreme events is in place, along with a fit-for-purpose data management system (Step 1.6).

STAGE 2: CLIMATE INFORMATION

Future changes in the climate will affect many of the critical maritime and inland navigation infrastructure assets, operations and systems identified in Stage 1. The steps in Stage 2, illustrated in Figure 5, help the user identify which climate parameters and processes are relevant and how these are projected to change under different climate change scenarios.

Before progressing to Stage 3 to identify and assess the risks associated with the climate hazard, data need to be collated and reviewed to understand both slow onset changes and the expected increases in the frequency or severity of extreme meteorological, oceanographic or hydrological events. Comparisons can then be made with baseline conditions, taking into account existing patterns or trends, and any uncertainties or limitations in the data.

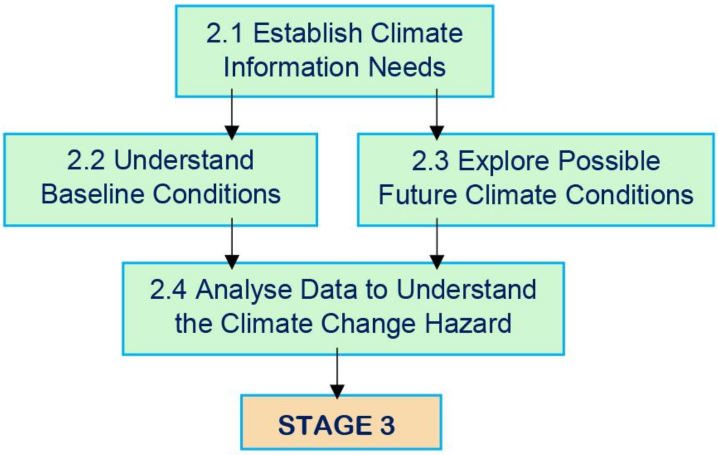


Figure 5: Stage 2 in the climate change adaptation planning process

Step 2.1 Establish Climate Information Needs

Climate information is available at different spatial and temporal scales, for example:

- global, regional, national, local and site specific
- annual, seasonal, monthly, daily and/or hourly

The decision about which climate data are needed and the appropriate level of detail or sophistication, will depend on:

- the location of the port or waterway
- the nature of the critical assets, operations and systems identified in Step 1.2 and the hazards to which they are susceptible (Step 1.3)
- the objectives and scope of the adaptation initiative and its planning horizon (Step 1.5) and the resources and technical expertise available

Understanding and quantifying existing conditions is important as this forms the baseline for the adaptation strategy.

2.1.1 Confirm Which Climate Parameters and Processes are Relevant

Organisations will already be aware of some climate parameters and processes of relevance because past events have caused damage or disruption. For example, strong winds, high waves or extreme rainfall may have adversely impacted on aspects of port or waterway performance.

The completed inventory from Step 1.3 showing the impacts to which critical assets, operations and systems are susceptible, can be used to inform the identification of parameters and processes of known direct relevance. Some typical parameters and processes are illustrated in Table 8.

Parameter or process → / Impact susceptibility ↓	Air temperature	Water temperature	Precipitation	Storminess	Sea level rise
Flooding due to overwhelmed drainage systems or high groundwater levels			✓	✓	
Overtopping due to high river flows, high tides or storm surges			✓	✓	✓
High in-channel flow velocities or changes in sea state			✓	✓	✓
Low river flow conditions, drought or reduced water supply			✓		
Changes in bathymetry, or sediment or debris transport			✓	✓	✓
River, sea or bank erosion			✓	✓	✓
Fog or other reduced visibility issues	✓	✓	✓		
Wind speed, strength, direction, duration	✓			✓	
Extreme cold, ice or icing	✓	✓			
Extreme heat or humidity	✓				
Changes in water chemistry		✓			
Changes in biological character	✓	✓	✓		

Table 8: Examples of typical relevant parameters and processes based on impact susceptibility

However, it is also important to be aware that the potential relevance of other climate parameters or processes may not yet have been recognised. There may be no record of extreme heat having adversely impacted the port, or the waterway might not previously have been closed due to drought conditions. The importance of such additional parameters or processes may only become clear as future climate scenarios are examined.

If it is not clear whether a particular climate parameter or process is relevant, records of near misses could be analysed where these exist. It will also be useful to explore hypothetical but plausible 'what if' questions. For example, what would happen to critical assets, operations and systems if double or half of the usual winter rainfall was received, or if there was a prolonged drought or heatwave?

Where the relevance of a parameter or process (e.g. temperature, sea level rise) remains uncertain, it is better to collate the available data, than to dismiss it now because it might become significant in the future.

2.1.2 Involve Stakeholders in Identifying Relevant Climate Parameters and Processes

Discussions with managers, operators and other stakeholders will help identify the full range of relevant climate parameters and processes. These discussions can be particularly important if consultants are carrying out the assessment because those responsible for the management of critical assets, operations or systems should be able to draw on personal experience and/or records to provide accurate information on existing and potential susceptibility.

A meeting or a workshop such as discussed in Step 1.4.2 would provide an ideal opportunity to develop consensus on the climate parameters and processes to which critical assets, etc. are already, or could be, susceptible.Box 6 illustrates the relevant climate parameters and processes identified by a wide range of internal stakeholders as part of the climate change risk assessment for Port Botany and Port Kembla in New South Wales, Australia.

In 2015, the **NSW Ports** (New South Wales, Australia) conducted a climate change risk assessment for their assets (Case Study 10). This study involved the port management team and various internal stakeholders responsible for asset management, infrastructure maintenance and operation, environmental planning, and community engagement. It aimed to identify the likely impacts of climate change, enabling the port to adapt as necessary to ensure the long-term resilience of potentially affected assets.

The key climate parameters and processes identified for the ports in question were sea level rise, air temperature, precipitation, winds, and potential changes in storm intensity and frequency. Port Kembla in particular is protected by significant breakwater structures and there is a risk that a change in wave and storm activity could result in increased overtopping and/or dislodgement of armour units from the structures. Other physical risks to port assets that were considered include:

- degradation of roads and pavements due to extreme temperatures and rainfall events
- increased risk of flooding damage due to higher frequency/intensity of extreme rain events
- increased risk of power failure and degradation of electrical and communications infrastructure due to extreme temperatures and/or severe storms
- potential for increased rates of deterioration of marine infrastructure due to increased exposure to saline water (e.g. associated with sea level rise or incidence of wave attack)

In addition to physical risks to port assets, an increased frequency of extreme weather events may impact on port operations. Issues identified in this regard included:

- large swell and high winds closing Port Botany and Port Kembla to shipping
- high winds delaying quay crane operations
- high winds causing empty boxes to fall from container stacks
- hot weather stopping stevedoring activity

This information was used to identify relevant climate variables as shown in the table below.

Climate parameters and processes relevant to assets and operations in two NSW ports

Critical asset/operation	Climate parameter or process	Potential impact
Roads	Air temperature, precipitation	Degradation of pavements
Buildings	Precipitation	Flooding
Electrical power systems	Air temperature	Degradation
Communications infrastructure	Air temperature	Degradation
Marine infrastructure	Mean sea level, storm surge, astronomical tide, sea level rise, waves	Degradation due to flooding
Berth area	Wind, waves	Operational downtime
Quay cranes	Wind	Operational downtime
Container storage area	Wind	Container damage

Box 6: Relevant climate parameters and processes for Port Botany and Port Kembla, Australia

Further information on which climate parameters and processes are of potential relevance to waterborne transport, ports and waterways can be found in the PIANC publication ‘Climate Change and Navigation’ (2008, update forthcoming) including, amongst others, metocean variables such as wind, waves, sea level and ice as well as more complex geographical response variables such as ocean circulation and estuarine morphology.

Step 2.2 Understand Baseline Conditions

2.2.1 Collate Baseline Climate Information

Various sources of observed, measured or hindcast modelled historical data provide the baseline against which the possible implications of future climate change can be assessed. Analysis of such historic information for relevant climate parameters and processes (see Step 2.4.1) will enable the organisation to:

- Understand existing recent patterns or trends, including determining whether these may be related to climate change, and how, if at all, they are already impacting on critical assets, operations or systems.
- Compare historic values to projected trends, helping to inform decisions on an appropriate adaptation pathway or make plans for investment in adaptation measures.
- Recognise when a particular threshold is likely to be crossed, in turn triggering adaptation action, preparation for the next phase of implementation, or a change to a different method.
- Understand some of the characteristics of historic extreme events.

Long-term (i.e. over multiple years and decades) historical datasets should be compiled for each relevant parameter or process wherever practicable.

The port or waterway organisation may already hold some relevant data. Discussions with internal and external stakeholders can identify potential sources of good quality baseline data, including information collected by third parties. Reliable local information is always of great value in climate change adaptation decision making

A wide range of international, regional and national authorities, scientific and academic institutions and other organisations collect and analyse relevant climate data. Long-term data from water level gauging stations, airport weather stations and wave rider buoys may be available from government organisations or research institutes. Temperature, atmospheric air pressure, moisture, and wind velocity and direction, as well as rain gauge/digital meteorological weather station results, are often freely available or can be purchased at low cost. In some cases, these resources may offer a wireless connection to specific sensors, data storage or downloadable datasets.

Table 9 illustrates the type of data that may be needed to inform the preparation of a climate change adaptation strategy and indicates where such data might be obtained. Annex 2A contains a further list of key sources of climate data, including both information on baseline conditions and climate change projections.

Climate-related parameter or process	**Options if parameter or process is relevant**		**Possible sources of existing information**
	Minimum data collection and recording	**More sophisticated data collection options**	
Precipitation	Rain gauge, daily precipitation (mm)		National weather forecasting service, local research or educational institutions
Water level	Water level at a specific location, recorded at least twice a day using a water level gauge with fixed reference level	Hourly, automated tidal gauge, nearshore/ offshore wave buoy	National weather forecasting service; nationally and internationally operated water level gauges
Currents/ flow rates	Anecdotal information logged by pilots/ users e.g. using the vessel's navigation system	Hourly, automated current velocity measurements (e.g. via Acoustic Doppler Current Profiler)	National and international forecasting services, information from port or waterway users

Climate-related parameter or process	Options if parameter or process is relevant		Possible sources of existing information
	Minimum data collection and recording	**More sophisticated data collection options**	
Bathymetry	Basic bathymetric survey (see Box in Annex 2B)	Single beam/multi-beam survey	National shipping authority, scientific research programme
Sediment or debris transport	Anecdotal information logged by pilots, port or waterway users, or those undertaking maintenance dredging	Hydrographic survey	Scientific research programme, information from port or waterway users
Wave height and direction, sea conditions	Anecdotal records from operators when a threshold is exceeded; log of approximate height, period and direction	Hourly records (wave height, period, direction), nearshore and offshore, wave buoy with associated water levels, automated records located nearshore and offshore	National weather forecasting and/or hydrographic services, nationally and internationally operated wave buoys, information from port or waterway users, Voluntary Observing Ship (VOS) data
Wind speed and direction	Anecdotal information logged by operators when a threshold is exceeded	Hourly records of 10-minutes mean values, automated records	Airports, national weather forecasting service, local research or educational institutions, port or waterway users
Storminess	Anecdotal records logged by operators when a threshold is exceeded	Automated records with a defined threshold	Airports, national weather forecasting service, port or waterway users
Fog or other restrictions on visibility	Manual log of frequency, duration, severity		Logs kept by pilots, information from port or waterway users
Air temperature and humidity	Manual log, average daily measurement	Automated records	Airports, national weather forecasting service, research or educational institutions
Water temperature	Manual log, average daily temperature	Automated records	Airports, national weather forecasting service, research or educational institutions
Atmospheric pressure	Manual log, average daily measure	Automated records	Airports, national weather forecasting service, research or educational institutions

Table 9: Baseline data requirements and possible sources

Efforts should be made to identify what is needed/available and to collate as much of this baseline data as possible from credible and authoritative sources.

Where there is no easy access to existing reliable and relevant information (e.g. the required data do not already exist, or their coverage or resolution is limited), Table 9: Baseline data requirements and possible sources should be used to identify what is needed and a monitoring exercise should be instigated.

Further guidance on developing and implementing local monitoring programmes is provided in Annex 2B.

2.2.2 Include Extreme Events

The collation of baseline data should cover not only slow onset changes in ambient conditions [UNFCCC, 2012]), but also historic extreme events.

This is important because climate change is widely expected to affect the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events. For example, warmer sea surface temperatures and increased evaporation are likely to contribute to larger and more intense tropical storms, with stronger wind speeds, larger surges and increased amounts of precipitation [Hoyos et al., 2006]. Increased climate variability may similarly lead to an increase in unprecedented meteorological, oceanographic or hydrological events, including those resulting from an accumulation of events that are not extreme when considered independently [IPCC, 2012].

Extreme precipitation, wind, waves, heat, humidity, cold, etc. pose risks to life, businesses and the environment. They can result in damage to waterborne transport infrastructure such as breakwaters, quay walls, terminal yards or drainage systems, and have the potential to cause disruption to the daily operations of ports, inland waterways and connected intermodal hubs.

Knowledge about extreme events is therefore crucial for effective contingency and disaster response planning. It is also used to inform design return periods, so an adequate understanding is essential if assets with a long residual life are being planned and/or if a substantial financial commitment is being made.

Many of the possible sources of climate information listed on Table 9 and in Annex 2A concern changes in average or typical conditions. Understanding the magnitude and frequency of possible future extreme events can be more challenging.

Recent climate extremes need to be included in baseline datasets because they may affect trends and values. There are growing numbers of examples of situations where recent events have not complied with previously derived trends, not only because the data series was not long enough but also – in cases – because information on recent events was not included in the analysis.

An example of this phenomenon is provided by the analysis of the extreme wave climate offshore of the Venice lagoon, which considered the entire (16 October 1987 to 31 December 2014) and reduced (16 October 1987 to 31 October 2009) sets of historical observations of significant wave height, H_s. In this case, a Peak Over Threshold analysis conducted for the two sets of data resulted in values of H_s for a return period of 100 years equal to 5.46 m and 4.82 m, respectively [De Marinis and Tomasicchio, 2017].

The difference that recent extreme events can make to data series is further illustrated by Figure 6 [Marsh et al., 2016], which shows the average December river flows on the English River Tyne. In December 2015, flows on the Tyne were more than 250 % of typical flows for this period. Similar observations were made on many other rivers across the North of England: in time series of around 40 years, the December 2015 maxima were clear outliers.

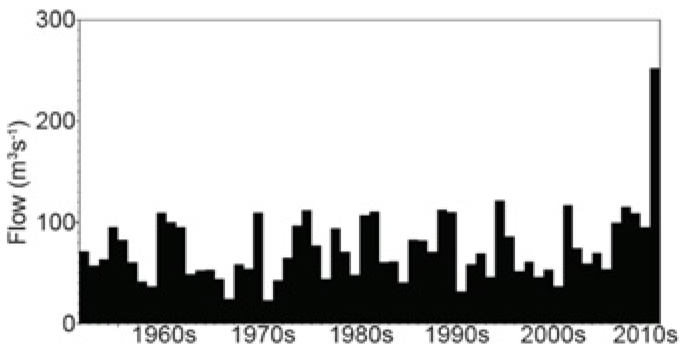


Figure 6: The December 2015 extreme rainfall event on the English River Tyne

Such events are characteristic of what is expected in future, i.e. more severe and frequent extreme events, and these examples illustrate very well the importance of capturing the longest possible dataset, including most recent events.

Step 2.3 Explore Possible Future Climate Conditions

2.3.1 Align Planning Horizon with Climate Change Scenarios

To understand how climate change might affect waterborne transport assets, operations or systems in the future, projections of future changes in relevant climate parameters and processes are needed.

As with baseline data, there are many different sources of information on climate change projections at different spatial and temporal resolutions (see Annex 2A). There are also uncertainties, and for many parameters and processes levels of uncertainty increase significantly over time.

Whilst recent trends and patterns may provide an adequate indicator of short-term future changes (see Step 2.4.1), adaptation strategies that have a planning horizon of 10 to 30, or beyond 30 years into the future, require different climate change scenarios to be considered.

Climate change scenarios enable users to take account of various uncertainties, including rates of change in overall greenhouse gas (GHG) emissions. They do this by providing an insight into the respective climate consequences of a range of possible future conditions, from an optimistic scenario where effective emissions' control measures are implemented at a global level, to a continuation of business-as-usual emissions or a 'no policy' situation. Reference to the range of possible future climate states described by these scenarios enables those preparing an adaptation strategy to develop responses that recognise and accommodate these uncertainties.

The most widely-used climate change scenarios are based on the 'Representative Concentration Pathways' (RCPs) i.e. greenhouse gas concentration trajectories developed by the Intergovernmental Panel on Climate Change [IPCC, 2013].

Four pathways that were subject to extensive climate modelling and research describe four different climate futures, all of which are considered possible depending on the quantities of GHG emitted in years to come [IPCC, 2013]. The RCPs are labelled according to a possible range of anthropogenic radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 W/m^2, respectively):

- RCP 2.6 is an optimistic emissions pathway representing scenarios in the literature that lead to very low GHG concentration levels
- RCP 4.5 is a stabilisation scenario where GHG emissions peak by 2040 and total anthropogenic radiative forcing is stabilised before 2100 through the employment of a range of technologies and strategies for reducing GHG emissions
- RCP 6.0 is a stabilisation scenario where GHG emissions peak around 2080 and total anthropogenic radiative forcing is stabilised after 2100 through the employment of a range of technologies and strategies for reducing GHG emissions
- RCP 8.5 is the most pessimistic pathway, characterised by increasing GHG emissions over time, representing scenarios in the literature that lead to high GHG concentration levels

Figure 7 illustrates that the RCPs and associated global mean surface temperature changes are indistinguishable in the short term (up to 10 years) and the trajectories show only a limited difference until 2050 (i.e. around 30 years from the date of preparation of this guidance).

The different scenarios do not diverge significantly until around 2050. Therefore, if a port or waterway organisation's adaptation planning horizon is less than (approximately) 30 years, the number of climate scenarios required for the purposes of the assessment can be reduced. This might be done by grouping, or using a combination (ensemble) of, the projections.

Beyond 2050, however, the divergence of the trajectories indicates the increased uncertainty about global temperature changes. Any adaptation strategy extending beyond 30 years should thus assess a wide range of possible future climate scenarios.

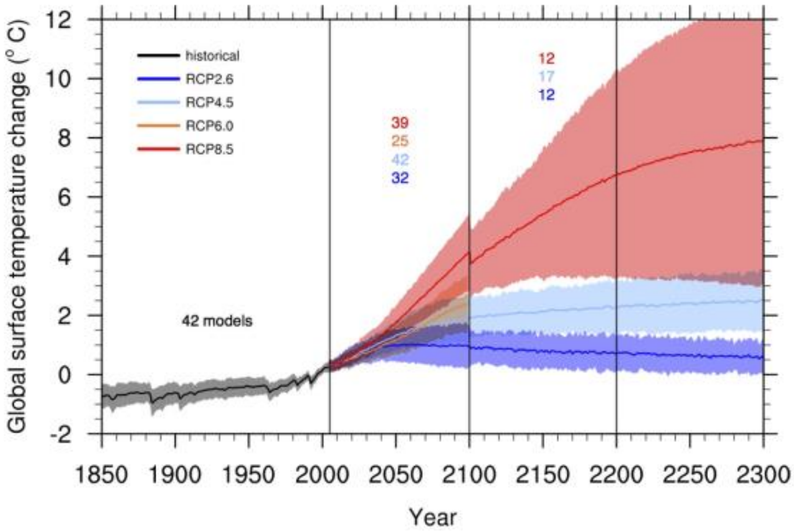


Figure 7: Time series of global annual mean surface air temperature according to IPCC's RCOs[3]

The recommended use of scenarios in port or waterway adaptation planning can be summarised as follows:

- If the planning horizon for a port or waterway adaptation strategy is ten years or less (short-term) and adequate historical data are available to help estimate future projections, the use of climate change scenarios may not be required. Nonetheless, the 'worst case' possibility should always be considered alongside the continuation of existing trends.
- If the planning horizon for the adaptation strategy is more than ten years but less than 30 years (medium-term), and the IPCC's RCPs are being used, the number of climate scenarios required can be reduced by using an ensemble (combination) of the different RCPs. If the RCPs are not being used, an equivalent minimum approach would be to identify and apply the 'most likely' and 'worst case' projections.
- If the planning horizon extends beyond 30 years into the future (long-term), separate reference should be made to each of the individual RCPs. If the RCPs are not being used, the widest possible range of equivalent assumptions from 'optimistic' to 'worst-case' must be explored, and a regular review of these assumptions (e.g. using sensitivity analysis) should be built into the adaptation strategy.

In all cases, the anticipated change in the frequency and severity of extreme events occurring during the planning horizon must also be properly considered (see Step 2.3.3).

The selection of climate change scenarios is fundamental to the outcome of the risk assessment (Stage 3). It is therefore essential that the stakeholders identified in Stage 1 participate in the process of agreeing which scenarios should be used.

2.3.2 Collate Climate Projections Data

The next step is to collate the available climate projections for each relevant climate parameter or process. Future projections are based on statistical or modelling simulations. For adaptation planning purposes, however, reference will typically be made to published data rather than undertaking bespoke

[3] Time series of global annual mean surface air temperature anomalies (relative to 1986-2005) from CMIP5 concentration-driven experiments. Projections are shown for each RCP for the multi model mean (solid lines) and the 5-95 % range (±1.64 standard deviation) across the distribution of individual models (shading). Discontinuities at 2100 are due to different numbers of models performing the extension runs beyond the 21st century and have no physical meaning. Only one ensemble member is used from each model and numbers in the figure indicate the number of different models contributing to the different time periods. No ranges are given for the RCP6.0 projections beyond 2100 as only two models are available. [IPCC, 2013]

climate modelling. For example reference might be made to storm surge and wave modelling from published changes in cyclone behaviour.

A good source of regional or national projections derived from the IPCC scenarios described in Step 2.3.1 can be found via the IPCC Data Distribution Centre website. If it is not possible or practicable to use the IPCC projections, or if supplementary information is needed, reference should be made to other recent regional or national climate change projections from authoritative sources (see Annex 2A) in order to compile a range of possible climate outcomes.

National standards of practice or government policy may also require certain minimum projections for particular parameters to be considered, for example with respect to infrastructure planning. Notwithstanding the presence of such guidance, the step presented here is important to assess the validity and adequacy of that guidance for the particular circumstance being considered.

An example of different scenarios that might be identified for use in adaptation planning is shown in Table 10. This table illustrates the European climate scenarios developed for a cross-sector research project undertaken in support of the 2013 EU Climate Change Adaptation Strategy [Holman et al., 2017]. The future climate conditions are intended to be used to inform a sensitivity analysis allowing the respective climate hazards to be identified and the range of possible climate futures compared (i.e. the steps dealt with in Stage 3 of this guidance).

Climate scenario	**Range of temperature projections***	**Range of precipitation projections***
Moderately high (RCP4.5)	+2.0 to +3.0°C	-4 % to +3 %
Extremely high (RCP8.5)	+3.7 to +5.4°C	+5 % to +13 %
* Both columns represent average annual change in 2071-2100 compared to 1961-1990		

Table 10 Climate scenarios developed as part of the IMPRESSIONS project exploring inter-dependent risks and opportunities posed by high levels of climate change

The World Bank Climate Knowledge Portal is an easy-to-use example of authoritative climate data presented at country level. This is one of many possible sources of information on climate change parameters and processes listed in Annex 2A to this guidance. This Annex includes both baseline data and climate change projections, collected and presented at global, regional and national level. However, it is by no means an exhaustive list, and the data listed therein are not endorsed. Rather Annex 2A provides an indication of the type of organisation from which useful data might be obtained.

Box 7 illustrates the data sources being used in a climate change adaptation assessment from the UNCTAD technical assistance project for coastal transport infrastructure in Caribbean Small Island Developing States (SIDS). Table 1 in the Introduction to this guidance provides further examples of the type and range of climate change projections identified for adaptation planning purposes in ports around the world.

From 2015-2017, UNCTAD implemented a technical assistance project aimed at improving the understanding of the implications of climate change for critical coastal transport infrastructure in **Caribbean Small Island Developing States** (Case Study 11). As part of this study, impact assessments with a focus on four seaports (and four airports) in Saint Lucia and Jamaica explored climatic changes forced by a 1.5°C temperature increase above pre-industrial levels, as well as under different emission scenarios and time periods in the present century.

Coastal inundation modelling by the European Commission's Joint Research Centre (ECJRC) was used to produce flood maps for seaports and airports, and marine inundation was projected for different periods under different emission scenarios. Extreme sea levels were simulated for the baseline historical period (1995) and under the 1.5°C warming scenario, for 9 return periods (1, 1/5, 1/10, 1/20, 1/50, 1/100,1/200, 1/500, 1/1000 years). In addition, simulations were carried out for 2020, 2030, 2040, 2050, 2060, 2080 and 2100 under two emission scenarios (RCP4.5 and RCP8.5).

In addition to coastal inundation arising from sea level rise, storm surges and waves, operational disruptions arising from other climatic stressors, such as extreme heat, precipitation and wind speed (i.e. those potentially causing operational disruption or damage) were also assessed. For the assessment of operational disruption caused by the exceedance of operational thresholds, climatic data were extracted from the Caribbean Community Climate Change Centre's (CCCCC) database that contains downscaled daily climate projections for the period 1970-2100 from the Regional Climate Model RCM PRECIS.

Box 7: Data used in climate change impact and vulnerability assessments for seaports in Jamaica and Saint Lucia

In the absence of any reliable quantitative sources of future climate change projections, the local historical information collated in Step 2.2.1 can be used, together with expert judgement and/ or analysis, to develop a range of future scenarios based on a qualitative assessment of the anticipated direction of change in each parameter. This is not an ideal approach, however, not least because of the need to accommodate the unexpected. As Table 10 indicates, it is possible, for example, that relatively drier conditions might be anticipated under one scenario while projections under another point to wetter conditions. Seasonal differences may also be more important in some locations than others. Whichever sources of information are used, lower bound, 'most likely' and upper bound or 'worst-case' scenarios should be identified or developed as a minimum. Sensitivity testing should also be used to check any assumptions made.

Finally, it is important to be aware that climate science develops very quickly, and updated information appears regularly. Sources of data should thus be re-visited regularly to capture new versions and to ensure that enhanced or previously unavailable data and information are accessed.

2.3.3 Accommodate the Possibility of Increasingly Frequent or Severe Extreme Events

The many uncertainties in climate science include future rates of change in GHG emissions, the implications of these changes for impacted climate parameters and processes, and the possibility that 'tipping points' will be exceeded. When the expectation that extreme events may become more frequent and severe is also taken into account, it is apparent that care is needed in using conventional statistical methods that rely on past events to reliably predict the magnitude of low probability future events (e.g. 100, 500, 1000, 2000-year average return periods) [Herbert et al., 2020, forthcoming], even if a long-term dataset exists.

Notwithstanding the changing climate, it is difficult to reach a conclusion on the likelihood of any particular event occurring on the basis of historical record or modelling unless the available records span a period significantly longer than the average recurrence interval being defined.

Box 8 illustrates the value of a comprehensive dataset whilst highlighting the errors that might arise when trying to define and analyse trends in the recurrence of rare extreme events even on the basis of significant historical data sets.

An investigation into the history of flooding in the Australian Brisbane River Catchment (Brisbane River Catchment Flood Studies: a history of living with flooding) provides a good example of the need for a longer-term data set because of year to year, decade to decade and even century to century variability.

Any examination of flood events in the Brisbane River Catchment limited to the period since 1900 might conclude that the severity and frequency of major flood events has recently increased, such that the average recurrence interval (ARI) of a major flood event is in the order of 50 years. However, flood records on the Brisbane River date back to the early 1800s, making this an exceptional set of data, and prior to 1900 eight major floods were recorded in the preceding 70 years. When these data are also considered, the same examination might estimate that the ARI of a major flood event is as frequent as 10 years. Over the full set of records (i.e. from the early 1800s to today), it could even be concluded that the trend in the severity and frequency of flooding over time has decreased.

These two opposing conclusions, both apparently correct on the basis of the separate data sets analysed, demonstrate the significantly different conclusions that can be drawn with insufficient data.

It is also of note from the more recent record that the major Brisbane River flood of 2011 occurred within a period of higher rainfall years that followed a sustained period of drought. Over a period of ten or even 20 years this could have been interpreted as an increase in flood frequency and severity. However, a review of the longer record shows a cyclic behaviour of clustered flood events over a period of decades. What appears to be a sign of change in this case may therefore appear 'normal' if a longer period is assessed.

The Brisbane River Catchment Flood Studies highlight that, while local data is important to understand trends in climate, caution must also be exercised in predicting trends in extreme events when the data set only includes a small sample of such events. Computer modelling of a much longer period than that for which measurements exist, including likely climate change effects on the model input parameters, may be necessary to reliably define the likely climate change effect on extreme climatic events.

Brisbane River Catchment Flood Studies https://www.qra.qld.gov.au/brcfs

Box 8: Example of the value of a long-term dataset, Australia

Establishing the probability of a certain critical threshold being exceeded can therefore represent a significant challenge in the context of the changing climate, yet recognition of the potential consequences of an 'unlikely-but-plausible' event is vital if maladaptation is to be avoided (see Stage 4).

The IPCC projections discussed in Step 2.3.2 do not include either the extreme lows or the extreme highs in the range: they cover only the 5 % to 95 % range of estimates. In the context of climate change adaptation, these extremes may be important to inform decision making [Hinkel et al., 2015]. The following paragraphs therefore provide some high-level guidance on how future extreme events can be anticipated and accommodated.

In some cases, it may be possible to obtain reliable projections of extremes from published sources (e.g. prepared by specialists in relation to major infrastructure projects). More often, however, a combination of historic evidence, recent local data, available future projections and expert opinion will be needed to derive a pragmatic 'unlikely-but-plausible' estimate for the parameter or process in question. By way of an example, Box 9 illustrates the derivation of a High-plus-plus (H++) scenario for UK sea level rise.

In response to the scientific uncertainty about some aspects of ice sheet behaviour and how the melting of the large ice sheets might affect sea level, the UK sea level rise projections include an additional H++ scenario (see www.ukclimateprojections.metoffice.gov.uk).

The maximum global mean sea level rise from the IPCC Fourth Assessment Report [IPCC, 2007] was supplemented by indirect observations of sea level rise during the last interglacial period and estimates of maximum glacial flow rates, to derive a low probability H++ absolute sea level rise range for the UK of 0.93 m to 1.90 m by 2100. This 'unlikely but plausible' scenario, which is intended for use in vulnerability testing, compares to projected relative sea level increases by 2095 of 0.21 m to 0.68 m for London and 0.07 m to 0.54 m for Edinburgh, both based on the 5^{th}-95^{th} percentile for the medium emissions scenario being used at that time.

Box 9: Development of a low probability but plausible High ++ sea level rise scenario, UK

In the absence of adequate historic extreme event information for a particular location, and if there are no reliable local estimates of what might happen in future, efforts should be made to identify data from adjacent locations or catchments. Such data might be interpolated with the objective of deriving a hypothetical but realistic estimate for use in the analysis. Indeed, information on changes in latitude, track, frequency and intensity of extreme storm events on a regional or even continental scale rather than a local one will form an important input into statistical analyses and sensitivity testing. In Europe, for example, there are records of seven extreme heatwaves since 2000 (in 2003, 2006, 2007, 2010, 2014, 2015 and 2017 [EEA, 2019]). This information could be used to help understand what is 'possible' in different parts of Europe in future.

There is also evolving evidence of situations where climate change has increased the probability of extreme events, sometimes markedly – including heatwaves in Australia, and certain cases of floods associated with extreme rainfall or with sea level rise [EASAC, 2018].

Finally, if no projections or other form of estimate of future extreme events exists, an informed 'guesstimate' will need to be made. Assuming an increase of +20 %, +50 %, +100 % or +200 % on the observed worst case at least enables some level of quantification and hence understanding of the potential consequences of an 'unprecedented' event.

Step 2.4 Analyse Data to Understand the Climate Change Hazard

2.4.1 Analyse Baseline and Projections Data

Where raw data have been obtained, these will need to be subject to a proportionate analysis to identify and understand the typical characteristics of each relevant baseline and future climate parameter or process. As a minimum, expert judgement should be used to determine whether the climate parameter or process has already increased, and whether it is expected to increase, remain the same, or decrease over the period for which data respectively projections are available. Arrows or other symbols, or a coloured scale, can be used to highlight the direction and, if available, relative rate of change. Qualitative or quantitative indicators can also be used, or a statistical analysis undertaken, to further quantify the extent (magnitude, percentage, etc.) of change. Table 11 provides an overview of the different types of analysis approaches that may be employed.

When analysing historical data, efforts should be made to distinguish between climatic variations or trends linked to natural, background variability; trends due to man-made alterations like deepening of tidal rivers to enable better shipping conditions with resulting changes in tidal currents; and those that may be associated with long-term climate-related changes. Depending on the parameter in question, natural variability may be exhibited over a period of months (e.g. seasonal variation), years (e.g. El Niño-Southern Oscillation) or inter-annually.

Details about periodic extreme events such as cyclones or hurricanes, heatwaves or droughts should always be highlighted alongside observed trends in relevant slow onset climate parameters or processes because extreme values may affect previous statistical trends and values (see Steps 2.2.2 and 2.3.3). The need for further analysis of extremes arises in many branches of science and engineering (e.g. predicting hurricane winds for suspension bridge design, or storm surge heights for coastal defence works). For climate change adaptation it may therefore be useful, or even necessary, to undertake an extreme value analysis (EVA) to identify and quantify extreme deviations from the median of probability distributions.

In all cases, the level of sophistication in the analytical methods selected and the presentation of the outcomes should be appropriate to: the nature and resolution of the data; the availability of expertise and resources; and the objectives of the adaptation initiative.

Approach	Relative complexity	Data analysis methods	Typical analysis outcomes
Expert judgement	Very Low	Expert judgement is used to determine whether a parameter or process increases, remains the same, or decreases over the time horizon. Limited analysis is required.	Scale or symbols indicating either: increase ↑, no change - or decrease ↓ in each parameter.
Indicator-based	Low	A qualitative assessment is undertaken to determine whether a parameter or process increases or decreases, based on coarse resolution information. A global climate model may be used to provide the baseline data/future conditions, but no formal analysis is done to downscale the results.	Scale or symbols indicating change, with some information regarding magnitude and timeline e.g. ++, +, o, -, --.
Formula-based	Medium	Empirical formulae are used to estimate changes in the parameter or process. Each calculation is typically spatially and temporally static, so a number of calculations may be required to determine how a parameter has changed or is expected to change in time or space. For example, overtopping formulas from EurOtop (2018) might be used to estimate overtopping.	A value is calculated for each parameter for key time periods.

Approach	Relative complexity	Data analysis methods	Typical analysis outcomes
Process-based modelling	High	Numerical models are prepared to model the physical process at a fine resolution both in space and time. The boundary conditions are often driven by global or regional models; these may require downscaling. Various models are commercially available e.g. using hydrodynamic, wave or sediment transport data.	Spatially and temporally varying values for each parameter.

Table 11: Overview of data analysis methods

In some cases, it will also be necessary to consider the interdependencies between parameters. For example, the total water level at a maritime port is the combination of tide level, atmospheric pressure, and storm surge. For such parameters, a joint probability analysis (JPA) may be required.

If the required data analysis is beyond the capability of the port or waterway organisation, some of the stakeholder organisations identified in Stage 1 may be able to help, or assistance could be sought from academic institutions, local government, or relevant not-for-profit organisations. Advice could also be obtained from a professional who has experience of analysing meteorological, oceanographic or hydrological data for ports or waterways. Engineering consulting firms, universities and research institutes typically provide such services.

If data are only available at the global or regional scale, consideration might exceptionally be given to commissioning a downscaling exercise to facilitate the use of these data. Downscaling is the process by which coarse resolution model results are translated down to a finer resolution. Specialists would need to be engaged in this. However, in most situations it will be more cost-effective to use sensitivity analysis to assess a range of scenarios than to embark on a downscaling exercise. For further details about downscaling, see Annex 2C.

2.4.2 Understand Data Limitations

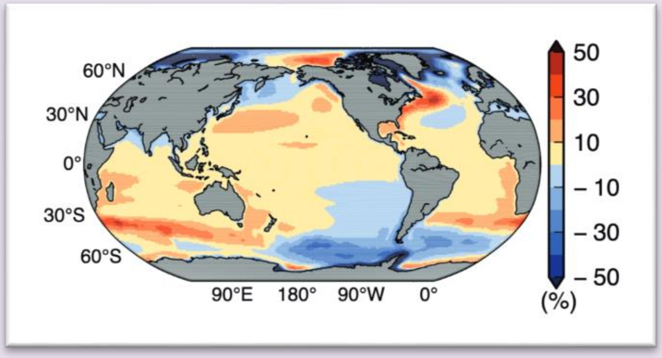
In collating and using climate baseline and future climate data, it is important to be aware that the quality and reliability of information can vary significantly, and misleading data result in misleading outcomes.

Potential data limitations include many types of uncertainty, data gaps and insufficient or erroneous records. There may also be issues with spatial or temporal resolution, or downscaling data from the global climate models may give contradictory results.

Modelled data inherently has uncertainty. The level of uncertainty should be understood before using the data. The reliability of global scale climate models tends to be supported by calibration and verification against other models. Some regional models, however, may not have been calibrated or verified. On the positive side though, regional models are usually of finer resolution and as such are able to include details such as local topography, bathymetry, and structures.

Insofar as the nature of the data is concerned, it is also important to understand exactly what is being presented because there can be significant differences in apparently similar information. Global sea level trends, for example, can be quite different from relative sea level trends because of ocean dynamic processes, movements of the sea floor, and changes in gravity due to water mass redistribution. These differences are illustrated by the example in Box 10. It is therefore important to thoroughly understand what has been measured (or projected) and to carry out the analysis accordingly.

For the RCP4.5 scenario ensemble (not including the dynamic ocean contribution in response to the influx of freshwater associated with land-ice loss and changes in terrestrial groundwater), mean relative sea level changes between 1986-2005 and 2081-2100 show that many regions are likely to experience regional sea level changes differing substantially from the global mean. As shown on the Figure [IPCC, 2013], regional changes in sea level reach values of up to 30 % above the mean value in the Southern Ocean and around North America and up to 50 % below the global mean in the Arctic region and some regions in the Antarctica. Whereas the described results have been computed for RCP4.5 scenario, they are representative to first order for all RCPs.



Box 10: Percentage of the deviation of the ensemble mean regional relative sea level change between 1986-2005 and 2081-2100 from the global mean value

With a good awareness of the potential issues, it is usually possible to make meaningful use of the available data. Conversely, using data in ignorance of its limitations can lead to erroneous outcomes, some of which will have significant cost consequences or social or environmental impacts.

Understanding and recording the level of confidence in the data used for adaptation planning purposes is therefore an important step, especially where significant investment is planned. The level of effort needed to reduce or manage uncertainties with confidence is discussed further in Step 4.1.

Outcomes of Stage 2

For those working through the climate change adaptation planning process, the following steps should be completed before progressing to Stage 3:

- The climate parameters and processes relevant to the critical assets, operations and systems identified in Stage 1 are confirmed (Step 2.1).
- Existing baseline data including information on extreme events have been collated for each relevant climate parameter or process and monitoring has been instigated to enhance local knowledge or fill gaps (Step 2.2).
- Depending on the planning horizon for the adaptation strategy, climate change scenarios are agreed, and climate change projections collated for relevant parameters and processes (Step 2.3).
- Data has been analysed to confirm baseline conditions, identify existing patterns and trends, and determine what is expected to change under each scenario. Both slow onset changes and expected changes in the frequency or severity of extreme meteorological, oceanographic or hydrological events have been considered. Data limitations are acknowledged (Step 2.4).

STAGE 3: VULNERABILITES AND RISKS

Stage 3 brings together the collated information on critical assets, operations and systems (from Stage 1) and the understanding about projected changes in the climate parameters and processes to which these assets, operations and systems are susceptible (from Stage 2), to identify and assess potential risks associated with climate change.

In order to make informed choices about adaptation options, the next steps involve understanding how climate change is likely to affect existing risks or introduce new ones. Steps 3.1 to 3.3 therefore describe how climate hazards (i.e. projected changes that have the potential to cause damage, disruption or similar negative effects) can be identified, quantified, and compared to the baseline situation, in turn highlighting future changes in the vulnerability of critical assets, operations or systems.

As illustrated on Figure 8, vulnerability assessment can be an exercise in its own right or it can be used to determine the scope of a more targeted risk analysis. A climate change risk analysis (Steps 3.4 to 3.7) explores the relative likelihood (possibility or probability) of the climate hazard occurring and the nature and relative acceptability of the associated consequences (impacts).

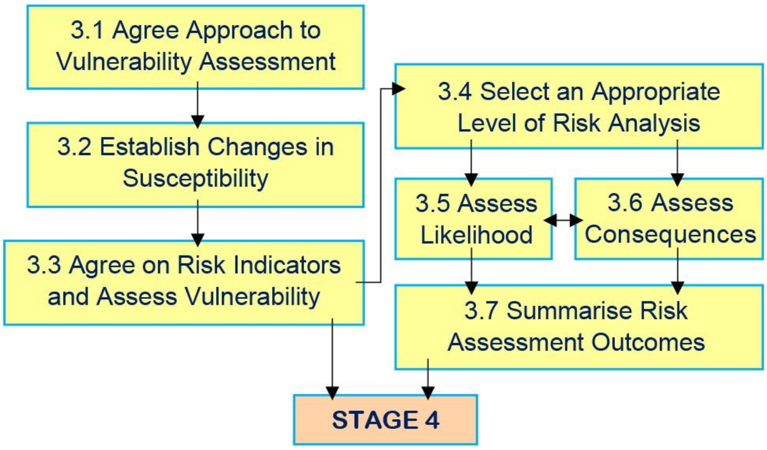


Figure 8: Stage 3 in the climate change adaptation planning process

Step 3.1 Agree Approach to Vulnerability Assessment

Vulnerability indicates the degree to which something is susceptible to, and unable to cope with, possible adverse effects. In this case, the effects in question result from changes in ambient climate conditions, variability and extremes.

The extent to which an asset, operation or system is vulnerable to changes in climate parameters and processes will vary according to its unique characteristics, including its susceptibility (exposure to the hazard), proximity to relevant thresholds and adaptive capacity.

A vulnerability assessment therefore involves, for each climate change scenario as appropriate:

- Determining whether the projected changes in relevant climate parameters and processes highlighted in Stage 2, will lead to a change in the susceptibility of any of the critical assets, operations or systems identified in Stage 1.
- Assessing whether vulnerability is likely to increase within the adaptation planning horizon when factors such as proximity to thresholds and the availability of adaptive capacity are taken into account.

A vulnerability assessment can either be a standalone exercise or it can act as a screening step for the next steps in the risk assessment process.

In order to determine whether climate change could affect the vulnerability of critical assets, operations or systems, the following questions need to be answered:

- Could the projected change in a relevant climate parameter or process lead to a change in the susceptibility of the asset, operation or system when compared to the current situation? If yes…
- Could this change in susceptibility lead to exceedance of a threshold or an increase in damage, disruption or another type of impact? If yes…
- Is there sufficient adaptive capacity to accommodate the projected degree of change for the duration of the planning horizon?

These questions, which can be elaborated into steps as shown in Figure 9, are elaborated in Steps 3.2 and 3.3.

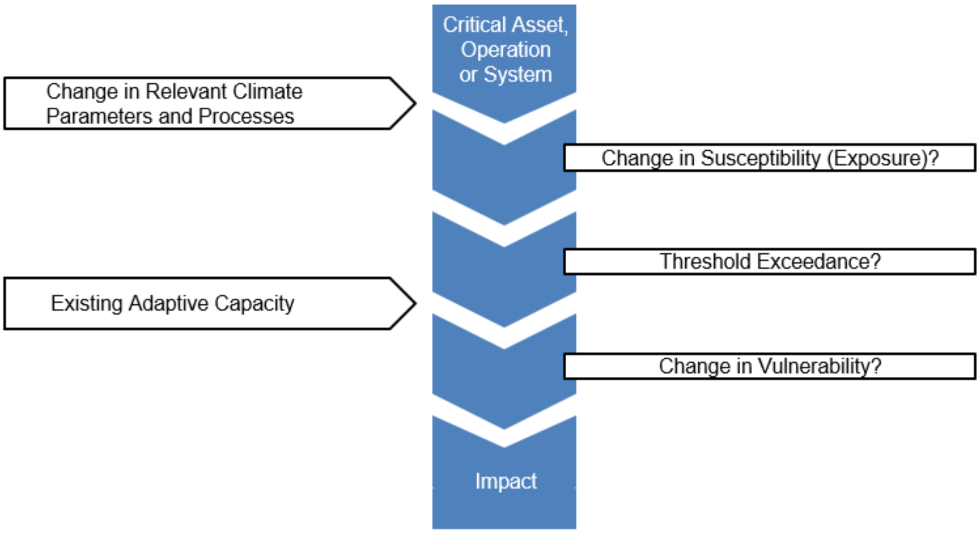


Figure 9: Key steps in assessing vulnerability over the planning horizon, under each scenario as appropriate

A vulnerability assessment, like other forms of risk assessment, can vary in its complexity or sophistication according to the characteristics used to determine criticality, the availability of the data, expertise and resources to support the analysis and so on.

There are a number of ways in which such an assessment can be carried out, based around the following general levels of complexity:

1. Use of in-house knowledge, local data and/or expert judgement to identify the scenarios in which thresholds could be exceeded, with potential associated implications for the vulnerability of the asset, operation or system.
2. Use of the output of Stage 2 as indicators to inform the same process.
3. Application of climate parameters and processes in a quantitative engineering assessment, for example, deterministic or probabilistic analysis of threshold exceedance.
4. Process-based modelling of the projected effects of climate change on relevant climate parameters and processes including, if appropriate in the context of the assessment, site specific analyses, high-resolution numerical models or possibly physical models.

These different approaches have different levels of complexity and residual uncertainty as indicated in Table 12.

Assessment approach	Typical level of complexity	Typical input data demand	Typical resource demand	Residual uncertainty
Expert judgement	Very low	Very low	Very low	High
Indicators	Low	Low	Low	Medium to high
Formulas	Medium	Medium	Medium	Medium
Process based modelling	High	High	High	Medium to low*

* But note that expert judgement is always needed to interpret model results

Table 12: Relative comparison of approaches to assessing vulnerability

The outcomes of the different assessment approaches depend on experience, acumen and competence. The judgement of a skilled expert with local knowledge might result in more valuable information than an unsophisticated model. When selecting the most appropriate approach to the vulnerability assessment, the following points should be considered:

- Establishing relative changes (i.e. an increase or reduction in susceptibility (exposure)) always requires reference to historical data as well as to future projections.
- Quantitative approaches for assessing vulnerability should not exclude a qualitative element. Even the most sophisticated quantitative assessments should always be complemented with qualitative information in order to capture the full range of issues, including both tangible and intangible aspects of vulnerability in its different dimensions. [Cardona, O.D. et al., 2012]
- Confidence levels in the climate data should always be recorded (Step 2.4.2). Where confidence in the data is high, it may be possible to make decisions based on the vulnerability assessment alone; conversely if confidence levels are low, it may be prudent to progress to the next stage of the risk assessment in any case so as to maximise confidence in the outcomes.
- If resources are limited but it is already clear that the potential risk could be significant, a precautionary approach should be taken and the asset, operation or system in question should automatically be 'screened in' for further assessment in 3.4.
- A high level of residual uncertainty does not preclude further progress: Step 4.1 explicitly discusses how residual uncertainties can be addressed through the selection of measures for inclusion on an adaptation pathway.

It is worth noting that an international standard [ISO 14090, 2019] entitled 'Adaptation to Climate Change, Principles, Requirements and Guidelines' has been published as the first in a range of proposed ISO Standards. This Standard provides a framework to help organisations identify and manage risks, assess climate change impacts and put plans in place for effective adaptation. A further Standard, ISO 14091, on vulnerability assessment and climate change adaptation is in preparation.

Finally, as with other Steps, key stakeholders need to be fully involved throughout the vulnerability assessment. A joint exercise might therefore be undertaken, or relevant groups may be invited to meetings where the process is discussed and asked to comment on the draft outputs. Their feedback should be incorporated before progressing to the next stage.

Step 3.2 Establish Changes in Susceptibility

The initial process of identifying which critical assets, operations and systems are susceptible to different climate hazards (Step 1.3) now needs to be refined in the knowledge of the projected changes in each climate parameter or process over the planning horizon (Steps 2.3 and 2.4 respectively).

The minimum objective of Step 3.2 is to differentiate between the following changes in susceptibility compared to the current situation: significant increase, increase, no change, reduction, significant reduction.

If the adaptation planning horizon is more than ten years, Step 3.2 needs to be applied to each climate change scenario. This is important because the susceptibility (i.e. exposure) of an asset, operation or system might change under one scenario but not under another.

In all cases, at least one unlikely-but-plausible extreme climate event scenario should be considered as part of this exercise (see Step 2.3.3).

The possibility of new climate hazards such as those associated with heatwaves, intolerable humidity, or prolonged droughts should be considered alongside anticipated changes or recent trends in relevant parameters or processes. The possibility of joint occurrences (e.g. a storm surge conditions coinciding with spring tides, or unprecedented rainfall and wind combinations) should also be taken into account.

Box 11 explains how different scenarios were explored in an approach designed to help the US Army Corps of Engineers evaluate the vulnerability of critical national defence coastal installations, and quantify the associated loss of performance, in situations when the capabilities of these installations are impacted by a combination of rising sea levels and coastal storm hazards.

The US Army Corps of Engineers developed a step-wise risk assessment approach to quantify the vulnerability of critical **Department of Defense** assets based on their susceptibility, sensitivity, and adaptive capacity to withstand storm forcings (tidal fluctuations, waves, winds, surge, sedimentation, saltwater intrusion, flooding, etc.) exacerbated by sea level rise (Case Study 8). For these nationally significant, high value assets, it was deemed appropriate to use numerical models to simulate coastal storms and assess regional, nearshore, surface, and subsurface conditions under a range of sea level rise scenarios.

Modelling covered 25 scenarios in total, comprising local mean sea-level rise of 0.5 m, 1.0 m, 1.5 m, and 2.0 m by 2100 combined with five simulated coastal storms ranging in intensity from 1-year to 100-year return intervals. The modelling outcomes provided an indication of anticipated impacts on each installation and its surroundings. Site-specific network modelling was then used to capture the effects on performance, taking into account the unique position, condition, and interdependencies of the critical infrastructure.

For the Norfolk Naval Station case study site, these investigations demonstrated that several critical systems were vulnerable and likely to be incapacitated once sea levels rise above 1.0 m from the present. Overall, the probabilities of damage to infrastructure and losses in performance increased dramatically after 0.5 m of sea level rise was experienced, indicating there is a ‘tipping point’ or threshold to be accommodated when undertaking future planning or operational activities on the installation.

Box 11: Use of scenarios in determining the vulnerability of USA Defense Department critical coastal installations

The list below provides some further examples of where a change in the susceptibility of an asset, operation or system might be anticipated as a result of changes in a climate hazard:

- An existing asset that was previously considered to be outside the flood risk area is expected to become exposed to a risk of flooding associated with sea level rise
- Operations such as pilotage could be affected by a projected increase in the severity of wind or wave conditions
- Inland navigation could be impacted if changes in seasonal precipitation lead to more frequent and prolonged high or low flow conditions
- Increased water temperatures may have implications for the frequency of vegetation cutting or clearance activities
- Maintenance dredging frequency or quantities could be affected by changes in wind or wave conditions or in seasonal precipitation
- Working conditions for equipment operations (or in offices or storage facilities) could be impacted by projected changes in maximum summer temperatures or in tolerable humidity levels
- Projected increases in air and water temperatures might affect the future economic viability of maintaining a fleet of ice-breakers.

Step 3.3 Agree on Risk Indicators and Assess Vulnerability

3.3.1 Threshold Based Approach to Define Risk Indicators

Design and operational thresholds, or other indicators of acceptable risk, represent an essential enabling element of climate change adaptation planning. Thresholds capture the point at which a change in a climate-related parameter or process might be expected to cause damage, compromise the integrity of an asset, lead to operational disruption including temporary closures of particular facilities, or otherwise impact on safety, business or the environment.

Recognising when an asset, operation or system is close to a particular threshold can provide an indication of its relative susceptibility (or of the amount of adaptive capacity (see Step 3.3.4)). Exceedance of a threshold usually indicates an expected impact. Thresholds are therefore used as a type of risk indicator.

Typical thresholds include maximum wind speed, maximum or minimum temperature or humidity, water or flood depth, and significant wave height (see Step 3.3.3) but economic and financial thresholds might also be relevant. For example, ports and waterways may previously have investigated whether it is most cost-effective to hire contractors or equipment to carry out activities such as maintenance dredging or vegetation clearance or to buy the necessary equipment and train or employ personnel to operate it. Climate change may alter the outcome if the same rationale is followed.

Threshold data can be obtained or derived from many sources including design documents, plant or equipment manuals, standard damage curves, health and safety regulations or protocols, expert knowledge and experience and so on. Every make and model of crane, for example, will have its own wind speed limits set by the manufacturer according to its configuration.

Threshold data need to be collated before progressing to Step 3.3.2. If appropriate, threshold information can be incorporated into the inventory of assets, operations and systems prepared during Step 1.2.

3.3.2 Define an Acceptable Level of Risk

In addition to operational thresholds where exceedance potentially represents an impact, the port or waterway organisation may have a pre-determined reference hazard level. For example, it may be company policy to provide protection against an event with a certain return period.

Determining the level of residual or ‘acceptable’ risk to an organisation is informed by several factors, including an understanding of historic occurrences. Many countries have developed flood depth-damage curves based on analysis of past events and on expert judgement. International organisations have also been active in this area, for example the European Commission has published global flood depth-damage functions [Huizinga and Szeqczky, 2017]. This type of information can be used to define an acceptable level of risk in situations where an organisation-specific or published operational threshold does not exist.

One issue in this regard, however, is the uncertainty inherent in climate change scenarios. As explained in Step 2.3.3, it is often not possible to be sure what an event with a current probability of 1:100 years will look like in, say, 30 or 50 years from now.

The outcomes of Step 1.5, including the main boundaries, constraints and opportunities, will have impacted decisions on what constitutes an acceptable level of residual risk. For many organisations, resource constraints may also have been an influencing factor. If adaptation objectives are to be realistic and practical, it might have been necessary to accept a greater than desirable level of residual risk.

Understanding how critical assets, operations and systems might be affected by climate change and the frequency and magnitude of the anticipated disruption will help determine adaptation priorities. For example, an organisation may decide to protect against a certain type of incident or a given level of disruption whilst strengthening the resilience of other assets, operations and systems to improve their ability to bounce-back (i.e. recover) after a more significant event.

Whatever type of risk indicator is selected, it should ideally be quantified or be capable of quantification, including defining classes or thresholds below or above which the acceptability (tolerance) of the risk changes. For example, a 20 % increase in maintenance costs might be deemed acceptable by an organisation, or a 5 % drop in revenue might represent the maximum that can be tolerated before action has to be taken.

Insofar as operational thresholds are concerned, these might be safety-related, or a minimum level of redundancy (representing flexibility) might need to be maintained. In all cases, appropriate thresholds and acceptable levels of risk both need to be agreed with the relevant stakeholders.

A threshold-based approach provides a consistent and practical risk indication: exceeding a threshold indicates that an impact is likely.

3.3.3 Determine Whether Thresholds Could Be Exceeded

If a simple evaluation based on local knowledge and expert judgement is being undertaken, the response to the question of whether the change in susceptibility identified in Step 3.2 could result in a threshold being exceeded may be a yes or no answer.

In other cases, it may be possible or necessary to indicate by how much a threshold might be exceeded and/or to establish the likely frequency of such exceedances. More complex statistical or probabilistic analysis or modelling can also be undertaken depending on the resources available and the objectives of the assessment.

Examples of threshold exceedance might include situations where:

- Projected wind speeds under several of the climate change scenarios investigated would exceed the recommended operating limits for cranes or straddle carriers, or would adversely affect the ability to berth ships.
- Design standards or flood depth damage curves would be exceeded in the more pessimistic scenarios, for example in relation to water levels, or overtopping and risk of failure.
- Projected reductions in seasonal rainfall could reduce water levels to below the minimum depth required for safe navigation in inland waters within 20 years.
- Within 25 years, projected extreme wave crest levels could reach the height of a superstructure or deck and thus result in a step-change in loading.
- Under some scenarios, changes in water level variation could affect berthing viability e.g. of RoRo vessels because of the linkspan or ramp configuration [PIANC, 1979].
- Projected winter wave conditions or sea state could make certain pilotage operations unsafe under most scenarios or they could exceed the safety threshold for access to the sea disposal site used to dispose of dredged material.
- Projected increases in the frequency of fog days could mean the numbers of pilots available to service port safety requirements is insufficient within 10 years.
- Changes in seasonal rainfall mean projected flood depths are likely to prevent safe vehicular access to parts of the site within 30 years.
- Projected maximum (or minimum) temperatures or high humidity levels would compromise the health and safety of port or waterway personnel, adversely impact on the handling or storage of sensitive cargo or exceed operating limits for certain equipment.
- Heatwave increases under all scenarios could adversely affect operations due to increased energy costs for cooling equipment within 10 years.
- Projected vegetation growth rates in warmer waters will mean revised cutting frequencies, making it financially preferable to buy, not hire, cutting equipment.

Figure 10 provides an example of how thresholds can be used to identify potential impacts and determine whether the projected change in a parameter or processes potentially increases vulnerability and therefore represents a climate hazard. In Figure 10 the relevant parameters and processes are extreme storm surge with a return period of 100 years and rates of sea level rise. When this combination of the parameters is compared to the elevation of the buildings, flood depths can be estimated for future conditions. The results show that under the scenario assessed, the changes in mean sea level in conjunction with extreme storm surge represent a hazard because around the year 2045 the flooding depth threshold is likely to be exceeded by a 100-year storm surge.

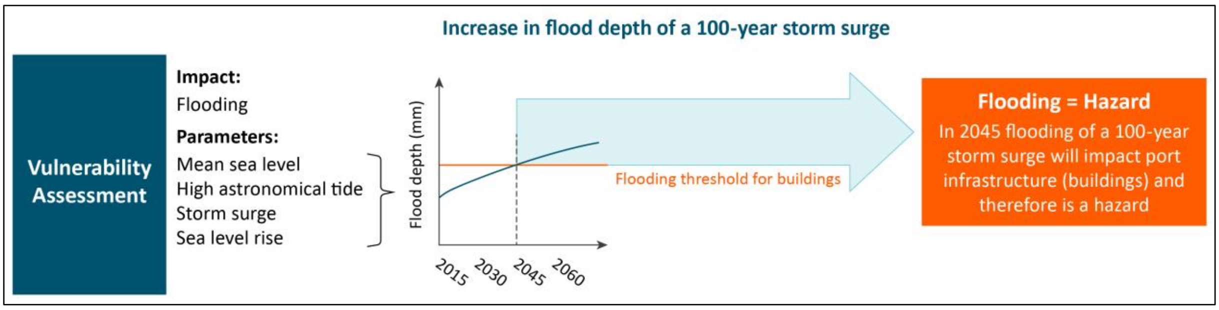


Figure 10: Use of thresholds to identify potential climate hazards

A case study that illustrates the use of operational thresholds in a vulnerability assessment to explore the potential impacts of climate change for coastal transport infrastructure is provided by the United Nations Conference on Trade and Development [UNCTAD, 2017]. This methodology was developed as part of a project intended to enhance the adaptive capacity of Small Island Developing States (SIDS) in the Caribbean. The details of the work are presented in Case Study 11 but Box 12 highlights how these thresholds were used to identify the potential direct impacts of climate variability and change in relevant climate parameters and processes.

Between 2015 and 2017, UNCTAD implemented a technical assistance project with a focus on climate change impacts and adaptation for coastal transport infrastructure in **Caribbean Small Island Developing States** (SIDS). The study (Case Study 11) aimed to build capacity in understanding of how coastal transport infrastructure, including seaports, is likely to be affected by climate variability and change and in identifying appropriate adaptation response measures.

As part of this study, the direct impacts of climate variability and change on operations were assessed using an 'operational thresholds' method. The potential direct impacts on infrastructure, meanwhile, were explored through modelling of marine flooding/inundation due to extreme sea levels (ESLs) under the present and future climate.

The operational thresholds approach included the following steps:

1) Identification of generic operational thresholds (e.g. extreme temperatures and rainfall) under which facility operations are impaired.

2) Collation of climatic data including projections from the Regional Climate Model (RCM) PRECIS (abstracted from the Caribbean Community Climate Change Centre – CCCCC – database), available projections in terms of emissions and potential impacts, approximate to the RCP6.0.

3) Operational thresholds and the RCM PRECIS climatic projections were compared to assess threshold exceedance frequencies.

This work showed that, in addition to the projected issues associated with marine inundation identified through the modelling, rising temperatures (above the 1.5 °C temperature cap, which may be reached as early as in the 2030s) are expected to cause operational problems for the Jamaican and Saint Lucian critical international transportation assets, in particular:

- By the early 2030s, staff working outdoors at the Jamaican and Saint Lucian international transportation assets could be at 'high' risk for 5 and 2 days per year, respectively; by 2081-2100, such days could increase to 30 and 55 days per year, respectively.

- Energy demand will increase e.g. for the Jamaican seaports, a 1.5 °C temperature rise will increase energy requirements by 4 % for 214 days per year; a 3.7 °C rise (2081-2100) will increase energy requirements by 15 % for 215 days per year. Similar trends are projected for Saint Lucia seaports.

Box 12: Operational thresholds approach for assessing the vulnerability of critical transportation assets in Jamaica and Saint Lucia

In situations where no quantified threshold (risk indicator) information is available, qualitative methods such as those often used in environmental impact assessment (EIA) might be applied to establish whether a particular asset, operation or system could be significantly affected by the identified change. Particularly where data are lacking, however, it is important to indicate the level of confidence in the findings and to ensure that sensitivity analyses are undertaken before implementing any measures.

3.3.4 Explore the Extent of Adaptive Capacity

Adaptive capacity refers to the ability to accommodate and adapt to change – in this case, the ability of existing port or waterway assets, operations and systems to accommodate change in average and extreme meteorological, oceanographic or hydrological conditions.

Practical examples of where ports and waterways have a degree of existing adaptive capacity (i.e. could handle an element of change with little adverse consequence) include:

- Critical facilities such as container vessel berths, or electricity sub-stations providing power to operations' centres including the VTS building, have been 'over-designed' enabling them to withstand currently projected storm surge levels or high flow conditions.
- There is redundancy in the system insofar as duplicate or alternative berths, storage facilities, equipment, access points, etc. already exist, or it is acknowledged that a particular asset is easily repairable or replaceable.
- Existing contingency plans have identified the need to instigate temporary restrictions on container stack height or to provide alternative berthing arrangements during severe weather, in turn helping to minimise effects on continuity of operations during an event or in a post-event situation.
- Storage heights of bulk cargoes exposed to weather have been reduced to control stockpile slumping due to higher or more intense rainfall and the effect of this contingency on port capacity has been taken into account.
- The port or waterway operator has a back-up power supply, a stock of sandbags, well-drilled emergency plans including necessary detours and diversions, and a store of readily accessible warning signs.

In general, where existing adaptive capacity is low, the asset, operation or system in question is likely to be more vulnerable to the effects of climate change. In these cases, adaptation action may need to be prioritised. Conversely, the availability of sufficient adaptive capacity throughout the adaptation planning horizon may allow investment to be delayed or even avoided. If an asset has a short residual life but capacity exists to accommodate the anticipated amount of change during that period, potentially expensive retrofitting action may similarly be avoided in favour of investment in a climate-resilient replacement in due course.

Whenever Step 3.3.3 identifies that a threshold (or other risk indicator) could be exceeded within the adaptation planning horizon, it is important to explore the role of adaptive capacity.

In order to help understand the extent of existing adaptive capacity, the following information should be collated and recorded, for example by adding extra columns to the inventory developed in Steps 1.2 and 1.3.:

- The design life and the residual life of the particular structure or asset (i.e. the number of years remaining after the originally-intended economic or technical life has been reached and before functional failure occurs).
- An indication of its current condition or status, structural integrity or health.
- Serviceability, in particular maintenance costs, can be a useful indicator of status, whilst also highlighting possible savings if investment in climate-resilient infrastructure results in a reduced maintenance requirement.
- Depth, elevation relative to Datum (fixed start point) or similar physical indicators.
- Current performance at system level or relative to business requirements.
- Existing flexibility or redundancy in the system; availability of alternatives.
- Relevant operational characteristics including operational thresholds and frequency of exceedance (see Step 3.3.3).
- Information about the impacts (consequences and costs) of recent extreme weather events or hydrological/oceanographic conditions (see Step 1.6.3).
- Consequences of failure (linked to criticality: see Step 1.2).

If the data needed to determine current condition or status, structural integrity or health, serviceability or functionality, etc. are insufficient or inadequate, steps should be taken to set up monitoring and/or data management systems to ensure future decisions are better informed (see Step 1.6.2).

In addition to carrying out an internal assessment, efforts should be made to understand and record how much adaptive capacity exists within the important links and interdependencies identified in Steps 1.2 and 1.4 (e.g. third-party infrastructure or services, or physical transfers of goods and services).

Particular attention should be paid to known weaknesses or inadequacies, whether these are internal or external. It is vital to recognise the weakest link in the chain so that action on this can be prioritised.

Colour coding, footnotes, etc. can be used to highlight the key factors determining adaptive capacity or vulnerability at department, site or facility level, including identifying possible priorities for action.

Summarising the outcomes of Step 3.3.4 on the critical assets, operations and systems inventory prepared in Step 1.3 might prove valuable. Table 13 illustrates how information contributing to the decision on available adaptive capacity can be included in this Template.

Maritime and inland port and navigation infrastructure			Criticality				Susceptibility to hazards causing impacts												Key facts							
																			Design data			Asset condition			Performance	
			Not critical	Unlikely	Probably	Yes	Flooding	Overtopping	Flow velocities/extreme waves	Low river flow	Changes in bathymetry	Bed or bank erosion	Fog or reduced visibility	Changes in wind	Extreme cold, ice or icing	Extreme heat, also humidity	Changes in water chemistry	Changes in biology	Design life (years)	Date of construction	Residual life	Good	Moderate	Poor	Maintencance cost	Performance against target
LAND-WATER INTERFACE; INTERTIDAL; RIPARIAN ZONE	Assets	Structures	Quay wall (i)				✓	✓	✓	✓		✓	✓	✓	✓	✓		✓		50	1994	25		✓		⇔ (amber)	✗ (red)
			Quay wall (ii)				✓					✓	✓	✓	✓	✓		✓		50	2014	45	✓			⇔ (green)	✓ (green)
			Fenders			✓								✓	✓	✓	✓	✓		15	2014	10	✓			⇔ (green)	✓ (green)
			Ladders			✓								✓	✓	✓	✓	✓		15	2014	10	✓			⇔ (green)	✓ (green)
			Slipway	✓																							
		Physical systems	Cathodic protection				✓						✓			✓		✓		10	2014	5	✓			⇔ (green)	✓ (green)
		Resources	Heritage resource (Lighthouse)				✓	✓	✓	✓				✓	✓	✓	✓			N/A	1950	N/A		✓		⇑ (red)	✓ (green)
			Beach nourishment			✓			✓	✓	✓	✓	✓						✓	15	2018	14	✓			⇔ (amber)	– (amber)
	Operations		Pilotage				✓			✓	✓	✓		✓	✓	✓				N/A	N/A	N/A	N/A	N/A	N/A	⇔ (green)	✓ (green)
			Dredging / disposal			✓				✓		✓	✓	✓	✓					N/A	N/A	N/A	N/A	N/A	N/A	⇑ (red)	✗ (red)
			Sailing / water sports events		✓																						
			Marker buoys navigation aids water sports events		✓																						

Legend	High	Moderate	Low
Increasing	⇑ (red)	⇑ (orange)	⇑ (green)
Stable	⇔ (red)	⇔ (orange)	⇔ (green)
Reducing	⇓ (red)	⇓ (orange)	⇓ (green)

Table 13: Snapshot from completed template illustrating how supporting information used to determine adaptive capacity can be recorded

3.3.5 Identify Other Indicators of Increased Vulnerability

In addition to considering adaptive capacity, several other factors can act as indicators of future vulnerability, for example:

- Maintenance effort: do records show an increasing level of effort, or higher maintenance costs compared to historic maintenance activity? This may indicate increasing vulnerability. The expected residual asset life might provide a proxy indicator if maintenance information is not available.
- Frequency of exceedance of operational thresholds: do records show increasingly frequent exceedances over recent years? This may suggest increased vulnerability if there is further unfavourable change in a key climate parameter or process.
- Has there been new development or are there new development plans in the vicinity? Vulnerability can be increased if, for example, a major new investment is planned in a potentially susceptible location, or if it is intended to modify certain operations such that these activities are more sensitive to key climate parameters.
- Do data exist on the consequences (delays, downtime, clean-up, damage repair) and associated costs resulting from recent and historic extreme weather or other hydrological/oceanographic events? Such data may provide an indicator of possible future risks. Box 13 illustrates how this type of information is included in the vulnerability assessment protocol developed and used by Transport Canada.

> The Public Infrastructure Engineering Vulnerability Committee or **PIEVC Protocol** (https://pievc.ca/assessments) is a free, publicly available methodology that has been used by Transport Canada to understand infrastructure vulnerability to climate risks. The development of this flexible and versatile tool helped to address several concerns, including that looking back at historic trends is no longer a reliable approach given the current rate of climate change. Rather, an approach based on risk science principles is needed.

The PIEVC Protocol has proven applicable to various transport modes. The five-step process enables the user to make informed judgments on which infrastructure components require adaptation and what measures to take. Vulnerability is established with reference to:

- infrastructure type and condition including physical condition, age, significance within the region, maintenance, operation and management amongst others
- the historic, recent and projected climate, including through flood plain mapping, intensity-duration-frequency curves and other regionally specific climate modelling scenarios
- historic and projected responses of the infrastructure to changes in relevant climate parameters and processes

Infrastructure data sources (e.g. element lists, plans, policies) and climate data sources vary depending on the mode, location, characteristics, and the nature of the asset being evaluated.

Box 13: Transport Canada use of a vulnerability assessment protocol, Canada

Whilst it is important to recognise potential vulnerabilities, care should also be taken to avoid mistakenly attributing recent changes or trends to the changing climate, for example:

- Notwithstanding a period of extreme weather conditions, a recorded increases in delays may be attributable to changes in labour practices or to the introduction of a new piece of equipment in the corresponding time period.
- Increased maintenance costs may be a function of the age of the asset rather than of increased overtopping or wave action.
- Changes in sedimentation may be caused by the construction of a new facility further along the coast rather than being related to changes in storminess.

In the absence of clear evidence regarding a causal link, it is important to keep an open mind on the possible causes of observed changes.

3.3.6 Complete Vulnerability Assessment and Report on Outcomes

The information gathered in Steps 3.3.1 to 3.3.5 facilitates the identification of climate change scenarios under which it can be concluded that vulnerability will increase because thresholds or other risk indicators are expected to be exceeded and there is insufficient capacity within the system to accommodate these changes.

There may also be situations or scenarios under which vulnerability will reduce (for example if the duration of extreme cold or the frequency of fog days is expected to reduce) and situations where there will be no change.

The outcomes of the vulnerability assessment can be documented and presented in many different ways. One option is to complete a summary table such as that shown in Table 14 for each of the scenarios assessed. In other cases, however, more detail will be required: for example, a statistical analysis and/or modelling exercise might be undertaken and a vulnerability assessment report prepared, to set the scope for a more detailed risk analysis.

Port Example Climate Change Vulnerability Assessment **SCENARIO 1 of 3**	**Compared to the baseline, <u>how does exposure</u> to the potential climate hazard <u>change</u> within the planning horizon?** ↑↑ **Significant increase** ↑ **Increase** → **No change** ↓ **Reduction** ↓↓ **Significant reduction**					**Considering relevant thresholds and existing adaptive capacity, <u>how is vulnerability</u> likely to be <u>affected</u>?** ↑↑ **Significant increase** ↑ **Increase** → **No change** ↓ **Reduction** ↓↓ **Significant reduction**				
Examples of relevant parameters or processes → Examples of critical assets, operations or systems ↓	Extreme heat	Sea level rise	Wind speed	Wave conditions	Seasonal rainfall	Extreme heat	Sea level rise	Wind speed	Wave conditions	Seasonal rainfall
Berthing and loading, offloading cargo	↑↑	↑	→	→	↑↑	↑	→	→	→	↑
Access to berth (e.g. navigation channels)	↑↑	↑	→	→	↑↑	→	↓	→	→	↑
Maritime structures	↑↑	↑	→	→	↑↑	→	↑	→	→	→
Quay equipment (e.g. cranes, ship loaders/unloaders, marine loading arms)	↑↑	↑	→	→	↑↑	↑	→	→	→	↑
Trucks/in-terminal vehicles	↑↑	↑	→	→	↑↑	↑	→	→	→	↑
Onshore structures	↑↑	↑	→	→	↑↑	→	→	→	→	→
Storage areas	↑↑	↑	→	→	↑↑	↑	→	→	→	↑
Onshore equipment (e.g. stacking or reclaiming machines, conveyors, rubber-tyre gantry cranes)	↑↑	↑	→	→	↑↑	↑	→	→	→	↑
Electrical power systems	↑↑	↑	→	→	↑↑	→	→	→	→	→
Drainage systems	↑↑	↑	→	→	↑↑	→	→	→	→	↑↑
Fuel systems	↑↑	↑	→	→	↑↑	↑	→	→	→	→
Road/rail access and internal road network	↑↑	↑	→	→	↑↑	↑	→	→	→	↑
Facilities for workers	↑↑	↑	→	→	↑↑	↑↑	→	→	→	→

Table 14: Example presentation for vulnerability assessment outcomes in a seaport

If the projected change in a climate parameter or process could increase susceptibility (exposure) such that the vulnerability of the asset, operation or system is expected to increase, the corresponding change in the parameter or process represents a climate hazard with potential consequences (impacts) for the port or waterway. Box 14 provides an example of how a vulnerability assessment was used to identify vulnerable areas and assets in the Port of Long Beach, USA.

A Climate Adaptation and Coastal Resiliency Plan developed by the **Port of Long Beach, California, USA**, used climate data, an inventory of port assets, and detailed sea level and storm surge inundation mapping to inform the development of vulnerability profiles for critical port infrastructure (pier infrastructure, transportation network, critical facilities, utilities, and the breakwater, see Case Study 2).

Based on low, mid and high range sea level rise scenarios and an increase in rainfall intensity, detailed inundation maps were prepared to identify where sea level rise-related (SLR) inundation or extreme tide (storm surge) flooding was expected. An overtopping assessment identified the locations most likely to overtop. Two tide conditions (daily high tide and extreme tide) were used, resulting in six mapped scenarios showing inundation depth and extent. Wave action was not included in this assessment. Potential future increases in precipitation of 20 % and 30 % were also evaluated and mapped.

The inventory and maps were used to identify vulnerable areas of the Port. Scoring criteria were developed to determine vulnerability based on susceptibility, sensitivity, and adaptive capacity of each asset. The most significant future impacts identified were associated with a combination of SLR and storm surge. The Port expects such impacts to become more pronounced as sea levels increase.

Box 14: Example of vulnerability assessment undertaken by Port of Long Beach, USA

Once it has been identified how climate change may affect critical assets, operations and systems, this conclusion can be added to the inventory as illustrated on Table 15. One or two red crosses against an asset, operation or system in the final column indicates that action is required (e.g. further analysis of risks or the identification and implementation of measures (see Step 3.3.8)).

Maritime and inland port and navigation infrastructure				Criticality				Susceptibility to hazards causing impacts												Key facts								
																				Design data			Asset condition			Performance		
				Not critical	Unlikely	Probably	Yes	Flooding	Overtopping	Flow velocities/extreme waves	Low river flow	Changes in bathymetry	Bed or bank erosion	Fog or reduced visibility	Changes in wind	Extreme cold, ice or icing	Extreme heat, also humidity	Changes in water chemistry	Changes in biology	Design life (years)	Date of construction	Residual life	Good	Moderate	Poor	Maintencance cost	Performance against target	Available adaptive capacity
LAND-WATER INTERFACE; INTERTIDAL; RIPARIAN ZONE	Assets	Structures	Quay wall (i)				✓	✓	✓	✓		✓	✓	✓	✓	✓		✓		50	1994	25		✓		⇔ (orange)	✖	✖✖
			Quay wall (ii)				✓					✓	✓	✓	✓	✓		✓		50	2014	45	✓			⇔ (green)	✔	✔
			Fenders			✓								✓	✓	✓	✓	✓		15	2014	10	✓			⇔ (green)	✔	✔
			Ladders			✓								✓	✓	✓	✓	✓		15	2014	10	✓			⇔ (green)	✔	✔
			Slipway	✓																								
		Physical systems	Cathodic protection				✓						✓			✓		✓		10	2014	5	✓			⇔ (green)	✔	✔
		Resources	Heritage resource (Lighthouse)				✓	✓	✓	✓				✓	✓	✓	✓			N/A	1950	N/A		✓		⇧ (red)	✔	✖
			Beach nourishment			✓			✓	✓	✓	✓	✓						✓	15	2018	14	✓			⇔ (orange)	–	–
	Operations		Pilotage				✓			✓	✓	✓		✓	✓	✓				N/A	N/A	N/A	N/A	N/A	N/A	⇔ (green)	✔	✔
			Dredging / disposal			✓				✓		✓	✓	✓	✓					N/A	N/A	N/A	N/A	N/A	N/A	⇧ (red)	✖	✖✖
			Sailing / water sports events		✓																							
			Marker buoys navigation aids water sports events		✓																							

Legend	High	Moderate	Low
Increasing	⇧ (red)	⇧ (orange)	⇧ (green)
Stable	⇔ (red)	⇔ (orange)	⇔ (green)
Reducing	⇩ (red)	⇩ (orange)	⇩ (green)

Table 15: Snapshot from completed template illustrating current adaptive capacity

3.3.7 Set Adaptation Priorities

In many cases, the outputs from the vulnerability assessment will need to be ranked or prioritised to ensure that the next steps focus on the most important potential impacts.

Priorities will usually be defined in accordance with the adaptation objectives set in Step 1.5. If resources are limited, however, the prioritisation exercise might need to target the assets, operations or systems deemed to be the most critical, sensitive or vulnerable; or those with the greatest change in relative vulnerability (e.g. illustrated on Table 14 by two red arrows).

Alternatively, a ranking to determine priorities might be based on the climate hazard. In these cases, the focus of the next steps would be on whichever assets, operations and systems are potentially impacted by changes in the climate parameter(s) or process(es) perceived to represent the greatest future threat. In the situation illustrated on Table 14, priority might be given to addressing impacts caused by extreme heat or changes in seasonal rainfall.

Priorities should always be determined in collaboration with key internal and external stakeholders.

3.3.8 Agree Next Steps

In cases where the planning horizon is relatively short, where confidence levels are high, or where the adaptation initiative is being undertaken as a broad or high-level exercise, the vulnerability assessment might provide sufficient information about the potential impacts of climate change to allow an infrastructure owner or operator to move directly to the identification of potential adaptation measures (i.e. Stage 4).

Otherwise the vulnerability assessment helps determine the scope of a more detailed (quantified) analysis of risk likelihood and consequence as described in Steps 3.4 onwards.

In both cases, the output of Steps 3.2 and 3.3 provide a record of which climate parameters and processes constitute the climate hazard as well as the potentially impacted (i.e. vulnerable) assets, operations and systems. A record should be prepared for each climate scenario investigated and the level of certainty in the conclusions should be noted.

The vulnerability assessment outputs should be shared with relevant stakeholders.

Step 3.4 Select an Appropriate Level of Risk Analysis

The next step in the overall risk assessment process involves analysing the likelihood that the climate hazard will occur, and the magnitude and severity of the consequences if it does.

This further analysis will provide a detailed understanding of the level of risk and the nature of the impact on critical assets, operations and systems. Subject to any caveats associated with confidence in the data, the outputs from this analysis will be used in Stage 4 to prioritise adaptation requirements and to inform the development of strategies that describe the required adaptation measures (i.e. pathways).

Some organisations have existing risk analysis procedures, incorporating established risk tolerance thresholds for critical assets, operations or systems that could readily be adapted for use in climate change assessments. The advantage of using such processes, with their associated presentational matrices, is that climate change risks can be assessed and presented in a familiar manner, easily understood by the organisation's risk assessors, risk managers, stakeholders and those making decisions on investment. A potential disadvantage, however, is that some of the climate-change specific issues outlined in the following steps may not currently be addressed within the bespoke process, for example the use of scenarios to address climate change uncertainties. This guidance document is therefore intended to be used alongside an organisation's own risk assessment procedures.

Where an organisation-specific approach does not exist, reference might be made to one of a number of published climate change-specific risk assessment procedures. Many such publications are generic or to relate to the design of new infrastructure but a number (e.g. Directorate-General Climate Action EC, 2011; Standards Australia, May 2013; West and Brereton, 2013, and UK's Committee on Climate Change, 2017) do include examples from the transportation sector.

Steps 3.4. to 3.6 herein do not duplicate the detailed guidance on the principles and practice of risk analysis available from these and many other sources. Rather these steps propose a simple, climate change-specific risk analysis procedure that can be followed if a basic analysis will suffice or if an organisation wants to go beyond a vulnerability assessment but lacks the expertise or resources to carry out a sophisticated risk analysis. In these cases, following Steps 3.4 to 3.6 enables the user of the guidance to progress to Stage 4 with a more thorough understanding of the main risks that need to be addressed.

For situations requiring or justifying a greater level of sophistication, a hierarchy of risk analysis approaches exists, ranging from an initial analysis through an intermediate procedure to an advanced assessment. An overview of these is provided in Annex 3A. Each represents a greater level of effort, resources and complexity and in return reduces the residual level of uncertainty. The levels can build upon each other. For example, an initial level analysis of a dozen different risks may identify one potentially significant or extreme risk that justifies a more detailed investigation.

As with other steps, a decision on the most appropriate level of risk analysis should consider the quantity and quality of the available data, the required resources and expertise, and the level of detail of the desired outcomes. An organisation can undertake more detailed risk analyses either as more data become available or as their approach to risk matures in other ways.

A simple analysis may suffice in many cases. However, if it is clear from the outset that the purpose of the risk analysis is to support large scale investment decisions and/or decisions in relation to infrastructure with a design life of several decades, or to deal with a potential structural failure as illustrated in Box 15, expert advice should be sought. In these cases, it is likely that an advanced level of analysis will need to be undertaken.

The **San Pedro Breakwater**, which provides the Port of Los Angeles, USA, with wave protection for its infrastructure, navigation, berthing, and cargo operations, was built just over 100 years ago. By current standards, its design can be considered obsolete. The breakwater also exhibits some structural issues of concern because its crest has settled an average 0.60 metres from its 4.25 metres mean lower low water (MLLW) design elevation. The average crest level of the breakwater is now around 3.65 metres, making the breakwater vulnerable to wave overtopping and damage in high 2 metres MLLW spring tides and storm wave conditions.

Whilst there was limited data available to define the breakwater fragility and several assumptions had to be used in a sea level rise impact assessment (Case Study 12), this analysis clearly indicated that sea level rise due to climate change would have a significant impact on the vulnerability of the breakwater. Increasing the breakwater crest elevation appeared to be a justifiable solution to reduce the risk of failure, but detailed analyses would be required to reduce the uncertainty in the breakwater fragility and to define a design crest elevation to adapt to SLR due to climate change. For the existing superstructure, these would include physical model tests for combinations of R/H, wave period and angle of incidence or, for the assessment of wave damage if alternative superstructure designs are considered.

Box 15: Example of analyses needed to assess the risk of breakwater failure, USA

Box 16 provides an example of a situation that justified an advanced level of climate risk analysis. This deals with the United States' Department of Defense need to understand the climate change and climate variability risks to its numerous coastal facilities in order to be able to identify and evaluate structural and non-structural risk-mitigating alternatives that would sustain critical assets and mission capabilities at an actionable scale under a wide range of sea level rise and storm scenarios.

An example of an advanced level risk analysis is provided by that carried out for the United States military base ports, such as in the Port of Norfolk, Virginia (Case Study 8). The US Army Corps of Engineers (USACE) developed a robust, scientifically informed, risk-based approach, specifically applicable to large scale coastal military installations threatened by coastal hazards and rising sea levels. This assessment approach enabled the **US Department of Defense** to identify climate change induced vulnerabilities in its portfolio of marine and land-based infrastructure (including naval bases). Changes in climate variability were included in the analysis. A series of stepwise procedures was established that couples multiple high-fidelity coastal storm models with installation-specific asset models and regional ecosystem response models, to systematically assess mission-related risks in a probabilistic manner using Bayesian networking. Putting vital assets in a risk context offers a nationally-consistent approach and a credible way of prioritising action in the face of constrained resources. USACE plan to use such advanced risk assessments to prioritise life safety risks for its own activities whilst also providing a basis for communicating risk so that stakeholders can make more informed decisions.

Box 16: US Army Corps of Engineers advanced risk analysis for coastal military installations, USA

However sophisticated or basic the level of risk analysis selected:

- Both internal and external stakeholders should be involved in and have the opportunity to provide input to the analysis.
- The analysis should include a 'business as usual' option to understand the risks if no action is taken.
- Care should be taken to ensure that all sources of hazards, areas of impacts, events (including changes in circumstances) along with their causes and potential consequences are identified and analysed commensurate to the objectives agreed in Step 1.5.

Step 3.5 Assess Likelihood

As explained in Step 2.3.1, there are many uncertainties inherent in climate science, including in the projection of future changes in GHG emissions and the scale at which changes are modelled. It is therefore not possible to be certain that any one particular climate change scenario will be realised.

In cases where Step 3.3 has identified the potential for a change in vulnerability under a certain scenario, it is therefore the relative likelihood of the hazard occurring or threshold being exceeded that needs to be determined. Table 16 provides an illustration of how likelihood might be described and rated in qualitative terms; quantified using a simple scale of 1 to 5; and presented using colour-coding following an initial risk analysis [West and Brereton, 2013].

Qualitative description of likelihood	Likelihood rating	
It is **expected that** the climate hazard will occur, that the threshold will be exceeded or there will be another significant impact within the adaptation planning horizon under all climate change scenarios investigated.	Almost certain	5
It is **likely that** the climate hazard will occur, the threshold will be exceeded or there will be another significant impact within the adaptation planning horizon under some of the climate change scenarios investigated.	Likely	4
The climate hazard **may** occur or the threshold may be exceeded or there may be another significant impact within the adaptation planning horizon under some of the climate change scenarios investigated.	Possible	3
The climate hazard **could** occur, or the threshold could be exceeded or there could be another impact within the adaptation planning horizon under one or more of the climate change scenarios investigated.	Unlikely	2
The climate hazard (or the exceedance of the threshold or the manifestation of an impact) is **not expected** to occur other than in exceptional circumstances within the adaptation planning horizon under most of the climate change scenarios investigated.	Rare	1

Table 16: Examples of determining and presenting risk likelihood

If the data are available to support a more detailed assessment, likelihood can be expressed as a probability of occurrence. For instance, a rating of 3 could represent a ±50 % probability while 5 may represent a ‘certainty’ near to or at 100 %.

In all cases where the planning horizon is more than ten years, the likelihood of hazard occurrence or threshold exceedance under each of the scenarios agreed in Step 2.3.1 should be assessed. This is important in order to ensure the range of full possible future climates is adequately reflected.

Taking this approach can provide confidence – for example, if the occurrence of a particular hazard or the exceedance of a certain threshold is ‘almost certain’ or is ‘unlikely’ under all the scenarios assessed. It can also warn of sensitivity – for example, the likelihood of occurrence or threshold exceedance may be ‘almost certain’ under one scenario, ‘likely’ under another, and ‘possible’ under a third.

Step 3.6 Assess Consequences

3.6.1 Record Magnitude, Severity and the Nature of the Impact

Climate hazards can affect port and inland waterways assets, operations, and systems in many different ways. For example, there may be:

- Physical risks (to asset integrity, condition, physical risk)

- Operational risks (to safety, security, delays, closures)
- Business risks (to continuity, reputation, efficiency, finance)
- Environmental risks (pollution, hazards, ecosystem services)

The overall consequence of a climate change hazard for a critical asset, operation or system is a function of the nature of the impact(s), its magnitude and severity. These characteristics can be derived and described using different approaches ranging from expert judgement or simple statistical methods through to detailed modelling and evaluation. Step 1.3 illustrated the typical impacts to which port and waterway infrastructure may be susceptible.

Stakeholders should be involved in identifying and assessing potential climate change impacts and their consequences. Whilst stakeholders' interests and priorities may be different from those of the port or waterway organisation, it is essential that these are acknowledged so that possible win-win adaptation measures can be recognised and explored in Stage 4 (e.g. Step 4.2.3).

3.6.2 Derive Consequence Ratings

In determining the potential consequence of an identified hazard, it is always important to bear in mind that:

- A small magnitude change is not always of low severity. For example, an asset may already be functioning, or a system may already be operating, very close to a critical threshold.
- A large magnitude change may not necessarily be of high severity. For example, there may be significant redundancy or adaptive capacity available meaning that even a large change can be accommodated.

Table 17 illustrates how a consequence 'rating' might be derived based on a generic, qualitative description. The criteria and terminology presented in this table should be modified to suit the local circumstances, even if an initial level of risk analysis is being undertaken. Such refinements might include:

- Introducing different metrics to suit the particular circumstances of an assessment or the objectives of the adaptation strategy (e.g. based on the criteria used to determine criticality; see Step 1.2.2), or
- Preparing quantitative indicators (for example a port or waterway operator may decide that a catastrophic impact would be characterised by severe injury or death 'to multiple individuals', disruption of port operations of 'more than one week', or damage to infrastructure 'exceeding US$ 1billion').

The more sophisticated the level of risk analysis being applied, the more important it will be to develop and apply quantifiable, site-specific metrics.

If the occurrence of the hazard would cause impacts that…	**… then an appropriate consequence rating is**	
Irreplaceably or permanently affect critical assets, operations or systems and thus threaten the viability of the port or waterway with possible implications for the regional or national economy, potentially lead to loss of life, cause significant and irreversible contamination with hazardous substances, prevent the import or distribution of post-disaster aid, or have similar potentially catastrophic implications.	Catastrophic	5
Have a significant, negative long-term effect on critical assets, operations or systems and thus compromise the business continuity of the port or waterway, potentially lead to serious injury, result in significant or irreversible environmental impacts, compromise the import or distribution of post-disaster aid, or have similar potentially major implications.	Major	4

Have a negative, locally significant and/or short- to medium-term effect on critical assets, operations or systems with implications for business continuity in the affected parts of the port or waterway; potentially lead to minor injury, cause moderately significant environmental impacts, affect the ability of the facility to import or distribute post-disaster aid effectively, or have similar moderately significant implications.	Moderate	3
Temporarily affect the efficiency or effectiveness of critical assets, operations or systems or aspects thereof but with no significant implications for business continuity overall, cause environmental impacts of minor significance, interrupt aspects of post-disaster aid import or distribution, or have similar implications of minor significance.	Minor	2
Have negligible implications for critical assets, operations or systems and hence business continuity, insignificantly affect the environment or the import and distribution of post-disaster aid.	Insignificant	1

Table 17: Examples of determining risk consequence

3.6.3 Prepare Risk Matrices

By combining the likelihood of the climate hazard as presented in Table 16, and the consequence ratings as presented in table 17, a risk matrix can be developed. Table 18 illustrates a typical format for presenting the outcomes of the risk analysis using a widely applied 'traffic light' approach. The risk scores in this example are shown using colours and/or numeric values. This type of matrix can, however, also present the overall risk using descriptions or other forms of classification. The level of risk is not fixed but a choice. Instead of separate colours, also a gradation between green and red could be used.

Likelihood → Impact ↓	Rare (1)	Unlikely (2)	Possible (3)	Likely (4)	Almost Certain (5)
Catastrophic (5)	5	10	15	20	25
Major (4)	4	8	12	16	20
Moderate (3)	3	6	9	12	15
Minor (2)	2	4	6	8	10
Insignificant (1)	1	2	3	4	5

Legend:

Level of risk	Required adaptation action
Very high risk	Immediate adaptation action required
High risk	Adaptation action required as high priority
Moderate risk	Adaptation actions to be implemented via day-to-day management
Low risk	Risks to be managed and monitored via routine internal procedures

Table 18: Typical presentation of risk assessment outcomes

This type of assessment matrix is commonly used to represent and report risk and serves as a basic framework for the development of an adaptation strategy. Whilst it is typically used to identify and represent negative consequences, it can also be modified to highlight benefits or opportunities (e.g. a reduction in the level of risk to navigational safety associated with fog, or in the days of waterway closure due to ice).

Attitudes to risk, and the level of accepted risk originally identified in Step 3.3.2 could usefully be reviewed at this stage in the process i.e. before moving on to identify and evaluate adaptation options.

In the example shown in Table 18, it might be the case that the acceptable level of residual risk is moderate, in which case the adaptation strategy to be developed in Stage 4 would prioritise action on the very high and high-risk consequences, at least in the short- to medium-term. In any case, another round of engagement with internal and external stakeholders will provide a useful check on the draft outcomes of the risk analysis and provide an opportunity for further feedback on levels of acceptability or tolerability.

The following two boxes, Box 17 and Box 18 provide examples of where ports in Colombia and in the UK have used this type of risk analysis process, and illustrate some of the outcomes. The details (risk categories, colour schemes, descriptions, etc.) differ between the examples, but both cases make clear how priorities for action were identified.

A climate change adaptation study for Terminal Maritimo Muelles El Bosque (MEB), in **Cartagena, Colombia** adopted a practical approach to assessing potential climate change impacts on imports and exports (Case Study 13). Amongst the activities carried out were literature reviews and analysis, and discussions with MEB staff and other stakeholders during a site visit. Using these sources, high level scenarios were developed that describe a range of potential climate change related impacts, and a financial analysis was then conducted [IFC, 2011]. Considering the uncertainties in future trade projections over long timescales, the study produced high-level estimates of potential impacts on MEB's revenues up to the 2050s.

The table below provides a snapshot of some of the outcomes. It illustrates the significance of different climate change risks and opportunities assuming that no adaptation takes place. Risk significance is evaluated by scoring the two dimensions of risk, namely the likelihood of a hazard and the magnitude of its consequence. Note that, where relevant, the risk assessment considered the implications of climate variability as well as average changes in the future climate.

Risk	Risk Category	Likelihood (1-5)	Consequences (1-5)	Risk Level
Vehicle movement inside the port (Section 5)				
Increased seawater flooding of port areas (observed SLR Scenario)	Operational	5	4	VERY HIGH
Increased seawater flooding of port areas (accelerated SLR Scenario)	Operational	3	5	HIGH
Increased maintenance of port unpaved areas	Operational	3	1	LOW
Demand, trade levels and patterns (Section 6)				
Reduction in total trade at MEB	Financial	3	3	MEDIUM
Reduction in grain imports at MEB	Financial	2	3	MEDIUM
Reduction in agricultural exports at MEB	Financial	3	1	LOW
Better relative performance of MEB compared to other ports	Reputational	4	n/a	OPPORTUNITY
Increase in certain agricultural exports at MEB	Financial	1	n/a	OPPORTUNITY
Goods storage (Section 7)				
Goods damage or loss due to seawater flooding (accelerated SLR scenario)	Reputational	5	4	VERY HIGH

Box 17: Climate change adaptation risk assessment for Terminal Maritimo Muelles El Bosque, Cartagena, Colombia

Associated British Ports (ABP) owns and operates 21 ports around the UK, handling over 92 million tonnes of cargo every year. **ABP's Climate Change Adaptation Report 2016 Update**, prepared for the British Government, assessed the key climate change risks likely to impact on a range of functions at Immingham, Hull and Southampton [ABP, 2016]. Their assessment used the latest climate change information and an existing internal risk management mechanism. It identified that the main risks were related to engineering and VTS/pilotage functions, and the projected impacts were associated with sea level rise and flooding, temperature increases and storminess.

Impact was scored against the highest of financial or reputational impact or service interruption:

Impact		% Earnings affected	Reputational	Service interruption
1	Minor	<1 %	Little coverage	<24 hours
2	Moderate	1-5 %	Limited effect	24-48 hours
3	Major	5-10 %	Local impact	48-96 hours
4	Catastrophic	>10 %	Adverse coverage	>96 hours

Likelihood considered the expected frequency of the event:

Likelihood	Expected frequency
1	Not expected in next 40 years; no evidence of occurrence in last 40 years
2	May occur in next 40 years and/or has occurred in last 40 years
3	May occur in next 10 years and/or has occurred in last 10 years
4	Likely to occur in next 5 years and/or has occurred in last 5 years

Overall risk ratings were determined using the table below:

Likelihood	4				HIGH RISK
	3		MEDIUM	RISK	
	2				
	1	LOW RISK			
		1	2	3	4
		Impact			

Applying this system led ABP to identify and classify 18 potential risks to engineering, dredging, hydrography, VTS and pilotage, including the following examples affecting the engineering and pilotage functions. In each case, mitigation measures and residual risks were also elaborated.

Business function: Engineering	Business function: Engineering
Climate variable: **Sea level rise**	Climate variable: **Storminess**
Primary impact: Flooding	Primary impact: Maintenance/repair delays
Threshold: Nominal quay height	Threshold: Weather windows
Potential impacts: Infrastructure damage, loss of power, knock-on consequences	Potential impacts: Delay in shipping movements
Impact: 3	Impact: 3
Likelihood: 4	Likelihood: 3
Risk rating: High	Risk rating: Medium

Business function: Pilotage	Business function: Pilotage
Climate variable: **Temperature**	Climate variable: **Storminess**
Primary impact: Staff operating conditions	Primary impact: Boarding compromised
Threshold: Tolerance limits	Threshold: Wind/swell conditions
Potential impacts: Health and safety (temperature controls, clothing required)	Potential impacts: Delays in vessel movement
Impact: 3	Impact: 3
Likelihood: 1	Likelihood: 4
Risk rating: Low	Risk rating: High

Box 18: Associated British Ports (UK) climate change adaptation risk assessment

Step 3.7 Summarise Risk Assessment Outcomes

Timely, transparent and targeted communication is essential if climate change risks are to be acknowledged and resolved effectively. Openness is also crucial if expectations are to be managed and if inclusivity is to be ensured.

Characterising and explaining uncertainty is an important part of this communication insofar as it improves collective understanding about the risks and assists with the selection, evaluation and implementation of adaptation measures. A report or another form of documentation of the risk assessment process and its outcomes should therefore be prepared.

The presentation of the risk assessment documentation can be organisation- or site-specific and tailored to a specific audience, but in all cases should provide an important trail to explain how the risk outcomes were derived.

Outcomes of Stage 3

For those working through the climate change adaptation planning process, the following steps should be completed before progressing to Stage 4:

- The approach to the vulnerability assessment has been agreed and changes in susceptibility have been confirmed (Steps 3.1 and 3.2)
- Risk indicators have been identified and vulnerable assets, operations and systems have been highlighted for each climate change scenario (Step 3.3)
- The need for and approach to a further risk analysis has been determined (Step 3.4)
  If appropriate, risk likelihood and consequences have been assessed to complete the risk analysis and to identify 'at risk' assets, operations and systems (Steps 3.5 to 3.7)

STAGE 4: ADAPTATION OPTIONS

Stage 4 sets out a series of steps to identify, screen, and where relevant evaluate, possible adaptation and resilience options. Options comprise measures or groups of measures to deal with the risks identified in Stage 3. These steps culminate in the development of 'adaptation pathways'. An adaptation pathway describes a sequence of actions (measures, modifications or other interventions) that are implemented in response to changes in meteorological, hydrographic or oceanographic conditions.

The overall approach to climate change adaptation can then be presented as an adaptation strategy. The implementation of measures on the adaptation pathways, and their subsequent performance in meeting the objectives of the strategy, are informed by monitoring.

Figure 11 illustrates these steps.

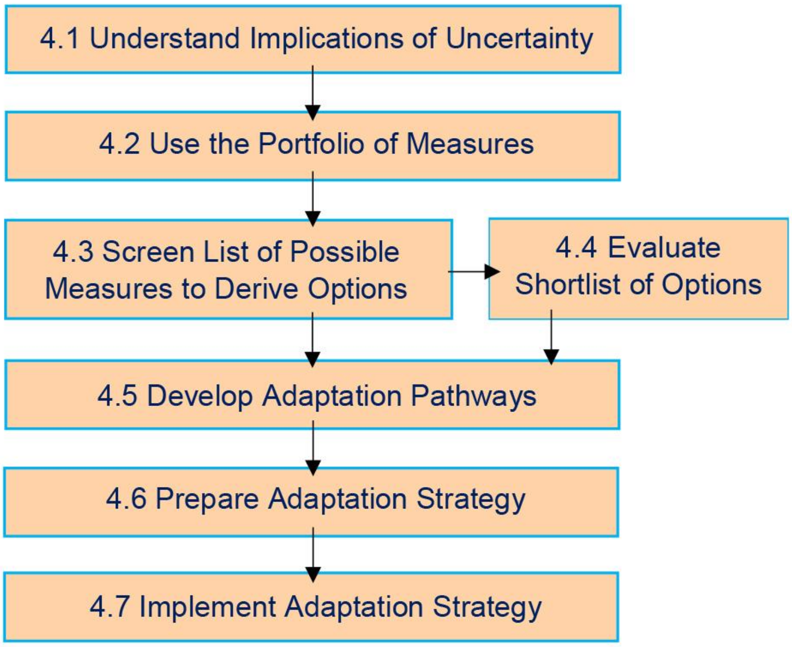


Figure 11: Stage 4 in the climate change adaptation planning process

Step 4.1 Understand Implications of Uncertainty: Role of Adaptation Pathways

For many organisations, climate change adaptation will represent a significant deviation from business as usual. The many uncertainties that have to be accommodated mean that the 'conventional solution' or the 'most obvious option' may no longer be the most effective, either technically or in terms of cost. Rather, a range of possible (traditional or novel) structural, operational and institutional measures needs to be considered on a site-specific basis.

Selecting the most effective measures and combinations of measures and determining how and when they can best be implemented over time as conditions change will often require thinking outside the box.

4.1.1 Avoiding Maladaptation

When identifying options to strengthen resilience and adapt to climate change, 'maladaptation' must be avoided. Maladaptation means failing to adjust adequately or appropriately to an anticipated change.

There can be a significant risk of under- or over- design or investment if adaptation decisions are taken without understanding the big picture. It is vital to avoid a decision that locks the infrastructure owner or operator into a solution with insufficient flexibility or capacity for future adjustment, or an investment that only works if climate parameters change in a certain way or at a certain rate. Such decisions may fail to deliver their anticipated functionality over the intended term and may even result in increased levels of risk.

Examples of maladaptation include:

- failing to secure an effective asset or to deliver the necessary redundancy or adaptive capacity because climate-related parameters change more quickly than projections suggested, or
- over-designing, adopting an inappropriate/irreversible design, or spending more than was necessary because climate does not change as rapidly as, or in the way that, current projections indicate.

Selecting short-term or interim options that strengthen resilience or otherwise help to reduce climate-related risks can help to address uncertainties and avoid maladaptation by providing time to collect data, carry out studies, explore alternative options, or seek additional investment.

4.1.2 Short-Term vs. Long-Term Measures

The first steps on an adaptation pathway will often be temporary, interim or short-term measures. In addition to the need to avoid maladaptation, such measures might be taken to prolong the functionality of an existing asset because retrofitting is currently too complex, or because the asset has a short residual life and is anyway due to be replaced in a few years. Precautionary measures might be considered if there is insufficient redundancy or adaptive capacity in the existing system. In the short to medium term, nature-based solutions that help strengthen the resilience of existing infrastructure or operations alongside other benefits may play an important role in an adaptation pathway.

In some situations, however, there may be an immediate need to move to a long-term solution, particularly if an unacceptably high risk to life, property or business continuity has been identified or if an expensive asset with a long service life is planned. In these situations, flexible, reversible or no-regret solutions should be sought, at least until such time as the climate change consequences are better understood.

4.1.3 Accommodate Uncertainty in Design

Even with the application of scenarios described in Step 2.3.1 or other forms of sensitivity testing, there will be situations where outstanding climate change-related uncertainties demand more flexible engineering solutions than is currently the norm.

If it is necessary to retrofit or replace an asset, or if new operations or systems are being introduced, these should be designed with the need for future modification in mind, with sufficient redundancy or contingency, or should be reversible where appropriate. The consequences of failure should also be understood and accommodated.

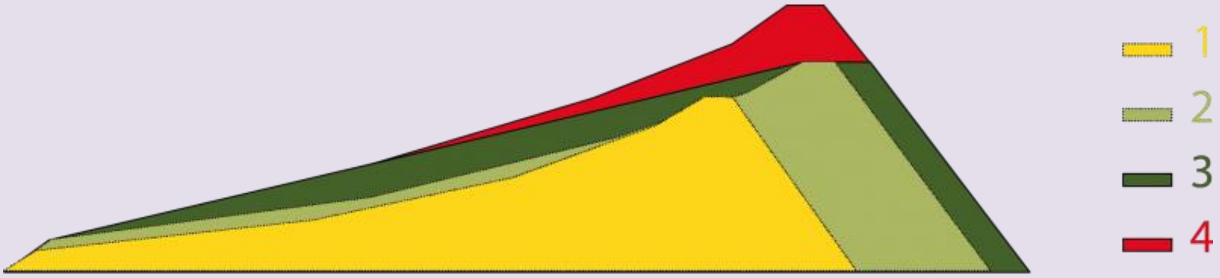
Build Flexibility into Design

Extreme conditions applied for the design of infrastructure such as quays or protective structures including breakwaters and flood defences, typically correspond to conditions that occur on average once every 50 or 100 years [Herbert et al., 2020, forthcoming]. Port and waterway operations such as cargo handling or pilotage, on the other hand, are generally governed by more frequent environmental conditions (i.e. monthly or annual conditions).

As the climate changes, so too will return periods. Some projections do exist – for example the IPCC Oceans and Cryosphere report (2019) concludes that extreme sea levels experienced once per century in the recent past will occur at least annually at many locations by 2050 under all RCP scenarios especially in tropical regions – but other parameters remain much more uncertain, both with regard to currently rare events and to relatively common ones [Hattermann et al., 2019 ; Kopp et al., 2014]. What will a 1 in 100 years storm event look like in 30 years from now? Could the current annual maximum wave height or wind speed occur monthly in future, or even weekly?

New or modified infrastructure with an intended design life of, say, 50 years needs to remain functional for that period irrespective of the actual rate and nature of change in key climate parameters. A breakwater may be required to provide protection against a 1 in 100-year storm but there may be insufficient certainty to understand what this storm will look like in 30 years' time. Rather than locking in to a single climate change scenario and investing in a breakwater of a certain height (i.e. an irreversible decision, risking maladaptation) it may therefore be preferable to design the base and structure such that it can be raised, strengthened or otherwise modified in future years as conditions demand. Box 19 provides an example of such a solution from Germany, where such solutions are considered as state-of-the-art.

The German state Schleswig-Holstein built the first so-called 'Klimadeich – Climate-Dyke' on the North Sea peninsula Nordstrand in 2014 with a design that already considers a safety margin of 0.5 m to be prepared for the foreseeable sea level rise. In order to obtain unforeseeable developments and new knowledge, the width of the top of the dyke was enlarged by 2.5 m for just 10-20 % of the construction costs of a traditional approach to enable an easy heightening of the structure at a later stage [Greiving, Maegdefrau, 2018] without the need for further land purchase.



1) Existing Dyke, 2) Dyke reinforcement with a climate surcharge of 0.5 m, 3) Adapted dyke profile for construction reserve, 4) Construction reserve for additional heightening in case of a more severe sea level rise

Box 19: The so-called Climate-Dyke of the German Federal State Schleswig-Holstein

Future upgrading or modification of infrastructure might involve raising, widening, deepening, extending, strengthening or decommissioning and re-building. Decisions on *when* such action is required are built into the adaptation pathway, informed by monitoring of the relevant climate parameters and processes as well as the condition and performance of the asset, rather than according to the dates shown on a pre-defined construction programme.

Incorporate Redundancy

Climate change uncertainties require that an appropriate level of redundancy is designed into vulnerable aspects of critical infrastructure. Redundancy in this context means the supplementation or duplication of key functions to increase resilience (see Step 3.3.4).

Over recent decades there has been a tendency to move away from incorporating redundancy in design because sophisticated modelling and design tools have encouraged an impression of greater certainty. Deliberate duplication (e.g. providing a backup generator) or over-design (e.g. adding 0.1 m to the height of a quay wall) may therefore diverge from recent practice. In a climate change context, however, including redundancy can help to strengthen adaptive capacity, improve overall longevity, and significantly reduce the potential losses associated with both long-term changes and – in particular – with extreme events.

Accommodate Consequences of Failure

The frequency and severity of extreme events will continue to increase as the climate changes but there are many associated uncertainties. Where structures or operations are prone to failure, understanding the consequences of such failures will therefore be vital. Such structures and operations will need to be designed to 'fail gracefully' rather than catastrophically. Achieving this might involve the design being modified, a different design being selected, or supplementary measures being introduced to improve resilience. Box 20 illustrates these ideas with reference to a flood defence.

A new or replacement flood defence is designed to protect against an extreme water level with a probability of occurrence of 1:100 years. It is recognised that climate change increases the likelihood of a larger event occurring within the design life of the structure, but the cost of constructing a defence to withstand such an event (e.g. with a current probability of occurrence of 1:250 years or greater) is prohibitive. The infrastructure owner therefore seeks to understand the consequences of failure of the flood defence by identifying the areas at most risk, and takes further action to accommodate this, for example by:

- designing the flood defence to ensure that any failure takes place in clearly defined, predicted locations (selected to ensure the most valuable assets remain protected)
- bunding (embanking) critical assets within the area at risk
- making provision to manage the flooding process by defining local flood compartments, identifying preferred flood storage areas, and creating preferential flow routes
- flood-proofing infrastructure within the areas that is expected to flood (e.g. raising electricity supply points and installing drainage)

Box 20: Understanding and preparing for the possible failure of a flood defence

It is also important to remember, however, that engineering responses to a structure vulnerable to extreme climate loads do not always involve strengthening. Box 21 provides an example of how understanding the consequences of failure led to a solution that deliberately weakened parts of a structure vulnerable to extreme climate loading in order to improve its overall resilience. This case study illustrates why such considerations are an important part of risk management.

When the wharf of the Lucinda Bulk Sugar Terminal in Australia was subjected to large waves during Tropical Cyclone Yasi in 2011, its concrete deck was stronger under wave uplift than the connections of the deck to the steel wharf structure. This led to the heavy concrete deck being lifted off the steel structure by waves, and then dropping down on it, causing significant impact damage to the wharf. Consideration of climate change issues when the wharf's repair was designed included the development of a hierarchy of structural capacities such that the deck will now fail before the deck's connections to the wharf do.

Box 21: Accommodating extremes in wharf repair design, Lucinda Bulk Sugar Terminal, Australia

Finally, the economic incentive to plan for failure can also be important. The inherent uncertainties of accommodating climate change, particularly extreme events, mean that an increasing proportion of new and retrofit developments will need to accept, and cater for, such risks. This is because the cost of providing protection against all eventualities is likely to be excessive in all but exceptional cases.

4.1.4 Understanding When to Act?

The uncertainties discussed in Step 4.1.3 mean it is not always clear *when* adaptation action will be needed. In order to manage uncertainty and deliver adaptation in a timely and cost-effective way, adaptive management principles should therefore be applied.

Adaptive management is a process where thresholds for action are agreed (Step 3.3.1) and stepwise decisions on implementation are informed by monitoring (e.g. of local trends in climate parameters, Step 2.2.1 or Annex 2B or asset condition or performance, Step 1.6.2).

Monitoring enables cost effective or just-in-time solutions by demonstrating, for example, that:

- sea level rise combined with increases in storm surge magnitude are reaching the threshold where investment in retrofitting a breakwater will be justified
- the number of days with significantly reduced visibility is approaching a specific threshold requiring the employment of an additional pilot to ensure continued safety of navigation without compromising acceptable working conditions
- the increase in the frequency of days with temperatures or humidity levels above an identified threshold now justifies investment in air conditioning or similar for port offices or for certain types of storage facilities
- the existing adaptive capacity for the asset or operation in question will soon be exceeded

Step 4.2 Use the Portfolio of Measures

4.2.1 Collate Information to Inform the Selection of Measures

In identifying measures to be included on the adaptation pathway for a particular critical asset, operation or system (or grouping thereof), reference should be made to:

- the nature of the hazard and its anticipated impact(s) (Step 3.6)
- relevant design or operational **thresholds** (Step 3.3.1)
- the nature, extent and significance of **residual uncertainty** in key climate parameters or processes (Steps 2.4) and the associated risk of **maladaptation** (Step 4.1.1)
- the amount of existing **adaptive capacity** or **redundancy** (Step 3.3.4)
- the asset's **residual life** or condition (Step 1.6.2)
- the **planning horizon** (Step 1.5.2)
- **risk tolerance** or the acceptable levels of risk (Step 3.3.2).

When these factors are all considered, a single solution may be available and acceptable in terms of the residual risk. More often, however, it will be preferable to develop a pathway of measures starting with temporary or interim actions that reduce risks whilst data are gathered, and confidence improves to identify the most potentially suitable longer-term options.

4.2.2 Prepare to Use the Portfolio of Measures

Table 19 supplemented by the impact-specific portfolio of measures, available in Annexes 4A to 4P, list a wide range of measures for adapting or strengthening the resilience of waterborne transport infrastructure.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Prioritise **maintenance** to maximise operational resilience and improve adaptive capacity Install **real-time monitoring** infrastructure Use **Cloud** (back-up) for data storage to reduce physical risks to systems **Relocate vulnerable assets and equipment** out of high-risk areas Revert to **phased array** for radar Invest in **redundancy**, temporary infrastructure or other physical back-up provision for critical assets (including power and water supply) **Reinforce, raise, strengthen** or otherwise protect or modify critical assets Install or develop new, **responsive** or **demountable infrastructure** or equipment Install **warning equipment** Nominate or provide physical **sanctuaries** Increase **storage capacity** Install **multi-modal equipment** Apply **nature-based solutions,** Working with Nature, soft engineering Install **treatment** or **reception facilities** Incorporate **flexibility** in new or replacement infrastructure design to allow for modification as conditions change Modify **material or equipment selection** to accommodate changing conditions Invest in **SMART** technology	Undertake climate change **risk assessment**, prepare **risk maps** **Prepare** and **raise awareness** of contingency, emergency or disaster response **plans** Introduce and regularly review **warning systems** Prioritise **asset inspection** **Educate** workforce, stakeholders, local communities Liaise and **coordinate with utilities** and other service providers; develop **information-sharing** protocols Improve (or instigate) **monitoring, record keeping** and **data management**, consider cybersecurity issues Undertake trend analysis or **forecasting** Develop **revised operational protocols**; modify **working practices** as conditions change Introduce and implement **adaptive management** procedures, base operations or working arrangements on monitoring outputs Allow for **flexibility** and responsiveness in programming (increase operational **hours**, modify staffing **rotas**, vessel **scheduling**, lock operation, etc.) Revert to **traditional, low tech,** ways of operating; ensure binoculars, telephone, paper charts, two-way radios are available Ensure availability of **transport** and **accommodation** for personnel during an incident **Temporarily** or **permanently restrict** activities in high-risk areas Nominate **safe routes** and **areas**, identify **diversions** Identify and exploit **interconnectivity** and **intermodal options** to maintain business continuity during events Provide **training** on new tools, codes of practice, procedures or **protocols**, ensure importance of **redundancy** is understood Facilitate **technology transfer**	Prepare strategic level climate change **adaptation strategies** Review and revise relevant **codes of practice, standards, specifications or guidelines** to accommodate changing conditions Review **health and safety** requirements and revise if needed Introduce **penalties** for non-compliance with standards Require **zoning** of assets, operations or activities based on risk Use local regulations (e.g. **byelaws**) to reduce risks, especially in multi-use locations Policies to encourage **relocation** out of high-risk areas Collaborate with **land-use planning** systems e.g. to introduce **set back** or **buffer areas** **Limit new infrastructure development** in high-risk areas Identify, secure and coordinate **alternative transport routes or modes** Promote **reduced insurance premiums** if improved resilience is demonstrated Set up **contingency** or disaster response **fund** Introduce and enforce **build-back-better** or build-out-of-harm's-way policy Facilitate **diversification** in facilities and employment as conditions change Improve **legal protection** for vulnerable habitats with risk reduction role (e.g. absorbing wave energy, providing erosion protection) Provide **grants or incentives** e.g. for development or maintenance of resilient infrastructure **Research** and develop novel tools and methods

Table 19: Generic measures for strengthening resilience or adapting assets, operations or systems

In line with the IPCC AR5 report [IPCC, 2013], the measures in Table 19 and in the Annexes have been categorised according to whether they are:

- **Physical –** including structural, engineered, technological, systems and service-based interventions. This category of measures covers hard and soft engineering measures, nature-based solutions, maintenance activities and new products
- **Social** – people-based, including operational, management, educational, information-related and behavioural measures. Awareness-raising, training, early warning, incident response, contingency planning, operational modifications and data collection are examples from this category
- **Institutional –** including governance, economics, law, regulation, policies and programmes. This category covers legal and financial incentives and penalties, mapping and zoning, spatial planning and the role of design or building standards

Social and institutional measures are especially important in preparing for the challenges that climate change will inevitably bring. Depending on the nature of the risks identified in Stage 3, changes in operations, management, maintenance or behaviour might be more cost-effective than a structural or technological solution, at least in the short to medium term. Institutional changes, for example in policy or financing, might similarly form part of a long-term solution.

Box 22 provides a practical example of the importance of considering social (operational) and institutional measures. In 11 out of 12 cases where a climate risk vulnerability assessment tool was applied by Transport Canada, it was determined that the resilience of existing infrastructure could be strengthened without the need for capital-intensive engineering interventions.

On the other hand, sometimes physical/structural measures are the only solution. Box 23 provides an example from Belgium of where a structural intervention was deemed necessary.

Transport Canada's experience in assessing climate risks using the **PIEVC Protocol** (https://pievc.ca/assessments) introduced in Box 13 highlights the importance of taking an open-minded approach and ensuring that a range of interested stakeholders is represented in the risk assessment process (e.g. operations, management, technical and environmental teams). Such engagement was shown to contribute significantly to a successful outcome, not least because the preferred actions often related to optimising the asset's maintenance and capital planning. Typical recommended measures included policy updating, initiating instrumentation and monitoring, making operational changes, and undertaking engagement activities. These types of activity deliver adaptation and strengthen resilience without requiring major investment.

In an evaluation of 12 climate risk assessments undertaken using the PIEVC protocol for surface and air transportation infrastructure, only one assessment (for an ice road in the Northwest Territories) required a capital-intensive engineering solution. The others showed that the desired level of resilience could be achieved through updating relevant policies, instigating studies and instrumentation, improved monitoring and management, or various operational measures.

Box 22: Example of the value of operational and institutional measures to improve resilience, Canada

Climate change is expected to cause more frequent and longer periods of drought in Belgium. The associated lower water levels will compromise the viability of the strategically important **Albert Canal**, reducing the available draft for inland navigation and making waterborne transport less attractive for the movement of goods.

To avoid future economic damage, the Flemish administration of Mobility and Public Works engaged with stakeholders to investigate potential solutions (Case Study 14). A series of preparatory projects led to the decision to pursue a structural intervention. A low water strategy was first developed for the canal. This was based on an inventory of water uses, ideas from stakeholders on how to reduce water use (i.e. behavioural measures), modelling, and discussions at stakeholder workshops.

The final outcome was a decision to install three of the largest Archimedes' screws in Europe, each 28 m long, 4.3 m wide and weighing 85 tonnes, in each of the six locks on the Canal. During drought periods, these screws will pump up to 15 m^3/s of water upstream of the lock. At other times, the screws will be used as a hydropower plant and the pumps will be used to generate electricity. The screws' design allows fish migration to protect biodiversity.

Box 23: Example of a structural solution to improving resilience, Belgium

4.2.3 Use the Portfolio to Identify a List of Measures for Screening

Measures in the portfolio (Annex 4) are listed according to the nature of the anticipated impact on the critical asset, operation or system as follows[4]:

- rainfall-related or groundwater flooding (see Annex 4A)
- flooding due to overtopping (see Annex 4B)
- high in-channel river flow velocities or changes in sea state (see Annex 4C)
- low flow or drought (see Annex 4D)
- changes in sediment or debris regime (see Annex 4E)
- bed or bank erosion (see Annex 4F)
- reduced visibility (see Annex 4G)
- change in wind characteristics (see Annex 4H)
- extreme cold, ice or icing (see Annex 4I)
- extreme heat (see Annex 4J)
- changes in ocean water acidity (see Annex 4K)
- changes in salinity or salt water intrusion (see Annex 4L)
- changes in vegetation growth (see Annex 4M)
- changes in species migration or range (see Annex 4N)
- changes in native species survivability or growth rate (see Annex 4O)
- introduction or spread of invasive, non-native species (see Annex 4P)

Reference should be made to the table(s) in Annex 4 that correspond to the impact(s) identified in the Stage 3 vulnerability or risk assessment.

For each impact affecting a particular critical asset, operation or system (or grouping thereof), potentially suitable short-term or interim, medium-term and long-term measures should be highlighted as appropriate.

Before accessing the impact-specific tables, be aware that the portfolio of measures is not intended to be a comprehensive list of possible solutions. *Rather it is intended as a source of ideas and inspiration to supplement local knowledge and experience. It aims to encourage those developing adaptation pathways to consider emerging technologies, soft engineering or nature-based solutions, changes in operations or maintenance practices, hybrid options, or policy interventions, alongside more conventional structural solutions.*

When reviewing the measures in the portfolio to identify a list of measures to be screened for their suitability, the following points should also be noted:

- Not all climate change adaptation requires the port or waterway to engage consultants or undertake expensive retrofitting programmes. There can be some very simple and cheap options, including prioritising maintenance to maximise operational resilience, developing extreme weather warning systems and putting contingency plans in place, modifying working practices, or awareness raising.
- There may not be a single solution. Climate change adaptation measures are typically explored simultaneously or implemented in-combination. Developing a phased adaptation pathway, possibly including measures from each category (i.e. physical, social and institutional) may be the most effective approach (Step 4.5).
- Climate change adaptation or resilience strengthening is often an incremental process, addressing immediate concerns whilst retaining flexibility to respond appropriately if future requirements vary

[4] In addition to the direct physical impacts highlighted above, a port or waterway may also experience indirect, economic effects as a result of climate change, for example associated with changes in agricultural production, manufacturing, tourism, etc. As noted in the introduction, the stepwise methodology set out in this guidance document can equally well be used to identify and assess the adaptation responses needed to address such changes.

as the climate changes. In some cases, however, adaptation has to involve transformative or disruptive change. For example, increases in flooding frequency or erosion rates may make continued cost-effective operation untenable, such that (part of) a port may have to close or re-locate, or the increased incidence of drought or low water levels may force a change to smaller, shallow draft vessels if waterborne transport is to remain viable.

- No or low-regret measures provide benefits under any foreseeable climate scenario including present day climate. Such interventions are useful irrespective of how climate parameters and processes change over time.
- Climate change is likely to drive collaboration in the interests of economic efficiency or to achieve cost savings. Win-win measures that provide co-benefits to other organisations may offer the possibility of sharing implementation costs, so should be explored. The pilot project Spadenlander Busch/Kreetsand from Germany (Box 24) provides a good example of a win-win solution. Organising a workshop with key stakeholders to discuss opportunities for collaboration could provide a useful means of identifying such measures.
- Adaptation measures might be implemented at a system or strategic level, or at the scale of the site, project, asset or operation. Measures might be grouped, or they might be implemented individually.
- Retrofitting existing infrastructure is listed in the tables as a generic option requiring a site- or asset-specific investigation into potentially feasible engineering designs. Figure 12 (from Howe and Cox, 2018) provides some examples of different upgrading approaches for retrofitting a breakwater or seawall but each type of asset will have different retrofitting possibilities.
- Nature-based solutions can enable a port or waterway to capitalise on nature's resilience. They may also represent a cost-effective solution. For example, some habitats provide important ecosystem services such as storm surge attenuation as was described in Box 5.
- Climate change is already driving innovation; future changes in the technical or economic feasibility of options for adaptation may need to be anticipated. Non-conventional or innovative solutions can be the best ones: it is important to take account of local conditions and think 'outside the box' taking note of the particular characteristics of the specific port or waterway.

The Port of Hamburg, on the **Elbe estuary** in northern Germany, is subject to a high amount of sedimentation due to tidal asymmetry, which results in the transport of sediments to the upper estuary and port area on the flood tide. As a consequence, there are high costs for maintenance dredging. Climate change is expected to exacerbate this 'tidal pumping' effect. Furthermore, high flood water levels in conjunction with storm surges can negatively affect port infrastructure.

In 2012, the Hamburg Port Authority set up the pilot project 'Spadenlander Busch/Kreetsand' using river engineering measures to reduce tidal range and to create space for water storage. The project will transform former dyke foreland into 30 hectares of shallow tidal waters. Besides modifying tidal action, valuable habitats are being created and an information centre and pathways along the dyke will allow residents and visitors to enjoy the site and enhance their understanding of the tidal system.

The IPCC scenarios and the regional climate change scenarios developed by the German Federal Ministry of Transport's research programme 'KLIWAS' (Impacts of climate change on waterways and navigation) were used to inform the hydro-morphological numerical modelling and for the design. The planning process also involved a broad range of stakeholders including environmental organisations, local administrations, and residents.

In 2020, when the river engineering works proposed under the pilot project will be completed, monitoring of hydro-morphological and ecological parameters will be carried out to assess the effectiveness of the works against the aim of reducing the sediment transport, modifying the tidal range, and meeting the objectives of the European Flora and Habitats Directive. [Meine, Gutbrod, 2010; BAW, 2012]

Box 24: Example of a win-win measure providing co-benefits to stakeholders, Germany

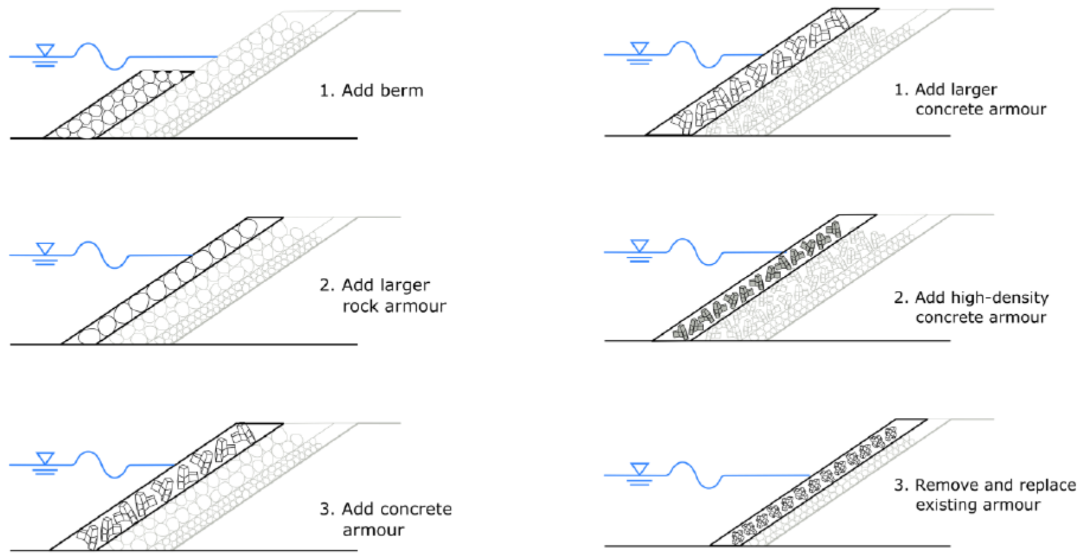


Figure 1 - Potential upgrade options for rock armour

Figure 2 - Potential upgrade options for concrete armour.

Figure 12: Retrofitting options for a breakwater or seawall

Reference to the portfolio of measures and other available references (e.g. the Guidebooks described in Box 25 for strengthening the resilience of inland or maritime navigation in Europe, or the Australian climate change adaptation guidelines for ports [Scott et al., 2013]) should be supplemented by local knowledge and experience to facilitate the preparation of an initial list of possible measures to manage each climate change impact.

This initial list of measures will provide the starting point for the screening exercise in Step 4.3.

The European MOWE-IT project assessed mitigation strategies to deal with extreme weather-related vulnerabilities across a range of transport modes including waterborne (Case Study 15). These strategies included short term options for dealing with disruption (including cross modal cooperation with less affected modes) as well as longer-term solutions.

Several guidebooks were prepared to help operators. For inland waterways, a Guidebook for Enhancing Resilience in European Inland Waterway Transport in Extreme Weather Events and for maritime transport a Guidebook for Enhancing Resilience of European Maritime Transport in Extreme Weather Events, were both published in 2014.

For inland navigation, the guidebook emphasises the vital importance of maintenance, and the crucial role of monitoring. Concepts such as 'fairway in a fairway' (informed by up to date or real time online information) are also highlighted. In the medium to term options to optimise, lengthen, shorten, raise or lower structural elements, whilst at the same time minimising river bed degradation, are acknowledged. A shift to more customer-oriented waterway management, the development and use of River Information Services, and the implementation of new information and communication technologies (e.g. improved weather forecasting and monitoring) are also proposed, along with measures to adapt and modernise the inland waterways fleet and associated port infrastructure-related modifications to accommodate the modernised fleet.

Box 25: EU Guidebooks for strengthening the resilience of European Inland and Maritime Navigation, Europe

Step 4.3 Screen List of Possible Measures to Derive Options

4.3.1 Agree Screening Methodology and Criteria

The next step is to screen the measures selected for each impact against locally applicable criteria. Screening aims to reject or eliminate any measures that prove unsuitable and to identify measures or combinations of measures (i.e. options) that are preferred or require more detailed evaluation.

When developing the screening criteria, reference should be made to the objectives developed in Step 1.5.3, and to the priorities defined in Step 3.3.7. Relevant internal and external stakeholders should be involved in the process.

Table 20 identifies possible screening criteria. These criteria are illustrative rather than definitive. They should be reviewed and modified as appropriate. For example they might be made more locally-specific, additional criteria may be added, or weighting factors applied.

Table 20 also provides some ideas on how the screening exercise conclusions might be presented using colour-coding. A symbol-based representation or a scoring system could similarly be employed. Either way, the main objectives are to eliminate measures that would prove unacceptable or not feasible and to identify measures or combinations of measures worthy of more detailed assessment. The application of the screening process is explained in Step 4.3.2.

Screening criteria	Extent to which the measure meets the criterion, alone or in-combination with other measures			
Compatible with objectives	Entirely	Mostly	Partly	Incompatible
Relative cost	Inexpensive	Moderate	Expensive	Prohibitive
Technical feasibility	Easy	Moderate	Challenging	Not feasible
Level of risk reduction	Significant	Moderate	Negligible	None/brings a new risk
Implications for other users or stakeholders	Positive	Neutral	Negative	Prohibitive
Impacts on physical or natural environment or heritage assets	Positive	Neutral	Negative	Unacceptable
Maintenance or management requirements	Negligible	Acceptable	Significant	Prohibitive
Risk of maladaptation	Low	Acceptable	Significant	Unacceptable
Extent of co-benefits	Significant	Moderate	N/A	N/A
Represents a no or low- regret measure	No-regret	Low-regret	N/A	N/A

Table 20: Indicative criteria for screening adaptation measures

4.3.2 Undertake Screening

Each measure or group of measures for a particular impact should be assessed against each of the criteria. Qualitative or quantitative information or a combination of both should be used. The completed screening table will identify measures that best meet the selected criteria and enable a decision to be made on which options should be taken through to the next step. It will also highlight whether any options should be rejected outright.

Note, however, that this type of high-level exercise may only determine the current ‘relative’ suitability of each option. Where several potential measures have been identified, separate tables might need to be prepared for temporary, short-term or interim options and possible longer-term options.

It is important to remember that climate change adaptation decision-making differs from ‘business as usual’. Measures should not be rejected at the screening stage simply because they are unfamiliar or because they are not a conventional solution.

Similarly, some measures that do not currently seem to be technically feasible or economically viable in the short term may become more relevant in the future as a wider range of responses to climate change are developed. The screening exercise may therefore need to be reviewed or repeated.

The outcomes of the screening exercise are best illustrated by an example. From the example shown in Table 21, Options 8 and 10 would likely go forward for a more detailed appraisal. Depending on the local situation, options 5 and 4 may also be taken forward.

Options (i.e. measure or group of measures)	**Objectives**	**Cost**	**Technical feasibility**	**Risk reduction**	**Impacts on users**	**Environmental impacts**	**Maintenance**	**Maladaptation**	**Co-benefits**	**No- or low-regret**
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Table 21: Example of screening outcomes

Even if it is the case that a single option is clearly favoured, a more detailed evaluation may still be beneficial or even necessary. For example, there may be a regulatory requirement to demonstrate that alternatives have been considered or to clarify which option is preferred from an economic perspective; absolute rather than relative values may be needed.

If too many options appear potentially suitable, an initial prioritisation exercise might take place, enabling the most promising option(s) to be evaluated in detail first with others revisited at a later stage if necessary.

The outcome of Step 4.3 is a shortlist of potentially suitable adaptation or resilience options relevant to the anticipated impacts on the (group of) critical assets, operations or systems. The screening process and its results can be revisited as necessary as part of an iterative procedure until a conclusion on suitable options is reached (see Step 4.6.1).

Step 4.4 Evaluate Shortlist of Options

Shortlisted options may need to be subject to a more detailed evaluation for a variety of reasons, for example if:

- different types of options appear viable or if trade-offs between different adaptation pathways are needed
- cost considerations, the requirements of financing organisations, or corporate protocols require that an economic analysis and/or an assessment of alternatives be undertaken, or
- the judgement of an experienced practitioner is not sufficient for other reasons

4.4.1 Available Evaluation Methods

Where the costs and benefits of different options require evaluation, various economic analysis methods and tools exist. These tools are not mutually exclusive and should be used in combination as appropriate to the requirements of the evaluation exercise.

Traditional cost benefit analysis (CBA) and cost effectiveness analysis (CEA) do not deal well with uncertainty so are most useful where the climate change adaptation planning horizon is short (e.g. ten years or less) and where climate risk probabilities are known and/or sensitivity is small. CBA and CEA are suitable for application to no or low-regret options but for more complex decisions investments they should be used in combination with other techniques [Tröltzsch et al., 2016].

Furthermore, techniques like CBA that use a discount rate to discount future cash flows back to their present value can be associated with an increased risk of maladaptation because less value is placed on future benefits. As it is often difficult to be sure exactly *when* the benefits of resilience or adaptation measures will be realised, other techniques such as sensitivity testing or probabilistic modelling should also be applied if the adaptation planning horizons extends beyond ten years. This is important if only to compare the respective outcomes.

Multi-criteria analysis (MCA) can be a relatively easy method to apply, including where alternative options need to be ranked. MCA relies on expert judgement but captures qualitative issues, so it works well where societal, environmental or similar costs and/or benefits are difficult to quantify. Uncertainties can also be integrated into the assessment criteria. The screening process presented in Step 4.3.2 is a form of MCA so the criteria described on Table 20 could be used or refined, or additional criteria could be added (e.g. relating to phasing, operational benefits, regulatory complexity, ability to be constructed).

Other commonly used methods that might be used to evaluate adaptation options include the following [Tröltzsch et al., 2016]:

- Iterative risk management: deals with uncertainty by using monitoring and research to support iterative analysis over the medium to long term in cases where risk thresholds are clear
- Real option analysis, for major capital investments: allows analysis of different climate change scenarios where economic valuation and climate risk probability information is available
- Robust decision making: a highly computational analysis to identify optimal operational and strategic options under different climate change scenarios can be applied where uncertainty and risk are both high (see Box 27)
- Bayesian belief networks: statistical cause and effect models that strengthen understanding of the relationships between climate risks, and aid examination of the benefits of different adaptation options and associated trade-offs

Portfolio analysis, scenario planning, cost-utility analysis, options evaluation and copula modelling are amongst many other potentially appropriate methods [Herbert et al., 2020] forthcoming). However, where the nature or scale of adaptation investment requires the application of these more complex methods, the port or waterway organisation may need to seek expert assistance.

4.4.2 Select Method and Evaluate Options

Prior to selecting a method and commencing the evaluation of shortlisted options, the following questions will require attention:

i. *Is it prudent to select a method that allows for comparison of scenarios?* In many cases, the robustness of the evaluation will be improved if options are assessed for their respective risk reduction achievement, other benefits, costs, etc. under a number of different climate change scenarios (see Step 2.3.1). The outcomes under each scenario should then be compared. Options that meet the criteria and deliver benefits irrespective of which climate change scenario is applied will usually be preferred to those that meet the criteria or are effective only under one scenario.

ii. *Is it preferable to prepare separate assessments for short- vs. long-term options?* Unless there are unavoidable interdependencies, or if early-implementation no-regret options are explicitly being compared to selected long-term targeted solutions rather than being considered as sequential steps, it may be better to assess the respective costs and benefits of temporary or interim options separately from the medium to long term options. Decisions on the latter can be deferred until monitoring has been instigated and/or relevant data collected.

iii. *What are the implications of not taking action to strengthen resilience and adapt?* Quantified and where possible, monetised information, will be important in making the business case for investment. The costs of inaction (i.e. the 'do nothing' scenario), which form the baseline for the evaluation, are derived from the risk assessment outcomes. They include the anticipated costs associated with future climate change-related disruption, damage or other limitations on functionality. In addition to the effects of slow onset changes such as increased air and water temperature and sea level rise, the potential costs and consequences of extreme events should be included. Step 1.6.3 discussed the importance of monitoring and recording such costs and Annex 1D provides a template for collecting these data.

The choice of an appropriate evaluation method will also be influenced by the following:

- the importance of rigour and/or transparency, which may favour a quantitative analysis
- the availability of resources and detailed data to be able to quantify effects
- the ease with which various components can be quantified or monetised
- the views and priorities of relevant stakeholders and co-beneficiaries

Box 26 and Box 27 respectively provide an example of cost benefit assessment being used to evaluate options for retrofitting armoured breakwaters in Australia and illustrate how a cost-effectiveness analysis was used to inform adaptation decision making at Port of Manzanillo, Mexico. Another example was provided in Box 16 explained how the risk analysis carried out for the Port of Norfolk Naval Station, USA, used Bayesian networking to systematically evaluate mission-related risks in a probabilistic manner.

An investigation into the physical and economic feasibility of rubble mound breakwater upgrades to address the threats posed by sea level rise, explored the physical and economic feasibility of upgrading rock and concrete armoured breakwaters with reference to case studies representative of typical Australian east coast sites [Harrison and Cox, 2015].

The implications for armour size, which varies with design wave height (and water depth) cubed, were assessed using two-dimensional wave flume testing of armour stability. This demonstrated that a single layer of larger upgraded armour stone can be placed on top of a conventional two-layer rock breakwater to provide additional protection against the effects of sea level rise.

Economic feasibility studies used cost benefit assessment and present value analyses to evaluate different planned upgrade sequences and determine a cost-effective strategy. This assessment confirmed that breakwater upgrade decisions are most sensitive to the discount rate which, in this case, influenced whether retrofitting should be undertaken as a one-off or phased activity.

Box 26: Cost-benefit assessment in the evaluation of retrofitting options for rubble mound breakwaters, Australia

A high-level analysis of the cost effectiveness of measures to deliver adaptation action on priority risks was undertaken as part of an IDB-funded study into adaptation options for the Port of Manzanillo in Mexico (Case Study 16). The approach used was aligned with recent literature on the cost effectiveness analysis of climate resilience measures. The comparative high, medium and low scores provided a relative comparison of the costs and the effectiveness of each option. These scores were based on expert judgement, the transfer of values from literature where available, and application of study-specific criteria.

The approach taken in the Port of Manzanillo study enabled the following generic conclusions to be drawn based on the findings of the cost effectiveness analysis:

- Operational measures tend to be low cost and to have a medium effectiveness at reducing risk.
- Engineered measures are often the most effective at reducing risk. However, they are generally costlier and have few positive (beneficial) additional consequences.
- Ecosystem-based and hybrid measures have more positive additional consequences, but they are typically not as effective as engineered measures at reducing risk. They tend to be more complex to implement, and the evidence base on them is weaker, so there is uncertainty regarding their effectiveness.

Box 27: Cost-effectiveness analysis outcomes of adaptation options at Port of Manzanillo, Mexico

In some cases, levels of uncertainty are such that climate risk assessments need to be updated on a regular basis to determine whether the changing conditions are leading to a different outcome, or whether it would be beneficial to apply a more sophisticated evaluation method. This was the case at Port of Los Angeles (see Box 28), where deep uncertainty about the potential rate and hence consequences of sea level rise needed to be understood in order to inform investment decision making on infrastructure upgrading.

RAND Corporation worked with the Port of Los Angeles to develop a model that evaluates the potential of large impacts from sea level rise and whether it is cost-effective to invest in infrastructure upgrades at unscheduled intervals. The decision-making tool addressed the strengthening of breakwater, wharves, buildings, and equipment; elevation of breakwater, wharves, buildings, roads, and rails; increasing channel dredging, and relocating chemical storage areas in the light of predictions of sea level rise for the west coast of California. [Lempert et al., 2012]

Further to the 2012 analysis and recognising that climate risk assessments must be reassessed periodically, the Port of Los Angeles built upon the RAND project and prepared an additional study assessing sea level rise risks and impacts. This subsequent study explored the characterisation of deeply uncertain climate change projections to support adaptation decision making by applying robust decision-making analysis. A 2018 report deals with various issues surrounding potential future changes in low probability, but large impact flooding events associated with changes in sea-levels and storm surges. Two specific investment decisions are addressed: (1) under what future conditions would a Port of Los Angeles decision to harden its facilities against extreme flood scenarios at the next upgrade pass a cost-benefit test, and (2) do sea-level rise projections and other information suggest such conditions are sufficiently likely to justify such an investment? Robust decision-making methods are also compared to and contrasted with a full probabilistic analysis. [Sriver et al., 2018]

Box 28: Accommodating deeply uncertain climate change projections to evaluate the costs and benefits of infrastructure upgrading at Port of Los Angeles, USA

For the user of this guidance, applying the evaluation method selected in Step 4.4 will confirm which options are best suited to address the impacts on critical assets, operations and systems.

Step 4.5 Develop Adaptation Pathways

When planning for climate change adaptation, a ‘pathway’ is preferred to a fixed ‘programme’. This is because residual uncertainties make it difficult or impossible to know exactly *when* a particular intervention may need to be triggered or a new measure introduced.

Developing an adaptation pathway for each anticipated impact on a critical asset, operation or system (or grouping of these) enables the port or waterway to accommodate uncertainty by highlighting the measures likely to be required but without fixing a date for their implementation.

Amongst the different options identified in Step 4.4 as being potentially suitable, some may be relatively simple and cheap to implement. These measures, described as the ‘low hanging fruit’, are often amongst the first steps on the adaptation pathway. In many cases they are no-regret measures, and some may yield other benefits in addition to those associated with climate change.

The initial measures, modifications or other interventions on the pathway can be implemented with confidence, while the timing (and sometimes even the nature) of future options is kept open. This flexibility can be crucial in avoiding maladaptation.

For longer-term interventions, instead of setting a deadline in terms of months or years, monitoring outcomes or other meteorological, hydrographic or oceanographic observations act as an early-warning system or confirm when a critical threshold is being approached (see Steps 1.6.2 and 2.2.1). For example, if an asset becomes vulnerable when mean sea level has risen by 0.50 m, a trigger level of 0.48 m of sea level rise may provide sufficient notice to begin implementing relevant adaptation measures.

Monitoring can also support short-term forecasts, triggering emergency and other rapid adaptation responses.

Table 22 illustrates how groups of suitable measures might be developed into an adaptation pathway. Adaptation pathways should be prepared in collaboration with stakeholders if appropriate.

Impact		Measure	Conditions triggering action
Sea level rise leading to increasingly frequent flooding of one of two general cargo berthing and loading areas in the port	1	Prepare contingency plan for alternative berthing arrangements	Immediate (no regret)
	2	Instigate monitoring of asset condition	Funding is secured
	3	Decision on retrofit of elevated quay superstructure vs. replacement asset	Monitoring of local sea level rise rates or asset deterioration or both, indicate the acceptable threshold will be exceeded within three years
Increased frequency of extreme wave and wind conditions exacerbating erosion of the mangrove swamp that provides the port with natural protection from storms	1	Develop and implement community engagement programme on role of mangroves as buffer; lobby for strengthened legal protection of remaining vegetated shorelines	Immediate (no regret)
	2	Instigate research and trials into appropriate mangrove planting and breakwater construction techniques	Funding is secured
	3	Design and implement mangrove planting strategy	Research outcomes are available; funding is secured
	4	Design and construct new breakwater (e.g. using brushwood or dredged material filled geo-tubes)	Monitoring of changes in wind and wave conditions, erosion rates and/or the sufficiency of the area of mangrove successfully re-established indicate that action will be needed within two years

Impact		Measure	Conditions triggering action
Accumulation of debris in harbour following extreme rainfall events	1	Improve maintenance of existing drainage system, trash screens, culverts, etc.	Immediate (no regret)
	2	Raise awareness with local people to reduce dumping of trash in upstream watercourses	Immediate (no regret)
	3	Upgrade existing drainage system	Monitoring of rainfall totals and system performance indicates that, even with enhanced maintenance, existing capacity is inadequate
	4	Investigate use, costs and benefits of temporary booms or debris removal equipment	Land use monitoring shows community engagement action is ineffective and/or residual risk from debris remains unacceptable
Excessive weed growth associated with increased water temperature is compromising navigational safety	1	Increase frequency of cutting and clearance to reduce risks to navigational safety	Immediate
	2	Research into biological or nature-based weed control options	Funding is secured
	3	Invest in a higher capacity cutting machine [only if research concludes biological control is impractical]	Water temperature and vegetation growth rates approach the critical threshold indicating that current cutting capacity close to being exceeded

Table 22: Examples of phased measures in adaptation pathways

Prior to finalising the steps on an adaptation pathway the results should go through a rigorous logic check to ensure that:

- all the adaptation objectives are met including criteria relating to the acceptable level of residual risk
- there is no internal incompatibility within or across pathways, and
- any internal and external interdependencies between port and third-party infrastructure, operations and systems have been addressed

Step 4.6 Prepare Adaptation Strategy

An adaptation plan or strategy summarises the assessment process and explains what is proposed going forward. Background information and the assessments carried out in Stages 1 (context and objectives), 2 (climate change projections and the scenarios used) and 3 (vulnerability and/or risk assessment) will be included or appended for transparency, along with the outcomes of the options' screening and/or evaluation process.

Importantly, the strategy will describe the measures to be implemented, according to the adaptation pathways identified in Step 4.5 for each critical asset, operation or system likely to be impacted by climate change.

The strategy will set implementation priorities where these are needed. It will also confirm roles and responsibilities where other stakeholders are also involved.

4.6.1 Agree Priorities

If funding or other constraints mean that not all the identified measures can be implemented immediately and choices have to be made, the organisation may have a prescribed process for determining priorities.

If there is no prescribed method, the following steps should be worked through in collaboration with relevant stakeholders, until agreement has been reached on a prioritised and affordable set of measures:

- Revisit Step 1.2.2 to establish whether the criticality assessment indicates which assets, operations or systems should take precedence
- Revisit the outcomes of the vulnerability or risk assessment (Steps 3.3.6 or 3.7) to confirm whether certain risks need to be addressed as a priority
- Revisit the selection of options (Step 4.2.3 and portfolio of measures (Annex 4)) to establish whether alternative less costly, no regret or win-win options exist or whether temporary measures can be implemented whilst resources are secured
- Modify the assessment or evaluation criteria, for example by applying weightings, and repeat Step 4.4.2.

Where urgent action is required to deal with an imminent threat, measures should be identified in the strategy as being high priority for implementation as soon as resources are available. An example of such prioritisation is highlighted in the Long Beach case study summarised in Box 29.

In addition to identifying near-term solutions for protecting the Port's most vulnerable areas, the Climate Adaptation and Coastal Resiliency Plan developed by the **Port of Long Beach, California,** USA (Case Study 2) recommended a suite of potential adaptation strategies intended to help the port maintain business continuity across its infrastructure and operations into the next century. A collaborative process was used to select a subset of these strategies for further refinement, and five strategies were prioritised and developed into detailed studies or concept designs.

Two of these prioritised strategies were linked to governance issues (incorporating climate change impacts into port policies, plans and guidelines; and a specific action to add sea level rise analysis to the Harbor Development Permitting Process). A third priority involved a study of the combined impacts of riverine and coastal flooding on Piers A and B; and two more addressed physical infrastructure vulnerabilities: improving shoreline protection and substation protection at Pier S.

Box 29: Prioritisation of adaptation action by Port of Long Beach, USA

In situations where adaptation resources have already been secured, a precautionary approach of early implementation may be justified, for example if:

- there is doubt about whether funding will still be available when it is needed in the future (i.e. the currently allocated resources might be used for other purposes in the meantime)
- the option will improve adaptive capacity, reducing the risk to the asset or operation in the event of extreme weather conditions, and possibly enabling significant expenditure to be reduced or deferred
- no or low-regret, or win-win adaptation measures will deliver other benefits in the meantime (e.g. enhancing marsh or mangrove habitats may have been identified as a medium-term option for wave attenuation as sea levels rise, but in the meantime, will provide additional fish nursery habitat, supporting local subsistence fishing activity).

4.6.2 Prepare and Consult on Adaptation Strategy

If relevant stakeholders and co-beneficiaries have been fully-engaged in the decisions about when and how to adapt, the format of the strategy can be agreed amongst those involved in the implementation process. It is nonetheless important that a strategy incorporates SMART goals and objectives (Step 1.5.3) and that it is a living document subject to frequent review and updating.

If third parties are involved in or could be affected by the proposed strategy, a draft should be made available for comment by interested organisations. The concerns and suggestions of respondents should be accommodated as far as practicable before the final adaptation strategy is agreed and signed off.

Box 30 gives an example from the Port of Rotterdam where the port worked with stakeholders in a staged approach to develop measures from the final adaptation strategy.

In this pilot study of flood risk adaptation measures for the Botlek area of the **Port of Rotterdam** (Case Study 1), a broad inventory was made of possible measures and a hierarchical approach to their assessment was adopted. The aim was to start from a broad overview to select favourable measures that contributed to the drawing up of a promising adaptation strategy.

The inventory was carried out on the basis of expert judgment and drawing on previous studies. The most promising measures were then selected through a process involving several steps.

Step 1 – Based on literature research and expert judgment, possible measures to control flood risks in the Botlek area were inventoried. This first selection was carried out by experts on the basis of reality and feasibility.

Step 2 – In dialogue with stakeholders, the measures were divided into possible adaptation strategies based on prevention, spatial planning or emergency response. The costs and benefits of these measures were then estimated. The measures with the least favourable cost-benefit ratio dropped out in this step.

Step 3 – The possible adaptation strategies were subsequently assessed for effectiveness, feasibility and time/flexibility, leading to a recommendation for the Botlek area in which measures from various possible adaptation strategies were selected.

Box 30: Working with stakeholders to develop an adaptation strategy, Rotterdam, The Netherlands

Step 4.7 Implement Adaptation Strategy

With a strategy agreed, the next step is implementation. Activity during the implementation phase is directly related to the type of adaptation measure. Simple adaptation measures – for example behavioural changes – might be implemented quickly with relatively little financial resource. More complicated adaptation measures, particularly those with many interrelated elements, may need significant planning and preparation, require considerable resources, and take a number of years to implement.

Whilst the scale and complexity of the activity will therefore differ, typical steps associated with implementation might involve some or all of the following:

- set up a project team(s)
- engage other interested and influencing stakeholders
- educate and build capacity
- secure funding
- prepare, develop, plan, design, taking note of the discussion on residual risk in Step 3.3.2 and on the need for innovative approaches and flexibility in design, etc. to reduce vulnerability (Step 4.1)
- obtain permissions or consents
- construct, launch and implement
- monitor, review and revise

4.7.1 Set-up Monitoring Programmes

Whenever an adaptation measure or group of measures is implemented, monitoring of its performance is essential, both to ensure maladaptation is avoided and to inform decisions on future actions along the adaptation pathway. Understanding how effectively a particular measure or combination of measures is performing in terms of both the risks identified (Steps 3.3.6 or 3.7) and trends in key variables or climate drivers (Step 2.4.1) will ensure measures can be revised or supplemented as necessary.

Monitoring should reflect the objectives or targets of the intervention (Step 4.5), with metrics or indicators (i.e. what is to be monitored) agreed accordingly. Monitoring results should be quantified as far as possible, for example by recording:

- the frequency of adverse effects such as overtopping or inundation
- the exceedance of operational thresholds, for example relating to berthing or loading

- economic losses due to delay or downtime
- maintenance costs
- damage repair or replacement costs
- safety target failures

When monitoring identifies that thresholds are being exceeded too frequently or that costs have increased to an unacceptable level, a decision can be made on whether to change the adaptation response or trigger the next phase of investment on the adaptation pathway.

Co-beneficiaries or other stakeholders should be involved in discussions about how performance is to be measured (i.e. where, when, how and by whom) and how 'success' is to be defined. If these co-beneficiaries or stakeholder organisations will be undertaking some of the monitoring themselves, roles and responsibilities should be agreed early to make sure nothing important is overlooked.

4.7.2 Promote Research and Technical Studies

In addition to monitoring activities, research and additional technical studies can provide information to help reduce uncertainty in order to support and inform implementation. Numerical modelling of physical processes, for example, can provide a detailed understanding of how vulnerable a particular asset is to climate change, enabling expenditure to be programmed appropriately. However, the costs of such investigations can be significant. Their 'value' in terms of monetary savings or reducing uncertainty therefore needs to be balanced against the expected benefits both in the short and long term. For example, if an existing asset is unlikely to be impacted for ten years, this type of investigation might be deferred until a future date.

4.7.3 Engage the Local Community

Public engagement and support may be desirable, or indeed necessary, for the successful implementation of an adaptation strategy. Some measures might require a change in the behaviour of the local community (e.g. stopping the disposal of garbage in watercourses or riparian areas). Others may rely on the assistance of local community groups such as fishermen or conservation organisations (e.g. the planting of mangroves to improve the natural buffer against flooding, or the monitoring and recording of local weather and hydro-meteorological conditions). Local populations may also need to be made aware of relevant components of disaster response or emergency plans, including how and when they should act.

In all cases, effective engagement and communication is essential to reduce misconceptions and misunderstandings about the effects of climate change and the measures needed to address its consequences.

Outcomes of Stage 4

For those working through the climate change adaptation planning process, completion of the following steps culminates in an agreed strategy for implementation:

- the management of uncertainties and the role of adaptation pathways are understood (Step 4.1)
- reference to the portfolio of measures has identified a list of potentially applicable short- or long-term adaptation and resilience options (Step 4.2)
- options have been screened against a set of agreed criteria and, if relevant, evaluated using an appropriate methodology (Steps 4.3 and 4.4)
- an adaptation strategy, setting out prioritised adaptation pathways for strengthening resilience and adapting critical assets, operations and systems, has been prepared and agreed with key stakeholders (Steps 4.5 and 4.6)
- a way forward on implementation, including further monitoring or research and stakeholder engagement where needed, has been determined (Step 4.7).

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OVERVIEW OF CASE STUDIES

Case studies were sought by the Working Group to illustrate some of the climate change adaptation actions that are being undertaken, internationally, in the wider port and navigation sector. This case study information is appended to the guidance as it was provided to the Working Group. The case studies have not been subject to detailed checking or endorsement by Working Group members.

Case Study 1 – Climate Change Adaptation in the Port Of Rotterdam: Botlek Water Safety Pilot Project

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Case Study 2 – Port of Long Beach (USA) Climate Adaptation and Coastal Resiliency Plan

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Case Study 3 – The Port Authority of New York and New Jersey

Case Study 4 – Port of London Authority (UK) Climate Change Adaptation Reporting

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Case Study 5 – Port of Providence (USA): Stakeholder Resilience Strategy and Vulnerability Assessment of Maritime Infrastructure

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Case Study 6 – Harwich Haven Authority (UK) Climate Adaptation Reporting

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Case Study 7 – Tuvalu Outer Island Maritime Infrastructure Project

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Case Study 8 – Risk Quantification For Sustaining Coastal Military Installation Assets and Mission Capabilities, Norfolk Naval Base, USA

Case Study 9 – A Qualitative Climate Risk Assessment for Avatiu Port, Rarotonga, Cook Islands

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Case Study 10 – NSW Ports Climate Change Risk Assessment for Two Maritime Ports: Port Botany and Port Kembla, Australia

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Case Study 11 – Climate Change Impacts on Coastal Transport Infrastructure in The Caribbean: Enhancing the Adaptive Capacity of Small Island Developing States (SIDS)

Case Study 12 – San Pedro Breakwater (Los Angeles, Usa) Sea Level Rise Impact Assessment

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Case Study 13 – IFC's Climate Risk And Ports Terminal Maritimo Muelles El Bosque, Cartagena, Colombia

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Case Study 14 – Albert Canal (Belgium): Pumping Installations/Water Power Plant

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Case Study 15 – MOWE IT – Management Of Weather Events In The Transport System

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Case Study 16 – Port of Manzanillo

CASE STUDY 1 – CLIMATE CHANGE ADAPTATION IN THE PORT OF ROTTERDAM: BOTLEK WATER SAFETY PILOT PROJECT

BACKGROUND

How is the case study relevant to climate change adaptation (e.g. understanding and assessing climate change risk, collecting and analysing data)?

The City of Rotterdam recognises that the climate is changing, and Rotterdam will be affected. Rainfall is already becoming heavier and causing more flooding in the city. As a low-lying delta city, Rotterdam will have to cope with the effects of an increase in the sea level and with varying river levels. The overall goal of the Rotterdam Climate Proof Programme is to make the city and port 'fully' resilient to climate change impacts by 2025 and ensure that it remains one of the safest port cities in the world. The adaptation strategy focuses on flood safety, accessibility for ships and passengers, adaptive building, the urban water system, and city climate. New port developments including port reconstruction are designed to be climate-proof and climate change assessments are integrated into the port's spatial planning. To allow for dealing with uncertainties, knowledge development is considered an important pillar of the strategy. (This general adaptation strategy for the city of Rotterdam is however not further discussed here but can be consulted online[5])

The city of Rotterdam is protected by the storm surge barrier Maeslantkering, which makes up the larger Europoortkering together with Hartelkering and the dyke ring at Rozenburg. These barriers are closed during high water levels (Amsterdam Ordinance Datum or NAP +3 metres and higher) to protect the hinterland against floods. Most of the Port of Rotterdam area however located outside these dykes.

The report 'Advies Deltaprogramma Rijnmond-Drechtsteden' published in 2014 concluded that a targeted research needed to be performed to ensure that local residents and companies in the Rotterdam region are protected against floods in the years ahead. This research was subsequently conducted in four areas that lie beyond the dykes. They are Dordrecht's historical port area, Noordereiland, Merwe-Vierhavens and Botlek. The Botlek area is situated in a section of the port area that is relatively elevated at around 4.5 metres above sea level and is partly protected by the storm surge barrier. Botlek was specifically selected for its situation within Rotterdam's larger port area, its ensuing economic importance and the presence of vital and vulnerable functions.

The Botlek Water Safety pilot project was undertaken in 2015 and 2016 by the Port of Rotterdam performed with the aim of examining the consequences of flooding as a result of climate change, in particular sea level rise.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

Who was involved in the project (internal and external stakeholders)?

The specific nature of the Botlek and Vondelingenplaat promotes a true partnership with the stakeholders in flood risk adaptation. It is an industrial area situated outside the flood defence system, and as such the companies are responsible for the risks of flooding themselves. At the same time, the area is of great economic importance. In the extreme event that companies in the area would flood, it could cause significant economic damage. So, companies and government have a stake in a flood resilient Botlek and Vondelingenplaat. Therefore, a thorough and careful stakeholder engagement process has been organised to organise the partnership, right from the beginning. Workshops were held to facilitate the dialogue between the partners in every step along the way: from joint fact finding of flood risks, to developing a flood risk assessment framework and formulating a flood risk adaptation strategy.

[5] http://www.urbanisten.nl/wp/wp-content/uploads/UB_RAS_EN_lr.pdf.

The pilot project is a joint initiative of the Port of Rotterdam Authority, the Municipality of Rotterdam, the Ministry of Infrastructure and the Environment and Rijkswaterstaat. It was executed in close collaboration with various private sector firms, utility companies and Deltalinqs. The project was jointly funded by the Ministry of Infrastructure and the Environment and the Port of Rotterdam Authority. The following parties were also involved in the pilot project:

- Companies in the Botlek area and Wall-Eemhaven
- Deltalinqs
- Deltaprogramma Ruimtelijke Adaptatie – Vitaal en Kwetsbaar
- Hollandse Delta Water Board
- DCMR, the Dutch environmental protection agency
- Province of Zuid Holland
- Rotterdam-Rijnmond Safety Region
- Utilities
- Sector organisations (e.g. Association of the Dutch Chemical Industry and the Dutch Association for Transport and Logistics)
- Rail and road authorities

The project was jointly funded by the Ministry of Infrastructure and the Environment and the Port of Rotterdam Authority.

MOTIVATION FOR ADAPTATION REPORTING

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

In contrast with areas situated within the dykes, areas located beyond the dykes were not traditionally required to comply with any national water safety norms. Residents and companies set up outside the dikes at their own risk from flooding. This means that they themselves bear responsibility for taking measures to limit the potential impact of a flood (e.g. from ocean inundation).

The main driver for undertaking the Botlek Water Safety pilot study was the European Seveso III directive, which came in mid-2016, and requires industries using and storing large amounts of hazardous materials to undertake risk assessments, including consideration of flood risk and climate change adaptation. All vulnerable infrastructure must be 0.5 metres above the flood planning level. In the Botlek area, the flood planning level is the 10,000-year water level.

To meet this requirement, a flood risk assessment was undertaken in 2015 for the Botlek area, and in 2016, a climate change adaptation strategy developed. The objectives of the project were to study the possibility and consequences of flooding in the Botlek area, to propose mitigation measures and formulate an adaptation strategy.

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

The assessment considered two sea level rise Delta scenarios:

- a range of +0.15 to +0.35 metres by 2050
- a range of +0.35 to +0.85 metres by 2100

The key challenge for the port under a climate change scenario is to provide sufficient protection against ocean inundation/flooding, while at the same time maintaining a sufficient flow of freshwater for navigation.

RESULTS OF RISK ASSESSMENT

How were risks assessed/what methodology was used?

Together with the stakeholders, an area specific flood risk assessment framework has been developed in the process. This framework is a tool that shows how flood risks relate to standards from existing external safety and water safety policies. The added value of the partnership was that the tool is widely supported for identifying when flood risks will no longer be acceptable. Furthermore, a joint fact-finding process has been initiated in the workshops; together translating the probability of flooding to potential consequences for people, the economy and the environment. This has resulted in a new understanding of flood risks in the Botlek area.

What were the main risks/what were the main outcomes?

The results of the pilot project show that the main outcome of a possible future flood will be economic damage. This damage comprises both direct damage to buildings, systems and other facilities and indirect damage resulting from business interruption and/or the sub-optimal utilisation of the available infrastructure. There is limited risk of environmental damage and flooding is expected to lead to few or no human casualties.

In some cases, the indirect damage will actually transcend the afflicted area. The various activities at Botlek are not only closely connected and mutually dependent within the area itself, but also interwoven with activities in the surrounding port areas and beyond (in regions like Schiphol and Chemelot, for example). The economic damage is heavily dependent on where the flooding takes place, and the type of company.

Flooding in the Botlek area would also have major consequences for crisis management measures. For example, it will become next to impossible for most emergency services to access the flooded areas. In addition, if the A15 motorway were to be flooded, this would limit evacuation options in the surrounding dike rings (Rozenburg, Voorne-Putten).

The pilot project has yielded numerous insights for the participating companies and public authorities that can be used to further improve their crisis management programmes.

IDENTIFICATION AND PRIORITISATION OF ADAPTATION MEASURES

How were the possible adaptation measures identified and which ones where recommended?

In this pilot study, a broad inventory was made of possible measures. The aim was to be able to start from this broad overview to select the measures that are most suitable for an effective adaptation strategy. The inventory was carried out on the basis of expert judgment and previous studies.

Subsequently, the most promising measures have been selected in various steps:

Step 1 – Based on literature research and expert judgment, possible measures to control flood risks in the Botlek area have been inventoried. The first selection was carried out by experts on the basis of reality and feasibility.

Step 2 – In dialogue with stakeholders, the measures are divided into possible adaptation strategies based on prevention, spatial adaptation or crisis management. The costs and benefits of these measures have been estimated. The measures with the least favourable cost-benefit ratio dropped out in this step.

Step 3 – The possible adaptation strategies were subsequently assessed for effectiveness, feasibility and time/flexibility. This assessment led to a recommendation for an adaptation strategy for the Botlek area in which measures from various possible adaptation strategies were selected.

The results of the pilot project served as input for the 'Strategic Adaptation Agenda for Areas Outside the Dykes'. The final report sets out adjustments and measures (adaptation strategy) that can be taken to avoid or minimise the negative effects of a flood and consequently protect the area in question in the years ahead.

PROJECT OR INITIATIVE OUTCOMES

What were the main lessons learnt?

- A process with stakeholders leads to new insights, awareness (and encourages) commitment.
- Joint fact finding leads to openness and creates space for solutions.
- A shared decision framework is helpful to explore to what extent risks are still acceptable and gives insight into the timing of measures.
- An effective region-wide adaptation strategy combines preventive measures with spatial adaptation and emergency response and tailors each measure to specific characteristics of an area (e.g. with regard to flood probability, the different activities in the area and area dynamics).
- Having a responsibility is not always associated with coming up with the most effective solutions, e.g. collective measures coordinated by public authorities versus private responsibility to implement measures to prevent or adapt to flooding.

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CASE STUDY 2 – PORT OF LONG BEACH (USA) CLIMATE ADAPTATION AND COASTAL RESILIENCY PLAN

BACKGROUND

Brief case study description

The Port of Long Beach is an important economic engine for Southern California and the nation and a critical gateway to global trade. Climate change and extreme storm events are already impacting the Southern California coast. Sea levels will continue to rise, and the frequency and magnitude of extreme storm events are likely to increase. The Port of Long Beach and its tenants will experience storm events with a greater potential to impact Port operations. Consideration of these impacts will allow the Port and its tenants to make sound, science-based decisions as they invest in their maritime infrastructure, and to prioritise their resource allocations in a way that considers near-term and long-term climate change vulnerabilities and risks.

The Port of Long Beach developed a Climate Adaptation and Coastal Resiliency Plan (CRP) to manage the direct and indirect risks associated with climate change and coastal hazards:

- The CRP includes a review of the best available climate science, an inventory of Port assets, and detailed sea level and storm surge inundation mapping. Together, these data sets informed the development of vulnerability profiles for the Port's infrastructure, transportation networks, critical buildings, and utilities.
- A broad suite of potential adaptation strategies was developed to reduce the Port's vulnerabilities. A collaborative process was used to select a subset of these strategies for further refinement.
- The CRP recommends near-term solutions for protecting the Port's most vulnerable areas and long-term strategies that can assist the Port in maintaining business continuity across its infrastructure and operations into the next century.
- The CRP provides a framework for the Port to incorporate adaptive measures related to projected climate change into its policymaking and planning processes, construction practices, infrastructure design, and environmental documents.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

Who was involved in the project (internal and external stakeholders)?

The project involved a consultant and staff from several divisions across the Port, including: Environmental Planning, Transportation Planning, Master Planning, Engineering Design, Programme Management, Risk Management

What types of infrastructure/operation/management activities were assessed?

A comprehensive inventory was developed to identify and organise Port assets and operations that are important for maintaining business continuity. The inventory catalogue's assets at the piers, wharves, and backlands, and includes utilities, roadways, rail assets, and critical buildings such as those housing security, administration, fire, and life safety functions. The assets most critical to the Port's business continuity were highlighted.

MOTIVATION FOR CONSIDERING ADAPTATION

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

The Port's vulnerabilities were highlighted in August 2014 when storm surge and wave hazards resulting from Hurricane Marie ravaged the Southern California coast. The Port suffered damage at the Navy Mole (Nimitz Road) and Pier F, and shipping operations were halted for multiple days. Access to the surrounding roads and facilities was impacted for several months. Although Hurricane Marie was considered a unique storm event due to its direction of attack relative to the coastline, the changing climate and ocean conditions may increase the likelihood of storm events that are outside observations of historical events.

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

While the exact timing of future climate events is uncertain, there is strong consensus that the global mean temperature is rising. This causes a rise in sea level due to thermal expansion and the melting of land ice (glaciers). Sea levels at the Los Angeles tide station adjacent to the Port are currently projected to rise 5 to 24 inches by mid-century and 17 to 66 inches by end-of-century, based on projections by the Coastal and Ocean Working Group of the California Climate Action Team (CO-CAT 2013) and the National Research Council (2012).

The project considered low, mid and high range sea level rise scenarios, and increase in rainfall intensity.

RESULTS OF RISK ASSESSMENT

How were risks assessed/what methodology was used?

Detailed inundation maps were created for the Port study area. The maps considered SLR inundation and extreme tide (storm surge) flooding of the Port property, as well as an overtopping assessment along the existing shoreline structures and the Port's breakwater. Each SLR scenario – 16, 36, and 55 inches – was evaluated under two tide conditions, (1) daily high tide and (2) extreme tide (represented by the 1-percent-annual-chance stillwater elevation), resulting in six mapped scenarios that highlight both inundation depth and extent. Wave action was not included in this assessment.

Increased precipitation may result in increased riverine flows that could also impact Port property and subject areas to temporary flooding. Potential future increases in precipitation of 20 percent and 30 percent and the impact of these increases on riverine flooding were evaluated and mapped. An overtopping assessment highlighted locations along the shoreline where riverine floodwaters were most likely to overtop existing channel banks and shoreline infrastructure.

The asset inventory and inundation maps were used to identify vulnerable areas of the Port. Scoring criteria were developed to determine climate vulnerability based on exposure, sensitivity, and adaptive capacity of each asset. The impacts of climate change on the Port will likely fall into three broad areas of concern: asset damage, cargo damage, and lost revenue due to facility impact/closure. The largest impacts are due to a combination of SLR and storm surge. While SLR is a gradual and long-term stressor, storm surge related to an extreme event can be sudden, unpredictable, and temporary. The impacts associated with storm surge are expected to become more pronounced as sea levels increase.

Vulnerability profiles were developed for these Port asset types: pier infrastructure, transportation network, critical facilities, utilities, and the breakwater.

What were the main outcomes?

<u>Pier Infrastructure:</u>

- Portions of Piers S and D would be inundated first by SLR. Under the most extreme projections, the backlands of Piers A, B, and C would also be inundated, as well the tip of Pier E.
- Piers F, G, J, and T would not be exposed to SLR or periodic flooding, but they may be isolated due to inundation on adjacent piers.
- The riverine floodplain is projected to expand along the wharfs of Pier A West and Pier B, as well significantly at the backlands of Piers A and B if there is a 20 percent increase in precipitation.
- Many portions of the pier structures themselves are not sensitive to damage from short-term flooding. If a portion of the pier is submerged, operations will stop, but they are expected to resume quickly post-flood. However, any wharf or backland infrastructure that has electrical components,

such as conveyors, communications, security systems, lighting, and shore-to-ship power systems, may be at risk from damage if not waterproofed or otherwise protected.

Transportation Network:

- Railways and roadways on Piers S and D will be the first to be directly impacted due to inundation from SLR, which will prevent cargo from leaving these piers. The Pier T railway would be indirectly impacted because it connects to the inundated rail on Pier S.
- Under the most extreme conditions, Piers A, B, C, and D would also be inundated, which would indirectly impact Piers F, G, and J, since they connect to the inundated railways. Roadways within Piers A, B, C, and tip of E would also be directly inundated, as well as the freeway, State Route 47, that connects to Terminal Island.
- Rail infrastructure materials are not sensitive to damage as a result of short-term flooding. If rails are submerged, train movement will stop, but would be expected to resume quickly post-flood.
- Roadways on Piers S and D are most vulnerable and directly inundated. Inundation will prevent cargo leaving these piers.
- Road materials are not very sensitive to damage from temporary inundation. If roads are submerged, vehicle movement will stop during flood depths over a few inches but would be expected to resume post-flood. Repeated inundation is more likely to cause deterioration.
- Rail speeds are slowed when temperatures reach around 90 degrees Fahrenheit to avoid buckling and derailment, which will occur more often as the frequency of hot days (over 95 degrees) increases.

Critical Facilities:

- The majority of critical building structures are located at a high elevation and will not be impacted by the modelled levels of SLR and storm surge.
- The most vulnerable building is Fire Station #24 (Pier S) the access to which will be inundated under the 16-inch SLR scenario. Under storm conditions, the Foss Maritime mooring of tugboats and barges will be indirectly impacted because the access road will be inundated.
- Extreme heat may cause electrical outages and area-wide brown-outs. Building heating and cooling equipment will be disrupted, including all computers and other mechanical and electrical systems, unless the building has backup generators. Employee comfort, health, and productivity may be impacted.

Utilities:

- In most cases, water distribution lines are underground and are currently inundated by groundwater. Apart from valve vaults, water distribution lines are not anticipated to be sensitive to SLR inundation.
- In general, sewer lines will not be susceptible to SLR inundation. Lift/pump stations could be inundated with ground or surface water from SLR, affecting the efficiency of these units or causing spills outside of the system.
- Stormwater systems are susceptible to SLR inundation. If the outfall area is inundated, the water cannot drain and will contribute to further flooding in the area. Rising groundwater due to SLR will exacerbate this impact. Further, if the pump station locations are inundated, they will no longer operate.
- Electrical systems that are vulnerable to SLR will no longer be operable if they are subjected to even minimal flooding. Electrical system components that will be impacted by flooding include switchgear, substations, transformers, switchboards, panel boards, and building/facility lighting.

Breakwater:

- The existing breakwater protects the Port of Long Beach and the Port of Los Angeles (Middle Breakwater) as well as a portion of the city of Long Beach shoreline (Long Beach breakwater). As sea levels rise, larger waves will impact the breakwater, resulting in increased transmission of waves into the protected harbour.
- Based on historical storm conditions, the Long Beach breakwater is most vulnerable to wave damage from wave runup and overtopping.
- The second most vulnerable area is the eastern portion of the Middle Breakwater; however, the overall impact is projected to be minimal if future storms track well with historical events.

IDENTIFICATION AND PRIORITISATION OF ADAPTATION MEASURES

How were the possible adaptation measures identified and which ones where recommended?

Drawing on best management practices and input from technical experts (coastal and electrical engineers, port and transportation planners, and environmental policy specialists), a preliminary list of potential adaptation strategies was established. Over 20 strategies were identified and categorised into one of three types:

- Governance (address Port-wide planning and design documents): by adding language to overarching policies/plans and in technical guidelines, both planners and designers start thinking about climate change from the start of a project.
- Initiatives (address informational gaps): by introducing initiatives, stakeholders and Port staff can continue to evaluate impacts on operations and physical damage that are associated specifically with climate change.
- Infrastructure (address physical vulnerabilities): by modifying existing infrastructure, such as strengthening sea walls or raising electrical equipment, the Port can be more prepared for future climate-related events.

A workshop was held with staff from Divisions across the Port to review all of the strategies to determine which should be considered a priority or a future consideration or omitted.

Evaluation was based on the following criteria:

Strategy type	▪ Governance ▪ Initiative ▪ Infrastructure
Asset Type	▪ Port-wide ▪ Piers ▪ Transportation – Rail ▪ Critical Facilities ▪ Utilities – Stormwater ▪ Utilities – Electrical ▪ Utilities – Security ▪ Breakwater
Climate Stressor	▪ Sea Level Rise (SLR) and first point of inundation (16-, 36-, or 55-inch) ▪ Storm Surge ▪ Extreme Heat ▪ Extreme Precipitation
Focus Area	Highlight vulnerable areas/assets of the Port, such as 'Pier S' or 'Port-wide'. Brief description of Strategy.
Point of Intervention	Description of how strategy would be implemented, e.g., by integrating it into the existing study, scheduled upgrade, etc.
Implementation Timeframe	Implement strategy timeline: ▪ I = Immediate ▪ S = up to 5 years ▪ M = 5 to 15 years ▪ L = over 15 years
Cost	Cost to implement strategy (Include incremental cost only; e.g., if it is recommended that a pier be raised, the cost will only identify the delta, not the cost for rebuilding the entire pier). ▪ $ = up to $ 500K ▪ $$ = $ 500K to $ 5M ▪ $$$ = $ 5M to $ 50M ▪ $$$$ = over $ 50M
Partners	Includes both internal (Port Divisions) and external (other agencies, tenants, etc.)

Five strategies were prioritised and developed into detailed studies or concept designs:

- Strategy 1 (Governance): addressing climate change impacts through Port policies, plans, and guidelines
- Strategy 2 (Governance): adding sea level rise analysis to the Harbor Development Permit
- Strategy 3 (Initiative): Piers A & B Study – Combined Impacts of Riverine and Coastal Flooding
- Strategy 4 (Infrastructure): Pier S shoreline protection
- Strategy 5 (Infrastructure): Pier S substation protection – evaluation of multiple strategies

PROJECT OR INITIATIVE OUTCOMES

What were the main lessons learnt?

- Timing is important – don't wait for the best data
- Collaboration with local agencies, organisations, academia is/will be important
- Staff input/support is essential
- There may be multiple adaptation options which require careful assessment
- Extreme weather events help highlight the potential impacts
- Adaptation is crucial

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CASE STUDY 3 – THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY

BACKGROUND

Brief case study description

How is the case study relevant to climate change adaptation (e.g. understanding and assessing climate change risk, collecting and analysing data)?

In 2016, the Port Authority of New York and New Jersey (PA), following the events and impacts of superstorm Sandy, evaluated the potential risks of future coastal flood inundation from various scale storms and the prospective impacts on port facilities. This study evaluated potential sea level rise and climate change impacts on infrastructure, assets, and operations over the next 40 years at the Port of New York and New Jersey (PONYNJ).

The study area included the southern peninsula of Port Newark (Port Newark South), which lies between the Newark Channel and the Elizabeth Channel. Port Newark South has a variety of operational components and a diverse set of tenants, including a container terminal, bulk, liquid bulk, warehouse operations, drayage facilities, as well as other port tenants.

The results of the evaluation provide high-level quantitative risk data and an understanding of how to assess options to manage that risk over time.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

All types of infrastructures/assets were taken into consideration.

Who was involved in the project (internal and external stakeholders)?

The work required a collaborative effort from various Departments within the PA and representatives from various tenant operations (external stakeholders) in Port Newark South to characterise assets and identify vulnerabilities to coastal flood hazards. PA and stakeholder experiences from Hurricane Sandy helped provide detail and context to develop a basis for understanding the potential damages and operational impacts of these coastal storm events.

MOTIVATION FOR ADAPTATION REPORTING

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

The events and impacts following superstorm Sandy were the drivers to start up this study.

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

The study evaluated the impacts and potential damages to various assets under several major event scenarios including both a mid-range projection (50^{th} percentile) and a high range projection (90^{th} percentile) for potential sea level rise (SLR) in the years 2025, 2035 and 2055.

Table 1. Sea Level Rise Values for Risk Assessment Application		
	Sea Level Rise Values (from NYC Panel on Climate Change Resilience Manual)	
Time Period	50th Percentile	90th Percentile
2025	6"	10"
2035*	9"	17"
2055	16"	30"

* 2035 values are interpolated, following Horton et al. 2015

In conjunction with these SLR projections, the study evaluated the impacts of four coastal flood conditions:

- 10-year event
- 50-year event
- 100-year event
- 500-year event

RESULTS OF RISK ASSESSMENT

How were risks assessed/what methodology was used?

Tenants provided input on potential impacts such as how they would function with loss of electricity, loss of water service, and equipment loss. Because Hurricane Sandy was still fresh in many of the tenant representatives' memories, most were able to recount which assets and infrastructure were impacted, and how they have adjusted or adapted their operations to meet a future event similar to Sandy.

To evaluate impacts on assets, the team utilised data gathered from the facility and tenants to create a database of buildings and operational components at Port Newark South, including each asset's criticality and vulnerability to flooding. The resulting database was overlaid in GIS along with data on topography, flood hazard data, wave height analysis, and six scenarios of projected future flooding amplified by sea level rise. The flood risk model was validated by cross-checking anticipated flooding under today's sea level with flooding experienced during Hurricane Sandy, as well as less extreme recent events.

The flood hazard impacts were then translated into a high-level quantitative risk assessment using FEMA's Hazus software. Hazus was used to estimate potential damages and losses to the assets and operational components based on estimated flood depths. For building assets, losses were calculated as a function of damage to the structure, contents, and inventory. Losses for operational components like gantry cranes were estimated through custom functions in Hazus. Losses were calculated on an event basis as well as by computing Average Annualised Loss (AAL), which is a loss statistic that estimates the expected losses per year averaged over time.

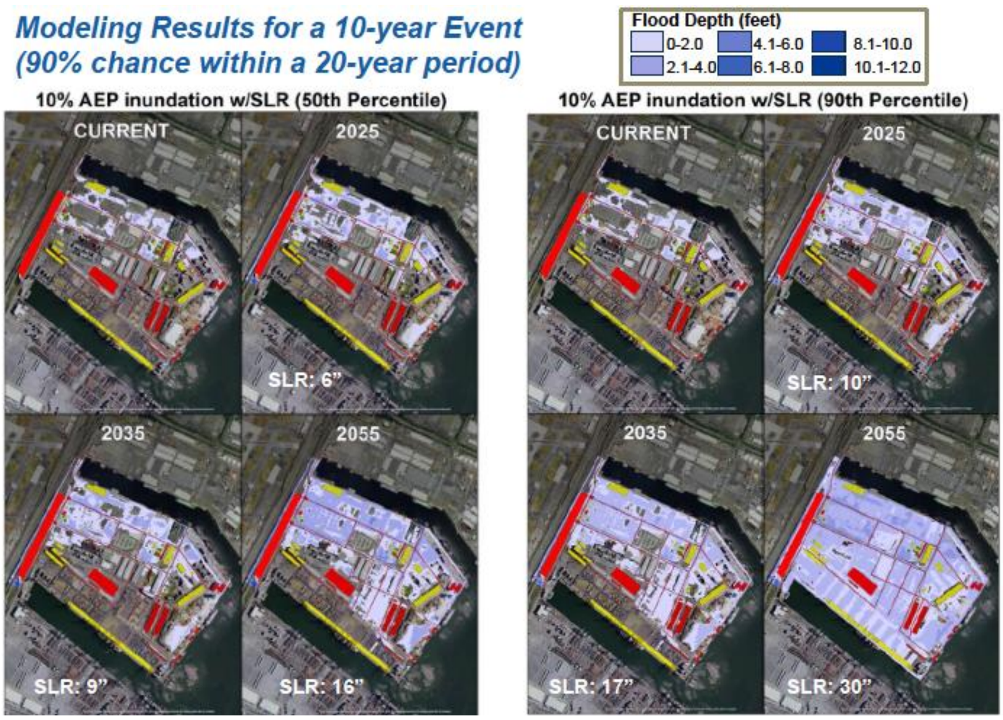
What were the main risks/what were the main outcomes?

The most obvious issues involved water damage to buildings, damage to electrical and electronics equipment, and issues associated with power loss. During the restoration work, tenants relocated their electrical systems above the Sandy flood elevation, raised or protected their electrical transformers, and stored their back-up generators and emergency equipment at higher ground or behind flood barriers.

Lack of electricity following Hurricane Sandy due to damaged power facilities and distribution infrastructure was one of the largest problems for many tenants. The PA is working with the local utility provider to better protect the electrical equipment on the Port in preparation for future flooding events.

Less apparent issues were the damage to cranes, stackers, and other mobile equipment, which significantly slowed many of the tenants' operations for months after. The situation addressed the appropriate locations and heights for the storage of extra crane motors, as well as the means of storage, as crane motors are large and heavy pieces of equipment. Tenants also grappled with how to protect immovable objects, such as truck scales and boiler systems, which are critical to operations. Fuel supply was also a critical issue in the region after Hurricane Sandy, both for keeping clean-up/debris removal equipment up and running and for the transportation of staff to and from their homes to assist in the clean-up.

Modelling showed that projected sea level increases will not only increase flood hazards through higher flood elevations and wave heights but will also increase the frequency of damage-inducing flooding events. Port Newark South can currently expect to experience inundation of approximately 12 % of the facility during the 10-year flood event. Looking at the mid-range (50th percentile) scenario, that inundation extent increases to 23 % of the entire facility in 2025 and eventually to 47 % by 2055. The projected increase in extent for the 10-year flood event under the mid-range and high-range sea level rise scenario is depicted in the figure below.



As the sea level rise and flooding extent at Port Newark South is modelled further into the future, the potential impacts become more apparent. Both the mid-range (50th percentile) and the high-range (90th percentile) sea level rise scenarios project a significant increase in inundation extent and depth for a 10-year event, a storm that today would be considered a minor nuisance flooding event. In the case of the 90th percentile sea level rise projection, the inundation is dramatically increased, inundating nearly the entire facility.

The damage and loss analysis found a general trend of increasing damage and loss for all flood events and sea level rise scenarios over time.

IDENTIFICATION AND PRIORITISATION OF ADAPTATION MEASURES

How were the possible adaptation measures identified and which ones where recommended?

Adaptation options that are relevant to the facility's potentially vulnerable infrastructure and assets were developed and presented during a design charrette with stakeholders.

PROJECT OR INITIATIVE OUTCOMES

What were the main outcomes? What were the main lessons learnt?

The study results, including increased coastal storm risk exposure and estimates for Average Annualised Loss (AAL), can be used to weigh the costs and benefits of adaptation options. Generally, four mitigation options can increase coastal storm resiliency informed by sea level rise predictions: elevation, relocation, protection, and accommodation.

Sea level rise is projected to exacerbate Port Newark South's vulnerability to coastal storms. The increased impact (higher depths) that will be associated with more frequent events represents a significant issue from both an operational and a damage/loss perspective.

As a port, Port Newark South's vulnerability to coastal hazards and sea level rise is in many ways an inherent aspect of its function. The assets and operations of an efficient port need to be on the water – the same source of increasing risk due to the impact of sea level rise. The objective of this study was to provide facility managers and tenants with a better understanding of those hazards and a framework to evaluate adaptation options. This information allows stakeholders to understand how best to weigh the costs of adaptation for major capital investments against potential long-term unmitigated risks.

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CASE STUDY 4 – PORT OF LONDON AUTHORITY (UK) CLIMATE CHANGE ADAPTATION REPORTING

BACKGROUND

Brief case study description

The Port of London Authority (PLA) manages the UK's largest Trust Port and the UK's second biggest port overall, handling more than 40 million tonnes of cargo, responsible for the employment of more than 40,000 people, and contributing over £ 3 billion to the economy annually. The tidal Thames, over which the PLA also has jurisdiction, is the busiest UK inland waterway, handling over five million tonnes of goods annually, 60 % of the UK's inland freight traffic. The Thames through London is also a major recreational resource. In total, the PLA's Port Control Service oversees the safe movement of 230,000 commercial and leisure vessels within the 95 miles of waterway in the Port of London each year, whilst 90 Thames pilots board and guide more than 10,000 of these vessels annually.

How is the case study relevant to climate change adaptation (e.g. understanding and assessing climate change risk, collecting and analysing data)?

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

Who was involved in the project (internal and external stakeholders)?

It was clear from the outset that a wide range of internal stakeholders would need to be involved in the development/preparation of the adaptation report. A series of facilitated workshops was therefore organised to enable key personnel to discuss the potential implications of climate change and evaluate possible responses. These workshops involved senior personnel from the following departments: harbour masters; navigation systems, civil and marine engineering; hydrographic surveying; corporate affairs; planning and partnerships; finance; environment; and marine services.

In addition to internal personnel, however, it was recognised that commercial terminal owners and operators as well as shippers; recreational users (especially in the upstream reaches); water companies (responsible for abstraction upstream, in turn affecting water depths in the upper tidal Thames); and various public sector and community groups all have an interest in the management of the tidal Thames. Dialogue on climate change matters, including awareness raising amongst these organisations was therefore recognised as being important.

The 2015 exercise to update the original climate change adaptation report was led by the PLA's Planning and Environment Manager and again involved representatives from across the organisation. In parallel to the updating procedure, in early 2015 the PLA initiated an exercise to develop a 20-year vision for the Tidal Thames. Climate change provided a necessary context for this exercise, which saw the PLA engage with groups and individuals throughout the wider Thames community including infrastructure, recreation and the environment.

MOTIVATION FOR CONSIDERING ADAPTATION

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

The Climate Change Act 2008 sets out the legal requirements for climate change mitigation and adaptation in the UK. Under the adaptation reporting power in this Act, the larger UK Harbour Authorities (those with a throughput of more than 10 million tonnes of commercial cargo annually) were required to prepare an adaptation report for submission to the Department for Environment, Food and Rural Affairs. The PLA submitted its first climate change adaptation report to the Secretary of State in 2011. This report raised awareness of climate change impacts within the organisation and proved to be of particular value when the Authority had to respond to extreme weather events during the winter of 2013-2014. In 2015, the PLA submitted an updated adaptation report to Government [PLA, 2015].

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

The 2011 adaptation report was based on the UKCP09 medium greenhouse gas emissions, 50 % probability scenario, supplemented by the more detailed projections being prepared for the Environment Agency's work on the TE2100 project, an initiative to review flood risk management options for the tidal Thames in London [Environment Agency, 2012]. The 2011 report also referred to the UKCP09 additional projections in relation to wind and fog. Both these parameters are of critical importance to the PLA's duties with respect to navigational safety and pilotage.

The work identified that the following climate-related changes have the potential to directly or indirectly affect the Authority's functions and activities:

- relative sea level rise including changes in significant wave heights
- changes in average seasonal precipitation with consequent changes in levels of high or low freshwater flow and implications for erosion, accretion and sediment transport
- air and water temperature increases; and related changes in water quality
- changes in wind (strength, direction) or fog (frequency, severity, duration)
- changes in the frequency of extreme events

For the 2015 update, the PLA carried out a review of all these data and was content that the forecasts were still valid notwithstanding some improved data availability in the meantime.

Changes in rainfall are critical for many of the PLA's operations. Since the 2011 report was prepared, the Climate Modelling Inter-comparison Project (CMIP5) concluded that predicted reductions in average summer rainfall will be less than estimated for the UKCP09 projections. For the purposes of the 2015 review, the PLA therefore considered that the assumptions used in its 2011 report as the worst-case scenario.

Improved data are also now available in relation to river flows, notably the Environment Agency's fluvial flow data collected under the Lower Thames Operating Agreement (LTOA). This work has confirmed the greater frequency of low flows in the summer months resulting in reduced water depths, and increased winter flow rates, both of which potentially impact on recreational use in the upper reached of the tidal River Thames.

RISK ASSESSMENT

How were risks assessed/what methodology was used?

A key outcome of the workshops held to inform the PLA's 2011 adaptation report was a matrix of potential impacts likely to affect operations and activities (i) in the short term (within ten years) and (ii) in the longer term. Further scrutiny of this matrix involving relevant departments enabled the Authority to identify and prioritise adaptation actions. Actions identified as being needed in the short term were then subject to more detailed cost benefit assessment.

What was the solution/what were the main outcomes?

This process highlighted that a wide range of activities and functions could be affected by climate change, and also that the changes were likely to vary according to location, from the outer Thames Estuary to the upstream limit of the tidal Thames in west London. In particular, the 2011 adaptation report identified the following risks:

- Changes in the amount and/or flow of water due to changes in sea level and/or changes in precipitation, potentially affecting navigational safety notably in the upstream area
- Vulnerability of navigational aids including VTS and radar to sea level rise and flooding
- Potential for changes in wind and fog to curtail navigation in central London and to increase difficulty of landing pilots on vessels in outer estuary
- Operational facilities at risk from sea level rise and flooding

- Changes in precipitation affecting bankside vegetation, particularly in the upstream reaches, inter alia increasing the number of trees requiring removal from the river (N.B. the PLA already clears more than 200 tonnes of driftwood and rubbish from the river in central London each year)
- Changes in water volumes, turbidity and temperature leading to increased incidents of algal blooms
- Implications of climate change for the issue of third-party licences

An important outcome of the first risk assessment process was the improved understanding of the potential implications of climate change for the upstream areas i.e. the tidal Thames through London. It had originally been anticipated that the main risks – and hence the need for adaptation measures – would be focused on the lower reaches i.e. out in the estuary. The evaluation process findings, which demonstrated that the most serious risks were primarily in the upper reaches, were therefore somewhat unexpected. These outcomes resulted in a complete change in emphasis within the organisation as to where the greatest focus on climate change adaptation measures would be needed.

Partly in the light of these findings, a comprehensive risk register has been developed. This register includes climate change as an external risk. According to the 2015 'update' report, adaptation requirements are now included in the PLA's quarterly reporting to the External Risk Committee, which is chaired by the PLA's Chief Executive.

IDENTIFICATION AND PRIORITISATION OF ADAPTATION MEASURES

How were the possible adaptation measures identified and which ones where recommended?

With regard to potential longer-term risks the report anticipated that measures would be needed in relation to:

- maintenance and management practices including bank or wall repairs or dredging
- working practice modifications in response to changes in wind or fog conditions
- increased river patrols and other management measures to ensure continued safety of navigation, especially for recreational users
- upgrading or providing new moorings

The 2011 adaptation report also stressed the importance of monitoring.

PROJECT OR INITIATIVE OUTCOMES

What were the main lessons learnt?

The 2011 report concluded that the development of corporate climate change policies and processes required urgent attention. It also noted that short-term action was required in relation to towpath tree management; and it drew attention in general terms to the importance of monitoring and improved preparedness.

Finally, the 2011 report highlighted the lack of awareness of climate change issues amongst those using the river, particularly the upstream areas. This was particularly relevant because of the projected seasonal changes in precipitation (increases in winter rainfall of up to 40 % by 2080 along with reductions in summer rainfall), which could have significant implications for leisure users particularly those using unpowered craft e.g. rowers and sailors.

In response to these findings, the PLA initiated a process of monitoring, an annual review meeting and the inclusion of climate adaptation progress in the Authority's Annual Report. In addition, the PLA undertook to use its participation in various Thames stakeholder groups to collect information on climate risks and to disseminate information and raise awareness.

The 2015 update report confirmed that the actions proposed in the 2011 report had mostly been completed. However, it also highlighted a number of further actions, some of which were implemented in response to an extreme event experienced in winter 2013-2014. This event had a significant adverse effect on navigation, notably on leisure users such as rowers, due to the unprecedented combination of an exceptional period of high fluvial flow levels and a strong ebb tide. Following this incident, a set of electronic and physical 'flag' warnings was introduced to notify all those participating in leisure activities on the tideway of the prevailing conditions. This was an action that the PLA was able to implement swiftly, having been alerted to the possibility of high-flow related problems through the earlier work.

Whilst there have been no specific financial savings to the PLA as a result of implementing these additional adaptation actions, there has been a considerable reputational benefit associated with avoiding collisions and other incidents as steps are taken to proactively communicate with river users and minimise the effects of extreme events.

The 2011 adaptation report stressed the importance of monitoring. By the time the 2015 report was prepared, a comprehensive climate change monitoring programme had been introduced covering parameters such as tidal heights and fog in addition to bathymetric surveys and river flow recording. Such monitoring is considered vital because recreational use of the river is continuing to increase, and it is important to warn users not only about high flow but also low flow conditions. The importance of communication of these risks, and also those associated with predicted and actual tidal heights is an ongoing priority to the PLA.

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CASE STUDY 5 – PORT OF PROVIDENCE (USA): STAKEHOLDER RESILIENCE STRATEGY AND VULNERABILITY ASSESSMENT OF MARITIME INFRASTRUCTURE

BACKGROUND

How is the case study relevant to climate change adaptation (e.g. understanding and assessing climate change risk, collecting and analysing data)?

The stakeholder vulnerability and resilience strategy assessment pilot project focused on the Port of Providence, a small North Atlantic port in Rhode Island, USA, with high exposure to hurricanes. The Port of Providence is defined here as the Providence and East Providence waterfronts between the Hurricane Barrier and Fields Point.

Maritime transportation serves a critical role in the Rhode Island economy, providing energy products, raw materials, and revenue from scrap metal and other exports. The Port of Providence supplies Connecticut, Massachusetts, and Rhode Island with petroleum products and handles bulk and break-bulk cargo totalling approximately 3.1 million tonnes in 2010. Numerous ancillary businesses depend on the port's functionality, including trucking companies, rail service, manufacturing companies, ship repair facilities, marine pilots, and dredging companies, generating more than $USD 200 million in economic benefits for the region and over 2,400 jobs.

The study area for this project includes ProvPort, the main port terminal, and 23 other waterfront businesses and industries which together take up nearly 573 acres of waterfront in Providence and East Providence. Though the state of Rhode Island has embraced climate adaptation planning in some of its policy and planning efforts, little work has focused on the resilience issues facing the Port of Providence. The Port of Providence does not have a centralised planning body such as a port authority to plan for long-range climate change resiliency.

The Port is located at the northern end of Narragansett Bay, an ecologically sensitive estuary that provides breeding grounds for marine life in the region. The length and orientation of Rhode Island's Narragansett Bay, and its proximity to the Atlantic hurricane zone, make it susceptible to extreme storm surges from the southerly winds that are generated when a hurricane passes to the west of the Bay.

Funded by the Federal Highway Administration and the Rhode Island Department of Transportation, this study brought together 30 key stakeholders from the Port of Providence to engage in a dialogue around the risks from a major hurricane at the Port. The study, conducted by researchers from the University of Rhode Island in 2015-2016, used three main tools to facilitate this discussion:

- a storm scenario with local-scale visualisations
- three long-term resilience concepts
- a decision support tool used to assess the relative merits of and prioritise the resilience concepts

The researchers adopted a scenario involving a direct hit by a Category 3 Hurricane as a plausible hurricane in Providence and measured the consequences of such a storm on the Port and its operations with a view to facilitating climate change resilience planning.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

Who was involved in the project (internal and external stakeholders)?

There is no official port authority in Rhode Island and the State plays no direct role in managing port operations or centralised planning, although the State's coastal agency, the Coastal Resources Management Council (CRMC), does regulate land use in the coastal area that the port occupies. Together the business that make up the Port of Providence most closely resemble a private service port.

The project was implemented under the guidance of a steering committee comprised of state and federal representatives from a range of organisations, including:

- Researchers from the University of Rhode Island
- Port of Quonset/Davisville
- Rhode Island Department of Transportation
- Rhode Island Climate Change Committee
- U.S. Army Corps of Engineers
- U.S. Coast Guard
- Rhode Island State-wide Planning
- Coastal Resources Management Council
- Commerce Rhode Island
- Providence Department of Planning
- U.S. Maritime Administration

The steering committee guided the overall research agenda and identified port stakeholders to be included in the project.

The focus of the study was to stimulate dialogue around long-range options for resilience investments and to assess the impacts of the hurricane scenario on the specific business premises and the transport infrastructure on which they are dependent, including the:

- 40 foot (12.2 metres) deep shipping channel
- Road network (Allens Avenue and Interstate-95)
- Providence and Worchester Railroad

Participants also considered the potential impacts on critical utilities such as electricity supply, water supply and telecommunications.

MOTIVATION FOR ADAPTATION REPORTING

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

The study was driven by the University of Rhode Island whose researchers have a focus on adaptation planning for ports. Having observed the impacts of Hurricane Sandy on the Port of New York and New Jersey in 2012, the study participants were motivated to better understand the potential impacts of a hurricane on the Port of Providence to inform long-term disaster management planning.

The discussion with study participants focused on resilience of the businesses and transport infrastructure to such storm events. Participants then considered how the level of resilience may be improved by adopting one of three so-called 'transformational' strategies, along with a 'Do-nothing' alternative:

- 'Protect' – Reduce risk by decreasing the probability of occurrence of impacts. This strategy proposes relocating the existing hurricane barrier further south to provide improved protection for the port
- 'Relocate' – Also known as retreat; reduce risk by limiting the potential negative impacts by moving assets out of the storm surge zone
- 'Accommodate' – Reduce risk by developing strategies to minimise the impacts to assets in their current location
- 'Do nothing' – That is, the existing level of resilience is maintained

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

The main data inputs to the study were observations from historical hurricanes, coupled with some numerical modelling and digital elevation data for inundation mapping. Catchment flooding was not considered in the study.

The study considered a Category 3 hurricane scenario. Numerical modelling of this storm scenario was undertaken for Narragansett Bay adopting a nominal 21-foot (6.4 metres) storm surge level based on historical observations. This is estimated at a 1 in 60-year storm tide level, with a 1.7 % chance of occurrence in any given year.

The Fox Point Hurricane Barrier, a 25-foot high barrier located north of the port, protects the downtown Providence area. It could also result in higher storm-surge levels just south of the barrier at the port, as surge waters would accumulate in Providence Harbour instead of spreading throughout the low-lying region now protected behind the barrier. The design water level for the adopted hurricane scenario lies at the threshold of the design criteria for the Fox Point Hurricane Barrier and represents the maximum surge the barrier was designed to withstand before overtopping.

Though climate change was not explicitly considered in the scenario, researchers informed participants that this scenario would have a higher likelihood of occurrence in future under climate change conditions. The National Ocean and Atmospheric Administration estimates that the Atlantic basin will see an increase in hurricane wind speed and rainfall intensity, with wind speeds approximately 4 % stronger for every 1°C increase in sea surface temperature, and a model-projected rainfall increase near 20 % by 2100.

RESULTS OF RISK ASSESSMENT

How were risks assessed/what methodology was used?

What were the main risks/what were the main outcomes?

Numerical and spatial modelling showed that about 86 % (490 acres) of the study area would be inundated by at least one foot of water in the adopted hurricane scenario. The spatial visualisations were reviewed by the study participants to consider the potential impacts on their businesses over the coming weeks, months and years after the event. Participants were instructed to focus on long-term consequences, as opposed to what might happen on the day of the event. A multi-criteria decision support tool was used to assess the four different strategies (Protect, Relocate, Accommodate, Do Nothing) against seven resilience goals.

The Protect scenario was considered by participants to be most effective in meeting their goals, followed by Relocate, then Accommodate, and finally Do Nothing. While all agreed that the Do-Nothing scenario was the least attractive option, it is the strategy currently being followed by the port community.

Six months after conducting the initial study, the researchers surveyed the stakeholders again to ascertain their preferred strategy and identify where they felt leadership responsibility lay. The government participants more strongly preferred the Accommodate strategy, for which businesses would be largely responsible for implementation, whereas the respondents from port businesses preferred the Protect strategy (relocation of the existing hurricane barrier), which they considered should be spearheaded by the government. Both government and business respondents felt that a new public/private collaboration, with strong leadership from the state, should take leadership responsibility for implementation of resilience measures.

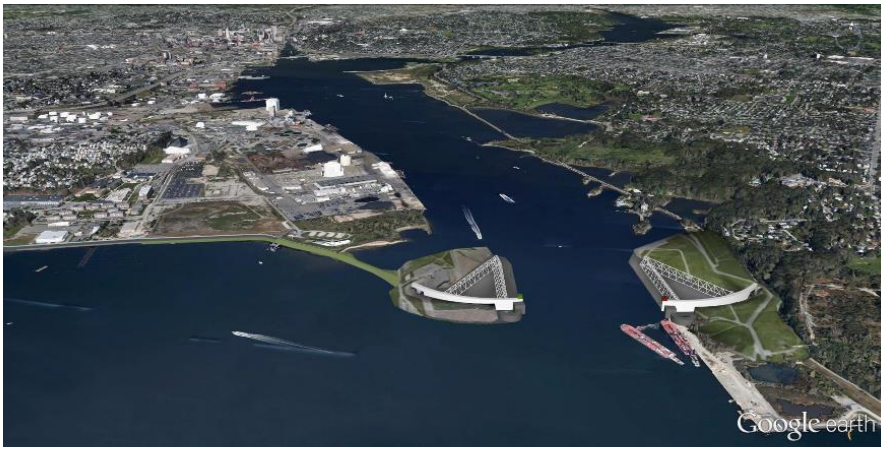
PROJECT OR INITIATIVE OUTCOMES

What were the main lessons learnt?

The key lessons learnt relate to:

- the need for early stakeholder participation in long-range planning
- the value in using visualisations for considering impacts of storm events
- the difficulty in allocating responsibility for implementation of adaptation measures
- the value in considering economic costs and benefits of adaptation
- the need for leadership in adaptation planning

The participants found that these exercises and decision support tools engaged them in critical thinking to better understand shared risk and complexity inherent in implementing meaningful resilience strategies. Though the workshop did not, by design, result in a concrete decision for action or specific plan, it represents an example of a pre-planning exercise necessary to lay the groundwork for future decision making in the face of climate change related hazard events.



While all participants agreed there was a need for strong public-private collaboration on disaster preparedness, the study highlighted the different views of stakeholders as to the allocation of responsibility for the mitigation of impacts. The private stakeholders had a strong interest in seeing the State take leadership in developing a high investment, longer term Protect strategy, while acknowledging that they should implement strategies to Accommodate in the short to medium term to minimise business impacts.

The study participants felt that a detailed cost-benefit analysis would have greatly assisted in decision making, in particular in identifying who bears the economic impacts of storms on the port operations and state economy and, therefore, how the cost of implementing measures to improve resilience should be borne by various actors. It would also assist individuals in making a business case to implement strategies to Accommodate storm events within their own organisations.

The final key finding was that, while all the stakeholders agreed that there was a need for adaptation planning for the Port of Providence, there was no specific lead for such an activity. It was considered that there was no immediate incentive to commence planning, and stakeholders were generally quite daunted by the task.

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CASE STUDY 6 – HARWICH HAVEN AUTHORITY (UK) CLIMATE ADAPTATION REPORTING.

BACKGROUND

Brief case study description

Harwich Haven Authority is a statutory UK Harbour Authority established by Act of Parliament in 1863. Located on the east coast of England, it has a duty to conserve, protect and improve Harwich Harbour and its approaches for the benefit of all its users. The Haven Authority provides services for shipping using several commercial ports including Felixstowe and Harwich International and for shipping on passage to the port of Ipswich; as well as pilot boarding and landing services for vessels bound *inter alia* for the rivers Thames and Medway. The area is extensively used by recreational craft, and there are several sailing clubs and marinas located in the area over which the Authority has jurisdiction.

Under the UK Climate Change Act (2008), the Secretary of State directed Harwich Haven Authority to prepare and submit a report describing the current and future predicted impacts of climate change on the organisation and setting out the Authority's proposals for adapting to climate change. This report was prepared and submitted to Government in 2011.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

Who was involved in the project (internal and external stakeholders)?

The Harbour Engineer led the exercise with support from the Harbour Master, and Environment and Health and Safety officers. Internal consultation took place with several other departments including: pilotage; vessel services; operations room including VTS, radar and VHF; maintenance dredging and disposal; marine engineering (provision and maintenance of vessels); civil engineering, provision and maintenance of jetties, pontoons, etc.; hydrographic surveying; navigation aids, beacons, buoyage (provision and maintenance); environmental monitoring; buildings design, maintenance and operation; personal; and licensing. The interests of the many commercial port and recreational stakeholders, as well as fishermen, environmental groups, local communities, local government and various regulators were also taken into account.

MOTIVATION FOR ADAPTATION REPORTING

What was the driver for considering climate change adaptation?

What adaptation issues were addressed?

Harwich Haven Authority was a 'reporting authority' under the UK Climate Change Act (2008). As such, the Authority was required to prepare and submit to the Secretary of State, a report containing an assessment of the current and predicted impacts of climate change insofar as these related to its statutory functions, and a statement of its proposals and policies for adapting to climate change in the exercise of its functions, along with associated timescales.

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

The assessment was informed by the projections described in the UK Climate Impacts Programme 09 (UKCP 09) and discussed in the 2010- 2011 Marine Climate Change Impacts Programme Annual Report Card. The review of these data confirmed that the following climate change parameters and consequences have the potential to directly or indirectly affect the Authority's functions and activities:

- relative sea level rise including changes in significant wave heights
- changes in average seasonal precipitation with consequences for levels of high or low freshwater flow and/or implications for erosion, accretion and sediment transport
- air and water temperature increases; and related changes in water quality, pollution
- changes in wind (strength, direction) or fog (frequency, severity, duration)
- changes in the frequency of extreme events

The UKCP 09 'medium greenhouse gas emissions' scenario was used as a basis for the assessment with the 2090 projections representing the 'long-term' change scenario. The high++ sea level rise projections were also considered.

RESULTS OF RISK ASSESSMENT

How were risks assessed/what methodology was used?

A qualitative and mainly high-level risk assessment process involving the responsible departments and functions within the authority identified sea level rise and a potential increase in the frequency of extreme (storm/surge) events as the main threat. Other potentially significant risks associated with projected increases in air and water temperatures and with any increase in fog frequency or increased wind strength were also highlighted.

What were the main outcomes of the risk assessment?

As a result of the assessment, the Haven Authority confirmed that the following potential consequences of climate change would require an adaptation response in the short to medium term:

- Increased risk of flooding of radar and radio equipment at Landguard Point, Shingle Street and Shotley as a consequence of sea level rise and/or any increase in the frequency of extreme events. Loss of this equipment would have a major and unacceptable impact on the Authority's ability to fulfil its statutory functions, so investigations into options for the relocation or modification of these assets were initiated. Responsibility: Harbour Engineer.
- Loss of power supply disrupting business. Loss of power, whether the loss of grid power due to flooding or extreme events and/or the inability of existing standby generation facilities to provide cover due to their location or mode of operation, would significantly affect the Authority's ability to fulfil its statutory functions. The Authority therefore explored alternative arrangements and prepared a contingency plan to deal with any loss of power supply and thus ensure the continuity of both day- to- day operations and essential safety- related (including response) activities. Responsibility: Harbour Engineer.
- Increased risk of flooding of buildings to seaward of flood wall as a result of sea level rise or any increase in frequency of extreme flooding/storm events. Operations currently carried out to seaward of the floodwall include buoy maintenance and activities on the jetties and pontoons. Loss of facilities for buoy maintenance would be a significant issue, but it was concluded that these facilities could be relocated. Predicted rates of sea level rise and frequency of extreme events are unlikely to lead to problems within the residual lifetime of the jetty and pontoon structures but sea level rise and flood risk will be material considerations when developing plans for renewal or replacement of the assets. Responsibility: Harbour Engineer.
- Increased risks of incidents arising from the increased numbers or activity levels of leisure vessels anticipated to be using harbour areas as a result of warmer air and water temperatures. Any significant increase in recreational use of the Haven could potentially increase the risk of serious incidents. This would in turn impact on the Authority's operations in that it requires staff, time and resources, which would not then be available for other matters. Responsibility: Harbour Master.
- Various increased operational risks associated with possible extended periods of winter fog and/or high winds e.g. reduced visibility; high windage; increased downtime. A number of the Authority's activities such as pilot transfer, buoy maintenance, or environmental monitoring could become more hazardous if there was additional fog or extended periods of high winds. These activities could take longer or require more resources to ensure continued safe operation (e.g. additional staff resources as Fog Watch Pilot could be required in the operations room). Responsibility: Harbour Master.

MONITORING

Harwich Haven Authority already had an extensive programme of monitoring in place, covering a wide range of physical and natural environment parameters. As an outcome of the adaptation reporting exercise it was agreed that climate change adaptation reporting and progress would become a permanent item in the Authority's annual submissions to both the Regulators' Group meeting and the Haven Authority's Safety and Environment Committee.

PROJECT OR INITIATIVE OUTCOMES

What were the main lessons learnt?

In their summary report to Defra on the adaptation reporting power, Cranfield University[6] highlighted that 'possibly the greatest legacy of the first round of the Adaptation Reporting Power is that it has been the catalyst behind many organisations formally considering their climate change risks and possible adaptation responses for the first time'. This was very much the case for Harwich Haven Authority as the adaptation reporting exercise highlighted several risks that had not previously been comprehensively assessed.

As an outcome of the reporting exercise, the Authority made proposals for implementation of several identified measures and for monitoring and evaluation of the process. Climate change adaptation was embedded in the organisation and became a permanent item in the Authority's annual report to its statutory Regulators' Group, the Harbour Liaison Group and the Leisure Vessels Committee. It will also be formally included in the Annual Report to the Haven Authority's Safety and Environment Committee and the Authority's Annual Report.

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CASE STUDY 7 – TUVALU OUTER ISLAND MARITIME INFRASTRUCTURE PROJECT

BACKGROUND

Brief case study description

This case study is from Tuvalu, a small island nation located east of the Solomon Islands in the South Pacific Ocean. The Government of Tuvalu has been working with the Asian Development Bank (ADB) to improve its outer Island maritime facilities. The project will help Tuvalu overcome connectivity problems that constrain its economic and social development. The only form of transport between islands is inter-island ships. At present there are three passenger/cargo ships and all goods must come onto and leave each island by ship. Each island has access to these ships once every 2-3 weeks. Goods and people must be transferred from the ship to the inner reef and the island by small workboats. The passage between the channels to the shoreline can be dangerous depending on the sea conditions and serious accidents occur, occasionally resulting in loss of life and high value goods. In addition, many outer islands have no docking facilities, and people must get on and off board laboriously and cargo must be carried.

The key aspects of the case study that may be of interest to the reader are:

- The remote nature of the site: The closest sizeable city is Suva in Fiji, a distance of over 1,000 kilometres. As for all the islands, Nukulaelae is only accessible by sea, and is a distance of 112 km from Funafuti. The remote nature of these islands presents a range of challenges, including for sourcing of construction materials and logistics for construction and maintenance. This has implications for procurement and design.
- Limited resources: the Government of Tuvalu has limited resources, both technical and financial, to construct and maintain infrastructure. They are therefore highly dependent on international donors and expertise for the provision of essential infrastructure.
- Dependence on maritime infrastructure: Tuvalu's main form of transport is by boat, and the inter-island ships provide a critical life line for residents. At present, the transfer of goods between the inter-island boat, the workboats/barges and the shore is very dangerous. In addition, being the only form of transport, the infrastructure must be accessible by a range of people, including those with limited mobility.
- Vulnerability to the impact of climate change: Tuvalu has been identified as being highly vulnerable to the potential impacts of climate change.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

The project is investigating infrastructure improvements at a total of around six sites. This case study focusses on the Nukulaelae site. The preliminary concept design for the Nukulaelae project incorporates the following elements:

- a new dredged channel at -1.5 m MSL (mean sea level) and turning basin for boats
- a new wharf landing/approach jetty on the southern side of the basin. The landing area and jetty must have universal access (e.g. for people with disabilities, children, the elderly, etc.)
- ramp for fishing vessels
- rehabilitation of cargo sheds, road access to this shed
- lighting along the structure, for night unloading when necessary
- two breakwaters

A design life of 50 years has been adopted for the project.

Who was involved in the project (internal and external stakeholders)?

The Climate Risk Assessment was undertaken by a climate change specialist with input from the following stakeholders:

- the project leaders, the Government of Tuvalu and the ADB
- engineering consultancy engaged to develop the design. Its team included engineers, a social specialist and procurement specialist
- a number of representatives from different government departments, including Marine and Ports, Environment, Public Works, Lands, Rural Development, Central Procurement Unit, Business and Investment Unit, and Gender
- project officers from associated ongoing projects being implemented by various donor agencies
- key civil society representatives including Tuvalu Non-Government Organisation (TANGO) and Tuvalu National Council of Women
- regional civil works contractors with current or past experience working in Tuvalu
- local leaders, women and youth representatives on each of the project islands

MOTIVATION FOR CONSIDERING ADAPTATION

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

As an island nation, Tuvalu is highly vulnerable to impacts of climate change. Infrastructure facilities, including wharves, breakwaters and other maritime infrastructure, are always vulnerable against sea level rise and frequent extreme weather events. Tropical cyclone Pam in March 2015 caused flooding and erosion of the west coasts and damaged maritime infrastructure. In Nanumaga, a ramp that had been helpful in loading and unloading cargo from the ships was washed away. In other outer islands such as Niutao and Nui, channels were silted up with boulders and sand.

Facing these difficulties, the government is committed to improving the maritime transportation network as articulated in the National Strategy for Sustainable Development – Te Kakeega II and the Infrastructure Strategic Investment Plan 2011-2015. By making maritime transportation more efficient and safer, Tuvalu envisages achieving the following objectives:

- economic development including fisheries
- improved livelihoods and safety conditions in the outer islands
- reduced migration from the outer islands to Funafuti, which currently faces problems with overcrowding, pollution, and spread of diseases

Since 2014, the Asian Development Bank has required all investment projects to consider climate risk and incorporate adaptation measures in projects at risk from climate change impacts. This in consistency with ADB's commitment to scale up support for adaptation and climate resilience in project design and implementation articulated in the *Midterm Review of Strategy 2020: Meeting the Challenges of a Transforming Asia and Pacific* (ADB, 2014a).

The ADB has established a Risk Management Framework aimed at reducing risks associated with climate change on investment projects by providing for climate risk assessments and inclusion of adaptation measures into projects at the design phase.

The initial risk screening undertaken for the Outer Island Maritime Infrastructure Project identified that the Project was at high risk from wind speed increase, offshore Category 1 storms, and sea level rise. All other risk topics were deemed to be low risk. These risk screening results have triggered the requirement for the preparation of a CRVA for the Project.

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

Due to the paucity of data available on current climatic and metocean conditions, the development of design parameters for present day water level and wave conditions was reliant on short term tide gauge data from Funafuti and WaveWatch3 data collected by the National Oceanic and Atmospheric Administration in the US. Additional monitoring/data collection was not considered feasible.

The climate change scenario adopted was RCP6.0 based on the current trajectory of emissions and adopting a 2065 planning horizon (or nearest available) consistent with the engineering design life of the infrastructure (50 years). The key resources consulted for information on existing and future climate for Tuvalu include:

- Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5)
- BoM & CSIRO (2014) Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and Updated Country Reports 2014. Pacific-Australia Climate Change Science and Adaptation Planning Programme
- TMS, BoM & CSIRO (2011) Current and future climate of Tuvalu. Pacific Climate Change Science Program. International Climate Change Adaptation Initiative

The key climatic parameters of relevance to the project that were considered in the CRVA were:

- sea level rise
- wind speed increase (and resultant impacts on waves)
- cyclones

RESULTS OF RISK ASSESSMENT

How were risks assessed/what methodology was used?

Following preparation of the preliminary concept designs, a Climate Risk and Vulneratbility Assessment (CRVA) was undertaken to inform the design development and ensure appropriate consideration of climate change adaptation requirements.

The CRVA involved the following steps:

- literature review to identify relevant climate change scenarios and projections
- risk assessment in accordance with ISO 31000:2009: “Risk Management – Principles and Guidelines” and AS 5334:2013: “Climate Change Adaptation for Settlements and Infrastructure – A Risk-Based Approach”. This involved setting the risk context/success criteria, assessing vulnerability and developing likelihood and consequence criteria. The success criteria included utilisation, functionality (‘user friendly’), maintenance and public safety
- developing potential adaptation measures for the identified climate change risks
- analysing the feasibility and cost-effectiveness of these adaptation measures
- prioritising the adaptation options

What were the main outcomes of the risk assessment?

The effects of sea level rise and increased nearshore wave heights were identified as representing an extreme risk to public safety. High risks included:

- more regular overtopping of the wharf, breakwater and ancillary facilities, making them unsafe or undesirable for use by the community
- permanent inundation of the shoreline connections and/or the wharf, making the infrastructure unsafe or unusable
- increased maintenance requirements due to increased nearshore wave heights and cyclonic activity

IDENTIFICATION AND PRIORITISATION OF ADAPTATION MEASURES

Which adaptation measures where recommended?

- Extend the jetty further inland, above future sea level. This may also require creating a raised mound where it meets the land, due to the low-lying nature of the island.
- Locate shore-based assets further landward above future sea level and/or storm surge level.
- Raise the breakwater crest levels and/or use larger armour units.

PROJECT OR INITIATIVE OUTCOMES

What were the main lessons learnt?

The main challenges for this project were the remoteness of the sites, lack of resources (both material and financial), and the lack of data. These characteristics are inherent to the location of these project sites and are therefore unlikely to be surmounted in the near future. Key considerations for such a project then become:

- Procurement – A local source of materials is unlikely. What materials could be used, where will they come from and how will they get to the site? Are the contractors experienced in working on such sites, and can they demonstrate they can overcome the logistical difficulties?
- Maintenance – Maintenance is generally a bigger concern than capital cost, keeping in mind the difficulties in obtaining resources to ensure the ongoing functionality of the assets. In some cases, it may be better to 'over-design' to minimise as much as possible future maintenance requirements and ongoing reliance on international donors.
- Lack of data – There is generally a lack of data on climatic conditions, which can present a challenge to establishing basic design parameters. For example, very limited or no tidal gauging has been done in locations such as Tuvalu, and therefore mean sea level and extreme water levels are not always known. Similarly, this represents a challenge for inferring future climatic conditions under climate change.
- Engineering feasibility – In some cases it is not possible to feasibly implement the typical adaptation measures. For example, Nukulaelae itself is very low lying, and therefore the ability to 'raise' infrastructure above future mean sea or storm surge levels is limited. Innovation in design can be important to overcome these constraints.

All these factors are significant drivers of the adoption of certain types of design and adaptive features for such projects.

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CASE STUDY 8 – RISK QUANTIFICATION FOR SUSTAINING COASTAL MILITARY INSTALLATION ASSETS AND MISSION CAPABILITIES, NORFOLK NAVAL BASE, USA

BACKGROUND

The objective of this study was to develop and test a risk-based methodology to evaluate threats to critical installation assets and to quantify the potential loss of mission performance when installation capabilities were impacted by a combination of rising sea levels and coastal storm hazards. The step-wise risk assessment approach used predictive inferences to quantify vulnerabilities of critical assets based on their exposure, sensitivity, and adaptive capacity to withstand storm forcings (tidal fluctuations, waves, winds, surge, sedimentation, saltwater intrusion, flooding, etc.) exacerbated by sea level rise. Hierarchical aggregations of assets were then arrayed in a relational network to capture interdependencies, and service interruptions were monitored from a systems perspective to capture the overall risk to mission performance.

This approach began with an environmental and geomorphological characterization of the baseline conditions of a region. Potential changes were mapped as likely to occur to the coastline under a variety of sea level rise (SLR) scenarios in a Geographic Information System (GIS) to better visualise the system's response to the combination of inundation and vegetative switching. High fidelity numerical models to simulate coastal storms and assess regional, nearshore, surface, and subsurface conditions were used under a range of SLR scenarios. These models generated a series of resultant forcings (winds, waves, surge, etc.) that impacted both the installation and its surrounding environs. An installation-specific Asset Capability Network (ACN) model was then created and used to capture the unique position, condition, and interdependencies of the installation's critical infrastructure in supporting the mission. An assessment of possible damages to the installation network was undertaken, and risks of mission impairment were quantified using probabilistic Bayesian analyses under the various storm and SLR scenarios.

This project scope and parameters were determined by the funding agency, the Strategic Environmental Research and Development Program (SERDP; https://www.serdp-estcp.org/) and were as follows:

- Develop analysis methods to assess the impacts of local mean sea-level rise of 0.5 m, 1.0 m, 1.5 m, and 2.0 m, and utilise these methods to assess the impacts to a coastal military installation.
- Include an assessment of the potential impacts caused by an increase in the frequency and intensity of storms.
- Include an analysis of the impacts due to: (1) inundation of land; (2) increased storm and flood damage; (3) loss of wetlands; (4) changes in erosion patterns and rates; (5) salt water intrusion in surface and ground waters; (6) rising water tables; and (7) changes in tidal flows and currents.
- For the specific military installation selected, examine:
  - loss of or damage to mission essential infrastructure
  - loss or degradation of mission capabilities
  - loss of training and testing lands
  - loss of transportation means, facilities and/or corridors
  - increased risk of storm damage
  - increased potential for loss of life (not including disease or other indirect health impacts)
- Utilise routinely available data and existing models.
- Develop methodologies capable of implementation at any DoD installation worldwide that may be affected by a rise in sea level.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

This effort was directed at the Naval Station Norfolk (NSN) in Hampton Roads, Virginia (located at the mouth of the Chesapeake Bay, North Atlantic coast of the United States) to test the efficacy of the approach. Stakeholders included the US Naval Facilities Engineering Command and the Naval Station Norfolk.

MOTIVATION FOR CONSIDERING ADAPTATION

With over 30 percent of the total United States population residing in coastal counties, changes in sea level represent a significant threat to coastal residents, infrastructure, and their way of life [Gill et al., 2009]. As a major U.S. land management agency, the Department of Defense (DoD) owns and operates numerous coastal facilities that are threatened. These Mid-Atlantic facilities carry out diverse tasks ranging from outdoor training activities (e.g. Camp Lejeune, North Carolina) to port and harbour facilities (e.g. NSN in Virginia) to air combat training (e.g. Langley Air Force Base, Virginia). In 2008, 30 of these installations were already experiencing increased risk due to SLR [National Intelligence Council (NIC), 2008].

The Mid-Atlantic coast (including these installations) supports a diverse ecological community and provides significant economic benefit to the region (e.g. migratory waterfowl hunting and blue crab shellfishery). Under SLR, both built and natural systems will undergo changes in structure and function which could drastically alter the system's capacity to provide these benefits and services. Although inundation is a primary concern, other effects of SLR such as increased storm susceptibility, barrier island migration, coastal erosion, wetland drowning, and saltwater intrusion should be accounted for to adequately understand the impacts of SLR on coastal installations [Gesch et al., 2009]. Of particular concern, conversion, migration, or loss of beach, marsh, or swamp features could result in loss of critical habitat and change storm surge attenuation.

CLIMATE CHANGE DATA USED

All modelling efforts for the case study focused on a series of 25 scenarios comprised of five prescribed sea level rise conditions ranging from 0.0 m to 2.0 m (by 2100) in combination with five simulated coastal storms ranging in intensity from 1-yr to 100-yr return intervals. In addition, three historical nor'easters were incorporated into the storm analysis (at the request of NSN managers) to capture the localised impacts of these unique storms, but were omitted from the risk-based analysis due to time and budgetary constraints.

RESULTS OF RISK ASSESSMENT

Risk-informed decision making implemented within the traditional military planning paradigm, requires information produced with decision-relevant risk analysis. Several guiding research questions have been used to fashion the study's technical approach:

1) What are the key pieces of information necessary to operationalize the risk assessment?

2) What is the risk of mission impairment or even failure if future sea level rise (SLR) were to happen at some level and a tropical (or extra-tropical) storm were to impact the study site?

3) Are there critical points of failure (i.e. specific assets that were most vulnerable) under any or all of the five prescribed SLR scenarios? These then could be provided to the managers to consider upgrades in advance of the potential threat.

4) What are the thresholds or tipping points?

With these motivations in mind, the team developed a series of goals and objectives to guide the development of a risk assessment framework.

Specific goals included:

- characterise the scope and magnitude of sea level change effects in existing and future no-action coastal installation conditions
- identify thresholds of significant onset of installation losses due to coastal hazard impacts
- advance the military's knowledge and capabilities for risk assessment as a strategic enabler to risk management

The project has had several significant outcomes. It produced a robust, scientifically informed risk-based approach that is applicable to coastal military installations threatened by coastal hazards and rising sea levels. As part of this effort, a series of stepwise procedures was established to couple multiple high-fidelity coastal storms models with installation-specific asset models and regional ecosystem response models to systematically assess risks to mission in a probabilistic manner using Bayesian networking.

A successful test of the framework on Naval Station Norfolk clearly illustrated the efficacy of the procedures and the benefits of deploying a risk-based approach. Numerous products were generated for the test case. For example, each model application generated a series of 25 forcings datasets and accompanying high resolution maps that captured the existing conditions and quantified the storm forcings (winds, waves, surge, etc.) impacting the area under the various sea level rise scenarios. Accompanying these analyses, several associated GIS-based products (model meshes, digital elevation models, land use cover classifications) have been produced for the study area. Although not a primary objective of this study, it is important to note that the test case also generated a series of GIS-based maps of forcings (winds, waves, surge, flooding, etc.) for the entire Hampton Roads area (for each of the SLR-storm scenarios studied) that can now be used to assess vulnerability of assets both inside and outside the installation, supporting community efforts to address the threats of SLR and coastal storm hazards from a regional perspective. The asset network model developed for the site offered a unique highly detailed systems perspective of the installation's service production (i.e. electric supply, water supply, waste removal, etc.), and has now been stored in the GIS database for use in future management and operations activities by the installation's personnel. The Bayesian model developed for the test site now holds more than 13,000 conditional probabilities characterising the fragility of the assets with regards to their location, condition, and structural composition. The relational Bayesian network quantifies impacts to capabilities and the risks to mission performance due to exposure to storm hazards and SLR.

Based on our analysis of NSN's site-specific vulnerabilities, sea level rise was found to be a significant and pervasive threat multiplier to mission sustainability, significantly increasing loadings on built infrastructure, and dramatically increasing risks to system capabilities and service provisioning. Using the framework, it was possible to identify several critical systems on the study site that were particularly vulnerable and likely to be incapacitated once sea levels rise above 1.0 metre on the site. The results show that the probabilities of damage to infrastructure and losses in mission performance increased dramatically once 0.5 metres of SLR was experienced, indicating a 'tipping point' or threshold that should be considered when undertaking future planning or operational activities on the installation.

IDENTIFICATION AND PRIORITISATION OF ADAPTATION MEASURES

The NSN Risk Model was also designed to explore adaptive management strategies via 'what if' scenario analysis. Proposed changes in the Asset Capability Network (i.e. insertions/deletions of assets or replacements/retrofits of assets) can be reflected in the model to actively manage system response and manage regrets. Several hypothetical modifications to the infrastructure network were explored to demonstrate these capabilities. In general, these analyses required either a change in the structure of the model's directed acyclic graph (DAG) (representing an insertion or removal of an asset) or a change in one or more of the conditional probability tables (CPT) (representing the replacement or retrofit of an asset). The four hypothetical modifications considered for this study included:

1. the removal of the primary steam plant from the infrastructure network
2. the removal of several backup electric power generators from the network
3. the flood proofing of these same generators
4. the flood proofing of the wastewater lift pumps, transformers, and backup electrical generators at each waterfront lift station

PROJECT OR INITIATIVE OUTCOMES

The analytical framework described herein can be used to evaluate relative performance of existing conditions, future no-action conditions, as well as structural and non-structural risk mitigating alternatives to sustain critical assets and mission capabilities at an actionable scale under a wide range of SLR and storm scenarios. Deploying this approach, defense installations can identify critical thresholds where minor mission impairment annoyances (on the order of ~1-2-hour delays in performance) evolve into catastrophic events (i.e. on the order of weeks or months). Once communicated to the planners and managers both on and offsite in an actionable construct through maps and network diagrams, installations can consider altering the status quo to incorporate proactive management strategies to prevent or anticipate impairments based on the risks (i.e. regret management). Moreover, military leadership can use these experiences to develop new guidance and policy to proactively address systemic, commonly occurring failures across the range of the military's holdings. In effect, this study offers a robust, scientifically defensible approach that transparently communicates potential risks to installations, while helping policymakers develop guidance to promote military readiness and sustainability in the face of climate change and sea level rise.

Taken together, the findings suggest that Department of Defense assets positioned on coasts and islands will be threatened by increased coastal hazards, which will ultimately threaten the Department's ability to sustain those resources needed for training, day-to-day operations, and assigned missions, in the face of climate change and sea level rise.

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CASE STUDY 9 – A QUALITATIVE CLIMATE RISK ASSESSMENT FOR AVATIU PORT, RAROTONGA, COOK ISLANDS

BACKGROUND

Brief case study description

How is the case study relevant to climate change adaptation (e.g. understanding and assessing climate change risk, collecting and analysing data)?

The vulnerability to climate change, and importance of, ports of Pacific Island countries to their national economies was brought to the attention of the Australian Government by the Australian Climate Change Adaptation Research Network for Settlements and Infrastructure and PIANC Australia following the Pacific Maritime Transport Alliance Conference held in Tonga in 2012.

In recognition of the importance of the Avatiu Port to the community of the Cook Islands, the Cook Islands Government initiated the project under the Pacific Adaptation Strategy Assistance Programme (PASAP) in partnership with the key stakeholders, the University of New South Wales' Water Research Laboratory, the Australian Government's Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education, and Climate Change Cook Islands.

The project uses Avatiu Port as a case study for implementing a qualitative risk assessment methodology that can later be applied to other Pacific Island ports. The methodology, through a process of surveys and information gathering with port and connected infrastructure managers in Rarotonga, was to identify the existing and primary risks of climate change on port facilities and operations. In addition, the project identifies the secondary risks to supply services for the Rarotonga and wider Cook Islands communities including fuel, energy, water, communications, transport, consumables and tourism. Critical linkages between the port and connected infrastructure services were identified their associated risks qualified. The project assessed existing adaptive capacity and present adaptation options for facilities and operations identified as being at high risk.

Funding for the project was provided by the Australian Agency for International Development (AusAID).

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

A 'key elements' approach from AGO (2006) was used to target port specific key elements through which risks were identified:

- vehicle movements inside the Port
- demand, trade levels and patterns
- goods storage
- environmental performance

- navigation and berthing
- goods handling
- inland connected infrastructure
- social performance
- insurance

The series of key elements were also developed to classify consequence [McEvoy et al., 2013 ; Stenek et al., 2011], including:

- interruption/halt to logistical operations
- interruption to boat movements
- increased maintenance costs
- deferment of capital expenditure
- increased insurance costs
- adverse reputational impact
- environmental impact
- regulatory impact
- lost time due to staff or contractor injuries
- adverse safety impact
- staff unable to attend works
- altered dredging schedule

Who was involved in the project (internal and external stakeholders)?

The importance of stakeholder engagement was recognised with meetings, discussions and interviews being held with many of the port staff and key managers and operational staff connected to infrastructure and service providers across government and the private sector. Information gathered from stakeholders included historical information on events that impacted the assets or operations in the past, and descriptions of the consequences arising from each of these historic events on the port, operations areas, connected infrastructure, and the region in general. Key stakeholder agencies consulted included:

- Cook Island Port Authority (CIPA)
- Emergency Management Cook Islands (EMCI)
- Cook Islands Trading Company (CITC; food and goods)
- Ministry of Infrastructure and Planning (MOIP; roads, bridges, drainage, water, waste)
- TRIAD Pacific Petroleum (fuel)
- Pacific Energy
- NES (National Environment Service)
- Airport Authority
- Cook Islands Tourism
- TAU (Te Aponga Uira; power-electricity)
- Telecom Cook Islands

MOTIVATION FOR CONSIDERING ADAPTATION

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

The Cook Islands comprise 15 islands spread over nearly two million square kilometres of ocean between French Polynesia and American Samoa. The town of Avarua is the capital of the Cook Islands and is located on the north coast of the Island of Rarotonga, within the southern group of volcanic islands. Avarua is the hub of the Cook Islands economy and is the most densely populated residential area on any of the Cook Islands. Government offices, the major telecommunications receivers/transmitters, water and solid waste treatment facilities, landfill sites, international airport, main fuel stores and Avatiu Harbour (which processes all incoming freight to Rarotonga and the other Cook Islands) are all situated along the Avarua to Nikao stretch of the Rarotongan coastline. Tourism is the main economic activity of the Cook Islands, and the tourism industry is heavily dependent on the functionality of this stretch of coast.

The northern coastline is dominated by two passages through the reef system, these being for Avatiu and Avarua harbours. Aside from the harbours the foreshore has either man-made or armoured slopes that form a 'bund' that varies in elevation from 2.5 to 5 metres Mean Sea Level (MSL). Landward of the foreshore bund the topography forms a lower basin with an elevation typically between 2 and 3 metres MSL. The lower inland area is drained to the lagoon via the stormwater network and streams.

The coastline of Rarotonga is typical of volcanic Pacific Islands, with a shallow fringing reef (approx. -0.3 metres MSL bed elevation) dropping into the ocean via a very steep carbonate reef system.

The key objectives of the project were to:

- understand the risks posed by changes to sea level and wave behaviour on coastal infrastructure and communities in the Avarua area, particularly during extreme events
- identify needs and develop options for responses to the risks
- build local capacity to understand the science and manage the risk assessment and planning process

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

For the Cook Islands, the ADB (2005) has identified the key climatic risks:

- extreme rainfall events
- drought
- high sea levels and extreme wave heights
- strong winds
- cyclones with occurrence of high sea levels, strong winds, and extreme waves
- extreme high air temperatures

Tropical Cyclones (TCs) are the biggest climatic risk facing the Cook Islands. Undoubtedly the worst cyclone in living memory for most residents of Rarotonga is TC Sally (1987), which resulted in widespread flooding from storm surge, overtopping and rainfall, but also destroyed and damaged many buildings along the coast through direct wave overtopping impacts. A series of five TCs in 2005 (Meena, Nancy, Olaf, Heta and Rae) also resulted in areas of significant localised damage. Although TC Sally (1987) and the 2005 cyclones resulted in significant destruction, TC sally was relatively low intensity (Category 2) while tracking over Rarotonga, and none of the 2005 cyclones tracked directly over the island. TC Sally was estimated at having a return interval of around 20 years. Events more severe than TC Sally have been recorded, including situations where storm surge is reported to have met the foot of the mountains in Avarua. Should such an event occur today, the complete township of Avarua would be almost completely inundated by storm surge, and the resulting destruction would be worse than occurred in TC Sally.

RESULTS OF RISK ASSESSMENT

How were risks assessed/what methodology was used?

The risk management methodology adopted for the project generally sought to align itself with the principles, framework and process set out by ISO 31000:2009, as adapted to port operations. The Australian Greenhouse Office [AGO, 2006] Guide to Climate Change Impacts and Risk Management was very useful in informing application of the standard in relation to climate change.

The key aspect of the project was the adoption of a hybrid risk/vulnerability approach [McEvoy et al., 2013] where consideration of current day vulnerabilities to extreme weather events is integrated with an assessment of future climate risks. This was found to be beneficial particularly useful in undertaking a 'first pass' vulnerability assessment that could not only act as a filtering tool, but would assist in identifying assets that required a more intensive risk assessment. It was considered preferable to keep measurement and recording at a minimum at this early, qualitative stage of the risk assessment.

The project methodology allowed for capture of factual and anecdotal information via a desktop study, and then a series of three surveys of port and connected infrastructure users:

- First Pass Vulnerability Assessment Part A – which considered the vulnerability of water-based, interface, land-based and connected infrastructure to extreme events associated with high wind, high rainfall, high waves, temperature, sea level rise, and cyclonic events (being a combination of several of these climatic factors)
- First Pass Vulnerability Assessment Part B – which considered how important each piece of connected infrastructure was to maintaining port operations
- Qualitative Risk Assessment – considering the outcomes of the first two surveys, the stakeholders rated the adaptive capacity of each asset for current and perceived future climate risk

What were the main outcomes of the risk assessment?

- Cyclones, which are projected to increase in intensity with climate change, create the highest risk to the port and connected infrastructure.
- The Port's practice of removing all assets (water and land based) from the Port region in advance of an approaching cyclone is an effective adaptation response which limits risk, and for the 1:20 year ARI TC Sally event operations were expected to resume within a few days.
- The wharves and berthing facilities at the Port were recently upgraded in 2012 (including allowance for sea level rise) and are in very good condition and possess adaptive capacity. There is around three to four-days' notice of a cyclone. Other adaptation measures that are employed by the Port prior to the arrival of a cyclone include:
    - Commercial and fishing boats are moved to higher ground, or in the case of large vessels cannot be transported overland, they are sent to sheltered moorings on the other side of the island
    - All the removable components of the Port facilities (including a mobile crane, tug boat and other plant and equipment) are also relocated to higher ground. Assuming little to no damage to these assets, the Port can resume operations within 12-24 hours following a cyclone
    - Securing of the three LPG gas containers that supply gas for cooking and water heating
- The recent upgrades to the Port ensure increased navigability, deeper basin allowance and more efficient quay wall alignment have assisted in limiting future climate related damage and risk.
- Notwithstanding the above, for a direct hit or impacts of a passing higher category cyclone (such as a 1:100-year ARI cyclone), the ability to respond and recover requires further assessment and planning and would likely result in longer downtime of Port operations.
- The Port relies upon the road and bridge infrastructure network, but can operate without water, power and communications.
- In contrast, the fuel, power, airport, goods and food (and thus tourism and the economy) rely heavily on the Port.

MONITORING

What monitoring was undertaken and why (e.g. weather or physical process variables, asset condition, performance of measures)?

Weather and climate are monitored by the Cook Islands Meteorological Service who also convey warning information from the RSMC Nadi Tropical Cyclone Centre. Tide data at Avatiu Port is collected by the National Tidal Centre as part of the Pacific Sea Level Monitoring Project.

No other monitoring data was obtained specifically for the project.

PROJECT OR INITIATIVE OUTCOMES

What were the main lessons learnt?

- For many such Pacific Island states, historical climatic data, tidal gauging, survey data and other data is lacking, which can be challenging when developing project-specific climatic projections.

While some data was used to inform the project, whether historical data or that collected during the course of the project, the methodology adopted highlighted the importance of anecdotal observations from historical events.

- The importance of engaging with stakeholders was invaluable in this study and should be considered necessary in any future climate change adaptation assessments for other Pacific Port projects.
- The study demonstrates the value of qualitative risk assessments in raising awareness (from CEO level through management and to operational staff) and the building of adaptive capacity.

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CASE STUDY 10 – NSW PORTS CLIMATE CHANGE RISK ASSESSMENT FOR TWO MARITIME PORTS: PORT BOTANY AND PORT KEMBLA, AUSTRALIA

BACKGROUND

Brief case study description

Port Botany and Port Kembla, located on the east coast of Australia, are managed and developed by NSW Ports under 99-year leases from the New South Wales (NSW) Government.

As the major container port in NSW, Port Botany is a vital part of the overall NSW logistics and transportation supply chain in facilitating trade growth in NSW. Port Botany is the sole container port servicing Sydney, the largest population centre in Australia and NSW, the most populated state and a major importer of goods. Port Botany is also the State's major facility for bulk liquids and gas.

Located around 90 kilometres south of Sydney, Port Kembla has historically serviced the needs of regional industries, predominantly coal (export) and steel (import of raw materials and steel products). In recent years Port Kembla has seen a diversification of its trade base to include general and breakbulk cargoes, containers and motor vehicle imports. It is the largest vehicle importing hub in Australia and the primary facility in NSW. It is also the principal grain export port for producers in Southern and South-Western NSW.

How is the case study relevant to climate change adaptation (e.g. understanding and assessing climate change risk, collecting and analysing data)?

In 2015 NSW Ports conducted a climate change risk assessment for their assets in both ports.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

Who was involved in the project (internal and external stakeholders)?

The risk assessment was facilitated by a consultant and involved stakeholders from various departments within NSW Ports, including personnel from various functions such as:

- management team (e.g. General Managers)
- strategic asset management
- engineering services
- operations and logistics
- environment and sustainability

These stakeholders are responsible for a range of functions in the port, such as:

- maintenance and operation of port infrastructure, including container terminals and berths, container handling and storage facilities, bulk liquids and gas storage facilities, the internal road network and truck marshalling area, and other assets
- environmental and sustainability planning, policy and management
- community and stakeholder engagement

MOTIVATION FOR CONSIDERING ADAPTATION

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

Following the purchase of the Port Botany and Port Kembla in 2013, NSW Ports prepared a 30-Year Master Plan and Sustainability Plan. The two documents outline a strategic vision for achieving sustainable and efficient management of Port Botany and Port Kembla. One of the goals articulated in the Sustainability Plan is: "To address the likely impacts of climate change on NSW Ports assets and adapt as necessary to ensure their long-term resilience."

As part of this process, NSW Ports undertook a qualitative climate change risk assessment. The risk assessment considered a range of factors that may impact port operations and assets in future. This included not only the direct impact of changes in climate, but also issues such as how government policy may affect the use of fossil fuels (and therefore shipping, e.g. of coal), and other potential changes in commodities being shipped through the port (e.g. grain export volumes).

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

At the time, the work was undertaken, the most up to date global climate change projections were from the Fourth Assessment Report (AR4) prepared by the Intergovernmental Panel on Climate Change (IPCC). The AR4 projections had been downscaled and regional projections developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Bureau of Meteorology (BoM) and reported in Climate Change in Australia [CSIRO and BoM, 2007]. The scenarios adopted were the near-term moderate climate change scenario and long-term upper range scenario.

RESULTS OF RISK ASSESSMENT

How were risks assessed/what methodology was used?

For their risk assessment, NSW Ports considered in a qualitative sense the potential impacts of climate change. Site specific numerical modelling was not undertaken for the project.

What was the solution / what were the main outcomes?

Sea level rise was not considered a significant climate change hazard for Port Botany or Port Kembla. Revised design criteria that take into account sea level rise and other climate change related impacts on water levels have been developed for fixed infrastructure such as new land reclamation or hard stand areas and breakwaters.

The key climate change-related hazards for the two ports were considered to be potential changes in sea-state and storm activity (i.e. wave heights, wave direction, and storm intensity and frequency). Port Kembla in particular is protected by significant breakwater structures and there is a risk the change in wave and storm activity could result in increased overtopping and/or dislodgement of armour units from the structures. However, the challenge in addressing the associated risk to the breakwaters is that the projections for future wave climate are too uncertain. It is at this stage unclear as to whether ongoing monitoring and reactive maintenance activities would suffice to manage the risk, or if significant works may be required at some stage in the future to increase the height or strength of the breakwater.

Other physical risks to port assets that were considered include:

- degradation of roads and pavements due to extreme temperatures and rainfall events
- increased risk of flooding and associated damage due to higher frequency and intensity of extreme rain events
- increased risk of power failure and degradation of electrical and communications infrastructure due to extreme temperatures and severe storms
- potential for increased rates of deterioration of marine infrastructure due to increased exposure to saline water (e.g. associated with sea level rise or increased incidence of wave attack)

In addition to physical risks to port assets, an increased frequency of extreme weather events may impact on port operations. Issues identified for consideration include:

- large swell and high winds closing Port Botany and Port Kembla to shipping
- high winds delaying quay crane operations
- high winds blowing over empty container stacks
- Hot weather stopping stevedoring activity

These aspects were assessed as being of low to moderate risk to NSW Ports. Given the relatively long timeframe for climate change with respect to asset life, it was thought that an adaptive approach to maintenance regimes and operating practices would be the most suitable risk management approach.

MONITORING

What monitoring was undertaken and why (e.g. weather or physical process variables, asset condition, performance of measures)?

No monitoring was undertaken specifically to inform this project, although NSW Ports routinely monitors a range of things, such as:

- water levels and offshore wave height and direction at Port Kembla
- condition of assets and associated maintenance records

Proposed changes to NSW Ports monitoring strategies are discussed below.

PROJECT OR INITIATIVE OUTCOMES

What were the main lessons learnt?

The first challenge relates to our ability to translate an understanding of the physical impacts of climate change into an appreciation of what these impacts may mean for NSW Ports' infrastructure and operations. NSW Ports decided that, while it was possible to allocate resources for numerical modelling of the site-specific impacts of climate change on Port Kembla and Port Botany, it would not necessarily add significant value due to the uncertainty in the climate change projections. While we can be relatively confident in the sea level rise projections, their greatest risk is in relation to the water level impacts of changes in wave heights and storm activity, for which the projections are much less certain.

For these reasons, NSW Ports considered the best value for money could be achieved by improved record keeping, such as:

- monitoring disruption to port activities due to storm events, and analysing the data for any trends over time (e.g. increase in rate or magnitude of disruptive events)
- standardising the maintenance processes across both ports to analyse trends in maintenance requirements and impacts on materials durability and performance
- continuing to monitor policy and trade patterns, and diversify the ports' throughput over time

Funds have also been allocated for a study to re-assess the existing breakwaters, which were identified as being potentially at risk from climate change. The study will consider the existing condition of the breakwaters and their vulnerability to increased damage or overtopping as a result of climate change.

Given that the port lands are elevated above future mean sea levels up to around 2100, this was considered sufficient, and a reactive management approach will be adopted in the short term.

NSW Ports' Development Codes require climate change risk assessments for new development proposals within Port Botany and Port Kembla. Proponents must consider design aspects relating to sea level rise and extreme weather events including high wind, high temperatures and storm surges.

Given the degree of uncertainty regarding the rate of future climate change, it may be appropriate to shift focus to developing trigger levels (e.g. an amount of sea level rise) that may lead to significant impacts on port operations, rather than a specific time-based planning horizon.

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CASE STUDY 11 – CLIMATE CHANGE IMPACTS ON COASTAL TRANSPORT INFRASTRUCTURE IN THE CARIBBEAN: ENHANCING THE ADAPTIVE CAPACITY OF SMALL ISLAND DEVELOPING STATES (SIDS)

BACKGROUND

Brief case study description

Small island developing States (SIDS) share a number of socioeconomic and environmental vulnerabilities that challenge their growth and development aspirations. Their climate, geographical, and topographical features as well as their critical reliance on coastal transport infrastructure, in particular seaports and airports, exacerbate these vulnerabilities, including their susceptibility to climate change factors, such as sea-level rise and extreme weather events. While recent studies by UNCTAD and others indicate that the Caribbean coastal transport infrastructure is vulnerable to mean sea level rise, storm surges and waves, heat waves and flash floods, climate change is projected to increase the region's vulnerability to hydro-meteorological hazards. At the same time, however, SIDS capacity to adapt and build the resilience of their coastal transport infrastructure is constrained. SIDS have limited capacity to conduct targeted risk - and vulnerability assessments and identify, prioritise and implement requisite adaptation options.

Against the above background, and drawing on earlier related work, since 2008, a technical assistance project on 'Climate Change Impacts on Coastal Transport Infrastructure in the Caribbean: Enhancing the Adaptive Capacity of SIDS' has been implemented by UNCTAD over the period 2015-2017. The main aims of the project were to strengthen the capacity of policy makers, transport planners and transport infrastructure managers in SIDS to understand climate change impacts on coastal transport infrastructure, mainly seaports and airports, and take appropriate adaptation response measures.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed and who was involved in the project (internal and external stakeholders)?

As part of the project, case studies focusing on two Caribbean SIDS (Jamaica and Saint Lucia) were carried out to (a) enhance the knowledge and understanding of the vulnerability of critical coastal transportation assets at the national level, and (b) to develop a transferable methodology for assessing climate-related impacts and potential adaptation options in Caribbean SIDS.

The draft case studies and methodology were reviewed and refined at a technical Expert Group meeting in June 2016 and were presented and discussed at two national capacity-building workshops held in Saint Lucia (24-26 May 2017, Rodney Bay) and in Jamaica (30 May-01 June 2017, Kingston). The workshops also provided an important opportunity for training and demonstration, as well as for feedback by a wide range of national stakeholders, with a view to finalising the case studies. A follow up technical meeting with key stakeholders from St. Lucia and Jamaica was convened, back-to-back with the regional workshop in Barbados, in December 2017, to take stock of progress, identify obstacles and lessons learned and consider further technical assistance needs.

To ensure significant multiplier effects, a regional capacity-building workshop on 'Climate Change Impacts and Adaptation for Caribbean Coastal Transport Infrastructure' was held in Barbados (5-7 December 2017, Bridgetown), bringing together seaports and airports authorities as well as a range of other stakeholders, experts, development partners, and organisations from the wider Caribbean region (21 countries and territories). The regional workshop provided an opportunity to present and discuss the findings of the national case studies for Jamaica and Saint Lucia, and to provide demonstrations and training on the methodology developed under the project. In the light of the impacts of the devastating hurricane season of 2017, the regional workshop also served as an important topical forum for exchange and discussion of collaborative action amongst stakeholders in the region. Regional workshop participants, as well as participating international experts, expressed the need for continued work in the area and identified several specific areas for follow-up.

UNCTAD's implementation of project activities benefited from collaboration with UNECLAC, UNDP, UNEP, the Caribbean Community Climate Change Centre (CCCCC), OECS Commission, as well as the Joint Research Centre of the European Commission (ECJRC) and academic experts, among others. PIANC participated in a technical expert meeting under the project, held in June 2016, to review and refine drafts of the case studies and methodology.

MOTIVATION FOR CONSIDERING ADAPTATION

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

UNCTAD has been working, 'ahead of the curve', on the implications of climate change for maritime transportation, since 2008[7], with a particular focus on impacts and adaptation needs of seaports and other coastal transport infrastructure. Direct weather and climate-related threats to ports include accelerated coastal erosion, port and coastal road inundation/submersion, increased runoff and siltation requiring increased dredging, water supply problems, access restrictions to docks and marinas, deterioration of the condition and problems with the structural integrity of road pavements, bridges and railway tracks. In addition, port and other transport operations (e.g. shipping volumes and costs, cargo loading/capacity, sailing and/or loading schedules, storage and warehousing) may also be severely impacted. Indirect impacts on ports and, more generally, international transportation, which are even harder to assess, arise through, for example, changes in the population concentration/distribution, as well as through changes in production, trade and consumption patterns, which are likely to lead to considerable changes in demand for transportation.

Port vulnerability varies across regions, and depends on many factors, including the type of risks faced, the degree of exposure and the level of adaptive capacity. SIDS are among the most vulnerable, as they are both prone to being affected by climate change-related (and other) natural disasters and have low adaptive capacity. The significance of weather and climate-related threats has been underscored by the recent impacts of Hurricanes Irma and Maria and other storms that wreaked havoc on several Caribbean airports and seaports during the 2017 hurricane season.

While the potential risk exposure for ports is significant, there are still important knowledge gaps about vulnerabilities, as well as the specific nature and extent of exposure that individual ports may be facing. Worth noting in this context are the results of an UNCTAD port-industry survey, which revealed important gaps in terms of information available to seaports of all sizes and across regions suggesting that urgent action should be taken to increase the knowledge base in ports.[8]

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

Impact assessments of changing climatic factors on coastal transport infrastructure and operations were carried out for climatic changes forced by a 1.5 °C temperature increase above pre-industrial levels, as well as for different emission scenarios and time periods in the present century.

State-of the art inundation modelling by the ECJRC produced flood maps focussed on ports and airports in Saint Lucia and Jamaica. Marine inundation was projected for different periods under different emission scenarios: extreme sea levels (ESLs) were simulated for the baseline historical period (1995) and under the 1.5 °C warming scenario, for 9 return periods (1, 1/5, 1/10, 1/20, 1/50, 1/100,1/200, 1/500, 1/1000 years). Simulations were also carried out for 2020, 2030, 2040, 2050, 2060, 2080 and 2100 under two emission scenarios (RCP4.5 and RCP8.5).

In addition to climatic factors forcing coastal marine flood inundation (i.e. sea level rise, storm surges and waves), other climatic stressors (e.g. extreme heat, precipitation and wind speed) that can cause operational disruptions/damages to the ports and airports considered in detail as part of the case studies were also covered. For the assessment of operational disruptions caused by the exceedance of operational thresholds, climatic data were extracted from the Caribbean Community Climate Change

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[7] For further information and documentation, see https://unctad.org/en/Pages/DTL/TTL/Legal.aspx.

[8] Port Industry Survey on Climate Change Impacts and Adaptation (UNCTAD/SER.RP/2017/18).

Centre's (CCCCC) database that contains downscaled daily climate projections for the period 1970 - 2100 from the Regional Climate Model RCM PRECIS.

RESULTS OF RISK ASSESSMENT

Important outcomes of the two case studies include an assessment of the potential vulnerabilities to climatic change of two Caribbean SIDS, focusing on potential operational disruptions and the marine inundation risk of critical seaports (also coastal international airports) in Jamaica and Saint Lucia. In that context, historical hydro-meteorological impacts and disruptions were summarised and direct and indirect impacts on the critical coastal transport assets of St. Lucia and Jamaica were assessed.

Approach to vulnerability assessment of critical coastal transportation assets

Direct impacts. The following approaches were adopted to assess direct impacts of climate variability and change (CV & C) on critical coastal transport infrastructure/assets in Saint Lucia and Jamaica:

- assessment of direct impacts of changing climatic factors on coastal transport operations using the 'operational thresholds' method
- assessment of direct impacts on coastal transport infrastructure through modelling of the flood/inundation due to extreme sea levels (ESLs) under the present and future climate

The operational thresholds approach included the following steps: 1) Identification of the operational thresholds (e.g. extreme temperatures and rainfall under which facility operations are impaired); as specific facility thresholds were not available, generic thresholds were used. 2) Collation of climatic data: Climatic projections from the RCM PRECIS were abstracted from the CCCCC database; available projections are for the SRES A1B scenario (which in terms of emissions and potential impacts, approximates the RCP6.0). 3) Operational thresholds and the RCM PRECIS climatic projections were then compared to assess threshold exceedance frequencies.

Assessment of the direct impacts on coastal infrastructure was carried out through modelling of the marine flood/inundation due to extreme sea levels (ESLs) under the present and future climate. ECJRC contributed to the study in that context. Extreme sea levels for different emission scenarios and periods in the 21st century have been estimated by combining projections of Mean Sea Level Rise (MSLR) with projections of astronomical tide changes, and the episodic coastal water level rise due to storm surges and wave set ups. Storm surges were simulated using a flexible mesh setup of the DFLOW FM model, whereas wave projections were provided by the spectral wave model WW3; in both cases, atmospheric forcing was provided by ERA-INTERIM projections. Effects of cyclones on coastal sea levels were also taken into consideration in the projections. The projected total ESLs were then used to simulate marine coastal flood/inundation on the basis of dynamic simulations using the open-access model LISFLOOD-ACC (LFP) and the available digital elevation models (DEMs).

Indirect impacts. Potential indirect CV & C impacts on tourism in Saint Lucia were also assessed. Since most of the tourist infrastructure is concentrated along the island beaches, potential CV & C impacts on St. Lucia's tourism (with potential implications for the demand for air transport) were projected through the 'proxy' of decreasing carrying capacity of the beaches due to beach erosion under different climatic forcings. The geo-spatial characteristics (e.g. beach width maxima) and other attributes (e.g. backshore development) of all ('dry') beaches of Saint Lucia were recorded using the images and other related optical information available in the Google Earth Pro application. Seven cross-shore analytical and numerical morphodynamic models were used in appropriate ensembles to project the response of Saint Lucia's 'pocket' beaches to long and short-term SLR.

What were the main outcomes of the risk assessment?

Key project outcomes included the assessment of potential vulnerabilities to climatic change in two Caribbean SIDS, focused on potential operational disruptions and marine inundation risks to coastal international airports and seaports of Jamaica and Saint Lucia under different climate scenarios.

The 1.5 °C temperature increase cap above pre-industrial levels – included as an aspirational goal in the Paris Agreement (Art. 2.2) and of particular importance for SIDS – was translated into a date year under the project. According to the analysis, the 1.5 °C temperature increase cap will be reached by 2033 under the IPCC RCP4.5 and by 2028 under the RCP8.5 scenario. Both operational disruptions and marine inundation are projected to increase significantly in Saint Lucia and Jamaica when the temperature rise cap of 1.5 °C is exceeded. See also IPCC 1.5 degrees report, Chapter 3, with reference to Monioudi et. al, 2018.

Climatic operational thresholds:

- Operational disruptions are projected when the temperature cap of 1.5 °C is exceeded. It appears that most operational problems for the Jamaican and Saint Lucian critical transportation assets will be due to rising temperatures (apart from marine inundation).
- Outside working conditions: by the early 2030s, staff working outdoors at the Jamaican and Saint Lucian international transportation assets could be at 'high' risk for 5 and 2 days/year, respectively; by 2081-2100, such days could increase to 30 and 55days/year, respectively.
- Energy needs: it was found that for e.g. the Jamaican seaports, a 1.5 °C temperature rise will increase energy requirements by 4 % for 214 days/year, whereas a 3.7 °C rise (2081-2100) will increase energy requirements by 15 % for 215 days/year. Saint Lucia seaports are projected to experience similar trends.
- Extreme rainfall: future disruptions due to intense (> 20 mm/day) and very heavy rainfall (> 50 mm/day) are projected not to differ significantly from those of the baseline period.
- Strong winds: the projections show that future winds will not affect significantly airport and seaport operations on the basis of these thresholds.

Limitations: As the climate projections from the CCCCC database do not include the effects of tropical storms/hurricanes, these results may be considered as underestimates. Also, facility-specific operational sensitivities that cannot be captured by generic thresholds (e.g. the disruptive effects of wind and wave directional changes on ship berthing) may also increase operational disruptions.

Coastal (marine) inundation:

Projections showed that the critical transportation assets of both SIDS would face rapidly increasing marine inundation risks compared with the current situation, with those of Saint Lucia being at higher risk than those of Jamaica. The results also suggest that, even under the 1.5 °C temperature increase cap, some of the critical assets of the islands will face increased direct marine inundation under extreme events, which will deteriorate very significantly and involve other assets later in the century. Flood maps illustrating the vulnerability to marine flooding of key international transport assets in both countries are available at SIDSport-ClimateAdapt.unctad.org (see also Monioudi et al. (2018)).

JAMAICA	
Kingston Freeport and Container Terminal (KCT)	By 2030, some areas of the KCT seaport are projected to be flooded under the ESL100, whereas by 2100, much larger areas will be affected. Its access roads are also projected to be vulnerable to flooding.
Historic Falmouth Cruise Port (HFCP)	HFCP cruise port will be very moderately affected until the 2080s, even by events with return periods in excess of 200 years. However, it appears that the low-lying access roads will be increasingly vulnerable to flooding.
SAINT LUCIA	
Port Castries (CSP)	The ESL100 is projected to impact docks severely, inundate berths, cargo sheds and cruise ship facilities and cause flooding of the city, even under 1.5 °C warming scenario; later in the century and under both RCP scenarios tested, CSP flooding is projected to deteriorate in the absence of effective adaptation measures.
Vieux Fort Seaport (VFSP)	VFSP appears vulnerable to marine flooding under all tested scenarios, which is markedly different from its previous experience.

PROJECT OR INTITATIVE OUTCOMES

A methodology was developed under the project to assist transport infrastructure managers and other relevant entities in SIDS assess climate-related impacts and adaptation options for coastal transport infrastructure. The methodology provides a structured framework for the assessment of impacts with a view to identifying priorities for adaptation and effective adaptation planning for critical coastal transport infrastructure. It takes a practical approach that uses available data to inform decision-making at a facility, local, and national level. Technical elements include an 'operational thresholds' method to determine the climatic conditions under which facility operations might be impeded, as well as coastal inundation modelling (see above). The methodology is transferable, subject to location specific modification, for use in other SIDS within the Caribbean and beyond.

The case studies and the workshops also generated a wealth of information on vulnerability assessment and adaptation processes in Caribbean SIDS. Major lessons learnt fall into three categories:

1. Data:

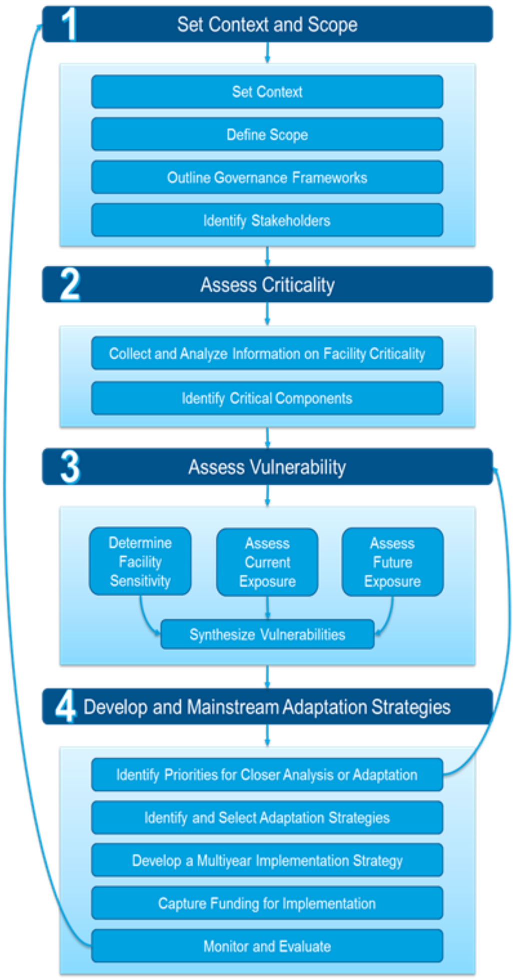
- Data collection efforts take time; many SIDS lack baseline data
- Site visits and interviews with local stakeholders are essential ('the map is not the terrain')
- Steps to validate stakeholder input from facility managers can ensure high-quality inputs
- Identifying facility specific sensitivity thresholds can help streamline and improve the vulnerability assessment process
- Further research, including detailed technical studies, as well as collaborative concerted action at all levels is urgently required

2. Awareness and coordination:

- Communication and collaboration among public and private sector stakeholders are key
- Ports/airports already taking action to increase resilience should share their success stories
- There is a need for regional cooperation, and to build a knowledge base and community of practice around vulnerabilities

3. Implementation:

- Organisational 'best practices' can increase resilience, and vice-versa.
- 'Mainstream' adaptation activities into existing planning and decision-making processes
- Climate change adaptation often comes down to a policy decision related to risk tolerance
- Financing for capital projects remains a major hurdle
- Ecosystem enhancements can play a significant role in reducing natural hazard risks, including coastal hazards and inland flooding



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CASE STUDY 12 – SAN PEDRO BREAKWATER (LOS ANGELES, USA) SEA LEVEL RISE IMPACT ASSESSMENT

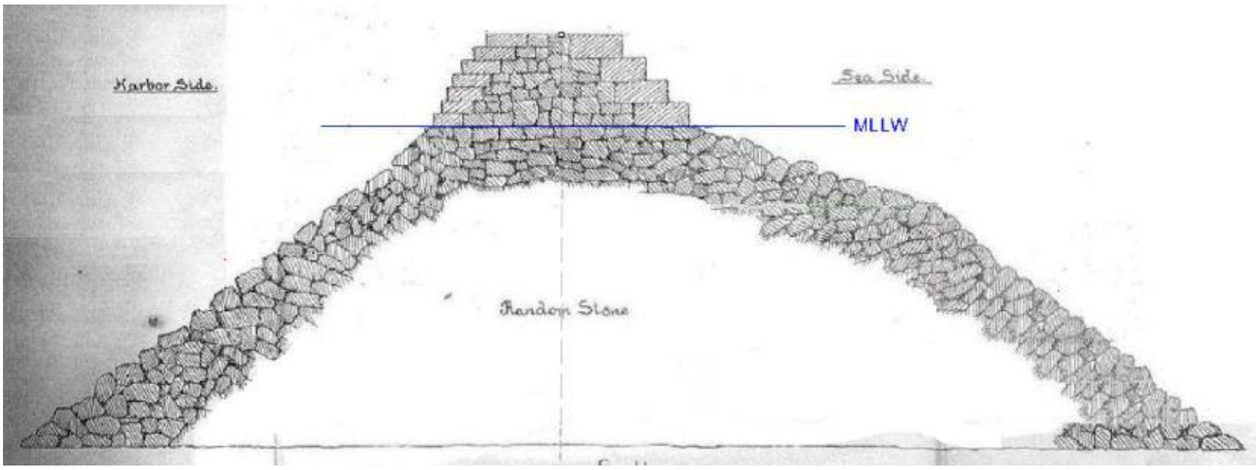
BACKGROUND

Brief case study description

The San Pedro Breakwater is one of the three U.S. Government breakwaters in San Pedro Bay (Los Angeles, California, USA). The breakwater provides the Port of Los Angeles with wave protection for its infrastructure, navigation, berthing, and cargo operations. It is located in approximately 15 metres water depth and consists of a superstructure of 8 to 25-tonnes fitted granite blocks underlain by a rubble mound substructure. It was built just over 100 years ago, and, by current standards, its design can be considered obsolete.

How is the case study relevant to climate change adaptation (e.g. understanding and assessing climate change risk, collecting and analysing data)?

Besides design considerations that make it vulnerable to damage, the breakwater exhibits some structural issues of concern. From a climate change vulnerability perspective, the key issue of concern is that its crest has settled an average 0.60 metres from its 4.25 metres mean lower low water (MLLW) design elevation. The average crest level of the breakwater is now around 3.65 metres. The reduced crest elevation makes the breakwater vulnerable to wave overtopping and damage in 2 metres MLLW spring tides and storm wave conditions. Sea level rise due to climate change is expected to exacerbate this situation, increasing the vulnerability of the structure and requiring adaptation to accommodate the increased risk.



SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/ operation/ management activities were assessed?

The assessment was limited to the condition of the breakwater and the increased vulnerability due to sea level rise.

MOTIVATION FOR CONSIDERING ADAPTATION

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

Since its completion in 1912, the San Pedro Breakwater has been damaged and repaired several times. Damage has typically occurred during strong El Niño years when, in Southern California, the mean sea level (MSL) could be as much as 0.30 metres above normal and the frequency of storms typically increase. The damage mechanism in all these events consisted of the displacement of numerous granite blocks from the superstructure due to the combination of high waves and high water levels.

During the El Niño of 1939, the breakwater suffered its first severe damage due to waves caused by the tropical storm of 25 September 1939. On 1 March 1983, during one of the strongest El Niño events on record, the breakwater was subjected to severe wave attack combined with exceptionally high water levels, which resulted in the most extensive damage the breakwater has suffered to date. At the Port of Los Angeles tide gauge, the measured peak water level during the storm was 2 m MLLW and the latest wave hindcast (3-hour interval, from 1970 to 2008 (39 years) [Halcrow, 2014]) showed that the storm generated 3.85 m, 17-second waves coincident with the peak water level. The breakwater was breached at six locations with one breach extending approximately 120 metres. In the El Niño winter of 1987-88, the breakwater was again subjected to severe wave attack during to the storm of 17-18 January 1988. This storm did not generate as large waves as the storm of 1983, and while the water levels were exceptionally high, water levels did not peak at the same time as the highest waves. The measured peak water level during the storm was 2.2 m MLLW and the latest wave hindcast [Halcrow, 2014] showed that the storm generated 1.6 m, 10-second waves at the time of the peak water level. Considering that the crest of the breakwater is on average at 3.65 metres MLLW and that spring tides can reach approximately 2 metres MLLW, the resulting approximately 1.7 metres freeboard is inadequate in high water level/storm conditions. The wave climate in San Pedro Bay exhibits wave heights higher than 1 metre approximately 5 % of the time and the 100-year wave height is in the order of 3.8 metres.

The settlement of the breakwater has resulted in a reduced freeboard and an increased likelihood of wave overtopping and damage, and the damage history evidenced that the San Pedro Breakwater is vulnerable to high waves and water levels. This was confirmed with an analysis performed with NN_OVERTOPPING, a neural network wave overtopping model developed by Deltares (2016), using surveyed cross sections of the breakwater and 39-year time histories of waves and water levels. The average discharges (i.e. water overtopping due to waves) computed for the storm of March 1983 (> 200 L/m/sec) were consistent with the damage produced by that storm. Finally, the wave and water level hazards were combined into a single hazard, the relative freeboard parameter R/H where R is the freeboard (= crest – still water level) and H is the significant wave height. A 39-year time history of R/H was computed and correlation between R/H and damage observed in condition assessments of the breakwater and 1:30-scale model tests [USACE, 1984] indicated that damage to the superstructure due to wave overtopping may occur in high wave/high water level conditions when R/Hs are in the order of 0.3 to 0.45, while damage to the foundation of the superstructure may occur in high wave/low water level conditions when R/Hs are in the order of 0.7 to 1.

Given the scientific evidence that sea levels are rising and that will continue to rise because of climate change, an increase in the vulnerability of the breakwater and frequency of damage is therefore expected. The damage due to high sea levels and severe storms that occurred in strong El Niño years can be considered representative of the damage that may occur in climate change scenarios when these conditions would be typical as opposed to episodic. Consequently, the impact of sea level rise (SLR) due to climate change on the vulnerability of the breakwater needed to be assessed. This was accomplished by performing a risk analysis by which the annual frequencies of failure of the breakwater were computed and compared for two scenarios: a) the current sea level and b) for a sea level scenario due to climate change.

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

Because cost would likely limit adaptation works to a one-time event and due to the uncertainty in end-of-the-century SLR projections, a 0.60 metre 'high' (A1FI) SLR scenario was selected from projections by the National Research Council (2012) for the year 2060 (50 years of additional service life from 2010). The annual frequency of non-exceedance of R/H was computed from the 39-year time history of R/H, and given that there is no basis to determine what distribution would be more appropriate to represent the fragility (probability of failure) of the granite block superstructure of the breakwater, a lognormal distribution was assumed as this distribution is often used in structural evaluations.

RISK ASSESSMENT

How were risks assessed/what methodology was used?

The methodology followed in the risk analysis consisted of selecting the sea levels for each scenario, estimating the corresponding annual frequency of non-exceedance of R/H and the breakwater fragility, performing a systems analysis, and risk quantification.

Failure was defined as the unacceptable degree of damage that would lead to loss of functionality (e.g. decreased capability to provide wave protection), and to repairs that would prevent further damage and restore functionality. For the purpose of quantifying the damage due to R/H and to estimate the fragility of the breakwater, unacceptable damage levels achieved in model tests [USACE, 1984] were used. To account for the variability of the wave conditions along the breakwater, as well as the variability of cross section geometry and stability, breakwater fragilities were estimated at representative locations for three segments of the breakwater: the 900-metre west segment, the 550-metre curved segment, and the 1,360-metre east segment. Along each segment, the breakwater's physical characteristics were assumed to be similar. The breakwater was modelled as a series system, where each segment performs and fails independently, and the breakwater fails when one or more segments fail.

What was/were the main outcome(s)?

The risk analysis was performed at a preliminary level and based on limited available information and engineering analysis. Consequently, it provided a conservative estimate of the annual frequency of occurrence of failure. It indicated that the mean annual frequency of breakwater failure due R/H is 0.11 for the current sea level, and 0.25 for a 0.60 metre SLR due to climate change by 2060, an increase by a factor of 2.3.

PROJECT OR INITIATIVE OUTCOMES

At 0.11, the mean annual frequency of failure due to R/H in the current mean sea level scenario is higher than the 0.03 annual frequency of breakwater failure estimated from the breakwater's damage and repair history. This discrepancy can be attributed to the limited data available to define the breakwater fragility and the assumptions used in the analysis. In any case, while this discrepancy could be perceived as large in an absolute sense, in relative terms it clearly shows that SLR due to climate change would have a significant impact on the vulnerability of the breakwater. Increasing the breakwater crest elevation appears to be a justifiable solution to reduce the risk of failure. Detailed analyses would be required to reduce the uncertainty in the breakwater fragility and to define a design crest elevation to adapt to SLR due to climate change. For the existing superstructure, these would include physical model tests for combinations of R/H, wave period and angle of incidence or, for the assessment of wave damage if alternative superstructure designs are considered.

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CASE STUDY 13 – IFC'S CLIMATE RISK AND PORTS TERMINAL MARITIMO MUELLES EL BOSQUE, CARTAGENA, COLOMBIA

BACKGROUND

Brief case study description

Muelles el Bosque (MEB) is a port terminal in Cartagena, Colombia. At the time of the study MEB employed approximately 250 people and handled four types of cargo: containers, grain, bulk materials and coke (in decreasing order of average throughput for the period 2005-2009). Between 2005 and 2010, containers represented the largest share of MEB's revenue. In 2008, MEB moved 1 % of Colombia's international trade (in tonnage). The 10ha-terminal is located in a mixed industrial and residential zone of Cartagena. It is composed of two sites, an island named 'Isla del Diablo' and an adjacent mainland area linked via a causeway road.

How is the case study relevant to climate change adaptation (e.g. understanding and assessing climate change risk, collecting and analysing data)?

Recognizing these issues, the IFC Adaptation Program aims to develop knowledge, tools and methods for analysing climate-related risks and opportunities to the private sector, and for evaluating adaptation responses. This is being achieved initially by undertaking case studies of some of IFC's investments, to investigate how they could be affected by climate change. Within this context, IFC has commissioned this report for a port, Terminal Maritimo Muelles El Bosque (MEB), in Cartagena, Colombia. The report presents the outcomes of an assessment of the potential risks and opportunities from climate change for MEB, along with analyses of climate-resilient actions that the company can consider.

The report aims to address the following questions:

- What risks and opportunities does climate change present for MEB?
- What are the most significant risks for MEB?
- How could MEB manage climate change risks in the most economically optimal way, taking account of environmental and social objectives?
- How could climate-related opportunities be developed and exploited?
- Where could MEB work in collaboration with other stakeholders to manage climate risks?
- What tools and techniques for climate risk assessment and management can be applied to understand these issues?

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

The study analysed effects of climate impacts on all key direct and indirect assets and operations that may affect the company's financial returns, and environmental and social performance. In addition to the assessment of terminal assets and operations in direct ownership or control of the company, additional elements included impacts on navigation in the region and the port's competitiveness, effects of climate change on the main goods transported through the port, and goods' movement beyond the port gates.

Who was involved in the project (internal and external stakeholders)?

The study was led by the International Finance Corporation (IFC) and elaborated by the consultancy Acclimatise, in cooperation with WorleyParsons, University of Oxford, Synergy, Exocol, and Universidad Nacional de Colombia.

The following institutions contributed to the study:

- Alcaldía de Cartagena de Indias – Secretaría de Infraestructura
- Centro de Investigación de la Caña de Azúcar de Colombia (Cenicaña)
- Centro de Investigaciones Oceanográficas e Hidrográficas de la Dirección General Marítima (CIOH)

- Centro Internacional de Agricultura Tropical (CIAT)
- Centro Nacional de Investigaciones de Café (Cenicafé)
- Corporación Autónoma Regional del Canal del Dique (CARDIQUE)
- Corporación Colombiana de Investigación Agropecuaria (CORPOICA)
- Departamento Nacional de Planeación (DNP)
- Dirección General Marítima (DIMAR)
- Federación Nacional de Cafeteros
- Fundación Natura; Instituto Colombiano Agropecuario (ICA)
- Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia (IDEAM)
- Instituto de Investigaciones Marinas y Costeras (INVEMAR)
- Ministerio de Agricultura y Desarrollo Rural
- Ministerio de Ambiente, Vivienda y Desarrollo Territorial (MAVDT)
- Puerto de Mamonal
- Sociedad Portuaria Regional de Cartagena (SPRC)
- Universidad de Cartagena
- Universidad de los Andes – Centro Interdisciplinario de Estudios sobre Desarrollo (CIDER)

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

For this study, a broad set of climate models and greenhouse gas emission scenarios (A2, A1B and B2) were considered, to capture the range of uncertainty in future climate change. Results of the regional PRECIS model were also used.

The observational data was obtained from a variety of local resources, principally from Instituto de Hidrologia, Meteorologia y Estudios Ambientales (IDEAM, the Colombian institute of hydrology, meteorology and environmental studies).

Climate and climate-related variables	Observed conditions recorded by meteorological stations and tidal gauges in Cartagena	Future scenarios from climate model projections
Mean temperature	• Between 26.7°C and 28.5°C (average monthly) • No obvious trend in temperature over the last 70 years	• Increases of 0.7 to 1.2°C by the 2020s, 1.2 to 2.2°C by the 2050s and 1.7 to 3.7°C by the 2080s (projected by an ensemble of Global Climate Models (GCM)) • Potential increases up to 6°C by the 2050s (projected by an ensemble of downscaled GCMs)
Mean precipitation	• Annual average rainfall was about 600mm per year in the 1940s and has risen steadily, to about 1,100 mm per year in the last decade • Increase of 6mm per year in 1941-2009; corresponding to a 0.6 % increase per year on wet days	• Assumed yearly increase of 0.6 % on wet days, based on continuation of observed trends • Climate models perform poorly at projecting future rainfall in Colombia
Sea level rise	• Rising at 5.6 mm per year (± 0.008 mm) *(Source: Tidal gauge data)*	• 'Observed sea level rise scenario': 5.6 mm per year, i.e. 504 mm by 2100 • 'Accelerated sea level rise scenario': 1,300 mm by 2100
Wind	• Calm or between 1.6 and 13.9 m/s for most of the time	• Increases by up to 0.2 m/s by the 2020s and 0.5 m/s by the 2050s and 2080s (projected by an ensemble of GCMs) • Winds in the range 3 to 10 m/s could become more frequent (projected by the regional climate model PRECIS)
Storminess and storm surges	• Not affected by tropical cyclones • Storm surge height up to 171 mm for a 1 in 300-year event	• Little to no change

RESULTS OF RISK ASSESSMENT

How were risks assessed/what methodology was used?

These analyses have been undertaken through a combination of desk-based studies and modelling, and discussions with MEB, government and Colombian climate change experts, during a two week visit to Colombia in November 2010. Discussions with MEB during the site visit were particularly important in helping to define the key risks associated with climate change. For the risk assessments, the study used both observed and projected future changes in climate conditions.

Risk significance is evaluated by scoring the two dimensions of risk, namely the likelihood of a hazard and the magnitude of its consequence. The consequence and likelihood ratings are scored from 1 (low) to 5 (high). Where relevant, the risk assessment considered the implications of climate variability as well as average changes in the future climate.

What were the main risks/what were the main outcomes?

The assessment for MEB revealed that among all the potential impacts that climate change could have on ports in general, only a few issues are of significance to MEB:

- impacts on vehicle movements inside the port due to sea level rise
- demand, trade levels and patterns
- goods storage
- navigation and berthing
- goods handling
- inland transport beyond the port
- environmental impacts
- social impacts

Others climate-related issues were found to be less significant for MEB but may be critically important to other ports. For example:

- Vulnerability to extreme coastal flooding due to mean sea level rise and changes in storm surges can be very critical in some ports, as shown by the costs of Hurricane Katrina for US ports. However, by virtue of its protected location in the Bay of Cartagena, and because Cartagena lies south of tropical cyclone tracks, MEB is unlikely to be affected by potential increases in tropical cyclones.
- High winds can cause damage to port buildings or equipment, as well as costly disruptions. However, Cartagena does not experience strong winds and climate models do not point to large increases in wind speeds in the region.
- It should be noted that, currently, climate models are not good at projecting changes in wind speeds and tropical cyclones. However, ongoing and future climate model improvements will increase confidence in these projections.

IDENTIFICATION AND PRIORITISATION OF ADAPTATION MEASURES

How were the possible adaptation measures identified and which ones where recommended?

For all the climate change risks identified across MEB's activities, the study identified adaptation measures. Where risks to MEB were found to be significant, an appraisal was undertaken of the costs and benefits of adaptation. The level of detail of these adaptation assessments is a function of the level of confidence in climate change projections: where there were reasonably good future projections (for example, for sea level rise), trigger dates for undertaking adaptation were identified and different adaptation scenarios were compared (e.g. incremental adaptation over time against 'one-off' adaptation).

The adaptation options recommended for consideration by MEB included:

- raising the height of the causeway road between the island and the mainland

- paving of the port's unpaved areas to reduce future maintenance costs, reduce vehicle maintenance, and minimise dust generation
- improve drainage capacity to reduce flood risk. It was recommended that this be complemented by a range of initiatives, such as improved inspection and maintenance practices and fitting tide flaps to drainage outlets
- investigate climate resilient commodities and consider the need to diversify or transition the types of commodities shipped through the port
- protect goods from inundation by seawater using measures such as, increasing floor levels of storages areas, providing emergency flood protection to storage areas, store perishables in less vulnerable port areas, and increasing the crest level of the wall protecting the port
- contract additional insurance to cover climate-related hazards (e.g. those that affect access to and from the port)

PROJECT OR INITIATIVE OUTCOMES

What were the main outcomes?

The objective of the study and their results were identification of climate risks and recommendation of adaptation options addressing those risks. Following on the recommendations of the work, MEB invested US$ 10 million in upgrading the port infrastructure to address the impacts.

What were the main lessons learnt?

Depending on facilities' characteristics, a relatively low investment in assessment of climate risks help a port improve its short- and longer-term performance, assist in medium- to long-term investment planning, and help in the overall competitiveness of a facility.

As with most climate change risk and adaptation assessments, the gaps and barriers identified in this study fall within the following categories:

- lack of quality localized data (such as LiDAR elevation datasets)
- uncertainty in future climate projections, relative to climate change timescales
- lack of knowledge of existing climate risks and adaptation measures
- short time horizon for investment decisions
- failure by other organisations to acknowledge climate change

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CASE STUDY 14 – ALBERT CANAL (BELGIUM): PUMPING INSTALLATIONS/WATER POWER PLANT

BACKGROUND

Brief case study description

In the eastern part of Flanders one of Belgium's biggest canals is situated: the Albert Canal. This canal connects the industrial zones from the (French-speaking) Walloon part of Belgium with Antwerp, Belgium's largest harbour. Ships can continue at both ends of the canal, to the Netherlands (e.g. Rhine, Rotterdam) and to France (Meuse). Because of the building of the canal also some important industrial areas were developed along it, making it an economically extremely important waterway for Belgium, with a total traffic of 40 million tonnes per year, avoiding 6,000 trucks daily on the highways.

The canal gets its water from the river Maas (Meuse), a river only fed by rain. The Maas is also feeding other canals, with the Juliana canal to the Netherlands being the most important. Therefore, agreements had to be established with the Netherlands to address situations of extreme weather events, including low water events. In some (rare) cases, the discharge of the river Meuse is not enough for feeding all canals in Flanders and the Netherlands and for maintaining a minimum discharge in the Meuse itself. During these periods, the water level of the Albert Canal can drop, so that the allowed draft for ships has to be reduced, making inland navigation less attractive as transport mode. Up to now these problems were addressed by a number of measures, such as lift-locking of professional shipping with less water and limiting water withdrawals for agricultural and nature management purposes, but these measures implied accepting associated economic and ecological damages.

Climate change is expected to cause more frequent and longer periods of drought in Belgium, which will lower the water level of the Albert Canal and in this way reducing the allowed draft for inland navigation and making it less attractive for the transportation of goods.

To avoid economic damage due to reduced navigability of the canal, De Vlaamse Waterweg nv, the former nv De Scheepvaart, part of the Flemish administration of Mobility and Public Works, has worked with stakeholders to investigate potential solutions. As an outcome of the study within each of the six locks of the Albert Canal three Archimedes' screws, each with a length of 28 metres, a width of 4.3 metres and a weight of 85 tonnes, will be installed – the largest in Europe.

In case of drought these screws pump up maximum 15 m^2/s of water upstream of the lock. In normal circumstances (an average availability of water), the screws are used as a hydropower plant and the pumps work as an electricity generator. The screws are designed to allow fish migration to protect biodiversity.

The first set of screws were installed in 2012 in Ham and are fully operational. The second set of screws are implemented in Olen and are operational in 2015. The third set was installed in Hasselt in 2018. Three more sets of screws will be installed in the coming years in Diepenbeek, Genk and Wijnegem.

How is the case study relevant to climate change adaptation (e.g. understanding and assessing climate change risk, collecting and analysing data)?

The case study is an example of an adaptation measure for inland shipping. In the preparatory phase climate science was interpreted and used. Also, climate change risks had to be assessed and understood.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

Inland waterway

Who was involved in the project (internal and external stakeholders)?

Within the organisation, a broad array of people were involved with of course the executive board and the engineering and planning division, but also environmental and hydrographic experts. External stakeholders consisted of government or regulatory agencies (also environmental agencies), environmental groups and local community representatives.

MOTIVATION FOR CONSIDERING ADAPTATION

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

The main driver for considering climate change adaptation was improving resilience and reducing vulnerability, mainly to drought and low water levels.

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

Water levels and changes in precipitation were used as parameters in quantified mid estimate plus high climate change projections. Both IPCC data and regional climate assessments were used.

RESULTS OF RISK ASSESSMENT

How were risks assessed/what methodology was used? What was the solution/what were the main outcomes?

The project mainly focused on identifying the best adaptation measure. The risk was already defined.

IDENTIFICATION AND PRIORITISATION OF ADAPTATION MEASURES

How were the possible adaptation measures identified and which ones where recommended?

The organisation 'NV de Scheepvaart' resorting under the policy area 'Mobility and Public Works' has searched for solutions together with its partners. Two major preparatory projects led to the eventual design of the measures, in which relevant stakeholders were involved. The first was the development of a low water strategy for the canal. This strategy was developed in four stages:

- In a first stage, the problem analysis phase, an inventory was made of different water uses, consulting water users about their ideas to reduce water use.
- In a second phase, different possible solutions were proposed, inviting feedback from all relevant stakeholders.
- In the third phase the effects of the solutions in terms of effectiveness and costs were analysed quantitatively with a suite of models and other analytical tools.
- In a fourth and final phase preferred strategies were discussed in a series of workshops with a broad range of stakeholders using water from the canal system for economic, ecological or societal reasons, including industries, shipping representatives, drinking water supply companies, power companies, nature protection organisations, municipalities and others.

Secondly, an environmental impact assessment was undertaken to choose the preferred option from the proposed solutions, taking into account various environmental dimensions, notably fish stock interests and noise.

MONITORING

What monitoring was undertaken and why (e.g. weather or physical process variables, asset condition, performance of measures)?

Continuous monitoring of discharge of the River Meuse and the Albert Canal and the water savings realised by pumping up the water coming from lockage takes place, but also the impacts of the pumps on the fishes are monitored.

PROJECT OR INITIATIVE OUTCOMES

What were the main lessons learnt?

Uncertainties in climate change projections and technical solutions and lack of funding were the main constraints.

Next to the realisation of the pumps with a capacity of 15m²/s to keep shipping on the canal possible in longer periods of drought, this project has also raised awareness among the different stakeholders on the consequences of climate change and low water levels, more specifically for water management of the canal. The stakeholders are also more aware that specific measures exist to solve this in a sustainable way.

Important success factors included the acknowledgement of ecological values and the attention to the development of a collaborative process in which all stakeholders were seriously engaged. As to the former, two ecological factors played a key role: the structural possibility to protect natural values in the Meuse valley by limiting extraction of Meuse water and maintain a sufficiently high run-off level, and the consideration of the fish stocks in the Albert Canal.

One of the main factors of success to collaborate was the awareness of the inadequacy of current solutions and projected worsening of the situation in terms of frequency and length of low water level.

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CASE STUDY 15 – MOWE IT – MANAGEMENT OF WEATHER EVENTS IN THE TRANSPORT SYSTEM

BACKGROUND

Brief case study description. How is the case study relevant to climate change adaptation?

The goal of the MOWE-IT project was to identify existing best practices and to develop methodologies to assist transport operators, authorities and transport system users to mitigate the impact of natural disasters and extreme weather phenomena on transport system performance. The project was funded by the European Commission's 7th RTD framework programme between October 2012 and September 2014. MOWE-IT was co-ordinated by the Technical Research Centre Finland (VTT) and involved 12 European research institutes and companies.

SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed? Who was involved in the project (internal and external stakeholders)?

The project-specific objectives of MOWE-IT were to:

1. Address the cross-modal features of the European transport system, key determinants of travel choice and distance-destination relationships between transport modes across Europe.
2. Undertake a mode-by-mode (road, rail, aviation and waterborne transport) review of impacts and mitigation strategies of natural disasters and extreme weather events currently available for industry, operators and regulators.
3. Prepare short-term options for dealing with induced disruptions, including the availability of alternative transport options in the form of less affected transport mode options.
4. Provide policy recommendations for longer term solutions to reduce disruption to the European transport system caused by extreme weather phenomena.
5. Involve stakeholders, including the transport industry and authorities from a variety of fields (border and customs control, emergency services, health sector etc.) in order to create an arena in which the adaptation process can be discussed in a cross-modal perspective and a wide geographical scope.

MOTIVATION FOR ADAPTATION REPORTING

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

The European transport system has shown vulnerability to external shocks due to weather events, which have partially or, in some cases, totally shut down part of the transport system. Dedicated practical applications to manage transport networks more effectively were expected to reduce the vulnerability of the European transport system to adverse weather events.

PROJECT OR INITIATIVE OUTCOMES

What were the main outcomes? What were the main lessons learnt?

The main outcomes of the project were the provision of guidebooks for enhancing resilience of rail, road, aviation, inland waterway and maritime transport. The guidebooks were considered an essential tool for decision makers, practitioners, and other stakeholders interested in reducing the impact of extreme weather events on transport. Based on the guidebooks created, policy recommendations were drafted, and a long-term implementation plan developed.

These deliverables were developed based on comprehensive literature reviews, information provided by the project partners, stakeholder interviews, and feedback received during the regional conferences held (stakeholder conferences).

Specifically for inland navigation, the guidebook emphasises the vital importance of maintenance, and the crucial role of monitoring. Concepts such as ‘fairway in a fairway’ (informed by up to date or real time online information) are also highlighted. In the medium-term options to optimise, lengthen, shorten, raise or lower structural elements, whilst at the same time minimising river bed degradation, are acknowledged. A shift to more customer-oriented waterway management, the development and use of River Information Services, and the implementation of new information and communication technologies (e.g. improved weather forecasting and monitoring) are also proposed, along with measures to adapt and modernise the inland waterways fleet and associated port infrastructure-related modifications to accommodate the modernised fleet.

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CASE STUDY 16 – PORT OF MANZANILLO

BACKGROUND

Brief case study description

The Port of Manzanillo in the State of Colima, Mexico, is one of the largest containerised cargo ports in the world. Nationally, it has positioned itself as the main port for the management of containerised cargo, accounting for 60 % of this cargo on the Mexican Pacific coast and 46 % of all the containerised cargo in the country.

Recognising the potential significance of climate change to ports, a Technical Cooperation between the Inter-American Development Bank (IDB) and the Administración Portuaria Integral of Manzanillo S.A. de C.V (API Manzanillo) was established. Through this cooperation, a group of consultants lead by the consulting firm Acclimatise were requested to carry out a study to help assess the capacity of the port to respond to potential climate change risks and to foster opportunities stemming from early action and adaptation responses.

How is the case study relevant to climate change adaptation (e.g. understanding and assessing climate change risk, collecting and analysing data)?

This study seeks to address the climate change threats and opportunities faced by the Port of Manzanillo. This task is accomplished through a comprehensive climate risk assessment that takes into consideration the port´s entire value chain and through the formulation of a climate change adaptation plan for the port.

The study aimed to address the following questions:

1. What risks and opportunities does climate change present for the port?
2. What key climate-related factors should API Manzanillo take into account to maintain its competitiveness and develop its medium- and long-term business strategy?
3. How could the port manage climate risks and uncertainties in the most financially optimal way, taking account of environmental and social objectives?
4. How could climate-related opportunities be developed and exploited?
5. How should adaptation actions be prioritised and sequenced in an Adaptation Plan?
6. Where could API Manzanillo work in collaboration with other stakeholders to best manage climate risks and take advantage of opportunities?


SCOPE OF ASSESSMENT: INDIVIDUALS AND INFRASTRUCTURE INVOLVED

What types of infrastructure/operation/management activities were assessed?

The study analyses how climate-related risks and opportunities could affect the various elements of the Port of Manzanillo's value chain and identifies and quantifies (where possible) the key risks and opportunities. Accordingly, it addresses the exposure and sensitivity of infrastructure and equipment associated with:

- navigation and berthing
- goods storage
- goods handling
- terrestrial and maritime transport routes, including inland rail and highways
- other port services

The study also takes into account social and environmental standards at the port as well as the potential effects of future changes in:

- demand and consumption patterns
- competition with other ports
- possible future agreements on GHG emissions (e.g. policy and taxes)
- evolution of the insurance market

Who was involved in the project (internal and external stakeholders)?

The following stakeholders were involved in the project:

- The consultancy Acclimatise, who led the study, with support from Worley Parsons, Consultect and some individual subject matter experts
- IDB staff members
- An IFC representative with expertise in undertaking similar projects
- Staff from API Manzanillo
- The port community, including representatives of 14 terminals, the Capitanía de Puerto (Harbourmaster), the Ayuntamiento de Manzanillo (Town Council of Manzanillo) and Ferromex (the rail company)
- A range of institutes from the State of Colima, including the:
    - Instituto para el Medio Ambiente y Desarrollo Sustentable del Estado (IMADES)
    - Centro Universitario de Gestión Ambiental from the University de Colima
    - Secretaría de Desarrollo Urbano del Estado de Colima
- A range of Federal Government entities including the:
    - Comisión Nacional del Agua
    - Centro Nacional de Prevención de Desastres
    - Comisión Nacional de Áreas naturales Protegidas
    - Comisión Nacional para el Conociemiento y Uso de la Biodiversidad
    - Instituto Nacional de Ecología y Cambio Climático
    - Insituto Mexicano del Transporte
    - Secretaría de Comunicaciones y Transportes
    - Secretaría de Marina
    - Secretaría del Medio Ambiente y Recursos Naturales
    - Secretaría de Turismo
- INECC, SEMARNAT and IMT provided external peer review of the study

MOTIVATION FOR CONSIDERING ADAPTATION

What was the driver for considering climate change adaptation? What adaptation issues were addressed?

The initial driver for the project was an application by a terminal operator for funding from IDB to expand their operations into a second terminal. The land that was the subject of the proposal was state-owned and managed by API Manzanillo, hence their involvement in the project. One of the conditions of funding imposed by the IDB was the completion of a port-wide study on climate change adaptation targeting supply chain interventions.

The IDB provided the funding and partnered with API Manzanillo to form a technical cooperation to undertake climate change adaptation funding. The International Finance Corporation (IFC) provided in-kind technical support to IDB.

CLIMATE CHANGE DATA USED

What climatic parameters and scenarios were used? Which data sources were used?

Three different future climate change scenarios were taken into account, namely, RCP 8.5 (high), RCP 4.5. (moderate) and RCP 2.6 (low). The climatic factors considered in the climate risk and vulnerability assessment included:

- changes in rainfall patterns (number of rain days, potential for dust generation)
- increases in the frequency of intense rainfall events and flooding
- sedimentation of the port basin as a result in increased rainfall intensity
- increases in average and peak temperatures and humidity
- mean sea level rise and storm surge
- increased intensity and duration of tropical cyclones
- higher wind speeds in more intense storm events

RISK ASSESSMENT

How were risks assessed/what methodology was used?

The study determined the level of present-day and future climate-related risk to each of the elements of the value chain of the port, making use of various methods to reflect the different sensitivity and exposure that can be attributed to each type of port activity. Risks identified were evaluated against four criteria:

1. Current vulnerability is high
2. Projected impacts of climate change are large
3. Adaptation decisions have long lead times or long-term effects
4. Large uncertainties – scale of future risk is uncertain but could be large

According to their level of importance, climate risks were prioritised, and their financial and economic implications quantified. Risk that rated 'high' against two or more of these criteria were considered 'high priority risks'. Similarly, whenever current vulnerability was rated 'high', the risk was identified as a 'high priority risk'.

A financial analysis was undertaken in three stages as follows:

- A 'Baseline case' – establishes baseline future projections (ignoring the effects of climate change) within a financial model in consultation with API Manzanillo and the terminals.
- A 'Climate change cases' – estimates the financial implications of climate change impacts for a range of scenarios within the financial model i.e. future climate change impacts with no adaptation.
- A 'Climate change with adaptation cases' – assesses the financial cost and benefits of adaptation options and identify economically optimal adaptation measures.

What was the solution/what were the main outcomes?

The priority risks considered are:

- Increased intensity of rainfall causing surface water flooding of the internal access road and rail connections and port entrance, causing disruptions to port operations.
- Increased frequency of intense rainfall events causing damage to infrastructure and equipment through surface water flooding.
- Increase in intensity of rainfall causing increased sedimentation of the port basin, reducing draft clearance for vessels and terminal access.

IDENTIFICATION AND PRIORITISATION OF ADAPTATION MEASURES

How were the possible adaptation measures identified and which ones where recommended?

Identification and prioritisation of adaptation measures was undertaken as follows by the study team:

1. First, adaptation measures were identified for each of the climate risks.
2. Adaptation measures were then prioritised as follows: (1) Measures that address priority risks were termed 'priority adaptation measures' and (2) Those that address medium and low priority risks are in turn, medium and low priority measures.
3. Within the set of priority adaptation measures, certain measures were identified that should be undertaken first.

A high-level analysis of the cost-effectiveness of the measures which deliver adaptation action for the priority risks identified was undertaken. The approach used is aligned with recent literature on cost effectiveness analysis of climate resilience measures. The comparative high, medium and low scores were primarily a relative comparison of the costs and effectiveness of each option, based on expert judgement, the transfer of values from literature where available and application of study-specific criteria.

The following high-level conclusions can be made based on the findings of the cost effectiveness analysis:

- Operational measures tend to be low cost and to have a medium effectiveness at reducing risk.
- Engineered measures are often the most effective at reducing risk. However, they are generally more costly and have few positive (beneficial) additional consequences.
- Ecosystem-based and hybrid options have more positive additional consequences, but they are typically not as effective as engineered options at reducing risk. They tend to be more complex to implement, and the evidence base on them is weaker, so there is uncertainty regarding their effectiveness.

PROJECT OR INITIATIVE OUTCOMES

What were the main lessons learnt?

Uncertainties about future climate conditions will always remain, and so it is important that Adaptation Plans place an emphasis on undertaking no regret, low regret, win-win and flexible adaptation measures first.

Adaptation actions can be more easily implemented when they respond to priority risks and when they clearly relate to success factors and development objectives of ports. Moreover, the inclusion of a stakeholder engagement plan can help different actors understand each other´s roles and responsibilities and help keeping track on the implementation of the plan´s adaptive measures.

It is important to take into consideration national, sub-national and sectorial adaptation policies in the development of adaptation plans for ports. This helps to ensure that adaptation measures at ports are well aligned with government objectives and may help port operators getting support and assistance from government when implementing adaptation measures.

What would you do differently?

It was recognised that on many occasions local entities would have developed studies and assessments incorporating some climate-related considerations. It is important to try to incorporate this information and to get buy-in from these entities early in the assessment process. This can facilitate access to data and provide legitimacy and credibility to the study´s results. Due to the timeline of the project it was not always possible to develop deep relationships with these actors. Stronger participation of local consultants from the project could have facilitated this interaction.

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ANNEXES STAGE 1

Annex 1A – Template Inventory

https://www.pianc.org/publications/envicom/wg178

Annex 1B – Template Stakeholders

https://www.pianc.org/publications/envicom/wg178

Annex 1C – Effective Stakeholder Engagement: Value of a Facilitated Workshop

Extreme weather events potentially linked to climate change are frequently reported in the media. However, if this general awareness is to be successfully translated into action on the ground, a number of guiding principles can be applied to ensure that both internal and external stakeholders are effectively and productively engaged in the adaptation planning process.

- Climate change communications and reasoning must be clear, meaningful and personally relevant.
- Technical jargon should be avoided wherever possible; the glossary is intended to help translate climate terminology into concepts that are familiar to individual stakeholders.
- A variety of media can be used, including face-to-face presentations, meetings, workshops, webinars, pop-up exhibitions and so on.
- Efforts should be made to build climate change awareness raising and discussion about future adaptation requirements into training procedures at organisation level or into existing initiatives such as corporate and social responsibility programmes as appropriate.

A Facilitated Workshop

An engagement approach that has worked well in a number of situations (see Case Study 4) has been to convene a facilitated workshop. The workshop environment provides an excellent opportunity for infrastructure owners, operators and managers along with other key stakeholders, to discuss how their respective assets, operations or systems might be affected by a variety of climate change scenarios, and to develop their ideas about how best to respond whilst also considering others' interests and requirements (e.g. to identify win-win opportunities).

To be most effective, such a workshop must be well-structured, follow a logical format and be effectively facilitated. The workshop facilitator can be someone internal to the organisation or can be external; they do not have to come from a specific discipline (a facilitator may have expertise in climate change scenarios, have waterborne transport infrastructure experience, be an engineer, practitioner, professional communications' specialist or an academic). However, to be most effective, the facilitator should:

- have a clear idea of the process to be followed, be experienced and confident to lead, and be able to get the best out of participants.
- be competent to develop a common understanding of the local situation and the main challenges likely to be faced.
- be confident in encouraging workshop participants to step back from any pre-conceived ideas, move beyond business-as-usual and to 'think outside the box'.

Climate change, including changes in the magnitude and frequency of extreme events, will require innovative and imaginative solutions. Depending on their expertise, the facilitator may be able to offer suggestions for alternative approaches if solutions cannot be identified or if technical or resource constraints seem likely to preclude conventional responses. More importantly, the facilitator's role is to help participants explore different ways of designing, constructing or using waterborne transport infrastructure or systems and options for modifying or replacing existing operational or management practices.

The facilitator also needs to recognise that people may find it difficult to engage in discussions beyond business-as-usual. Barriers to engagement can be related to perceptions and how people acquire knowledge (cognitive) or related to behavioural standards or norms (normative). They could also be political or economic.

In order to overcome such barriers, discussion about climate change and adaptation or resilience measures might initially focus on social, environmental or reputational implications or opportunities. Highlighting existing or known risks can be a useful starting point for introducing discussion about future risks.

Participation Going Forward

Whichever approach is used to start the discussion, the active participation of those responsible for potentially impacted assets, operations and systems is important to generate engagement and ownership. This engagement and ownership will be vital to the subsequent steps of assessing vulnerabilities and risks and identifying, evaluating and implementing climate change adaptation measures.

Annex 1D – Costs and Consequences of Extreme Weather Events

A lack of data on the costs of inaction (i.e. the consequences of not investing in strengthened resilience) can represent a barrier to justifying investment in improving climate-resilience.

Quantified, and ideally monetised, information on the consequences of downtime, disruption, damage or other limitations on functionality (irrespective of their cause) can support the business case for investment in climate change adaptation. In particular, when an extreme meteorological, oceanographic or hydrological event is experienced, a record should be kept of which assets, operations or systems were affected; the costs of clean up, repairs or additional maintenance; the length of time before normal service resumed and the associated financial or economic impacts.

In order to facilitate the collection of this type of information whenever business is interrupted, a template such as that in the table below might be used.

EVENT OR INCIDENT		
Topic	**Information to be recorded** *[Delete the guidance notes in the square brackets and complete this column as indicated]*	**Costs** *[Delete notes and insert amount]*
Date (and name) of incident or event		N/A
Nature of incident or event	*[Wherever possible, provide information on (relative) duration, magnitude, etc.]*	N/A
Facilities or locations affected	*[Note the facilities or operations impacted e.g. terminal, fairway, berth, whole port].*	N/A
Additional information about the event	*[For weather-related events, consider how the event is compared to previous events? Could it be explained as an incremental continuation of an observed trend or otherwise exacerbated by natural changes? Or was it somehow exceptional, unprecedented or otherwise out-of-the-ordinary? Were warnings received and if so, was effective action taken to reduce the consequences?]*	N/A

CONSEQUENCES		
Closure, downtime, delays, loss of function, business interruption	*[Include the number of hours closure or delay and the activities affected; the operation(s) interrupted and duration of the interruption]*	*Approximate costs if exact figures are not available*
Clean up and/or implications for maintenance	*[Include a full list of clean-up activities. Identify any additional maintenance requirements resulting from the incident or event]*	*Approximate costs if exact figures are not available*
Damage	*[Include the nature of the damage; any implications for operation (i.e. constrained but still operable; out of action)]*	*Approximate costs if exact figures are not available*
Other business implications	*[Note any other direct and indirect losses to the business resulting from disruption or downtime, including during the post-incident or post-event recovery periods]*	*Approximate costs if exact figures are not available*
Implications for stakeholders	*[Describe and where possible quantify the implications of the incident or event for port or waterway users, external stakeholders, or the wider environment. Include disruption or interruption of activities, downtime, clean-up, and damage]*	*Indicative costs if exact figures are not available*
SUMMARY		
Total cost of event		*[Keep in mind: an approximate cost is better than no cost information]*
Proportion of cost covered by insurance	*[Provide percentage or other indication]*	N/A
Implications for business performance	*[Indicate how business performance was affected, both locally and at system level. For example, record the impacts as deviations from agreed targets/using agreed metrics]*	N/A

It may be appropriate to develop and agree standard ‘unit costs’ for certain types of disruption or downtime to make the reporting process easier, but any information, even if it is anecdotal or if a range is provided, is more useful than no information.

Irrespective of how the information is to be collected, it must be recorded in a consistent way, and the mechanism for so doing should be well-publicised. For example, the data collection template can be downloadable on the organisation’s website or developed as an app; a paper version might be made available; and/or an event ‘logbook’ might be placed in the harbour master’s office. Photographs and/or videos of the events can also provide a useful source of information for comparative purposes, both with previous or subsequent events, including an assessment of their effects. This type of information also helps more generally in optimising port and waterway infrastructures [PIANC, 2016].

In order to ensure that a 'complete picture' of the consequences of an incident or event is obtained, external stakeholders should be asked to submit information about the effects on their interests or activities. This is particularly important where organisations such as terminal operators, onward transport providers or recreational water users are affected, but there is also value in understanding the implications of an event for the wider local community or environmental protection groups. A parallel recording procedure should therefore be provided for these organisations, and an awareness-raising exercise undertaken to explain why this recording helps improve preparedness for future extreme events.

If necessary, post-event reminders should be issued to those responsible for affected assets or operations, to try to capture as much information as possible before it is forgotten or lost as the business moves on.

Annex 1E – Guiding Principles for Setting up a Fit-for-Purpose Monitoring and Data Management System

Data Collection

Data collection and management are crucial to effective and efficient climate change adaptation. Amongst other things, collecting and managing data will allow infrastructure owners and operators to:

- understand the actual local impacts of climate change
- plan for and understand when to implement adaptation measures and decide 'how much' of a measure is needed
- monitor the efficiency of measures that have already been implemented

Monitoring and recording data can be realised in different ways at various levels of detail. In many cases even low-resolution data, which can be gathered using quite simple methods and little effort, will be significantly better than holding no data.

Monitoring does not necessarily have to be sophisticated. Rather, it should be fit-for-purpose. Generic or anecdotal recording may be adequate in certain cases. If monitoring is being used to inform phased implementation or adaptive management decision making, it may be important to establish whether a particular threshold has been crossed, for example, triggering the next phase of implementation, or instigating a change to a different method.

Decisions on monitoring locations, methods and programmes, as well as the level of precision required, will be case specific, as will considerations such as the frequency of checking equipment for accuracy, calibrating results, etc.

A detailed and comprehensive record of trends or patterns in relevant climate parameters and processes; the status of assets, including instances of structural damage, and operational downtime, can be developed based on monitoring undertaken by port or waterway operators or other organisations. The cooperation of interested parties, including long-term stakeholders for example, should be encouraged in the ongoing development and implementation of a monitoring programme.

Data Management and Review

Information collected as part of routine activities (e.g. inspections) should be recorded in a standardised format including, as a minimum, parameters such as date, time, location, driver, parameter or variable, unit and associated observations.

The importance of having a simple, coordinated process in place to facilitate the logging of climate-related data in a standard, ideally digital, format to avoid losing information over the years cannot be overstated. A secure back-up system is also needed.

Paper records can also be used but this will increase both the risk of data being lost and the amount of effort required to process the data.

Whenever possible, it is preferable to align monitoring and recording of data for climate change adaptation purposes with existing data management procedures if these exist. Integrating this as part of objectives, policy, protocols and operating procedures within a formal 'system' (e.g. Quality Assurance, Environmental Management, and/or Integrated System) would be prudent.

Having collected and collated data, it is important to ensure that the data log or management system is kept up-to-date and is readily accessible to all those involved in climate change adaptation decision-making. Relevant departments within the business, along with any other organisations or stakeholder groups that are collaborating on climate change adaptation initiatives, need to be made aware of the monitoring programmes and ongoing changes to them.

Raising awareness of the existence of these data and their intended use should similarly be included into corporate systems, and the availability and use of relevant information should be mentioned in induction, training and awareness programmes.

Data quality needs to be ensured and reviewed on a regular basis, and review, feedback and updating processes should be implemented. Data being collected or supplied by third party organisations should similarly be quality-assured and regularly reviewed.

For these and other reasons, it is important to retain data when a system is upgraded or renewed. To be of maximum value, data series should be accurate, consistent, and homogenous: when investing in a new data storage or management system it is therefore worth the extra effort to ensure compatibility and consistency can be maintained.

Finally, it should always be borne in mind that climate change adaptation will be an ongoing, iterative process. In some cases, ongoing organisational processes such as risk management, emergency planning, sustainable reporting, etc. may trigger a regular review of whether adaptation objectives are being achieved, amongst other things drawing on monitoring outcomes. If there are no existing processes driving such a process, a five-yearly review should be instigated to determine whether already implemented measures are effective; whether additional measures are needed; and whether the adaptation goals and objectives need to be updated or amended.

ANNEXES – STAGE 2

Annex 2A – Data Sources

There are many sources of information on climate change parameters and processes, including projections. The table below lists some of these, but this is by no means an exhaustive list, and the data listed therein are not endorsed. Rather the table provides an indication of the type of organisation or report from which useful data might be obtained.

Data Source	Climate parameter	Additional Information
GLOBAL-LEVEL EXAMPLES		
AVISO	• Mean Sea Level • Waves	Satellite information http://www.aviso.altimetry.fr/en/data.html
Climate Forecast System Reanalysis (CFSR)	• Various such as wind, relative humidity, air Temperature and many more.	Global high resolution, third generation reanalysis product https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr Limitations: relatively few evaluations of CFSR have been conducted so the performance is not well known.
COPERNICUS Marine Environmental Monitoring Services	• Temperature • Salinity • Sea surface height • Currents • Ice • Wind • Waves	Global analysis forecast https://cds.climate.copernicus.eu/cdsapp#!/home http://marine.copernicus.eu
Global Climate Observing System, World Meteorological Organization	• Temperature • Physical, chemical and biological • Atmosphere, oceans, terrestrial	Provides users with access to climate observations, data records and information based on the concept of Essential Climate Variables https://public.wmo.int/en/programmes/global-climate-observing-system
IBTracks, NOAA	• Tropical Cyclones	Global set of historical cyclones https://www.ncdc.noaa.gov/ibtracs/
IPCC Fifth Assessment Report	• Various such as mean sea level, air temperature and many more	Global projections https://www.ipcc.ch/report/ar5/ Limitations: Is not suited for extreme values analysis as it does not include the highest 5%.
NCAR Research Data Archive	• Various	Large collection of meteorological and oceanographic observations, operational and reanalysis model outputs, and remote sensing datasets to support atmospheric and geosciences research, along with ancillary datasets, such as topography/bathymetry, vegetation, and land use. https://rda.ucar.edu/
NOAA National Buoy Center	• Waves	Global wave buoy data http://www.ndbc.noaa.gov/obs.shtml
PODAAC	• Physical oceanography	https://podaac.jpl.nasa.gov https://podaac.jpl.nasa.gov/datasetlist
PSMSL (Permanent Service for Mean Sea Level)	• Sea level	http://www.psmsl.org/data/obtaining/complete.php

Data Source	Climate parameter	Additional Information
The World Bank Climate Change Knowledge Portal.	• Baseline and future projections per country (or city) • Temperature and precipitation, but with evolving datasets on other parameters such as observed sea level rise.	http://sdwebx.worldbank.org/climateportal/
ThinkHazard! is an initiative of the World Bank and the Global Facility for Disaster Reduction and Recovery	• Hazard classification • Includes river, urban and coastal flooding, cyclones, extreme heat and drought.	http://thinkhazard.org/en/
WorldClim	• Precipitation • Temperature	Global climate grids with spatial resolution of about 1 km^2. http://www.worldclim.org
REGIONAL-LEVEL EXAMPLES		
Caribbean Community Climate Change Centre (5Cs) database	Projections for • Temperature • Precipitation • Humidity • Wind speed • Soil moisture • Evaporation	Portal for climate change information in the Caribbean, Available at: http://www.caribbeanclimate.bz/. New datasets are added regularly. Current datasets include: • PRECIS Regional Climate Model – 50-km spatial resolution, daily-scale projections • GCMs – 25-km spatial resolution daily-scale projections (e.g. soil moisture content, convective rainfall rate, evaporation rate, large-scale rainfall rate, maximum temperature, minimum temperature, humidity, wind speed). Available for 15 GCMs.
EMODnet Central Portal	• Various	Marine data in Europe http://www.emodnet.eu
European Centre for Medium-Range Weather Forecasts	• Various	https://www.ecmwf.int/
The IPCC Data Distribution Centre	• Observations, computer simulations and analyses ranging from socio-economic to the physical climate	http://www.ipcc-data.org.
North American Regional Climate	• Precipitation • Temperature	High resolution climate change simulations http://www.narccap.ucar.edu/data/

Data Source	Climate parameter	Additional Information
Change Assessment Program (NARCCAP)		
Providing Regional Climates for Impact Studies (PRECIS)	• Precipitation • Temperature	Database developed by MetOffice https://www.metoffice.gov.uk/research/applied/international-development/precis
Sea Conditions	• Sea temperature • Surface currents • Waves	Forecast model data for Europe www.sea-conditions.com
NATIONAL-LEVEL EXAMPLES		
National synthesis reports to the UN Framework Convention on Climate Change	Future projections including temperature and, in some cases, extremes	National reports, typically providing a synthesis of high-level climate projections for each country including change in average temperature. Some provide projections for more extreme variables. The level of detail in each report varies by country: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/national-communications-and-biennial-update-reports-non-annex-i-parties/national-communication-submissions-from-non-annex-i-parties
National websites for wave and sea level records	• Wave levels • Sea levels	The Italian record, for the entire country, since 1989: http://dati.isprambiente.it/dataset/ron-rete-ondametrica-nazionale/
NOAA National Centers for Environmental Information	• Various	https://www.ncdc.noaa.gov
Local in-situ data	• Various, site dependent	Local organizations may have relevant in-situ data measurements. For example: • Canada Great Lakes Water Levels: http://www.waterlevels.gc.ca/eng/find/region/6 • Australian Government Bureau of Meteorology: http://www.bom.gov.au/marine/ • Channel Coastal Observatory in England. Online: https://www.channelcoast.org • National Oceanic and Atmospheric Administration for North America http://www.noaa.gov/our-work • Italian Research Council, ISMAR_CNR, Venice https://www.cineca.it/it/content/il-modello-numerico-cosmo

Annex 2B – Meteorological, Hydrological and Oceanographic Monitoring

Information on meteorological, hydrological or oceanographic conditions should be collated to build up an accurate picture of local trends and the occurrence of extreme events. Such data will facilitate the understanding of potential impacts, facilitate an assessment of the likelihood or probability of extreme events, and provide basic information for other further studies as and when these are needed.

Before embarking on a data collection exercise, efforts should be made to establish whether relevant data already exist: general information on meteorological and hydrological measuring techniques and data processing is available from various sources, for example the World Meteorological Organization (WMO) (see Annex 2A).

However, if a lack of available data might represent a constraint on adaptation planning (for example if information is not available to enable the identification of areas at risk from flooding, or to facilitate understanding of the implications for sediment transport of changes in run-off or an increase in storminess) local data collection and monitoring should be instigated. The value of such information to adaptation planning cannot be overstated: climate change adaptation decision-making does not require sophisticated data rather what matters is that data are fit-for-purpose.

Collecting Local Data

If it is necessary or appropriate to collect local data, these can be collected via various means: automated, real-time, manual or anecdotal. Careful consideration should be given to the likely future use of the information prior to putting recording procedures in place. This will help to ensure that data are collected in the right locations and at an appropriate level of detail given the availability of resources.

The following table provides a brief overview of the advantages and disadvantages of different types of data collection methodologies.

Methodology	Potential advantages	Potential disadvantages
Automated and real-time	High quality and high frequency of data	Cost and time to install and maintain Cost and time to specify the correct equipment or tool, parameter, location etc.
Automated	High quality of data Generally high frequency of data	Cost and time to install and maintain Cost and time to specify the correct equipment or tool, parameter, location etc.
Manual	Low instrumental costs Easily and quickly implemented	Need to ensure the parameter is consistently measured and recorded Generally lower frequency than automated In general, higher personal efforts
Anecdotal (log)	Better than no data, especially if collected regularly and systematically	Can be infrequent or intermittent Generally lower accuracy (e.g. visually observed data)

Good industry practice as promoted by professional bodies, should always be followed when monitoring is initiated. Temperature and humidity units, for example, should not be placed in a position facing the sun but should ideally be located in a shaded area. A rain gauge should be mounted no higher than two metres from the ground. A wind gauge should ideally be installed at a height of around 10 m but needs to be higher than surrounding buildings or obstacles, (e.g. on an open roof exposed to wind from all directions).

Water level and water depth monitoring is also possible at very modest costs and personnel effort. A tidal gauge will provide an adequate reading of water level within the port or waterway. Water depth can be measured using a small boat, a GPS and a rope and lead. The available guaranteed accuracy of

GPS devices, excluding differential GPS, is approximately ±10 m in horizontal and approx. ±6 m in vertical direction for 95 % of the measurements. Therefore, the use of consumer GPS devices are sufficient for determining latitude and longitude of measuring points (horizontal surveys) but not for measurements of water levels, which have to be carried out with higher accuracy of at least 0.5 m. Adequate bathymetric and topographic measurements, corrected for the tide as appropriate, can nonetheless be collected at very low cost (for example, for an investment of less than US$ 1,000 [Esteban et al., 2017]. Some examples of how relevant data can be collected on a tight budget are illustrated below.

- Esteban et al. (2017) set out a methodology allowing adequate bathymetric and topographic measurements, corrected for the tide as appropriate, to be collected for an investment of less than US$ 1,000. Their useful paper, 'How to Carry Out Bathymetric and Elevation Surveys on a Tight Budget: Basic Surveying Techniques for Climate Change Planning' provides a series of worked examples.

- With the rapid growth of the Internet-of-Things (IoT) technology, a significant reduction of the cost of measurements can be realised by adopting the latest commercial sensors, radio frequency communication and mobile computation modules available from market and integrating them into hydrographic instruments. The Institute of Hydrological and Oceanic Sciences of the National Central University in Taiwan, for example, plays an active role in developing low cost hydrographic instrumentation. Ready for operation are e.g. a low-cost drifter system to track river and nearshore currents [Zhong et al., 2016] as well as a low-cost wave buoy especially for nearshore use [Cheng et al., 2017].

- Students from the Anton de Kom University, Paramaribo, Suriname, are monitoring the progression of a series of massive mud waves along the coast. Some of the outcomes of this work are informing a collaborative 'Building with Nature' (see YouTube video here) initiative at the endangered Weg naar Zee area, famous for vegetable growing, home to fishermen and religious sites. In 2016, work by Conservation International Suriname, with local donors, was undertaken to protect the coastline against flooding from rising seawater and salinisation of arable land using a permeable dam (100 m wide, 200 m length, 2 m height, 0.5 m depth) from local plant materials to capture sediment and fostering an environment for mangrove regrowth. A benefit of the natural water defence project was to the local port authority in making them aware of how rapidly these features are moving/changing and hence an improved understanding of the potential future implications for port access.

- In the southern India state of Tamil Nadu, a region which has witnessed a surge in storms, floods and beach erosion in the last decade and where a 1.0 m rise in sea levels by 2050 could affect more than 100,000 fishermen as well as ports, roads and other infrastructure, local fishermen and other stakeholders have undertaken a mapping exercise using open source software/geographic data and affordable technology on smartphones (https://www.bbc.co.uk/news/world-asia-india-45080917). The resulting detailed maps of scale, which include land use patterns as well as current high tide, low tide and hazard lines in accordance with local official requirements, are being submitted for official approval.

The Suriname and Tamil Nadu initiatives illustrate how local stakeholders including academic institutions can assist in monitoring changes, for example in river or coastal morphological features. Specifically, a small investment in training to ensure consistent and comparable outcomes can be useful in situations where students or other stakeholders can undertake regular, supervised, monitoring or surveys. The outcomes of such work can help the nearby port or waterway operator understand relative rates of change in parameters that have the potential impact on operations or activities in the medium to long term.

New Monitoring Systems and Big Data

The term 'big data' refers to the collation and analysis of very large data sets to help identify patterns and trends that might otherwise not be obvious or may be difficult to discern with confidence. With the rapid evolution of technology, it is expected that big data will play an increasingly significant role in future monitoring systems, with subsequent benefits for the management and maintenance of structures and facilities. These new technologies and their application for structural health monitoring are likely to have an important impact on the assessment of the performance of structures and operations, including under climate change effects.

Whilst there are limited uses of big data in the current design of structures, it is expected that digital technology and sensors will become increasingly integrated into these structures and buildings in the near future as new methods and technologies for the health monitoring of structures are researched and developed. One example is the use of wireless sensors in reinforced concrete structures, which can measure and transmit in real time different parameters impacting on the performance of the structure.

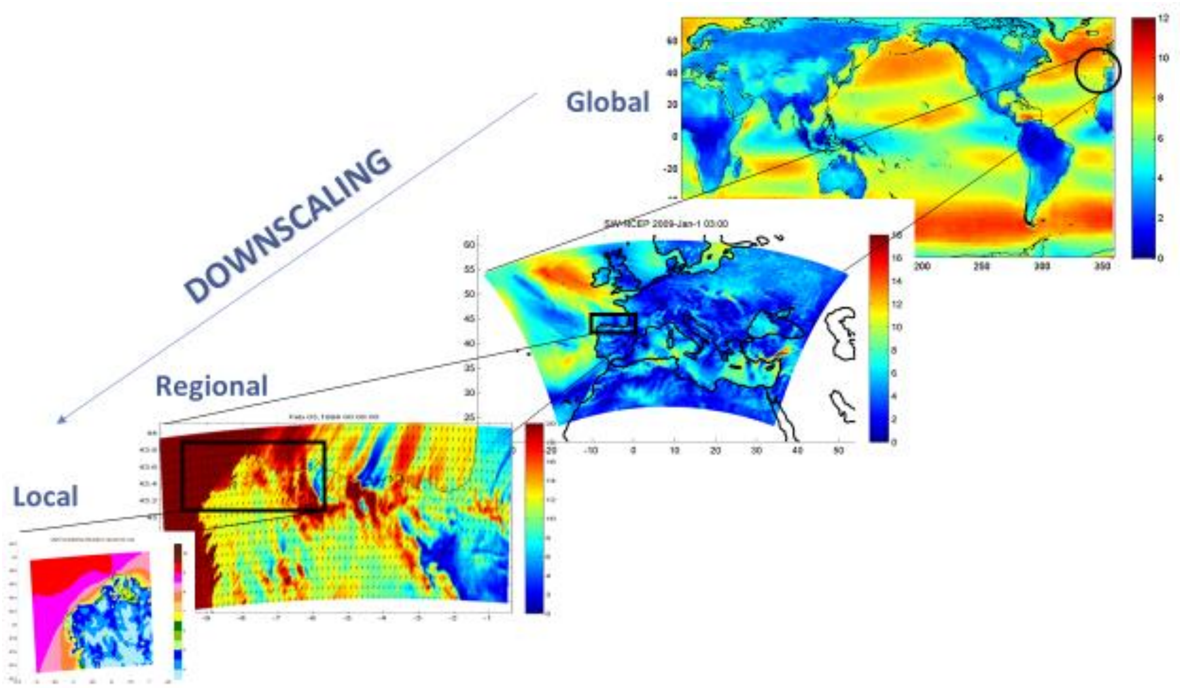
The assessment of the new sets of big data obtained will improve understanding of the most relevant climatic variables and will help to establish more accurate trigger levels for climate change adaptation measures, including for maritime structures such as quay walls and buildings and other facilities near the sea or waterways.

Annex 2C – Downscaling

The term downscaling describes the procedure of taking information known at large scales to make more local scale information.

Two main approaches of downscaling climate information are available: dynamical and statistical downscaling. Dynamical downscaling means to apply high-resolution climate models on a regional sub-domain using observational or lower-resolution climate model data as boundary condition, which is illustrated on the figure below.

Physical principles are used to reproduce local climates in a computationally intensive process. Statistical downscaling is a two-step process. Firstly, statistical relationships between local climate variables (e.g. local wind speed distribution) and large-scale predictors (e.g. large-scale wind) have to be developed. Secondly, these relationships have to be applied to the output of large-scale climate model experiments to simulate baseline or future local climate characteristics.



As noted in the table below, however, both downscaling methods have advantages and disadvantages, and there has been a great deal of debate in the literature (e.g. Benestad (2016)) about the reliability of these processes. If it is deemed necessary to undertake such an exercise, downscaling should therefore only be undertaken by experts. Furthermore, any port or waterway organisation commissioning a downscaling exercise should be aware of these issues in order to have confidence in the outcomes. In many situations it will be more cost-effective to use sensitivity analysis to assess a range of scenarios than to embark on a downscaling exercise.

Downscaling method	Advantages	Disadvantages
Statistical downscaling	Computationally efficient Requires only monthly or daily model output Can relate model output directly to impact-relevant variables not simulated by climate models Can be applied to any consistently-observed variable Can provide site-specific estimation Can be used to generate a large number of realisations in order to quantify uncertainty	Based on the essentially unverifiable assumption that statistical relationships between predictors remains stationary under future change Sensitive to the choice of predictors and model's ability to simulate these predictors Tends to underestimate temporal variance Requires long-term observed data
Dynamic downscaling	Explicitly consists of both large-scale and small-scale physical processes, up to the resolution of the model Regional climate response is consistent with global forcing Provides data that is coherent both spatially and temporally and across multiple climate variables Can be used in regions where no observations are available	Assumes that sub-grid parametrisation schemes remain stationary in the altered climate Sensitive to initial boundary conditions from larger model Difficulty to generate multiple scenarios Computationally demanding

ANNEX – STAGE 3

Annex 3 – Levels of Risk Analysis

'Initial' Level Analysis of Climate Risks

The initial level of climate change risk analysis is typically qualitative and may be relatively basic. It uses readily available historic or baseline information, for example in relation to the status and residual life of the asset, or on the levels of damage or disruption sustained during previous events and the associated financial losses. Such information may already have been collated (for example in Section 1.4.2) or it may need to be collected.

Records about past extreme events and their consequences can be especially useful in an initial risk analysis because these events can be used as proxies, or windows into the future, enabling assumptions to be made about what could happen if such an event is manifested more frequently or permanently within the adaptation planning horizon.

Where possible, the data collated to inform the vulnerability assessment should be used to understand and assess potential future impacts. In other instances, assumptions have to be made. For example, in the absence of evidence proving the link between overtopping and climate change, an initial risk analysis might need to work from an assumption that sea level rise or increased water levels will result in more frequent overtopping of a breakwater.

Whilst some quantification or statistical evaluation might be involved, local information and expert judgement will inform many of the outcomes of an initial level analysis.

If the objective of the adaptation strategy is to develop a high-level indication of possible future risks associated with climate change, this initial risk analysis may be sufficient to provide owners, operators and managers with the overview needed, for example to instigate targeted monitoring programmes or to prepare contingency plans.

If the objective of the adaptation initiative is ambitious but the scale of assessment is constrained by a lack of resources, an initial level of risk analysis will at least enable the owners, operators or managers of ports and waterways to prepare a more informed ranking of risks, allowing the available resources to be targeted towards addressing the most significant risks. However, as residual levels of uncertainty may be high at this level of risk analysis, several climate change scenarios should always be considered.

'Intermediate' level analysis of climate risks

The next level of risk analysis increases in complexity, using relatively higher resolution, more granular data and undertaking more rigorous consideration or observations of relevant climate parameters and processes. It may still be qualitative in many respects, but it is characterised by greater depth of analysis. For example, it may use evidence about exposure; measured information on the effects of past events; and/or evaluation of regional impacts and potential existing and future trends. It may also be the case that approaches are combined – for example, an intermediate risk analysis might use evidence of an observed increase in overtopping of the breakwater structure but work with an assumption (rather than evidence) that this will result in an increased rate of breakage of armour units.

An intermediate level risk analysis typically incorporates information about operational objectives, performance metrics, physical assets, and capabilities that were developed during the initial risk assessment. It generally also requires a greater level of resourcing in terms of both time and cost. This may be considered to be justified by the reduction in residual uncertainty levels.

'Advanced' level analysis of climate risks

An advanced approach to analysing climate risks requires more detail but usually produces a less uncertain outcome. This level of risk analysis is sophisticated and might rely on higher resolution data with deeper granularity. Continuing with the example used above, in this case photographic surveys may be used to prove that the observed increase in sea/water level and more regular overtopping has increased the damage to the breakwater armour units.

Advanced risk analysis is likely to involve computer modelling of potential impacts or probabilistic assessments covering a suite of return periods for example and may result in outcomes such as detailed flood maps for each asset or operation and expected damage curves showing an evolution over time.

This level of risk analysis estimates combined potential losses over a defined planning horizon. It therefore seeks to significantly reduce or even eliminate uncertainty (e.g. in rates of climate change over longer planning horizons) and can use modelling to improve the assessment. Advanced risk analysis is also appropriate to characterise uncertainty in the net present value of risks, which might be relevant for making decisions about investments in adaptations to climate change.

It is especially important to carry out an advanced analysis of this nature if decisions need to be made on large investments, facilities related to national security, or high cost infrastructure with a design life of several decades.

ANNEX – STAGE 4

Annex 4 – Portfolio of Measures

The measures in the following tables were identified through an extensive international engagement exercise involving Working Group members and their colleagues from 14 countries; running workshops in Europe (UK, Norway), Asia (The Philippines), Africa (South Africa) and America (USA); and input from several international associations (International Maritime Pilots' Association; International Harbour Masters' Association; European Sea Ports Organisation, UNCTAD and others).

Annex 4A – Rainfall-Related Flooding

Annex 4A highlights measures that can be adopted to deal with **more frequent or extreme, rainfall-related flooding** of operational areas, including surface water flooding when heavy or prolonged rainfall overwhelms drainage systems (also known as pluvial flooding). Some of these measures might also be relevant where issues are associated with increasingly frequent or extreme **groundwater flooding**. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Ensure effective **maintenance** of existing **drainage system**, storm drains, culverts, interceptors, separators, and trash screens, etc. Install and maintain **sustainable drainage systems (**SuDS), reed-beds, gullies, other flood run-off, conveyance or storage infrastructure; exploit nature-based solutions Increase **drainage capacity** Understand role of **green infrastructure** (green walls, roofs, streets) in local runoff attenuation Investigate **flood** diversion or **storage** options beyond the port or waterway estate Acquire and install, or hire (more powerful) **pumps** to drain surface flooding or ground waters **Install** relief slots, drain holes, or valves in decks or other infrastructure Invest in **demountable** flood **defences, sandbags,** pallets, bricks or similar for temporary raising, etc. **Raise** or construct **embankments** around critical assets and equipment (e.g. back-up generators, pump-house); install water splash or **scour protection** Install **flood-proofing** measures (e.g. barriers, gates, shutters, electricity supply modification)	Improve (or instigate) **monitoring** and **record keeping** on location-specific surface water-related metrics, including area affected Use **topographic survey** outcomes and 'during event' **monitoring** to understand flood risk area Prepare, review and regularly update **flood risk maps** and **flood response plan**; raise user awareness Consider **flood risk modelling** exercise Provide or improve **forecasting** and **flood warning** systems Prepare or enhance existing **Flood Resilience Action Plan** and consider need for **adverse weather plan** Develop and raise awareness of **new operational protocols** for flood response e.g. preparation, evacuation Review **stacking procedures** e.g. use empty container or install permanent shelving at stack base Flexibility in **staffing rotas** to respond to climate-related events Provide **accommodation** and **transport** for personnel to use during an incident Provide **training** in use of demountable defences, placing sandbags, raising assets, etc.	Promote **proactive collaboration** with those responsible for critical infrastructure and utilities/services and other transport modes on **flood risk management planning** to **protect business continuity** Mapping and **zoning** to help relocate sensitive activities out of flood risk area or to identify flood storage areas; link to **land-use policy** Encourage **relocation** out of flood-prone areas Provide, secure, and coordinate **alternative transport routes** and logistics to access port or facilities **Reduce insurance premiums** if improved resilience is demonstrated Provide grants / **financial incentives** to encourage investment in resilient infrastructure, including for **nature-based** drainage, storage or other **solutions** **Build-back-better** or 'build out of harm's way' policies for flood-damaged or damage-prone infrastructure Ensure investment policies take into account **life-cycle resilience**, making provision for expected changes Review and revise relevant **standards, specifications or guidelines** Require the preparation of **flood risk management plans**; ensure active participation of all stakeholders

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Strengthen resilience of lighting masts, electrical systems and substations that lie at ground level to avoid critical failures **Replacement** or **compaction** of buried pipes/manholes to prevent uplift from increase in buoyancy caused by groundwater level rise **Raise elevation** of access roads, storage facilities, etc. **Relocate** critical assets and plant equipment to elevated platforms; upper floors/mezzanine or otherwise out of flood risk area Revisit **planning of temporary facilities** such as location of stockpiling of collected snow and ice, into drainage systems Explore opportunities for alternative **floating infrastructure**	Review **port traffic management** plan if flooding affects access; identify and implement diversions/detours; prepare and use signage Temporarily or permanently **restrict sensitive activities** in flood-prone areas Research and development into **novel flood-proofing methods**	Introduce **penalties** for non-compliance with standards or requirements Improve **legal protection** for vulnerable habitats with buffering function (e.g. absorbing wave energy, providing erosion protection)

Annex 4B – Flooding Due to Overtopping

Annex 4B highlights measures that can be adopted to deal with **more frequent flooding** of operational areas **due to overtopping** (fluvial flooding). Most measures are also relevant to more frequent or extreme coastal or estuarine flooding, for example associated with **sea level rise or storm surge**. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures	**Social measures**	**Institutional measures**
Structures, systems, technologies, services	People, behaviour, operations, information	Governance, economics, regulation, policy
Ensure timely maintenance **dredging** of ports and inland waterways to maintain conveyance capacity	Improve (or instigate) **monitoring** and **record keeping** on location-specific overtopping-related metrics, including area affected	Mapping and **zoning** to identify water retention areas; link to **land use policy**
Ensure effective **maintenance** of existing **drainage system**, storm drains, culverts, interceptors, separators, and trash screens, etc.	Use **monitoring** outcomes, including **topographic** and pre- and post-flood **hydrographic** surveys to characterise flood risk	Collaborate with stakeholders including utilities, services, other transport modes on **flood risk management planning** to **protect business continuity**
Temporarily or permanently **raise**, strengthen **or retrofit** existing **flood defences, quays**, etc.	Prepare, review and regularly update flood risk maps and **flood response plan**; raise user awareness	Encourage **relocation** out of flood-prone areas
Reinforce structures such as revetments, wave dissipating block and parapets	Provide or improve **forecasting** and **flood warning** systems	Provide, secure, and coordinate **alternative transport routes** and logistics to access port or facilities
Reinforce facilities, protection barriers, yard furniture, etc. near the base of key assets	Develop and raise awareness of **new operational protocols** for flood response e.g. preparation, evacuation, monitoring of moorings	Provide grants/**financial incentives** to encourage investment in resilient infrastructure including **nature-based** drainage, storage or resilience **solutions**
Raise aprons and breakwaters to protect against inundation and wave overtopping	**Optimise locations used for operations** such as cargo handling to mitigate loss of materials and equipment	**Build-back-better** or 'build out of harm's way' policies for flood-damaged or damage-prone infrastructure
Steepen apron **gradients** to accelerate drainage	Flexibility in **staffing rotas** to respond to climate-related events	Ensure investment policies take into account **life-cycle resilience**, making provision for expected changes
Raise bridges, decking, jetties, revetments, dams, spillways, superstructure, etc.	Provide **accommodation** and **transport** for personnel to use during an incident	**Reduce insurance premiums** if improved resilience is demonstrated
Assess and if required increase number and strength of **bollards/quays** and mooring lines	Provide **training** in use of demountable defences, placing sandbags, raising assets, etc.	Improve **legal protection** for vulnerable habitats with flood risk reduction role (e.g. absorbing wave energy, providing erosion protection)
Introduce new **mooring technology** e.g. vacuum mooring systems	Review **stacking procedures**, e.g. use empty container or install permanent shelving at stack base	Review and revise relevant **standards, specifications or guidelines**
Assess tug and tug **towing strength** so that it is sufficient for increasing vessel size		

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Deck design with relief slots; drain holes, valves; wave walls Improve resilience and reduce flood risk by promoting **nature-based solutions** (Working with Nature, beach nourishment, living shorelines) **Bund or raise critical assets (**e.g. back-up generators, pump-house); install water splash or **scour protection** **Relocate, or raise elevation** of, access roads, storage facilities **Relocate** critical assets to elevated platforms; upper floors/mezzanine; out of flood risk area **Co-locate** critical systems; central system in addition to remote stations Ensure effective **maintenance** of existing **drainage** system; manage run-off rates Ensure adequate supply of **sandbags**; bricks/pallets for temporary raising, etc. Acquire and install, or hire (more powerful) **pumps**; **demountable** flood **defences** Install and maintain **sustainable drainage systems**, gullies, flood conveyance infrastructure; make space for (temporary) **water storage** within port or waterway estate Install **flood-proofing** measures (e.g. barriers, gates, shutters, electricity supply modification) Investigate upstream **flood** diversion or **storage** options Explore opportunities for **floating infrastructure**	Review **port traffic management** plan if flooding affects access; identify and implement diversions/detours; prepare and use signage Temporarily or permanently **restrict sensitive activities** in flood-prone areas Research and development into **novel flood-proofing methods**	Require the preparation of **flood risk management plans** Introduce **penalties** for non-compliance with standards or requirements Be aware of and support initiatives to identify and track **emergency towing vessels**

Annex 4C – High Flow or Extreme Sea State Conditions

Annex 4C highlights measures that can be adopted to deal with **more prolonged or frequent high in-channel flow velocities or sea state changes (agitation, extreme wave) conditions**. Some of these measures might also be relevant where climate change is impacting on flows or currents in estuaries. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Provide **safe havens** (sanctuaries) or additional moorings **Raise** bridges, decking, jetties, revetments, dams, spillways, superstructure **Strengthen** decking, jetties, revetments, dams, spillways fendering, bridges, lower level of buildings, etc. Provide **surface protection** to banks, etc. to resist internal and external erosion including under asymmetrical loading Construct new or modify existing **breakwaters** (e.g. armour unit selection, orientation, height) Exploit **nature-based** resilience e.g. create offshore berms or barrier islands; supplement or enhance marsh, mangrove or other intertidal habitats **Dredge** to improve conveyance in rivers Develop new **responsive**, flexible or **demountable infrastructure** e.g. ramps, pontoons, fendering, berthing or pilotage facilities Divert excess flows to **flood storage** areas Provide **hydraulic structures** of an adequate capacity to pass water under a canal Modify **vessel design** to accommodate new conditions; strengthen **chains**, **anchors**	Improve (or instigate) **monitoring** and **record keeping** on relevant location-specific flow or wave-related metrics Invest in affordable, intelligent **portable or wearable devices** for monitoring or data collection Produce up to date electronic **bathymetric** charts; promote **ECDIS** for inland waterways (Electronic Chart Display and Information System) Use adaptive management concept to improve **flexibility** in scheduling and **working arrangements** (e.g. berthing), **working times** and **conditions** (e.g. fishing fleet) Provide or improve **strong stream** or high wave forecasting abilities Develop or improve **strong stream warning systems** (physical or electronic flags) Increase **pilotage** provision Optimise **daily operation** time in transport vessels Develop and raise awareness of **new operational protocols** for operations in strong stream or high wave conditions Apply temporary **restrictions o**n (non-essential; recreational) **use** of water area	**Relocate fairway** to less exposed location **Limit new development** in high risk areas **Reduce insurance premiums** if improved resilience is demonstrated Provide grants / **financial incentives** to encourage investment in resilient infrastructure, including nature-based solutions Review and revise relevant **standards**, specifications (including for vessel design and moorings) Review and revise speed limits, etc. Introduce **penalties** for non-compliance with standards, speed limits, etc. Use **byelaws, zoning** or local regulation to reduce risks in multi-use locations e.g. zoning for recreational use Improve **legal protection** for vulnerable habitats with role in reducing wave energy

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Assess and if required increase number and strength of **bollards/quays** and mooring lines Review, modify or introduce new **mooring technologies**, e.g. vacuum mooring systems Optimise use of **River Information Systems** (RIS) or vessel traffic services (**VTS**) Review and revise **anchorage** arrangements; consider re-siting Upgrade manoeuvring aids, **navigation aids** (beacons, lights, buoys, etc.) Ensure provision of **back-up** when relying on automated or remotely operated equipment (e.g. double up on AIS base stations, transceivers, radar stations, etc.) **Co-locate** critical systems; central system in addition to remote stations	Introduce diversions, one-way systems, or **temporary closures** of port or waterway Allow increased **wait times** in anchorages; improve **queuing** procedures Exploit interconnectivity, **inter-modality**: use other modes to retain **business continuity** during high flow periods	

Annex 4D – Low Flow or Drought

Annex 4D highlights measures that can be adopted to deal with **more prolonged or frequent low flow or low water level conditions** (i.e. in channel). Many measures are also relevant in the context of **drought** or other changes causing a **water supply deficit**. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Provide **safe havens** (sanctuaries) or additional moorings Create water-saving basins/water reservoirs or **leakage reduction** measures for locks, canals, dams Explore **water diversion or flow supplementation** options from other systems **Water re-use**, e.g. introduce backlift pumping Construct new **water storage** facilities, reservoirs Develop/install **responsive**, flexible or **demountable infrastructure**, e.g. ramps, pontoons, fendering, berthing or pilotage facilities Lengthen or otherwise **retrofit** existing gangways, walkways, linkspans, etc. Capital/maintenance **dredging** to provide or retain fairway **depth**; to provide adequate depth at berth if quay walls allow Use of groynes, training walls, etc. to manage fairway position Modify **vessel design** to accommodate new conditions (e.g. install sensors to detect shoaling; shallower draft; modify vessel weight or reduced weight; hull strengthening to allow drying out at berth) Increase **storage capacity** for use during low water events Install **multi-modal cranes** and other equipment for use when low flow precludes river use	Develop or improve electronic charts, **forecasting systems** Review or modify **hydrographic survey** frequency or post-event procedures; relocate channel; enhance **marking** regime Use real-time data (from vessels; hydrographic surveys) to select '**best water**' (i.e. adequate depth) for navigation; develop and utilise enhanced, sophisticated **passage planning** e.g. fairway within a fairway Increase **pilotage** provision; increase use of **tugs** Use **dynamic under keel clearance** (DUKC) technologies Use adaptive management concept to improve **flexibility** in scheduling and **working arrangements** (e.g. dredging; berthing, lock-use; loading to reduce draft; one-way traffic; water flow management) Modify **lock-use logistics** to reduce net water use Develop or improve **low flow warning systems** (physical or electronic flags) Develop **new operational protocols** or codes of practice for low flow operations. Raise awareness or provide **training** Research and development into **novel water saving methods** Apply temporary **restrictions o**n (non-essential; recreational) **use** of water area	Develop or coordinate **water allocation** programmes; ensure navigation is included Collaborative programmes to develop multi-user **storage and supply** systems Provide grants/**financial incentives** to encourage investment in resilient infrastructure; for reducing water use Encourage **relocation** of susceptible facilities Review and revise relevant **standards**, specifications, speed limits, etc. Introduce **penalties** for non-compliance with standards, speed limits, etc. Use **byelaws, zoning** or local regulation to reduce risks in multi-use locations **Limit new development** in areas at high risk

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Review/upgrade manoeuvring aids, **navigation aids**, (beacons, lights, buoys, etc.) Ensure provision of **back-up** when relying on automated or remotely operated equipment	Introduce diversions, one-way systems, or **temporary closures** of port or waterway Exploit interconnectivity and **inter-modality** options to maintain business continuity during low flow events	

Annex 4E – Changes in Sediment Regime

Annex 4E highlights measures that can be adopted to deal with observed changes in **bathymetry** or in **sediment or debris transport, deposition and accumulation**. Such impacts may result from climate-related changes in precipitation, snowmelt, river flow, wave conditions or storminess. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Reduce sediment run-off into watercourse using sediment traps, **buffer strips**, etc. **Remove redundant structures** that promote the deposition of sediment or debris **Research** into innovative prevention or removal methods Install and **maintain trash screens, booms**, etc. **Reduce deposition** by realigning channel or structures; constructing training walls, berms, groynes, current or flow deflectors, breakwaters, etc. Ensure timely **dredging** to maintain conveyance capacity **Beneficially re-use** or relocate **dredged sediment** Review/upgrade manoeuvring aids, **navigation aids**, (beacons, lights, buoys, etc.) Accommodate sediment in managed realignment, set back or **ecological enhancement** initiatives e.g. groyne bays Set back or **relocate at-risk infrastructure** or assets Install **multi-modal cranes** and other equipment for use when sediment or debris accumulation precludes river use Modify **vessel design** to accommodate new conditions (e.g. install sensors to detect shoaling; shallower draft)	**Monitoring** and **record keeping** on location-specific sediment or debris-related metrics Review or modify **hydrographic survey** frequency or post-event procedures Relocate channel; enhance **marking** regime Use real time data (from vessels; hydrographic surveys) to select '**best water**' (i.e. adequate depth) for navigation Develop and utilise enhanced, sophisticated **passage planning** Increase **pilotage** provision; use **dynamic under keel clearance** (DUKC) technologies Use adaptive management to improve **flexibility** in scheduling and **working arrangements** (e.g. dredging; berthing, lock-use; loading to reduce draft; one-way traffic; water flow management) Monitor and **adaptively manage trash screens**, booms, drainage systems Enhance management or **maintenance protocols** for trash screens, booms, drainage **Educate** local communities about consequences of trash disposal around watercourse Develop **new operational protocols** or codes of practice for debris removal; raise awareness or provide **training**	**Incentives** for nature-based sediment management solutions Review and revise relevant **standards**, specifications, speed limits, etc. Introduce **penalties** for non-compliance with standards, speed limits, etc. Effective upstream **land-use planning** and management Encourage **relocation** out of areas susceptible to deposition or accumulation **Zoning** based on compatible use of riparian areas Introduce and enforce policies to **discourage** (informal) **habitation** in high risk riparian areas

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
	Research into means of preventing debris washing into navigable areas; or techniques for **rapid removal of debris** Temporary **restrictions o**n (non-essential; recreational) water **use** Introduce diversions or **temporary closures** Exploit interconnectivity and **inter-modality** options to maintain business continuity	

Annex 4F – Bank or Bed Erosion

Annex 4F highlights measures that can be adopted to deal with **increases in bed or bank erosion**. Such impacts may result from climate-related changes in precipitation, snowmelt, river flow, wave conditions or storminess. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Install, **maintain** or enhance bank **protection**, water splash or scour protection Construct **breakwaters**, berms, training walls, current or flow deflectors Use **nature-based solutions** wherever practicable, e.g. beach nourishment; restoration or planting of mangroves, saltmarshes, riparian vegetation; restoration of reef ecosystems Reconsider/reduce **dredging requirements** **Re-use dredged material** as bund or breakwater (e.g. in geotubes, behind low-level retaining structure) Managed realignment, **set back** or **relocate** at-risk assets Optimise **protection** or burial of sub-sea cables	Review or modify **hydrographic survey** frequency or post-event procedures Prioritise **inspection** and **monitoring** of vulnerable infrastructure Review and modify management or **maintenance protocols** Review or modify **maintenance dredging** regime to respond to changing conditions; to avoid exacerbating erosion Introduce and implement **adaptive management** procedures; plan operations or working arrangements based on monitoring outputs **Research** into innovative erosion control measures **Raise awareness** of links between vessel speed and design and consequences of wash for erosion; aim to **modify behaviour**	Improve **legal protection** for vulnerable habitats with erosion protection role Introduce temporary or permanent **zoning** or **restrictions on use** to reduce erosion risk Introduce or revise **speed limits** to reduce wash; enforce **penalties** for non-compliance Provide grants/**financial incentives** to encourage investment in resilient infrastructure, including nature-based solutions Accommodate risk by including **set-back** or **buffer zones** in land-use planning policy Encourage **relocation** out of erosion-prone areas **Build-back-better** or 'build out of harm's way' policies for damaged or damage-prone infrastructure Ensure investment policies take into account **life-cycle resilience**, making provision for expected changes

Annex 4G – Reduced Visibility

Annex 4G highlights measures that can be adopted to deal with **increases in frequency or severity of reduced visibility**, for example due to the incidence of fog or blizzard conditions, sandstorms, etc. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Install or improve **warning equipment**, fog horns, radar, high visibility lighting, etc. Review/upgrade manoeuvring aids, **navigation aids**, (beacons, lights, buoys, etc.) Install or improve **instrument-only** navigation **equipment** Ensure provision of **back-up** when relying on automated or remotely operated equipment; (e.g. double up on AIS base stations, transceivers, radar stations, etc.) **Co-locate** critical systems; central system in addition to remote stations Install **visibility measuring** instrumentation Review or upgrade **River Information Systems** (RIS) or vessel traffic services (**VTS**) Use **airtight equipment** to reduce condensation issues Install **multi-modal cranes** and other equipment for use when prolonged fog precludes river use	Improve (or instigate) **monitoring** and **record keeping** on location-specific fog-related metrics Invest in affordable, intelligent **portable or wearable devices** for monitoring or data collection Develop or improve **warning systems**; review and refine **response** procedures Use adaptive management concept to improve **flexibility** in scheduling and **working arrangements** (e.g. berthing, lock-use; one-way traffic) Enhance **pilotage provision** e.g. for certain vessel classes; increase pilot numbers, training Flexibility in **staffing rotas** to respond to climate-related events Revert to **traditional** means or **methods** of navigation Develop **new protocols** or codes of practice for operations in poor visibility (recreational use, pilotage, etc.). Awareness raising or provision of **training** Temporary or permanent **zoning** or **restrictions on** (non-essential; recreational) **use** Introduce diversions, one-way systems, or **temporary closures** of port or waterway Exploit interconnectivity and **inter-modality** options to maintain business continuity	Use **byelaws, zoning** or local regulation to reduce risks in multi-use locations, e.g. permanent or weather-related zoning to separate commercial from recreational navigation traffic or a ban on recreational use if a pre-determined threshold is exceeded Temporary **speed limits** with **penalties** for non-compliance

Annex 4H – Changes in Wind Characteristics

Annex 4H highlights measures that can be adopted to deal with **changes in wind speed/strength, direction, or duration** affecting infrastructure or operations. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Strengthen, raise or otherwise **retrofit existing** protective **infrastructure** Install **wind deflectors** to reduce wind load Construct new wind breaks or protective infrastructure using **nature-based solutions** where practicable **Reinforce** protection for key assets potentially affected by wind pressure Install new or strengthen storm-pin or **tie-down** points, especially for cranes; also braking systems **Modify design** of structures (e.g. cranes) to reduce vulnerability Assess and if required **increase number and strength** of bollards, quays and mooring lines. Introduce **new mooring technology**, e.g. vacuum mooring systems Assess tug and tug **towing strength** so that it is sufficient for increasing vessel size **Relocate** vulnerable assets Use **demountable equipment** that can be removed/stored when a warning is received **Widen, dredge** or **enlarge** waterway to facilitate continued use	Improve (or instigate) **monitoring** and **record keeping** on location-specific wind-related metrics Install anemometers; develop or improve **warning systems** Invest in affordable, intelligent **portable or wearable devices** for wind monitoring or data collection **Review susceptibility** of existing infrastructure, assets and operations including the effects of windage on vessels, use of tugs **Relocate** or modify vulnerable operations and activities Develop **new operational protocols** or codes of practice e.g. use of tie-downs; stacking or lashing of containers; tug use; vessel movement; bunkering; recreational use; mooring monitoring during high winds; switch off radar if practicable when certain wind speed is exceeded Raise awareness or provide associated **training** Consider alternative **pilot boarding** locations, procedures; review mooring plans for high wind conditions; practice for high wind conditions in mooring simulators Use adaptive management concept to improve **flexibility** in scheduling and **working arrangements** (staffing rotas, berthing, boarding, bunkering) Provide **accommodation** and **transport** for personnel to use during an incident	Use **byelaws, zoning** or local regulation to reduce risks in multi-use locations, e.g. permanent or weather-related zoning to separate commercial from recreational navigation traffic or a ban on recreational use if a pre-determined threshold is exceeded Encourage **relocation** of wind-prone assets or activities out of high-risk areas Provide grants/**financial incentives** to encourage investment in resilient infrastructure Review or revise relevant **design codes**, **standards** or operational parameters, including for vessel stability, windage Implement a **build-back-better** or 'build out of harm's way' policies for wind-damaged or damage-prone infrastructure Ensure investment policies take into account **life-cycle resilience**, making provision for expected changes Implement temporary **speed limits** Introduce **penalties** for non-compliance with standards, speed limits, etc.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Review or upgrade **River Information Systems** (RIS) or vessel traffic services (**VTS**) Review and revise **anchorage** arrangements; consider re-siting Ensure provision of **back-up** when relying on automated or remotely operated equipment; (e.g. double up on AIS base stations, transceivers, radar stations, etc.) **Co-locate** critical systems; central system in addition to remote stations Install **multi-modal cranes** and other equipment for use when wind conditions preclude river use	Temporary or permanent **zoning** or **restrictions on** (non-essential; recreational) **use** Introduce diversions, one-way systems, or **temporary closures** of port or waterway Exploit interconnectivity and **inter-modality** options to maintain business continuity	

Annex 4I – Extreme Cold, Ice or Icing

Annex 4I highlights measures that can be adopted to deal with **changes in the extent, duration or frequency of extreme cold, ice or icing**. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Consider **storage** or **diversion** channels to accommodate additional snowmelt volume Prioritise **maintenance** of critical infrastructure Review **placement methods and location** of stockpiles of collected snow and ice, for release into drainage systems Adapt **vessel design**, e.g. ice strengthening, enclosed bridge Maintain (unfrozen) **water provision** on berths, e.g. for fire-fighting Review **icebreaker** provision, use of **ice booms** Improve **resilience** of fuel storage and distribution system including for land transport **Maintenance** and appropriate **treatment**, e.g. of access and roads within port estate Improve **thermal efficiency** of buildings with adaptive measures, e.g. insulation, ventilation Use **SCADA** to monitor temperature, humidity	Improve (or instigate) **monitoring** and **record keeping** on location-specific cold, frost, icing and snowmelt metrics **Raise awareness** amongst workforce and stakeholders of the issues associated with prolonged cold or early melting issues Develop or improve **warning systems** (for both frost/icing and ice or snowmelt) **Prepare** and **raise awareness** of extreme cold emergency response **plans** **Review susceptibility** of existing infrastructure, assets and operations, particularly to **reduction in permafrost, early snowmelt**, etc., as well as prolonged **extreme cold** events Develop **new operational protocols** or codes of practice; raise awareness or provide associated **training** **Relocate** or modify vulnerable operations and activities Use adaptive management concept to improve **flexibility** in scheduling and **working arrangements** according to temperature and conditions (e.g. staffing rotas, berth-scheduling; ice-breaking; port access) Review **pilotage** procedures	Implement measures to ensure **onward transport** networks remain functional Provide grants/**financial incentives** to encourage investment in resilient infrastructure Encourage **relocation** out of damage-prone areas Review **health and safety** legislation for cold weather operations Review or revise relevant **design codes**, **standards** or cold weather operational parameters Introduce **penalties** for non-compliance with standards

Annex 4J – Extreme Heat

Annex 4J highlights measures that can be adopted to deal with **changes in the extent, duration or frequency of extreme heat**. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Vegetation management: planting of **heat or drought resistant vegetation**, e.g. where structural stability relies on root mat Provision of **shade**, using nature-based solutions where practicable Use **heat-tolerant or resistant** plant, equipment, infrastructure or materials Modify or replace heat-sensitive **opening mechanisms** and similar on bridges, locks, etc. Improve **thermal efficiency**; design for temperature regulation; improve insulation or ventilation; install air-conditioning or cooling systems on vessels; in offices, storage facilities, etc. Install **climate-controlled cabins** for critical equipment and systems including radar (e.g. bolted-down, insulated container) Review **vessel design** including insulation or ventilation of cargo space, accommodation, etc. Use **SCADA** to monitor temperature, humidity	Improve (or instigate) **monitoring** and **record keeping** on location-specific heat-related metrics Prepare and regularly review extreme heat **warning systems** **Prepare** and **raise awareness** of extreme heat response **plans** Introduce and implement **adaptive management** procedures; plan operations or working arrangements based on monitoring outputs Ensure flexibility in **staffing rotas** to optimise productivity whilst providing adequate respite **Raise awareness** of heat-related issues; provide appropriate first-aid training Research into new heat-resistant or **heat-tolerant plant, equipment**, materials, etc.	Review **health and safety** legislation for hot weather operations Provide grants/**financial incentives** to encourage investment in resilient infrastructure **Insurance** or contingency fund to assist in event of prolonged heatwave Improve **legal protection** for heat-vulnerable habitats and species with a risk reduction role (e.g. absorbing wave energy, providing erosion protection)

Annex 4K – Ocean Water Acidity

Annex 4K highlights measures that can be adopted to deal with the implications for waterborne transport infrastructure of **increases in ocean water acidity**. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Review and improve existing **corrosion protection** systems Review and revise **maintenance** schedules for corrosion-vulnerable infrastructure and assets Construction **materials selection** process, e.g. concrete to account for acidity changes New **infrastructure design** to take into account potential loss of wave attenuation effect of coral reef Review/revise **anti-fouling** measures to take account of ambient conditions	Improve (or instigate) **monitoring** and **record keeping** on location-specific water-related metrics (water pH, reef health) Prioritise **inspection** of critical infrastructure Develop **data-sharing** procedures **Technical awareness** of implications of pH level changes for vessel coatings; corrosion protection, etc. Develop and use **new corrosion-resistant materials** **Education** on role of coral reefs in coastal protection and climate related risks Develop **contingency plan** covering future loss of protective role of coral reef (wave attenuation); draft-critical under keel clearance operations; and related issues Use **dynamic under keel clearance** (DUKC) technologies	Review or revise relevant **design codes**, **standards** or operational parameters in relation to acidity Prepare and implement coral reef **conservation plan** Increase **legal protection** for reefs and other vulnerable habitats providing coast protection or other risk reduction functions

Annex 4L – Salinity or Saltwater Intrusion

Annex 4L highlights measures that can be adopted to deal with the implications for waterborne transport infrastructure of **changes in salinity or saltwater intrusion**, including changes in ground water salinity. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
New **infrastructure design** to take into account consequences of changes in salinity Select salinity-tolerant **construction materials** Review/revise and prioritise **maintenance** for assets that are vulnerable to corrosion or to changes in salinity levels Modify **vegetation management** regimes to accommodate changes in salinity	Improve (or instigate) **monitoring** and **record keeping** on location-specific water-related metrics, e.g. location and behaviour of **salt water wedge** Prioritise **inspection** of critical infrastructure **Research**, develop and use salinity-resistant **materials** **Education** about effects of salinity on characteristic plant and animal species and implications of future change **Technical awareness** of effect of increased salinity on electrolytic corrosion	Review or revise relevant **design codes**, **standards** or operational parameters in relation to salinity tolerances Improve **legal protection** for salinity-vulnerable habitats and species with a risk reduction role (e.g. absorbing wave energy, providing erosion protection)

Annex 4M – Vegetation Growth

Annex 4M highlights measures that can be adopted to deal with the implications for waterborne transport infrastructure of **changes in native vegetation growth rates** resulting from warmer water temperatures. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Create **lagoons** or plant **buffer strips** to reduce nutrient input to waterways Install **screens, booms,** etc. to reduce risk of blockage of intakes, propeller fouling, etc. due to excessive growth Develop and apply innovative **mechanical clearance** methods Prioritise **maintenance** of critical infrastructure to optimise adaptive capacity	Improve (or instigate) **monitoring** and **record keeping** on location-specific vegetation-related metrics Prioritise **inspection** of critical infrastructure **Educate landowners** about native species to foster understanding and effective management **Engage** users and other **stakeholders** in monitoring to help inform vegetation management decision making Develop **data-sharing** procedures Develop and implement local **vegetation management plans** including contingency measures **Reduce use of nutrients, fertilisers**, etc. to reduce algal blooms and excessive weed growth Modify cutting or **clearance frequency** or **methods** **Research** into novel vegetation management methods (e.g. introduction of natural predators)	Review or revise relevant **design codes**, **standards** or operational parameters in relation to native vegetation use and management Develop and implement **ecosystem level** native vegetation conservation and management plans

Annex 4N – Species Migration or Change in Range

Annex 4N highlights measures that can be adopted to deal with the implications for waterborne transport infrastructure of **changes in species migration or range** resulting from warmer water temperatures. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Facilitate diversification or otherwise cater for the consequences of any significant shift in range of the target species currently relied on by commercial or recreational fishing, or wildlife watching Modify existing or provide new **harbour infrastructure** to accommodate water temperature-related changes in use **Relocate** activity (e.g. provide new infrastructure) to follow those same target species	Improve (or instigate) **monitoring** and **record keeping** on location-specific target species-related metrics **Engage** users and other **stakeholders** in monitoring to help understanding of species' migration or shifts in range Share data on **species abundance and health** **Mapping** of species migration over time; shifts in range of key species; use to inform relocation vs. alternative use decisions Research and develop **new opportunities** (i.e. different target species or activities) at the existing location	Provide grants/**financial incentives** to enable relocation or support diversification amongst those that lose income due to species' migration National or regional **adaptation strategies** for affected sectors

Annex 4O – Native Species Survivability or Growth Rates

Annex 4O highlights measures that can be adopted to deal with the implications for waterborne transport infrastructure (such as earth embankments) of **changes native species survivability or growth rates** associated with air temperature changes. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Focus on **maintenance and management** of existing species to maximise short term resilience and improve **adaptive capacity** **Replant** with alternative (e.g. heat or drought-tolerant) species Adopt other **nature-based solutions** Install revetment, piling or other **engineered solution** as natural vegetation degrades, i.e. replace functions such as wave attenuation, soil binding, or provision of shade	Improve (or instigate) **monitoring** and **record keeping** on location-specific vegetation-related metrics (e.g. evapotranspiration rates) **Engage** users and other **stakeholders** in monitoring to provide information on species' health Review and **modify maintenance regimes** where native species play a role in supporting critical infrastructure or operations Modify **vegetation management** practices, or otherwise manage ecological conditions to **promote restoration** and recovery Develop and implement **vegetation management plans** including contingency measures **Research** into, develop and use native, drought-tolerant species for bank protection, towpaths, etc.	Improve **legal protection** for drought-vulnerable habitats and species with an ecosystem service function Review or revise relevant **design codes**, **standards** or operational parameters in relation to native vegetation use and management Provide grants/**financial incentives** for measures to improve resilience of vegetated infrastructure

Annex 4P – Invasive Non-Native Species

Annex 4P highlights measures that can be adopted to deal with the implications for waterborne transport infrastructure of **invasive non-native species (INNS) establishment or spread** facilitated by changes in air or water temperature. Note that these measures are not discrete: they are often explored simultaneously or implemented in-combination.

Physical measures Structures, systems, technologies, services	**Social measures** People, behaviour, operations, information	**Institutional measures** Governance, economics, regulation, policy
Remove redundant structures that may provide 'stepping stones' for species' spread Install **ballast water treatment** systems, reception facilities, etc. Ensure application of state-of-the-art **antifoulants** to potentially affected infrastructure	Improve (or instigate) **monitoring** and **record keeping** on location-specific INNS-related metrics **Educate** stakeholders about the threats posed by INNS and about avoidance and management options, e.g. inspections, **check-clean-dry** **Provide training** on INNS identification and management methods Prioritise **inspection** of critical infrastructure **Engage** users and other **stakeholders** in monitoring to provide information on INNS distribution and abundance Develop **mapping** and information-sharing tools, protocols, apps, etc. to record presence or spread of INNS Develop **early warning systems** and local contingency plans Review and modify management or **maintenance** regimes for vulnerable infrastructure (e.g. intakes, outfalls, earth embankments) Develop **new** preventative methods e.g. anti-foulant **products** or **systems** Research and develop eradication techniques, **biological controls**, etc. for target species Facilitate knowledge and **technology transfer**	Prepare and implement **marine biosecurity** plans Review or revise relevant **design codes**, **standards** or operational parameters Introduce or strengthen **regulations** to reduce risk of new introductions Introduce or strengthen **penalties** for non-compliance e.g. for failing to prevent new introductions Engage with regulators and others in the preparation of national or regional **emergency response plans**

Cover picture: Port Botany, NSW Ports, Australia.
See Case Study 10

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