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Climate-resilient infrastructure: Getting the policies right

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by Lola Vallejo and Michael Mullan (OECD)

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ABSTRACT

Climate change will affect all types of infrastructure, including energy, transport and water. Rising temperatures, increased flood risk and other potential hazards will threaten the reliable and efficient operation of these networks, with potentially large economic and social impacts. Decisions made now about the design, location and operation of infrastructure will determine how resilient they will be to a changing climate.

This paper provides a framework for action aimed at national policymakers in OECD countries to help them ensure new and existing infrastructure is resilient to climate change. It examines national governments' action in OECD countries, and provides recent insights from professional and industry associations, development banks and other financial institutions on how to make infrastructure more resilient to climate change.

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Keywords: adaptation, climate change, infrastructure, risk management

RÉSUMÉ

Le changement climatique aura un impact sur tous les types d'infrastructure, notamment l'énergie, le transport et la gestion de l'eau. L'élévation des températures, du risque d'inondation ainsi que d'autres aléas potentiels menaceront la fiabilité et l'efficacité du fonctionnement de ces réseaux, avec des répercussions potentiellement importantes sur l'économie et la société des pays concernés. Les décisions prises aujourd'hui pour la conception, l'emplacement et la gestion des infrastructures détermineront leur degré de résilience face au changement climatique.

Cette étude propose un cadre d'action aux décideurs publics nationaux des pays de l'OCDE, pour les aider à s'assurer que leurs investissements dans les infrastructures nouvelles ou existantes sont résilients au changement climatique. Elle examine les initiatives menées à ce jour par les pays de l'OCDE, et donne un aperçu des efforts récents des associations professionnelles, des fédérations industrielles, des banques de développement ainsi que d'autres institutions financières pour renforcer la résilience de l'infrastructure au changement climatique.

Classification JEL : H54, O18, Q54

Mots clés : adaptation, changement climatique, infrastructure, gestion des risques

FOREWORD

This working paper on "Climate-Resilient Infrastructure: Getting Policies Right" has been overseen by the Working Party on Climate, Investment and Development (WPCID). It was written by Lola Vallejo and Michael Mullan, and overseen by Simon Buckle.

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EXECUTIVE SUMMARY

This paper provides a framework for action to help ensure the resilience of new and existing infrastructure to climate change. It is primarily aimed at national policymakers in OECD countries, but the underlying principles are applicable more broadly.

Infrastructure assets and networks are capital-intensive, long-lived and interdependent across sectors. Decisions made now about the location, design and operation of these assets will determine their longer-term resilience to the effects of climate change. Strengthening resilience in this area is an essential component of climate adaptation, particularly since adequate, reliable infrastructure underpins growth. Taking climate resilience into account can protect investment returns, support business continuity and meet regulatory requirements. As such, infrastructure owners, operators and investors have an incentive to manage these risks, but a range of barriers may prevent them from doing so. These barriers include a lack of awareness or information, short-termism and misaligned regulatory incentives.

A comprehensive approach is required to overcome the barriers to infrastructure resilience and avoid locking in vulnerability to climate change. This paper identifies four priority areas where action by national governments could support infrastructure resilience:

- Ensure that state-owned utilities, professional associations and regulators have sufficient capacity to use climate projections, and facilitate partnerships between sectors to better understand and address infrastructure interdependencies.
- Account for climate risks when making public sector investments. Review the allocation of liabilities and investment responsibilities between the public and the private sector in Public Private Partnerships (PPPs) in light of climate change.
- Align spatial planning policies, national and international technical standards, and economic policies and regulation in support of infrastructure resilience. Governments may want to ensure international, national and local approaches are aligned in order to facilitate private-sector adaptation.
- Raise the profile of climate risk disclosure by encouraging participation in voluntary initiatives, supporting the development of common approaches at the international level and using information gained from risk disclosures when planning climate adaptation at the national level.

1. INTRODUCTION

Reliable, efficient infrastructure underpins sustainable economic and social development.[1] OECD countries and emerging economies are going to invest significant public and private resources into infrastructure, both to upgrade existing systems and build new networks to support economic growth. The New Climate Economy report estimated that worldwide investments in infrastructure will need to increase from USD 3.4 trillion per year currently to about USD 6 trillion per year by 2030 to meet these objectives (NCE, 2016). Policy objectives, such as decarbonising electricity generation, will be an additional driver of investment.

Climate change poses increasing challenges for infrastructure. Sea-level rise, changes in temperatures, rainfall or other climatic factors will affect all types of infrastructure. Extreme weather events illustrate the types of disruption that may become more frequent. For example, flooding of transport links during Hurricane Sandy restricted travel for the 5.4 million weekday passengers (New York City, 2013). The sets of hazards vary by country. For instance, the UK's infrastructure will be affected by a range of climate impacts including flooding (Table 1). Canada and Scandinavian countries' infrastructure will also be affected by the thawing of permafrost, while Australia's will have to cope with high temperatures and reduced water availability.

As a consequence of climate change, design thresholds for safe and efficient operation may be breached more frequently, or projects may have to function within tighter margins between "normal" operation and critical thresholds, resulting in decreased efficiency of equipment and more frequent periods of restricted operation. This could lead to reduced asset lifetimes, higher running costs and capital expenditures, loss of income, and increased risk of environmental damage (European Commission, 2013a). Damages from climate hazard impacts to critical infrastructures in Europe could increase 10-fold by the end of the century (Forzieri, 2015).

[1] For the purpose of this paper, infrastructure is defined as the assets and networks providing essential services to society in the field of energy, water and sanitation, road, rail, air and maritime transport, as well as flood protection.

Table 1. Illustration of climate impacts on infrastructure in OECD countries: United Kingdom

	Sea level rise				Rainfall						Temperature						Other factors				
	Damage or disruption from coastal flooding	Tide locking	Saline intrusion	Coastal erosion	Damage or disruption from river flooding	Damage or disruption from pluvial flooding	Droughts and low precipitation	Altered capability or efficiency	Biological processes	Stability of earthworks	Severe heat	Severe cold, snow, ice	Altered capacity or efficiency	Subsidence and/or desiccation	Biological processes	Demand for service	Lightning strike	Humidity	Solar radiation	Fog	Storminess and wind damage
Rail	x			x	x	x	x	x		x	x	x	x	x		x	x	x			x
Road	x			x	x	x		x		x	x	x	x	x		x		x		x	x
Ports and marine transport	x	x		x		x					x	x	x							x	x
Potable water	x		x	x	x	x	x	x	x		x	x	x	x	x	x					x
Waste water and sanitation	x	x	x		x	x	x		x		x	x	x	x	x	x					
Flood and coastal erosion management	x	x		x	x	x				x	x			x	x						x
Nuclear and fossil-fuel energy generation	x			x	x	x	x			x	x	x	x								x
Renewable energy generation	x				x	x	x	x					x						x		x
Power systems, transmission and distribution	x				x	x					x		x				x				x
Energy demand	x				x	x	x				x	x				x			x		

Source: (Dawson, 2015).

Decisions made about the location, construction and operation of infrastructure provide an opportunity to reduce vulnerability to the physical impacts of climate change. Improving the climate resilience of new or existing infrastructure can be achieved by reducing its exposure or sensitivity to climate-related hazards through a wide range of context-specific adaptation responses. Adaptation measures may entail implementing 'hard' civil engineering measures to protect assets or "soft" measures, for example modifying maintenance routines or information-sharing practices (Box 1) or by working with nature (Annex 3). These measures can have very different costs, both in absolute and relative terms with respect to an overall construction or retrofitting project.

Box 1. Selected infrastructure projects integrating climate resilience in OECD countries

- **Deepwater Container Terminal (DCT) Gdańsk (Poland)**: In planning for the building of a second cargo terminal, DCT's feasibility study recommended that the height of the quay wall should take into account sea level rise projections. As one of the lenders for the project, the European Bank for Reconstruction and Development (EBRD) conducted a risk screening and a technical climate change assessment, which recommendations were factored in the loan negotiations. These recommendations confirmed DCT quay wall's height provisions, and led DCT to establish a communication channel with the Port Authority to receive relevant information on sea level extremes and potential for waves to overtop the port structures. Measures relevant for climate change adaptation were estimated to make up to 25% of the project's capital expenditure (EBRD, 2014).

- **Électricité de France (EDF) nuclear power plants (France)**: Cooling through air or water sources (such as rivers, sea or aquifers) is key to thermal power plants' functioning and to nuclear plants' safety in particular. Following summer heatwaves in 2003 and 2006, EDF launched a 'Great Heats' (Grands Chauds) plan to ensure nuclear plants would be able to comply with the regulations governing river temperatures, even with climate change. This led to investments such as improving cooling equipment, but also lower costs measures such as revising the fleet's maintenance plan or monitoring climate information and periodically revising safety standards, such as in 2009 and 2014 (SFEN, 2015).

- **Brisbane Airport New Parallel Runway (Australia)**: Following a detailed risk assessment, analysis of interdependencies and 22 months of stakeholder engagement, the second runway of Brisbane airport was built at a height of 4.1 metres above sea level, exceeding both the minimum level recommended by engineering consultants (3.5 metres) and the current 1-in-100 year storm tide level (2.3 metres). In addition, tidal channels and a new sea wall along the northern boundary of the airport were built, and the taxiways linking the new runway with the apron areas were also designed to withstand a 1-in-100 storm surge event. The cost during the preliminary design to incorporate consideration of climate change impacts was negligible, and the Brisbane Airport Corporation estimated that the additional outlay of funds during construction was outweighed by the confidence that there would be no need to upgrade the runway for at least the next 50-60 years. (Australian Government, 2013; NCCARF, 2013).

In some cases, addressing the risks from climate change will require action now, while in others the priority will be to build in flexibility to allow for later responses. Early action is most likely to make economic sense if (i) early action may be cheaper than delay; (ii) current benefits are large; and (iii) it takes a long time to put in place the necessary adaptation measures (Fankhauser, 2016).[2] Conversely, when those conditions do not apply it can make more sense to build in flexibility for the future rather than taking action now (ADB, 2015). Sophisticated approaches to decision making, such as Real Options Analysis or Robust Decision Making, can be helpful if the appropriate decision is sensitive to the climate outcome. More details on the range of decision-making tools available and their applications are provided in OECD (2015a).

[2] Analysis suggests that the current cost of remediating climate-related losses is on average four times the cost of protecting infrastructure and businesses against climate impacts (Viner et al., 2015).

Adopting a resilient approach to respond to climate change also means accepting that some disruptions are occasionally unavoidable. Climate-resilient infrastructure systems minimise the consequences of disruptions, for instance by including contingency planning that allows for safe failure of assets, in addition to featuring robust infrastructure design (ITF, 2016).

Taking climate resilience into account ought to be in the self-interest of infrastructure owners, operators and investors, as it can benefit their investment returns, business continuity or regulatory compliance. They are often best placed to manage risks to their operations and determine the most appropriate mitigation strategies. However, a lack of information regarding climate hazards or upstream vulnerability, short-termism, or misaligned regulatory incentives can all act as barriers to adaptation.

Governments have increasingly recognised that a coordinated policy response is needed to support infrastructure's climate resilience (Canada National Round Table on the Environment and the Economy, 2009; HM Government, 2011; European Commission, 2013a). By having the right policies and measures in place, national governments have the opportunity to ensure that future investment supports resilience and avoids locking-in vulnerability.

This paper draws from a literature review, an expert workshop and detailed case studies to identify the range of instruments in use and the emerging lessons on their effectiveness. It identifies and is structured around four areas in which governments can focus their efforts to facilitate climate-resilient infrastructure:

- **Improving risk assessment and information to support decision making.** This can be done by ensuring data on projected natural hazards is available and accessible, raising awareness and building the capacity of relevant decision makers. This can be supported by undertaking high-level risk assessments to identify the exposure of existing infrastructure.
- **Screening and factoring climate risks into public investments.** When investing in or commissioning infrastructure, governments can require contractors and suppliers to demonstrate they have considered climate risks.
- **Enabling infrastructure resilience through policy and regulation.** The private sector's incentives to adapt are shaped by the policy and regulatory environment. Governments can facilitate climate-resilient infrastructure by removing policy or regulatory distortions, or adding regulatory requirements to consider climate risks.
- **Encouraging climate risk disclosure.** Climate risk disclosure can encourage action to manage those risks, as well as revealing interdependencies and supporting the design of public policy.

2. IMPROVING RISK INFORMATION AND ASSESSMENT TO SUPPORT DECISION MAKING

Recommendation: Governments should collaborate with scientists, utilities, professional associations and regulators to build capacity for using climate data and projections. Governments should facilitate partnerships between sectors to improve the understanding and management of interdependencies.

Climate-related information, including data and projections, is a pre-requisite for making informed decisions about the choice, design and timing of adaptation actions for infrastructure. In particular, there is a need for (i) robust observations and projections for climatic and hydrological trends into the future; (ii) tools and technical capacity to interpret information and draw out its implications for decision-making; and (iii) forums that help to manage interdependencies by safely sharing information between infrastructure operators, both within and between sectors.

Availability of information on climate hazards

Climate projections are available at different levels of resolution, but there can be a trade-off between robustness and capturing fine grain detail. There is generally greater confidence in projections at a larger geographical scale, and for some quantities (e.g. temperature) rather than others (e.g. precipitation). At the global level, the International Panel on Climate Change (IPCC) presents the state of the evidence from a hierarchy of global climate models regarding projected changes to the world's climate (IPCC, 2013a), and includes downscaled projections for 35 world regions. Most OECD countries have also produced their own national-level climate projections or have statistically downscaled projections from IPCC modelling to understand how changes in climate variables will affect them (Annex 1.a), such as France's Drias or the United States NASA Earth Exchange Downscaled Climate Projections (NEX-DCP30). Some large countries where climate impacts may differ widely in direction and intensity in different regions have provided information at the local level. For example, Australia has regionalised its Climate Change in Australia (CCIA) projections following three levels of disaggregation: mega cluster (Southern Australia), cluster (Southern Slopes) and sub cluster (Southern Slopes - East Tasmania).

Infrastructure adaptation has to account for the uncertainties inherent in climate projections. Climate models represent the best scientific understanding of how the climate may change, but the climate is an extremely complex system. As such, even projections from the latest models are subject to uncertainty, with some climate drivers being better understood than others. While there is confidence in many of the changes related to the surface temperatures and sea-level over the globe, there is far less confidence in projections that rely on how climate change might affect the dynamics of the climate, e.g. rainfall patterns and extreme weather (Shepherd, 2014). This uncertainty supports the case for flexible approaches to infrastructure provision and retrofitting that enable changes to be made as new observations or modelling improvements emerge.

Decision-support tools that incorporate deep uncertainty into asset appraisal, such as Real Option Analysis (ROA) and Robust Decision Making (RDM) can be used to guide infrastructure investments

(OECD, 2015a). These decision-making approaches aim to identify options that would perform well in a range of potential futures, rather than optimising against a single projection.

Tools and capacity building to understand infrastructure exposure

The raw outputs of climate models have to be processed before they can be used by infrastructure planners and operators. Dedicated platforms are increasingly being developed to improve user access, facilitate the production of customised outputs, and provide important notes of caution regarding the confidence and use of the climate projections. In some countries, these platforms have explicitly targeted planners in climate-sensitive infrastructure sectors. At the national level, Geoscience Australia improved the National Exposure Information System (NEXIS) database in 2012 to better support studies regarding the implications of climate change impacts on major infrastructure in Australia. At the regional level, the Climate Futures for Tasmania project has produced sophisticated hydrological projections that support HydroTasmania's planning efforts (Bennett et al., 2010).

Climate risk assessments combine projections with other data sources, such as hydrological modelling or analysis of the impact of past extreme events, to assess climate exposure. Exposure refers to the presence of people, ecosystems, infrastructure, or assets in places that could be adversely affected (IPCC, 2013b). Climate risk assessments at the national or sectoral levels primarily support the development of policies, but may also point towards risks for specific infrastructure projects. All OECD countries have undertaken assessments of the potential impacts from climate change on at least one infrastructure sector (Annex 1.b). Assessments to date have been predominantly qualitative, but these can provide a first step towards quantification of costs and scale of risk, potentially by focusing on a sector or a hazard as was the case for Australia's transport networks at risk of coastal change (ATSE, 2008; Department of Climate Change and Energy Efficiency, 2011).

However, national or sectoral climate risk assessments are only a starting point and there will still be a need for more detailed analysis to understand the vulnerability of a particular asset or network. A major challenge in OECD countries is to ensure that the skills and tools are in place to interpret and use climate information for risk assessments and incorporate those insights into infrastructure design.[3] Specialised tools can help achieve this challenge. For example, the United States Federal Highway Agency (FHWA) has developed a tool to help transportation agencies select appropriate materials for road surfaces and understand the types of flooding that an area is likely to experience in the future.

There is a growing volume of high-level guidance and capacity-building activities to support the integration of climate risks in infrastructure projects' governance and economic analysis. The European Commission has released guidelines outlining the roles and responsibilities of large investments' project teams in integrating climate resilience, including the steps to follow throughout the conventional asset lifecycle (European Commission, 2013b). Other guidelines show how economic analysis can be used to assess the possible impacts of climate change on investment projects, as well as the technical and economic feasibility of a range of "climate-proofing" options (HM Treasury and Defra, 2009; C3 for Natural Resources Canada, 2012; ADB, 2015).

[3] This message emerged from the OECD Expert Workshop, February 2016 and Case Study 2.

Addressing interdependencies

When one infrastructure asset fails, the effects can cascade to affect other assets or networks that relied on it to function, thus creating a chain of failure, also known as a “domino effect”. Most infrastructure assets are interdependent. For example, water treatment plants need electricity from the grid to function, and ports require nearby roads or railways to be accessible to transport goods or passengers. These interdependencies are particularly significant in cities, given the dense spatial concentration of assets.

Ongoing research is modelling complex, interdependent infrastructure systems to better understand their vulnerabilities to climate change and other challenges. The UK’s first national infrastructure systems model (NISMOD) models risks and vulnerability to current and projected climate, but also the demand and capacity for infrastructure services to support long-term planning (ITRC, 2015). This was developed with public funding, via the Engineering and Physical Sciences Research Council (EPSRC). NISMOD is currently being used by utility companies, engineering consultants, the UK Institution of Civil Engineers and parts of the UK government to analyse risks and inform infrastructure decisions. Other modelling and decision-making tools are tailored for cities that wish to understand their infrastructure interdependencies and identify their vulnerability hotspots in case of natural disasters. These include DOMINO in Canada (Robert et al., 2012) and ROSAU in France (Egis, 2015).

Overall, analysis of infrastructure interdependencies remains at an early stage, despite evidence showing that interdependencies play a significant part in losses from extreme weather events. For example, a vulnerability assessment for Stockholm’s Slussen lock (Annex 4) showed that most of the catastrophic losses arose from disruption to the electricity supply rather than direct damage to assets (MSB, 2012). The assessment of Boston's Central Artery's vulnerability to flooding and sea-level rise similarly highlighted the strong interconnectedness of its facilities (e.g. electric, ventilation and security systems) (Annex 5).

Information sharing and collaboration between public and private authorities can support better understanding and management of interdependencies. Collaboration is critical to identify vulnerability hotspots, prepare contingency plans and share capacity in times of disruption. A combination of public and private operators as well as regulators and policy-makers may manage or have a strong influence over the infrastructure network. However, they may be hesitant to share or collate information on commercial sensitivity or national security grounds. The creation of groups or networks can help to build trust between partners and facilitate the sharing of relevant information, as well as developing suitable processes for the safe sharing and use of sensitive data. Examples of how governments are facilitating this process can be found in Box 2.

Box 2. Examples of government-led information-sharing networks on infrastructure resilience

- **Partnership for Energy Sector Climate Resilience (United States):** The United States Department of Energy has established this voluntary partnership, which brings together 18 utilities providing electricity to about a third of the countries' consumers as of November 2015.[4] By creating a community of parties committed to increase their resilience to extreme events and climate change and reporting on their results, the partnership facilitates the exchange of knowledge and best practices at the working level and supports information sharing and capacity building. The partnership was instrumental in releasing a departmental guide to climate resilience planning in the electricity sector (U.S. Department of Energy, 2016).

- **Trusted Information Sharing Network (TISN, Australia):** This network was established by the Australian government in 2003 as Australia's primary national engagement mechanism for business-government information sharing and resilience building initiatives. It provides a secure environment for critical infrastructure owners and operators (across seven sector groups) to meet regularly to share information and cooperate. It works across sectors to address security and business continuity challenges, related to a range of threats including natural hazards and climate change impacts. The Attorney General's Department supports the TISN by providing technical analysis through the Critical Infrastructure Program for Modelling and Analysis (CIPMA) (Australian Government, 2015).

- **Critical Infrastructure Warning Information Network (CIWIN, European Commission):** CIWIN is a protected public internet based information and communication system operational since 2013, offering accredited members of the European Union's critical infrastructure protection community the opportunity to exchange and discuss information related to a range of hazards and share good practices across multiple sectors particularly in the case of transboundary interconnected networks. CIWIN is a pillar of the European Programme for Critical Infrastructure Protection (EPCIP) and its related directive (EU, 2008/114), which address risks from natural disasters, terrorism and criminal activity.

Evaluating the overall effectiveness of these different tools and initiatives for providing climate information, high-level risk assessments or supporting capacity building and collaboration is challenging. This is due to the diverse scope of these initiatives and guidelines, their specific operational contexts as well as their relatively recent creation.

[4] Personal communication from US Department of Energy, 3 December 2015.

3. SCREENING AND FACTORING CLIMATE RISKS INTO PUBLIC INVESTMENTS

Recommendation: Governments should ensure their investments take account of climate risks. They should also review the sharing of liabilities between the public and the private sector in Public Private Partnerships (PPPs) in the light of the potential impacts of climate change.

Risk screening, the process of assessing infrastructure projects to identify potential vulnerabilities to climate change, is an important component of efforts to build resilience. Governments can encourage this process in several ways:

- Public financial institutions may directly screen their investments to ensure physical climate risks are addressed.
- Require the private sector to account for climate risks when submitting tenders to build infrastructure (traditional public procurement), operate an infrastructure service or both build and operate (public private partnership).

Screening of public sector finance for infrastructure

When infrastructure projects are financed by public financial institutions, regulatory requirements (see section 4.2) or internal rules can require climate risks to be considered. Climate resilience can be integrated into documents such as the investment mandate, responsible investment charters or climate-related strategic documents. Some financial institutions are now screening their investments for climate risks and developing proprietary tools to do so:

- The European Investment Bank (EIB) is rolling out a systematic climate risk screening tool at the pre-appraisal and appraisal stage and piloting in-depth climate risk and management analysis for its projects in the water sector. It intends to extend the use of in-depth assessments to other sectors (EUFIWACC, 2015). Building resilience to climate change is one of the Bank's three strategic areas in its Climate Change Strategy (EIB, 2015).
- The Nordic Investment Bank and the Council of Europe Development Bank, which finance mostly infrastructure projects, are preparing guidelines to introduce mandatory screening of climate risks in their projects (EUFIWACC, 2015).
- The European Union has made an explicit commitment to "climate-proof" the major projects co-financed by the European Structural and Investment Funds for the 2014-2020 period and requires an 'analysis of the environmental impact taking into account climate change adaptation needs' (Regulation (EU) No 1303/2013, Commission Implementing Regulation (EU) 2015/207, from Paunescu, 2015).

At the national level in OECD countries, there is little evidence that public finance institutions investing in domestic infrastructure (such as CDC in France or KfW in Germany) are formally integrating climate risks into their lending and investment decisions.[5] These institutions operate within the context of national plans for infrastructure investment and these plans tend to make limited reference to climate risks. Some of the OECD countries producing forward-looking and cross-sectoral infrastructure plans also mention the need to make networks and assets more resilient to climate change (Infrastructure UK, 2014; New Zealand National Infrastructure Unit, 2015; Infrastructure Australia, 2016; US Department of Homeland Security, 2013). However, the discussion of climate resilience in these plans tends to be generic.

Development Finance Institutions are at the forefront in the use of climate risk screening tools. There is ample evidence regarding the increasingly systematic integration of climate risk to their decision-making and planning processes. Many development banks, whether multilateral or bilateral, have piloted mandatory climate risk screening following an organisational mandate or developed sophisticated screening and decision-support tools (Annex 2). Their experience with implementation has revealed some challenges. In particular, internal evaluations have identified the misalignment of these dedicated tools with project risk analysis, as well as a lack of adequate technical support and training (AfDB, 2013; IDB OVE, 2014).

Resilience criteria in public procurement

The benefits of increased climate resilience ought to be captured in the procurement process. The financing and commissioning of an infrastructure project may be delegated to a private contractor or a local authority, which will then be invited to submit a tender through a competitive bidding process in order to access funding, through a grant or a concession for its operation.[6] Integrating climate resilience generally incurs an additional cost for potential bidders, both in developing their proposals and potentially in the final cost of the project. This could put them at a competitive disadvantage relative to the bidders that choose not to integrate this factor if the benefits of increased resilience are not fully considered in the procurement process.

Public procurement is increasingly considering the lifecycle costs of goods, services and assets, and ‘green’ procurement is increasingly used as a tool to achieve environmental policy goals. The use of this approach is facilitated in EU member states by the 2014 Procurement Directive (European Union, 2016). This directive allows awarding authorities to include social, environmental and other policy conditions for public contracts and concessions. It also allows awarding authorities to reject an abnormally low bid if it indicates a failure to observe social, labour law or environmental protection obligations.

However, a screening of National Communications to the UNFCCC shows limited evidence of climate resilience being integrated in public procurement. An exception to this is that the 2014 management contracts between the state and national railway operator (SNCB) in Belgium now refers to climate adaptation in its environment chapter. As the contract defines the missions of public utility of SNCB and payments for delivering them, it could be used as a basis for demanding reliable service in the face of climate impacts.

[5] Based on a screening of their investment strategy, climate strategy or responsible investment charters.

[6] Under a public contract, an economic operator is awarded a fixed payment for completing the required work or service. Under a concession, an economic operator receives substantial remuneration as a result of being permitted to run the work or service.

Time horizons and risk-sharing arrangements in Public Private Partnerships

The longer-term impacts of climate change can lie outside the time horizons considered in current valuation practices of public private partnerships (PPPs). Current PPP guidelines suggest that costs and revenues be forecast over the life of a project. Although PPPs tend to be long term (e.g. 20 - 30 year) contracts (Araujo and Sutherland, 2010), the project length may still not cover the whole lifetime of the asset. The benefits of increased resilience after the project end date will not be reflected in the contract value (Maddocks, 2012).

Risks linked to the PPPs should be priced accurately and allocated to the party best positioned to manage them (OECD, 2012), either by reducing the risk ex-ante or bearing the resulting losses ex-post. The contracting process should also examine the capacity of the entities to bear the risks that they have been assigned. Physical impacts from climate change have the potential to put a long term financial burden on the partnership by reducing its expected returns or preventing the project from functioning during its full expected lifetime. The consequences of this are particularly serious for the public sector as it usually bears the unaccounted risks in PPP contracts. Australia, Belgium and the UK are among the few OECD countries with PPP frameworks that distinguish between weather events and "force majeure" events, which are considered unforeseeable. In the UK, for instance, flooding and storms are defined as “relief events” for which the contractor bears financial responsibility (HM Treasury, 2012).

The policy frameworks and infrastructure planning documents governing PPPs generally do not require explicit consideration of climate change impacts, either in OECD countries (Infrastructure Australia, 2015; European Commission, 2003; UK Treasury, 2013), or developing countries (World Bank, 2016). There are, however, some exceptions, notably at the regional level in Australia (Australian Government Productivity Commission, 2012) and in North America:

- Since 2011, Queensland and Tasmania require cabinet submissions for government projects to consider potential climate risks. The Queensland Climate Ready Infrastructure initiative requires local governments to consider climate change adaptation when applying for infrastructure grants to the Queensland Government.
- Since 2009, the Council of Australian Governments requires state and territory governments' strategic plans for infrastructure in capital cities to cover climate change adaptation. Infrastructure funding is linked to meeting these criteria.
- The West Coast Infrastructure Exchange (WCX) was established by the states of California, Oregon and Washington in the United States and British Columbia in Canada. WCX aims at developing innovative methods to finance and facilitate the development of infrastructure in the region by developing a framework for infrastructure investment and principles for certification. The consideration of resilience and climate risks features among the WCX’s standards for infrastructure projects (WCX, 2013).

Adaptation will tend to reduce rather than eliminate the risk of damages from climate change. Improving the identification and integration of climate-related risks in PPPs could improve the financial management of these potential losses. This integration could include a more detailed definition of relief, compensation and force majeure events. It could also include strengthened contractual requirements for insurance coverage (PPIAF, 2016). Requirements for contractors to be adequately insured enable the government to reduce its potential exposure as insurer of last resort, and provide an incentive for infrastructure providers to reduce risk and therefore the cost of cover.

Colombia provides an illustration of how risk reduction and insurance are complementary and the importance of having a clear allocation of risks. Following damages incurred from the 2010-2011 La Nina season, concessionaires requested USD 60 million from the government to cover their losses. In response, the government passed a series of laws in 2013 to ensure future infrastructure projects would be better protected against natural hazards and enhance insurance requirements to protect these investments against natural catastrophes (GFDRR, 2013). Other financial instruments that could be used to address climate risk in PPP contracts include index-based weather derivatives, catastrophe risk deferred draw-down options (CatDDO), sovereign insurance schemes and property catastrophe risk insurance (World Bank, 2016).

In principle, infrastructure projects that address future climate risks and are less vulnerable to natural hazards should be more attractive to investors and cheaper to insure. This could strengthen the business case for investment in resilience projects, by providing the investor with a stream of benefits over time. There is, however, limited experience in those approaches, but innovative financial tools are being proposed. These include the proposal to fund investments in resilience by providing pre-defined rebates on catastrophe bonds (Vajjhala and Rhodes, 2015).

4. ENABLING INFRASTRUCTURE RESILIENCE THROUGH POLICY AND REGULATION

Recommendation: Spatial planning policies, national and international technical standards, and economic policies and regulation can all play a role in enabling infrastructure resilience to climate change. Governments may want to ensure international, national and local approaches are aligned in order to facilitate adaptation by the private sector.

Public policy and regulation can be used to encourage the private sector to integrate climate resilience into infrastructure planning and management. Climate resilience has been mainstreamed in some countries' policies: examples include spatial planning, mainly through the Environmental Impact Assessment, as well as technical and economic regulation which influence infrastructure. More than one-third of OECD countries are revising at least one national technical standard for infrastructure. There has also been activity by two of the major international bodies for standardisation: the International Standards Organisation (ISO) and the European Committee for Standardisation (CEN) are reviewing their technical and management standards to account for climate change adaptation.

Spatial planning for new infrastructure

Good spatial planning requires the systematic assessment of environmental, social and economic factors to assist land users in selecting options that increase the land's productivity, are sustainable and meet the needs of society (FAO, 1993). By taking into account potential impacts from climate change, spatial planners can contribute to the reliability of infrastructure at the outset by reducing exposure to climate hazards.

Key spatial planning tools such as the Environmental Impact Assessment (EIA), and to a lesser extent Strategic Environmental Assessment (SEA), are increasingly being used to incorporate climate change impacts and adaptation within existing approaches to project design, approval and implementation. The purpose of EIA is to assess potential environmental impacts before deciding on whether or not to undertake the project, and to develop and apply measures to avoid or minimise those impacts as conditions of approval for the project. SEA is required for national plans, programmes, regional development and land-use plans. These strategic assessments may also be required for sector plans and policies in areas such as energy, transport, agriculture, forest management and manufacturing.

Traditionally, EIA has involved assessing the possible impacts, whether adverse or beneficial, that a proposed project (generally infrastructure related) may have on the environment. However, there are now some examples where the scope of the assessment has been expanded to examine the impact of climate change on the project. Australia and the Netherlands have both used EIA to address climate change impacts (Agrawala, 2011). For instance, the Netherlands' 2006-2015 flood management plan "Room for the River" integrated adaptation into its EIA by using climate projections to assess how water levels in the Rhine could change in the future (Verheem and Laeven, 2009).

The EIA process in EU Member States has been strengthened by an amendment to the EIA Directive (2014/52/EU amending 2011/92/EC) in May 2014, which places a stronger emphasis on climate

change mitigation, adaptation and resilience across the screening, scoping and assessment process. EU Member States have until May 2017 to transpose the amendments into their own regulations. The EU had previously published guidance documents on integrating climate change considerations into EIA and SEA (European Commission, 2013c).

In addition to EIA, integrating adaptation into infrastructure planning frameworks can support the management of climate risks. In the UK, major infrastructure project applications are reviewed by the Planning Inspectorate to ensure they comply with a set of National Policy Statements. Each National Policy Statement (NPS) states the government's objectives for the development of nationally-significant infrastructure in the sector, including how current and projected capacity and demand have been taken into account. There are twelve designated or proposed statements, spanning the energy, water and transport sectors (Planning Inspectorate, 2017). These statements include an explanation of how to account for climate change adaptation and mitigation. Developers of major projects in the UK have to provide evidence of how the latest climate projections have been considered and their proposal's robustness to extreme changes beyond the range provided by those projections.

The results of a recent review of the effectiveness of the NPS' implementation for climate adaptation were positive. In particular, the review found that the inspectors had consistently considered climate risks in granting planning permission (ASC, 2014). For instance, inspectors recognised the vulnerability of the Hinkley Point nuclear power station's site to the effects of climate change and sea level rise and ensured the site's design accounted for climate change projections.

Other countries have stated their intention to integrate assessment of climate change risks into the planning and construction of infrastructure. Mexico has made a general commitment for all infrastructure sectors in its National Climate Change Strategy (line of action A2.12), while Hungary will focus on power system planning (6th National Communication to the UNFCCC).

Authority and competences regarding spatial planning in OECD countries are most often either concentrated at the sub-national level, or shared between national and sub-national levels (Silva and Acheampong, 2015). Land use planning frameworks are decided at the national level, but local authorities have a critical role in implementing them, and sometimes issuing their own regulatory requirements. When that is the case, neighbouring regional level rules should be coherent between themselves, as well as with the national framework. For instance, when conducting construction to rebuild and protect energy and utilities infrastructure following Superstorm Sandy, the regulators of the adjacent states of New York and New Jersey chose different protection standards (protection against a 1-in-100 year flood + 3 feet [91 cm], and 1-in-100 +1 foot [30 cm] respectively). Meanwhile at the federal level, the White House set a complementary Federal Flood Risk Management Standard (Executive Order 13690). This mandated that retrofits of critical infrastructure receiving financial support from the Federal Emergency Management Agency (FEMA) should be protected against a 1-in-100 years flood event. There is a safety margin of 2 ft (61cm) for critical infrastructure, and a safety provision of 1 ft (30cm) for other infrastructure.

There is a risk of distorted incentives for local authorities when the benefits of new development accrue locally, while some of the costs of extreme events are borne by regional or national governments. This short-term economic incentive can lead to developing in increasingly risky areas, storing up risks and hidden costs for the future, both for protecting assets and providing compensation in the event of losses. UNISDR conducted a case study in Spain, where liberalisation led to development in risky areas, to identify the necessary conditions for a 'risk sensitive land use planning' (Burby et al., 1999). Risk-sensitive planning allows communities to find the right mix of both development and risk reduction. It provides financial incentives to project developers and local authorities, as well as supporting greater collaboration between planning administrations and disaster reduction authorities (Sudmeier et al., 2013).

Sector regulation and economic incentives

Infrastructure regulators have an important role in supporting resilient water, energy and transport infrastructure networks. Two-thirds of OECD member countries have regulators with responsibility for more than one sector, for instance water and energy (OECD, 2015b). Regulators can be tasked with the delivery of environmental outcomes, such as environment protection, social outcomes such as safety, or economic regulation such as service affordability, effectiveness and reliability. Climate change impacts are considered in some regulatory environments, mostly by energy and to a lesser degree by water and transport regulators. Examples of this are presented below.

Regulators can encourage resilient infrastructure by modifying technical requirements to account for future climate change. For instance, many nuclear energy regulators consider how climate change may affect flood risk and water temperatures when assessing the safety of nuclear plants or allowing the discharge of cooling water to the environment (NEA, 2017).[7] In 2012, France's Nuclear Safety Agency updated its water discharge regulation in case of heatwaves in light of new evidence on the impact of discharged water temperature on fish populations (SFEN, 2015). Switzerland has also modified the supervision and licensing processes for hydroelectric dams and reservoirs, as well as for transmission and distribution networks for gas and electricity, to better account for climate change impacts. It is also examining the need to adjust regulations governing the temperature of cooling water released back into rivers (Swiss Confederation, 2013). In 2014, the New York state utilities regulator (Public Service Commission) approved a settlement requiring power utility Con Edison to use state-of-the-art measures to plan for and protect its electric, gas and steam systems from the effects of climate change. The regulator stated that climate-resilience considerations should ultimately be broadened to include all utilities (Fazio and Strell, 2014).

Regulators can also encourage investment in resilience by setting standards for service reliability. Finland's 2009 Electricity Market Act requires that, by the year 2028, distribution networks be designed, built and maintained in such a way that electricity interruptions due to storms or snow do not exceed 6 hours in densely-populated areas and 36 hours in other areas. Disruptions to electricity services from storms are generally caused by airborne material, such as trees and branches. This will be affected by climate change due to longer growth seasons for vegetation and more extreme wind gusts, with implications for companies' vegetation management and tree felling practices. The Finnish Government has also plans to invest EUR 3 500 million to bury distribution cables (Ministry of the Environment and Statistics Finland, 2013).

In several OECD countries, stricter reliability and resilience requirements have been set or are envisaged for "critical infrastructure", which cover disruption due to natural hazards. In France, the "operators of vital importance" defined in 2006 (Secrétariat Général de la Défense et de la Sécurité Nationale) are required to produce protection plans to prepare for a range of hazards. However, these plans do not take into account the possibility of simultaneous hazards or the potential cascading failures between different infrastructure networks (CGEDD, 2013).

Economic regulators can be mobilised to integrate climate change adaptation into infrastructure operation and management, but need to balance this with ensuring value for money for the consumer. As an illustration, a regulator may wish to clarify the conditions under which the costs of investments in climate adaptation measures can be reimbursed or passed on to consumers. Economic incentives that provide flexibility in meeting regulatory requirements can also encourage infrastructure owners and

[7] Nuclear energy requires large amounts of cooling water, and plants located in estuarine or coastal environments can both be vulnerable to erosion and flooding, or impact the environment when released water used for cooling at a higher temperature in the environment.

operators to increase supply efficiency and reduce service demand. Germany plans to examine options within the framework of incentive regulation to allow additional adaptation-relevant investments for power generation transmission and distribution to be accredited or reimbursed. This issue will be considered through the newly founded Working Group on Regulation (Future-Oriented Grids Platform) which brings together representatives of the Federal Ministry for Economic Affairs and Energy (BMWi), the Federal Environment Ministry (BMU) and the Federal Network Agency (BMUB, 2012).

Promoting resilience, in particular from climate change, is part of the mandate and processes of its energy (Ofgem), water (Ofwat) and rail regulators (ORR) in the United Kingdom. All have aimed to refine the price control review mechanisms to reflect longer asset life spans, and encourage a focus on longer run issues and better management of uncertainty (Defra, 2013), and are collectively thinking about cross-sectoral resilience through the UK Regulators Network (UKRN). The UKRN Adaptation Group is co-ordinating a cross-sector review of the penalties and incentives in place to encourage increased resilience to weather and climate change (UKRN, 2016). The UK government (responsible for policy in England) and the Welsh government introduced a new legal obligation ("primary duty") for Ofwat to further improve resilience in the 2014 Water Act. However, in researching the implications of this duty for Ofwat, an independent review found that there was no agreed definition of resilience, a lack of consistent measures and fixed resilience standards in the water sector. This review found that overall there was a lack of evidence on the efficacy of the current regulation model in encouraging justifiable resilience investments to be made (Resilience Task and Finish Group, 2015).

National and international technical standards

In the field of infrastructure construction and maintenance, builders and operators are bound by a set of technical and management standards, originating from regulatory requirements (such as Building Codes) or voluntary practices formalised by trade bodies. These standards can apply to the data collected in technical investigations (timescale, modelling and socio-economic projections used), the specifications of the material, equipment and products used, or to the project design and management processes. They can be tailored at a regional or national level, or applied internationally (such as those from the global International Standard Association).

Technical standards can play an important role in scaling-up climate resilience in infrastructure investments. To do so, they need to be applied in a consistent manner with the support of training and enforcement capacity as necessary. Infrastructure standards accounting for climate change aim to address an inherently uncertain issue, while applying uniformly across different contexts. The advantage of this uniformity is that they can be straightforward to understand and apply. However, where risks are context-specific, standardised approaches could lead to over- or under-investment in resilience. For this reason, the development of new and the adjustment of existing standards to account for climate change impacts on infrastructure is generally a lengthy process led by an organisation with recognised engineering expertise (ITF, 2016).

In the absence of national regulations, consultations with local stakeholders are often used to define acceptable levels of risk and appraise potential adaptation measures. These can, however, take a long time and require significant financial resources, as was the case for the redevelopment of Stockholm's Slussen (Annex 4) and the Netherlands' Room for the River project (Annex 3).

At the international level, two major standardisation organisations are reviewing existing standards to take into account potential climate change impacts. The European Committee for Standardisation (CEN, Centre Européen de Normalisation) began this process in May 2014, and the International Standards Organisation (ISO) in June 2015. The ISO is focussed on developing a set of standards for vulnerability assessment, adaptation planning, and adaptation monitoring and evaluation,

through the newly formed Adaptation Task Force (ISO, 2015). Following the adoption of the European Adaptation Strategy in 2013, the European Commission mandated the CEN to amend and extend in scope the European civil engineering technical standards, known as Eurocodes. These revisions focussed on transport and energy infrastructures, as well as buildings and construction (European Commission, 2014). The reviews led by CEN and ISO cover the assessment, re-use and retrofitting of existing infrastructure, as well as the design of new developments.

Both sets of climate-resilient international standards will be widely applicable. ISO is a non-governmental organisation and its standards are voluntary. However, they can be adopted in some countries as part of their regulatory framework, or be referred to in legislation for which they serve as the technical basis. Under the Procurement Directive, EU Members are bound to accept designs to the EN Eurocodes, or require technically equivalent solutions (European Commission, 2004).

Sector-specific organisations are also contributing to the technical definition of climate-resilient infrastructure. For instance, the World Association for Waterborne Transport Infrastructure (PIANC) set up a dedicated working group to develop technical guidance on climate change adaptation for maritime and inland port and navigation infrastructure, which is expected to report in 2017 (PIANC, 2014, 2015).

Some standards from different "families" may cross-reference each other to avoid duplication. For instance, the revision of Eurocodes plans to incorporate ISO standards on atmospheric icing of structures, and actions from waves and currents on coastal structures.

Approximately one-third of OECD countries are revising at least one mandatory national infrastructure standard to account for climate change adaptation. A screening of OECD countries' 6th National Communications to the UNFCCC and national associations' sources shows that a revision has already been completed in seven countries (Australia, Canada, Denmark, Germany, Korea, Norway and Sweden), and is either ongoing or planned in five more countries (Table 2).

The first standards to have been revised regard drainage specifications, often for road transport infrastructure. Revisions account mostly for an increased likelihood and severity of heavy precipitation, which can lead to surface or river flooding. For instance, in revising its road drainage standard in 2008, Sweden updated the estimated return periods for critical events and introduced a climate safety factor compensating for an anticipated increase in future precipitation.

In some countries, notably Australia, regional governments have also released technical guidance to ensure infrastructure design is resilient to climate change. The Western Australian government's Standard and Technical Guide on Addressing Climate Change in Road and Traffic Engineering, for example, is helping planners, designers and managers identify climate change risks relevant to construction of roads and bridges. The state road operator (WA Main Roads) is integrating climate change considerations into design standards and road upgrades across the state and requires that the implications of a 300mm sea-level rise (450mm for structures) be considered as part of planning, design and construction for all rehabilitation and expansion projects near coastal areas.

In addition to these technical guidelines, several national standards organisations have released risk management guidelines that focus on climate adaptation or resilience planning for buildings and infrastructure (British Standards Institution, 2011; Standards Australia, 2013; US National Institute of Standards and Technology, 2015). These guidelines emphasize the usefulness of predefined risk management processes, following the standards for quality management (ISO9001), environmental management (ISO14001) and business continuity management (ISO 22301).

Table 2. Planned, ongoing and completed revisions of standards in OECD countries

	Country	Details
Completed	Australia (Engineers Australia)	Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering (2013, 3rd edition) Australian Rainfall and Runoff handbook (2015)
	Canada (Standards Council of Canada, Indigenous and Northern Affairs Canada)	Northern Infrastructure Standardization Initiative (NISI). Four standards completed in 2014-15 on foundations supported by heat exchangers, moderating the effects of permafrost degradation on existing buildings, managing changing snow loads, and community drainage. Geotechnical site investigation (in permafrost) standard to be published early 2017.
	Denmark	Road drainage design standards (Vejdirektoratet, 2009. Vejkonstruktioner, Avvandingskonstruktioner).
	Germany	The Commission on Process Safety (KAS) updated in 2011 its Technical rule on precipitation and flooding for flood safety of plants subject to the German Major Accidents Ordinance.
	Korea	The Korea Expressway Corporation has strengthened the design requirements for drainage capacity, bridge design and embankment slopes (Quium, 2015).
	Norway (transport agencies)	Handbook on the design of road drainage structures (2011).
	Sweden	Design rules for road drainage (VVMB 310 Hydraulisk dimensionering, 2008:61)
Ongoing	Australia (Austroads)	Australian Transport Assessment and Planning Guidelines to cover public, road and rail transport, and include appropriate guidance on climate change adaptation for transport planning and project appraisal (Australian Government, 2015).
	Canada (Canadian Commission on Building and Fire Codes [CCBFC] and Standards Council of Canada [SCC])	The CCBFC is currently updating 6,000 specific climatic design values used in the National Building Code of Canada. The SCC is currently updating existing infrastructure standards to ensure climate resilience, developing guidance to account for climate change adaptation in new standards, and continuing work on NISI.
	France (Ministry of Environment, Energy and Sea [MEEM])	The MEEM (formerly MEDDE) has led the Centre of Expertise on Hazards, Environment, Mobility and Planning (CEREMA in French) to identify over 80 standards that may require updating, focusing on transport infrastructure and a better consideration of climate extremes (MEDDE, 2015; CEREMA, 2015).
	Germany	BMVBS/DWD and the German Institute for Standardisation are updating climate data standards for buildings and infrastructures.
	Netherlands (Delta Commission)	Update of design guidelines for infrastructure to account for changing characteristics of rain showers. Definition of a national basic minimum level for water safety and update of levels in rivers area, parts of the Rhine Estuary-Drechtsteden region, and in Almere.
	New Zealand	The National Infrastructure Plan (2011) focuses on the development of design and construction standards (where cost-effective) that ensure infrastructure is able to withstand natural hazards and long-term changes, such as those resulting from climate change. The 2015 Plan focuses on the creation of metadata standards for roads, water infrastructure, and built assets by mid-2016 in order to better understand asset performance.
	United States (National Institute of Standards and Technology [NIST])	NIST's Disaster Resilience Standards Panel will recommend improvements to standards and consider the development of further guidelines.
Planned	Hungary	Revision of the regulation of construction design and area use from the aspect of climate change.

5. ENCOURAGING CLIMATE RISK DISCLOSURE

Recommendation: Governments can facilitate climate risk disclosure by encouraging reporting when there are gaps in existing voluntary privately-led initiatives, supporting a common framework at the international level and using this information when planning climate adaptation at the national level.

The disclosure of climate change risks facing infrastructure, whether at the asset-, company-, investor- or sectoral level can help guide investment decisions. Disclosure can also encourage infrastructure owners and operators to improve their management of risks, and provide information to support public decisions to strengthen resilience. In this paper, climate risks are understood to refer to the physical risks arising from weather-related events or resource scarcity. This definition does not include other climate-related risks, such as the possibility of legal challenges arising from those who suffered losses and damages from climate change, nor the transitional impacts[8] arising from the decarbonisation of the economy (Bank of England PRA, 2015).

Owners or operators of infrastructure assets or networks that have identified and addressed their climate risks are less likely to suffer disruptions and provide more stable returns on investment. Disclosing information related to climate risks can benefit several categories of stakeholders and these benefits have encouraged the development of voluntary mechanisms.

Infrastructure project developers and engineers

For developers of new infrastructure, highlighting the "best in class" status of their projects for climate resilience could have reputational benefits, provide competitive advantage and improve access to finance. However, in contrast to increasing corporate disclosure regarding transitional impacts (OECD and CDSB, 2015), reporting of vulnerability from potential climate impacts is at a very early stage.

Monitoring risks from climate change and planning adaptation efforts at the corporate level faces different methodological challenges than monitoring greenhouse gas emissions. Greenhouse gas emissions can be compared using a single metric (tonnes of CO_2 equivalent), equivalences (Global Warming Potential) and internationally agreed accounting methods (e.g. Greenhouse Gas Protocol). Meanwhile, climate impacts may be felt through multiple hazards (changing weather patterns, sea level rise, changes in water availability and temperature, etc.) over different timescales. The nature of the risks arising from this and appropriate responses are very context specific.

Industry associations for civil engineering and infrastructure have started creating verified standards and tools to assess how well climate risks are being considered in specific infrastructure projects.

[8] These refer to the impacts of accelerated depreciation of carbon-intensive assets resulting from the transition to a low-carbon economy, such as the early retirement of coal-power stations.

These include CEEQUAL (2003) in the UK, ENVISION (2010) in the United States and the Infrastructure Sustainability Rating Tool (ISCA, 2012) in Australia (Annex 3). As an illustration, the Peace Bridge in Northern Ireland earned a CEEQUAL-Excellent rating in recognition of its preparedness for flood risk: the underside of the deck was located above the level of a 1-in-200-year tidal flood event, including an additional allowance for climate change.

Although is it difficult to estimate the proportion of total infrastructure projects to have been certified, the use of resilience ratings remains limited. As of 2015, the Australian Infrastructure Sustainability tool was applied to 56 projects. CEEQUAL received applications for around 700 formal verified assessments worldwide, of which around 300 have been completed, for a cumulative value of around GBP 27 billion. Of the remainder of applications to CEEQUAL, around 120 have been postponed or cancelled as a result of lack of funding, changes in client requirements or other reasons.

Credit and insurance institutions

From the perspective of investors, the risks created by climate change are an increasingly important criterion for strategic asset allocation. These risks include physical climate impacts, as well as transition risks and potential legal liabilities. Investor associations are developing guidance for asset owners that provide a range of factors to consider in addressing the risks and opportunities associated with climate change, including physical climate impacts on private and public sector infrastructure (GICCC, 2015; Mercer, 2015).

The majority of investors specialised in infrastructure investment state that they monitor and assess physical risks from climate to the infrastructure they manage. According to asset managers responding to the Global Investor Survey on Climate Change, over 70% of their infrastructure assets were monitored for physical climate change risks and impacts, either routinely or as part of a one-off exercise (Box 3) (Mercer, 2013).

Box 3. Consideration of physical risks from climate change on infrastructure by public and private investors in Australia

- Hastings Fund Management: Hastings is a specialist manager of infrastructure equity and debt investments, currently managing approximately AUD 7.4 billion. It has investments in assets located in Australia, the US, the UK and Europe (airports, toll roads, seaports, gas and electricity transmission, and water utilities). Climate change risks are included in the qualitative and quantitative assessment of Hastings' infrastructure investments at the investment proposal stage and on an ongoing asset management basis. This includes the consideration of whether infrastructure assets have been built with sufficient characteristics to cope with potential changing conditions: material strength, height from sea level or wind ratings.

- AustralianSuper: The pension fund with over AUD 75 billion under management, assessed the extent to which the six largest infrastructure assets in their portfolio (including airports, a sea port and a toll road) may be vulnerable to a changing climate in the medium term (2030) and the long term (2070). The study identified the components of the asset responsible for the generation of investment returns and modelled each component using a variety of climate change scenarios and data supplied by the federal government agency for scientific research in Australia (CSIRO).

Source: Mercer (2013), GICCC (2015).

This awareness of climate change underpins the sector's drive for greater disclosure on climate risk and increasing use of existing reporting frameworks, such as the CDP (formerly known as the Carbon

Disclosure Project) and the Global Reporting Initiative (G4). In 2015, the CDP was used by 5 000 organisations and the G4 initiative by 7 500 organisations. Both frameworks require companies to report on the physical and regulatory risks and opportunities they face from climate change. They also have to report on the financial impact those risks and opportunities could have on costs, demand for products and services, capital availability and investment opportunities. The Financial Stability Board (FSB) industry-led task force on climate financial disclosure (TCFD) developed voluntary industry-specific disclosure standards. These standards focus on the financial risks stemming from physical and nonphysical climate-related impacts, including transition and liability risks, and apply to both financial and non-financial respondents (such as energy and utilities companies).The TCFD recommended that climate risk disclosure should form part of businesses' core public financial filings, and support informed investment, credit and insurance underwriting decisions about the companies that report. The TCFD also encouraged the use of scenario analysis to explore how the risks from climate change could be affected by different sources of uncertainty (FSB TCFD, 2016a and 2016b).

Policymakers

As most critical infrastructure is owned and operated by the private sector in OECD countries, governments need to verify that climate risks are identified and managed appropriately and fill any gaps that have been identified. This information can improve their capacity to plan for disaster risk management, emergency preparedness and national adaptation strategies, or give them greater confidence that essential services will cope with climate change. Governments and financial regulators may choose to request companies in the infrastructure sector to manage and disclose their climate risks. They can also encourage disclosure in the financial sector and thereby contribute to the integration of climate risk as an investment, lending and underwriting criteria.

In general, existing laws and regulations already require disclosure of climate-related risks in financial filings if they are deemed material[9] (FSB, 2015; Debevoise & Plimpton, 2016). However, France is the only G20 country that requires listed companies to disclose in their annual reports the financial risks related to the effects of climate change and the measures adopted by the company to reduce them (MEDDE, 2015; UNEP FI, 2015). The UK government required organisations providing critical public services to report on physical risks from climate change through a regulation. This regulation, the Adaptation Reporting Power, was transformed into a voluntary scheme for the second round of reporting.

There are few examples of disclosure of physical risks from which to draw lessons on how effective they could be in supporting risk management. However, initial evidence suggests that government initiatives can play a role in raising awareness and kick-starting private sector action. An independent evaluation had found the ARP to have been useful in leading to a greater consideration of climate change and adaptation, and greater engagement, both internally and across the supply chain, for all the reporting organisations (Cranfield, 2012). The invitation to the UK Bank of England Prudential Regulatory Authority to report on the "Impact of climate change on the UK insurance sector" under the Adaptation Reporting Power contributed to the FSB's drive for G20-wide standards, which was led by the Governor of the Bank of England's (Bank of England PRA, 2015).

Climate disclosure initiatives from public authorities should add value to investor-led initiatives rather than duplicate them, be enforceable and provide incentives for reporting. The US Securities Exchange Commission (SEC) and the Canadian Securities Administrators (CSA) have reporting systems

[9] Derived from a principle of financial reporting, material information is information on economic, environmental, social and governance performance or impacts that should be disclosed on the grounds that it is (a) highly relevant to an organization and (b) is expected by key stakeholders as it may significantly affect their assessment of the organization.

on environmental risks and liabilities, both physical and regulatory, including climate risks. These apply to publicly listed companies with over USD 10 million in assets and all issuers of securities (except investment funds) (CSA, 2010; SEC, 2007 and 2010). A survey on climate disclosure found that companies tended to provide significantly more detailed information under the CDP scheme than in their mandatory reports to the SEC (Ceres, 2014). This gap may be due to the perception that SEC guidelines are less clear, or that reporting to the SEC has fewer benefits in terms of visibility than for the CDP.

Governments and international organisations also have a role to play in supporting the alignment of national schemes and the implementation of vulnerability assessment and reduction initiatives together with private actors, business and environmental NGOs. Two initiatives were launched at the UN Climate Summit in 2014:

- The Statement of Fiduciary Duty and Climate Risk Disclosure is a collective commitment by many utilities, construction companies and institutional investors to increase the use of the Climate Change Reporting Framework (CDSB, 2012). Public regulators can also sign the statement as Statement Associates. The Framework requires a qualitative assessment of the organization's exposure to significant risks and opportunities associated with climate, and an assessment of the financial implications of that exposure.

- The 1-in-100 initiative aims to build a consortium of major financial, regulatory, accounting and scientific institutions to (i) identify the portion of their investments and assets at risk of a climate-related disaster with a 1-in-100 year magnitude, and (ii) to account for the risk in their investment portfolios and integrate incentives for resilience. This initiative arose from collaboration between the Willis Group, the UN Secretary-General's Climate Change Support Team and UN International Strategy for Disaster Reduction (UNISDR).

6. AREAS FOR FUTURE WORK

This report analyses the main policy levers that national policymakers can use to ensure that new or existing infrastructure is made more resilient to climate change impacts. They can i) support the provision of information and the coordination within or between sectors, ii) ensure climate risks are accounted for in public investments and transparently allocated between public and private partners in contractual arrangements, iii) enable infrastructure resilience through spatial planning policy, sectoral regulation or technical standards or iv) encourage the financial disclosure of climate risks and support private initiatives for transparency. These levers are already used by several national and regional governments across the OECD, as shown by this paper.

Although this paper has focussed on the role of national governments, the resilience agenda will require action by many different stakeholders. In the public sector, there is a need for collaboration between local, regional and national government. Infrastructure is also often privately owned and operated. Many private actors have also taken action to manage vulnerability from climate change, such as operators assessing their risks, or investors and insurers supporting a more transparent accounting of climate risks. All of these initiatives would benefit from a closer collaboration between these actors and national governments, and also within the governments themselves. This will help to identify potential regulatory barriers to action or evidence gaps, as well as helping to manage spillover risks. Ultimately, government frameworks should seek to complement and facilitate actions by regulators, engineering and investor associations, and academia.

This paper shows the growing volume of activity that is underway to support resilience. However, the importance of ensuring that infrastructure is climate resilient warrants more efforts to monitor and evaluate the effectiveness of governments' actions. There is a need for mutual learning between countries as they pursue this agenda. Some of the key remaining issues that this could help illuminate are:

- the costs, benefits and effectiveness of policy and regulation levers, for example spatial planning
- analysis of PPP frameworks and contracts to understand their contribution to building resilience
- an in-depth review of the investment practices and climate risk screening tests of OECD national development banks for infrastructure, in collaboration with national governments.

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ANNEX 1: OVERVIEW OF NATIONAL CLIMATE SCENARIOS AND RISK ASSESSMENTS

a) List of OECD countries national level climate change scenarios (online portal, report)

	Last update	Name	Responsible authorities	Link
AUSTRALIA	2015	Climate Change in Australia: Projections for natural resource management regions	CSIRO and Bureau of Meteorology	www.climatechangeinaustralia.gov.au/
AUSTRIA	-	Climate Future in Alpine Region	Central Institute of Meteorology and Geodynamics (ZAMG)	www.zamg.ac.at/cms/de/klima/informationsportal-klimawandel/klimazukunft/alpenraum
BELGIUM	2014	Overview of a few regional climate models and climate scenarios for Belgium	Royal Meteorological Institute of Belgium (RMI)	www.meteo.be/meteo/view/fr/15526885-20141007+climate+services.html
CANADA	2014	Plots of Climate Projections of Canada using CMIP5 data	Canadian Climate Data and Scenarios	www.ccds-dscc.ec.gc.ca/index.php?page=download-cmip5
CHILE	2007	Estudio de Variabilidad Climática en Chile para el Siglo XXI [Climate vulnerability study in Chile for the 21st century]	National Commission on the Environment (CONAMA), Geophysics Dept of Chile University	www.dgf.uchile.cl/PRECIS/
CZECH REPUBLIC	2008	RCM ALADIN-CLIMATE/CZ Simulation of 2020-2050 climate over the Czech Republic	Czech Hydrometeorological Institute	www.cbks.cz/sbornik08b/Stepanek_Skalak_Farda%20fin.pdf
DENMARK	2014	Fremtidige klimaforandringer i Danmark [Future climate change in Denmark]	Danish Meteorological Institute (DMI)	www.dmi.dk/fileadmin/user_upload/Rapporter/DKC/2014/Klimaforandringer_dmi.pdf
ESTONIA	2014	Climate change scenarios for Estonia based on climate models from the IPCC AR4	Estonian Research Council	www.kirj.ee/public/Estonian_Journal_of_Earth_Sciences/2014/issue_3/earth-2014-3-166-180.pdf
European Union	2012	Climate change, impacts and vulnerability in Europe	European Environment Agency (EEA)	www.eea.europa.eu/publications/climate-impacts-and-vulnerability-2012
FINLAND	2015	Mennyt ja tuleva ilmasto [Observed and projected climate]	Finnish meteorological institute, Environment Institute (SYKE)	www.ilmasto-opas.fi/en/datat
FRANCE	2015	Drias, les futurs du climat [Climate Futures]	Meteo France, CERFACS, Institut P. S. Laplace	www.drias-climat.fr/
GERMANY	-	German Climate Atlas	German Meteorological Office (DWD)	www.dwd.de/EN/climate_environment/climateatlas/climateatlas_node.html
GREECE	2011	Environmental, Economic and Social aspects of climate change in Greece	Bank of Greece	www.bankofgreece.gr/BogEkdoseis/ClimateChange_FullReport_bm.pdf
HUNGARY	2010	Összefoglaló Magyarország éghajlatának várható alakulásáról [Summary of expected developments in Hungary's climate]	Hungarian Meteorological Service	www.met.hu/doc/tevekenyseg/klimamodellezes/OMSZ-ELTE_eghajlati_osszefoglalo_2010.pdf
ICELAND	2008	The Science of Climate Change	Committee on Climate Change, Icelandic Meteorological Office	www.vedur.is/loftslag/rannsoknir/visindanefnd/
IRELAND	2015	Ensemble of regional climate model projections for Ireland	Met Éireann, Environmental Protection Agency	www.met.ie/news/display.asp?ID=364
ISRAEL	2007	Effects and Projections of Climate Change in Israel	Israeli Climate Change Information Center (ICCIC)	www.sviva.gov.il/InfoServices/ReservoirInfo/DocLib4/R0201-R0300/R0220.pdf

Annex 1a) continued on next page.

ITALY	2015	Il clima futuro in Italia: analisi delle proiezioni dei modelli regionali [Italy's future climate: analysis of the regional model's projections]	Italian National Institute for Environmental Protection and Research (ISPRA)	www.isprambiente.gov.it/files/pubblicazioni/statoambiente/SA_58_15.pdf
JAPAN	2012	Climate Change and its impacts on Japan	Meteorological Agency, Ministry of the Environment	www.env.go.jp/en/earth/cc/impacts_FY2012.pdf
KOREA	2013	Korea Climate Change Report	Korea Meteorological Administration	www.climate.go.kr/home/cc_data/2017/Korea_Climate_Change_Report.pdf
LATVIA	2015	Second Assessment of Climate Change for the Baltic Sea Basin	International Baltic Eath Secretariat at the Helmholtz-Zentrum Geesthacht	www.baltic-earth.eu/BACC2/index.html
LUXEMBOURG	-	National Communications to the UNFCC (2010) refer to the European Environment Agency (EEA) climate projections for central & eastern Europe.		
MEXICO	2013	Actualización de escenarios de cambio climático para México [Update of climate scenarios for Mexico]	National Institute of Ecology and Climate Change	http://escenarios.inecc.gob.mx/
NETHERLANDS	2015	KNMI 2014 Climate Scenarios (KNMI'14)	Royal Netherlands Meteorological Institute (KNMI)	www.klimaatscenarios.nl/
NEW ZEALAND	2016	Climate Change Projections for New Zealand: Atmosphere Projections Based on IPCC AR5	Ministry for the Environment, National Institute of Water and Atmospheric Research (NIWA)	www.climatecloud.co.nz/CloudLibrary/nz-climate-change-projections-final.pdf
NORWAY	2015	Klimaframskrivninger [Climate Projections]	Meteorologisk Institutt, Uni Research, NVE	www.klimaservicesenter.no/faces/desktop/scenarios.xhtml
POLAND	2009	EU Project ENSEMBLES	UK Met Office (coordinator), Polish Research Centre for Agricultural and Forest Environment,	www.meteo.unican.es/downscaling/intro
PORTUGAL	2015	Portal do Clima- Climate change in Portugal	Instituto Português do Mar e da Atmosfera	www.portaldoclima.pt/en/
SLOVAK REPUBLIC	2012	New climate change scenarios for Slovakia based on global and regional general circulation models	Slovak Hydrometeorological Institute, Comenius University	www.shmu.sk
SLOVENIA	-	Climate Variability in Slovenia and its impact on the aquatic environment	Slovenian Environment Agency	www.arso.gov.si/o%20agenciji/knji%C5%BEnica/publikacije/Okolje_se%20spreminja.pdf
SPAIN	-	Proyecciones climáticas para el siglo XXI [Climate projections for the 21st century]	Agencia Estatal de Meteorologia (AEMet)	www.aemet.es/fr/serviciosclimaticos/cambio_climat
SWEDEN	-	SMHI Climate Scenarios	Swedish Meteorological and Hydrological Institute	www.smhi.se/en/climate/climate-scenarios
SWITZERLAND	2011	Swiss Climate Change Scenarios (CH2011)	C2SM, MeteoSwiss, ETH, NCCR Climate, OcCC	www.ch2011.ch
TURKEY	2013	A holistic view of climate change and its impacts in Turkey	Istanbul Policy Center, Istanbul Technical University	www.ipc.sabanciuniv.edu/en/wp-content/uploads/2012/09/A-Holistic-View-of-Climate-Change-and-Its-Impacts-in-Turkey.pdf
UNITED KINGDOM	2009	UK Climate Projections 2009 (UKCP09)	Met Office	http://ukclimateprojections.metoffice.gov.uk/
UNITED STATES	2014	NASA Earth Exchange Downscaled Climate Projections (NEX-DCP30)	NASA's Climate Data Services (CDS)	http://ukclimateprojections.metoffice.gov.uk/

Source: National documents.

b) Coverage of infrastructure in national climate risk assessments

	Author (publication date)	Year	Sectoral focus			Climate hazard focus			Nature of assessment	
			Multi-sectors	Transport only	Water only	Multi-hazard	Coastal change only	Flooding only	Qualitative	Quantitative
AUSTRALIA	Department of Climate Change and Energy Efficiency	2011					x			
	Department of Climate Change	2009	x	x			x		x	x
	Academy of Technological Sciences and Engineering	2008	x			x			x	
AUSTRIA	Federal Ministry of Agriculture, Forestry, Environment and Water Management	2013	x			x			x	
BELGIUM	National Climate Commission	2010	x			x			x	
CANADA	Natural Resources Canada	2014	x			x			x	Case studies
CHILE	National Environmental Commission	2010	x			x			x	
CZECH REPUBLIC	Ekotoxa Ltd., Ministry of the Environment	2015	x			x				x
DENMARK	Danish Government	2008	x			x			x	
ESTONIA	SEI Talinn	2015	x			x				x
European Union	European Commission	2013	x			x			x	
FINLAND	Ministry of Agriculture and Forestry	2013				x				x
FRANCE	Ministry of Ecology and Sustainable Development	2009	x			x				x
GERMANY	Federal Environment Agency	2015	x			x			x	
GREECE	Bank of Greece	2011	x			x				x
HUNGARY	Farago, T; Lang, I; Csete, L. (eds)	2010	x			x				x
ICELAND	Ministry of Environment	2010	x			x				x
IRELAND	Irish Climate Analysis and Research UnitS (ICARUS) for the Environmental Protection Agency	2010	x					x		x
ISRAEL	Ministry of Environmental Protection	2008	x			x				x
ITALY	Ministry of the Environment and the Sea	2014	x			x			x	
JAPAN	The Environment Research and Technology Development Fund, Ministry of the Environment, Japan's Strategic Research and Development Domain	2014			x	x				x
KOREA	Ministry of Environment	2010	x			x				x

Annex 1b) continued on next page.

LATVIA	Ministry of Environmental Protection and Regional Development	2012	x					x		x
LUXEMBOURG	Ministère du Développement durable et des infrastructures	2014	x			x				x
MEXICO	Ministry of the Environment and Natural Resources	2013			x		x	x		x
NETHERLANDS	PBL Netherlands Environmental Assessment Agency	2012	x			x			x	
NEW ZEALAND	New Zealand Government	2008	x			x			x	
NORWAY	Ministry of the Environment	2010	x			x			x	
POLAND	Ministry of the Environment	2013	x			x				x
PORTUGAL	Portuguese Republic	2010	x			x			x	
SLOVAK REPUBLIC	Ministry of the Environment	2014			x				x	
SLOVENIA	Ministry of the Environment	2010	x			x				x
SPAIN	Ministry of the Environment and the University of Castilla La Mancha	2005	x			x				x
SWEDEN	Swedish Commission on Climate and Vulnerability	2007	x			x			x	
SWITZERLAND	Organe consultatif sur les changements climatiques	2007	x			x			x	
TURKEY	Ministry of Environment and Urbanization	2012	x			x				x
UNITED KINGDOM	Committee on Climate Change	2016	x			x				x
UNITED STATES	U.S. Global Change Research Program	2014	x			x				x

Source: National documents.

ANNEX 2: INTEGRATION OF CLIMATE RISK INTO DEVELOPMENT FINANCE INSTITUTIONS' INVESTMENT PROCESSES

Development bank Adaptation finance own resources	**a) Requirement**	**b) Screening & decision management tools**	**c) Evaluation of implementation**
World Bank Group (WB) USD 2 855 million (2014)	In line with the WBG Strategy (2013), WB's fund for the poorest countries (International Development Association, or **IDA**) now i) incorporates climate and disaster risk considerations into the analysis of development challenges and priorities, and, when countries agree, in the content of programs and results frameworks; and ii) screens all new project and sectoral/national programme for climate risks. The fund focusing on private sector in developing countries (International Finance Corporation or **IFC**), follows Performance Standards (2012) that define private sector client responsibilities for managing environmental and social risks, including identifying climate risks and adaptation opportunities and promoting sustainable use of energy and water resources.	- Eight Climate and disaster risks screening tools, with sectoral focus on Agriculture, Water, Roads, Coastal flood protection, Energy and Health are publically accessible since April 2015. They build on the 85 Climate Country Adaptation profiles. - World Bank Urban Risk Assessment (2013) helps cities screen for hazards and guide project and city managers in a detailed assessment of a city's risk through risk mapping, resilience studies and institutional gap analysis.	According to a 2013 Independent Evaluation Group report focusing on WB and IFC, climate risk identification was ad hoc and almost entirely devoted to climate variability rather than climate change: - Climate risks do not fit into the World Bank Operational Risk Assessment Framework (ORAF). - IFC tests [until 2013] for climate sensitivity during the period of its financial investment (<10y in 58% and <15y in 91% of cases), instead of the operational life of the project. The report welcomes the inclusion of climate risks into IFC Performance Standards. The report does not evaluate the systematic IDA risk screening, which was introduced later.
ADB (Asian Development Bank) USD 665 million (2014)	Since 2014, the IDB has institutionalized a framework to systematically identify proposed investments that may be adversely affected by climate change at the very early stages of project development and incorporate risk reduction measures in the project design (p. 48, **Figure 1** from ADB, 2015).	Guidelines for climate proofing investments by sector: road transport (2011), agriculture, rural development and food security (2012), energy sector (2013), as well as "meta guidelines" for water aimed at practitioners in Asia and the Pacific (2015).	-
African Development Bank (AfDB) USD 605 million (2014)	Alongside the Climate Risk Management and Adaptation Strategy (CRMA, 2009), AfDB's Climate Change Action Plan 2011-2015 (CCAP, 2010) set out to develop tools and mechanisms to assess vulnerabilities and build climate resilience into its projects.	The AfDB Climate Safeguard System (CSS) tool to assess vulnerabilities, screen risks and identify adaptation options was piloted in 2013 for eventual application to all Bank-funded projects. All projects initiated between 2007 and 2009 were retrospectively screened for climate risks and the vulnerable ones made resilient (CCAP, 2010).	The Quality Assurance Department 2013 progress report on CCAP implementation highlights that despite the availability of different tools and methodologies for mainstreaming climate change into the Bank's policies and projects, Bank task managers are still struggling with project-level integration of climate risks to generate information for project design and implementation.
*European Bank for Reconstruction and Development (EBRD)** USD 188 million (2014)	EBRD systematically integrates climate risk assessments and adaptation measures in their investment operations by conducting climate sensitivity screening, tailoring asset design and management, training employees to manage risks, and creating adapted financial solutions (EBRD SEI, 2014). The importance of climate risks is recognised in its Environmental and Social Policy's Performance requirements on Assessment and Management of Environmental and Social Impacts, and Sustainable Resource Management (EBRD, 2014).	Tools for risk screening in place. Detailed analysis with sector-specific tools currently in development. (EUFIWACC, 2015).	-

Inter-American Development Bank (IDB) USD 81 million (2014)	The IDB Climate Change Strategy (2011) followed by the Climate Change Action Plan (2012-2015) made adaptation activities a primary development priority and set out to mainstream climate change resilience across its operations and activities.	The IDB Environmental Safeguards Unit (ESG) has developed a screening toolkit for all new projects (October 2013), with regional declinations for the Caribbean region (2014).	A thematic evaluation (2014) from the Office for Verification and Oversight revealed that the tool had not yet been integrated into project risk analysis and there seemed to be limited demand for training from IDB staff as of November 2014.
Asian Infrastructure Investment Bank (AIIB)	In its draft Environmental and Social Framework (under consultation until 23rd October), the IIAB "recognizes the need to support (…) adaptation measures in its operations" and "aims to support its Clients in their evaluation (…) of the implications of climate change on its operations".	The Environmental and Social Assessment required IIAB clients to "assess potential transboundary and global impacts, including climate change".	-
Nordic Development Fund (NDF)	Since 2009 NDF has a new mandate to provide financing for projects contributing to climate change and development objectives in selected, mostly low income, developing countries. Its latest criteria for project screening and identification feature an adaptation section (2016).	The Project Identification and Screening Methodology (2013) was originally designed as a tool to secure a rigorous and systematic analysis of the climate change and development relevance of projects suggested for NDF's financing.	-
France (AFD)***	Systematic climate risk assessment for each project during preparation phase and plans to systematise in-depth analysis studies for projects at risk.	Procedure in place. Tool for preliminary risk screening being upgraded. Pilot phase ongoing for in-depth analysis. (EUFIWACC, 2015).	-
Japan (JICA)**	The Guidelines for confirmation of environmental and social considerations (2002) do not mention climate change, but the 2011 Climate Finance Impact Tool for adaptation (C-FIT Adaptation) aims to mainstream adaptation into Japanese ODA (JICA, 2011).	The C-FIT Adaptation is also designed to screen for risks in the early stages of project development, and contains sectoral guidelines for project level adaptation.	-
Germany (KfW)*** Development Bank	Systematic climate risk assessment for each project during preparation phase, in-depth analysis studies for projects at risk. (KfW Development Bank, 2011). The screening establishes whether there is any indication that a project depends to a significant degree on climate parameters, e.g. wind or precipitation. It also checks whether the adaptive capacity (resilience) of the people or ecosystem can be significantly increased, and follows-up with an in-depth assessment if needed.	Tools and procedure in place. ECA methodology pilots in 2015. (EUFIWACC, 2015).	-

* Members of European Financing Institutions Working Group on Adaptation to Climate Change (EUFI WACC), together with the European Commission.

** Members of the International Development Finance Club (IDFC).

*** Members of EUFI WACC and IDFC.

Source: (Ricardo-AEA, 2013; World Bank, 2015).

ANNEX 3: CASE STUDY - BUILDING THE ROOM FOR THE RIVER FLOOD PROTECTION PROGRAMME (NETHERLANDS)

The Room for the River programme is a set of civil engineering works on 34 sites across the Netherlands, aiming to reduce flood risk by reinstating a more natural and dynamic flow for rivers Rhine, Meuse, Waal and Ijssel. This programme was initiated at the national level by the government following narrowly averted major floods in 1993 and 1995 that came close to overtopping the existing system of defences. The programme reflects a paradigm shift in water management in the Netherlands, away from an emphasis on higher and stronger dikes to a broader approach. The lengthy preparation of the programme saw i) the government implement major changes in the spatial planning system through the Spatial Planning Key Decision, ii) regional authorities propose a selection of the measures to be taken based on a technical decision making tool, and iii) parliament earmark the entire budget for implementation prior to the start of the works.

The programme is unique in its scale and centralised impulse, but some of its lessons can be applied to other smaller projects. For instance, continuous engagement with local stakeholders played a central role in fostering the acceptability of the solutions which required difficult trade-offs. Detailed planning and monitoring coupled with budget certainty facilitated the move from undertaking vulnerability assessment to implementing measures to reduce this vulnerability. Lastly, measures designed to work with nature, sometimes labelled 'green infrastructure', can preserve flexibility towards potential futures, and generate important co-benefits that support both public acceptability and sound financial outcomes.

I. Project description

Secure and effective water management is of the utmost importance for the existence of the Netherlands. The country is situated in the delta of three river systems that flow into the North Sea, with 26% of the land below sea level and 55% at risk of flooding (PBL, 2010). The Netherlands is the second largest exporter of agricultural products globally, with exports of EUR 80.7 Billion in 2014 (Ministry for Economic Affairs, 2015).

The Netherlands' Room for the River programme is a set of civil engineering works on 34 sites across the country, aiming to reduce flood risk by reinstating a more natural and dynamic flow for rivers Rhine, Meuse, Waal and Ijssel.

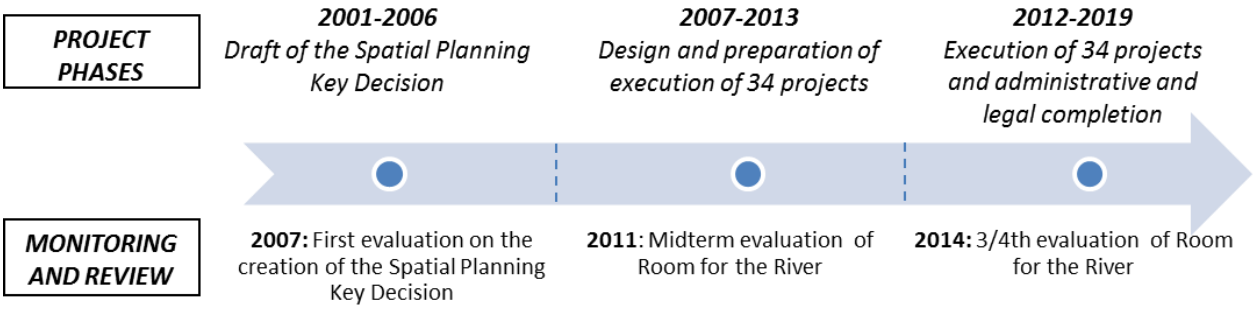
The Room for the River approach was designed following the narrowly averted major floods in 1993 and 1995, the latter forcing the evacuation of 250 000 people. At that time, the main approach to river water management focused on containing the rivers' width with ever-higher dikes. But following these near-misses and the more apparent limits of containing river water with stronger dikes, the Dutch government drafted new policy guidelines in 1996 that moved away from dike reinforcement towards an approach of allowing rivers to take more space instead (Brink, 2009). This shift to river widening was formalised in the 4th Water Management Note published by the Dutch government in 1998 (Ministry for Transport and Water). It stated the government's strategic decision to prevent high water levels through the removal of unnatural obstructions, recovery of secondary channels and lowering of flood plains.

Following a few years during which Rijkswaterstaat explored potential options, the design of the Room for the River programme started in earnest in 2000. The programme focuses on the four main rivers running through the central part of the Netherlands and aims to increase their maximum flow from 15 000

to 16 000 m^3 per second. In addition to contributing to the protection of the livelihoods of over four million people, the program is designed to improve the quality of the immediate surroundings at its sites. The total preparation took approximately twelve years to complete, including a necessary modification of the spatial planning system through the Spatial Planning Key Decision, or SPKD (*Planologische Kernbeslissing Ruimte voor de Rivier*) in 2006. The implementation phase runs from 2012 to 2019, but most of the flood protection objectives were on track to be met by 2016 (Room for the River, 2016).

The programme was initially proposed by the government, and then approved by the Dutch parliament, which granted Room for the River the status of a "major project". Parliament consequently required the Minister of Infrastructure and the Environment to report twice a year regarding the project's progress (Fig. 1). This report covers the general progress of the program as well as identifying any changes in scope, budget and planning. It draws from the local reports produced by implementing regional authorities. Responsibility for implementing this programme is shared between the Minister of Infrastructure and the Environment and the Secretary of State for Economic Affairs. Many stakeholders were involved in the programme, included regional governments, citizens, contractors, business, knowledge institutions, legal authorities and NGOs. Building public support for extra flood protection measures, including river widening, was instrumental in allowing the project to be adopted.

Figure 1. Room for the River preparation and monitoring timeline



The programme is implemented by Rijkswaterstaat at the national level, and by regional water authorities at the local level. Rijkswaterstaat, founded in 1798, is the national executive agency for integrated water management and is currently part of the Ministry of Infrastructure and the Environment. The organisation is responsible for the design, construction, management and maintenance of the main infrastructure facilities for flood protection, as well as the road and waterway networks in the Netherlands. Rijkswaterstaat also monitors water levels along the coast, in rivers and in lakes, and issues early warnings of threats of storms and high water levels. At the local level, the 22 Regional Water Authorities are responsible for regional management, including flood protection, regional water management and treatment of urban wastewater.

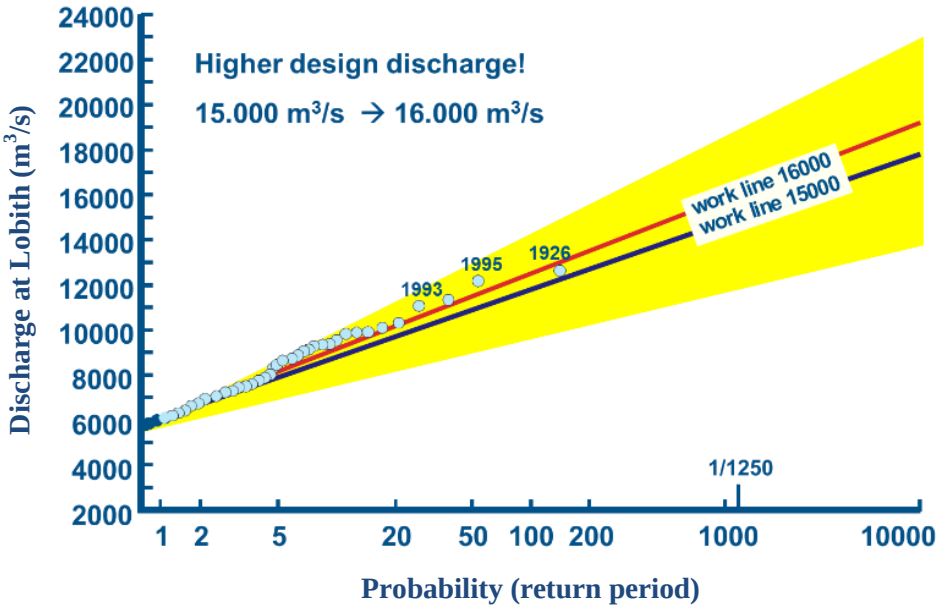
II. Vulnerability analysis

The Netherlands is continuously updating what it defines as the level of acceptable flood risk and safety standards for dikes at the national level. This is done through the work of the Delta Committee and the Delta Programme. The first Delta Committee was installed after the major flood of 1953 in the south-western part of the Netherlands and brought together scientists, policymakers and representatives from the private sector. In 1960, the Delta Committee conducted one of the first cost-benefit analyses in the country by balancing the costs of strengthening levees against its expected benefits (Botger and Te Linde, 2014). Because at the time the ways in which dikes could fail and the socio-economic impact of flooding were difficult, if not impossible, to compute, the Committee proposed to focus on the exceedance probabilities

(also known as design loading conditions). These are the probability that water levels would rise sufficiently to overtop a given dike in a given year. These exceedance probabilities ranged from a 1 in 250 (in the Meuse Embankments) to a 1 in 10 000 chance of flooding (South Holland) throughout the country.

Since 1996, in line with the advice of consecutive water committees responsible for defining flood protection norms, the Law on Water Embankments (*the Wet op de Waterkering*) mandates that Dutch river dikes should be able to withstand water levels that occur with a probability of 1 in 1250 years. The heights of the dikes comply with a design discharge based on a statistical analysis of all the peak discharges that occurred since 1901, giving an indication of the probability of the different possible water levels. The result of this statistical analysis is a graph with the probability of occurrence of high water levels on the X-axis and the drainage capacity of the rivers on the Y-axis (Figure 2). It shows how the exceptionally high water levels in 1993 and 1995 led to an increase of the safety standards for dikes through an adjustment of the design discharge, as the line of potential water levels (blue line) shifted upwards (red line). Taking into account the 1993 and 1995 events, a 1 in 1250 per year event would correspond to a discharge of 16 000 m^3 per second instead of 15 000 m^3 per second as previously estimated.

Figure 2. Design discharge (Room for the River, 2000)



However, this adjusted design discharge does not account for potential long-term effects of climate change. In 2011, the Dutch government started a review of its flood safety standards as part of the Delta programme using new criteria. The tolerability of risks is assessed in light of factors such as economic growth, population growth and climate change. The effects of climate change are modelled using climate projections from the Royal Netherlands Meteorological Institute. Safety standards are now defined in terms of allowable probabilities of flooding rather than exceedance probabilities. In other words, the new flood norms are based on the probability a flood occurs and the potential social-economic impact it could have, instead of focusing on the likelihood that high waters overtop the dikes. In addition, the new norms guarantee equal flood protection for all Dutch citizens: flood defences are designed to ensure that the chance of a Dutch person being killed by a flood is less than 1 in 100 000 per year. The new safety standards should apply to 234 specific levee sections throughout the country, and be embedded in an update of the 2010 Water Act, which is expected to come into effect in early 2017.

III. Climate resilience measures

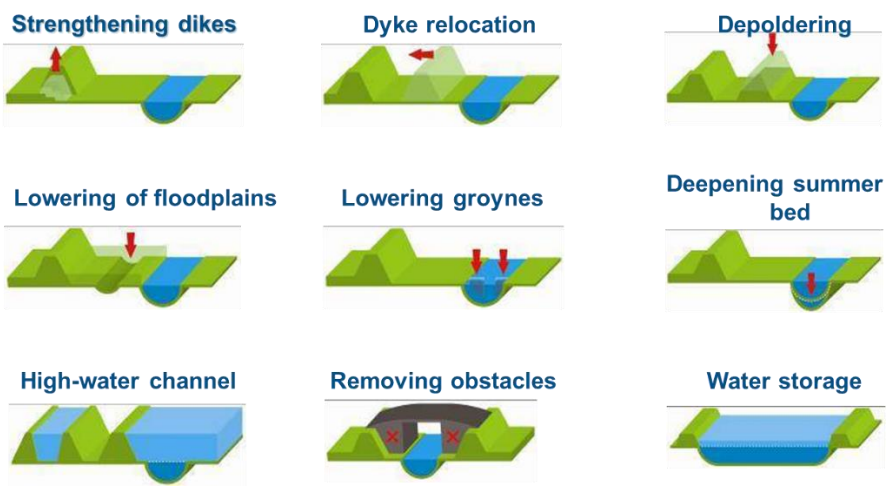
As stated, the paradigm shift to river widening was formalised in the 4th Water Management Note in 1996. Two cost-benefit analyses subsequently assessed the efficiency of the proposed implementation measures.

The main study guiding the Room from the River programme (Ruimte voor Rijntakken) was led by Deltares and Rijkswaterstaat and went through an iterative process. Each step of the research increased the knowledge of the functioning of the river system and the capabilities, limitations and consequences of the potential measures. The study then examined the *different types* of measures, the various combinations of measures (*alternatives*) and the *variants* of the alternatives, in which the distribution of discharge across the river branches varied (Rijkswaterstaat, 2000). Schematically, three types of river widening measures were examined to retain the water level of the rivers if the design discharge increases:

- measures in the main channel
- measures in the floodplains
- measures inside the diked area.

Room for the River incorporates several types of "building with nature" measures, including lowering and broadening of the floodplains, creation of river diversions and temporary water storage areas and restoration of marshy riverine landscapes. The programme took into account the fact that all rivers are different and require a specific solution for making space for the river. In total, nine types of measures can be distinguished within the Room for the River programme (Figure 3).

Figure 3. Types of flood protection measures in the Room for the River programme



The effect of each measure was quantified through the reduction of river water levels on the spot and upstream. The area considered depended on the gradient of the river on the spot, the construction design of the dikes and obstacles to the river flow in the area. The "hydraulic effectiveness" was then derived from the degree of reduction in water levels (in mm) and the distance over which this reduction occurred (in km), and expressed in square meters. This hydraulic effectiveness metric made it possible to compare the efficiency of each measure against their cost of implementation. The estimated costs of each measure included compensation costs for agricultural damage, the purchase of homes and adjustment costs for roads and other infrastructure, to account for the change in land use.

Large-scale diversion of dikes, high water channels, lowering of summer river beds and the use of groynes all scored as the most efficient measures, while excavating floodplains was the least efficient one (Rijkswaterstaat, 2000). This analysis showed that measures in urban areas would be very efficient and facilitate substantial reductions in river water levels, even allowing for their high costs and potential for disruption in densely populated areas. However, the analysis did not fully capture the potential remediation costs in case of contaminated soil, or certain benefits that may arise from future arrangements on shared use (e.g. recreation, sand extraction), increased social value, or from potential catalytic effects on the project area's development.

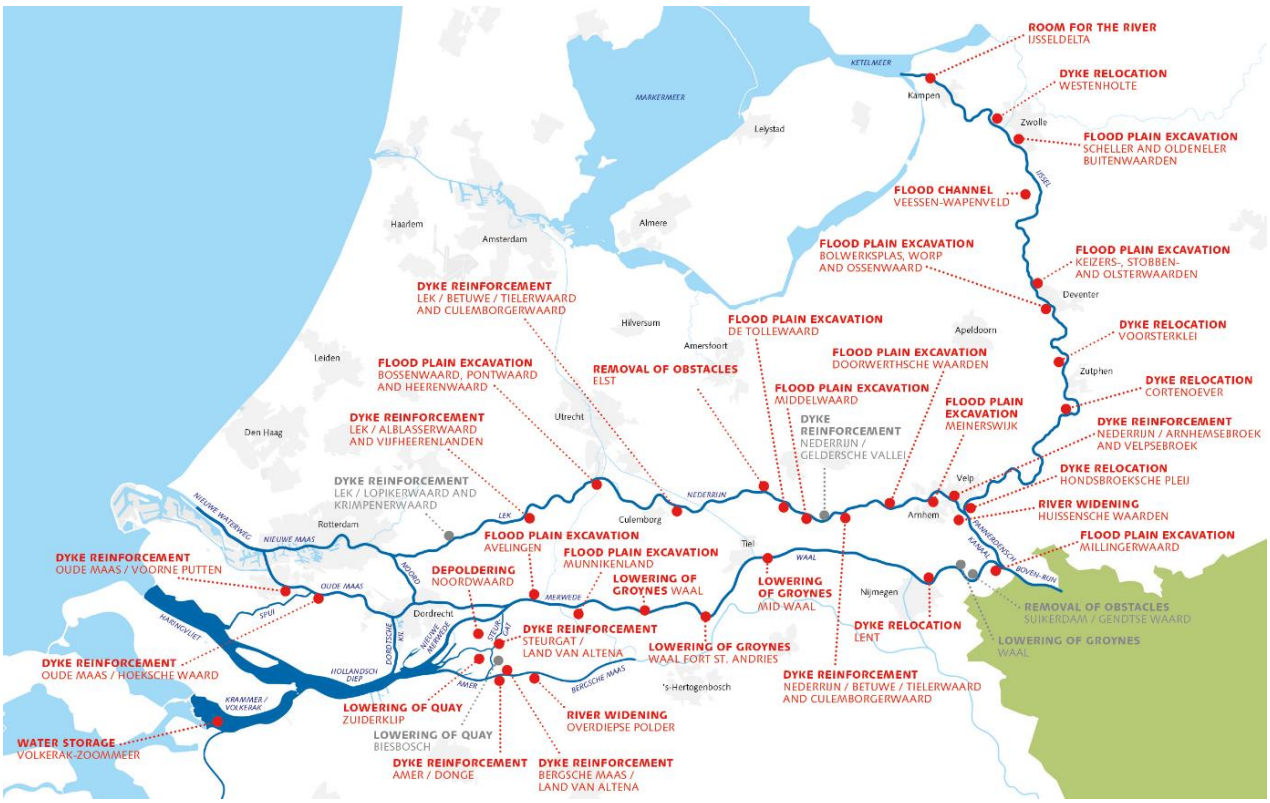
In 2005, the Netherlands Bureau for Economic Policy Analysis (*Centraal Planbureau*, or CPB) carried out a cost-benefit analysis of the Spatial Planning Key Decision. In order to value the benefits of each measure, CPB calculated their potential improvement in flood protection, spatial quality and recreational opportunities in the area. The CBP stated that over 600 river widening measures would be cost-effective, and concurred with the spending of more than EUR 2 billion in the river delta area (CPB, 2005).

Potential measures were assessed regarding their efficiency over a 100 year period, and designed to retain their value over the long term while allowing for later modifications to accommodate future expected discharges (Spatial Planning Key Decision, 2007). Instead of a separate focus on each of the individual projects, this programme facilitated a comprehensive approach and contributed to building support from the local stakeholders (Room for the River, 2015a). A decision tool calculating the hydraulic consequences of a combination of various river widening measures (Building Blocks programme) was made available to all stakeholders. This allowed them to experiment with and to explore visually the effectiveness and interdependencies of measures to reduce water levels. Ultimately, a coherent package of 34 flood protection measures was formed from a list of over 600 proposals.

These 34 measures were defined in the SPKD and sent by the minister to parliament, which approved it in 2006. The passing of the SPKD guaranteed a single programme budget covering all the projected implementation costs and a central programme office to administer the project. Of the 34 projects, 22 were to be implemented by regional authorities, which incorporated local policy demands and public wishes into the flood protections measures, such as urban or nature development (Room for the River, 2015b). By the end of 2016, 31 of the 34 planned projects should have achieved their flood protection objective. The three remaining projects should do so by 2017-2019 (Room for the River, 2016).

Even after the flood protection and spatial quality objectives are met, the projects continue to be administered until regional authorities request the minister to accept the work and discharge them of further liability.

Figure 4. Map of 34 flood protection measures forming the Room for the River project



IV. Financing resilience

The budget for the entirety of the Room for the River programme was secured prior to any implementation works. At the start of the project in 2007, the Dutch Parliament approved a fixed budget of EUR 2.5 billion for the implementation of the 34 measures in the Room for the River programme. This budget is earmarked in the budget of the Ministry of Transport, Public Works and Water Management under a special "Delta fund". Due to the programme's "major infrastructural project" status, the parliament is the only institution authorised to change the programme's budget (and not, for instance, a ministry). Throughout the years of implementation, the budget has been adjusted for inflation. It includes all costs, including human resources budget, research, design, real estate purchases, execution and risk reserve. Regional partners also fund smaller parts of the programme's budget, in particular to fund additional spatial quality improvements. The measure's maintenance is part of the regional water authorities and Rijkswaterstaat routine activities and funded through their budget lines.

Initiated alongside the Room for the River Programme, the Dutch Flood Protection Program focuses on reinforcing dikes that no longer meet the legal flood protection standards, and is the other main water management infrastructure investment programme. It has a different financing system, including more specified project funds, a 50/50 co-financing agreement with the Regional Water Authorities and financial stimulation of innovations. The Ministry of Infrastructure and the Environment annually publishes a list of priority projects, following consultation with the Regional Water Authorities. These are selected on the basis of cost-effectiveness, weighing up the benefits (reduction in flood risk) against the costs of reinforcement. Since 2014, the capital cost of these reinforcements is 90% funded by government grants while the remaining 10% is funded by the competent Regional Water Authority, in line with the Water Act. This funding excludes any maintenance costs and is deposited in the Delta Fund. In 2015, the

Regional Water Authorities collectively contributed over EUR 180 million to the Delta Fund. Exceptionally, the Minister may provide a grant for up to 100% of the actual costs in the case of experimental dike enforcements to stimulate innovation which may benefit the Dutch Flood Protection programme.

V. Discussion of success factors and challenges

Official reviews of the Room for the River programme have cited three main success factors (Berenschot, 2007; Erasmus University Rotterdam and Berenschot, 2011; Andersson Elffers Felix, 2013):

- a focus on benefit sharing with a wide range of stakeholders
- comprehensive government funding from the start of the project
- increased flexibility due to building with nature.

Sharing benefits

Stakeholders, notably the national government, the provinces, Regional Water Authorities and municipalities, cooperated actively throughout each step of the process through steering committees, consultation groups, stakeholder meetings and knowledge exchange programs. Local governments and stakeholders had the opportunity to propose adjustments to the national government's initial proposals through community representation, project design evenings and via social media. This collaboration has been formalized by an agreement between the Minister of Infrastructure and the Environment and regional governments. The agreement established the framework set by the national government, including the general outline of the project, objectives, available budget and timeframe. The programme office acted as a facilitator between the national and local stakeholders, in addition to overseeing the whole project.

This dialogue was particularly important in ensuring that the interests of affected people were considered when homes and businesses needed to be relocated to enable river widening. A total of 119 houses and 66 businesses (including farms) had to be relocated to make room for the river and therefore received financial compensation and administrative support for their resettlement. The stakeholder dialogue also enabled project modifications that accommodated local preferences. In the Overdiepse Polder, for instance, the programme initially proposed the dredging of an ancillary channel that would have rendered agricultural activities impossible. In response, a group of 17 farmers in the community proposed building dwelling mounds for their houses and farms instead. By raising the farms a couple of meters above ground, the polder could overflow during times of high water without posing a threat to the community, while allowing agricultural activities to take place during the rest of the year. The community's suggestion led to a redesign of the measure.

Overall, collaboration between government and local communities contributed to maximising the economic co-benefits in the project areas, in line with the programme's objective of increasing the attractiveness of surrounding areas (Room for the River, 2015b). As measures reduced the flood vulnerability of the project areas, they provided an incentive for further development. For instance, the Room for the River project at the city of Nijmegen led to an innovative river park. In some cases, the implementation of flood protection measures prompted the renewal of roads and railways, the rehabilitation of industrial sites or the development of plans for road infrastructure. Flood protection measures created new areas that might be flooded a few times a year, and are not adapted to capital-intensive forms of land use. However, these areas could still be suitable for the development of agricultural activity, economic activity such as clay and sand extraction, water recreation and enjoyment of nature, which may still provide additional revenues. In the previous example of Overdiepse Polder, for instance,

the Room for River programme spurred a redistribution of land amongst the farmers that stayed. Eight of the 17 farmers who requested a modification of design ultimately decided to relocate their farming activities out of the polder. However, the remaining nine farms ultimately became more economically viable because they could expand their businesses by purchasing land from the departing farmers.

Comprehensive funding

As noted above, the entire budget of the Room for the River programme was allocated in 2001 by the national government and approved by parliament. Any subsequent modification to this budget would have required parliamentary approval. Some regional partners provided additional funding in order to pay for additional flood protection measures. In addition to this overall budget stability, any spending is closely monitored by an external accountant who verifies that regional water authorities spend their budget as planned. As a result of the extensive project planning and detailed budget monitoring, Room for the River is one of the few Dutch infrastructure projects to be completed mostly on time and within budget (Andersson Elffers Felix, 2014).

Flexibility from building with nature

The programme has introduced new techniques and approaches to protect against flooding. Instead of the traditional focus on heightening dikes and infrastructure improvements, the Room for the River programme has been building with nature by adopting an integrated view of the functioning of the rivers and their environments. Room for the River focused on measures that make use of natural processes, so that it would have a positive effect on nature, through natural dynamics such as wind, water, sediment and vegetation. Digging out secondary channels in the floodplain, for example, stimulates the existing flora and fauna by providing a more sheltered water body where fish and small animals can flourish.

The use of natural systems led to solutions that adapt more easily to inherently uncertain and variable weather conditions and ecological processes. Implementing and maintaining this type of solution required the use of adaptive pathways for decision-making and an adaptive governance approach. The programme used multiple scenarios of future socio-economic and physical developments (e.g. climate change or land use) and possible actions. The programme's adaptive governance approach included principles of continuous and collective learning to include new insights and knowledge, a participatory monitoring programme, wide participation of stakeholders and a continues process of reflexive decision-making.

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ANNEX 4: CASE STUDY - RETROFITTING THE SLUSSEN LOCK (STOCKHOLM, SWEDEN)

Slussen is a lock between the Lake Mälaren and the Baltic Sea that also serves as a key transport node for the City of Stockholm. The New Slussen project is redesigning and retrofitting the existing 80-year-old structure, with works starting in 2016. Intended to last for another 100 years, the new facility incorporates elements of climate resilience and flexibility by design. The foundations of the new Slussen facility will be oversized for current conditions in order to bear the heavier loads from rising sea levels and the higher flood gates that are projected to become necessary from 2050 onwards. The revised lake regulation plan will, for the first time, account for climate change impacts, including projected sea level rise and changes in the 1-in-10 000 year flow to 2100. This plan includes a new system of hydrological monitoring and forecasting to inform the lake's water regulation. Among other benefits, the project plans to more than double the discharge capacity of the lake in order to reduce the high risk of flooding around Lake Mälaren today and in the future.

Considering the strategic importance of the project for Stockholm and its region, substantial resources were dedicated to environmental impact-, vulnerability- and cost-benefit assessments, as well as stakeholder engagement. The City of Stockholm, which is the sole owner of Slussen's site, leads and entirely finances the lock's redevelopment. Efforts to get other potential beneficiaries of flood protection and clean water provision to contribute to the project's funding have not yet succeeded.

I. Project description

Forming the central junction between north and south Stockholm, Slussen is a strategic infrastructure asset with regards to transport, clean water provision and flood protection for Stockholm and the Mälardalen region. Slussen's lock allows boats to transit between Lake Mälaren and the bay leading to the Baltic Sea (Saltsjön), and also contains a cloverleaf exchange for cars, pedestrian passageways and railway tracks. Slussen is Sweden's second largest public transport hub after Stockholm Central Station. The lock also acts as one of the gates between freshwater (Mälaren) and saltwater areas (Saltsjön), thereby playing a key role in the provision of clean water. When the lake's waters rise, due to spring snow melting for example, the lock's gates can also be opened to discharge excess water and prevent flooding.

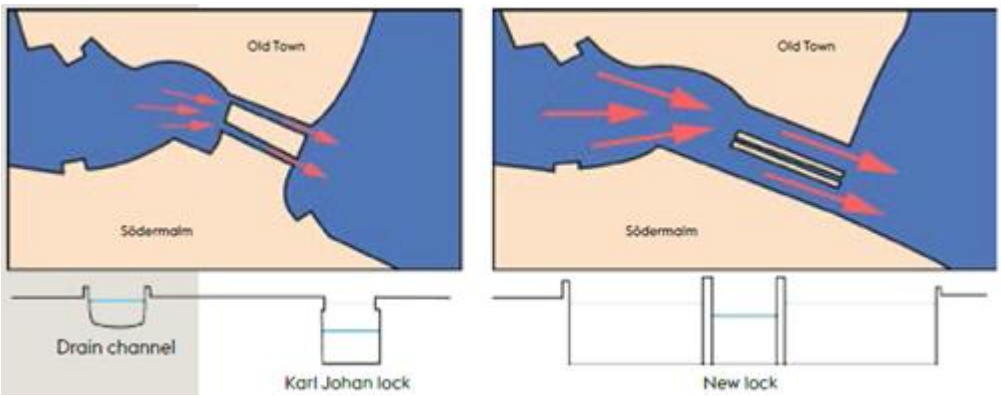
The current lock structure dates back to 1935, and builds on three previous structures from the 17th, 18th and 19th centuries, which were designed to facilitate shipping, trade and road transport. The New Slussen project consists of a retrofitting and redesigning of Slussen. The main driver for retrofitting the structure is a concern for public safety. Sections of its existing foundations have sunk by 25 cm in places and are at risk of collapsing (Figure 5).

Figure 5. Slussen needs for asset replacement (City of Stockholm)

The project aims to achieve three main objectives and functions at the site:

- Flood and Water Management: By building larger channels, the New Slussen project should allow the lock to release nearly five times more water from Lake Mälaren to the Salt Lake, up to 1 400 m³/s (Figure 6). Coupled with a new water regulation plan for the lake and a responsive system of hydrological monitoring and forecasting, the increase of drainage capacity reduces the risk of inundation in Stockholm and its region.

Figure 6. Schematic of New Slussen improved drainage capacity



By preventing inundation around the lake and saltwater intrusion from the Baltic Sea to the freshwater of Lake Mälaren, New Slussen aims to safeguard the provision of safe drinking water for more than two million people living around the lake.

- Transportation: New Slussen will create more lanes for buses and bikes, and fewer for cars. By 2030, this is projected to increase public transport traffic by 26%, double pedestrians and cycling traffic, while reducing car traffic by 33% (Table 3).

Table 3. . Traffic at Slussen today and in 2030 (projections)

Transport mode	Daily users today	Projected number of users in 2030
Buses and underground	400 000	505 000
Pedestrians & cyclists	49 000	103 000
Cars	30 000	20 000

- Quality of life: The development also includes new green and commercial spaces to make the lock more attractive to locals and visitors.

The New Slussen project is led by a dedicated team within Stockholm's local government (City of Stockholm), which is the sole owner of the site. Planning authorities have led consultations regarding the need to refurbish Slussen since 1991, but proposed designs were often contested by the public. The current design was selected in 2008 following an architectural competition, with on-site preparatory works starting in 2012-2013. A change of local government in 2014 led to a subsequent revision of the project, including its costs. Building work itself started in 2016 and should be completed by 2025, split in two

phases to preserve a working traffic connection at all times between the two central neighbourhoods it links (Gamla Stan and Södermalm).

II. Vulnerability analysis

The main climate-related risk taken into consideration for the design of New Slussen is flooding from Lake Mälaren, given sea level rise and the lake's low drainage capacity. Several vulnerability studies have quantitatively assessed current and future flood risk around the lake. Modelling, science and observations from the Swedish Meteorological and Hydrological Institute (SMHI) underpinned analysis by national authorities (Swedish Commission on Climate and Vulnerability, 2006; MSB, 2012a and 2012b) and local ones (City of Stockholm, 2011).

The towns surrounding Lake Mälaren are highly vulnerable to flooding, according to analysis by SMHI. In the winter of 2000, Stockholm was severely affected by a flood which nearly inundated an underground station in the city centre. Under current conditions, SMHI estimates there is a 10% probability that an even worse flood than in 2000 could occur within the next 10 years, due to the lake's insufficient water discharge capacity. Currently, the mean water level difference between the lake and the sea is less than 70 cm.

An initial study assessed the current and projected vulnerability to flooding of Lakes Mälaren, Hjälmaren and Vänern and recommended a range of adaptation measures. This study was undertaken as part of a national assessment on climate risk and opportunities (Swedish Commission on Climate and Vulnerability, 2006 and 2007). Stockholm was identified as one of the cities that could be severely affected by the flooding of supply tunnels for the water, sewage treatment, electricity, telecommunications and district heating networks and the disruption of several public transport services throughout the city. In terms of adaptation measures, the Commission on Climate and Vulnerability recommended that Stockholm's county administrative board lead further research into potential impacts. The Commission also identified the retrofitting of Slussen as one of the major opportunities to increase drainage capacity.

Following this study, the City of Stockholm started drafting the masterplan for the retrofitting of Slussen in 2006. Based on the findings of the national Commission, the City put flood prevention at the centre of the project. A team of officials from SMHI and over 50 environmental experts worked for six years to develop a proposal for a new regulation plan for Lake Mälaren, based on an Environmental Impact Assessment (City of Stockholm, 2012). The team assessed the costs and benefits of different drainage capacities for the lake and proposed a level of acceptable risk of flooding around the lake, considering today's climate and future climate change. Background work included hydrological and climate modelling, environmental-, vulnerability- and cost-benefit assessments as well as several stages of stakeholder engagement at the national, regional and local level. The proposed lake regulation plan required the Land and Environmental Court to grant an environmental permit for its implementation. An application was submitted in 2012 (Mannheimer Swartling, 2012), and the environmental permit became legally binding in 2015.

The City of Stockholm's study considered flood impacts on railways, major roads and housing. It considerably improved on the previous modelling by adding flood duration as a parameter, considering the impacts of floods with different levels of severity[10] and making more detailed financial estimates of asset damages (City of Stockholm, 2012). While the Commission on Climate and Vulnerability (2006) recommended an increase of drainage capacity up to 1 000 m^3/s, the City of Stockholm's study increased this level to 1 200 m^3/s (City of Stockholm, 2012).

[10] The City of Stockholm (2012) projected the impacts from a 1-in-500 year event and a 1-in-1 000 year event, in addition to the 1-in-100 and 1-in-10 000 year events considered in the Commission on Climate and Vulnerability (2006) study.

In 2010, Government mandated the Swedish Civil Contingencies Agency (*Myndigheten för Samhällsskydd och Beredskap*, or MSB) to analyse further the consequences of flooding around Lake Mälaren (MSB, 2012a and 2012b). A key part of this study, led in parallel to the City of Stockholm's, focused on the direct and indirect physical and financial impact of flooding on critical infrastructure assets around Lake Mälaren (WSP, 2012a).[11] This impact and cost assessment study used a combination of desk-based geographical information system (GIS) analysis for roads and technical field work to assess the flood exposure of critical public infrastructure, including socio-economic costs.[12] This work resulted in a database of all damages occurring on public critical assets for different water levels, up to a level slightly above that of a 1-in-10 000 year event.

The study inventoried 451 assets within the flood prone area related to energy production and distribution, sewerage, water distribution, digital and telecommunications, as well as ports that provide "vital societal functions". Of these, the study identified 180 sites or infrastructure assets vulnerable to 1-in-1000 year floods, with many of those vulnerable at levels slightly above 1-in-100 year floods. The analysis highlighted 22 assets providing service to very large parts of the population in various municipalities, for which flooding would typically involve the non-delivery of electricity, drinking water, sewerage, or heating. The analysis identified for which water levels within a 0.86m-3.10m elevation range[13] assets would tip from suffering low-to-no-impacts (green) to catastrophic-impacts (dark red) (Figure 7). Demonstrating the importance of interdependencies with regards to infrastructure vulnerability, the study found that most of the catastrophic impacts were not caused by direct flooding of the facilities, but rather due to flooding of the electrical systems those facilities depended upon.

This MSB study estimated that a 1 metre rise in lake water level, equivalent to a 1-in-100 year event and assumed to last three weeks, would affect 22 critical infrastructure owners and operators due to operational failure, costing them a total of EUR 64 million. A water level rise of 2.2 metres, equivalent to a 1-in-10 000 year event, would cost operators nearly EUR 1 billion. These estimates do not account for the indirect costs of infrastructure disruption and the impacts of a lack of essential services to communities and businesses.

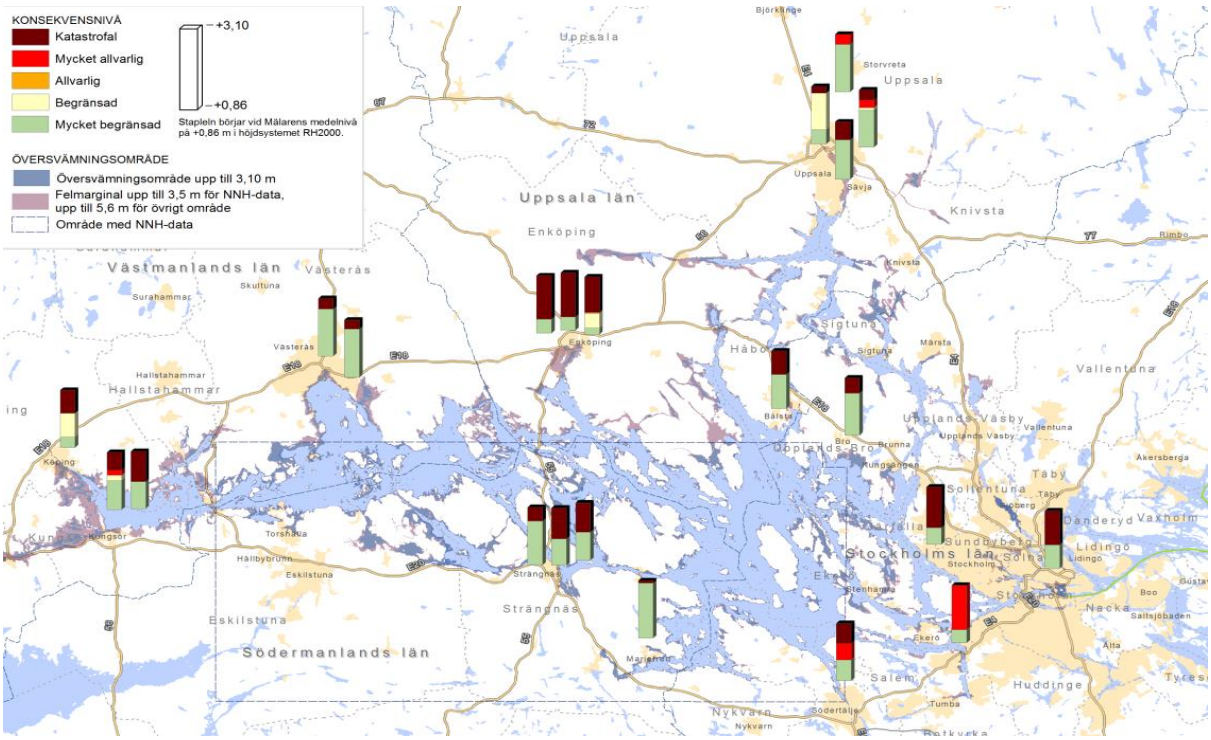
SMHI conducted several sensitivity analyses of future climate change on behalf of the city of Stockholm, to feed into the masterplan and the new water regulation plan for the Slussen project. These analyses factored in future sea levels, changing temperature conditions and a change in inflow to Lake Mälaren. The climate adaption of the new facility covers the lifetime of the structure, projected to be about 100 years (SMHI 2011a and 2011b).

[11] MSB funded simultaneously three other studies on the mapping of historical flood events' impacts, the populations at risk in flood-prone areas around Lake Mälaren, and hydrological and geographical analysis of the Lake's flood risk.

[12] The assessment cost in the region of EUR 200 000 (EUR 50 000 for the GIS analysis for roads, EUR 150 000 for field work) and covered all 24 municipalities surrounding Lake Malaren.

[13] The average water level of Lake Mälaren (1968-2015) was 0.86m.

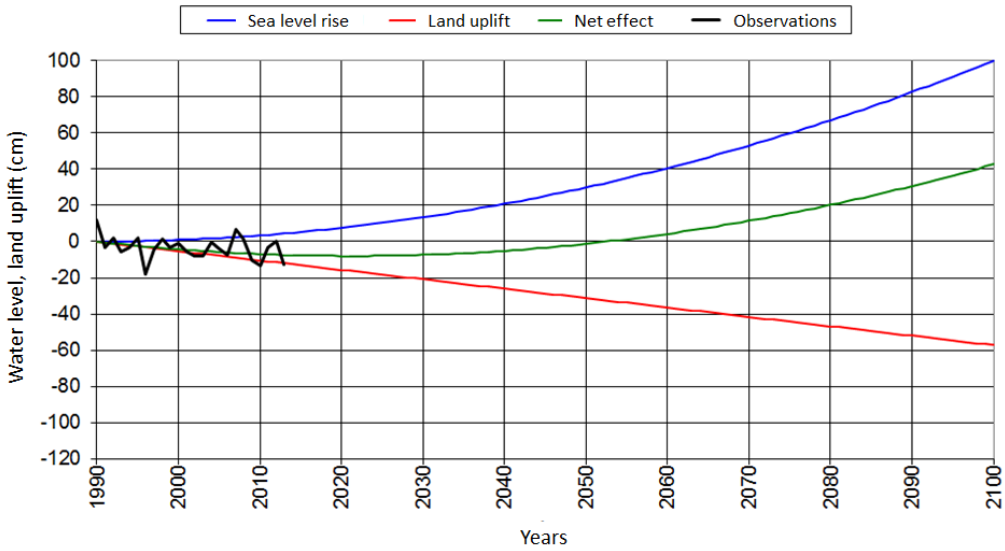
Figure 7. Variation in sensitivity to flooding for 22 public critical infrastructure assets around Lake Mälaren



The Stockholm area is subjected to two opposing forces: rising water levels in the Baltic Sea related to climate change, and a geological process known as ‘land uplift’ causing its land to rise. Land uplift has been the dominating force since late 18th century, causing a net decline in sea levels of 90cm over the 1774-2015 period (SMHI 2011). In the high-emissions scenario (RCP 8.5) of IPCC 5th scientific assessment (IPCC, 2013), the sea level rise of the Baltic Sea bordering Stockholm is projected to be counteracted by land rise until about 2050, after which Stockholm will experience a net increase in sea levels in relation to the 1990s (Figure 7). Based on these assumptions the mean level of the Baltic Sea outside Stockholm would rise by about half a metre by 2100.

The starting point (zero metre) of the elevation system needs to be regularly updated in Sweden to account for the continuous effects of land uplift and sea level rise. Another important contribution to the performance and accuracy of the analyses conducted by the City of Stockholm and MSB was therefore the adoption of a new official digital elevation model of Sweden (RH2000), launched for the Mälaren region by the National Land Survey (*Lantmäteriet*) in late 2011. The model complemented the height measurements carried out by the City of Stockholm and MSB in various sites around the lake and enabled more reliable modelling of elevation relative to water levels.

Figure 8. Projected sea level rise in Stockholm under a high-emissions scenario (1990-2100)



III. Climate resilience measures

Based on the vulnerability assessments, cost-benefit analysis and consultations described above, the New Slussen lock has been designed for what was deemed an acceptable level of risk. The level of risk New Slussen can withstand from the Lake Mälaren and the Baltic Sea bay is:

- a 1-in-10 000 year inflow of freshwater into the lake (from extreme rainfall and rapid snow melt for instance), combined with a rise in the mean water level of the Baltic Sea by 2100
- a 1-in-300 year event of maximum high tide position in the Baltic Sea, in combination with the highest, but not the most probable, projected sea level rise due to climate change over the next 100 years (0.5m), and a local rise in sea level due to strong wind.

This means that the new Slussen facility can cope with a sea level that is more than two meters higher than today's average water level in the Baltic Sea bay (Saltsjön).

The project includes three main measures which will make the asset, the City of Stockholm and the Mälardalen region more resilient to climate change:

- *Addressing the current and future flood risk due to climate change* around the Lake Mälaren by increasing the lock's drainage capacity from 300 m^3/s to 1 400 m^3/s by widening and deepening its existing channels.[14] Overall, New Slussen more than doubles the total discharge capacity of Lake Mälaren.
- *Building in climate adaption and flexibility in the project's design* to accommodate higher flood risk levels, by 'oversizing' the foundations for the whole facility and to support the heavier water loads from the sea and the higher flood gates that will become necessary from 2050 onwards.

[14] In parallel, the City of Stockholm is also doubling the drainage capacity of the neighbouring Hammarby lock from 70 to 140 m^3/s.

- *Elaborating a new water regulation plan* to account for climate change impacts. In addition, this plan integrates a new system of hydrological monitoring and forecasting, led by SMHI, to allow the regulation of water levels in the lake to be more responsive.

To assess whether to invest in resilience measures, analysis conducted by WSP for the City of Stockholm study (WSP, 2012b) provided an assessment of the potential costs associated with flooding, following the formula:

Potential damages = Risk of flooding (Risk of water levels) Duration of flood in days* Cost for society per day*

These avoided damages, representing the investment's benefits, were weighed against the estimated investment costs for the water regulation component of the New Slussen project (EUR 88 million in 2011 prices). A 1-in-1000 year event would cause damage valued at EUR 650 million to assets related to energy, sewage, rail, housing and ports. A 1-in-10 000 year event would cause further damages to roads and significantly prolong the outages, increasing losses by EUR 100 million. In addition, relatively low water levels (equivalent to a 1-in-100 year event) would cause substantial damages to sewage plants and affect drinking water quality, which is not included in these estimates. In total, the benefits were found to outweigh the costs by a factor of 6.8 for the chosen standard of protection.

In addition to those direct benefits, the project offers a range of co-benefits. Lake Mälaren provides a range of ecosystem services, including the provision of clean water, which outweigh the estimated investment costs (Löfmark et al, 2014). In its natural state, the lake's water level would vary by 2 meters throughout the year, but since the 1940s, regulating operations have strived to keep the water levels constant regardless of the seasons. The new water regulation plan reintroduces a more dynamic management and allows the lake to behave more like a natural lake, responding to natural variations of water inflows during spring time. These variations should benefit the flora and fauna along the banks of Lake Mälaren, therefore strengthening its ecosystems and preserving several Natura 2000 sites by the lake.

Beyond the end of the century when the mean sea level rise in the Baltic Sea may have risen by half-a-meter, additional regional measures to prevent flooding around Lake Mälaren may be necessary. Long-term planning for climate adjustment is the responsibility of county administrative boards around Lake Mälaren, which have been investigating different options for regional adaption such as the construction of flood barriers outside the City of Stockholm in the Stockholm archipelago.

IV. Financing resilience

The City of Stockholm is currently set to carry the largest share of the project's final estimated budget of EUR 1.3 billion (SEK 12.1 billion). This includes new traffic infrastructure, construction of a new bus terminal, digging of drainage channels and a complete renovation of the lock. This budget represents a 50% increase from the initial (2010) estimate of EUR 850 million (SEK 8 billion) due to the delays, increased scope and an increased risk reserve following protracted legal battles regarding the project's master plan, environmental permit and proposed modifications to traffic. The budget for the water regulation part of New Slussen (EUR 88 million in 2011) only accounts for 7% of the project's total cost.

In its report on flood risk to the Lakes Mälaren, Hjälmaren and Vänern, the Swedish Commission on Climate and Vulnerability had declared the works at Slussen to be of national interest. The Commission's report stated it would be "reasonable" for the national government to contribute to the cost of increased drainage capacity, for instance through funds for disaster prevention, along with the City of Stockholm and the Maritime Administration.

In line with another recommendation from the Swedish Commission on Climate and Vulnerability (2007), a special negotiator was appointed in 2010 by the government to facilitate a process of clarifying the shared responsibilities and costs between the City of Stockholm and other stakeholders (municipalities, county councils and others). The detailed assessment of potential costs and benefits produced by MSB (2012b) and the City of Stockholm (WSP, 2012b) showed that, taken collectively, municipalities around the Lake Mälaren stand even more to benefit from this project than the City of Stockholm. However, the negotiator's efforts were unsuccessful in making other municipalities contribute financially to the investments in flood and water management related to the Slussen's retrofit. Building work has already started, but the City of Stockholm continues to look into funding options to involve other institutions that stand to benefit from New Slussen.

V. Discussion of success factors and challenges

The impetus for retrofitting the Slussen lock and traffic junction is the safety of the 400 000 people that use it every day, given the current state of its foundations. However, this retrofit will have an impact on the facility's current and long-term capacity to provide clean-drinking water to more than 2 million people in 40 municipalities and flood protection to more than 20 municipalities surrounding the lake. In addition to this, the retrofitting of Slussen facilitates low-carbon transportation in the City of Stockholm. Given the strategic nature of this project, the final plans for New Slussen were only finalised after years of planning, engagement, and legal processes to get approval for the masterplan and acquire the necessary environmental permits.

The New Slussen project has several design and management features that account for climate change, and should contribute to flood protection and clean water provision for the Stockholm region over the next century. The lock's foundations will be technically oversized for today's conditions, but are built to support the higher flood gates that should become necessary by 2050. The newly adopted regulation plan for Lake Mälaren is the first one ever to account for climate change impacts and gives SMHI a monitoring role, with provisions to regularly review the plan's performance and adjust its parameters if necessary. Both of these features build in flexibility into a large civil engineering project, and balance current costs and aesthetic impacts with future potential needs.

The vulnerability assessment phase also accounted for climate change to ensure the New Slussen structure will continue to function during its projected lifetime. SMHI integrated climate projections of sea level rise, temperature and precipitation into its hydrological modelling of Lake Mälaren to understand current and future flood risk. To better understand the actual vulnerabilities of properties and infrastructure neighbouring the lake to flooding, the City of Stockholm and MSB have conducted several detailed studies, which highlighted the flooding risks, sensitivity and interdependencies, and costed potential damages. Cost-benefit analyses demonstrated that the retrofitting work led by the City of Stockholm has monetary benefits for wide range of stakeholders around the lake, thereby supporting the case for them to contribute to the costs. However, in the absence of other policy instruments, there is still an incentive for free riding.

Making a systematic and consistent assessment of infrastructure interdependencies is complex, and uncovering asset vulnerabilities sometimes runs into issues of commercial confidentiality and safety sensitivities. The project lead cited three success factors for the MSB analysis in 2012: the active sharing of information and expertise between the managers of municipalities themselves, transparency regarding the purpose and schedule of the analysis for asset owners, and the possibility for contributors to have their information managed as security classified data (which very few ultimately asked for).

In the absence of national standards for climate-resilient civil engineering and flood protection, stakeholder engagement was used by the City of Stockholm to help set tolerated risk levels. Considering

the strategic importance of the project both for Stockholm and Sweden, significant resources were dedicated to consulting with national, regional and local authorities, and stakeholders (including farmers and water companies in the region) to inform them about the risks and consequences, and to give them the opportunity to influence the final plans in line with their preferences. Special consultations were led on key issues such as the acceptable risk of flooding, and the goals and methods of certain assessment such as the environmental impact assessments of the natural environment and agricultural lands by the lake shores.

The main challenge met by the New Slussen project that is relevant for other climate-resilient infrastructure projects regards the uncertainty on financing. Despite having collected evidence on the benefits of the project to a range of stakeholders, the City of Stockholm has, yet, not managed to get them to contribute to the project's financing. These practical challenges fit into a broader conversation at the national level. The government has appointed a panel of experts, convened by SMHI, to decide on principles for allocating responsibility to finance adaptation measures. The panel's conclusions are due to be released in 2017 and may refer specifically to the New Slussen case.

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ANNEX 5: CASE STUDY - RETROFITTING THE BOSTON CENTRAL ARTERY/TUNNEL (MASSACHUSSETS, USA)

The Massachusetts Department of Transport-Federal Highways Agency (MassDOT-FHWA) Pilot Project 'Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Options for the Central Artery' was carried on between 2013 and 2015 by a team of six experts from the Massachusetts Department of Transport (MassDOT), University of Massachusetts-Boston (UMass), University of New Hampshire (UNH) and the Woods Hole Group (WHG). Its purpose was to assess the vulnerability of Boston's main highway, the Central Artery/Tunnel (CA/T), to coastal flooding, and to develop appropriate adaptation measures. In order to do so, the team designed a new hydrodynamic model capable of simulating potential flooding patterns focusing on the CA/T system but including all of Boston. They identified vulnerable structures under current conditions, 2030 and 2070-2100 scenarios, accounting for different future sea-level rise values and identified a range of structural and operational adaptation measures. The study highlighted the strong interconnectedness of Central Artery's facilities (e.g. electric, ventilation and security systems), such that all structures were prioritised equally.

However, the process to start budgeting for or implementing the adaptation strategies developed by the team has not started in the 18 months following the completion of the vulnerability study. Instead, MassDOT is evaluating cheaper and quicker solutions to protect the highway now and to 2030. Nonetheless, this study seems to have had an impact on the perception of sea level rise as a key threat for coastal infrastructure. Other ongoing infrastructure projects in Boston have used findings from this study for their vulnerability assessments and to help design resilience measures.

I. Project description

The Central Artery/Tunnel Project (CA/T) is a megaproject involving the reconstruction of the Central Artery, which is the main highway through the heart of the City of Boston and a major North-South transportation corridor in New England. Initiated in 1991 and concluded in 2006, the CA/T Project replaced a deteriorating six-lane elevated highway with a new eight-to-ten lane underground highway, two bridges over the Charles River and an extension of Interstate 90 to Boston's Logan International Airport and Route 1A (MassDOT-FHWA, 2015). It cost USD 15 billion in total to build 161 lane miles (259 km) of highway in a 7.5 mile (12 km) corridor. The CA/T handles about 536 000 vehicles per weekday, compared to 75 000 vehicles for the elevated highway that it replaced (Flint, 2015).

Figure 9. Schematic of the Central Artery/Tunnel (CA/T) system (Mass DOT, 2015)

However, there are concerns that the functioning of the CA/T could be compromised by climate-related hazards, notably coastal surges and flooding. The CA/T project design criteria were a 1 000-year flood elevation for tunnel portals and a 100-year flood elevation for all other CA/T structures (the latter in accordance with the 1990 Massachusetts Building Code). However, these design standards did not account for the implications of future sea-level rise on the structure's integrity. All structures in locations subject to wave action were designed with additional provisions for a minimum wave height of 1.5 feet (46 cm). The effects of Hurricane Sandy on New York City and New Jersey in 2012 raised concerns about Boston's vulnerability if faced with a similar event.

Early in 2013, a team of experts from the MassDOT, UMass, UNH and the WHG proposed a vulnerability study of the CA/T against extreme weather events and future climate. The Federal Highway Administration (FHWA) met half of the project's total cost (USD 525 000) under the 'Pilot Projects: Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Analysis Options program'. The other half of the study's budget came from MassDOT.

The initial aims of the MassDOT-FHWA Pilot Project were to (MassDOT-FHWA, 2015):

- assess the vulnerability of CA/T to sea-level rise (SLR) and extreme storm events
- investigate and develop adaptation options in order to reduce identified vulnerabilities
- establish, building on the first two objectives, an emergency response plan for tunnel protection and/or shutdown in the event of a major storm.

The governance of the project involved a wide range of stakeholders, from researchers, federal institutions, to local authorities and civil society. The platforms for their respective contributions were:

- Technical advisory committees, guiding the operations and assisting with modelling and methodology. These committees are composed of MassDOT personnel and experts from government agencies and research institutions (Miller et al., 2014).
- Institutional knowledge meetings, providing assistance for the selection of priority assets and composed of personnel across MassDOT.
- Stakeholder meetings with funders, government agencies, local authorities and NGOs (Miller et al., 2014).

Although the anticipated duration of the project was 18 months, the project lasted seven months longer than expected due to difficulties in identifying and classifying facilities, as well as transferring data into new databases (MassDOT-FHWA, 2015). The current version of the pilot project was delivered to FHWA in June 2015.

II. Vulnerability analysis

The City of Boston is highly vulnerable to coastal flooding due to its geographical location. Sea levels are rising three or four times faster than the global average at the Northeast coast of the United States, where Boston is located (Asbury, H. S et al, 2012). Hallegatte et al. (2013) ranked Boston as the 8th most vulnerable city in the world by risk and relative risk (in percentage of GDP) of coastal flooding. Its vulnerability is likely to increase in the future, due to the rising sea-levels and the projected increased incidence and severity of storm surges. Considering its strategic role in the metropolitan and regional transportation, as well as its function as major channel for evacuation and emergency response in case of extreme events, the Central Artery needs to be well protected against natural hazards. For this purpose, the project team decided to attribute to the CA/T system very low-tolerance for risk of failure (against 1-in-100 and in 1-in-1 000 storm surges depending on structures) in order to achieve the highest level of protection and preparedness. The classification was approved by the MassDOT District 6 Administration, the authority responsible for the CA/T in the Boston metropolitan area.

The project team initially planned to focus its analysis on the most vulnerable assets, but it became clear that the degree of interconnectedness between assets meant that the system had to be analysed as a whole. This conclusion was derived from two parallel data collection and analysis operations. The project team both analysed the existing asset and maintenance management databases (Maximo) and created its own Central Artery Tunnel system Database (CATDB) using asset inventories and elevation surveys completed during field visits. The new CATDB database was designed to complement and triangulate data from Maximo, and provide information on the relationships between different assets and facilities (see table 4). The CATDB classification allowed the team to subsequently develop a more targeted vulnerability assessment for each type of structure.

Table 4. Asset management databases for the Central Artery

Database	Maximo	CATDB
Source	Existing database currently extended to the whole Highway Division	Relational database created by the project team
Main characteristics	- Centralized online asset-management database system. - Includes drainage components, drainage maintenance, mowing, sweeping and road repair. - In the future, may also include other assets such as lighting facilities, information technology components, fence lines, guardrails and pavement markings. - Designed to integrate with other technologies such as GIS and the Massachusetts Management Accounting and Reporting System (MMARS).	- Relational database that identifies, locates and classifies CA/T facilities. - Designed to interface with GIS and Maximo. - Includes manually added data from other MassDOT sources, such as MMIS, and from the field visits. - Classifies facilities into two categories: **Structures**: Buildings or other types of structures located, partially or completely, on or above the ground surface and therefore have at-grade exposures to water infiltration during flood events , e.g. closed caption television cameras, tunnel atmosphere monitoring systems, lighting. Each structure can contain one or more facilities. **Structural Systems**: A collection of vertically or horizontally adjacent structures, only encompassing CA/T facilities. This category highlights the close inter-dependency of adjacent structures' vulnerability to flooding.

Source: MassDOT-FHWA, 2015

The team developed the Boston Harbour Flood Risk Model (BH-FRM) for the vulnerability assessment to simulate the propagation of floods in the Boston area. The team estimated that a more sophisticated approach was needed compared to the "bathtub" approach that had been used in a previous flood mapping of the Boston Harbour (MassDOT-FHWA, 2015). The bathtub approach consists of increasing the water surface elevation values and comparing the result with the elevation of the land, without accounting for the dynamic nature of storm events. The new model was designed to include these storm events. Through the BH-FRM model, the team simulated various flooding scenarios depending on different future sea-level rise values. The inclusion of sea-level rise into their modelling constituted an important innovation since the CA/T design standards had not taken sea-level rise into account (MassDOT-FHWA, 2015).

Given the level of uncertainty concerning future sea-level rise projections, the project team considered a High (H) 2.0 m mean sea-level rise value, Intermediate High (IH) 1.2 m, Intermediate-Low (IL) 0.5 m and Lowest (L) 0.2 m scenario as in Parris et al. (2012). The timeframes analysed for the MassDOT CA/T vulnerability assessment were 2030, 2070 and 2100 (MassDOT-FHWA, 2015).

The team developed its vulnerability assessment by creating several maps of potential flooding patterns using the projected maximum surface elevation and flooding depth, and overlaying these maps with the structures databases (MassDOT-FHWA, 2015).

When evaluating the exposure of the CA/T, the team decided to give the different structures equal priority because of their high level of interconnectedness. Tunnel facilities such as lighting, closed circuit cameras and atmosphere monitor systems could not work in isolation. All needed to be operational to ensure the tunnel's safety. With regards to sensitivity and adaptive capacity, the team also decided that any amount of water intrusion in structures or facilities, no matter how small, could pose a serious threat

due to leakages in foundations, or electrical systems. Therefore, the team affected the maximum level of sensitivity to flooding to all structures and the minimum level of adaptive capacity (MassDOT-FHWA, 2015; Douglas et al. 2015).

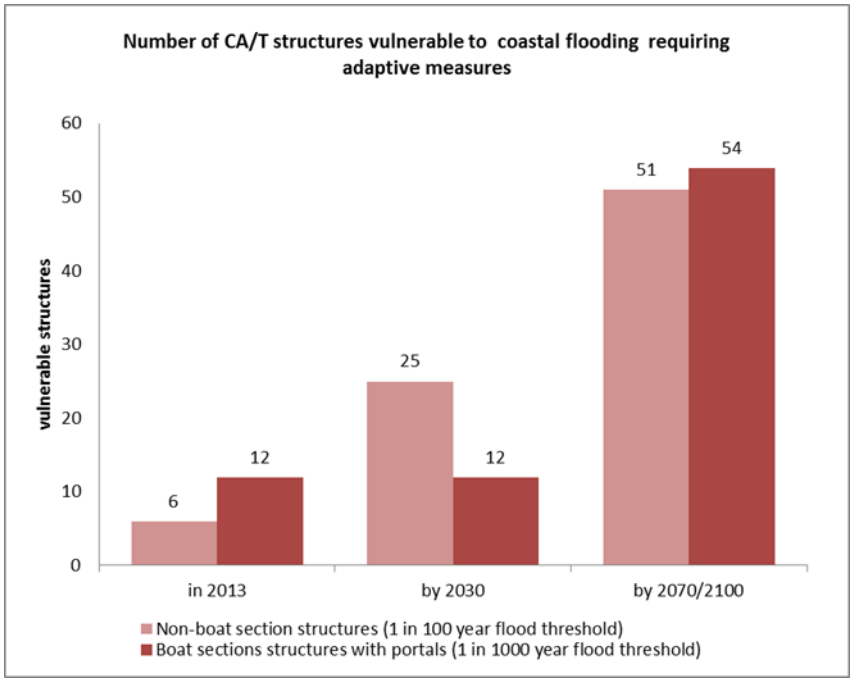
The vulnerability assessment found that, under current climate conditions, 18 structures require adaptive measures and the number of vulnerable structures would grow over time (MassDOT-FHWA, 2015) (Figure 10). The team focused on two types of sensitive structures: non-boat section structures and boat sections with portals.[15] Six non-boat section structures were found to be vulnerable from a 1-in-100 year storm event under current climate conditions, growing to an additional 19 by 2030 and to an additional 26 by 2070-2100, for a total of 51 affected non-boat section structures (MassDOT-FHWA, 2015). Both under current climate conditions and for the 2030 scenario, 12 boat sections with portals appeared to be vulnerable to flooding from a 1-in-1 000 year flood event. The number would reach 54 over the period 2030 to 2070-2100.

The project recommended several hard adaptation measures, both at the local level and at the regional level, in order to provide a level of protection that would meet the desired performance standards for the Central Artery. To adjust adaptation strategies to possible changes in the coastline and to future improvements in climate change understanding, the study recommended re-running the hydrodynamic model every seven to ten years.

In terms of local adaptation measures, the project recommended either the employment of temporary self- supporting barriers and inflatable dams, or the construction of walls and watertight gates depending on the potential depth of flooding. Risk preferences and regulation for protection were different depending on the type of infrastructure, and whether the structure was a non-boat section or a boat-section with portal. This is because the consequences of flooding a tunnel entrance (boat section with portal) would be particularly severe. The critical thresholds used to assess the structures' vulnerability were 1-in-100 year for non-boat sections and 1-in-1000 year flood event for boat sections with portals, in line with the safety standards recommended by the Design Guide for CA/T structures and the 1990 Massachusetts Building Code (MassDOT-FHWA, 2015).

[15] A boat section is a tunnel section that is opened at the top – a paved roadway "floor" with two sidewalls and without a "roof". A boat section with portal is a boat section that either enters into, or exits out of a tunnel at a portal. It differs from an open boat section, which leads into or out of any other type of tunnel section (MassDOT-FHWA, 2015).

Figure 10. Number of CA/T structures vulnerable to coastal flooding requiring adaptive measures



Source: MassDOT-FHWA, 2015

III. Climate resilience measures

The rule of protection for non-boat sections is based on the need to avoid floodwaters reaching the foundations of the structures (MassDOT-FHWA, 2015). Considering that self-supporting barriers can protect against a flood depth of 3 ft (91 cm), experts judged that the use of such barriers could be recommended from 2 ft (61 cm) of flood depth. Once 1-in-100 year flood's depth exceeded 2 ft, experts recommended scaling up safety measures through the construction of walls around the structures' perimeter. The walls' height should be adapted to the level of flooding.

For boat section with portals, the project team could not assess if the surrounding walls could withstand floods or not, and used the ground level around each boat section as the critical elevation threshold. Therefore, for any 1-in- 1000 year flood where the depth exceeds 0.5 feet (15 cm) in the area around the boat section walls, protection measures should be upgraded from inflatable dams to watertight gates (MassDOT-FHWA, 2015).

By applying these rules of protection to the flooding patterns simulated through the BH-FRM model, the project team recommended a series of adaptation measures. For the non-boat section structures, self-supporting temporary barriers would be sufficient to protect the facilities for the 2013 and the 2030 scenarios. However, by 2070-2010, depending on future sea-level rise values, approximately 30 non-boat section structures would need to be protected by flood walls. Concerning boat sections, seven portals were initially found to be vulnerable to current flooding and to require the construction of watertight gates covering the full height of the portal. However, following the publication of the report, MassDOT

examined these seven structures and found that some did not need any protection, while the others could be sufficiently protected by temporary protection measures.[16]

The MassDOT-FHWA project also stressed the importance of combining protection of specific sites with regional adaptation measures, in order to defend flooding entry points (i.e. water arriving from a vulnerable section of coastline) and achieve an optimal level of protection. This combination has the potential to be more cost-effective than relying upon site-level protections alone. However, implementation of collective approaches can be thwarted by coordination and collective action barriers, as well as by conflicting interests and agendas between the stakeholders (MassDOT-FHWA, 2015). The authorities responsible for the implementation differ depending on the scale of the measures: MassDOT is in charge of the installation of the local protections, while state and local stakeholders are responsible for regional adaptation.

By analysing flood risk maps, the team identified two vulnerable points where water could affect the CA/T system that could be suitable for regional adaptation measures under the 2013 scenario and an additional one affecting surrounding neighbourhoods. It projected that the number of vulnerable entry points would increase by an additional 2 by 2070. Some of the possible adaptation measures recommended by the report are the construction of seawalls and natural berms, as well as the improvement of existing infrastructure such as dams (MassDOT-FHWA, 2015).

The pilot project took into account only the entry points that could have affected MassDOT facilities, and the team, for reasons of time and coherence with the objective of the report, did not extend the scope of their analysis to knock-on effects that flooding might have had on other types of infrastructure besides CA/T or on the population.

Since the report's submission in June 2015, MassDOT District 6 Administration has reviewed the recommendations and is considering alternatives to those proposed by the MassDOT-FHWA study for CA/T flood protection. Budget constraints are driving this further evaluation of resilience measures, as explained further in the next section.

IV. Financing resilience

The MassDOT-FHWA project calculated the costs of the recommended adaptation measures using existing civil engineering cost estimates. Protecting non-boat section structures by 2100 would cost around USD 47 million (Douglas et al, 2015). The protection of tunnel entrances under current conditions would cost approximately USD 27 million upfront, with a further USD 150 million required over the course of this century (Douglas et al, 2015). The total cost for local adaptation measures by 2100, USD 224 million, would represent 1.49% of the total cost of the CA/T project. These figures do not include any related maintenance costs and depend on the success of the regional adaptation measures and future climate and model predictions.

The total cost of regional adaptation measures was not estimated, due to the variety of possible solutions applicable to some of the flooding entry points, which entails a broad range of expenditure (MassDOT-FHWA, 2015). However, the report takes one of the two regional adaptation projects deemed necessary in the current scenario as an illustration: the modular seawall recommended for the protection of the Shraffts' parking area. Upfront costs in 2013 reach approximately USD 3-3.5 million, in addition to annual maintenance costs of USD 15 000 (MassDOT-FHWA, 2015: 111). For the 2030 scenario, the capital costs would rise to USD 10-12 million due to the construction of an additional section of 3 500 feet (1 km) (MassDOT-FHWA, 2015: 111).

[16] Personal communication from Steven Miller, MassDOT (June 21st 2016).

The MassDOT-FHWA project also does not include any attempt of quantification of future benefits deriving from the implementation of the adaptation measures, nor an estimation of the potential cost of failing to adapt. This makes it hard to assess the cost-effectiveness of reaching the recommended standards of protection.

The report frames vulnerability to extreme weather events as an imminent risk rather than focussing solely on the potential future effect of climate change, as some of the structures appear to be vulnerable under current conditions. MassDOT may be eligible to apply for federal funding from the FHWA, which can be used for adaptation. This funding could cover up to 80% of the necessary investment costs[17]. But following the review of the report's recommendations by the MassDOT Administration, these were neither formally approved nor funded. MassDOT has instead approved an in-house strategy that aims to provide protection over the next 15 years at a lesser cost, and can be deployed more quickly. This strategy is based on the placement of removable flood walls, the creation of a tunnel emergency flood response plan in case of closing of portals and ramps with removable flood walls, the use of sandbags to protect certain structures, and a rehabilitation program for outfall tide gates (ensuring storm surge does not back into the drainage system). A consulting assignment is currently being approved to assess MassDOT's in-house plan. This situation reflects several factors: the constrained state budget coupled with the need to conduct a more detailed cost-benefit analysis on the permanent adaptation options. In planning for future permanent protections, the BH-FRM modelling may need to be updated.

V. Discussion of success factors and challenges

The MassDOT-FWHA Pilot Project conducted a sophisticated assessment of the vulnerability of the Central Artery of Boston to coastal flooding and elaborated adaptation responses. This analysis highlighted that action was urgently needed under current conditions, and that climate change was strengthening the case for action in the future, especially in light of the highway's importance in everyday metropolitan transportation and in emergency response. Due to its high-resolution modelling and analysis, this study identified vulnerable CA/T structures. Some of these structures were found to require immediate adaptation measures.

One of the main contributions of this study was to highlight the level of interconnectedness of the CA/T system, which makes the whole system vulnerable to closure if one of its constituent parts becomes impassable or damaged by storm surge flooding. The demonstration that each and every facility, such as the CCTV cameras and the atmosphere monitoring systems, was crucial to the functioning of the tunnel, led the team to consider the whole system as equally vulnerable. This consideration was the main determinant for the adaptation measures recommended by the team. This Pilot Project has also pointed out the need for regional adaptation policies across the metropolitan area when dealing with interconnected and extensive assets.

This project identified the need to retrofit parts of the Central Artery infrastructure at a total cost of USD 224 million. This vulnerability study has influenced FHWA and MassDOT policies and activities. The report, for instance, has contributed to upgrading sea level rise as one of the criteria that need to be satisfied in order to address the Massachusetts Environmental Policy Act (MEPA). The MEPA, formulated by the Executive Office of Energy and Environmental Affairs (EEA), mandates state agencies to study and take into account the environmental consequences of their actions, including permitting and financial assistance (EEA, n.d). The Massachusetts Climate Change Adaptation Report (EEA and Adaptation Advisory Committee, 2011) had already stressed the need to explore mechanisms for addressing the potential impacts of climate change (such as sea level rise) as part of EEA's Massachusetts Environmental Policy Act (MEPA) review process. According to the FHWA, information from the vulnerability study can

[17] Personal communication, Becky Lupes FHWA (21st June 2016).

also be used in National Environmental Policy Act (NEPA) reviews consistent with the Climate Guidance developed by the White House Council on Environmental Quality (CEQ) that calls for federal departments and agencies to incorporate climate change considerations into their NEPA reviews (CEQ, 2016).

Another contribution of this project has been the creation and the employment of a hydrodynamic model, the Boston Harbour Flood Risk Model (BH-FRM). This model is capable of simulating flooding patterns while accounting for the dynamic nature of such physical events. This represents an advance when comparing with studies generally conducted both in Massachusetts and in the US on infrastructure vulnerability to climate-related events. Previous vulnerability assessments concerning the City of Boston developed their simulations of flooding, sea level rise scenarios and storm surge either through a "bathtub model" approach or using simple statistical or empirical models. On a national basis, such a level of sophistication in modelling was unprecedented for any study conducted for the Department of Transportation. This type of model has laid the ground for a more sophisticated vulnerability assessment for other coastal facilities in Massachusetts and in general in the US. MassDOT's decision to expand the model to the entire Massachusetts coast and islands is a testimony to this potential (DePaola, 2015). This new two-year project aims at assessing the vulnerability of MassDOT's transportation systems along the whole Massachusetts coastline.

One of the key lessons learnt was that the project could have benefited from more ex-ante planning. The team undertook a tentative process of classification and identification of the facilities, dedicating considerable time to field visits (MassDOT-FHWA, 2015: 114). Most of the visits, however, turned out to be superfluous following the decision to assign the same level of vulnerability to all CA/T structures. It would have saved time if sensitivity had been discussed at the outset. Nonetheless, some of the field observations were ultimately useful for the development of adaptation recommendations, as some of their features were not fully captured in digital data.

Furthermore, the implementation of the study's recommendations is still at an early stage. This is mainly due to the way this project was conceived: the team's purpose was primarily to conduct a vulnerability assessment and suggest possible preventive measures, rather than developing a detailed pathway towards the implementation of adaptation strategies. The vulnerability analysis is very innovative and thorough, while the adaptation strategy suggested is less defined. A stronger collaboration with the MassDOT personnel responsible for the implementation of such measures in the project's scoping and governance may have resulted in a change of emphasis. In particular, a stronger focus on implementation, including the provision of a detailed cost-benefit analysis.

The lack of a cost-benefit analysis represents one of the potential shortcomings of this study. The report quantified the investments needed but not the benefits of those investments. Quantifying these benefits would strengthen the business case for investment in protective infrastructure. MassDOT is currently planning on conducting this analysis by hiring an external consultant.

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