BACKGROUND PAPER

Environmental Change Institute

ADAPTATION OF INFRASTRUCTURE SYSTEMS

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Summary

Infrastructure systems, defined in this paper as conventional "economic infrastructure" (energy, transport, digital communications, water, and waste management), sustain civilizations. Many of these systems are vulnerable to the impacts of climate change such as sea level rise, river and surface water flooding, landslides, wildfires, permafrost melt, droughts, and other extreme events. We estimate that more than 200,000 km of roads are currently exposed to climate-related hazards worldwide which could increase to 237,000 km by 2050 due to climate change, without inclusion of the new highway construction that will take place in that period.

Expansion and modernization of infrastructure systems almost always accompany economic development.[1] It is estimated that US$80 trillion of investment in new and existing infrastructure is required worldwide over the next 15 years.[2] Decisions are being made now that will lock in risks for decades to come, threaten the viability of infrastructure investments, and burden countries with escalating economic and human impacts and repair costs.

The purpose of this background paper is to examine and extend the evidence for adaptation to climate change within infrastructure systems. We review climate risks to infrastructure, the current state of adaptation, and the barriers that inhibit further adaptation action. We highlight key steps that may be taken to adapt existing infrastructure systems to make them more resilient in the face of a changing climate, and examine how, in future, infrastructure can be planned, designed, and delivered to cope with climate change. We recommend a more

About this paper

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comprehensive approach to adaptation of infrastructure systems as part of the overall goal of achieving sustainable infrastructure systems. Enhancing the resilience of infrastructure systems requires action in the following three predominant areas:

1. **Securing performance of infrastructure assets in a changing climate**. Carefully prioritized investments to strengthen and protect infrastructure assets can yield benefits in terms of avoiding damage, disruption, and reconstruction costs that greatly outweigh the investment costs. Engineering design standards and codes need to be enhanced, applied, and enforced to address a changing climate. Performance-based design places the onus on the designer to devise ingenious ways of achieving the requisite levels of performance. Nature-based solutions (NbS) also offer ways of reducing risk that can be adaptable to future change and yield multiple co-benefits. The most cost-effective time at which to prepare assets for climate change is during the initial design or major refurbishment; however, retrofit programs for existing infrastructure will also be required. Therefore, climate change considerations should be integrated throughout the life cycle of asset management systems.
2. **Enhancing system resilience**. Infrastructure systems are important because of the services they provide to individuals, society, and the economy. The ways in which services are provided by infrastructure networks can often be made more resilient in order to cope with, and recover from, extreme and disruptive events, such as through the development and operation of forecasting, warning, and emergency management systems. Diversified supply chains with stocks that are sufficient to cope during an emergency are inherently more resilient than many of today's just-in-time systems. Managing demand for water and energy enhances system resilience and saves the costs and impacts of consuming these resources. Financial instruments such as direct payments and well-designed insurance can help individuals and asset owners to cope during extreme events.
3. **Planning for sustainable infrastructure development**. The greatest opportunities for managing climate risks often exist during the early stages of planning and designing infrastructure systems. Concerns about climate risk and adaptation need to be brought "upstream" in long-term development and spatial planning, and become mainstreamed in development policies and plans from the outset. Climate risks to infrastructure need to be considered on a broad spatial scale in order to open up more resilient options and help to avoid locking in vulnerability. Planning climate-resilient infrastructure development involves long-term systems thinking and exploring diverse options in a range of possible futures to yield better and more sustainable infrastructure worldwide.

Our vision is for adaptation and resilience to be embedded throughout the life-cycle of infrastructure planning, project preparation, finance, design, delivery, operation, and maintenance. This requires a **strong commitment from governments** (national, city, and local), who play leading roles in steering the provision of infrastructure to mainstream sustainability through adaptation. Decision-makers need to recognize that infrastructure assets that may exist for decades, or even centuries, face a very uncertain future. Infrastructure investments need to be designed and implemented to cope with unpredictable threats and extreme events. **This requires design standards and codes of practice to incorporate the effects of climate change**.

Organizations that finance infrastructure, including multilateral development banks, have the opportunity to **promote best practices through standards and sustainability reporting**. Providing finance to investment programs, rather than solely to individual projects, offers greater opportunities to manage climate risks. Infrastructure investors must recognize that physical climate risks threaten the returns on their investments, scrutinize how these risks are being managed, and incentivize adaptation and resilience. The insurance industry can help by applying its statistical, geographical, and engineering expertise to quantify risks and incentivize adaptation.

Making the case for adaptation action **requires a sound evidence base, underpinned by economic analysis, to inform adaptation decisions**. The analysis needs to be proportionate to the scale of the challenge, as well as realistic, given the context. Decisions with the greatest economic and societal implications will require rigorous analysis of the costs of different adaptation options, the benefits of avoided damage from climatic extremes, and the many co-benefits that resilient infrastructure can bring for sustainable development. More routine decisions can incorporate adaptation through the use of codes and best practices. A previous example of the impact of infrastructure failure is the US$5 billion loss to the New York City Metropolitan Transportation Authority during Hurricane Sandy, emphasizing the case for timely adaptation.

Climate risk analysis depends upon in-depth local knowledge of asset location, condition, and the operations that take place on infrastructure networks. A **data revolution** is underway that is providing new information on climate risks and adaptation options for decision-makers. **Technical capabilities** to analyze complex infrastructure systems and pinpoint climate vulnerabilities have advanced rapidly in recent years. However, awareness and capacity among decision-makers to use today's analytical tools must improve if resources for adaptation are to be targeted effectively. International cooperation is required to build capacity where it is most needed.

1 Introduction

1.1 Infrastructure: Critical Networks for Sustaining Civilizations

While there is no unique definition of infrastructure, common categorizations[3,4] almost always include networked systems that deliver services such as energy, water, waste management, transport, and telecommunications. Broader definitions also include social infrastructure, such as social protection systems, healthcare systems (including public health), financial and insurance systems, education systems, and law enforcement and justice. Some definitions extend to also include housing, as well as the buildings in which social infrastructure services are provided. In this background paper, we focus on networked economic infrastructures (energy, transport, telecoms, water, and waste), while recognizing that adaptation of buildings is primarily addressed in the Global Commission on Adaptation's (GCA's) background paper on cities. We emphasize that economic infrastructure systems are complex socio-technical systems because they comprise accumulations of physical technology that are embedded within human systems and are operated on behalf of society.[5,6] This interplay between the physical and the social provides the potential for lock-in, whereby long-lived assets shape future patterns of behavior and development. For example, the construction of highways will affect preferences for transport in private cars[7] and lock-in lower density patterns of urban development.

The fact that virtually all infrastructure services are delivered via complex socio-technical networks has profound implications. While networks yield progressively increasing benefits as they grow in size, they are costly and risky to initiate. Infrastructure provides essential services, such as water and energy, to individuals and businesses. It also enables people to access other services, such as healthcare and education, and participate in the economy by accessing markets and traveling to work. Unreliable infrastructure systems limit the productivity of businesses and public services,[8] add to production costs, and undermine business competitiveness. Infrastructure also protects people from hazards, for example, wastewater treatment limits human contact with pathogens in sewage.

Given the fundamental roles that infrastructure plays, it is not surprising that infrastructure systems have been found to play such cross-cutting roles within the UN Sustainable Development Goals (SDGs), as outlined in Box 1.[9] The SDGs are central to the UN's 2030 Agenda for Sustainable Development, which is being aligned and coordinated with efforts to achieve the Paris Agreement on climate change and the Sendai Framework for Disaster Risk Reduction (SFDRR) (Box 2).

Protective infrastructure systems, such as flood protection schemes, urban drainage, and water reservoirs, are sometimes known as "infrastructure for resilience,"[10] and defend societies from the impacts of climate-related hazards. The social infrastructure of emergency management (e.g., firefighting) can also be thought of as being "infrastructure for resilience." With every passing year, such systems are increasingly stressed as a result of a growing population and the ever-increasing threats of climate change,[11] and need to be adapted to be able to cope with changing and more uncertain threats. However, the role of infrastructure in adaptation extends far beyond the need to strengthen infrastructures such as flood defenses that provide protection against climate hazards. In view of a highly uncertain future, all infrastructure must be planned, designed, and operated flexibly to cope

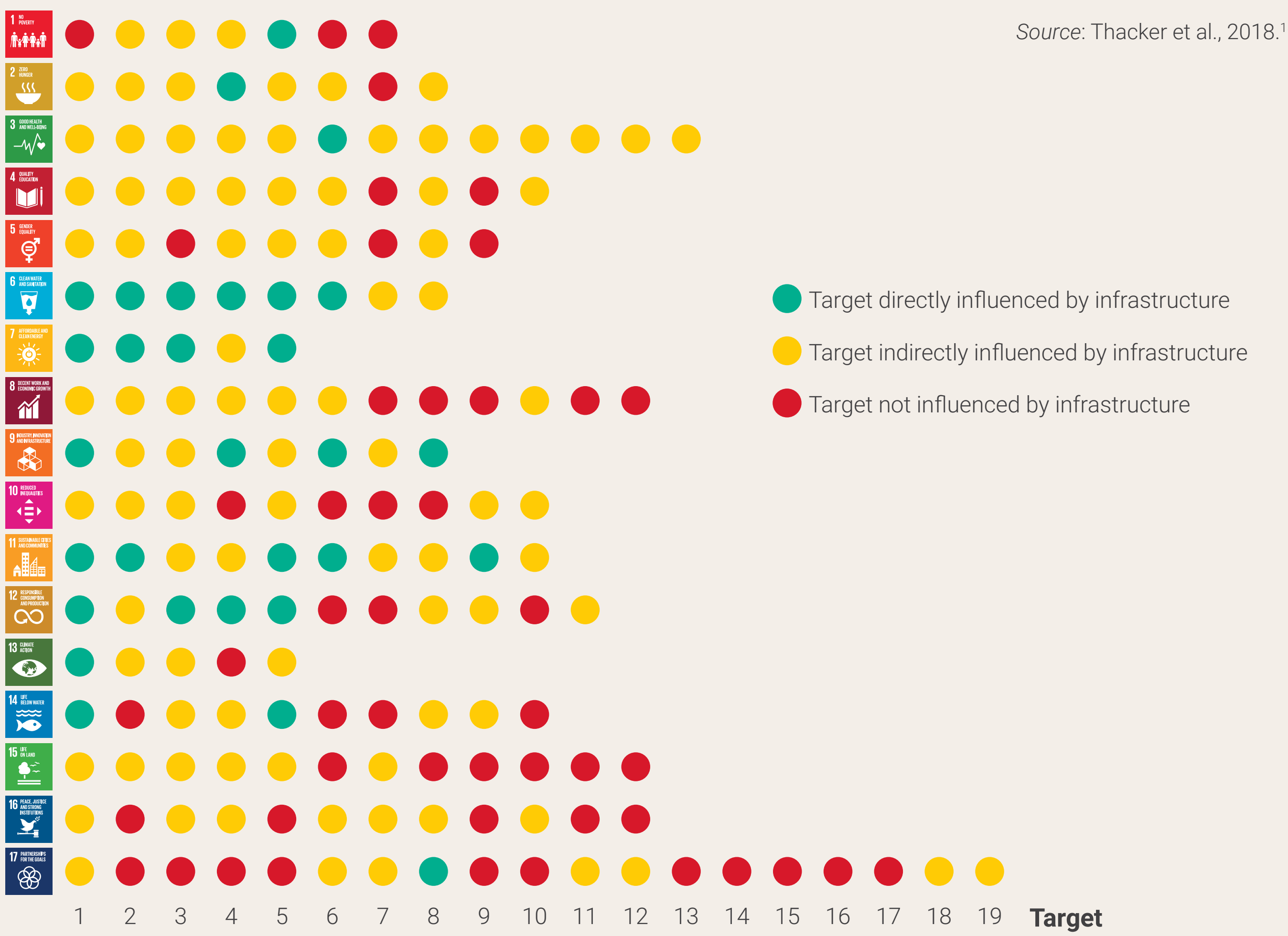
BOX 1 The Role of Infrastructure in the UN SDGs

Thacker et al.[12] analyzed the multiple links between infrastructure systems and the UN SDGs (Figure 1). The provision of infrastructure services was found to either directly or indirectly influence the attainment of all SDGs, including 72 percent of the targets. This includes all targets for SDG 3 (Good Health and Wellbeing), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 11 (Sustainable Cities and Communities).

The importance of infrastructure may seem less obvious for SDG 5 (Gender Equality). However, in rural Africa, for example, infrastructure shortfalls impact women most severely, as 87 percent of all transport occurs on foot, which women are more likely to do than men.[13] The provision of accessible energy and water supply infrastructure in communities would underpin a more equitable pursuit of economic, social, and leadership activities, and limit the time spent in unpaid domestic work.[14]

As well as the requirement for infrastructure to deliver the SDGs, the targets of the SDGs provide guidelines on *how* infrastructure should be delivered by means that avoid undesirable impacts and share the benefits of infrastructure equitably. This includes targets to adapt and improve the resilience of cities and human settlements (11.B) and to strengthen resilience and adaptive capacity to climate-related hazards and natural disasters (13.1).

FIGURE 1 Influence of Infrastructure Systems on the Sustainable Development Goals and Targets



Source: Thacker et al., 2018.[15]

BOX 2 Synergies Between the 2030 Agenda for Sustainable Development, Paris Agreement, and SFDRR

Box 1 illustrates the fundamental role that infrastructure plays in delivering the SDGs, which are central to the **2030 Agenda for Sustainable Development**. Other UN agreements and commitments also relate significantly to infrastructure systems, notably the Paris Agreement on Climate Change and the SFDRR.[16]

The **Paris Agreement** committed countries to undertake ambitious efforts to combat climate change and adapt to its effects, with enhanced support to assist developing countries to do so. Parties to the Paris Agreement agreed to a long-term goal for adaptation, namely to increase the ability to adapt to the adverse impacts of climate change, as well as foster climate resilience and lower greenhouse gas emissions. Transformation of infrastructure systems is central to both mitigation of greenhouse gas emissions and adaptation to the impacts of climate change. Therefore, nationally determined contributions (NDCs), which are at the heart of the Paris Agreement, should demonstrate how infrastructure will be decarbonized and adapted to the impacts of climate change.

In the context of the Paris Agreement, potential synergies and trade-offs between mitigation and adaptation have been widely recognized.[17,18] Adaptation may involve improving standards of carbon-intensive infrastructure construction work, noting that concrete and steel production is also set to make a proportionately increasing contribution to global greenhouse gas emissions once the energy sector has been decarbonized.[19] On the other hand, well-designed adaptation can also contribute to mitigation, for example, by using low-carbon construction materials and adopting NbS that sequester carbon as well as enhance the climate resilience of infrastructure systems. Further advancing the coherence between NDCs and the 2030 Agenda can help to place climate action firmly into a long-term development pathway that aligns national development priorities with the objectives of the Paris Agreement.

The **SFDRR** provides further motivation for action to enhance the resilience of infrastructure, in particular through the target to substantially reduce disaster damage to critical infrastructure and disruption of basic services by 2030. Opportunities for synergies arise through a consideration of National Adaptation Plans and National Disaster Risk Reduction Strategies, including instruments such as the Sendai Framework Monitor. Hence, there is a strong case to be made for examining how best to leverage advocacy, policies, programs, implementation mechanisms, multi-stakeholder action, resources, and partnerships for both the SDGs, disaster risk reduction, and climate action.

with climate change, emphasizing the need for *resilient infrastructure*.

1.2 Why is Infrastructure a Priority for Adaptation?

Infrastructure systems have several characteristics that make them priorities for climate change adaptation, including:

1. **Infrastructure networks provide critical services for society and the economy**. Failure of infrastructure networks can cause major societal and economic disruption, which can spill over from where the climate hazard hits to have wider impacts. For example, in England, eight times as many properties (20 million) are at risk of being impacted by utility failure during a flood event than are at risk of direct flooding from rivers and the sea (2.4 million).[20] Adaptation is needed to minimize the potential for impacts on this scale.
2. **Infrastructure networks are geographically extensive resulting in global exposure to climate hazards**. Due to their function to connect people and resources, infrastructure networks are inevitably distributed over large spatial domains. These places are almost inevitably exposed to some climate hazards such as flooding, storms, droughts, heatwaves, wildfires, landslides, and permafrost melting.
3. **Some infrastructure systems provide protection against climate hazards**. Flood protection systems

(including natural protection systems such as mangroves, saltmarshes, dikes, levees, seawalls, and barriers) are inadequate in many places[21] and will need to be further adapted to cope with future climatic conditions.[22,23] Water storage (in groundwater and reservoirs) helps to manage climatic variability and prolonged droughts.

4. **Infrastructure increasingly operates as an interdependent "system-of-systems."** This means that there is potential for cascading failures and systemic risks.[24] Some dependencies are simple (e.g., energy companies need water to cool thermal power plants, and water companies need energy to pump water), whereas others are much more complex.[25] The sluggish economic recovery of Puerto Rico after Hurricane Maria in 2017 reflects the extent of the damage to the power network and other complementary systems.[26]

5. **Investments in infrastructure lock in patterns of development and exposure to climate hazards for decades to come**. Most infrastructure assets are intended to last for a long time, so will experience the effects of climate change. They are inherently difficult and costly to adapt. Moreover, infrastructure investments can lock in patterns of economic development, particularly via the interplay between infrastructure development and urbanization. This means that infrastructure investment decisions may be practically irreversible. It is extremely important that climate risks and adaptation plans are considered early in the infrastructure planning process and, where possible, implemented flexibly to avoid irreversible decisions that may be regretted in the future.

6. **Infrastructure makes an essential contribution to the human and institutional capacity that is required for societies to make the right adaptation choices**. Public services and institutions depend on infrastructure. Public buildings and those who work in them cannot operate without infrastructure. This is critically important during emergencies when governments have to coordinate evacuation and recovery. However, in the longer term, adaptation will rely on human capacity and effectively functioning institutions, which could be impaired by inadequate infrastructure services.

Factoring in adaptation, and questions of resilience more broadly, can open up thinking about the co-benefits that resilient infrastructure can provide for people and communities.

2 Physical Climate Risks to Infrastructure Systems

Networked infrastructure systems represent particular points of vulnerability to climate change due to their central importance to the functioning of economies and societies.[27] Dependence on infrastructure is rapidly growing and changing, for example, in the ubiquitous reliance on information and communication technology. Societies, economies, and infrastructure networks are increasingly interdependent owing to the digitization of societies worldwide. Information and communication technologies are now embedded in all other infrastructure sectors and have led to complex interdependencies between sectors, with the potential for cascading failure.[28] The increasingly ubiquitous dependence on electricity as the predominant energy vector for modern societies, which is partly a consequence of action to mitigate carbon emissions, further increases these interdependencies.

Meanwhile, technological trends towards decentralization, such as via the widespread uptake of distributed renewable energy generation technologies (photovoltaic panels and wind power), may enhance the resilience of infrastructure networks.[29,30] However, the benefits of decentralized technologies are constrained because they are embedded within multi-scale coupled socio-technological systems, that require governance schemes to establish infrastructure policies and priorities, mobilize finance, and procure, operate, and regulate infrastructure networks.

The location, design, and operation of infrastructure will determine how societies are impacted by the risks of climate change. This includes the following infrastructure risks that are related to climate hazards (see Table 1):

- **Direct climate damage to infrastructure assets**. Climate change is likely to exacerbate damage to infrastructure networks due to floods, storms, extreme temperatures, wildfires, landslides, permafrost melting, bridge scour, coastal erosion, and other environmental hazards. These hazards may result in assets being completely destroyed or badly damaged in ways

TABLE 1 Example of Climate Hazards to Infrastructure Sectors

	FLOODS	DROUGHTS	HEATWAVES	(WIND) STORMS	GEOHAZARDS (INCLUDING SUBSIDENCE AND LANDSLIDES)	PERMAFROST MELT	WILDFIRES
Water and wastewater	✓✓	✓✓	✓		✓		
Transport	✓✓		✓	✓✓	✓✓	✓✓	✓✓
Energy generation	✓✓	✓	✓	✓		✓✓	✓
Energy distribution	✓✓		✓	✓✓	✓	✓✓	✓✓
Flood and coastal defenses	✓✓			✓	✓		
Solid waste	✓		✓				✓
ICT	✓✓		✓	✓✓	✓		✓✓

Adapted from: Dawson et al. 2016.[31]

Notes: A single tick denotes a relationship, a double click denotes a strong relationship. These do not consider dependencies between infrastructures.

that render them inoperable and costly to replace or repair. For example, in 2018, the total global economic impact of natural hazards alone was US$160 billion, of which 78 percent was climatological, 14 percent was hydrological and 8 percent was geophysical.[32] Climatological impacts may occur as sudden shocks requiring costly replacement or repair, or as chronic impacts, such as the effect of soil shrinkage on buried pipes or permafrost melting in the Arctic, that materialize over prolonged periods.

- **Climate disruption to the operation of infrastructure networks**. Damage to infrastructure assets from climate risks leads to service disruption. However, disruption may occur even without direct damage to infrastructure assets. Ships may be unable to navigate or dock in ports during extreme storms. Drought-induced low flows and increased water temperatures in rivers mean that thermoelectric power plants that rely on cooling water will have to shut down. Reservoirs that run dry during prolonged droughts will threaten water supplies and hydropower production.

Climatic disruptions to infrastructure services impact users of these services, who may be located far from where the climate hazard actually hit.[33] These impacts may ripple through the economy via knock-on effects on supply chains.[34] Some examples of these economic impacts are described in this background paper.

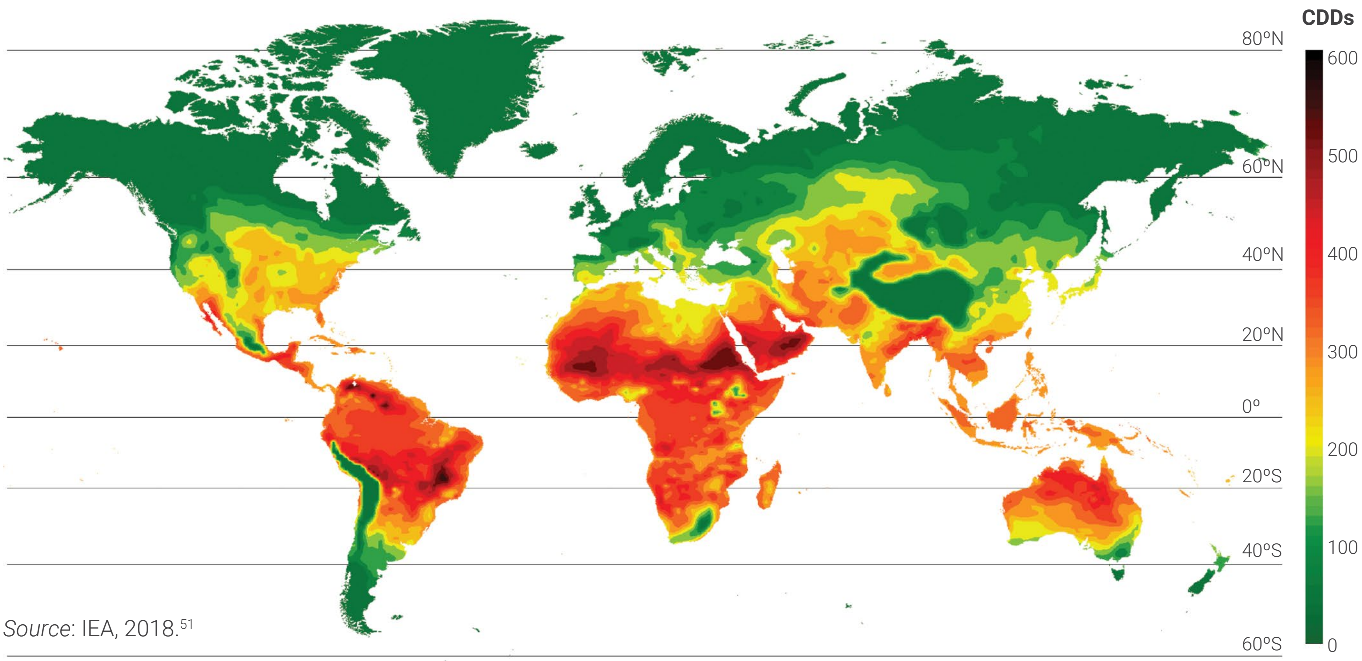
- **Infrastructure-induced exposure to climate hazards**. Infrastructure enables development in hazardous locations such as floodplains and mountain sides. More than half a century ago, Gilbert White[35] identified how construction of flood protection systems promoted further urbanization, which could ultimately increase flood risk (the "levee effect"). Construction of transport infrastructure opens up places for development, increasing exposure to climate hazards. Increased exposure, in particular of urban areas, is an inevitable consequence of development; however, decisions about infrastructure often determine where and how development takes place and, hence, the extent of the adaptation required in the future. These development patterns further influence the provision of infrastructure.

BOX 3 Examples of the Impacts of Climatic Extremes on Infrastructure Systems

- Heatwaves in 2003 and 2009 disrupted cooling water supplies to nuclear power plants in France,[36] significantly decreasing the French nuclear power generation level and resulting in electricity being imported from neighboring countries. In 2009, one-third of all nuclear power stations in France, the biggest European electricity exporter, were put out of action.[37]
- In 2005, Hurricane Katrina left 2.7 million customers without electricity in the U.S. states of Florida, Louisiana, and Mississippi. Infrastructure was also severely affected, with 72,447 utility poles destroyed, 8281 transformers and 1515 transmission structures damaged, and 300 substations offline. Furthermore, 3 million telephone lines in Alabama, Louisiana, and Mississippi were damaged.[38]
- The climate and ecology of California create a landscape that is prone to frequent and intense wildfires. Two of the most destructive wildfires in the state's history occurred in San Diego, namely the Cedar Fire in 2003, which burned 1100 km^2 of land and destroyed 2820 structures, and the Witch Fire in 2007, which burned 800 km^2 of land and destroyed 1650 structures and 56 miles of electricity lines. The cost of the total economic damage from the county fires exceeded US$1.5 billion.[39]
- The 2011 floods in Thailand damaged or destroyed 1700 roads, highways, and bridges, costing US$4.5 billion (THB139.0 billion). Airports across Thailand were also hit, including in Bangkok. The city's secondary airport (Don Mueang) was forced to close in October 2011 after floodwater crept into the main terminal building and over the facility's runways. The president of Airports of Thailand reported that approximately US$4.8 million (THB150.0 million) was required to repair the runway.[40,41] Flood damage to manufacturing plants disrupted supply chains around the world.
- During Hurricane Sandy in 2012, the New York City Metropolitan Transportation Authority sustained roughly US$5 billion in damages to the city's infrastructure and lost revenue.[42,43] A total of 7.5 million people were left without power[44] and the electricity sector propagated risks to other sectors.[45]
- In 2017, Hurricane Harvey disrupted crude oil refining operations in Texas, via flooding and power outages, affecting an estimated capacity of 2.4 million barrels, representing 13 percent of the country's total refining capacity.[46] These disruptions also resulted in increases in gasoline prices. In October 2018, Hurricane Michael caused a 42 percent reduction in the Gulf of Mexico crude oil production and one-third of natural gas output in one day.[47]
- Although the full extent of the damage from the devastating cyclone, Idai, in south eastern Africa has yet to be calculated, the UN estimates approximately US$1 billion (R14.6 billion) worth of damage to infrastructure due to the cyclone.[48]

The impacts of climate-related extreme events that have been observed in recent years provide an indication of the large-scale and possible implications of climate risks to infrastructure (Box 3). These events can only be attributed to anthropogenic influence on the climate in probabilistic terms,[49] and represent a small number of high-profile examples of the many ways in which climatic extremes can impact infrastructure systems. Further insights can be gained from "what-if" scenario analysis of these disasters, such as what would have happened if the flood had been higher, or had struck a different place or at a different time?[50] Less dramatic impacts of climate change, such as desiccated soils resulting in damage to buried infrastructure, are more commonplace and may accumulate greater impacts in the long term.

FIGURE 2 Projected Increase in Cooling Degree Days (CDDs), 2016–50



Source: IEA, 2018.[51]

2.1 Climate Drivers of Demand for Infrastructure Services

Climate change will influence the demand for infrastructure services. Increasing temperatures will change patterns of demand for energy, shifting from heating in winter to cooling in summer (Figure 2).[52] The term cooling degree day (CCD) refers to the extent to which the mean temperature exceeds a defined benchmark, in this case 18°C. The International Energy Agency (IEA) estimates that in a scenario based on current climate policy ambition (the "Baseline Scenario"), CDDs will increase by an average of around 25 percent by 2050 at the global level. This would lead to a threefold increase in energy demand for cooling in that time period, from 2020 TWh in 2016 to 6200 TWh in 2050, all in the form of electricity. The share of cooling in total energy consumption in buildings would more than double from 6 to 14 percent. Demand for space cooling can account for a large share of the increase in peak electricity demand, a critical factor in determining overall capacity in an electricity generation system, as it represents the highest level of demand measured over a period of time. During extreme heat events, cooling demand has been estimated to represent more than 70 percent of peak residential demand in some cases. Increased and prolonged peak electricity demand, such as during extreme heat events, can create risks for energy system resilience if there is an insufficient capacity to meet the elevated demand, or if higher demands are placed on equipment, such as transformers in electricity distribution systems, which are called on to operate at higher and prolonged levels. In the case of extreme heat, high temperatures can reduce the efficiency of the equipment itself.

Increasingly arid conditions, caused by a combination of higher temperatures and changing patterns of precipitation, will drive greater demand for irrigation water. Hot and dry climatic conditions are also associated with increased domestic, industrial, and agricultural water use,[53,54,55,56] though per capita water consumption in water-scarce regions varies enormously, which further highlights the need for demand management as an adaptation strategy.

2.2 Quantifying Climate Risks Related to Infrastructure

While adaptation may provide opportunities and co-benefits, the primary benefit of adaptation is the avoided or reduced damage from impacts of climate change. Thus, quantification of the required degree of adaptation and its associated benefits, requires projections of climate impacts. As climate impacts materialize in various ways in different places, we require methods that can explore a wide range of possible future conditions, including many different possible extreme events. Risk analysis provides such a framework, as it entails systematic analysis of the distribution of possible climate-related hazards, combined with mapping and quantification of exposure and vulnerability to climate hazards, should they materialize. Estimates of climate risk can be wrapped within a framework of uncertainty analysis, to explore the implications of uncertainty regarding future climatic and socio-economic changes.[57,58]

Quantified risk analysis has many limitations, particularly in terms of the data required, our partial understanding of the ways in which climate impacts materialize, and inevitable uncertainties about the nature of future changes.[59] However, the capacity for performing risk analysis that pinpoints vulnerabilities and provides the basis for proportionate adaptation action is advancing rapidly.[60] Further improving these methodologies and enhancing the capacity for their uptake worldwide is one of the greatest adaptation opportunities.

Climate risk analysis for infrastructure systems (Figure 3) involves combining:

- Climate hazard information (e.g., extreme precipitation[61] or the wind speed of possible storms);
- The exposure of infrastructure assets (i.e., whether they are located in places that could potentially be impacted by one or more climate hazards);
- The vulnerability of infrastructure assets (in this context, “vulnerability” refers to the sensitivity of the asset to a hazard of given severity, e.g., the depth of flooding an electricity substation can withstand before it ceases to function);
- The connectivity of infrastructure assets to each other to form networks, to other infrastructures to form systems-of-systems, and to infrastructure users to deliver services;[62]
- Quantified understanding of the ways in which the system may be operated and adapted during disasters (e.g., provision of back-up facilities, rerouting traffic down other roads, determining the speed at which damaged assets can be brought back online);
- Socio-economic data on the use of infrastructure and the services being delivered (e.g., how much freight passes through a port each day or how many people a wastewater treatment plant serves); and
- Data on economic interdependencies is crucial to understand the potential for wider economic disruption. Although a production site may not be directly impacted, analysis of disruptions in its supply chain will enable understanding of why it cannot obtain the supplies it needs, or provide customers with its service products.

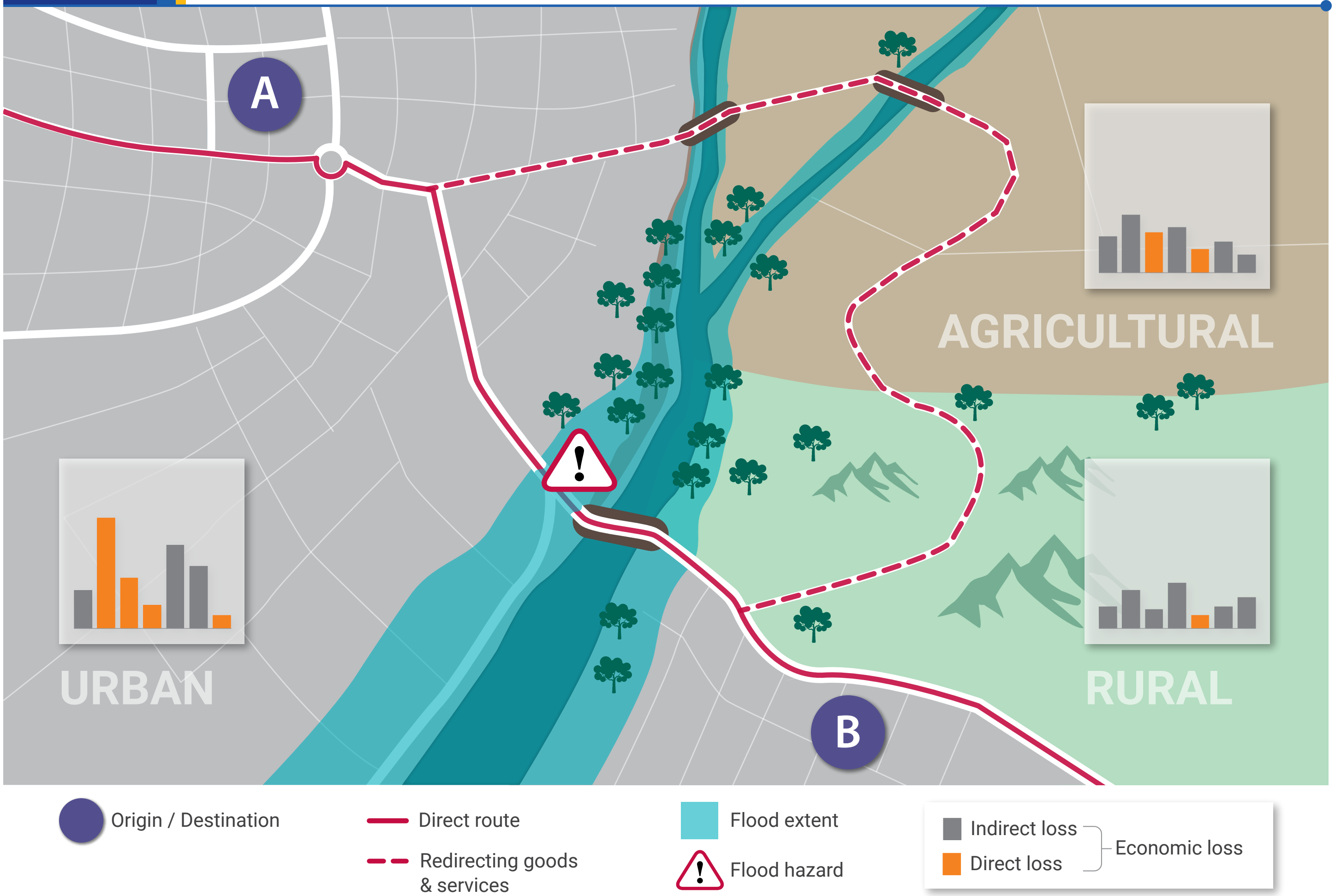
Each of these pieces of information can be mapped in order to calculate the economic impact of climate risks for a given scenario.[63] This type of analysis can also help to quantify social impacts (e.g., how damaged road transport can affect the accessibility of health and social services) and facilitate benefit-to-cost and trade-off analyses for risk management.[64,65]

Key challenges for assessing climate risks to infrastructure include, but are not limited to, defining the system and its dependencies, failure modes and associated interactions, data availability and reliability, uncertainties and their quantifications, projection of asset inventory, and consequence analyses, projections, and economic valuations.

The risk analysis framework outlined above particularly applies to network infrastructure such as energy, transport, telecommunications, and piped water supplies and sewage systems. Some distributed infrastructures, such as tube wells for water supply or household/village-scale renewable energy that does not rely so strongly on physical networks, can be analyzed as a set of independent point assets. Large water infrastructure, such as dams, also operate as systems; however, connectivity is provided via river networks and the associated hydraulic infrastructure, thus the approach to modeling and risk analysis involves explicit representation of the hydrology of river basins as well as the operation of the hydraulic infrastructure.

Risk analysis involves repeating many variants of the chain of events from materialization of a climate hazard, impacting upon an infrastructure network, and subsequent wider economic impacts. Analysis of the full range of possible severities and locations of a hazard, particularly its spatial pattern, is required to estimate climate risk.

FIGURE 3 Diagrammatic Representation of Climate Hazards, Infrastructure Exposure, Infrastructure Service Disruption and Economic Impacts



While exhaustive testing of all combinations is not feasible, a thorough risk analysis will extensively sample plausible scenarios. Examination of the statistical dependence between climate hazards in different locations, as well as between multiple different hazards, will provide a more thorough understanding of the spatial and temporal trends of climate risks.

Climate risk will change in the future for a variety of reasons. A risk analysis provides a “snap shot” of risk that is conditional on assumed climate and socio-economic exposure and vulnerability. The analysis can be repeated to demonstrate the effect of potential future changes, such as sea level rise, which increases the risk of coastal flooding, or urbanization, which can increase exposure to climate hazards. This will help decision-makers to understand how risks can evolve under different scenarios. Adaptation actions strengthen infrastructure assets, and enable better planning of, for instance, urbanizing floodplains, or managing the demand for water, which can be included in the risk analysis to test their effectiveness at reducing flood risk.

2.3 Assessments of the Scale of Climate Risks to Infrastructure and the Benefits of Adaptation

There have been many qualitative reviews of climate risks to infrastructure systems,[66,67,68,69,70] some examples of which are provided in Table 2. Quantifying these risks is much more challenging; however, rapid advances in geospatial datasets and computational capacity are increasingly enabling detailed analyses of climate risks to infrastructure networks at very large scales (see Box 4),

TABLE 2 Illustrative Impacts of Climate Change in Different Infrastructure Sectors

	TEMPERATURE CHANGES	SEA-LEVEL RISE	CHANGING PATTERNS OF PRECIPITATION	CHANGING PATTERNS OF STORMS
ENERGY	Reduced efficiency of solar panels. Reduced output from thermal plants due to limits on cooling water temperatures. Damage to grid: wires and transformers. Increased demand for cooling.	Inundation of coastal infrastructure, affecting generation, transmission and distribution.	Change in output from hydropower generation. Disruption of energy supply due to flooding. Damage to grid from increased vegetation. Insufficient cooling water.	Damage to assets: e.g., transmission and distribution networks; wind turbines.
TRANSPORT	Melting road surfaces, expansion of bridge decks and buckling railway lines. Damage to roads due to melting of seasonal ground frost or permafrost. Changing demand for ports at open sea routes due to melting of arctic ice.	Inundation of coastal infrastructure such as ports, roads or railways.	Disruption of transport due to flooding: damage to bridges and culverts from flooding. Damage to road bed for non-paved roads. Changing water levels disrupt transport on inland waterways. Landsliding induced by changing rainfall.	Damage to assets, such as bridges. Disruption to ports and airports.
TELECOMS	Increased cooling required for data centers.	Inundation of coastal infrastructure, such as telephone exchanges.	Flooding of infrastructure. Damage to infrastructure from subsidence.	Damage to above ground transmission infrastructure, such as radio masts.
WATER	Increasing demand for water (e.g., for irrigation). Increased evaporation from reservoirs: change in water quality that can impact ecosystems. Increased requirement for additional water and wastewater treatment.	Inundation of coastal infrastructure. Salinization of water supplies.	Decreased and more variable water available for use. Increased risk of river embankments being overtopped or damaged.	Damage to assets. Increased stormwater discharges into sewers.
SOLID WASTE	Increasing incidence of fires in landfills. More frequent waste collection required to reduce problems with vermin and odor.	Erosion of coastal landfill. Increase in waste arising due to flood events.	Flooding of treatment facilities and landfill sites.	Disruption to waste transport (land and marine).

Adapted from: Cardona et al., 2015.[71]

BOX 4 Permafrost Melt and Damage to Infrastructure

Across much of the Arctic region, infrastructure and its dependent communities sit on top of a thick layer of permafrost that has stabilized the ground for millennia. However, this frozen soil is melting due to rises in global temperatures,[72,73,74] causing significant damage to settlements and infrastructure networks.

Hjort et al.[75] recently reported that nearly 4 million people, constituting approximately 75 percent of the current population in the Northern Hemisphere permafrost area, and 70 percent of current infrastructure in the permafrost region are located in areas with high susceptibility for thaw of near-surface permafrost by 2050. This high hazard zone entails more than 36,000 buildings, 13,000 km of roads, and 100 airports. Furthermore, 45 percent of globally important hydrocarbon extraction fields in the Russian Arctic are in regions where permafrost melt may lead to substantial ground instability and severe damage to the built environment. There is also considerable risk for the central oil and natural gas transportation routes, as 1590 km of the Eastern Siberia–Pacific Ocean oil pipeline, 1260 km of the major gas pipeline originating in the Yamal–Nenets region, and 550 km of the Trans–Alaska Pipeline System are located within the highly vulnerable area. The Yamal–Nenets region is particularly important, as it is the primary natural gas extraction area in Russia, and provides the European Union with more than one-third of its pipeline imports.

Unfortunately, even substantial cuts in global greenhouse gas emissions would not result in significant changes for infrastructure risks from permafrost melt by 2050. Hjort et al.[76] reported that the most critical Arctic infrastructure will remain at risk of permafrost melt, even if the Paris Agreement target of 1.5°C of warming is achieved. Thus, adaptive measures such as insulation of infrastructure, refrigeration with thermosyphons (passive heat exchangers), and designing structures to better absorb ground surface elevation changes from subsidence or heave should be taken to prepare for the challenges of melting permafrost.[77]

even at the global level.[78,79] While the global picture is not yet complete, it can be supplemented with recent national and subnational studies. The findings presented here combine evidence from previous studies along with new analyses for the GCA.

2.3.1 TRANSPORT INFRASTRUCTURE

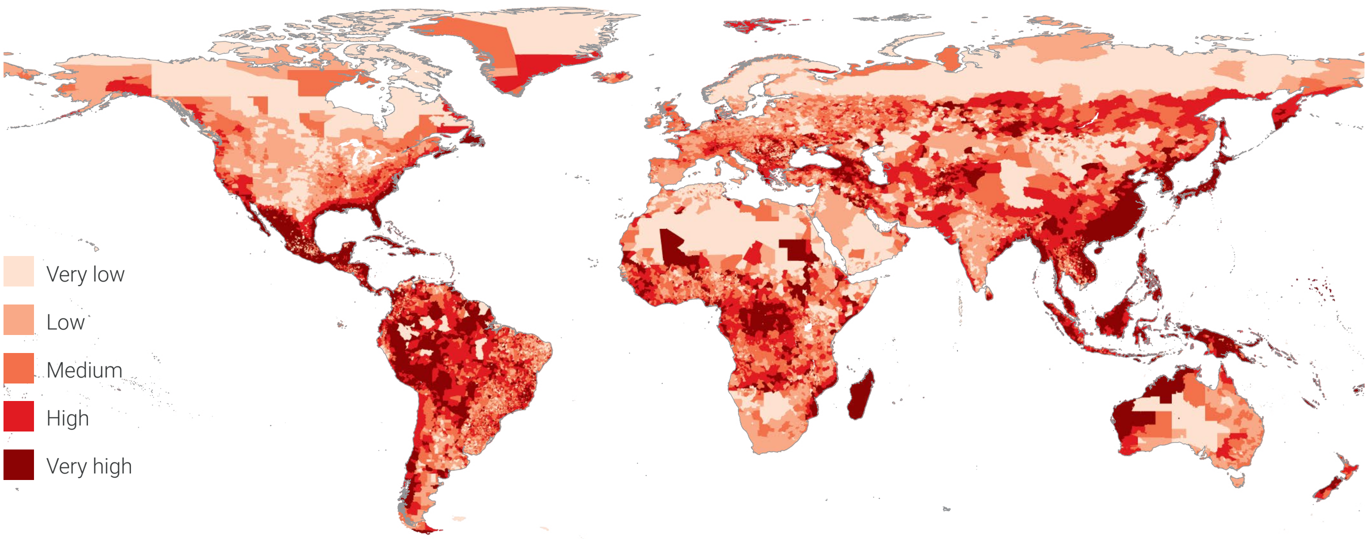
Climate risks to the transport sector were extensively reviewed by the International Transport Forum (ITF).[80] Here, we report on a recent global-scale analysis that has sought to quantify risks to transport infrastructure (Figure 4), which we have extended to assess the future effects of climate change.

2.3.1.1 Road and rail infrastructure

At present, the greatest exposure of road and rail infrastructure to climate hazards is to surface flooding, followed by tropical cyclones and river flooding (Figure 5).[81] Surface flooding is caused by intense rainfall, resulting in local accumulations of water. In this background paper, assets are only considered to be exposed when the probability of occurrence of the hazard exceeds the assumed design protection standards of the assets. For coastal and river flooding specifically, we only assume that infrastructure assets are exposed and the area inundates if the severity of the hazard exceeds the design standard.

High-income countries have the greatest cumulative length of transport infrastructure, followed by upper-middle-income and lower-income countries (Figure 6). However, due to greater flood protection standards for river and coastal flooding, high-income countries have fewer kilometers exposed.[82] Many of the areas of highest exposure in Figure 4 align with high cyclone hazard areas such as the Caribbean, the U.S. Gulf and East coast, Eastern China, South Asia, and Japan. Riverine flooding is the predominant climate risk in low-income and lower-middle income countries, with Africa responsible for the largest share. On the other hand, Europe and central North America experience major exposure to surface flooding. On a country level, results show that, in absolute terms,

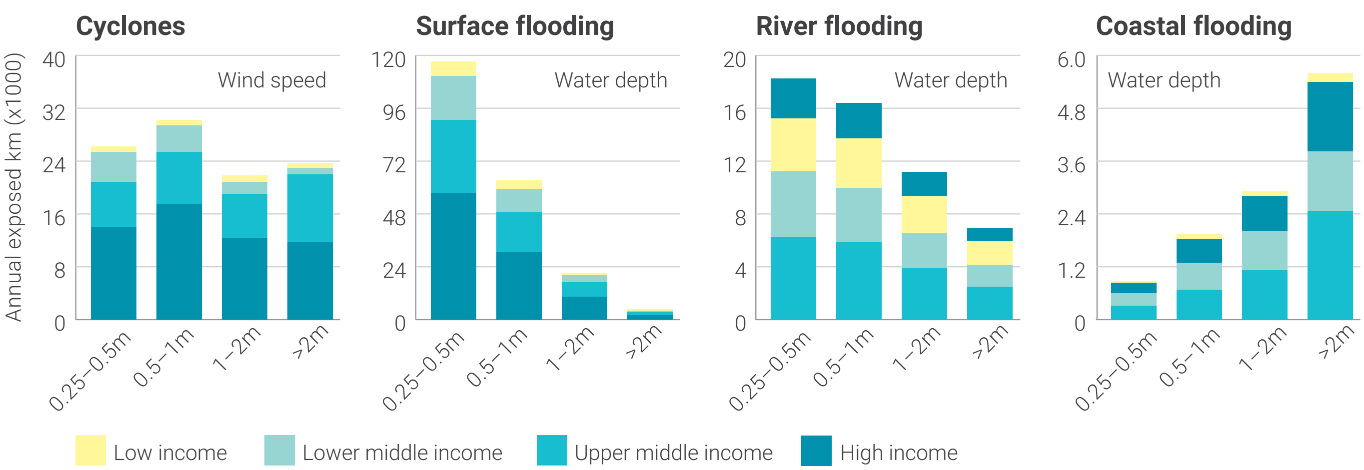
FIGURE 4 Global Transport Infrastructure Exposure to Flood Hazards



Notes: The classification is based on 20th percentiles of road and rail assets that are exposed to flood hazards.

Source: Koks et al., 2019.[83]

FIGURE 5 Exposure of Road and Rail Infrastructure



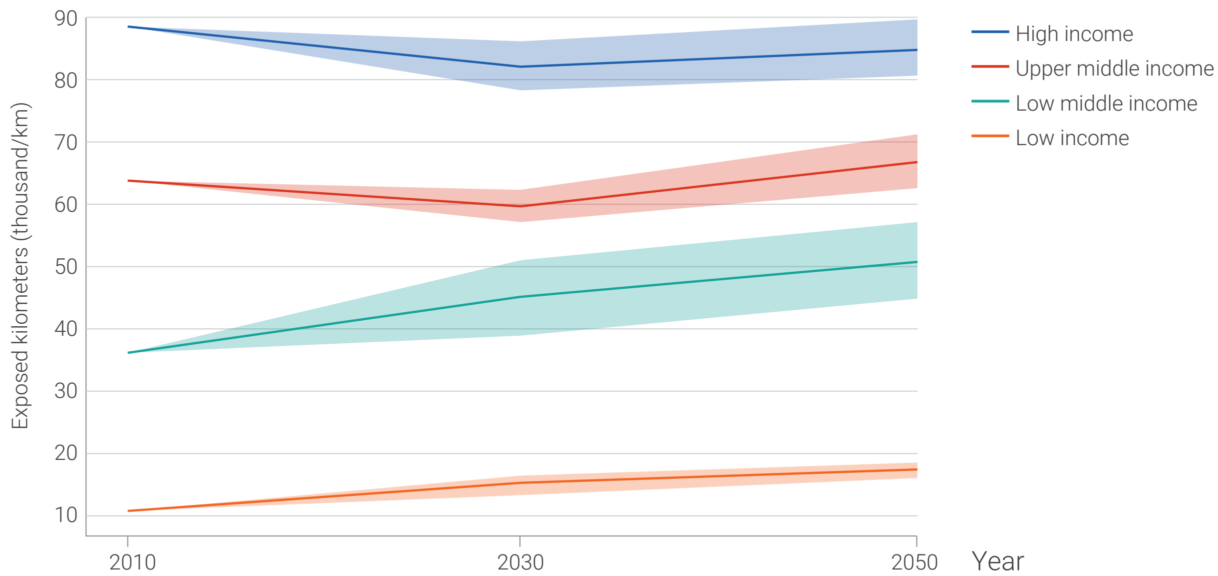
Notes: Graphs depict exposure for four income groups and per flood hazard intensity band.

Source: Koks et al., 2019.[84]

multihazard exposure is greatest in Japan and China, while in relative terms, South Sudan (2.1 percent) and Madagascar (1.4 percent) have the highest multihazard exposure to their transport infrastructure. These high levels of exposure are primarily driven by fluvial flooding and cyclones for South Sudan and Madagascar, respectively.

We estimate that worldwide more than 200,000 km of roads are currently exposed to climate-related hazards, which could increase to 237,000 km by 2050 due to climate change, without including the new highway construction that will take place in that period. We estimate global expected annual damage (EAD) from direct asset damages between US$3.1 billion and US$22 billion, of which approximately 73 percent is expected to be caused by surface and river flooding. Aggregate infrastructure damages only represent a small percentage of global

FIGURE 6 Kilometers of Road Exposed to Flooding Globally



Notes: Based on GLOFRIS projections of future flood risk for an RCP 8.5 scenario[85] and global road infrastructure exposure analysis.[86]

maintenance spending; however, in some countries, the EAD may reach 0.5–1 percent of gross domestic product (GDP) annually.

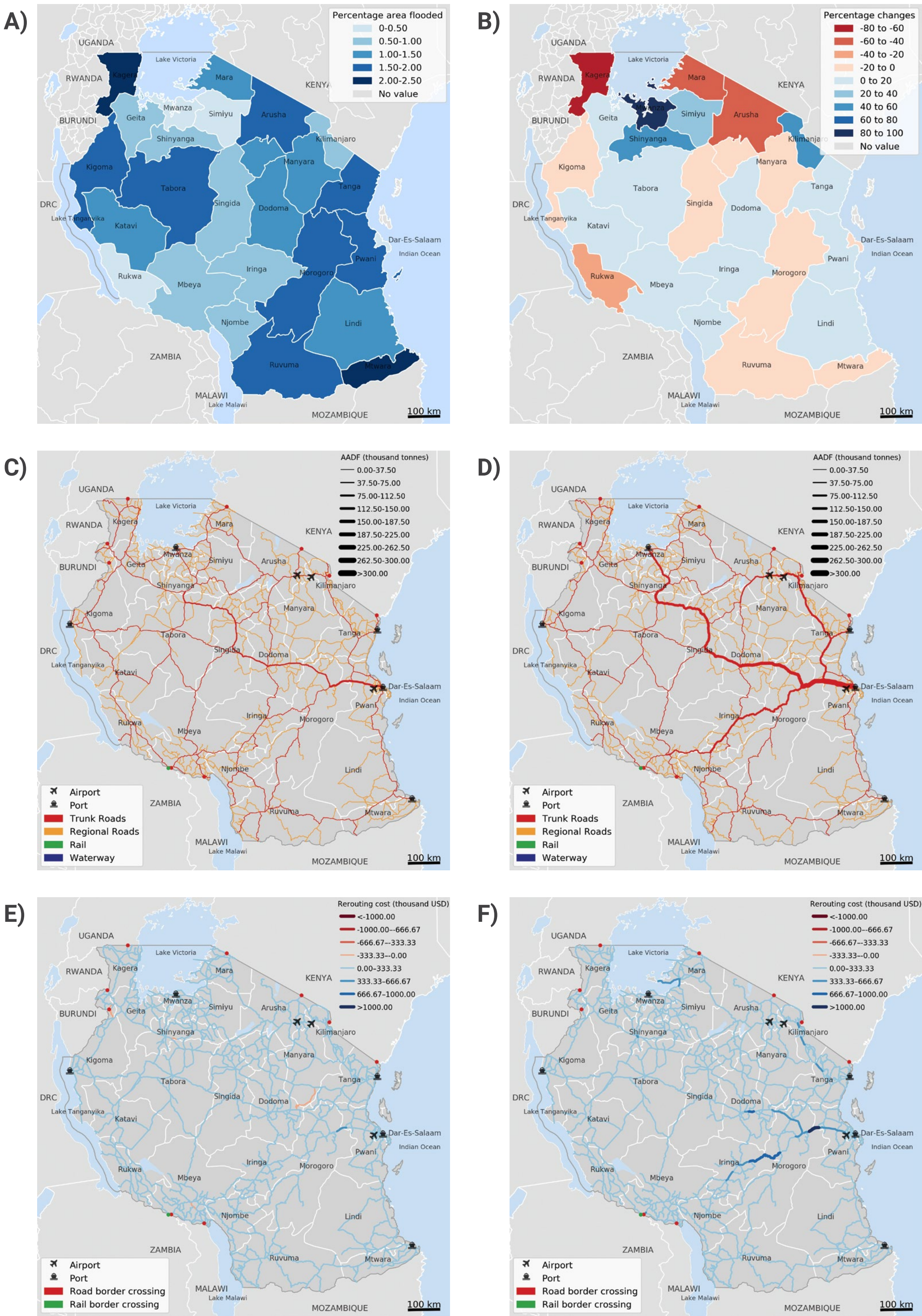
Climate damage and disruption to transport infrastructure impacts people, industries and supply chains. In the USA, it is estimated that the costs of adapting road and highway infrastructure to climate change could increase to about US$6 billion annually in 2075 ($970 million if discounted at 3 percent).[87] Analysis by the World Bank estimates that, in Africa, climate change could lead to large increases in the disruption time of the transport network. In the worst climate scenarios this could be up to 2.5 times historic disruption due to extreme temperatures, 76 percent higher due to precipitation, and 14 times higher due to flooding.[88] More recent analyses by the World Bank in Tanzania[89] and Vietnam[90] have begun to quantify these risks and identify hotspots of network vulnerability, providing a basis for adaptation planning. Our analysis in Tanzania examined flood risks to the road and rail network at present (Figure 7a), how these are projected to change in the future (Figure 7b), and the current use of the road network (Figure 7c) and how that is projected to change through to 2030 (Figure 7d). The biggest change in the 2030 transport freight flow will be seen along the Tanzania Railway Central route, where the flow volumes are projected to increase annually by 22–27 percent. The potential impact of increasing flood risk on the transport network was examined by testing every link in the network and calculating the costs of rerouting freight elsewhere (Figure 7e), and how that might increase in future if further steps are not taken to adapt the road infrastructure network (Figure 7f).

Analysis of Vietnam's transport networks by Oh et al.[91] also illustrated the threat of climate change, with the exposure of the national-scale roads network to extreme river flooding increasing from between 720 km to 1163 km in the current flooding scenarios, to between 786 km to 1180 km under a future RCP 4.5 scenario. The model results show that failure in certain locations of the road networks may result in daily losses of up to US$1.9 million, while railway failures may result in losses as high as US$2.6 million per day.

2.3.1.2 Airports, ports, and inland waterways

Inundation from sea level rise, increased frequency of extreme precipitation events, and storm surges pose threats to airports, seaports, and inland waterways. According to a recent study conducted for the EU,[92] the number of European airports that face the risk of inundation is expected to increase by almost 60 percent between 2030 and 2080, increasing the number of

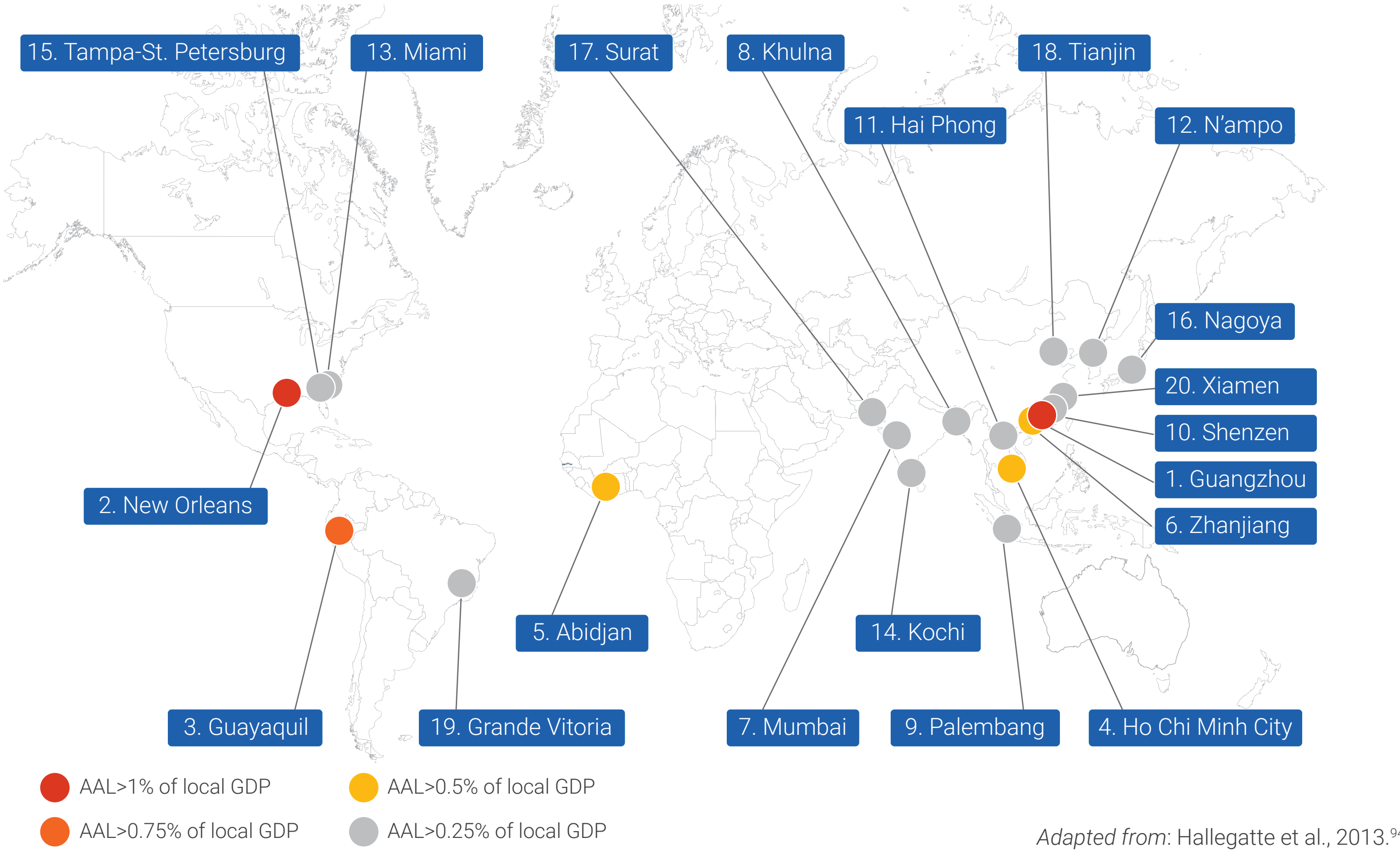
FIGURE 7 Economic Risk Analysis of Flood Risk to Road and Rail Transport in Tanzania



Notes: A) Percentage of region at risk of flooding; B) Projected change in flooded area (2019-30); C) Annual Average Daily Flow (AADF) in tons (2016); D) Projected AADF (2030); E) Freight rerouting costs for road network links (2016); and F) Projected flow rerouting costs for road network links (2030). Projected changes are from an ensemble of five Global Climate Models (GCMs) in the CMIP5 project (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M) under RCP 6.0 scenario.

Source: Pant et al., 2018.[93]

FIGURE 8 The 20 Port Cities Where Relative Average Annual Losses are Greatest



Adapted from: Hallegatte et al., 2013.[94]

vulnerable airports to 196. Airports Council International members recently adopted a resolution (ACI 3/2018 on resilience and adaptation to climate change) encouraging airports to consider climate change resilience and adaptation and develop mitigation measures in their masterplans.[95] Such measures include protection for coastal airports from sea level rise, ground accessibility during disruptive weather, longer runway requirements for aircraft take off at higher temperatures, electrical supply during storms, and undermined ground foundations, amongst others.[96]

Seaports are most severely impacted by sea level rise and storm surges. In Europe, 64 percent (852 ports) of all seaports are expected to be inundated by the end of the century as a result of sea level rise, and an additional 190 ports are at risk of riverine inundation for the 100-year flood event.[97] However, predominantly due to Europe's high protection standards and small port size, no European port cities rank in the top most vulnerable ports in the world, as classified by Nicholls et al.[98] and Hallegatte et al.[99] in their assessments of the 136 largest coastal port cities. Economic analyses showed that average global flood losses will increase from US$6 billion in 2005 to US$52 billion by 2050.[100] These losses are concentrated in only a few port cities (Figure 8), and only 13 cities reported losses greater than US$100 million, with three American cities (Miami, New York City, and New Orleans) making up 31 percent of the global aggregate losses across the 136 cities assessed. This is due to the high asset value of the port infrastructure and low flood protection levels. Contrastingly, in Amsterdam, the flood exposure is extremely high (US$83 billion of assets exposed to the 100-year flood), but the average annual losses are estimated at approximately US$3 million. This low value is due to the highest standards of flood defenses. Climate change and increased rates of subsidence mean that protection of infrastructure assets in the world's port cities will need to be upgraded to avoid unacceptable losses (in excess of US$1 trillion).[101]

Inland waterways are most vulnerable to droughts when low water levels impose limitations on navigational services for extended periods of time.[102] Reduced water levels will force operators to reduce vessels' load factors, which in turn result in an increase in the number of vessels required to compensate the reduced load. Despite flood events lasting for shorter periods of time than droughts, severe events can have significant impacts on inland waterways transport. According to Liu et al.,[103] for instance, the 2010 floods in the Yangtze river basin caused direct economic losses of US$14.4 billion. Their study analyzed flood trends in the basin and estimated that for every one percent increase in the incidence of extreme weather events, China can be expected to experience direct economic losses of approximately US$500,000 from the Yangtze inland waterways transport. Such high economic losses are due to approximately 55 percent of the total freight volume on China's inland waterways network being along the Yangtze.[104]

2.3.2 ENERGY INFRASTRUCTURE

Energy infrastructure includes power plants, transmission and distribution networks, and substations, pipelines and refineries. These may be subject to climate hazards including extreme weather events, changes in water availability, unusual seasonal temperatures, rising sea levels, wildfires, and permafrost thaw (Table 2).[105]

2.3.2.1 Thermoelectric power plants

In 2010, thermoelectric power (fossil, biomass, and nuclear fueled) contributed 16,473 million MWh (81 percent) of current electricity generation worldwide.[106] These plants commonly use water for cooling. Climate change poses a risk to these cooling water supplies, particularly where they derive water from freshwater sources that may be impacted by droughts. Water use relies predominantly on the type of cooling technology, as well as plant efficiency. Steam can be cooled using technologies that have varying water needs; once-through (open loop) systems withdraw the most water, while re-circulating (closed-loop) systems withdraw significantly less. In addition to the amount of water withdrawn, the proportion that is "lost" through evaporation relative to the amount of water that is returned to surface water bodies and potentially reused downstream is also relevant.

Climate change is expected to reduce the amount of river water available for efficient power plant operations as well as rivers' capacity to absorb waste heat, leading to a loss of thermoelectric generation.[107] Using a coupled hydrological–electricity modeling framework, for example, with data for 1427 thermoelectric power plants, van Vliet et al.[108] projected reductions in usable capacity for 81 to 86 percent of the thermoelectric power plants worldwide for 2040–69 (Figure 9, Figure 10).

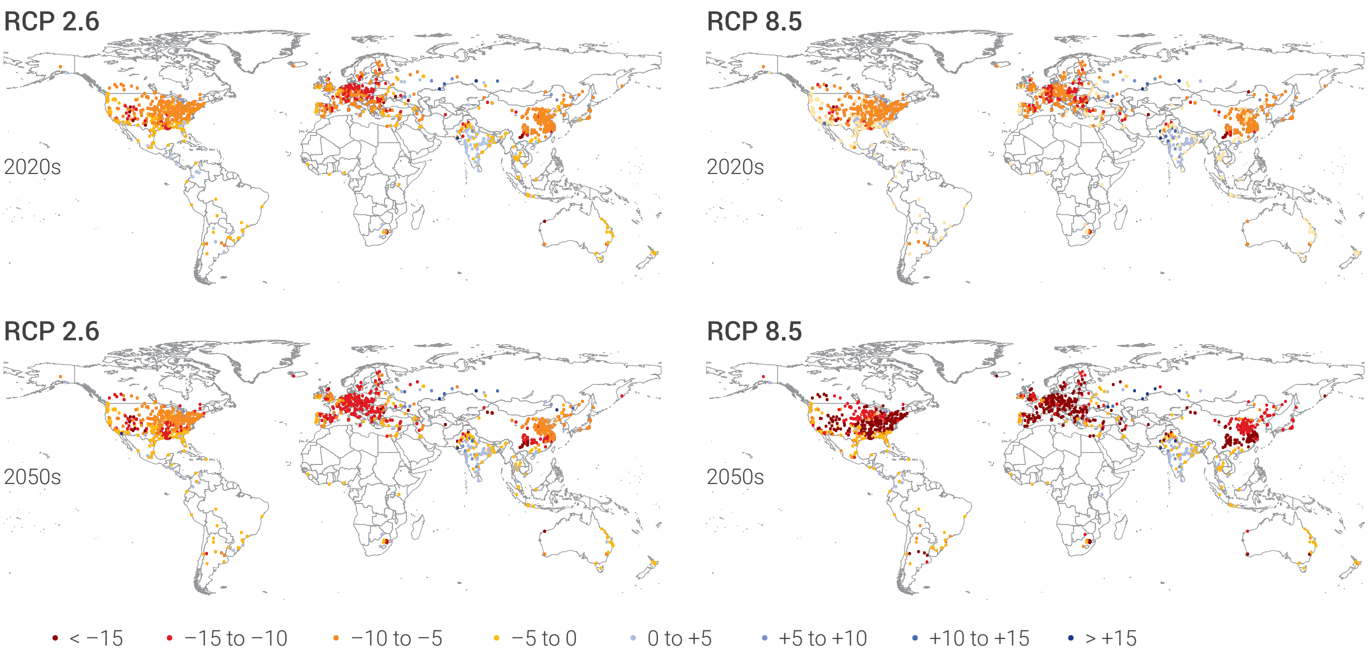
Coal-fired power plants account for 11 percent of total industrial water consumption in China, and about 75 percent of their water consumption is from regions with absolute or chronic water scarcity.[109] In north China, over 50 percent of power generation capacities with aggregate capacities larger than 100 GW are facing low-flow water risks (coal power plants close to the coast are excluded from this study). Nationally, around 30 percent of power generation capacities face low-flow water risks in April and around 10 percent face low-flow water risks from July to October (Figure 11).[110] These risks are concentrated during the winter (November, December, and January) and spring (February, March, and April) because the repercussions of the monsoon in the region reduce water availability across China, while electricity and water demand is higher during these two seasons due to increased consumption for heating purposes.

2.3.2.2 Hydropower

Hydropower contributes 3402 million MWh (17 percent) of current electricity generation worldwide, and is the dominant power source in South America (63 percent of total electricity generation).[111] Climate change affects hydropower production due to changes in inflow and evaporation from reservoirs. Although climate change is expected to have different impacts on water availability in different regions in the world, on a regional scale, hydropower production is projected to reduce at the majority of existing dams around the world.[112] However, studies in the USA have shown that climate change tends to increase overall hydropower generation due to generally increasing river runoff under higher emissions scenarios in the Pacific Northwest.[113]

Using a coupled hydrological–electricity modeling framework with data on 24,515 hydropower plants, van Vliet et al.[114] showed reductions in usable capacity for

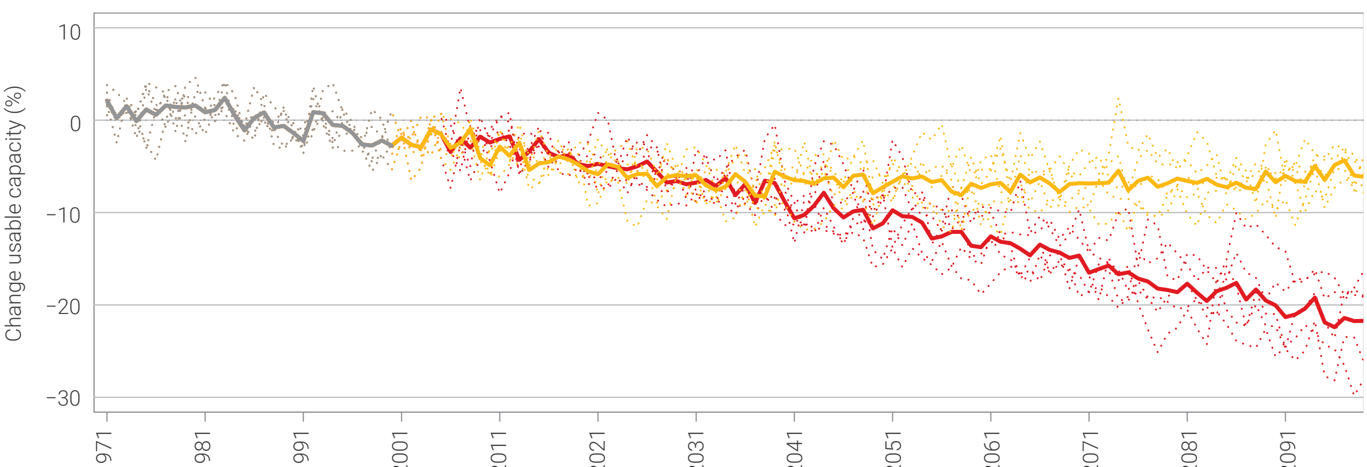
FIGURE 9 Relative Changes in Annual Mean Usable Capacity of Thermoelectric Power Plants



Notes: Relative changes in annual mean usable capacity of thermoelectric power plants for RCP 2.6 and RCP 8.5 for 2010–39 (2020s) and 2040–69 (2050s) relative to the control period 1971–2000.

Adapted from: van Vliet et al., 2016.[115]

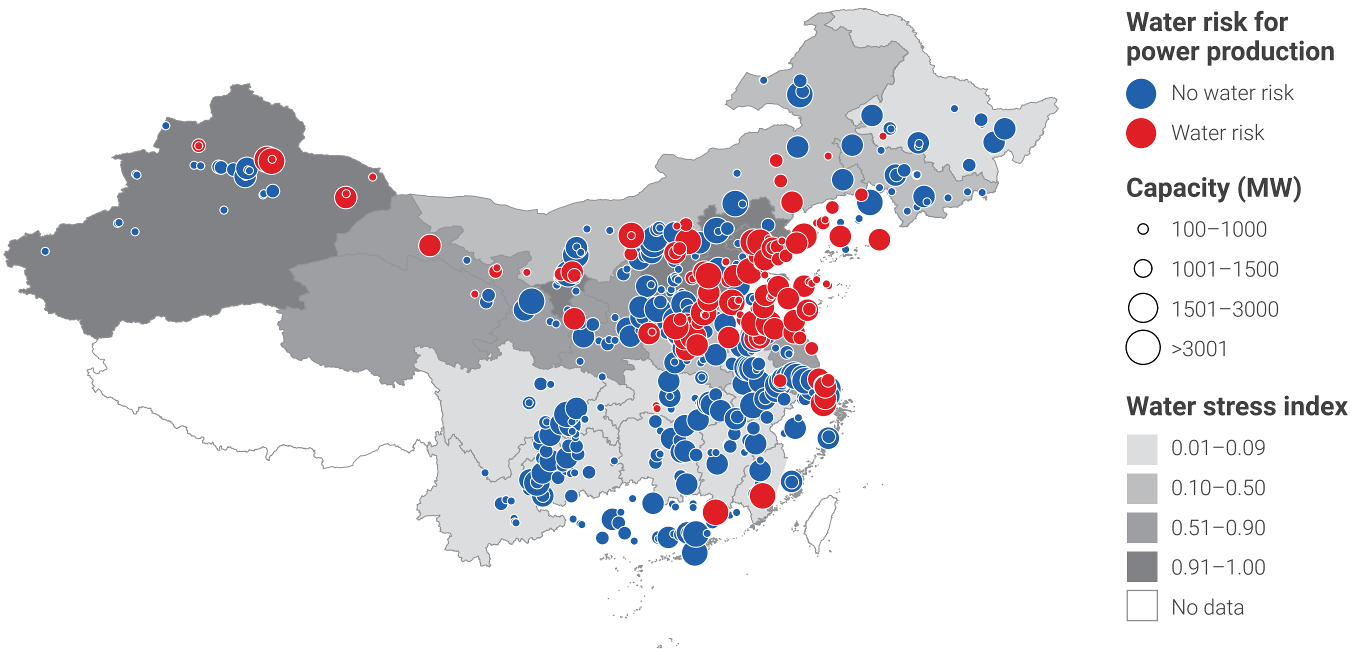
FIGURE 10 Global Trends of Changes in Annual Mean Thermoelectric Power Usable Capacity



Notes: Global trends of changes in annual mean thermoelectric power usable capacity for 1971–2099 based on the GCM-ensemble mean results (thick lines) and for the five individual GCMs separately (thin dotted lines) for both RCP 2.6 (yellow) and RCP 8.5 (red).

Source: van Vliet et al., 2016.[116]

FIGURE 11 Low-flow Water Risks for Coal Power Industry in China's Most Dry Regions



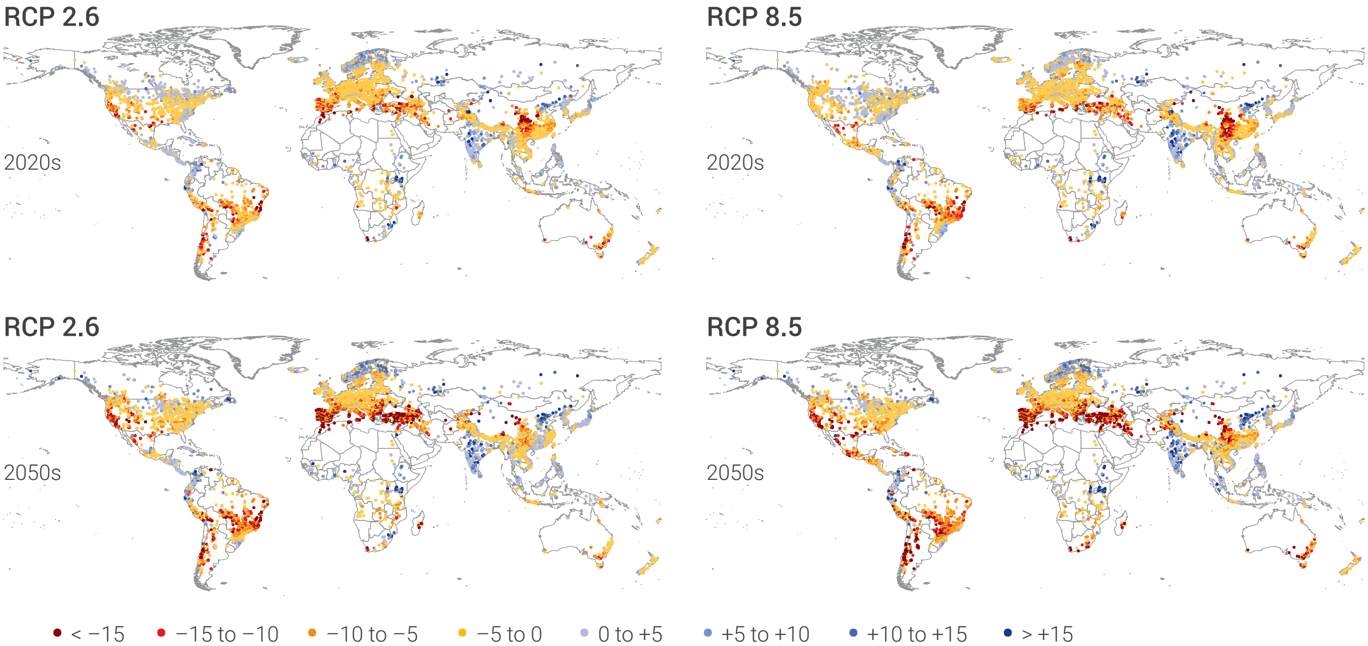
Adapted from: Liao et al., 2019.[117]

61–74 percent of the hydropower plants. Moreover, in regions where flows are increased, the positive impacts on hydropower productions are limited by the generating capacity, whereas in regions where flows are decreased, hydropower tends to be affected by compounded impacts from reduced inflows and increased evaporation from the reservoirs (Figure 12, Figure 13). A World Bank study into the impacts of climate change on hydropower and irrigation expansion plans in Africa's main river basins (Niger, Senegal, Volta, Congo, Nile, Zambezi, Orange)[118] showed that, in scenarios of drying climate conditions, failure to integrate climate change in the planning and design of power and water infrastructure could entail losses of hydropower revenues of between 5 and 60 percent (depending on the basin) and increases in consumer expenditure for energy up to three times the corresponding baseline values. In wet climate scenarios, failure to adapt to the opportunities of increased river flows for hydropower could lead to foregone revenues of around 15–130 percent of the baseline.

In countries that are heavily dependent on hydropower production, climate variability could pose serious socio-economic risks by affecting electricity supplies. For example, drought conditions in Pakistan resulted in the water levels of its two largest dams reaching "dead" levels, beyond which water is unable to be drained via gravity, which was a historic first for the Tarbela Dam.[119] During the 1991–92 drought in the Zambezi basin in Southeast Africa, a decline in hydropower production resulted in an estimated reduction of US$102 million in GDP and US$36 million in export income.[120] Conway et al.[121] highlighted that since the expanding hydropower capacity in both East and South Africa is largely located within the same climatic zone, the risk of concurrent climate-related electricity supply disruptions will be elevated in both regions by 2030. Interregional electricity transmissions, diversification of electricity generation sources, and drought management are all feasible adaptation measures.

Reduced hydropower capacity often leads to increased fossil fuel power production, which will then contribute to global climate change. Although increased emissions would be modest on a global scale,[122] some hydropower-dependent countries would struggle to meet their emission targets. For example, from 2013 to 2014, greenhouse gas emissions from the power sector in Brazil had increased due to lower than average water inflows and a higher utilization rate of thermoelectric power plants. According to a World Bank assessment, the annual emission during a dry year in Brazil can be four times higher than that in a wet year.[123]

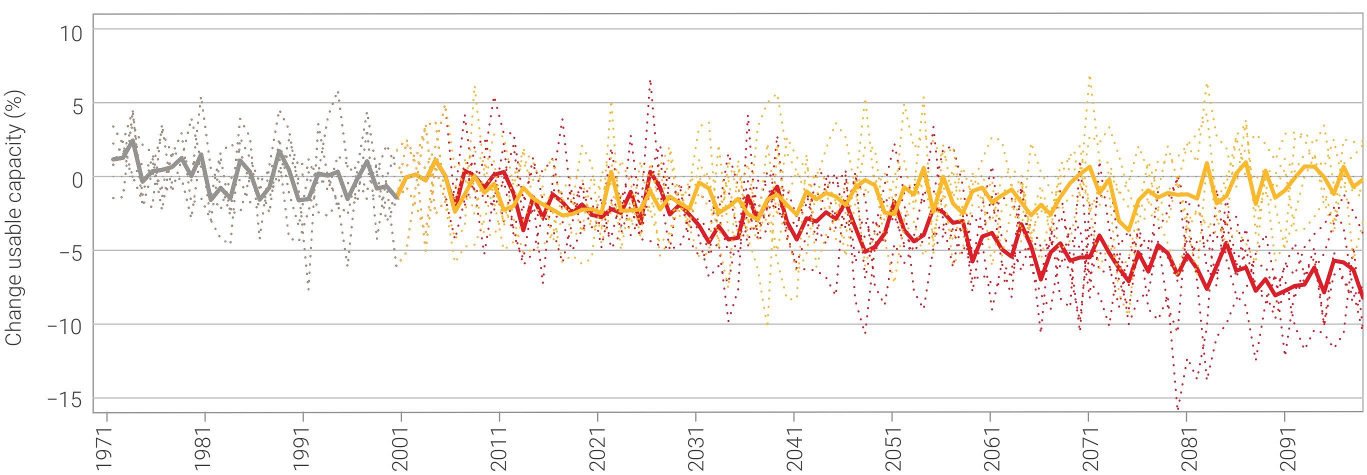
FIGURE 12 Relative Changes in Annual Mean Usable Capacity of Hydropower Plants



Notes: Relative changes in annual mean usable capacity of hydropower plants for RCP 2.6 and RCP 8.5 for 2010–39 (2020s) and 2040–69 (2050s) relative to the control period 1971–2000.

Adapted from: van Vliet et al., 2016.[124]

FIGURE 13 Global Trends of Changes in Annual Mean Hydropower Usable Capacity



Notes: Global trends of changes in annual mean hydropower usable capacity for 1971–2099 based on the GCM-ensemble mean results (thick lines) and for the five individual GCMs separately (thin dotted lines) for both RCP 2.6 (yellow) and RCP 8.5 (red)

Source: van Vliet et al., 2016.[125]

TABLE 3 Estimates of the Cost of Water Supply Infrastructure and Adaptation

STUDY	OBJECTIVE OF THE STUDY	SPATIAL SCALE	METHODOLOGY	COST ESTIMATE
Briscoe (1999)[126]	Estimating 1990 spending on water infrastructure.	All developing countries worldwide	Literature review	US$65 billion/year.
Woetzel et al. (2016)[127]	Estimating current and future (year 2030) spending on water infrastructure.	Global	Literature review	US$200 billion/year in 2016. US$500 billion/year in 2030.
Kirshen (2007)[128]	Estimating adaptation costs for two scenarios of socio-economic and climatic changes (IPCC scenarios B1 and A1b).	200 countries around the world including many African countries.	Simple unit cost estimates	Additional US$130–140 billion/year by 2030 compared to 2000 for Africa.
Ward et al. (2010)[129]	Estimating the cost of adaptation to climate change for the industrial and municipal water supply sectors.	Global including Africa	Intervention-based needs assessment	US$19 billion/year for developing countries (US$3-6 billion/year for Africa) for the period up to 2050.
Schmidt-Traub (2015)[130]	Estimating the investment cost for ensuring access to safe water and improved sanitation including the incremental costs for dam construction and flood protection.	Global	Literature review	US$49 billion/year for the period 2015-30, with major investments needed in low and lower-middle income countries.
Kahil et al. (2018)[131]	Scenario analysis for Africa of future water demands and adaptation responses.	Africa	Hydro-economic model	US$66 billion/year for Africa in 2010, increasing to US$66-80 billion/year in 2050 depending on scenario.

Source: Kahil et al., 2018.[132]

2.3.3 WATER INFRASTRUCTURE

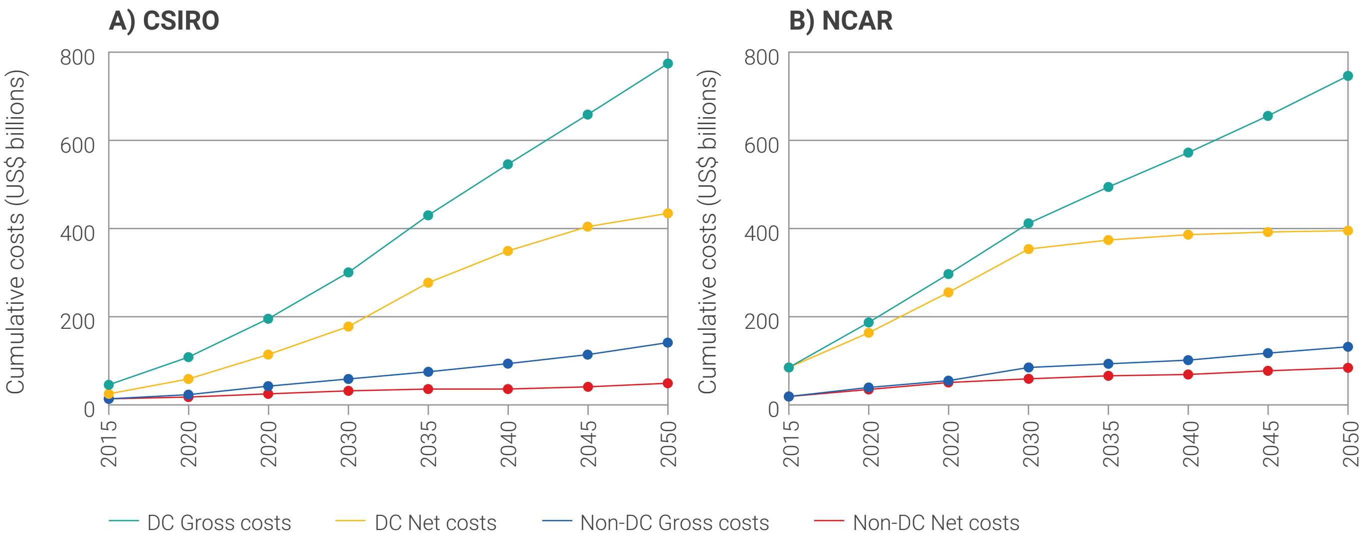
Water infrastructure includes water supplies (for domestic water needs, industry, and agriculture), wastewater treatment, urban drainage, and flood defenses, which are subject to multiple climate-related risks.

2.3.3.1 Water supply

Various studies have examined the cost of providing water infrastructure to serve global water needs, most recently in the context of SDG 6 (Table 3); however, only some of these studies have examined how the need for adaptation to climate change might increase those costs. The global additional climate adaptation costs for industrial and municipal water supply were estimated by Ward et al.[133] (Figure 14). Estimates of the net and gross adaptation costs differ greatly because many countries will benefit from climate change in terms of water supply. However, globally, the total costs outweigh the avoided costs (benefits). Strzepek et al.[134] examined water supplies on a national scale in the contiguous United States under a range of climate change mitigation scenarios, and concluded that mitigation substantially reduces hydro-climatic impacts on the water sector. Similarly, the impacts of climate scenarios on water resources have been extensively explored in the United Kingdom,[135] including detailed examination of adaptation options.[136]

Major droughts are an ever-present threat in almost all countries, and are set to increase due to climate change and the influence of socio-economic change on the demand for, and use of, water.[137] Globally, 54 cities have

FIGURE 14 Cumulative Costs of Climate Change Adaptation in the Water Supply Sector



Notes: Cumulative costs (2005 US dollars) of climate change adaptation in the water supply sector for developing countries (DCs) and non-developing countries (non-DCs). Two different models (CSIRO and NCAR) were used to estimate future reservoir storage needs.

Adapted from: Ward et al., 2010.[138]

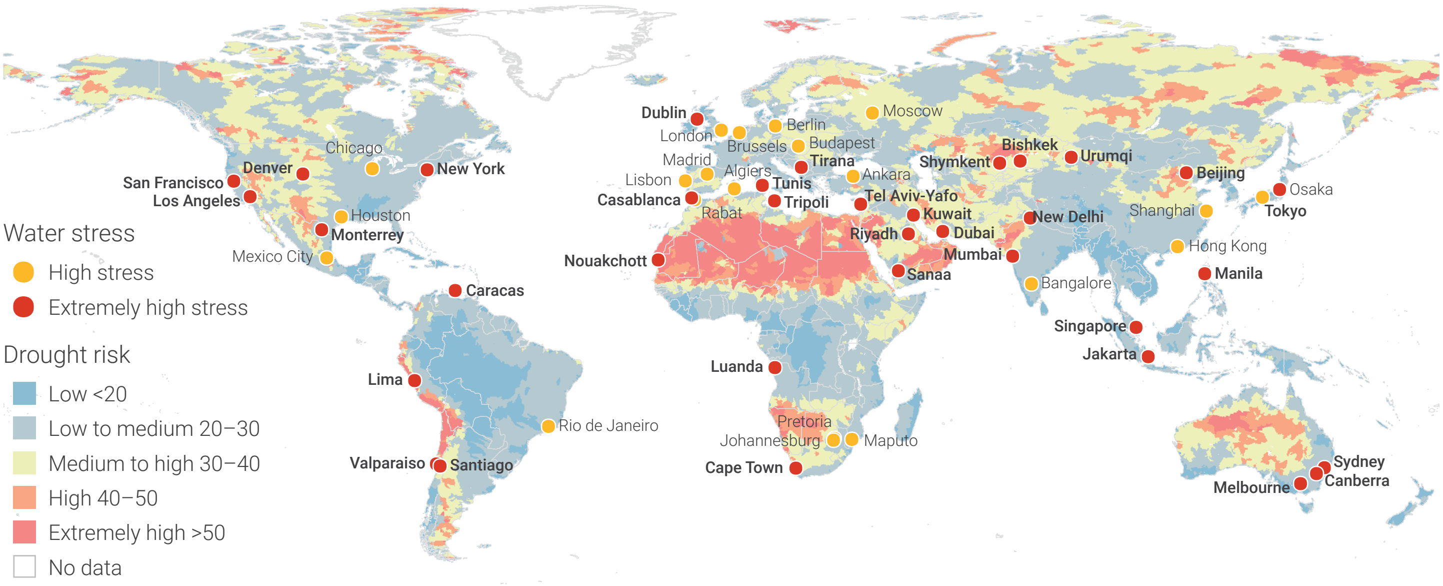
been identified to be in drought hazard zones, half of which are located in Asia, and particularly in Arabic countries in which increasing urbanization and economic development is taking place in very dry countries (Figure 15).[139] While there may not be as many water-stressed cities in Africa as in Asia, the severity of water stress in some African cities has persisted over decades. For example, Cape Town has been afflicted by long periods of drought for a number of years, culminating in early 2018 in the prospect of the city running out of water. These shortages are driven by increasing demand from the economy and the population of the city as well as from water users in the surrounding area, and climate projections indicate that droughts will become longer and more frequent in the future.[140] In the USA, the average cost of droughts is estimated to be between US$6 billion and US$8 billion annually, and their frequency and severity are also expected to increase, particularly in the southwestern states.[141]

Given the impacts of climate change, the resilience of water infrastructure is an issue even in countries that are not traditionally considered to suffer from water scarcity. The UK's National Infrastructure Commission[142] estimates that there is a 1 in 4 chance that over the next 30 years large numbers of households will have their water supply cut off for extended periods due to drought, and that coping with these shortages with emergency water supplies, such as road and ship tankers, would cost US$49 billion (GB£40 billion) over the next 30 years. Around half that amount (US$26 billion) would need to be invested to build resilience into the UK's water supply system over the next 30 years. Maintaining the current levels of resilience (to the worst historic drought) in the face of rising population and environmental and climate pressures until 2050 would require an additional capacity of around 2700–3000 million liters per day in England, with the southeastern region requiring the most.

2.3.3.2 Wastewater

Climate change poses major challenges to wastewater infrastructure. Increasingly intense rainfall leads to increased rates of inflow, which increases the chances of system overflows of raw wastewater to the receiving environments. A key issue for many cities, even in developed countries, is the existence of combined sewer and stormwater systems, which may result in combined sewer overflow events during heavy rains, and thus contribute to pollution of the surrounding waterways. Similarly, wastewater treatment plants are often at greater direct risk of flooding given the tendency to locate the assets in lower lying areas or near rivers and coasts to take advantage of gravity conveyance and for proximity to

FIGURE 15 Global Patterns of Drought Risk



Notes: Drought hazard map from Aqueduct Drought Risk Map[143]; water stressed cities classified by Deltares, 2018.[144]

a disposal water body. Water-scarce regions will require increasing investment in wastewater reuse.[145]

Hu et al.[146] demonstrated how existing Chinese wastewater treatment plants (WWTPs) are exposed to changing flooding probabilities under a range of different climate scenarios. For an event with a 30-year return period under a scenario of moderate climate change, up to 472 WWTPs supplying 176 million people could additionally be affected by 2035. Further in the future (2036–55), the number of people exposed could rise by up to 208 million compared with today's figures. Impacts in the case of a warmer scenario are estimated to be slightly lower, but similarly severe.

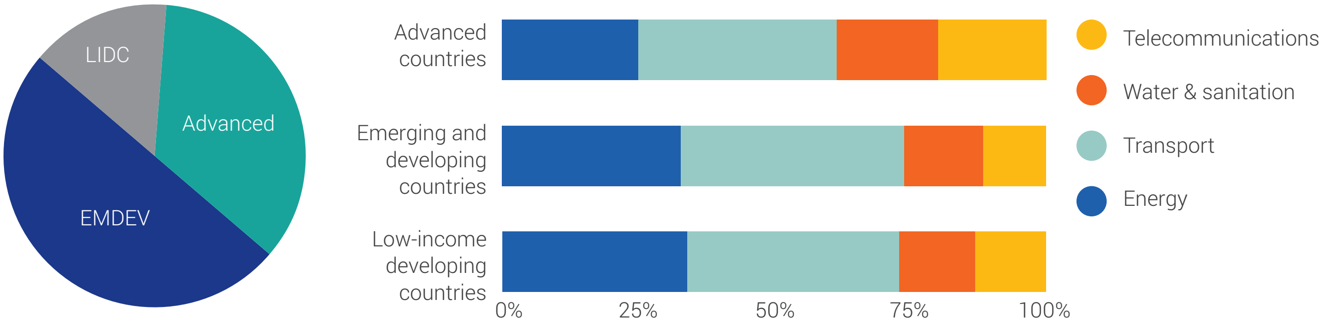
3 Adapting Infrastructure Systems

3.1 Adaptation Needs in Different Country Contexts

High-income countries have large amounts of infrastructure that was largely built in the last or even the nineteenth century. This infrastructure was not designed for a changing climate and may be in a deteriorating condition or nearing the end of its life. These assets will be retrofitted or replaced either as they reach the end of their useful lives or in response to policy priorities such as the low-carbon transition. In some cases, such as flood defenses, climate impacts may accelerate the need to replace these assets. When major new investment decisions are made, such as to replace fossil fuel power plants, it is crucial that climate risks are fully taken into account and opportunities for building in flexibility to adapt to uncertain future conditions are explored. However, the scope for doing so is constrained by the cumulative effect of previous decisions that are now difficult or expensive to reverse. For example, retrofitting air-conditioning to the London Underground would be far more challenging than it would be to include it at the outset in a new system.

The greatest rates of infrastructure investment are taking place in **middle-income countries** (Figure 16) to meet the needs of rapidly urbanizing and industrializing economies. There is urgent requirement to address congestion and unreliable infrastructure services that may be inhibiting economic and human development, resulting in harmful environmental impacts. While this new development offers more options to get things right from the outset, there is a risk that the often breathtakingly rapid roll-out of infrastructure is storing up major climate risks for the future and locking in unsustainable patterns of development.

FIGURE 16 Percentage of Projected Cumulative Infrastructure Demand By Sector and Income Groups



Notes: Percentage of projected cumulative infrastructure demand by sector and income groups 2015–30.

1. LIDC includes low-income and lower middle-income countries; EMDEV includes emerging economies and upper middle-income countries; advanced includes upper high-income and lower high-income countries.
2. Projections are based on the mid-point of range estimates. They exclude fossil fuels extraction and use, expenditure to enhance energy use efficiency, operation and maintenance costs, and additional investments in sustainability.

Adapted from: Bhattacharya et al., 2016.[147]

Low-income countries have the greatest gap between current levels of infrastructure access and reliability and what is required to meet the SDGs. Most of their infrastructure investment is in the future; however, capacity building is required at present to establish rigorous planning and decision-making processes to ensure that the urgently needed infrastructure systems will be resilient to climate risks. Demonstrating climate resilience should assist in the challenge of mobilizing the capital needed for infrastructure investment. There is a need to develop appropriate processes and standards that enable adaptation to be mainstreamed in infrastructure development without becoming an obstacle to meeting human needs.

The requirements for adaptation vary across geographical contexts, as well as across income groups.[148] For example, **small island developing states** (SIDS) are particularly vulnerable to climate hazards (Box 5). Hurricanes, intense rainfall, flooding, and landslides cause major disruption from which islands struggle to recover. Like all countries, SIDS depend upon infrastructure networks that provide transport connectivity, energy, water, and digital communication. However, SIDS are characterized by their relative isolation and sparse networks, and even "everyday" hazard events that cut-off one road can cause severe disruption, while an intense hurricane can devastate an entire nation. In 2010, Hurricane Tomas destroyed bridges and triggered hundreds of landslides in St Lucia, disrupting lifeline infrastructure with damage that exceeded 43 percent of the annual GDP.

3.2 Quantifying the Benefits of Infrastructure Adaptation

Several studies have examined the costs of adaptation at national scales.[149,150,151,152,153] Some of these have examined the costs of adaptation of infrastructure systems,[154,155,156,157] but relatively few have examined the benefits of climate risk reduction to infrastructure systems alongside the costs on a large scale. Here, we summarize the few existing studies and present new analysis at global and national scales.

3.2.1 TRANSPORT INFRASTRUCTURE

In the road sector, the additional cost of making infrastructure resilient to climate change is estimated to be between 3 and 10 percent of total project investment costs.[158,159] This includes the costs of increasing flood protection standards, upgrading the design standards for surface flooding, upgrading the drainage system, and enforcing bridge design standards. We have calculated the benefits of adaptation to strengthen infrastructure assets by comparing the cost of adaptation action with the

BOX 5 Infrastructure Adaptation in Saint Vincent and the Grenadines

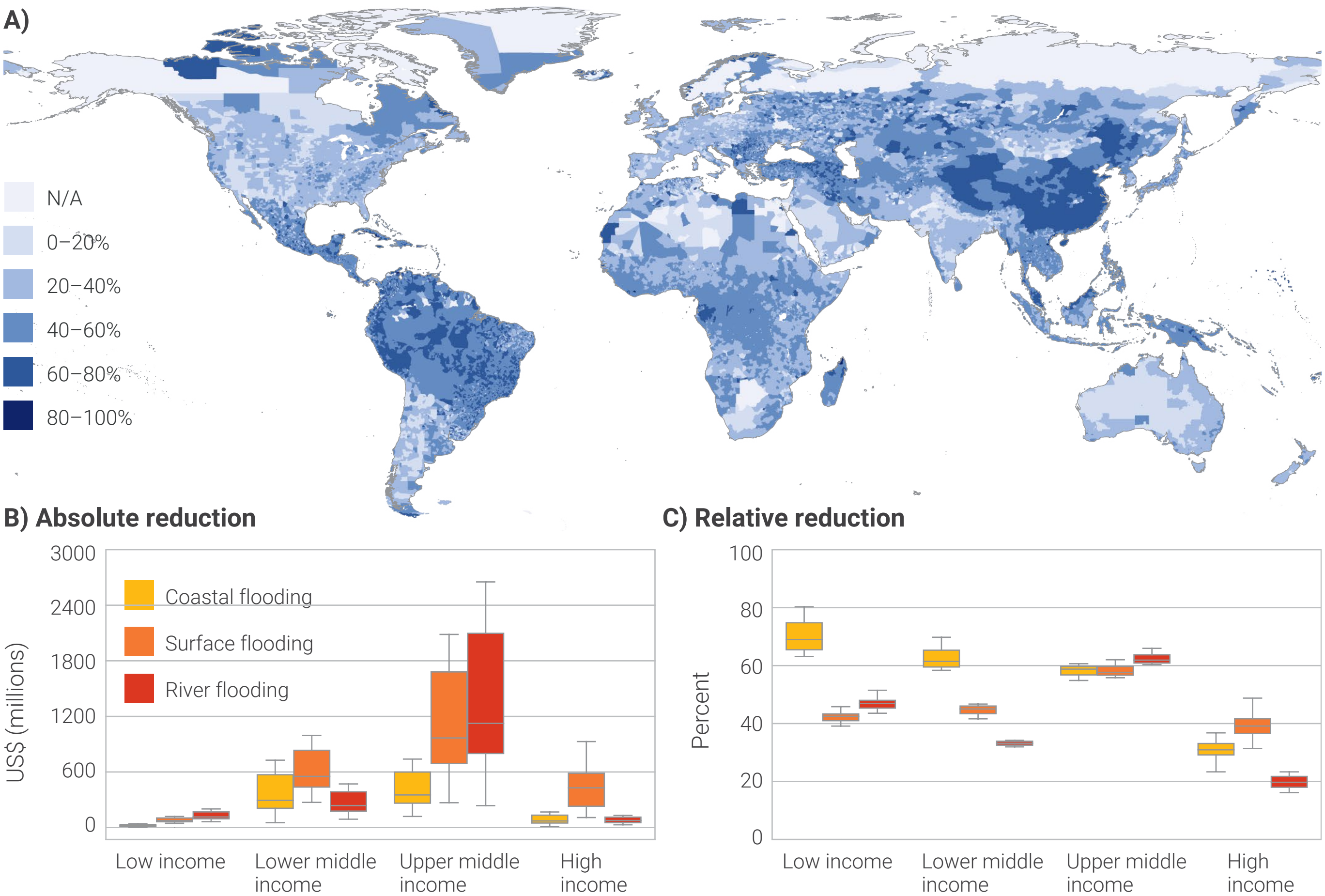
In SIDS, rises in sea level and greater occurrence of storm surges necessitate extensive flood risk management infrastructure to reduce exposure to water-related hazards. Energy, water supply, and waste management systems should be designed such that affected communities can continue to receive basic services in the event of a disaster, including fuel and adequate sanitation. Following the storm and flood in 2013 that caused severe damage to infrastructure, the United Nations Office for Project Services (UNOPS) partnered with the Government of St Vincent and the Government of Mexico to enhance the resilience of the island's infrastructure. This involved the reconstruction of bridges to connect the northern communities to the capital in the south. In addition, 1.5 km of roads were repaired and a river defense system was constructed to protect the houses built along the river banks. All infrastructure was rebuilt and rehabilitated with a particular focus on community involvement and resilient design practices; for example, the main bridge was designed to withstand a category 5 hurricane. UNOPS employed local workers and trained them on the principles of resilient construction and also provided capacity building for the Ministry of Transport officials.

Source: Thacker et al., 2018.[160] *Image source*: UNOPS, 2018.[161]

avoided direct damage due to flood risk (Figure 17 and Figure 18).[162] This is a narrow estimate of the benefits of adaptation, as it does not take into account the benefits of avoiding wider economic disruption. Nonetheless, improving flood protection standards can reduce the total EAD by up to 42 percent, but is only cost efficient if upgrades are targeted at where the benefits are greatest. This analysis provides the evidence that is needed to target adaptation investments in infrastructure networks.

A recent analysis by the World Bank in Vietnam[163] showed that under every climate hazard scenario, it is beneficial to invest in the climate resilience of a significant proportion of national-scale roads. The analysis suggested that, for some national-scale roads, upgrading to climate-resilient designs could cost up to US$3.4 million per kilometer, compared with US$1.0 million per kilometer to build roads to existing standards. However, the high economic benefits of such investments justify these high costs. When the top 20 assets with highest maximum benefit-to-cost ratios

FIGURE 17 Risk Reduction to Global Transport Infrastructure due to Flood Design-standard Upgrades



Notes: A) presents the total combined reduction in EAD per region, B) presents the absolute reduction in EAD for coastal, surface and river flooding, and C) presents the relative reduction in EAD for coastal, surface and river flooding.

Source: Koks et al., 2019.[164]

FIGURE 18 Benefit-cost Ratios for Investment in Transport Infrastructure Adaptation

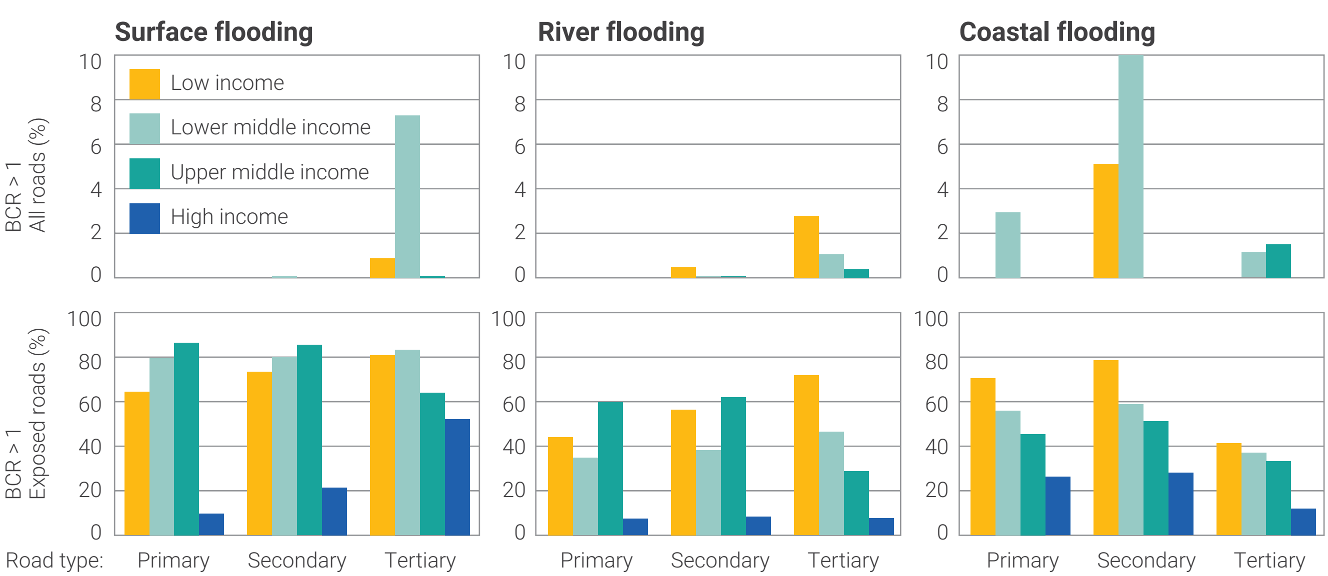
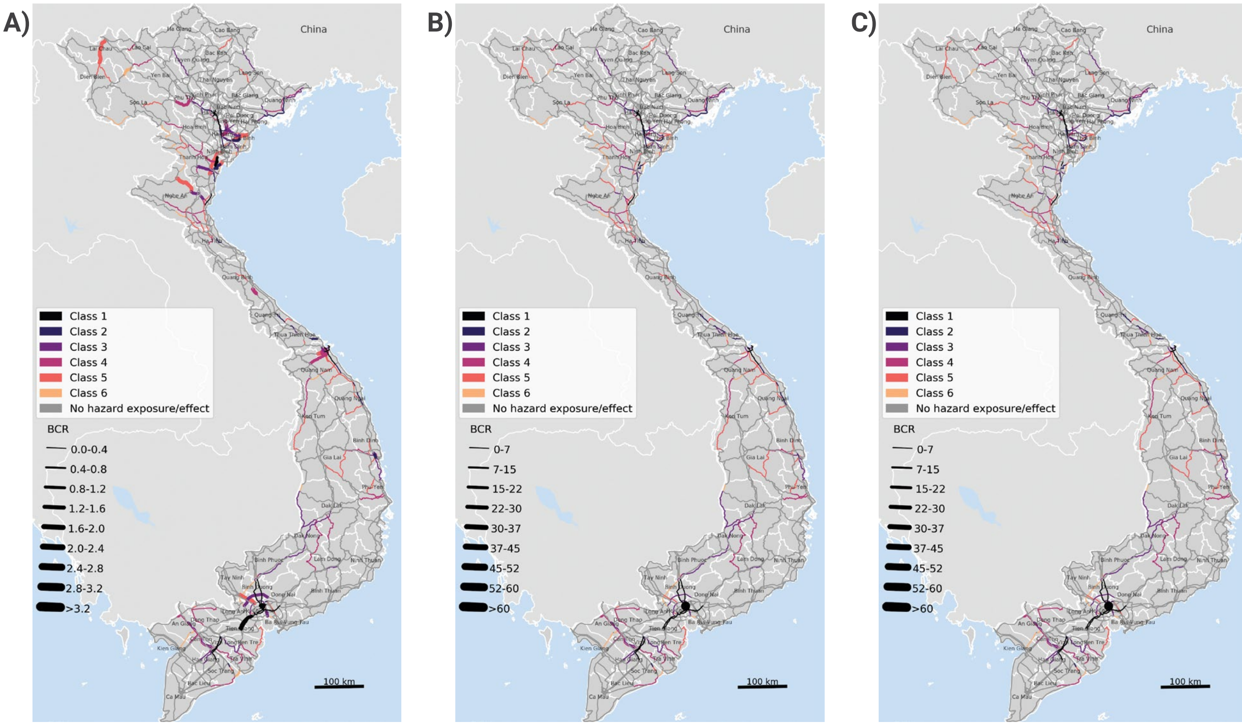


FIGURE 19 Comparisons of BCRs of Adaptation Options for National-scale Road Network Links in Vietnam



Notes: Comparisons of BCRs of adaptation options for national-scale road network links in Vietnam subjected to A) current 2016 levels of extreme river flooding, and future 2030 levels of extreme river flooding under B) RCP 4.5 and C) RCP 8.5.

(BCRs) are selected, the analysis shows that for these 20 assets, a cumulative climate adaptation investment amounts to approximately US$95 million initially, and is approximately US$153 million over 35 years (Figure 19). The cumulative benefits over 35 years, estimated by adding the benefits from individual links of such investments are substantial, and range between US$651 million and US$3.65 billion. All these values are discounted to present values. The results show a significant uplift of BCR of adaptation when climate resilience investments are made to avoid future risk levels of extreme river flooding. Vietnam's road networks require investments to overhaul existing road assets to higher climate-resilient design standards.

As well as physical adaptations from the transport network, the study examined how risk can be managed by facilitating modal shifts between road, rail, and waterways. Even a 10 percent modal shift can have a positive impact on reducing the economic impacts of road failure. A reduction of around 20–25 percent in economic losses can be achieved from only a 10 percent modal shift from road to other modes. Vietnam's transport networks need to function as integrated multimodal systems, which can be achieved by improving existing multimodal linkages and creating new ones.

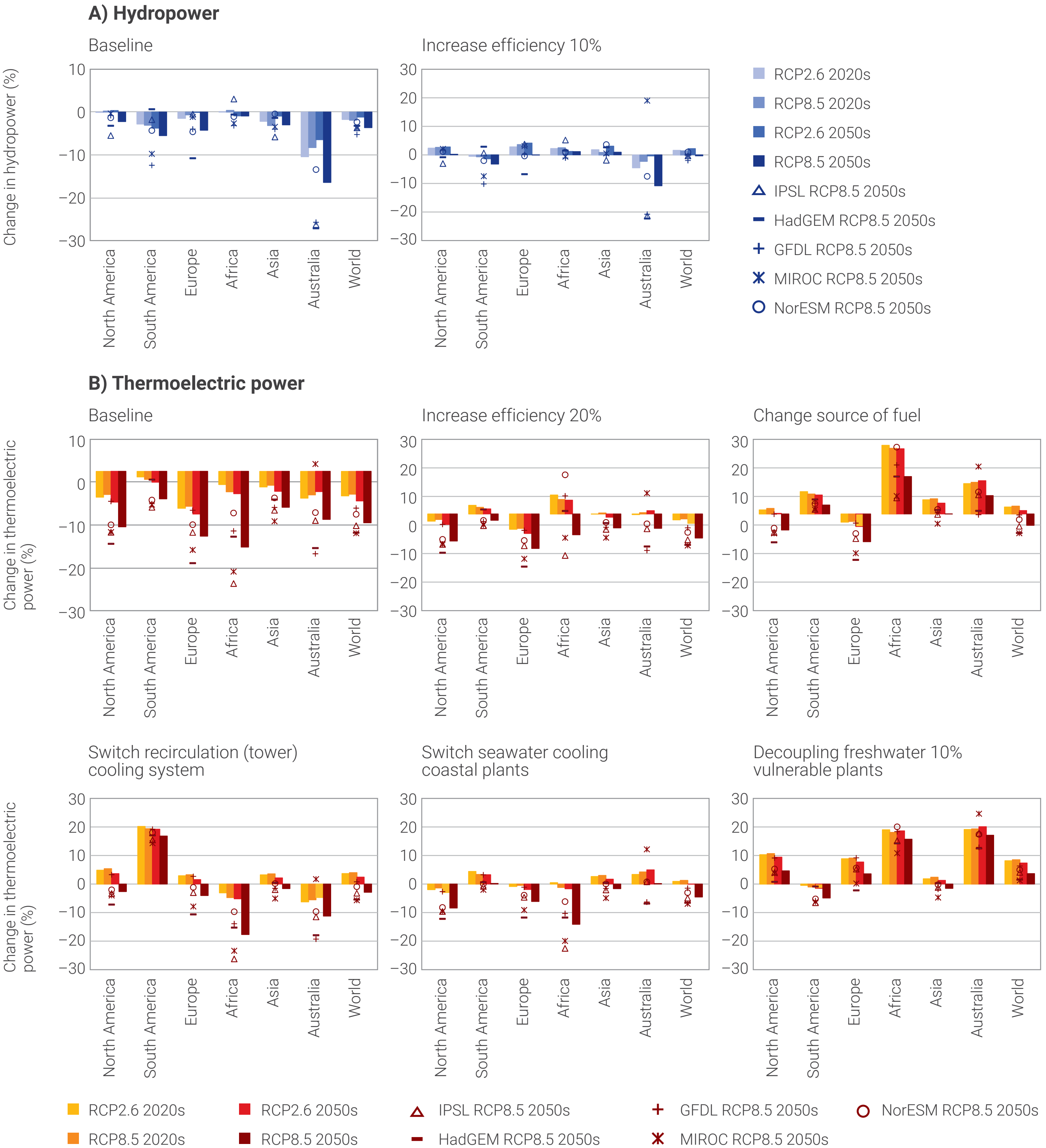
3.2.2 ENERGY INFRASTRUCTURE

3.2.2.1 Adapting hydropower and thermoelectric power plants

A report by van Vliet et al.[165] tested adaptation options to mitigate the vulnerability of thermoelectric power plants to cooling water shortages and temperature increases and future water constraints for hydropower. They focused on:

- increasing the efficiencies of hydropower and thermoelectric power plants;
- replacing fuel sources for thermoelectric power plants (coal- and oil-fired plants replaced by gas-fired plants);
- replacing once-through cooling systems with recirculation (wet tower) cooling systems;

FIGURE 20 Relative Changes Baseline Settings and Adaptation Options of Hydropower and Thermoelectric Power



Notes: The Global Climate Model (GCM)-ensemble mean changes are presented by the bars. Changes for the five individual GCM experiments for RCP 8.5 (2050s) are presented to show the range between them.

Adapted from: van Vliet et al., 2016.[166]

- switching to seawater cooling for thermoelectric power plants close (<100 km) to the coast; and
- decoupling from freshwater resources by switching to seawater and dry (air) cooling for the 10 percent of thermoelectric power plants that are most vulnerable to water constraints under climate change.

Analysis of the various adaptation options showed that increasing total efficiencies of hydropower plants by up to 10 percent (e.g., efficiency of 0.82 becomes 0.90), is able to completely offset the mean annual impacts of increased water constraints under changing climate for most regions (North America, Europe, Africa, and Asia; Figure 20A). However, on a monthly timescale, reductions in capacity are still found after a 10 percent efficiency increase (worldwide average maximum reductions of 1.0–6.2 percent for RCP 2.6–8.5 in the 2050s). Small reductions in mean annual usable capacity of hydropower are projected for South America and Australia, but there is a wide range of uncertainty due to the range of climate model projections.

For thermoelectric power, van Vliet et al.[167] found that increased power plant efficiencies also positively contribute to reducing water demands and decrease the vulnerability to water constraints under climate change (Figure 20B). However, a higher increase in power plant efficiencies of up to 20 percent (e.g., efficiency of 0.45 becomes 0.54) is still insufficient for most regions to mitigate overall reductions in cooling water use potential under a changing climate. Changes in sources of fuel are more effective for most regions in reducing plant vulnerabilities to water constraints. On average, fuel switching to higher efficiency gas-fired plants with lower cooling water demands can be sufficient to mitigate plant vulnerability to water constraints for the 2020s (+2.5 to +2.8 percent for RCP 2.6–8.5) and for the 2050s under a low concentration (+1.2 percent for RCP 2.6) globally. However, this adaptation option will be insufficient for North America, Europe, and Asia under high concentrations for the 2050s (−4.0 percent for RCP 8.5 worldwide). The strongest positive impacts were found for Africa and Australia, where the relative number of coal-fired plants that can be substituted by gas-fired plants is high. A switch to recirculation (wet tower) cooling decreases water withdrawals and reduces plant vulnerabilities to water constraints. This can result in smaller reductions or even slight increases in usable capacities (+3.7 to +4.0 percent for the 2020s and +2.4 to −2.9 percent for the 2050s), indicating that adaptation can more than offset the impacts of climate change. A switch from freshwater to seawater cooling for plants along the coast also reduces vulnerabilities to freshwater constraints. However, a decoupling of cooling water systems from freshwater resources for the 10 percent most severely impacted plants is a more effective adaptation option. Assuming a decoupling from the freshwater system by a switch to seawater and dry (air) cooling (including also efficiency losses), van Vliet et al.[168] estimated a global average increase in usable thermoelectric power capacity of +8.2 and +8.6 percent (2020s) and +7.4 and +3.7 percent (2050s) for RCP 2.6 and RCP 8.5, respectively.

3.2.2.2 Flood protection of power plants

In a new global analysis of flood risk to power plants, we analyzed the benefits of protecting these plants from river and coastal flooding. We examined power plants with a power output of 4223 GW, that are at risk from river flooding, estimating how many of these plants would be impacted at different return periods depending on their current level of flood protection, and how that impact could be reduced by increasing flood protection to a given level (Figure 21). For example, assuming 0.5-m protection to power plants, around 700 GW of generation capacity is at risk from the 100-year flood.

3.2.3 WATER INFRASTRUCTURE

3.2.3.1 Water supplies

Ward et al.[169] estimated the costs of providing water supply infrastructure (reservoirs, desalination, recycling, and rainwater harvesting) to meet growing industrial and domestic water supplies to be about US$73 billion per year through to 2050 (Figure 22). They estimated that adapting to climatic impacts on water availability would cost an additional US$12 billion per year, with 83–90 percent of this being in developing countries, with the highest costs in Sub-Saharan Africa.

Kahil et al.[170] examined the types of adaptation options and their associated costs in more detail for Africa, which are summarized in Figure 23. This hydro-economic modeling study emphasizes how future water scarcity in Africa will be driven by increasing demands, predominantly from the agriculture sector, whose need for water is set to increase in future.

FIGURE 21 Benefits of Protecting Power Plants from Floods of a Range of Return Periods

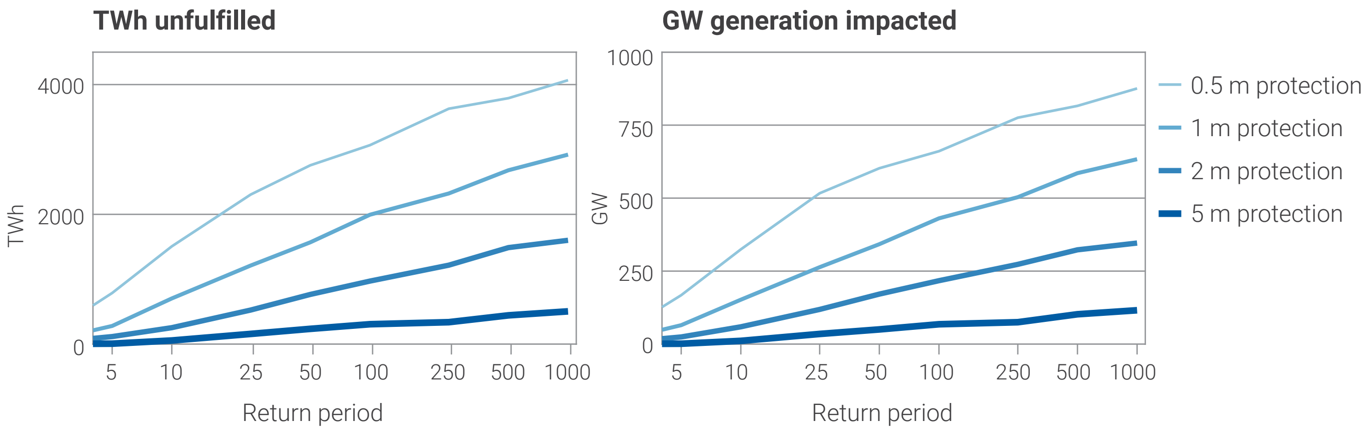
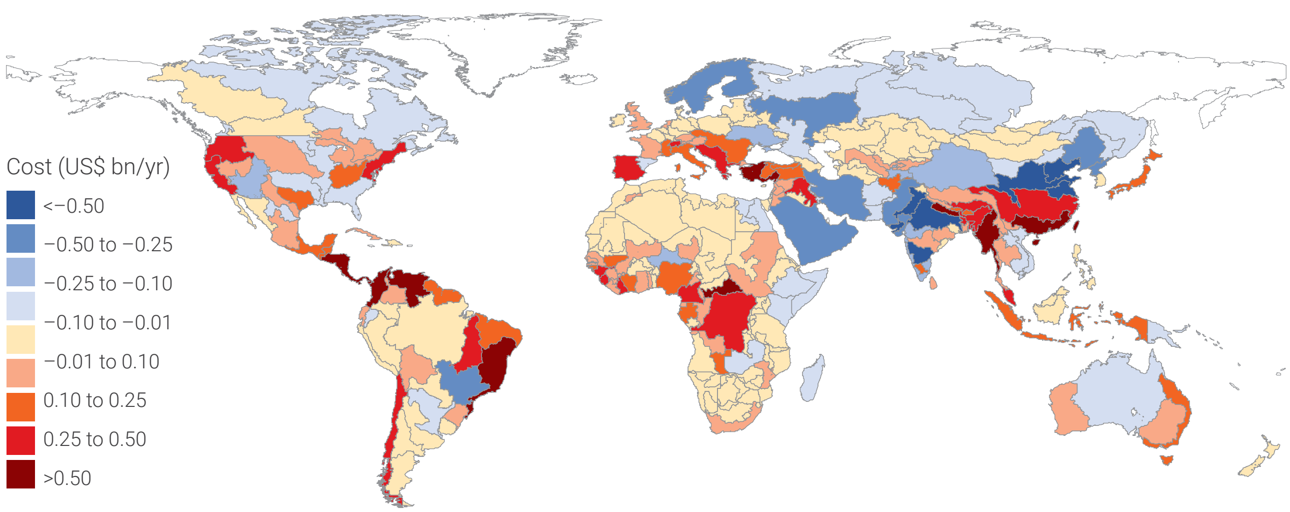


FIGURE 22 Average Annual Climate Change Adaptation Costs for Industrial And Municipal Water Supply



Notes: Average annual climate change adaptation costs (US$ bn/yr) for industrial and municipal water supply, using climate projections from the NCAR CCSM3 climate model. Negative costs (shown in blue) refer to avoided costs as a result of climate change.

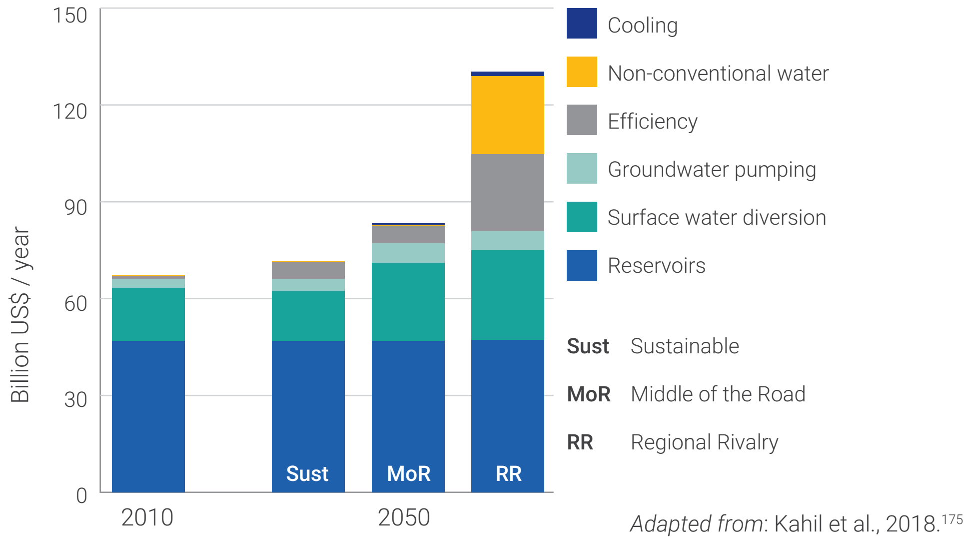
Source: Ward et al., 2010.[171]

3.2.3.2 Increasing flood protection levels

Hinkel et al.[172] estimated that the global costs of protecting the coast with dikes would be significant, with annual investment and maintenance costs of US$12–71 billion in 2100, depending on the climate and socio-economic scenario (Figure 24). However, the costs would be much smaller than the global benefits of avoided damages, even without accounting for (the avoided) indirect impacts on regional production supply. Hallegatte et al.[173] estimated that spending US$50 billion per year (annualized) on flood defenses for coastal cities would reduce expected losses in 2050 from US$1 trillion to between US$60 and US$63 billion.

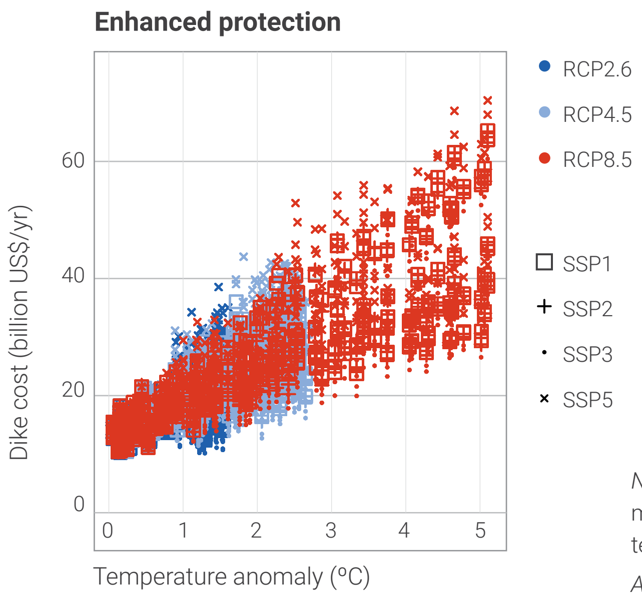
Similarly, Ward et al.[174] used a global-scale flood risk assessment model, GLOFRIS, to examine the benefits and costs of adapting to increasing river flood risk using structural flood protection measures, namely dikes and levees. They showed that future risk (in 2080) can be kept constant to current levels (both in terms of absolute values and relative to GDP), and mapped regions in which this could be achieved through structural measures with benefits that outweighed the costs. Robust areas are found across most of North America, Northwestern and Central Europe, the Indian Subcontinent, large parts of East and Southeast Asia, and large parts of Australasia. Studies show that the benefits of structural measures also

FIGURE 23 Costs of Water Supply Infrastructure in Africa in 2010 and 2050 for Three Adaptation Scenarios



Adapted from: Kahil et al., 2018.[175]

FIGURE 24 Global Annual Cost of Coastal Defenses



Notes: Global annual cost of coastal defenses (capital and additional maintenance cost) from 2000 to 2100 versus global mean temperature anomaly with respect to 1985–2005.

Adapted from: Hinkel et al., 2014.[176]

outweigh the costs in the Indian Subcontinent, parts of Central Africa, and along the Nile Valley, although future risk in these regions would still increase compared with that of today.

Based on a global river width database and hydrological modeling, Lim et al.[177] reported that globally, increasing the river flood defense level from a 5- to 20-year return period led to a reduction of around 7 percent of flood-induced global GDP losses and reductions of 1–4 percent in the size of the affected populations. Using a different method that also considered future socio-economic changes and a wider range of flood risk management measures, Jongman et al.[178] estimated that the reductions in global fatalities and losses from river flooding would be as high as 5960 (69 percent) and US$468 billion (96 percent) (average of all projections), respectively, by the 2080s under a high-adaptation scenario.

3.3 Making Adaptation Decisions

Throughout this background paper it is clear that we regard infrastructure adaptation primarily as a challenge of decision-making at each stage in the gestation of an infrastructure system (see Figure 25). Infrastructure planning, design, and asset management decisions are constantly being made. The challenge is to embed adaptation, so that climate risks are understood at each stage and options for risk management are fully appraised with consideration of other policy objectives. The appraisal process involves weighing up the costs of adaptation with the benefits of risk reduction.[179] Uncertainties also need to be weighed up in the decision-making process, as the costs and benefits of adaptation will be subject to severe uncertainties.[180,181,182,183]

Good decision-making requires information. Our vision for embedding consideration of climate risk and adaptation at all stages in the infrastructure decision-making process depends on better information being made available worldwide. In Section 3.3.1, we discuss the transformative opportunities that now exist to provide information for risk and decisions worldwide.

3.3.1 SECURING PERFORMANCE OF INFRASTRUCTURE ASSETS IN A CHANGING CLIMATE

Decisions about adapting infrastructure assets and networks need to be made using a range of different scales. Design decisions for individual assets need to consider the projected climatic conditions that assets will be exposed to in the future. This may include increased flood levels in extreme events (e.g., due to sea level rise or changed rainfall patterns), wind damage to infrastructure in hurricanes (including direct wind loads and the effect of falling/flying debris). There will always be a residual risk of a climatic extreme that exceeds the design condition of any asset, especially as future climatic conditions are highly uncertain. Adaptation can never be absolute and there can be no universal target for the standard of protection as climate risks and adaptation benefits depend on location and context. Nonetheless, it is reasonable and necessary to work towards a situation in which climate change is incorporated in the design and management of every infrastructure asset and flexible options are prioritized wherever feasible (see Table 4 for examples). Engineering design standards and codes need to be applied and enforced, while NbS also offer ways of reducing risks that are more resilient in the long term and yield multiple co-benefits (Box 6).

Asset management and maintenance are crucial for ensuring the continued performance of infrastructure assets and systems. Asset management systems can be readily adapted in response to changing climatic conditions (e.g., by adjusting the frequency of vegetation management). However, sufficient resources are required to ensure that systems can cope with more severe climatic conditions, such as more intense rainfall. Whole-life costing can help to ensure that sufficient funds are allocated for asset management.

Incremental investments in adaptation when assets are being upgraded are often the most cost-effective opportunities to strengthen resilience. This includes activities such as relocating back-up generators out of the basement or adding more distribution connectivity to build in redundancy.

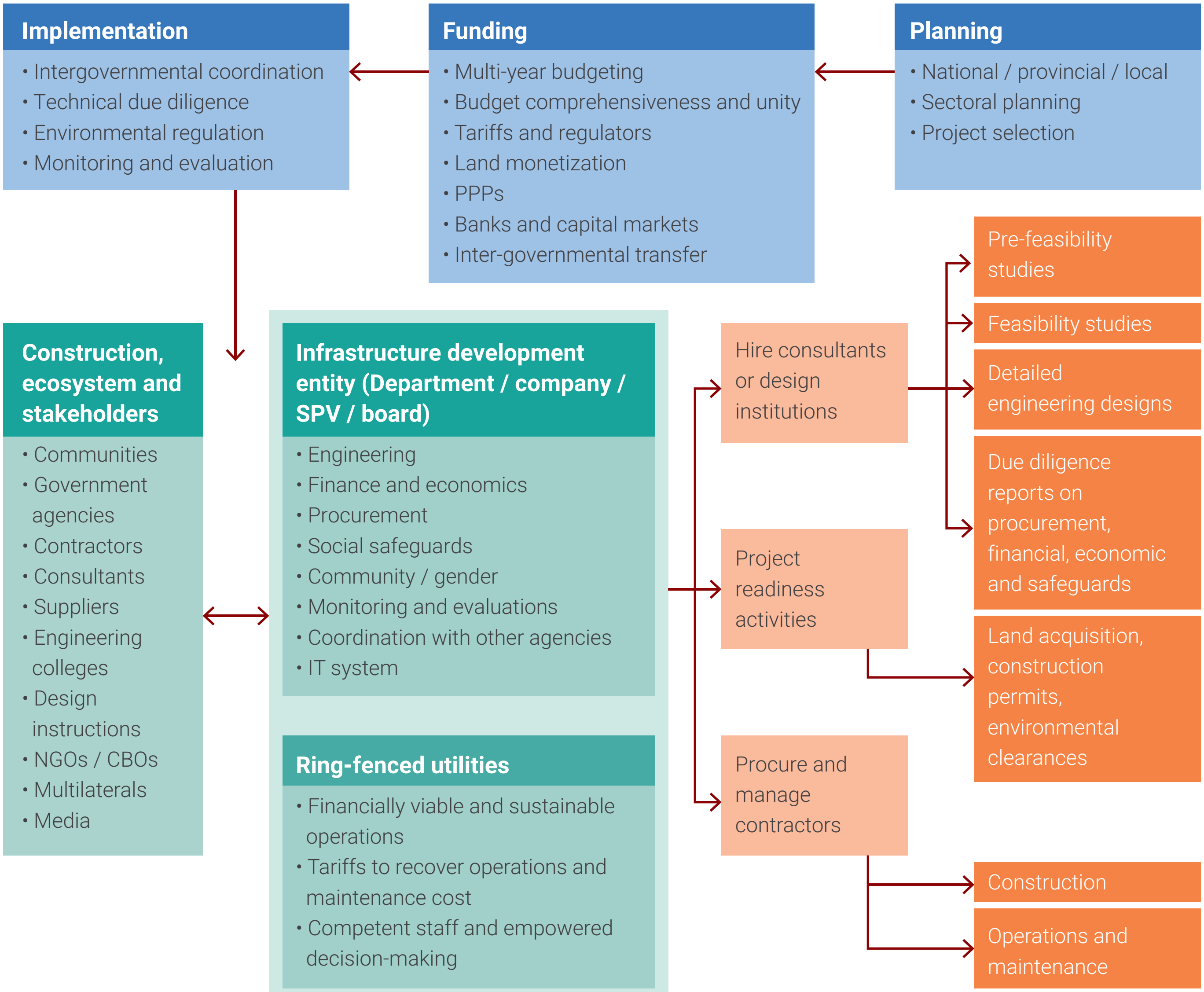
When major investments are required, in either new infrastructure or refurbishment, further opportunities may exist to enhance the resilience of infrastructure assets. For example, a highway corridor can be raised to become a flood barrier, provide reliable egress, and serve as a staging area for rescue efforts during extreme weather events. Alternatively, it could be made lower and designed with permeable surfaces to become a flood conduit or water absorption feature, depending on what is most appropriate to its location. Other examples of secondary or augmented utility is a power plant that can serve as a dark start resource for a city (i.e., an independent power station that does not rely on the external transmission network), a parking garage that can also store floodwater, and tower companies that can sell priority access to emergency services.

3.3.2 ENHANCING SYSTEM RESILIENCE

Infrastructure systems are important because of the services that they provide to individuals, society, and the economy. There are many ways in which service provision on infrastructure networks can be made more resilient to cope with and recover from extreme and disruptive events:

- **Forecasting and warning systems** enable infrastructure systems to be prepared during the onset of extreme

FIGURE 25 The Process of Planning and Implementing Infrastructure Projects



Adapted from: ADB, 2017.[184]

events (e.g., modifying reservoir operations in response to a drought forecast) and assist the management of infrastructure to avoid direct damage and disruption (e.g., prohibiting high-sided vehicles when high winds are forecast).

- **Diversified supply chains** enable essential goods and services to be substituted from different locations when supply chain disruptions occur.[185]
- **Storage of resources (e.g., of water, energy) and inventories** enables continued operations during temporary disruption and helps to minimize economic impacts (Box 7). Just-in-time delivery has been optimized to minimize the costs associated with holding stock, but makes systems very vulnerable to disruption.[186] A careful balance needs to be struck between efficiency and resilience, which may be modified based on warning systems. Energy storage provides back-up supply in the event of disruptions as well as relieving supply pressures, particularly during times of peak demand.
- **Demand management**, both in the long run and during disruptions such as droughts, reduces the stress on

TABLE 4 Examples of Adaptation Options for Climate-Proofing Energy Sub-sectors

ENERGY SUB-SECTOR	TECHNOLOGY AND STRUCTURAL MEASURES	MANAGEMENT AND SITING MEASURES
Thermal and nuclear power	• Adopt alternative cooling technologies such as closed loop and dry cooling.	• Site plants based on water access and away from high-risk areas. • Use alternative water sources, including grey water or seawater.
Hydropower	• Enhance reservoir capacity. • Improve design and location of spillways to manage changing water levels. • Culvert and drainage sizing revised for hydrological uncertainty. • Development of upstream sediment control facilities or sediment bypass tunnels/facilities. • Reassessment of dam type to allow overtopping (i.e., concrete dam). • Adapt concrete mix design to withstand more temperature variations. • Additional slope protection and stabilization measures. • Installation of variable speed turbines or turbines with higher efficiency for a wide range of discharges.	• Modify management procedures for water storage. • Site plants based on projections of hydrological conditions. • Enhance debris removal. • Demand-side management to reduce water consumption and enhance water re-use. • Creation of regulatory bodies that are mandated to develop and apply improved operating strategies.
Solar energy	• Modify surface material for PV panels for improved light diffusion. • Adapt material durability to extreme wind and precipitation.	• Site solar PV panels based on projected changes in cloud cover and air temperature. • Site CSP based on water availability. • Adjust design of buildings with passive and active solar heating. • Demand-side flexibility – enhance the installation of rooftop solar PV.
Wind power	• Alter turbine design to withstand high winds. • Improve material durability. • Fortify off-shore potential for wind energy. • Taller and larger wind turbines to improve efficiency.	• Site turbines based on projected changes in wind speed and direction, and exposure to extreme weather events.
Transportation, transmission and distribution (T&D)	• Increase T&D line capacity and ability to withstand higher snow and ice load. • Modify pipeline materials to be waterproof and able to withstand freeze-thaw cycles. • Replace wooden utility poles with steel poles.	• Place T&D lines underground. • Improve vegetation management around wires. • Site pipelines away from areas of high flood risk, extreme freeze-thaw cycles, and melting permafrost.

BOX 6 Sponge Cities

The concept of a "Sponge City" was introduced by the Chinese Central Government in 2013, in response to the increasing flood impacts inundating 234 cities across the country that year.[187,] Under the guidelines, sponge cities will collect, store, purify, and utilize 70 percent of rainwater across 80 percent of the urban area by 2030, through the combination of natural and engineered infrastructure.[188,189] The approach aims to change the traditional thinking and management design of discharging stormwater runoff to avoid inundation, to inviting and utilizing stormwater as much as possible. The Central Government is financially supporting the implementation of sponge cities across the country and has selected 16 initial pilot cities.[190]

The Jinhua Yanwei Island Park, located in the heart of Jinhua City, is a prime example of a successful sponge city. The project was completed in May 2014 and was awarded the World Architecture Festival's landscape of the year in 2015.[191,192] The design made use of former sand quarries, vegetating them with native wetland species on water-resilient terraced river embankments. The monsoon floods inundate and deposit fertile silt over the terraces, eliminating the requirement for irrigation and fertilization at any time of the year. The inland area is also entirely permeable through the extensive use of gravel reused from the site, and the pedestrian bridge connecting the cultural park to the city is elevated above the 200-year flood level. Overall, the project is a great success, with over 40,000 visitors using the park and bridge every day since it opened in May 2014.[193]

Image source: Waterbucket, 2017.[194]

infrastructure systems, enabling them to cope better with shocks.[195,196,197]

- **Financial instruments** like direct payments and well-designed insurance can help people to cope in extreme events and recover more quickly afterwards.

3.3.3 PLANNING FOR SUSTAINABLE INFRASTRUCTURE DEVELOPMENT

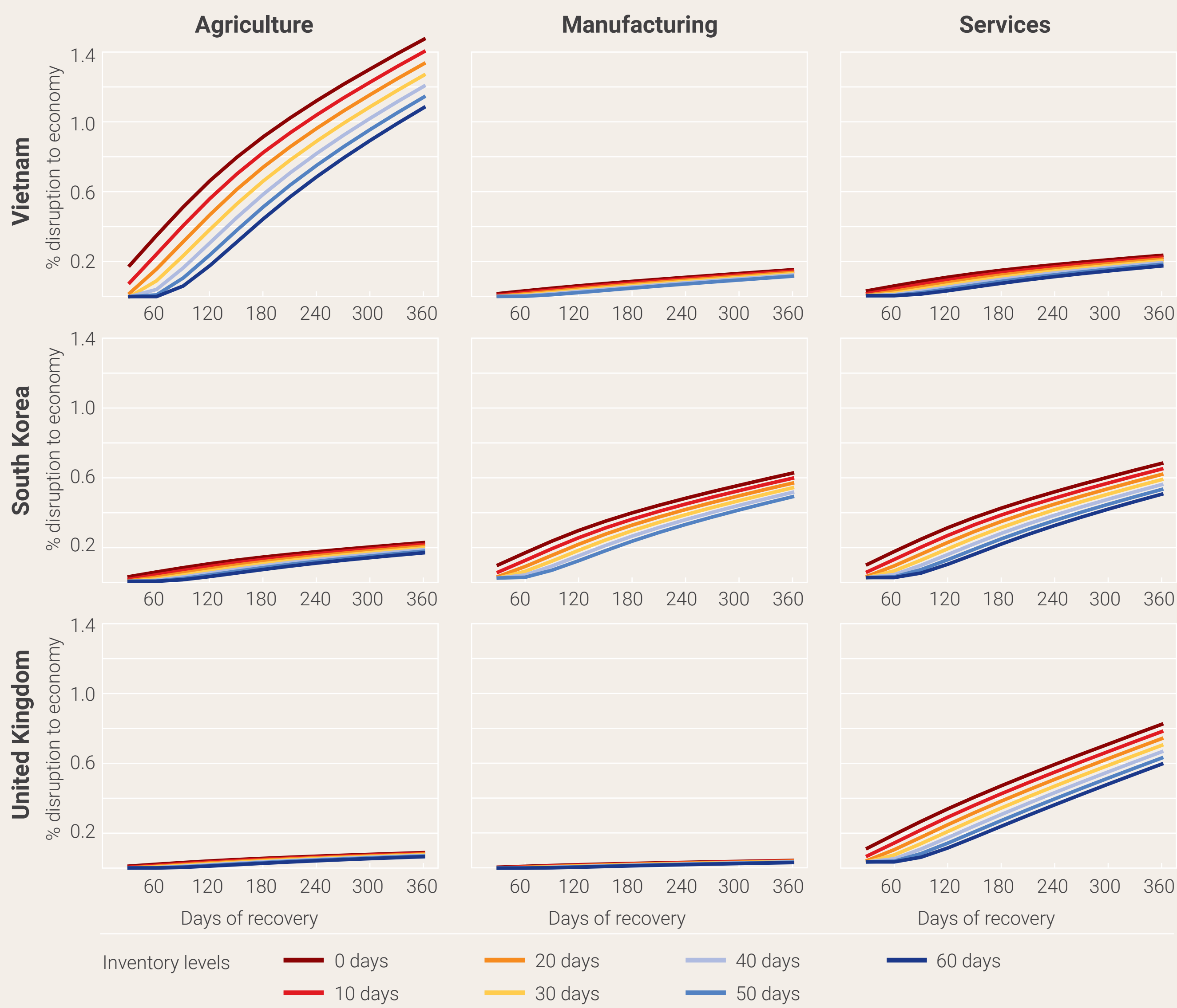
Adaptation needs to be considered from the earliest stages in the infrastructure planning and project inception processes.[198] Decisions regarding the location of new infrastructure are often made early in the planning process, yet they are critical for determining the exposure of infrastructure to climate risks. Some infrastructure is bound to be sited in hazardous locations (e.g., ports are on the coast and waterways), but in other instances, early review of options can reveal more resilient ways of developing systems.

Decisions regarding critical national infrastructure typically originate within national and state governments, and as part of national political processes. This is often as part of broader economic and spatial planning processes, for example, regarding urbanization and the location of future growth poles. Plans and proposals may emerge from

BOX 7 Quantified Analysis of the Costs And Benefits of Increasing Economic Resilience

We analyzed the sensitivity of different economies to infrastructure disruption during climatic extremes. Using the Multi-Regional Impact Assessment Model,[199,200] we analyzed the percentage of gross value added, that is lost due to increasingly lengthy infrastructure disruptions in three contrasting economies, namely Vietnam, South Korea, and the United Kingdom. The economic impact is projected to increase more or less linearly with the duration of disruption. The impact of infrastructure failure depends on the relative scale of economic sectors and the infrastructure systems they depend on. Oh et al.[201] demonstrated how the agriculture sector in Vietnam is sensitive to disruption of the transport network, which supplies domestic and international markets and incorporates stretches of road that are particularly vulnerable to climate change. They demonstrated that diversification of the network (including encouraging switching to railways) can help to reduce the economic loss. Our analysis further demonstrates how a modest increase in stocks (represented by the different colored lines in Figure 26) can help to reduce the economic impacts of disruption to supply chains.[202]

FIGURE 26 Analysis of the Economic Impacts of Critical Infrastructure Failure



different ministries and may be coordinated by finance or planning ministries, or specialist infrastructure units that advise these ministries. These are critical points for mainstreaming adaptation. The challenge is how to relate climate considerations to other policy demands (such as economic development, poverty alleviation, mitigation of carbon emission, resource efficiency, and biodiversity conservation). Decision-makers typically face multiple policy demands and need to be aware of climate risks to infrastructure plans, the benefits of adaptation, and potential synergies and trade-offs with other policy objectives.

Some major infrastructure decisions extend beyond the borders of a nation, such as transnational transport corridors, transboundary rivers, and regional energy transmission networks. Adaptation on these scales will require regional analysis of climate risks[203,204] and exploration of options for cooperative management of those risks. For example, analyses of the Eastern Nile in the context of possible climate changes in the region has demonstrated how cooperative approaches to reservoir management can help to manage drought risk for neighboring counties.[205]

Early discussions with financiers such as multilateral development banks (MDBs) are another point of leverage at which issues of climate risk and adaptation can be identified and explored. Planning climate-resilient infrastructure development involves systems thinking for the long term and exploring diverse options in a range of possible futures which will yield better and more sustainable infrastructure worldwide. Given the potential for decisions to become irreversible ("lock-in"), there is an urgent need to embed the principles of sustainable development in infrastructure decision-making.[206]

While national economic, spatial, and infrastructure plans are handled by national government, regional and city governments also play a crucial role in establishing local infrastructure priorities. In Section 2 of this background paper, we described how climate risks are sensitive to local conditions. City and local governments are well-placed to understand the local characteristics of climate risks and ensure that they are embedded in city development and infrastructure plans (Box 8).

4 Barriers and Enabling Actions

Adaptation of infrastructure systems to climate change should be in the interests of the people and institutions who own and/or are responsible for those systems. In this background paper, we have argued that there is no fixed target for infrastructure adaptation, therefore, the "right" amount of adaptation should depend on consideration of how the costs of adaptation compare with the benefits (in the broadest sense) of climate risk reduction and other co-benefits. That does not mean that every single decision, from design to maintenance, should be subject to cost-benefit analysis. As will be examined in Section 4.4, there is a place for proportionate regulation to set standards (which may be context-specific) to ensure there is a reasonable level of adaptation.

However, while risk reduction is a good motive for adaptation, we observe multiple barriers (e.g., inadequate information, excessive discounting of future risks, limitations in capacity for implementation, and limitations in available finance and technology) that mean that adaptation is not occurring at the scale one might expect.[207,208]

The organizations with responsibility for infrastructure seldom carry the full costs of failure or the future costs of adaptation. The consequences of infrastructure failure are usually widespread, particularly when a catastrophic failure occurs. These impacts include direct damage to infrastructure assets, which the infrastructure owner will have to repair, possibly with assistance for disaster recovery. In addition, disrupted infrastructure users seldom receive compensation. This disruption may impact people's access to essential services, such as healthcare and education. Impacts ripple further through the economy, for example, through disruptions to supply chains or disincentivization of investment. Ultimately, these impacts are felt by all of society, the economy, and the environment. Because non-state infrastructure owners and operators do not carry all of these risks (even if they are a government department), they need to be incentivized to manage the risks for which they are responsible. This requires a strong commitment from governments (national, city, and local) who play leading roles in steering the provision of infrastructure. Even where infrastructure is owned and operated by the state, there are many actors within

BOX 8 Planning to Avoid Increasing Vulnerability

Dhaka, the capital of the world's most densely populated country, Bangladesh, has been growing in an organic way, with the majority of the population, businesses, infrastructure, and economic activity gravitating towards the western part of the city. By extrapolating the current growth rate, it is expected that the population of the city will be 24.6 million by 2035. Therefore, there is a growing concern that this development path can only deliver up to a certain point. In response to these concerns, the World Bank has submitted a report, *Toward Great Dhaka*[209], that assessed and recommended how to direct Dhaka onto a better growth path.

Due to the availability of vast amounts of vacant land so close to the core of the city, the Dhaka Structure Plan 2016–35 highlighted that to reinforce economic development, East Dhaka could represent an opportunity for new, less congested, more productive, and more livable urban development. However, since East Dhaka is susceptible to flood risk, options for flood risk management were included from the outset in this ambitious urban development plan. The World Bank has assessed four development scenarios until 2035:

A. Business as usual (BAU)

B. Building the eastern flood embankment

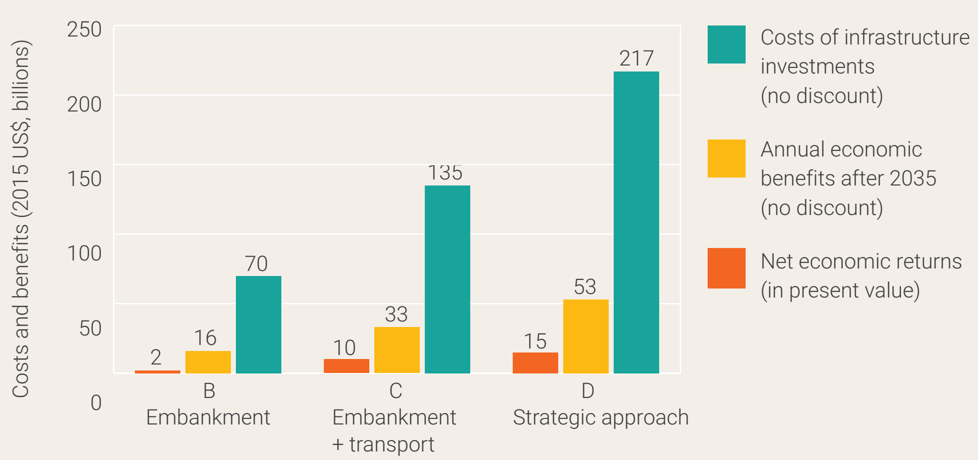
C. Building the eastern flood embankment and modern transport scheme

D. A strategic approach

The Bangladesh Water Development Board estimated the cost of the eastern embankment to be US$35.6 billion, excluding land acquisition and resettlement expenses. The cost of the transport infrastructure was estimated at US$8 billion, in addition to the US$14 billion required for transport investments for scenario A. While the costs of this integrated approach, which include flood risk management and other resilient infrastructure are large, the resulting economic benefits are enormous. As shown in Figure 27, the economic output of Dhaka is predicted to increase between US$16 billion and US$53 billion per year from 2035 onwards, depending on the scenario. Therefore, a single year of future output is more than the initial investment required for the three key interventions. Retrofitting East Dhaka later could be as expensive and challenging as retrofitting West Dhaka is now. Therefore, a coherent set of upfront interventions in East Dhaka could avoid irreversible encroachment, significantly transform Greater Dhaka, and boost Bangladesh's economic growth.

Source: Bird et al., 2018.[210]

FIGURE 27 Costs and Economic Benefits of Resilient Infrastructure Development in East Dhaka



Adapted from: Bird et al., 2018.[211]

government who may not be aware or incentivized to take adaptation action.

In the following sections, we examine policies and instruments that can help to mainstream adaptation in infrastructure planning, design, implementation and management.

4.1 Spatial Planning

Regulation of where construction takes place is a crucial determinant of future climate risks to infrastructure and buildings. Construction of new infrastructure not only potentially exposes new assets to climate risk, but also tends to stimulate building nearby, further adding to climate risk. Effective land zoning has long been recognized as an important way of managing risks from natural hazards. Climate change makes this process more complex due to uncertainties about future climate hazards (see Section 4.6).

The economic geography of many developing countries and emerging economies is rapidly changing, with rapid urbanization and the development of new economic corridors and special economic zones. These major commitments to the location of economic activity (which may be more or less planned) will be accompanied by development of necessary infrastructure, which will in turn promote further economic development. Climate risks and adaptation need to be embedded in this process in order to avoid locking in major vulnerabilities.

As spatial planning involves delicate trade-offs between different objectives for the use of space, it is an inherently political process that is often highly contested. By incorporating potential climate change impacts at the outset of infrastructure projects, spatial planners can contribute considerably to the long-term reliability of infrastructure systems. Key spatial planning tools, such as an environmental impact assessment (EIA), and to a lesser extent a strategic environmental assessment (SEA), are increasingly being used to identify and incorporate climate change impacts and adaptation throughout the project life cycle. An EIA assesses the potential environmental impacts of a project and identifies measures to avoid or minimize these impacts as conditions of approval for the project prior to its implementation.[212] National plans and programs, as well as regional development and land-use plans require an SEA. These strategic assessments provide a framework for sector plans and policies in areas such as energy, transport, and water infrastructure.

The Room for the River program (Box 9) is an example of how a strategic approach has been adopted to reallocate land to enable adaptation in densely populated areas of the Netherlands. In the United Kingdom, applications of major infrastructure projects are reviewed by the Planning Inspectorate to ensure compliance with a set of National Policy Statements (NPS). The government's objectives for nationally significant infrastructure projects are detailed in each NPS, which also incorporate current and projected capacity and demand. There are 12 designated or proposed statements, spanning the energy, water, and transport sectors.[213] These include support on how to account for climate change adaptation and mitigation. Developers in the United Kingdom need to provide evidence for how the latest climate projections have been incorporated in their designs to demonstrate robustness to extreme changes beyond the typical climate change projections.[214]

4.2 Regulation

Regulators can encourage resilient infrastructure by modifying technical requirements to account for future climate change (see also Section 4.4 on standards and codes). 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.[215] For example, Switzerland has revised the supervision and licensing processes to better account for climate change impacts for hydroelectric dams and reservoirs, as well as for transmission and distribution networks for gas and electricity. The country is also assessing the need to modify regulations governing the temperature of cooling water released back into rivers.[216] Regulations for cooling water discharges in the Netherlands were also changed after the drought of 2003. In the United States, provisions within the Clean Water Act regarding cooling water discharges have been modified, encouraging a switch to closed loop cooling systems (rather than open loop, as discussed in Section 2.3.2.1).

Regulators can also encourage investment in resilience by setting standards for service reliability.[217] For instance, storms cause disruptions to electricity services due to

BOX 9 Room for the River

The Netherlands is one of the most densely populated countries in the world, with half of its land surface below sea level. The Dutch landscape has been shaped by sea floods and the responses to these floods. However, in 1993 and 1995, flooding hit the Netherlands from behind its defenses, resulting in the evacuation of 250,000 people and 1 million head of livestock. The Dutch Room for the River program invested US$2.4 billion (EUR€2.2 billion) to give their river network more room to be able to manage high water levels. At more than 30 locations, various measures, including relocating dikes, widening and deepening river channels, lowering the level of the floodplain, implementing side channels alongside the main river channel, and removing obstacles such as bridges, have been implemented to increase rivers' conveyance and improve flood safety. The program protects the 4 million residents to a flood frequency of 1:1250 years.

One of the measures implemented was the widening of the river at the Overdiepse Polder. The Bergsche Maas river levels have declined by 27 cm during periods of high water through the lowering of the dike on the north bank. Removal of a poldered flood barrier usually renders the area no longer suitable for human activities; however, in the case of the Overdiepse Polder, the farmers designed a proposal for the construction of dwelling mounds (terps). This has enabled the farmers to continue to live and work in this riverside location.

The success of the Room for the River program has been attributed to the "multilevel water governance," where provinces, municipalities, regional water authorities, and Rijkswaterstaat have cooperated on the implementation and monitoring of the program. Residents and business communities have also been involved from the outset. The accomplishments of the Room for the River program have been internationally recognized, and have inspired similar development in other major deltas, such as the poldered region of the Mekong delta in Vietnam.

Source: Ruimte Voor de Rivier, 2019.[218]

Image: Royal HaskoningDHV, 2019.[219]

airborne material such as trees and branches. Such impacts are likely to be affected by climate change due to more extreme wind gusts in particular regions of the world. In Finland, the 2009 Electricity Market Act requires that, by 2028, electricity distribution networks should be designed, constructed, and maintained in such a way that storms or snow interruptions do not exceed 6 hours in densely-populated areas and 36 hours in other areas.[220]

Stricter requirements for "critical infrastructure" reliability and resilience to natural hazards have been, or are being, set in several Organization for Economic Cooperation and Development (OECD) countries. In the United Kingdom, resilience of infrastructure systems to climate change is part of the mandate of its energy (Ofgem), water (Ofwat), and rail (ORR) regulators, who have aimed to improve the price control review mechanisms to reflect longer asset life spans and to better manage inherent uncertainties.[221] The UK Regulators Network, founded in 2014, facilitates cross-sectoral resilience of infrastructure systems to climate change across the United Kingdom.[222]

Since many infrastructures are publicly procured, mandating climate adaptation regulations in public procurement processes provides an important point of leverage. For example, requiring publicly supported infrastructure investments to undertake climate resilience assessments would not only reduce the climate risk faced by individual assets, but would also help to build capacity for carrying out such assessments in both public and private sectors.

Governments and multilateral development banks are increasingly incorporating resilience-related requirements into project approval to encourage consideration of climate change impacts at the project development stage. The European Commission's Environmental and Impact Assessment Directive was amended in 2014 to include the consideration of climate change impacts on infrastructure projects that require an EIA.[223] In Canada, guidelines have been issued on incorporating climate change into the federal EIA process.[224]

To reach projects and companies beyond the scope of the environmental assessment process, governments have also adopted policies to encourage businesses to identify and address risks specific to them. In 2014, President Obama signed an executive order, requiring the integration of climate resilience into all U.S. international development work to the extent permitted by law. The order specifies that agencies must assess and evaluate climate-related risks to and vulnerabilities within agency strategies, plans, programs, projects, investments, and overseas facilities, and adjust these according to the evaluations made.[225] Similarly, in the European Union, major projects (i.e., large infrastructure projects) cofinanced by the European Structural and Investment Funds are required to undertake a climate risk and vulnerability assessment, and include appropriate adaptation measures when needed. The UK Adaptation Reporting Power asks companies, including energy generators and transporters, to report on how they project climate change will impact them, and propose ways of managing these impacts. This information is included in reports produced by the companies and are made publicly available.

The UK's National Infrastructure Assessment is produced by the National Infrastructure Commission (NIC) to provide a strategic long-term view on national infrastructure provision. In November 2018, the NIC embarked on a study of the resilience of the UK's infrastructure, which will build on previous studies in the UK's Climate Change Risk Assessment[226] and the Committee on Climate Change.[227]

4.3 Climate Risk Reporting

There is growing interest in how better understanding and management of physical climate risks can be incentivized through climate risk reporting. Different versions of risk reporting exist, including financial risk reporting for asset owners,[228] risk screening as part of project preparation processes, and risk reporting by infrastructure operators as part of national risk assessment processes. The process of risk reporting helps to expose risks that people may not have been fully aware of. It provides the required evidence if climate risks are to be properly priced into the value of privately-owned assets, including equity stakes in infrastructure or bond finance, which is secured on infrastructure assets. Infrastructure owners and operators in the private sector can be incentivized to better manage climate risk through risk reporting, particularly where risk reporting may have a material influence on the value of their assets.

Climate risk screening helps to ensure that climate change adaptation has been considered at critical points in the project preparation process. For example, the EIB has rolled out a business process to identify and reduce physical climate risks in investment loans. Also, the World Bank are developing a Rating System for Project Resilience which is intended to help target investments at projects that have more effectively managed climate risks. This could lead to projects benefiting from a good resilience rating gaining better access to capital. The ratings could also be used for investors with social objectives to select projects that build the resilience of the beneficiaries, for instance, through the creation of resilient bonds built based on the rating system. Rating systems could provide a simple tool for public procurement, making it easier for governments to require their vendors to consider and address disaster and climate risks in their projects. However, there are inevitable limitations in what can be achieved with risk screening, as climate risk management needs to be a *process* that continues throughout the project life cycle. Thus, there is a limit to what can be achieved at any specific stage in project preparation. There is also a question as to whether screening promotes "BAU" projects and does not encourage more creative thinking about adaptation.

Governments need to verify that climate risks are appropriately identified and managed for critical infrastructure that is owned and operated by the private sector, and request companies to disclose their climate risks.[229] In many countries, disclosure of financial fillings of climate risks are already required within laws and regulations.[230,231] France is the only G20 country that requires listed companies to disclose the financial risks of climate change impacts in their annual reports, including the measures that have been taken to reduce them.[232,233]

Mandatory climate risk reporting has been shown to provide internal benefits to organizations by raising awareness of climate risks at higher levels within the organization and giving climate risk management added legitimacy.[234] As well as incentivizing adaptation, this mechanism is designed to encourage sharing of information on infrastructure interdependencies and to inform national climate change risk assessment.[235]

A range of verified ratings and tools have been established for civil engineering and infrastructure projects to assess how well specific projects are considering climate risks (e.g., CEEQUAL in the United Kingdom, ENVISION in the United States, and the Infrastructure Sustainability Rating Tool in Australia), but their use remains limited.[236] The GRESB assessment framework introduced a new module to assess adaptation and resilience in infrastructure investments.[237] While each of these standards is tailored to their particular user base, their proliferation risks dispersing effort and creating rival data sets, which could slow the measurement and analysis of adaptation and resilience. There is enormous value in reaching a consensus regarding adaptation and resilience metrics.

4.4 Standards and Codes

Standards and codes determine how infrastructure is designed and implemented, but they need to be appropriate and enforced. In this background paper we have argued that since there is no fixed target for adaptation, adaptation choices should be informed by cost benefit assessments (CBAs), considerations of tolerable risk, and the range of future uncertainties. It would be time-consuming to apply CBAs to every single adaptation decision, but codes provide a simpler set of rules that are intended to ensure that standards are uniformly and universally applied. However, codes need to be appropriate to the context in which they are applied in order to ensure that standardized approaches do not lead to systematic over- or under-investment in resilience.[238] It can take a very long time to develop codes, and outdated practices may be applied in the meantime, which is a serious risk considering the urgency of adaptation.

The environmental loading that infrastructure is designed to resist (e.g., wind loading or river flows) is set out in design standards and codes of practice. Traditionally, these standards have been based on statistical analyses of weather observations (e.g., wind speeds); however, climate change means that previous environmental statics may change in the future. This means that statistical estimates, which have always been subject to uncertainty, are now even more uncertain.[239] Nonetheless, authorities are beginning to incorporate climate change in design standards.

Performance-based design, which has been widely adopted for the design of earthquake-resistant buildings,[240] helps to promote engineering creativity and ensure that designs are context-appropriate by requiring designers to demonstrate how they will achieve the requisite levels of system performance. The emphasis is on specifying the outcome rather than how it is to be achieved. A performance-based approach provides more flexibility to deal with change and the unpredictable nature of climate change risks. In the USA, for example, the city of Cambridge, Massachusetts has adopted a standard to protect to the projected 2070 10-year flood level from precipitation or sea level rise/storm surge (whichever is higher), as well as a standard to be able to cope with the 2070 100-year flood elevation.[241]

Revision of infrastructure standards and codes to account for climate change is the prerogative of specialized civil engineering institutions or trade associations. Over the last 15 years, an increasing number of institutions have revised several standards related to infrastructure. Two major international standardization organizations, the European Committee for Standardization (CEN, Centre Européen de Normalisation) and the International Standards Organization (ISO), are reviewing existing standards to better incorporate the risks from climate change. By 2020, the CEN plans to revise their Eurocodes, a set of European civil engineering technical standards for buildings, transport, and energy infrastructure,[242] and are also adjusting product standards to account for climate change. The ISO is developing a set of standards through its adaptation task force to better assess vulnerability, plan adaptation, and monitor and evaluate adaptation performance.[243] Both of these reviews cover the assessment, reuse, and retrofitting of existing infrastructure, as well as the design of new developments.[244]

Sector-specific organizations are working to define standards for climate resilience in their areas. Box 10 describes an example of the collaborative development of climate-resilient standards for rural roads in India. Similarly, the World Association for Waterborne Transport Infrastructure (PIANC) established an action plan to provide technical guidance on adaptation of maritime and inland port and navigation infrastructure to climate change impacts.[245,246] England's Highways Agency has developed new codes for pavement design and improvements in existing and new road drainage systems.[247] From 2002, hurricane straps and other construction features that help reduce damage from hurricanes were mandated in building codes in the U.S. state of Florida.[248]

The American Society of Civil Engineers (ASCE) Flood Resistant Design and Construction standards define requirements for buildings, which include energy infrastructure. These cover building performance, the use of materials, and siting requirements to minimize flood risk.[249] In Canada, guidelines for adapting infrastructure in the Arctic region have been developed by the Standards Council of Canada through the Northern Infrastructure Standardization Initiative. These guidelines, which apply to both new and existing infrastructure, describe standards for buildings, building foundations, and drainage systems that can accommodate changing conditions, such as permafrost melt and changing snow load risk. ASCE is presently preparing a standard for sustainable infrastructure.

4.5 Co-benefits

Many of the options for adaptation of infrastructure systems that have been considered in this report will bring additional benefits besides the primary benefit of reducing physical climate risk. A strong case for adaptation can be made based on the benefits of reducing vulnerability to today's climatic variability and extremes. In addition, well-designed adaptation options can deliver other benefits, such as enhancing the livability of places and restoring the natural environment.

Promoting co-benefits can help to build an immediate case and public support for adaptation. Policies to manage demand for infrastructure services can save users' money and reduce greenhouse gas emissions, as well as enhance the resilience of infrastructure systems by increasing their capacity margins.

NbS bring multiple co-benefits by enhancing biodiversity and other ecosystem services. To fulfil its function, infrastructure is dependent on a number of ecosystem services, including flood regulation, coastal storm protection, erosion control, landslide prevention, water quality regulation, air quality regulation, and carbon sequestration and storage for climate regulation.[250] There is increasing interest in the possibility of substituting "green infrastructure" for "grey infrastructure,"[251] or using them in complementary ways. NbS have most commonly been used in the water sector, for example, for flood protection, groundwater recharge, and to mitigate water quality issues.[252,253,254,255] They have also been used to reduce the risk of landslides and slope instability, for example, through conservation and restoration of upslope vegetation and the use of bio-engineering techniques to stabilize soils.

BOX 10 Development of Best Practices and Standards for Climate-resilient Rural Roads in India

The World Bank is supporting a national-scale programmatic approach to climate resilient roads in India. The Pradhan Mantri Gram Sadak Yojana (PMGSY) program aims to upgrade the core network of approximately 1.1 million km of rural roads to "all-weather" status, connecting villages to nearby markets or higher category roads, ensuring economic and social resilience of rural communities in vulnerable locations. Out of this sanctioned length, approximately 565,000 km of road has been constructed to date. This program is currently the largest rural roads program in the world.[256]

Overarching Strategy

The majority of India's existing rural road network is susceptible to damage from floods, intense rainfall, landslides, waterlogging, and droughts. In the state of Uttarakhand, the 2013 flash flood (collapse of the Chorabari glacial lake) affected over 900,000 people, killing 580 and destroying the road network, which badly hampered rescue and relief operations.[257] In response to such challenges, the PMGSY program approach is to integrate climate risks and opportunities at every level of policy planning, investment design, implementation, and network operations. This is achieved with each new road project following the subsequent strategic steps:

- Coordinate between departments to generate and share climate-related data for project planning and design;
- Map short- and long-term climate risks, their impacts on road infrastructure, and possible mitigation/adaptation measures;
- Describe available adaptation options for roads in flood-prone areas;
- Estimate costs and benefits of possible adaptation options; and
- Provide a framework and recommendations for maintenance and updates to road assets in future uncertain conditions.

Design Standards and Maintenance

The PMGSY program closely collaborates with Indian engineering institutions to ensure appropriate design standards are applied to the construction of rural roads. Some of the key design standards for vulnerable rural roads in hillside environments include:[258]

- The minimum gradient should be 1–2 percent to avoid ponding of water on the road surface, while the maximum gradient permitted is 8 percent. This range should ensure that road surface drainage is adequate and functioning.
- Use causeways rather than culverts, but if culverts are used, ensure they are properly sized and designed.
- Have well-vegetated slopes using deep-rooted vegetation, to stabilize the earth.
- Keep up-to-date on road maintenance.

As part of the program, there is a three-tier quality supervision system in place, spanning from local to state and national quality monitoring. By introducing an independent inspector, the contractor on the project must complete the work to the quality standards required in the contract. Ensuring the contractor is not responsible for quality assurance avoids frequently experienced issues regarding lower standards of the completed work.[259]

The program encourages and trains local agencies and villagers to participate in the construction of the roads, and informs them of the basic road maintenance tasks for the future. This provides a sense of local road ownership for its operation and maintenance. A concept currently being discussed is the creation of a "climate resilience road fund" to fund responses to ensure and restore functionality, such as emergency maintenance and repairs.[260] Alongside the inclusion of the local communities, the program also provides specially-designed training and awareness programs for policy and decision-makers, consultants, and contractors on the importance of integrating climate resilience into rural road plans and designs in India.

The potential for NbS is explored in more detail in the accompanying Background Paper on the Natural Environment and Adaptation.

4.6 Dealing with Uncertainty

Uncertainties regarding climate risks and the costs and benefits of adaptation are a persistent barrier to action. Since the most harmful climate risks materialize as extreme events, they are, by definition, infrequent; therefore, decision-makers may not pay them sufficient attention (availability bias). Trends in extremes are difficult to detect, and the Intergovernmental Panel on Climate Change tends to only report "low confidence" in whether these phenomena are being influenced by climate change. Therefore, decision-makers are unsure about the amount of adaptation required to cope with climate change now, and are even less sure about what to plan for in the future. Infrastructure systems are particularly subject to uncertainty because they are composed of long-lived assets, which will inhabit a future world that is uncertain in many senses, not just climatically but also technologically and socio-economically.

Projecting the impacts of climate change (and hence the benefits of adaptation) involves a "cascade of uncertainty",[261] which begins with the uncertainties in climate projections (greenhouse gas emissions, global climate change, regional effects, and extremes), but also incorporates the uncertain impacts of climate on infrastructure systems. As illustrated in Section 2 of this background paper, despite rapid advances in our capacity to perform risk analyses of infrastructure systems, the sensitivity of these systems to climate hazards and the socio-economic consequences of damage and disruption are only just beginning to be understood.

The effectiveness of adaptation options is also uncertain, depending on how novel or well-studied the options are. Many of the phenomena that infrastructure adaptation options seek to modify, such as slope stability or coastal erosion, are complex because they involve the interplay between engineered and natural systems. NbS that seek to work with natural processes potentially bring many co-benefits (e.g., by restoring ecosystems), but their behavior is more complex and less predictable than conventional engineered systems, which represents a barrier to their uptake.

4.6.1 INFORMATION PROVISION

Climate-related information, including data and projects, is fundamental for making informed decisions about the design and timing of infrastructure adaptation actions. In particular, there is a need for:

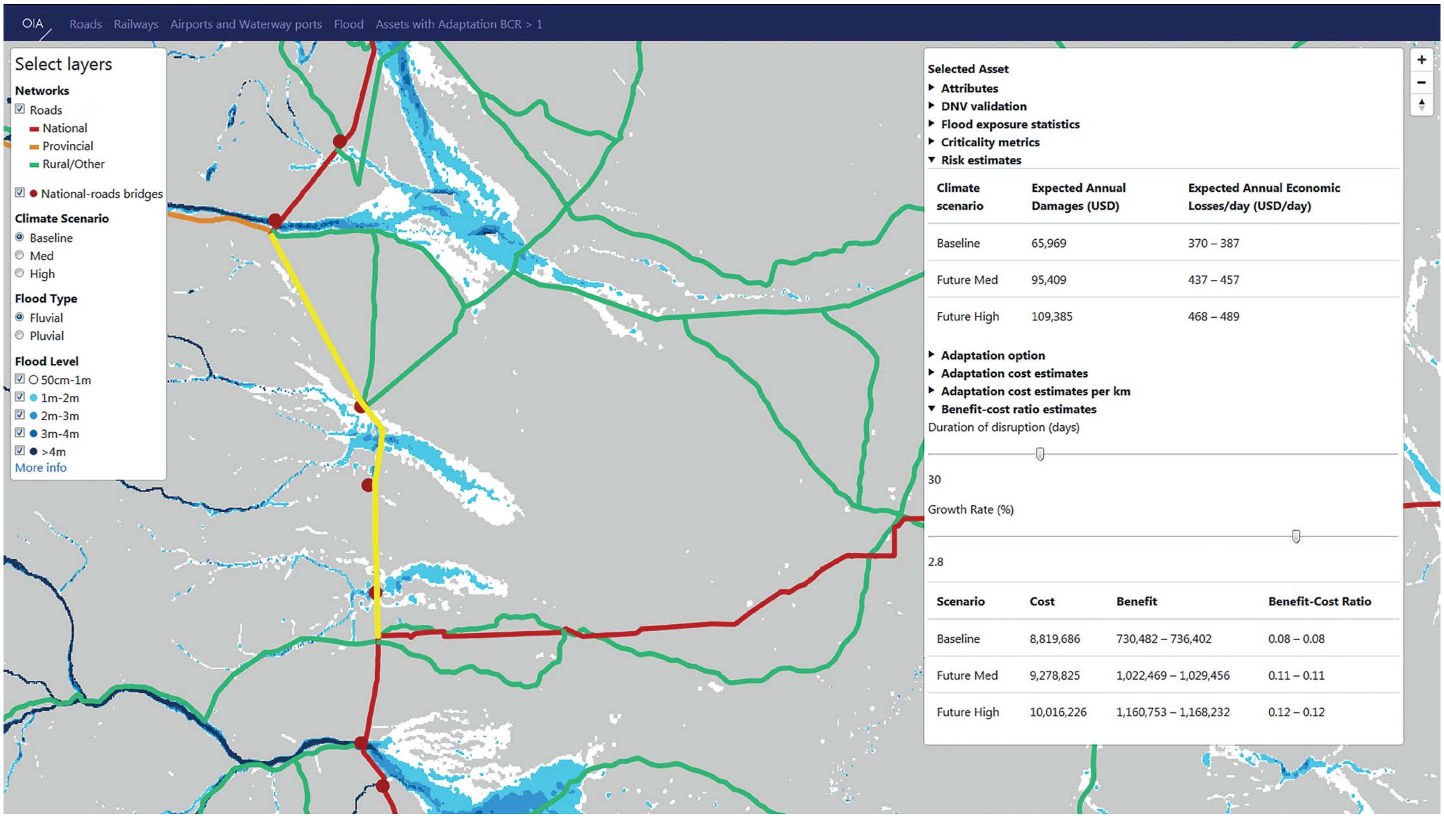
- Robust observations and modeled projections for future climatic and hydrological trends;
- Tools and technical capacity to analyze and interpret information and the consequent implications for decision-making; and
- Forums that facilitate management of interdependencies through the safe sharing of information between infrastructure operators, both within and between sectors.[262,263]

While there are inevitably many uncertainties in the understanding of climate risks to infrastructure and the benefits of adaptation, there is often more knowledge available than decision-makers are aware of. There is growing experience of the practice of adapting infrastructure systems to climate risks. The best practice reviews, guidance documents, and other knowledge sources that we have reviewed for this Background Paper and recommend include:

- Routledge Handbook of Sustainable and Resilient Infrastructure;[264]
- Climate-Resilient Infrastructure: Adaptive Design and Risk Management;[265]
- Adapting Infrastructure and Civil Engineering Practice to a Changing Climate;[266] and
- Ready for Tomorrow: Seven Strategies for Climate-Resilient Infrastructure.[267]

A data revolution is taking place, based on a combination of new big data sources and computational capacity that is enabling risk analysis calculations to be performed on a large scale. We have exploited this data revolution for much of the analysis reported in this background paper using new global climate hazard analyses and open source infrastructure data sets (e.g., OpenStreetMap, Enipedia, and Global Energy Observatory). These data sets combine the potential of global satellite observation with local knowledge, which is extremely important, as the behavior

FIGURE 28 Screen Shot of a Tool Developed for the Government of Argentina with World Bank Support to Pinpoint Vulnerabilities in the Transport Network to Flood Hazards



of infrastructure assets depends to a large extent on the specific local conditions as well as the infrastructure's design and condition.

Figure 28 provides an example of a web-based interface for navigating the transport infrastructure dataset that was developed as part of the World Bank funded Transport Risk Analysis in Argentina. This platform provides a geospatial interface for examining road and rail infrastructure assets, together with the spatial extent of climate hazards, to inform prioritization of adaptation decisions in the transport sector.

Governments support knowledge-building through the improved collection and dissemination of climate projections and weather data, which aid comprehension of projected climate change impacts. The European Commission[268] has provided a summary of available resources to assist the development of climate resilient infrastructure. There is a range of high-level guidance for specific infrastructure sectors, including transport (ITF, 2016),[269] energy (IEA, 2015),[270] and water (OECD, 2013),[271] as well as across the infrastructure sectors

Once physical impacts have been projected, they need to be translated into risks that are understood by infrastructure planners, designers, and asset managers.

4.6.2 DECISION-MAKING UNDER UNCERTAINTY

In the face of uncertainty, it is beneficial to identify robust infrastructure plans and designs, including systems that will perform acceptably well under a wide range of possible future conditions. Methods for adaptation decision-making under uncertainty have flourished in the last decade and infrastructure systems, in particular water resource systems, have been the foremost example of application of these methodologies.[272,273,274] While there are many variants of methodologies for robust decision-making under uncertainty, they share the following characteristics:

1. Consideration of a wide range of possible future conditions.

2. Avoiding, or only tentatively using, probabilities to quantify the relative likelihood of future conditions, because of the severe uncertainties regarding the magnitude of future changes.

3. Testing the performance of alternative adaptation options and evaluating performance with respect to one or more performance metrics.

Some methods also incorporate a "scenario discovery" step that seeks to identify the combinations of future conditions that may lead to undesirable system performance.

There is almost inevitably a trade-off between robustness and cost. There is also a trade-off between robustness and the desired level of risk,[275,276] because a system that is highly optimized to achieve a target level of risk is vulnerable to the unexpected, whereas the same system will be able to guarantee the desired performance more robustly if the tolerable level of risk is higher.

Robustness can be achieved by introducing flexibility to adapt in the face of future changes (further discussed in Section 4.6.3). It can also be attained by designing to resist a wide range of possible future loadings.

4.6.3 ADAPTIVE MANAGEMENT

Systems that can adapt when confronted with unexpected or changing future conditions are inherently better at coping with future uncertainty. While infrastructure systems are often very costly to adapt or retrofit, approaches to enhance adaptive management can be promoted, such as:

- **Design for adaptability**. Given the very high cost of retrofitting infrastructure, it can be cost-effective to design for future adaptation. This involves incurring up-front costs to reduce the future cost of adaptation, for example, by widening the foundations of a flood protection embankment so that the embankment can be readily raised in the future.[277,278] Kuala Lumpur's SMART tunnel is a road tunnel that also serves as a drainage tunnel during storms. A theoretical framework underpinning decisions of this type is *real options theory*.[279]

- **Demand-side options**. Actions to reduce demand for infrastructure services and/or shift demand to less congested times (e.g., smart metering) increase the gap between the use of the system and its ultimate capacity. This means that when stress (e.g., droughts) or shocks occur, there is more capacity to cope. Demand-side adaptations are also attractive because they usually save costs for utility users.

- **Incremental adaptations**. While some adaptations of infrastructure supplies involve "lumpy" investment commitments, others (such as fixing leaks in water pipes) are more incremental. Actions to manage demand (e.g., household water metering and incentives) are also amenable to being made more or less aggressive depending on urgency. These incremental options are attractive ways of responding to uncertainty because the scale of action can be adapted.

- **The use of land**. The way in which land is allocated is fundamental to adaptation decision-making. It is costly to reallocate land once it has been allocated to urban uses. Leaving land available for future adaptation (e.g., to enable setting back of flood defenses) leaves options open for the future, although there is a cost of foregone opportunities for development.[280]

- **Adaptation pathways**. Adaptation occurs through a sequence of decisions that may be characterized by a decision tree. The use of adaptation pathways was first promoted in the Thames Estuary 2100 project, which developed a "scenario neutral" approach whereby critical adaptation decisions planned to be triggered by thresholds of sea level rise (without predicting when that sea level rise would occur)[281] (Box 11). This approach was further elaborated by Haasnoot et al.[282]

4.7 Capacity Building

We have argued that there are actions that can be taken to address barriers to adaptation and improve decision-making. However, all of these actions, from the methods for adaptive management to the enforcement of regulations, require human and institutional capacity. Individuals with the appropriate range of skills are required to analyze climate risks, pinpoint vulnerabilities, appraise adaptation options, access finance, and implement policies in a sustained and purposeful way. There is also a requirement for institutions that can manage data, allocate resources, and enforce regulations, as well as recruit and retain the right people. These are particular challenges in developing countries that lack the requisite human

BOX 11 Adaptation Pathways in the Thames Estuary

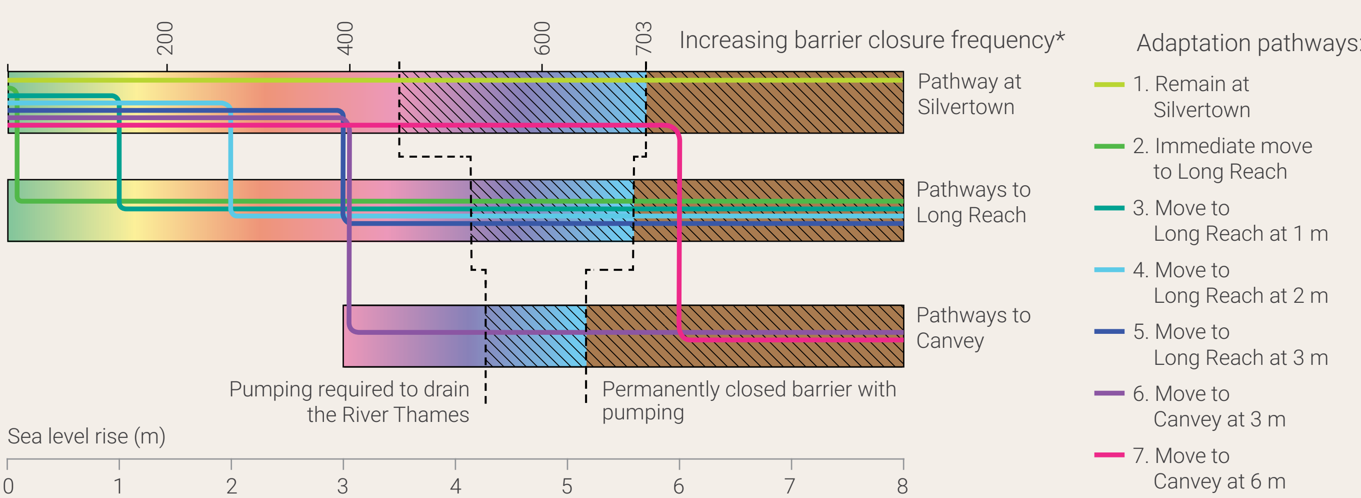
London is currently protected from coastal and tidal flooding by the Thames Barrier at Silvertown and a series of embankments, walls, and barriers on either side of the estuary from Silvertown towards the sea (Figure 29). If it were not for the Thames Barrier, the center of London would be flooded by extreme surge tides.

The possible effects of accelerating sea level rise in London during the 21st century have been extensively studied,[283,284] notably in the Thames Estuary 2100 (TE2100) study. TE2100 proposed a strategy for a series of adaptation measures whose timing would depend on the rate of sea level rise,[285] including new barriers at Long Reach or Canvey. In more recent analyses, two critical adaptation thresholds have been identified: (1) when mechanical pumping has to be provided alongside the moveable tidal barrier in order to drain the River Thames; and (2) when a permanently closed barrier with pumping to remove all of the river flow becomes the only viable means of avoiding flooding (Figure 30). There is a range of feasible adaptation pathways, all of which start with the current situation of opening the Thames Barrier at Silvertown and finish with a closed barrage at one of the three sites. The adaptation pathway that most cost-effectively and robustly maintains risk at a tolerable level involves moving the Thames Barrier 17 km towards the sea if mean sea level rises 2 m above present levels.

FIGURE 29 Thames Estuary Flood Defense System

Notes: Flood defense system, including the existing Thames Barrier site at Silvertown and possible new barrier sites at Long Reach and Canvey. *Source*: Hall et al., 2019.[286]

FIGURE 30 Adaptation Pathways for the Thames Estuary Flood Defenses



Notes: Adaptation pathways, assuming no raising of the flood walls in central London. * Number of times per year when the barrier is closed, up to a maximum of 703 per year, which is every high tide. *Source*: Hall et al., 2019.[287]

capacity. In small island developing states, small size means that it can be difficult to build a critical mass of technical expertise.

Infrastructure adaptation requires a cadre of people who are equipped with interdisciplinary skills, ranging from the technicalities of the structure and function of infrastructure systems, to the nature of climatic extremes and environmental responses and the economics of decision-making. A wider range of skills needs to be covered in the curriculum of infrastructure decision-makers, and these people need to be adept team-workers. We have highlighted the rapid proliferation of new data sets and tools that can help decision-makers in all parts of the world to better understand infrastructure decisions and the climate risks they are exposed to.[288]

4.7.1 INSTITUTIONAL CAPACITY

Adaptation is complex because it spans across many functions of government (national, regional, and city) and the private sector. Therefore, implementing adaptation policies requires a high degree of coordination. Adaptation is seldom the top priority for any of the relevant government ministries with responsibility for infrastructure and the environment; therefore, the arrangements for adaptation coordination require the capacity to keep adaptation on the agenda.

The formation of interdepartmental committees and working groups can often bring together disparate government players to share information and reduce duplication. The importance of coordination between national and subnational levels of government is evidenced by the coordinated response to Hurricane Sandy in 2012 by the U.S. Federal Emergency Management Agency, and state and local authorities, which facilitated access to federal financial resources and communication among all government levels.

Governments also bring together private and public sector stakeholders. For instance, effective energy facilities and design standards are supported by the coordination of governments, regulators, operators, and technical experts.

Legal arrangements, such as mandatory climate risk assessments and adaptation plans, are aligned with national infrastructure plans and can provide a robust framework that ensures that adaptation is not overlooked.

4.7.2 INFRASTRUCTURE FINANCE

Though accurate estimates of the full (private and public) financial flows to adaptation and mitigation are difficult to obtain, estimates of only public flows demonstrate that the US$12.9 billion in public flows for adaptation were less than half of the US$38.9 billion flows for mitigation.[289] Macquarie’s Background Paper for the GCA entitled “Measuring and valuing adaptation to climate change” argues that there is a need to increase the finance directed towards adaptation and to ensure that infrastructures on which modern economies depend are resilient to climate change. Infrastructure investors must recognize that physical climate risks threaten the returns on their investments. They therefore need to scrutinize how these risks are managed and incentivize adaptation. The African Facility for Climate Resilient Investment[290] is intended to provide a knowledge hub for decision-makers and financiers in order to sustain Africa’s growth.

While investment in resilience can bring extra cost, it also creates value, since more resilient infrastructure is more valuable than infrastructure that is vulnerable to sea-level rise, higher ambient temperatures, or extreme weather events. A challenge for investors in infrastructure (as well as for policy makers, regulators, and other stakeholders) lies in measuring that added value as a means to justify and incentivize the additional investment required. Resilient infrastructure is not adequately rewarded with a lower cost of capital or higher credit rating. Furthermore, regulation or standards are not sufficient to support the necessary investments.

In their Background Paper, Macquarie cites draft work with Willis Towers Watson, that identifies the three-fold challenges of:

- **Deal flow/top-down level**. Sovereigns and supranational institutions struggle to identify, prioritize, and construct portfolios of infrastructure investments based on resilience considerations. As a result, even when governments attempt to incorporate physical climate risk considerations in infrastructure development, this is performed in an inefficient or disconnected manner.
- **Asset design and structuring level**. There are inadequate incentives for the integration of resilience considerations in the design and structuring of investments. It remains an analytical challenge to

understand what levels of capital expenditure lead to an optimized level of exposure (i.e., the climate-related operation expenditure over the life span of the asset) with a corresponding increase in cash flow predictability.

- **Financing level**. The lack of cost-of-capital incentives, together with the nature of project finance, undermines the integration of climate risk considerations within infrastructure investments.

Projects continue to be the unit of currency in infrastructure finance, when, as we have argued here, some of the greatest opportunities for embedding adaptation exist upstream of the project preparation process. A shift from project finance to programmatic finance of infrastructure systems provides the opportunity to shift adaptation planning "upstream" and "upscale," where there is most potential to manage future vulnerabilities. A review of the "programmatic approach" that was adopted by the Climate Investment Funds[291] found that the use of the programmatic approach had significant advantages over a project-by-project approach. It contributed to important outcomes, including:

- An organized and consultative way to prioritize investments;
- A successful platform for MDBs for joint programming and division of labor;
- An opportunity to link national strategies and priorities with resources; and
- Increased ownership, awareness, and a willingness for broader strategic dialogue within governments.

5 Conclusions

Climate change is a major threat to the infrastructure systems that sustain societies. Major economic and societal disruptions induced by natural catastrophes are propagated and amplified through infrastructure networks. For example, in England, eight times as many (20 million) properties are at risk of being impacted by utility failure during a flood than are at risk of direct flooding from rivers and the sea (2.4 million). In developed countries, most of the infrastructure has been designed and built without consideration of climate change, while in emerging economies, huge amounts of infrastructure development is now taking place that could lock in future vulnerability if steps are not urgently taken to mainstream adaptation decision-making. The scale of the planned infrastructure investments over the next decades provides a great opportunity to integrate adaptation alongside other development objectives, while also recognizing their trade-offs.

There has been very rapid development in understanding the options, priorities, and pathways for adapting infrastructure systems. This is reflected in city-scale, national, and global programs, as well as reports on infrastructure risks by governments,[292] the World Bank,[293] engineering institutions,[294] and the insurance industry[295]. A global Coalition on Disaster Resilient Infrastructure was announced in New Delhi in March 2019.[296] This growing level of interest is motivating a quest for better methodologies and datasets to assess climate risks, prioritize action and develop long-term adaptive strategies. It recognized that making good adaptation decisions requires evidence for infrastructure network vulnerabilities, risks, adaptation costs, and benefits under climate change-driven extreme weather events and chronic changes including sea level rise.

Adaptation of infrastructure systems is underway, albeit not at a pace that is commensurate with the scale of current climate risks or their projected increase in the future. This includes strengthening of infrastructure assets and action to reduce demand for infrastructure services, such as water demand management. Risk screening, procurement processes, and regulations mandate the consideration of climate risks, for example, by multilateral development banks. Physical climate risk reporting, such as through the initiative of the Task Force on Climate-Related Financial Disclosure, is further incentivizing the consideration of climate risks by the finance sector.

In this background paper, we have illustrated the state of the art in climate risk assessment and adaptation studies. Data sets and capabilities now exist to quantify climate risks to energy, transport, and water infrastructure on a global scale. This evidence shows that 200,000 km of roads are currently exposed to climate-related hazards, and could increase to 237,000 km by 2050 due to climate change, not including the new highway construction that will take place in that period. Climate change means that 81–86 percent of the thermoelectric power plants worldwide will have their usable capacity constrained by reduced cooling water availability in the period from 2040 to 2069,[297] and reductions in capacity could be experienced at 61–74 percent of the hydropower plants. Power plants with a total capacity of 700 GW and less than 0.5 m of flood protection are currently susceptible to flooding during the 100-year flood. The cost of providing water supplies in developing countries is expected to more than double by the 2050s.

We also provide new data-driven evidence on national, regional, and global-scale climate risk and adaptation assessments to highlight recent advances made in infrastructure risk and adaptation metrics for informed policy-making. National-scale studies illustrate how advanced risk analytics are being used to highlight vulnerabilities in infrastructure networks at national and transnational scales (e.g., Tanzania). The analysis reported that Vietnam is going one step further by appraising the costs and benefits of a range of measures to reduce risk, to inform NDCs to meet the goals of the Paris Agreement. The proliferation of data-driven models has shown that there is great opportunity to bridge the gap between scientific evidence required by policy makers in making informed decisions about infrastructure planning and climate change adaptation. While recognizing and highlighting the infancy of any definitive national or global practice integrating infrastructure climate risk assessment and planning, this background paper makes the case for an evidence-based integrated framework for climate risk analysis and adaption planning.

Our vision is for such evidence-based adaptation and resilience to be embedded throughout the life cycle of infrastructure planning, project preparation, finance, design, delivery, operation, and maintenance. This requires strong commitment from governments (national, city, and local), multilateral development banks, and the private sector, which all play roles in infrastructure planning, procurement, and regulation. We have argued that adaptation needs to be brought "upstream" and "upscale" in the infrastructure decision-making process so it is integrated from the outset of national infrastructure planning and becomes integral to a strategic approach for ensuring sustainable infrastructure systems and services in the future. In many instances, this will involve transnational collaboration, such as for transnational river management and energy transmission. Delivering on this vision will require capacity building, finance and, above all, political commitment to sustainable and resilient infrastructure.

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ABOUT THE ENVIRONMENTAL CHANGE INSTITUTE

The Environmental Change Institute is Oxford University's interdisciplinary institute for research into the complex processes of global environmental change, the exploration of sustainable responses, and the promotion of change for the better through partnership and education. The ECI leads the UK Infrastructure Transitions Research Consortium which has pioneered methods for infrastructure systems analysis and adaptation planning in the UK and worldwide.

ABOUT THE GLOBAL COMMISSION ON ADAPTATION

The Global Commission on Adaptation seeks to accelerate adaptation action and support by elevating the political visibility of adaptation and focusing on concrete solutions. It is convened by 20 countries and guided by more than 30 Commissioners, and co-managed by the Global Center on Adaptation and World Resources Institute.

GLOSSARY OF KEY TERMS

Adaptation

Initiatives and measures taken to adjust natural and human systems to be able to suit a changed environment as a result of actual or expected climate change. It refers to changes in processes, practices, and structures to moderate potential damages or benefit from opportunities associated with climate change.

Hazard

An agent that has the potential to cause harm to a vulnerable target.

Infrastructure Systems

Networked systems that deliver services such as energy, water, waste management, transport and telecommunications. Broader definitions also include social infrastructure (e.g., social protection systems, healthcare systems (including public health), financial and insurance systems, education systems, and law enforcement and justice).

Mitigation

Interventions taken to reduce the severity of impact from climate change.

Resilience

Climate resilience is the capacity for a socio-ecological system to absorb stresses and maintain function in the face of external stresses imposed by climate change.

Risk

The probability that exposure to a hazard will lead to a negative consequence.

Sustainable infrastructure

Infrastructure projects that are planned, designed, constructed, operated, and decommissioned in a manner to ensure economic and financial, social, environmental (including climate resilience), and institutional sustainability over the entire life cycle of the project.

Vulnerability

The diminished capacity of an individual or group to anticipate, cope with, resist, and recover from the impact of a hazard.