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CIViC: Critical Infrastructure Vulnerability to Climate Change

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Rialtas na hÉireann
Government of Ireland

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EPA RESEARCH PROGRAMME 2021–2030

CIViC: Critical Infrastructure Vulnerability to Climate Change

(2016-CCRP-MS.41)

EPA Research Report

Prepared for the Environmental Protection Agency

by

University College Cork

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Modern society relies on the effective functioning of critical infrastructure (CI) networks to provide public services, enhance quality of life and spur economic growth (Boin and McConnell, 2007). It is thus vital to examine how Ireland's extensive and valuable CI networks will perform not only today, but into the future, considering climate change effects. This project examines the vulnerability of, and risks to, Irish CI due to climate change on two levels. A geographic information system (GIS)-based high-level approach is used as a form of risk screening to examine vulnerabilities across Ireland's four CI sectors, namely transport, energy, water and information and communications technology (ICT). This work is presented in Part A of the report. Having examined the output of the high-level analysis, and noted the limitations of such a broad approach for informing actual climate change adaptation actions, a more detailed, fully quantitative risk analysis is explored in Part B of the report for a single aspect of Ireland's CI. Part B develops a step-by-step approach, before implementing it to illustrate a fully quantitative risk-based decision support framework.

The key risks identified from the GIS-based risk-screening analysis in Part A are as follows:

- Transport sector: fluvial flooding and coastal inundation/coastal flooding are key climate change risks.
- Energy sector: climate change risks related to extreme wind speeds are likely to be a major challenge, with increased risk of flooding also of concern. Cascading failures from the energy sector into other sectors are also a key multi-sectoral risk.
- Water sector: key climate change risks include flooding and wastewater treatment overflow related to extreme rainfall events and cascading failures from the energy sector. Future projected reductions in summer rainfall volumes also pose a risk to Ireland's water supply resource.
- ICT sector: climate change threats related to extreme wind speed risks are a key concern, as are cascading failures from the energy sector.
- The cross-sectoral geospatial risk ranking tool developed herein, which accounts for only the geographical proximity of infrastructure assets, highlighted Ireland's main urban areas as climate change risk hotspots; however, some rural areas also had high relative risk ranking values.

While the high-level analysis aided in identifying key risks, the detailed quantitative analysis described in Part B was required to help inform actual climate adaptation action, owing to the complex and costly nature of adaptation actions. Key outputs and findings of this work include the following:

- A step-by-step framework was developed that, when applied, will provide quantitative risk-based decision support for climate change impacts and climate change adaptation analysis for infrastructure.
- A case study showed that climate change impacts for power pole networks are likely to be significant, with projected increases in pole wind failures of 24% in Cork and 16% in Dublin by mid-century under representative concentration pathway 4.5.
- Climate change adaptation strategies that mitigate climate change impacts on network performance were easily developed; however, it was far more challenging to develop cost-effective adaptation strategies.
- One of the adaptation strategies developed herein projected a net present value of +€25/pole by mid-century, i.e. approximately €50 million in savings across the Irish network versus the business-as-usual approach.

The key lessons and recommendations for future work, as discussed in Chapter 13 of the report, are:

- More in-depth risk-screening analysis across Ireland's CI networks, with more detailed assessment of the consequences of failures (i.e. criticality of assets) and vulnerability (likelihood of damage given the hazard), would be very useful, as the scope of the current project was somewhat limited by project scale, i.e. a desk study scale with a budget of <€100,000.

- A GIS-based risk-screening approach can be effective in highlighting possible climate change risks, but is limited in its ability to actually inform appropriate climate change adaptation actions for CI (which tend to be costly measures).
- It is thus vital that we move towards more detailed, fully quantitative assessments (ideally probabilistic) for all CI sectors that can inform effective adaptation actions, thus avoiding opportunity costs associated with risk neglect, worst-case thinking, etc.
- Cascading failures and interdependencies across infrastructure networks, especially arising from power failures, are an important consideration and should be examined in detail for Ireland's CI.

The study highlighted the need for CI sectors to collect and share detailed and regionally specific information (GIS data) on operations, procedures, failure incidents, costs, etc.

1 Introduction

Critical infrastructure (CI) is defined by EU legislation (Council Directive 2008/114/EC) as "an asset or system which is essential for the maintenance of vital societal functions. Damage to CI through natural disasters, terrorism, criminal activity or malicious behaviour, may have a significant negative impact on the security of the EU and the well-being of its citizens" (EU, 2008). The recommendations of the Irish Citizens' Assembly on how the state can make Ireland a leader in tackling climate change, published in 2017, refer to CI as including energy, transport, built environment, water and communications infrastructures (Citizens' Assembly, 2017). Ireland's National Adaptation Framework (NAF) groups transport infrastructure, energy and gas networks, and communications networks under CI as one of four key thematic areas for Ireland's adaptation planning (DCCAE, 2018a). In general in the international literature, the definition of what constitutes CI can vary from country to country, with no unanimous agreement on which infrastructure networks are considered critical (Hammerli and Renda, 2009). In the present report, the term CI is used to refer to the four infrastructure sectors that are perhaps most commonly referred to as CI internationally, namely transport infrastructure, energy infrastructure, water infrastructure, and information and communications technology (ICT) infrastructure.

Modern society relies on the effective functioning of these CI networks to provide public services, enhance quality of life, sustain private profits and spur economic growth (Boin and McConnell, 2007). In this context, it is important to consider how these infrastructure networks will perform not only today, but also into the future. The Intergovernmental Panel on Climate Change (IPCC) states that climate change has unequivocally had an impact on various aspects of the natural and built environments, including our CI (IPCC, 2014a). It is therefore vital to quantify potential increases in risk to existing CI, with a view to reducing future vulnerability through climate adaptation. This, however, is not straightforward given (1) the scale of CI networks; (2) the variation in characteristics and vulnerability associated with elements across the network (Ryan *et al*., 2014); (3) the natural temporal and spatial variability of the climate (Feser *et al*., 2011); (4) the complexity of impacts that arise from interactions of different climatic effects (i.e. temperature, rainfall, wind speeds, etc.) (Ryan *et al*., 2016); (5) the uncertainty associated with climate change predictions (Nolan, 2015); and (6) the uncertainty associated with predicting the long-term performance and deterioration of infrastructure assets (even without climate change effects) (Ryan and O'Connor, 2013). Thus, the implementation of effective climate adaptation strategies for CI will require detailed assessment incorporating uncertainty and variability using probabilistic methods. Such detailed assessments are in effect quantitative risk-based decision support tools. These tools are particularly important for CI networks, where climate adaptation strategies for vast networks can cost many millions of euros. Part B (Chapters 10–12) of this report presents an illustrative case study of a detailed probabilistic assessment that provides risk-based decision support for one element of Ireland's CI, namely power distribution pole networks. Importantly, a general framework for a detailed probabilistic assessment is also presented in Part B and can be applied to any type of infrastructure network.

Although these detailed assessments are essential in informing effective adaptation actions, the first requisite step in adaptation planning is to get a general understanding of climate change risks posed to Ireland's CI. This information can be obtained through high-level risk assessments, which help establish the more general vulnerability of Irish CI sectors to climate change and the risks posed, increasing industry, government and public awareness. These assessments are, in effect, a risk-screening tool. A number of valuable studies have been conducted in an Irish context to this end in recent years (DCCAE, 2018b; DTTAS, 2017). The work presented in this report aims to build on these studies through a geographic information system (GIS)-based high-level analysis of the existing risk, and possible future risks, posed to Ireland's CI across the four main sectors. This high-level analysis is presented in Part A (Chapters 3–9) of the report.

The report is laid out so that the reader can navigate easily to the aspects of the Critical Infrastructure Vulnerability to Climate Change – CIViC – project that are of interest. As mentioned, Part A presents the high-level assessment. Chapter 3 in Part A provides details of the literature review and the methodology used for the GIS-based high-level risk assessment. The findings of the analysis for the different sectors are then presented separately in the four subsequent chapters (Chapters 4–7). If the reader requires information on how to conduct a more detailed quantitative risk assessment, they are referred to the framework presented in Part B. As discussed above, Part B also illustrates the effectiveness of such an approach, quantifying climate change risks and the cost–benefit outcomes of climate adaption actions for an Irish CI network.

The overall aims and objectives of this report are outlined below:

1. Develop a **framework for conducting a GIS-based high-level climate change risk assessment** (CCRA) for CI (Part A).
2. Conduct a high-level climate change risk-screening analysis for Irish CI using the framework, **providing high-level insights into the vulnerability of Irish CI to climate change** (Part A).
3. Having illustrated the capabilities and limitations of the high-level assessment, **present a quantitative risk-based decision support framework** that utilises detailed probabilistic risk modelling to quantify both projected climate change risks and the appropriateness of climate adaptation actions (Part B).
4. Illustrate the usefulness of the risk-based decision support framework as a tool for informing climate change adaptation actions through a **case study of the Irish energy distribution network** (Part B).

2 Policy Context

2.1 Summary of Irish Climate Change Policy

In response to the 2009 EU White Paper on adapting to climate change (EC, 2009), the then Department of Environment, Community and Local Government developed a National Climate Change Adaptation Framework (NCCAF) in December 2012 (DECLG, 2012a). This marked the first step in developing a comprehensive national policy to encourage the implementation of adaptation measures aimed at reducing vulnerability to climate change impacts across key economic sectors and at the local level. The National Policy Position on Climate Action and Low-Carbon Development (DECC, 2013) established the fundamental national objective of achieving a transition to a competitive, low-carbon, climate-resilient and environmentally sustainable economy by 2050. Climate change adaptation will play a crucial role in successfully achieving this transition. The Climate Action and Low Carbon Development Act (Government of Ireland, 2015) provided for the preparation of plans covering climate change mitigation and adaptation with the purpose of meeting the National Transition Objective. The 2015 Act was Ireland's first piece of dedicated climate change legislation and, importantly, put the development of the NAF and the sectoral adaptation plans on a statutory footing.

Building on the 2015 Act, Ireland's first NAF was published by the then Department for Communications, Climate Action and Environment (DCCAE) on 19 January 2018, and will be reviewed at least once every 5 years. The NAF provides for the preparation of statutory sectoral adaptation plans and specifies the national strategy for the application of adaptation measures (sectoral and local) to reduce the vulnerability of the state to the negative effects of climate change and avail of any positive effects of climate change that may occur. The first NAF and its successors aim to set out the context to ensure that local authorities, regions and key sectors can analyse the important climate change risks and vulnerabilities, implement climate resilience actions and ensure that climate adaptation considerations are mainstreamed into all local, regional and national policymaking. The first NAF outlines an approach to climate adaptation in Ireland that involves the whole of government and society. Under the NAF, seven government departments are required to prepare 12 sectoral adaptation plans. In May 2018, Sectoral Planning Guidelines for Climate Change Adaptation were published with the aim of supporting the 12 sectors identified in developing their adaptation plans under the 2015 Act, while ensuring consistency and coherence between the approaches adopted. At a local level, the NAF requires that each local authority make and adopt local adaptation strategies with the support of the four climate action regional offices (CAROs), established in 2018. In December 2018, Local Authority Adaptation Strategy Development Guidelines (DCCAE, 2018c) were also published to assist local authorities with this task. All sectoral and local adaptation plans were submitted to government for approval in September 2019. In June 2019, another significant climate change policy document was launched by the DCCAE in the form of the Climate Action Plan 2019 (DCCAE, 2019). The whole-of-government plan sets out an ambitious course of action over the coming years to address the issue of climate breakdown. The plan's primary focus is reducing CO_2 emissions for Ireland, but climate adaptation is also discussed in Chapter 16 of the policy document. Figure 2.1 shows the evolution of Irish climate policy.

2.2 The Policy Context of the CIViC Project

The CIViC project is one of a number of research projects (including Connection Nature, Urb-ADAPT, EcoStructure and C-Risk) exploring the area of climate change impacts and risks for Ireland. The CIViC project focuses solely on Irish CI and has two main elements, both of which seek to inform Irish climate change policy:

1. Part A: the first part of the project comprises a high-level national CCRA of the four main CI sectors (i.e. transport, energy, water and ICT). It uses GIS data to take account of the spatial

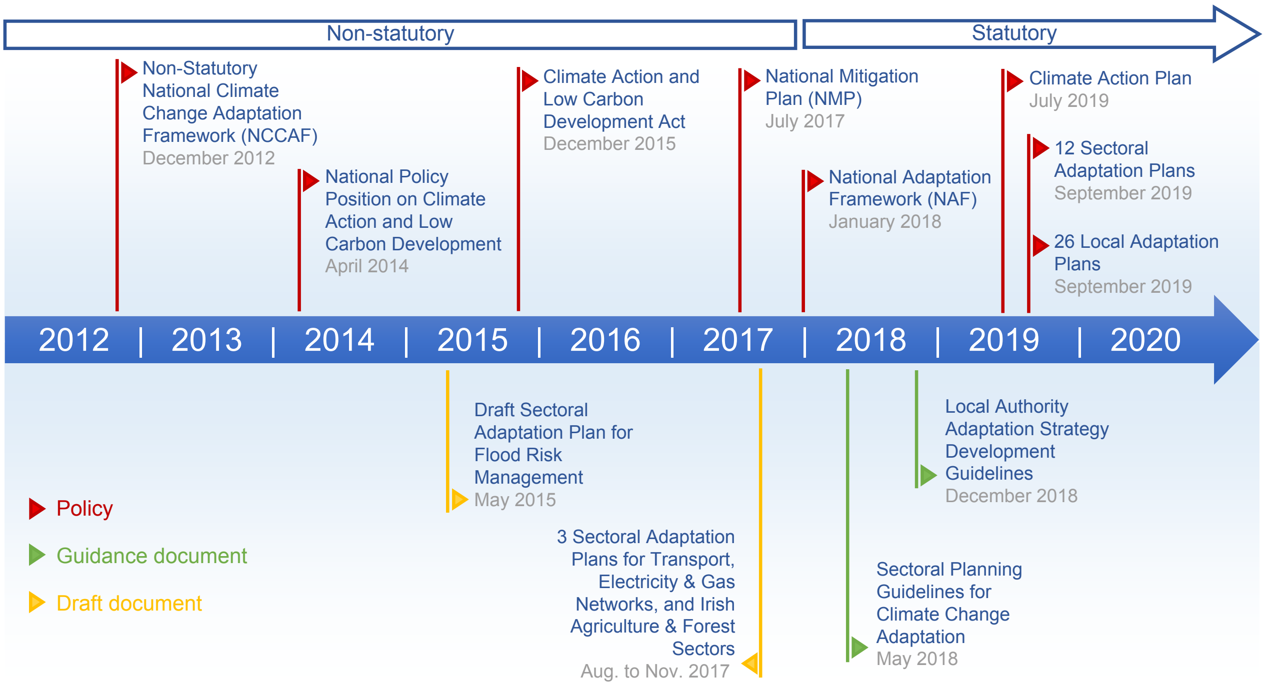

Figure 2.1. Evolution of Irish climate policy (adapted from Flood *et al.*, 2020).

variability of the current climate, climate change projections and CI location and subsequent hazard exposure.

2. Part B: building on the analysis in Part A, the second part of the project provides a framework for progression from high-level risk-screening analysis to a more informative quantitative risk assessment that can be actively used to inform climate adaptation action for infrastructure assets/networks that were flagged as potentially at risk in Part A.

It is hoped that these two elements of work will contribute to the aims of the NAF and the 2019 Climate Action Plan in developing a more climate resilient Ireland in the following ways:

1. The high-level analysis in Part A sets out a GIS-based risk-screening approach. This framework could be utilised in sectoral climate adaptation plans to help locate CI assets/networks that are potentially at risk from climate change. Aspects of the framework have already significantly informed the methodology underpinning the GIS-based assessment in the latest draft statutory Climate Change Adaptation Plan for Transport Infrastructure (DTTAS, 2019).
2. The CIViC project involved a considerable level of engagement with national infrastructure stakeholders and the creation of a GIS inventory of Irish CI for the transport, energy, water and ICT sectors. A number of challenges were identified in this regard relating to data-sharing and commercial/security sensitivity issues. It is envisaged that this report will assist in future GIS-based assessments as part of the NAF through (1) highlighting the need for CI owners/operators to develop and share GIS data relating to CI going forward (subject to non-disclosure agreements where appropriate); (2) the identification and collection of public GIS data; and (3) the establishment of a precedence for data-sharing in collaboration with stakeholders.
3. The outputs and findings of the high-level GIS-based risk assessments in Part A build on existing national studies (DCCAE, 2018b; DTTAS, 2017) and provide an enhanced understanding of the full range of sectoral vulnerability to climate change across the four CI sectors. It is envisaged that the findings will thus assist in developing a number of relevant climate change adaptation plans under the NAF.

4. Importantly, Part B of the report illustrates a framework for how sectors and local authorities can progress from risk screening to quantitative risk analysis and subsequent quantitative risk-based decision support. This progression is essential to ensure the avoidance of significant opportunity costs associated with implementing suboptimal climate adaptation measures. The case study presented in Part B for the energy sector helps illustrate the approach in real-life terms and highlights the advantages of using risk-based decision support in practice.

Points 1, 2 and 3 fall within the scope of the first three steps of the adaptation planning process developed in the Sectoral Planning Guidelines for Climate Change Adaptation (shown in Figure 2.2). The quantitative risk-based decision support tool developed (point 4) can be adopted and adjusted for any infrastructure network, contributing to the achievement of step 4 (assessment of priority impacts) and step 5 (development of adaptation plans) in Figure 2.2 below.

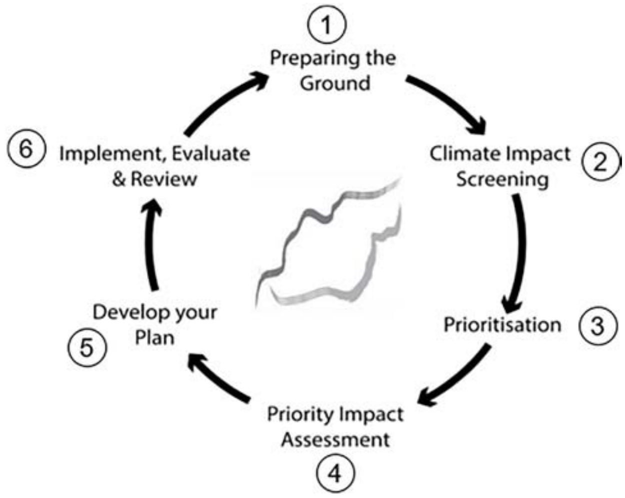

Figure 2.2. Schematic diagram of the adaptation planning process (from DCCAE, 2018d).

Part A

High-level Climate Change Risk Assessment of National Critical Infrastructure

3 High-level Risk Assessment

The first part of the CIViC project was aimed at conducting a high-level assessment of climate change risks to the existing national CI (i.e. transport, energy, water and ICT), using GIS data to consider spatial variability. In Ireland, four draft sectoral adaptation plans were prepared under the non-statutory 2012 framework (DAFM, 2017; DCCAE, 2018b; DTTAS, 2017; OPW, 2015). These reports constitute an important contribution to Irish climate change literature. However, they do not consider the spatial distribution of the infrastructure system or the climate hazards, but rather aim to establish the relationship between the climate hazards on the one hand and the various assets of the CI sectors on the other. However, climate hazards present large spatial variability, and the vulnerability of a given CI asset depends highly on its geographical location and surrounding environment. Consequently, there is a need for a national GIS-based high-level analysis of the climate risks posed to Irish CI that accounts for spatial variability. This GIS-based analysis can contribute to future iterations of the NAF as a first step towards the development of appropriate adaptation measures across the different CI sectors. Importantly, the NAF is required to undergo review by the Minister for the Environment, Climate and Communications at least once in every 5-year period.

It is noted that interdependencies between sectors, or susceptibility to cascading failures, is also an important consideration, as recognised in the C-Risk project (Flood *et al.*, 2020). In practice, however, considering interdependencies in CCRA on a local or regional level is challenging owing to a lack of clear connections between CI systems' functionalities and between stakeholders of the various sectors (Dawson *et al.*, 2018). Given that the CIViC project was a desk study-scale project (budget <€100,000), it was not possible to consider CI sector interdependency herein, in addition to the high-level analysis for all sectors and detailed probabilistic assessment (Part B). However, because of the importance of sectoral interdependencies, steps were taken to examine the geographical proximity of CI assets across the various sectors. Consequently, this risk-screening analysis considers only the geospatial proximity of CI assets, one of the four infrastructure interdependencies classified by Rinaldi *et al*. (2001) as physical, geographical, cyber and logical. However, accounting for this geographical proximity of infrastructure assets across sectors constitutes a useful initial step in considering a minimum level of intersection between the various infrastructure systems. This shift towards consideration of interdependencies is important given that infrastructure vulnerabilities to climate change are generally assessed independently for each sector, and sectoral adaptation strategies are developed (DCCAE, 2018a,c; DTTAS, 2017).

Section 3.1 presents a brief literature review of national, European and international reports and research papers on high-level CCRAs. Section 3.2 presents the framework for the GIS-based high-level CCRA used in this study. The implementation of the high-level approach is then presented for each of the four CI sectors, i.e. transport, energy, water and ICT, in Chapters 4–7, respectively. Chapter 8 summarises some of the results of the cross-sectoral geospatial risk ranking that incorporates the four CI sectors and their geographical proximity.

3.1 Literature Review

The increasing need to understand how climate change may affect the various infrastructure sectors has led infrastructure management specialists and policy actors across the globe to invest in projects on CCRAs of national CI (EU, 2013; Street, 2016; US Department of Energy, 2016). Many works have been carried out at European level (Dawson, 2017; HR Wallingford, 2014; Koutroulis *et al.*, 2018) and beyond (AFW and CVC, 2017; Fisk, 2017; Kember, 2012; Mazumder *et al.*, 2018) to further understanding of the repercussions of climate change on CI. For instance, the European research project RAIN (Risk Analysis of Infrastructure Networks) (Nogal *et al.*, 2016) describes a multidisciplinary approach for risk analysis of the land transport networks and the energy and telecommunication systems in response to extreme weather events (EWEs). Under the EU INTACT (Impact of Extreme Weather on Critical Infrastructure) project (Bucchignani and Gutierrez, 2015), a platform was developed that offers stakeholders and policymakers decision support methods and tools that enable them to plan for infrastructure resilience in the context of a changing climate. Other researchers have looked in more detail at parts of the CI network (e.g. Bastidas-Arteaga and Stewart, 2019). A review of the main projects related to the analysis of climate risks posed to infrastructure can be found in Sanchez-Matellanes *et al*. (2018).

In the literature, different approaches for high-level vulnerability assessment to climate change can be found. Some national assessments (Dawson, 2017; DCCAE, 2018a; DTTAS, 2017; Melillo *et al*., 2014; Stevens, 2008; Vonk *et al*., 2015) provide a relatively general consideration of the impacts of future climate change on national CI by stating the major and minor climate risks and their potential trends in the future, based on published evidence. Other assessments develop ranking matrices of, for example, sectors' vulnerability levels to climate change (Zebisch *et al*., 2005), impact levels of EWEs on CI (Nogal *et al*., 2016) or relationships between infrastructure sectors and individual climate threats (Dawson *et al*., 2018). Such matrices typically make it easier to understand the various climate impacts, and may serve as a strategy instrument for decision-makers. Another approach proposed in HR Wallingford (2014) introduces spatial indicators to measure the exposure of CI in the UK to current and projected climate threats. This approach allows a quantification of the portions of infrastructure assets exposed to various climate risks.

These high-level approaches provide different levels and forms of information that are all necessary for the national assessment of risks to CI posed by climate change and are complementary. This information can be further complemented by a geospatial CCRA that aids in developing sectoral adaptation plans and identifying areas or local assets for more detailed assessments. In fact, there is high variability of climate and individual asset vulnerability within a sector, depending on geographical location (HR Wallingford, 2014). For example, even when a high-level national assessment identifies the road network as being at high risk from flooding, some road sections will never be exposed to flooding. It is, therefore, important to also consider the exact geographical location of the potentially vulnerable assets, and also climate threat data if available. This can be achieved using a GIS-based approach, which accounts for spatial variability, as proposed in section 3.2. It is noted that, in addition to this literature review, a detailed review of Irish CCRAs by sector is provided at the start of Chapters 4–7.

3.2 GIS-based High-level Risk Assessment Framework

The GIS-based framework used in this study for CCRA aims to (1) provide an approach that considers the geographical locations of CI assets, (2) assess the possible portions of infrastructure networks at risk under present and future climates and (3) highlight climate risk hotspots on a national level by taking into account the importance level of assets from various sectors and their vulnerability to the climate threat in consideration. This risk-screening approach provides sectoral vulnerability matrices and two types of maps. The first type highlights the potentially high-risk assets within a sector (e.g. transport, ICT) for a given climate threat considering climate change. The second type of map is climate threat specific (i.e. can be developed for each climate threat, e.g. flooding, extreme wind events, etc.) and is a gridded cartogram that highlights possible climate change risk hotspots considering all sectors. Further discussion on the high-level framework and its application can be found in a journal publication from the authors (Hawchar *et al*., 2020), and results, including some figures and tables, are reproduced here under the terms and conditions of the Creative Commons Attribution license CC-BY-4.0 (https://creativecommons.org/licenses/by/4.0/).

The high-level GIS-based approach used herein is summarised in Figure 3.1. As can be seen from the figure, the framework consists of six steps that require input data on CI, climate threats and climate change projections. The figure shows exactly which data are required in each of the first four steps in the framework. The outputs of the approach (i.e. informative maps) are obtained from performing steps 5 and 6 of the framework. The methodology consists of, first, building a GIS inventory of the national CI and assessing the importance level of the various assets based on measurable criteria. Then, the relationship between the critical assets and climate threats is established to help identify which infrastructure networks are vulnerable to which climate threats (e.g. road network susceptible to flooding, power network susceptible to extreme wind

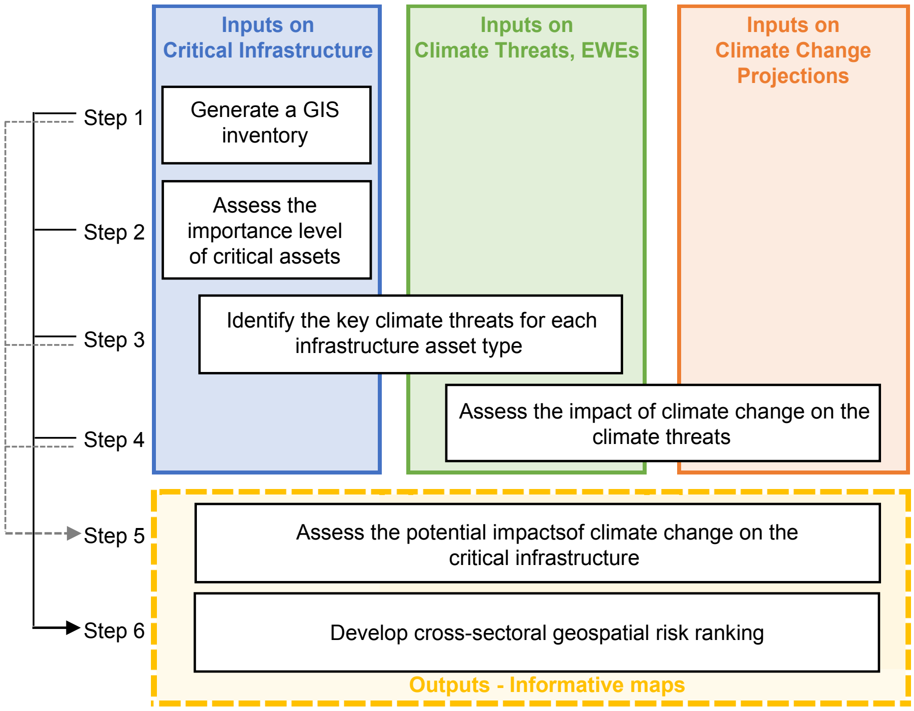

Figure 3.1. Flow chart of the high-level GIS-based assessment of CI vulnerability to climate change. Source: Hawchar *et al*. (2020).

speeds). Step 4 constitutes the first consideration of climate change, whereby available maps for national climate change projections (average temperature rise, sea level rise, etc.) are used as indicators of possible changes to climate threats and the likelihood of occurrence of EWEs. This, combined with the CI geospatial inventory, provides a high-level indication of the possible impacts of climate change on the CI, as a form of risk screening. The last step of the approach involves the development of cross-sectoral semi-quantitative risk ranking maps that account for critical assets across the various sectors that are vulnerable to the same climate threat. This facilitates the identification of climate risk hotspots for a given climate threat (e.g. flooding) through consideration of cross-sector geographical proximity. The text below presents the six steps of the framework in more detail and highlights the various outputs of the overall approach.

3.2.1 *Generate a GIS inventory of national critical infrastructure*

As the technology develops, GIS is becoming ubiquitous across a range of sectors, with many infrastructure databases being developed worldwide. The maps of national infrastructure systems can often be obtained from reliable online sources of readily available national data or from national stakeholders through collaboration. It should be noted that some infrastructure network data (e.g. from the drinking water network, overhead electricity transmission networks, ICT data centres) can be commercially and, in some cases, security sensitive. Consequently, some such GIS data are either not made available by the asset owners or are shared with non-disclosure agreements, limiting the communication of the data. This may affect the completeness of the analysis or the sharing of the assessment outputs (i.e. risk-screening maps). Obtaining GIS data across all CI sectors was a significant challenge for this study and, as will be discussed in the following sections, the inability to obtain CI GIS data limited the scope of the high-level analysis for the energy, water and ICT sectors to varying degrees.

3.2.2 *Assess the importance level of national critical infrastructure assets*

A common definition of the importance or criticality of infrastructure assets is “the level of contribution of the infrastructure to society in maintaining a minimum level of national and international law and order, public safety, economy, public health and environment”

(Theoharidou *et al*., 2009). In the literature, several methods have been utilised to describe the importance level of an asset (Feteke, 2011). In general, it is related to the number of customers supplied who would be substantially affected by the infrastructure failure. Thus, ideally, the assessment of the infrastructure importance levels within a network would be done at an asset level, quantifying the potential impact (societal, economic, etc.) associated with failure of the elements within the network. The approach will vary across the different infrastructure types, from road sections, which may have alternative routes, to power plants, power transmission lines, etc. A complete analysis must also consider interdependencies between infrastructure networks. As previously mentioned, this can be difficult to achieve, but, if ignored, the impact of failure of, for instance, an element of energy infrastructure may not be considered beyond the energy sector, underestimating the consequences of failure of that element through omission of the costs of cascading failures in other networks. This also gives rise to the question of who should finance resilience-increasing measures for assets that have potentially significant impacts outside their own sector. The detailed assessments of importance above are a considerable undertaking, especially if examining all of the CI networks, i.e. power, water, transport, etc. Although this is important work and should be examined in future research in Ireland, such a detailed assessment of importance level was outside the scope of the CIViC project, which had to consider all of the CI networks as part of a desk study-scale project. Consequently, a more general importance factor approach was used in this study, with the main aim of creating an importance index that can be used for all asset types from various infrastructure sectors. This involves classification of the importance of an asset based on the asset role (i.e. at local, regional, national or international level). The classification of asset types into these four categories is dealt with on a sector-by-sector basis in Chapters 5–7, using metrics such as number of daily journeys per rail station, population equivalent for wastewater treatment plants, power generation capacity for power plants, etc. A distinction is made in this study between assets of national importance (e.g. national roads, national commercial ports, large wastewater treatment plants) and assets of vital national importance (e.g. large power stations, telecommunication data centres), the failure of which is characterised by a much higher number of affected customers, and will probably cause cascading failures. An importance index is defined for each importance level, as shown in Table 3.1. It is noted that more detailed classifications can be used, especially when implemented by an infrastructure owner/operator who may have access to insightful customer usage numbers.

3.2.3 Identify the key climate threats for each infrastructure asset type

This step consists of determining the existing climate threats that each asset type is vulnerable to (i.e. existing threats before consideration of climate change impacts). At this stage, an information matrix can be developed to highlight the key relationships between climate threats and infrastructure systems (Dawson *et al*., 2018). A relationship exists if the occurrence of the climate threat may result in partial or total loss of the infrastructure system functionality. This statement can be linked to a definition of vulnerability widely used in climate change studies, which is “the degree to which a system is likely to experience harm due to exposure to a hazard” (Fussel, 2007; Turner *et al*., 2003). Accordingly, the relationship level can be classified as “none”, “low”, “medium” or “high”, and can be associated with a vulnerability index, as shown in Table 3.2.

Table 3.1. Grid of importance index

Infrastructure importance level	Importance index, *I*
Local	1
Regional	2
National	3
Vital National/International	4

Source: Hawchar *et al*. (2020).

Table 3.2. Grid of vulnerability index

Relationship level between climate threat and infrastructure system	Vulnerability index, *I*
None	0
Low	1
Medium	2
High	3

Source: Hawchar *et al*. (2020).

It is important to note that ranking relationship levels or vulnerability can be difficult and is country specific. The development of the high-level matrix requires the review of national (DCCAE, 2018b; DTTAS, 2017) and international (Dawson, 2017; Dawson *et al*., 2018; Fu *et al*., 2016) reports and sources of evidence to identify the priority risks and the relationship levels. Moreover, expert judgment is a determining factor that needs to be considered to guarantee the rigorousness of this assessment (Mach *et al*., 2017). Quantification of vulnerability requires more detailed analysis, as illustrated in Part B of this report.

3.2.4 Assess the impact of climate change on the climate threats

It is likely that climate change will have an impact on the risk profile of our CI in the future. This impact could be brought about by a change (increase or decrease) in frequency or intensity of EWEs, or by the emergence of a new risk that had not previously existed in a given country or region (Islam and Tuli, 2017). In this study, the impact of climate change on climate threats was assessed by (1) identifying the major climate change parameter or parameters that are relevant to the climate threat considered (e.g. annual rainfall amount related to drought, number of very wet days related to fluvial flooding) and (2) estimating the potential impact of the projected change in the identified parameters on the frequency and intensity of the climate threat in question.

The most recent and complete Irish study on climate change projections at the time of writing was conducted in 2015 (Nolan, 2015). The climate projections were generated using the COSMO-CLM (versions 4.0 and 5.0) and WRF (version 3.6) regional climate models (RCMs). These projections were generated by downscaling five Coupled Model Intercomparison Project 5 (CMIP5) global climate model (GCM) data sets, namely HadGEM2-ES, EC-Earth, CNRMCM5, Model for Interdisciplinary Research on Climate (MIROC) 5 and MPI-ESM-LR. In this study, 4-km and 6-km grid spacing RCM data were considered, then all RCM outputs were re-gridded to a common 6-km grid over Ireland using the method of bilinear interpolation. The higher resolution data allow sharper estimates of the regional variations in climate projections. The climate fields of the RCM simulations were archived at 3-hour intervals. The future climate was simulated using the IPCC Special Report on Emissions Scenarios (SRES) A1B, A2 and B1 (IPCC, 2000) and the representative concentration pathway (RCP) 4.5 and 8.5 emission scenarios (IPCC, 2014b). The RCP4.5 and B1 scenario simulations were used to create a “medium- to low-emission” ensemble, while the RCP8.5, A1B and A2 simulations were used to create a “high-emission” ensemble. Data from two time slices, 1981–2000 (the control) and 2041–2060, were used for an analysis of projected changes in the mid-21st century Irish climate. The historical period was compared with the corresponding future period for all simulations within the same RCM–GCM group. This results in future anomalies for each model run, that is, the difference between future and past. The reader may refer to Nolan (2015) for a detailed presentation of these projections. These climate change data provided in a mapped format (i.e. GIS maps) are used in the present study. Sea level rise projections were not considered in the 2015 report by Nolan; however, it is noted that the same author is currently undertaking a study that will provide information on sea level rise around Ireland with a resolution of 79 km. In the interim, for this report, the sea level predictions published by the European Environment Agency are used (EEA, 2017). This European study predicts an increase in relative sea level in 2081–2100 compared with 1986–2005 of over 0.3 m near the north and east coasts of Ireland, and over 0.4 m near the south and west coasts, for the medium- to low-emission scenario.

It is noted that step 4 of the approach is not infrastructure sector specific. Therefore, the relationship between climate threats and the relevant climate change projection data is established and presented in Table 3.3. This avoids repetition in Chapters 4–7, where the high-level risk analysis approach is applied to the transport, energy, water and ICT infrastructure sectors, respectively. For the assessment of the impact of climate change on climate threats, Table 3.3 defines the major climate trigger(s) for each threat. The third column of the table specifies the climate change projection data that were used in this study to assess the impact of climate change on each climate threat. It is noted that, for the particular case of climate change impact on fluvial and coastal flooding in Ireland, the flood maps of the Office of Public Works (OPW) are used. These maps were developed from a comprehensive catchment-based analysis approach adopted by OPW

Table 3.3. Major climatic triggers for climate threats

Climate threat	Major climate triggers	Relevant climate change projection parameter
Coastal flooding and erosion	Storm surge	Sea level rise and change in coastal erosion rate
Fluvial flooding	Heavy rainfall	Change in the number of very wet days and seasonal change in rainfall
Pluvial flooding	Periods of intense precipitation	Change in rainfall intensity and change in number of very wet days
Bridge scour	Flooding, high river flow	Change in number of very wet days
Extreme storms	High wind speed	Change in extreme wind speeds
Cold spells	Temperature below 0°C	Change in number of ice and frost days
Heatwaves and drought	Long period of high temperatures and low rainfall	Change in seasonal daily maximum temperature and number of consecutive dry days
Landslide	Heavy rainfall	Change in seasonal rainfall

Source: Hawchar *et al.* (2020).

for flood risk assessment and management. The OPW flood extent maps are developed for "present day" and two future scenarios of climate change, the mid-range future scenario (MRFS – increase in extreme rainfall depth and peak flood flows of 20%, and sea level rise of 0.5 m) and the high-end future scenario (HEFS – increase in extreme rainfall depth and peak flood flows of 30%, and sea level rise of 1 m) (OPW, 2015). It is noted that the allowances for the MRFS and HEFS adopted by the OPW for mean sea level rise (0.5 m and 1 m, respectively) would be close to the average and the top end of the projections from the IPCC Fifth Assessment Report (IPCC, 2014b), respectively. The IPCC Fifth Assessment Report predicts, with medium confidence, that global mean sea level rise for 2081–2100, relative to 1986–2005, will likely range from 0.26 m to 0.55 m for RCP 4.5, and from 0.45 m to 0.82 m under RCP 8.5. The more recent *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (IPCC, 2019) predicts even larger rises, with projections of global sea level rises between 0.43 m (likely range of 0.29–0.59 m; RCP 2.6) and 0.84 m (likely range of 0.61–1.10 m; RCP 8.5) by 2100 (medium confidence) relative to 1986–2005. As stated by the OPW (2015), the allowances for increases in rainfall depths and/or flood flows have a more limited evidence base, but, based on existing science, are within the limits of plausibility. This comparability gives confidence that it is acceptable to adopt the MRFS and HEFS in this study along with the projections from the Nolan analysis (Nolan, 2015). The OPW flood maps are available for different flood event probabilities in terms of a percentage annual exceedance probability (AEP): 10% (1-in-10-year event); 1% (1-in-100-year event); 0.5% (1-in-200-year event); and 0.1% (1-in-1000-year event). Hence, in the present study, for fluvial and coastal flooding-related risks, the OPW maps were used, negating the need to infer change in climate threat from a surrogate climate indicator. However, when this level of information is not available in other implementations of the framework, indicative relationships between climate threats and projected change in climate parameters as in Table 3.3 were used for this high-level analysis.

3.2.5 *Assess the impacts of climate change on critical infrastructure*

This step builds on the previous steps to examine the potential impacts of climate change on CI through high-level geospatial methods. It consists of overlaying the geospatial information of the infrastructure systems with the maps of projected changes in the identified climate parameter(s). Maps of existing or future climate risks (e.g. flooding, landslides) – if available – are also used in this step. The integration of GIS-assisted analysis makes it possible to perform a regionally specific (rather than national) assessment of potential climate change impacts. The resulting maps are used to identify and locate infrastructure assets in areas with a projected increase (or decrease) in risk of climate threats, and to quantify the current and future vulnerable assets (i.e. size of infrastructure network portions at risk). Note that this step is performed on a sectoral level, in the sense that it is performed separately for each infrastructure network of each sector. Therefore, the importance and vulnerability indices introduced under steps 2 and 3 are not used at this stage but are used in step 6.

3.2.6 Develop cross-sectoral geospatial risk ranking

This step delivers cross-sectoral (i.e. multi-sectoral) semi-quantitative risk ranking maps that take into account the geographical proximities of various assets from different sectors that are vulnerable to a specific climate threat. As previously discussed, this accounts for one of the four infrastructure interdependencies classified by Rinaldi *et al.* (2001) as physical, geographical, cyber and logical. The output of the analysis provides gridded maps that facilitate ranking the risk level of the grids by taking into account the importance level and the vulnerability of assets within the grid to the climate threat considered.

The relative risk mapping associated with the threat *th* (e.g. extreme winds, fluvial or coastal flooding) is based on the relative risk index R_{th} that is calculated for each grid (g) as follows:

$$R_{th}^{(g)} = \frac{M_{th}^{(g)} - M_{th}^{min}}{M_{th}^{max} - M_{th}^{min}} \in [0,1] \tag{3.1}$$

with,

$$M_{th}^{(g)} = \sum_{a=1}^{n_a} (I_a \cdot V_{a,th}) \cdot m_a^{(g)} \tag{3.2}$$

where $m_a^{(g)}$ is a measurement index (i.e. number or length) of the asset type a within the grid g, and n_a is the total number of asset types in the study. I_a is the importance index of asset a, and $V_{a,th}$ is the vulnerability index of asset a to the threat th (refer to Tables 3.1 and 3.2). $M_{th}^{(g)}$ denotes the weighted measurement index of the assets within the grid g. M_{th}^{min} and M_{th}^{max} are the minimum and maximum values of $M_{th}^{(g)}$ over the whole grid, respectively. Note that the unit of measure m is not the same for the different types of assets. It can, for instance, be a length, in the case of linear network assets (e.g. roads), or a counter, in cases of discrete assets. Importantly, the semi-quantitative nature of this analysis means that it is only indicative of risk and is thus only suitable for risk screening. The framework for full quantitative risk assessment is presented and illustrated in Part B. There are a number of limitations to the approach, which are presented in section 3.3 for clarity.

The risk ranking maps do provide some insight into the geospatial relative risk of CI across the various sectors for a given climate threat. This semi-quantitative high-level analysis can therefore be used to highlight climate change risk hotspots at a national level (i.e. risk screening), indicating areas that require more detailed analysis, using probabilistic modelling and other methods (e.g. Stewart and Deng, 2015). When the maps are combined with the climate change projection maps, climate change risk hotspots can be identified where (1) the relative risk of CI assets is high and (2) the future climate threat is projected to increase locally, as indicated by the climate projection parameter. Based on the assessment results, advice can be given on prioritisation of areas for further detailed investigation that can be used to actually inform appropriate climate adaptation action (readers are referred to Part B for this form of analysis).

3.3 Discussion of the High-level Approach

The GIS-based approach presented in section 3.2 for the high-level CCRA of national CI is aimed at providing insights – mainly in a mapped format – into the locations of national critical assets that are likely to experience impacts from climate change and, therefore, would require further, more detailed, quantitative risk assessments, incorporating uncertainty and variability using probabilistic methods. The integrity of the outcomes and results of the high-level study will depend to a large extent on the completeness and quality of the GIS data obtained.

This section aims to highlight the potential and limitations of the GIS-based high-level risk analysis approach presented herein. It also draws attention to the challenges faced during the implementation of this approach when examining Irish CI.

- The GIS-based approach presented herein can be applied to any set of CI sectors, in any country. However, this high-level approach is mainly intended for CCRA in sectors, or indeed countries, that are currently at an early stage of consideration of climate change adaptation strategy implementation for infrastructure, in line with the recommendations of the IPCC's Fifth Assessment Report (IPCC, 2014b).
- The creation of the cross-sectoral risk ranking maps in step 6 of the framework requires a specific set of values for the indices of the asset importance and vulnerability levels. Note that these values are open to interpretation and vary

widely between countries. This form of risk-ranking map should not be confused with a quantitative risk analysis, where detailed assessment is conducted to ascertain vulnerability (the probability of failure given hazard), probability of hazard, consequences of failure, etc.

- For the high-level approach in Part A, the vulnerability and importance indices may also change with time (e.g. new infrastructure developed, maintenance or protection measures put in place). Only future changes in climate are considered in Part A. It is also noted that equation 3.2 in step 6 requires a measurement index. The selection of these measurement indices across different forms of infrastructure is not straightforward and is again open to interpretation.
- This approach primarily focuses on investigating the future vulnerability of national CI under a changing climate based on only the existing infrastructure networks. However, it is noted that climate adaptation measures are developed for long-term, rather than short-term, objectives and should thus ideally also consider planned future infrastructure and potential technological developments where possible. Technological developments, such as increasing the electrification of the transport network, have been considered in this study, but a lack of GIS data has meant that planned future infrastructure developments have not been incorporated.
- The high-level approach presented is based on identifying, under step 4, the main climate change projection parameter that dictates the projected change in each future climate threat. While this is a first step in hazard and risk analysis, sophisticated computer modelling needs to be used to accurately model some future climate threats. Yet, in practice, in most countries work on developing climate threat models considering climate change is still relatively underdeveloped because of the high degree of uncertainty related to topographical, hydrodynamic and climate models (Meyer *et al.*, 2012).
- The assessment of future risks posed to CI due to climate change is based on the available regional climate change projection data. However, these data present, in general, considerable uncertainties. This is primarily the result of (1) the natural variability of the climate system, (2) the variability and uncertainty associated with EWEs, (3) uncertainties in future regional climate due to the coarse resolution of climate models, (4) uncertainties due to the formulation of the models themselves and (5) uncertainties in the future atmospheric composition. Consequently, any result from CCRAs should be considered with caution, with the understanding that there is inherent uncertainty associated with the input data used. Ideally, attempts should be made to capture all sources of uncertainty and variability using quantitative risk analysis based on probabilistic modelling. Such an approach is presented and illustrated in Part B of this report.

4 Climate Change Risk Assessment of the Transport Sector

4.1 Existing Assessments for the Irish Transport Sector

In 2017, the Department of Transport, Tourism and Sport (DTTAS) published its first adaptation plan – *Developing Resilience to Climate Change in the Irish Transport Sector* (DTTAS, 2017) – under the non-statutory framework of 2012 (DECLG, 2012a). This plan presented a high-level overview of potential sectoral vulnerabilities to climate change and constituted a starting point for the preparation of a statutory sectoral adaptation plan, which was submitted to government on 30 September 2019. The first sectoral adaptation plan outlines the likely effects of climate change on the transport system, including land transport (road and rail), and maritime (port) and aviation networks. It is a high-level plan that seeks to identify vulnerabilities at a broad level and, accordingly, is not infrastructure specific. This DTTAS plan identifies the priority climate changes with impacts for transport as follows: (1) projected increase in the frequency of extreme precipitation events and the associated risk of high river flows; (2) ongoing and projected changes in sea level and projected changes in the occurrence and intensity of storm surge; and (3) projected increase in average temperature, and projected increases in frequency and duration of heatwaves (temperature extremes).

DTTAS released a draft version of the Statutory Climate Change Adaptation Plan for the Transport Sector for public consultation (DTTAS, 2019). This plan examines the risk to the transport sector in considerably more detail than the first DTTAS plan, and utilises a GIS mapping framework, informed in part by the framework set out in this project, to examine climate change projections in the context of infrastructure locations. The finalised plan was published in 2019 following approval by government.

In addition to the DTTAS plans prepared under the NAF, various actors within the transport sector have developed climate adaptation responses. Transport Infrastructure Ireland (TII) has also prepared a strategy for adapting to climate change for Ireland's light rail and national road network (TII, 2017). TII has developed a modelled strategic flood map for the national road network that identifies likely vulnerable road sections that require further detailed assessment. TII has also developed a comprehensive flood management protocol for addressing flooding risks on the national road network. Primary climate change vulnerability assessments have also been carried out by Irish Rail to assess the vulnerability of Ireland's east coast railway to the main climate challenges facing it: storm surges and sea level rise (Bambrick, 2017). Under this study, a coastal vulnerability index is calculated for the various sections along the coastal railway line between Bray Head and Wicklow town. These index scores are then calculated and generated as a shapefile on Irish Rail's GIS asset management system.

4.2 Application of the High-level Risk Assessment Framework to the Transport Sector

This section presents the application of the high-level risk assessment approach developed in Chapter 3 to the transport sector. The outcomes of each step of the framework are presented and discussed, with a sample of the results obtained from the analysis presented. The same format is adopted in the following chapters examining the other CI sectors. Figure 4.1 also presents the GIS data for the transport sector to give some insight into the density and nature of Irish CI networks. Further details of the application of the framework to the transport sector can be found in a journal publication from the authors of this report (Hawchar *et al.*, 2020).

4.2.1 Generate a GIS inventory

Ireland's transport infrastructure includes the land, aviation and maritime transport sectors. Table 4.1 identifies the transport infrastructure systems considered in this study and shows the source of the corresponding GIS data. Figure A1 in the CIViC supplementary material document (available from the project's Principal Investigator, Dr P. Ryan) presents the GIS data for the transport sector, to give some insight into the density and nature of Irish CI networks. This figure can also be found in Hawchar *et al.* (2020).

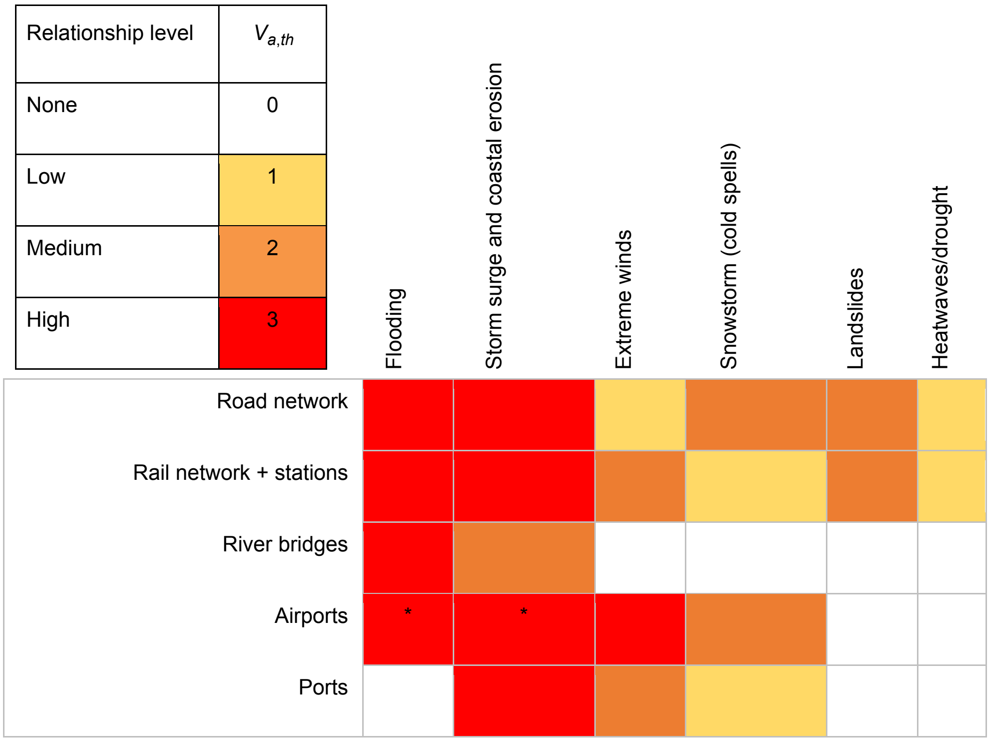

Figure 4.1. Vulnerability matrix for Irish transport infrastructure systems. $V_{a,th}$, vulnerability index of asset *a* to the climate threat *th*. *The high relationship level relates only to Shannon Airport. Source: adapted from Hawchar *et al*. (2020).

Table 4.1. Source of GIS data for transport infrastructure systems

Transport infrastructure system		GIS data source
Land	National/regional roads	TII (stakeholder)
		The Irish roads network can also be found online through the GeoHive Data Catalogue (https://geohive.ie/catalogue.html)
	Rail network and stations	Irish Rail (Iarnród Éireann) (stakeholder)
		The Irish rail network can also be found online through the GeoHive Data Catalogue (https://geohive.ie/catalogue.html)
	Road/rail bridges	The over-water rail and road bridges were obtained herein using ArcGIS to identify the intersections between water courses and the road and rail networks
Aviation	International airports	Added manually: the GPS coordinates are available on Google Maps
Maritime	International ferry ports Local ferry ports Commercial ports	Available online on the Marine Irish Digital Atlas (MIDA) website (http://mida.ucc.ie/pages/atlas/search/search.php?stopic=title&viewRegion=&themeView%5B%5D=&sTitle=ports)

GPS, global positioning system.

4.2.2 Assess the importance level of critical infrastructure assets

Various criteria can be used to assess the importance of road sections (e.g. average daily traffic density, average repair cost and losses following an EWE, strategic role) (Hughes, 2016). Given the resource constraints of the current study (being a desk study-scale project), and in view of the need to consider the whole range of CI types, a relatively simple criterion was used herein. The importance level was determined by the type of road based on the Irish national road classification, i.e. national, regional and local roads, as a somewhat crude measure of road importance. This is analogous to the New Zealand One Network Road Classification system that was used as one of the key components in a more detailed criticality analysis approach put forward for New Zealand by Hughes (2016). When considering the rail network, the importance of a station herein was assigned based on the average daily number of journeys (boarding and alighting). This information was obtained from the Irish Rail census for 2017, which classified 11 out of 147 stations as large (average number of daily journeys ≥ 6000) (NTA, 2018). When considering rail lines, the classification of individual rail sections is not straightforward, because the consequence of failure of a portion of the rail line depends on the location of the damaged portion within the overall network. For instance, if even a small section of a rail line is flooded, passengers will be unable to travel from station A to station B along that route, and service on the entire route may be interrupted because of the limited rerouting options for most of Ireland's rail network. Localised damage to a given section will also have a higher impact (i.e. cause delays or result in cancelled journeys) if the section serves several routes. The extent of the impact will also depend on the number of journeys per day on each route, the rerouting options available, etc. Given these complexities and the scale of this project, all railway lines were assumed to have the same importance level of 3 herein (i.e. the same as national roads). Only rail-over-river and road-over-river bridges are considered in the study. Maps of these bridges were developed by the project team in ArcGIS by intersecting the road and rail networks with the water courses. Bridge importance level is dictated by the section of the network it serves, i.e. national road, rail line, etc.

Ireland's National Aviation Policy classifies Dublin Airport, Cork Airport and Shannon Airport as state airports, i.e. primary gateways through which air traffic accesses Ireland (DTTAS, 2018). Ireland has four international ports, approximately 20 commercial ports and 50 local ferry ports. The commercial ports are classified by the Irish National Ports Policy as ports of national significance (tiers 1 and 2) or regional significance (DTTAS, 2013). This information was used to classify the importance of these infrastructure assets. The critical transport infrastructure systems considered in the high-level GIS-based analysis are listed in Table 4.2. The same table also gives the importance index for each asset type.

Table 4.2. Inventory of the critical Irish transport infrastructure systems considered in the study and their importance indices

Assets		Importance index
State airports		4
Ports	International ferry	4
	Local ferry	3
	National commercial ports	3
	Regional commercial ports	2
Train stations	Large	3
	Small	2
Rail lines		3
Roads	National	3
	Regional	2
Bridges	On rail line	3
	On national road	3
	On regional road	2

Source: Adapted from Hawchar *et al.* (2020).

4.2.3 Identify the key climate threats for each infrastructure asset type

Figure 4.1 presents the relationships between the main critical assets of the transport sector and the main climate threats in Ireland under existing conditions (i.e. this step is not focused on climate change). The corresponding vulnerability indices are determined in accordance with the strength of the relationship between the threat and the infrastructure system, as discussed in Chapter 3 and presented again in the top panel of Figure 4.1. The matrix in Figure 4.1 (bottom panel) was developed through an extensive review of national government and stakeholders' reports on infrastructure performance and EWEs (DTTAS, 2017, 2016), and of European (Dawson, 2017; Fu *et al*., 2016; HR Wallingford, 2014; Martinovic *et al*., 2018) and other international studies (AFW and CVC, 2017; Fisk, 2017). The assessment also incorporated records of past events and insights from Irish transport infrastructure owners and operators (e.g. Irish Rail, TII, Dublin Airport Authority, Shannon Airport Authority), which were obtained through meetings and workshops. The past events considered in the development of the matrix included the most recent extreme storms [i.e. Storms Diana (2014), Desmond and Frank (2015), Ophelia (2017) and Diana (2018)], cold spells, landslides, etc.

4.2.4 Assess the impact of climate change on climate threats

As stated in section 3.2, this step is not infrastructure sector specific and thus, to avoid repetition in Chapters 4–7, both the procedure and outcomes for assessing the impact of climate change on climate threats was discussed in section 3.2.4 (see Table 3.3 for outcome).

4.2.5 Assess the impacts of climate change on critical infrastructure

Potential climate change impacts on flooding risk

The OPW flood maps were used for the assessment of the future vulnerability of the transport infrastructure to flooding. The OPW maps indicate the location of the transport assets that are at risk from fluvial and coastal flooding in the present day, and under the MRFS and HEFS. For instance, Figure 4.2 shows the location of national road sections and rail lines and stations that are projected to be at risk from a 1-in-100-year fluvial flood event (i.e. AEP of 1%) under the HEFS (i.e. are located in the predicted flood extents). Table 4.3 provides quantitative information about the exposure of the rail network to fluvial and coastal flooding. This table gives (1) the lengths of rail line sections that are projected to be at risk from flooding; (2) the percentage increase in these lengths due to climate change under the two OPW future scenarios with respect to the present day; and (3) the number of rail stations at risk.

Table 4.3 indicates that, based on the available mapping, under present-day conditions, the railway network is more at risk from fluvial flooding than from coastal flooding, with a bigger proportion of the network currently located in fluvial flood extents. Examining the potential impacts under the two climate change scenarios (MRFS and HEFS), the table indicates potentially substantial increases in flooding risk for both fluvial and coastal flooding. For instance, for the AEP of 10%, the current conditions result in 21 km of rail line in the coastal flood extent and 44 km of rail line in the fluvial flood extent. Under the MRFS, these figures increase to 47 km and 68 km, respectively. The extent of potential increases in flooding risk under climate change is also clearly illustrated through comparison of the AEPs in Table 4.3. This risk-screening high-level analysis indicates that the predicted impact of the 1-in-1000-year coastal flooding event on the rail network under the present-day scenario (46 km potentially flooded) may be similar to the impact of the 1-in-10-year coastal flood event under the OPW MRFS (47 km potentially

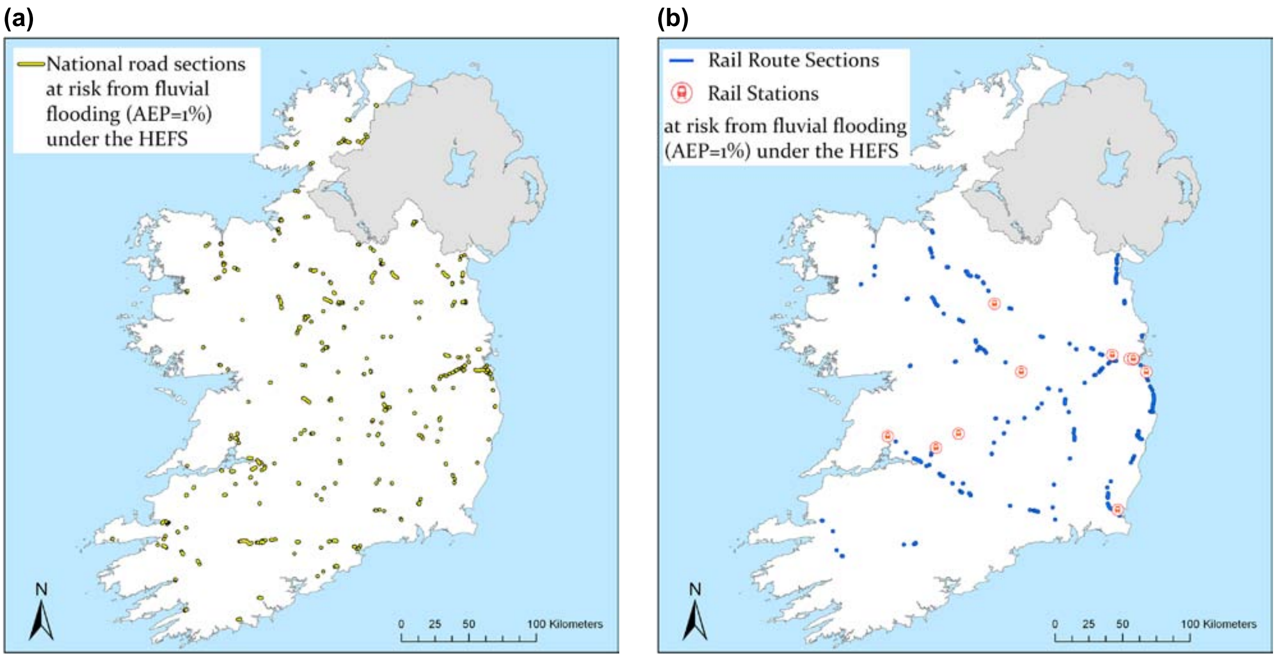

Figure 4.2. Location of (a) national road sections and (b) rail lines and rail stations exposed to risk from a 1-in-100-year fluvial flood event (AEP = 1%) under the OPW HEFS. Source of part (a): Hawchar *et al.* (2020).

Table 4.3. Lengths (and projected percentage increase in length) of Irish rail line sections and number of rail stations located in areas at risk from flooding using the OPW flood maps

	Coastal flooding			Fluvial flooding		
AEP	**Present day**	**MRFS**	**HEFS**	**Present day**	**MRFS**	**HEFS**
10%	21 km – 1 station	47 km (+96%) 6 stations	59 km (+146%) 10 stations	44 km – 1 station	68 km (+55%) 3 stations	111 km (+152%) 7 stations
1%	–	–	–	65 km – 5 stations	118 km (+82%) 5 stations	154 km (+137%) 11 stations
0.5%	35 km – 4 stations	74 km (+111%) 11 stations	83 km (+137%) 11 stations	–	–	–
0.1%	46 km – 7 stations	82 km (+78%) 12 stations	99 km (+115%) 12 stations	135 km – 10 stations	149 km (+10%) 9 stations	190 km (+41%) 14 stations

Source: Hawchar *et al.* (2020).
AEP, annual exceedance probability; HEFS, high-end future scenario; MRFS, mid-range future scenario.

flooded). For fluvial flooding, the predicted impact of the current 1-in-100-year fluvial flooding event on the rail lines (65 km potentially flooded) is similar to that of the 1-in-10-year fluvial flooding event under the OPW MRFS (68 km). While these high-level analysis findings are useful for first-pass screening, it is again noted that such a broad analysis has a number of limitations. For example, the assessment does not account for the level of the track and the height of the potential flood; thus, a portion of track could be in a flood extent for a given flood event but may not be affected by the flood because of the height of the rail embankment. This limitation is perhaps less relevant for rail stations for access reasons. Again, in this context, it is noted that the high-level analysis is merely a risk-screening tool that can be used to indicate where further, more detailed, analysis should be conducted.

Comparing the magnitude of impacts between fluvial and coastal flooding, it is noted that, while in the future there is still likely to be greater risk of fluvial than coastal flooding, coastal flooding exhibits a greater percentage increase in potential risk due to climate change. This can be seen looking at the range of AEPs for the MRFS in Table 4.3, where, on average, the length of track and stations exposed to flood extents approximately doubles for coastal flooding, whereas for fluvial flooding the length of track in flood extents increases by approximately 50%, while stations affected remain, on average, unchanged. In the context of the significant increase in coastal flooding risk, it is again noted that the OPW sea level rise assumptions utilised by the OPW to generate the flood risk maps (0.5 m under the MRFS and 1 m under the HEFS) are slightly higher than the projections for the year 2100 in the recent *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (IPCC, 2019). This 2019 IPCC report predicts global sea level rises of between 0.43 m (0.29–0.59 m, likely range; RCP 2.6) and 0.84 m (0.61–1.10 m, likely range; RCP 8.5) by 2100 (medium confidence) relative to 1986–2005. The OPW does, however, rightly point out that estimates of sea level rise cannot be provided with confidence owing to limited understanding of some important effects, noting that some studies have predicted sea level rise well in excess of the IPCC predictions [e.g. Jevrejeva *et al.* (2014) predicted a rise of nearly 2 m by 2100] (OPW, 2015).

Potential climate change impacts on bridge scour risk

Figure 4.3 shows the map of Irish road and railway bridges and viaducts, and the locations of the two major bridge scour events reported in Ireland (DTTAS,

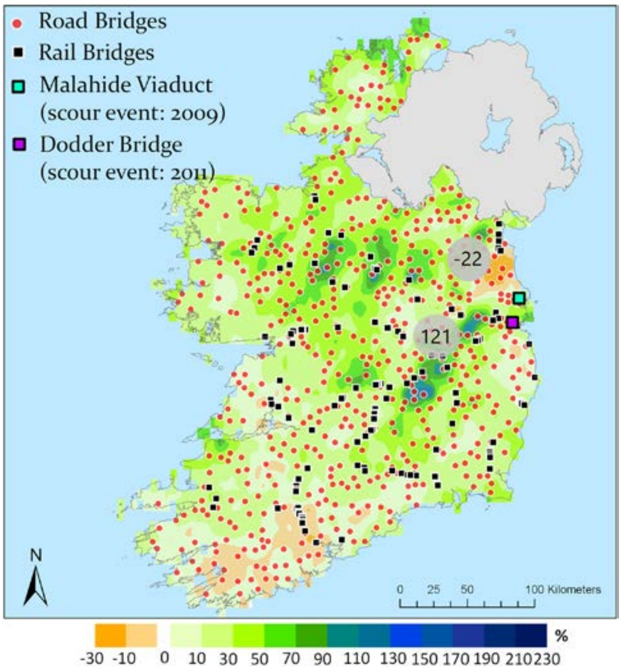

Figure 4.3. Location of road and rail river bridges in areas subjected to an increase in the number of very wet days in autumn, for the medium- to low-emission scenario. Source: Hawchar *et al*. (2020).

2017). As established in section 3.2 (Table 3.3), the number of very wet days is the climate change projection parameter identified as of interest for bridge scour. Consequently, to facilitate a high-level assessment of climate change-induced changes in bridge scour risk, Figure 4.3 presents the map of the projected change in the number of very wet days in autumn for the medium- to low-emission scenario, overlaid with the water course bridge locations map. Before discussing the results, it is noted that the narrative of regional variations in precipitation in Ireland between the east and the west of the country can depend on which regional/global climate model combination is used. While this study utilised the most up-to-date and complete set of Irish climate projections available at the time of analysis (Nolan, 2015), it is still important to be mindful of the limitations associated with rainfall climate projection data in general. Work is ongoing in Ireland to decrease the uncertainty associated with rainfall projections through actions such as increasing RCM ensemble sizes (Nolan, 2015).

The map of river bridges and projected rainfall change shows that a considerable number of river bridges are located in areas where the number of very wet days is predicted to increase in the future (i.e. locations where we might expect more frequent and severe heavy rainfall events). Figure 4.3 also indicates that the bridges in the centre of Ireland, where heavy rainfall days are expected to increase by up to 121%, will experience the greatest climate change-related increases in scour risk, whereas bridges located to the north of Dublin and in the south-west of the country may experience reductions in scour risk in the future. At the locations of the Malahide Viaduct and Dodder Bridge, which have failed as a result of bridge scour over the last decade, the number of very wet days in autumn is projected to increase by 32% and 24%, respectively. However, as these assets were recently repaired to modern standards, the asset vulnerability to failure is likely to have been reduced, leading to an overall reduction in risk profile despite the expected increase in climate threat.

Again, it is important to note here that this high-level assessment of potential climate change impact on bridge scour risk is highly simplified and does not constitute a full probabilistic quantitative assessment. In a more complete study focused on bridge scour risk, each bridge of concern could be assigned to a catchment and consideration could be given to how changes in rainfall in a given catchment would affect river flows at the bridge location, leading to assessment of the change in climate hazard. The assessment would then need to consider the vulnerability (probability of scour occurring on the bridge) given bridge geometry, pier foundations, age of the bridge, etc.

Potential climate change impacts on sea level rise and coastal erosion

As indicated by the vulnerability index in Figure 4.1, coastal erosion is considered to be a major risk for coastal transport infrastructure assets. The map in the left-hand panel of Figure 4.4 shows the annual erosion rates (m/year) provided by the OPW for the Irish coastline. These rates are modelled as constants over time, up to 2050. The average value of the coastal erosion rate is equal to 0.5 m/year. It is noted that the OPW erosion maps have been produced for existing conditions only and do not currently account for future climate changes such as sea level rise, increased storm frequency or associated variations in erosion rates (OPW, 2010). Projected future sea

Figure 4.4. Assessment of the impact of coastal erosion and sea level rise on transport assets. Source: adapted from Hawchar *et al*. (2020).

level rise can be used as an indicator of possible changes in future risk of costal erosion. The centre map of Figure 4.4 shows the location of rail line that runs along the coast on the north-east of Ireland (zone 4) and which is currently at risk from coastal erosion and storm surge according to a recent Irish Rail study (Bambrick, 2017). With an erosion rate varying between 0.1 and 0.42 m/year along the coast adjacent to this rail section, and a projected increase in sea level rise of between 0.3 and 0.4 m by the end of the century (EEA, 2017), a high-level finding is that the climate risk to this rail section is expected to further increase in future. It should, therefore, be investigated further using detailed quantitative risk assessment methods to investigate the impact and, indeed, the appropriateness of adaptation measures using the framework presented and illustrated in Part B of this report. The map in the right-hand panel of Figure 4.4 uses star symbols to highlight the locations of coastal sections (defined as being within 7 km of the sea) of the national road network. It can be noted that most of these sections are located on the west and south coasts, where the sea level rise is expected to be the highest (EEA, 2017).

Potential climate change impacts on extreme temperature risks

The projected increases in maximum daytime summer temperatures of 0.7–2.0°C and 1.3–2.6°C for the medium- to low-emission scenario and high-emission scenario, respectively, are likely to result in more heatwaves (Nolan, 2015). Yet, and in view of the relatively temperate climate of Ireland, risks from extreme high temperatures and heatwaves (e.g. lateral buckling of railway lines) are not as critical as they are in other countries (Yang and Bradford, 2016). For instance, buckling of railways and melting of tarmac are rare events in Ireland, with less than one occurrence per year (DTTAS, 2017). However, the probability of occurrence will possibly increase in future, as more extreme high-temperature events are projected to occur (Nolan, 2015). On the other hand, with the projected warmer winters for Ireland, risks from cold spells, snow and ice are expected to decrease in the future. For instance, GIS mapping indicates that Ireland's ports and airports will experience a reduction in ice days per year of between 29% and 88%. This will result in reduced snow- and ice-related disruptions to the port and airport infrastructures. The impact of such events on airports was seen during Storm Diana, which hit Ireland in November 2018, resulting in the cancellation of 14 flights at Cork Airport (Sukhija, 2018). The cold spell in winter 2010, accompanied by heavy snowfalls, caused disruptions to Cork and Shannon Airports and caused the closure of Dublin Airport on six occasions over the 30 days of severe weather. Dublin ferry sailings were also cancelled for a full day because of the snowstorm (DTTAS, 2017).

Potential climate change impacts on landslide risk

This assessment was conducted as part of the CIViC project, but, in the interests of brevity, is not included in the main report. The analysis can be found in Appendix A3 of the CIViC supplementary material document (available from the project's Principal

Investigator, Dr P. Ryan). Details of this analysis are also included in an open access journal publication by the report authors (Hawchar *et al.*, 2020).

4.3 Summary of Transport Sector Findings

This GIS-based CCRA for the Irish transport sector concludes that the increase in risk from fluvial flooding will probably be the major challenge in the future for transport infrastructure, namely the road and rail networks and Shannon Airport. The second major risk is likely to be from sea level rise, coastal erosion and coastal flooding. While the present and future exposure of the road and rail networks (i.e. in terms of length in km) to fluvial flooding is higher than it is for coastal flooding, the percentage increase in exposure is higher for coastal flooding. This highlights the need to develop adaptation strategies for the coastal transport infrastructure, which is expected to be at greater risk in future. The analysis indicated that future risk from bridge scour is expected to be higher for bridges located in the centre of Ireland, with a possible decrease in risk for river bridges located in the south of the country. Landslide events interrupting the transport network are rare at present in Ireland; however, in the future, the risk from landslides is likely to increase for roads located in the west of the country and for the rail line located in the south-west of Ireland. Finally, it is also noted that the transport infrastructure may be vulnerable to cascading failures from other parts of the CI networks, specifically ICT failures and particularly energy sector failures. Possible cascading effects from the energy network to the transport network are likely to become more significant in the future, as the transport network moves towards increased electrification in line with the recent all-government Climate Action Plan (DCCAE, 2019). As will be discussed in Chapter 5, key climate threats for the energy sector include extreme wind speeds and flooding.

5 Climate Change Risk Assessment of the Energy Sector

5.1 Existing National Assessments for the Irish Energy Sector

In February 2018, the then DCCAE (now the Department of the Environment, Climate and Communications) published the *Adaptation Plan for the Electricity and Gas Network Sector* (DCCAE, 2018b) under the non-statutory framework of 2012. This plan could be seen as a first step towards understanding vulnerabilities and building resilience in the energy sector. The plan outlines areas of vulnerability at present, sets out the steps that can be taken to prevent or minimise future adverse climate impacts within the sector and also outlines methods to exploit possible climate change opportunities. The DCCAE (2018b) study identified the key climate change variables for the energy sector as flooding/change in precipitation, changes in wind energy content, temperature rise and sea level rise. This initial plan does not deal with spatial considerations or use quantitative methods, but instead constitutes a starting point for the development of the statutory sectoral adaptation plan for the electricity and gas networks sector. The DCCAE developed an updated plan, which was submitted to government for approval in September 2019. In addition to the NAF, Nolan *et al*. (2012) published a research paper examining the impact of climate change on the wind energy resource for Ireland using the RCM. The approach used in this paper was later improved in another study through use of a multi-model ensemble approach (Nolan *et al*., 2017).

5.2 Application of the High-level Risk Assessment Framework to the Energy Sector

As per the previous chapter, this section presents the application of the high-level risk assessment approach developed in Chapter 3 to the energy sector.

5.2.1 *Generate a GIS inventory*

Difficulties were encountered when trying to obtain GIS data for the energy sector. The energy sector infrastructure in Ireland is primarily managed by three companies: the Electricity Supply Board (ESB), EirGrid and Gas Networks Ireland (GNI). While each of these companies actively engaged with the project team and provided valuable insights, many types of GIS infrastructure data were deemed highly commercially sensitive and therefore could not be released. The inability to obtain comprehensive GIS data sets has somewhat limited the scope for GIS-based assessment in this chapter. Table 5.1 provides the details of the energy infrastructure systems that could be considered in the project and shows the sources of the corresponding GIS data. It is noted that some progress was made relating to governance issues associated with obtaining electricity GIS data during the project; however, the extent of progress was not sufficient to facilitate release of the GIS data within the project timeframe. The ESB did provide extensive input into the work presented in Part B of this report and insights into some key vulnerabilities across the energy network (discussed in Chapter 5).

Table 5.1. Source of GIS data of the energy infrastructure networks

Energy infrastructure system		GIS data source
Gas network	Underground pipelines network	Obtained through a signed non-disclosure agreement with GNI for underground high-, medium- and low-pressure pipelines (A non-interactive map is available at https://www.gasnetworks.ie/corporate/company/our-network/pipeline-map/)
Electricity network	ESB generation plants and wind farms	Manually entered in ArcGIS (An interactive map is available at www.esb.ie/our-businesses/generation-energy-trading-new/generation-asset-map)

5.2.2 *Assess the importance level of critical infrastructure assets*

The importance of electricity generation plants (including wind farms) herein was linked with their maximum capacity [in megawatts (MW)], which reflects the approximate number of customers and businesses a plant serves (HR Wallingford, 2014). Large power stations (capacity ≥ 100 MW) are classified as assets of vital national importance (i.e. importance index = 4, classified in section 3.2, step 2). Small power stations (< 100 MW) are assigned an importance index of 3, as shown in Table 5.2. It is recognised, however, that this approach fails to reflect the fact that not all plants in Ireland are operational at any one time and that the power supply mix in Ireland is changing in line with a reduction in the reliance on traditional fossil fuel power stations.

Table 5.2. ESB power plants: generation capacity and corresponding importance index

Energy assets	Asset name	Capacity (MW)	Importance index, *I*
Thermal stations	Marina	90	3
	Lough Ree Power	100	4
	North Wall	106	4
	West Offaly Power	135	4
	Dublin Bay	410	4
	Poolbeg	463	4
	Moneypoint	915	4
	Aghada	963	4
Hydro stations	Clady	4.2	3
	Carrigadrohid	27	3
	Inniscarra	27	3
	Poulaphuca	38	3
	Golden Falls	38	3
	Leixlip	38	3
	Cliff	65	3
	Cathleen's Falls	65	3
	Ardnacrusha	86	3
Wind farms	Carrane Hill	3.4	3
	Crockahenny	5	3
	Mount Eagle	6.8	3
	Black Banks	10.2	3
	Carnsore	11.9	3
	Grouselodge	15	3
	Woodhouse	20	3
	Tullynahaw	22	3
	Garvagh Glebe	26	3
	Mountain Lodge	31.5	3
	Raheenleagh	35.2	3
	Derrybrien	59.5	3
Pumped storage power station	Turlough Hill	292	1

For the natural gas network, the importance of an underground pipeline can be associated with its function, i.e. transmission under high pressure (7–85 bar), distribution under medium pressure (0.1–7 bar) and distribution under low pressure (< 100 mbar) (DCCAE, 2018b; HR Wallingford, 2014). Logically, a failure affecting a transmission pipeline would affect more users (i.e. over a larger zone) than the failure of a distribution pipeline. Thus, primary high-pressure gas pipelines are considered assets of vital national importance and given an importance index of 4. Table 5.3 provides a summary of the importance index values for the energy infrastructure systems for which GIS data were available.

5.2.3 *Identify the key climate threats for each infrastructure asset type*

Figure 5.1 represents the relationships between the main critical assets of the energy sector and the main climate threats in Ireland under existing conditions (i.e. this step is not focused on climate change). The corresponding vulnerability indices are determined according to the strength of the relationship between the threat and the infrastructure system, as discussed in Chapter 4 and presented again in the table at the top of Figure 5.1. The matrix in Figure 5.1 was developed through a review of national government and stakeholders' reports on infrastructure

Table 5.3. Inventory of the critical Irish energy infrastructure systems considered in the study and their importance indices

Assets		Importance index
Power stations and wind farms	Large (capacity ≥ 100 MW)	4
	Small (capacity < 100 MW)	3
Gas network	High pressure	4
	Medium pressure	2
	Low pressure	1

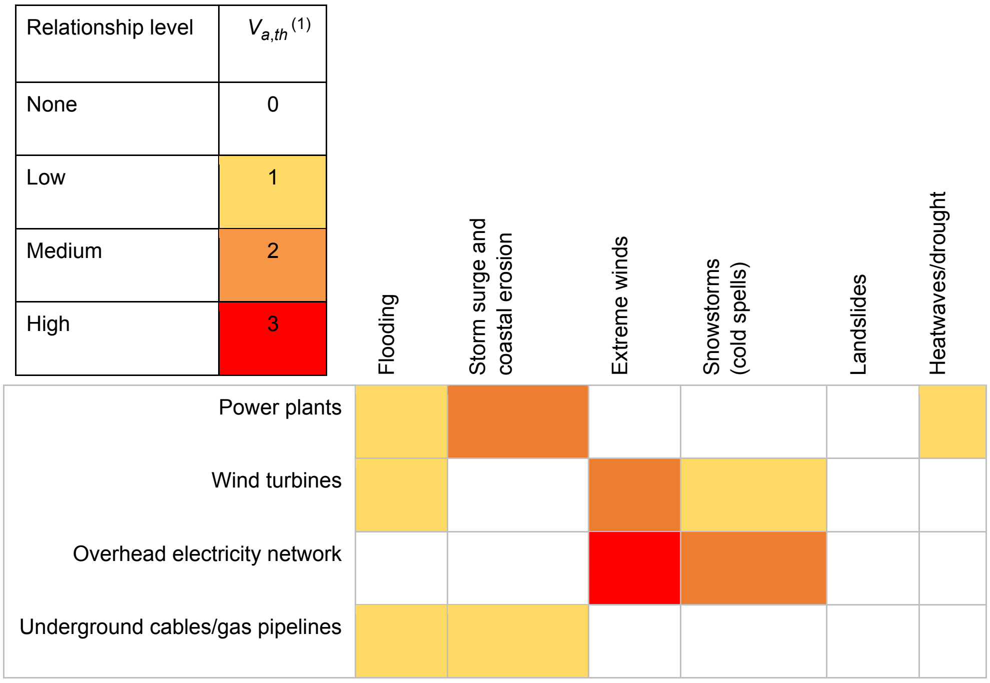

Figure 5.1. Vulnerability matrix for Irish energy infrastructure. $V_{a,th}$, vulnerability index of asset *a* to the climate threat *th*. Source: adapted from Hawchar *et al.* (2020).

performance and EWEs (DCCAE, 2018b), as well as European (Dawson, 2017; HR Wallingford, 2014) and other international (AFW and CVC, 2017; US Department of Energy, 2016) studies. The assessment also incorporated records of past events and insights from Irish energy infrastructure owners and operators across the various sectors (e.g. ESB and GNI), which were obtained through meetings and workshops. It is noted that overhead electricity networks are included in the matrix in Figure 5.1, but not in Table 5.1. This is done solely to provide insight into the vulnerability of this important element of the CI network to climate threats. The overhead electricity lines are not included in the GIS-based high-level risk analysis, as the GIS data for the overhead electricity transmission and distribution grids could not be obtained from the corresponding energy companies for commercial sensitivity reasons, as previously mentioned.

5.2.4 Assess the impact of climate change on climate threats

The completion of this step, which is not infrastructure specific, is described in section 3.2.4 (see Table 3.3 for outcomes).

5.2.5 Assess the impacts of climate change on critical infrastructure

Potential climate change impacts on flooding risk

The flooding risks to underground pipelines and wind turbines would most likely be limited to ground movement and soil compaction following heavy rain or drought conditions. Power plants (namely thermal and hydro stations), on the other hand, are normally located near water sources (ocean or river), and thus could be at risk from potentially damaging inundation due to flooding and storm surge events. Hydro stations are located over river courses and thus their locations are particularly susceptible to risks from fluvial flooding and seasonal fluctuations in water flow. A fluvial flood event might have indirect impacts on hydro stations that use the river water, even if the station is outside the flood extent, as a result of increases in river flow during the flood. Table 5.4 identifies the thermal and hydro stations in Ireland located in areas at possible risk from fluvial and coastal flooding under existing conditions based on the OPW flood risk maps (OPW, 2015). The pumped storage power station and ESB wind farms listed in Table 5.2 are not located within OPW flood map extents and thus do not appear in

Table 5.4. ESB power stations exposed to potential risk of flooding

	Fluvial flooding	Coastal flooding
Hydro stations		
Ardnacrusha	✓✓	✓
Carrigadrohid	✓✓	
Inniscarra	✓✓	
Leixlip	✓✓	
Thermal stations		
Aghada		✓✓
Dublin Bay	✓	✓
Lough Ree Power	✓✓	
Marina	✓✓	✓✓
North Wall	✓	✓
Poolbeg	✓	✓
West Offaly Power	✓✓	

A single tick (✓) indicates that a station might be at risk from flooding; a double tick (✓✓) indicates that the station is located in the flood extent.

the table. A double tick in the table highlights the power stations whose geolocation is within the OPW flood extents for existing conditions. It is noted that a power station is usually represented by a point in ArcGIS. However, in reality, these assets can extend over a large area, with the station at risk if any of its infrastructure assets are located in areas at risk from flooding. To account for this, and the high-level nature of this analysis, a single tick is assigned to a power station if any part of the 7 km × 7 km grid square in which it is located is subject to flooding. This single tick thus represents a significantly lower risk level, whereby the asset is simply being flagged for a brief further investigation. Importantly, a flooding event can also cause inundation of electricity substations located in low-lying areas; however, GIS data could not be obtained for these substations, so they could not be included in the analysis.

In the context of climate change, and in line with the high-level framework steps set out in Chapter 3 of this report, Figure 5.2 shows maps of the ESB power stations located in areas currently at risk of fluvial flooding based on the OPW flood risk maps, overlaid with a map of predicted future change in the number of very wet days. Maps are shown for changes in very wet days in both autumn and winter, under the medium- to low- and high-emission scenarios. This figure is presented as an example of a high-level screening tool for energy infrastructure, which provides a rough first approximation of which stations might experience increases in fluvial flooding risk in the future due to climate change. With the exception of three stations in the south in Cork (Carrigadrohid, Inniscarra and Marina stations), the number of very wet days is expected to increase in future for all mapped stations. Figure 5.3 presents the GIS-based information in a different form, plotting the 10 ESB power stations currently located in areas at risk from fluvial flooding as per the OPW existing flood extents, together with the values of predicted percentage change in number of very wet days in autumn and winter, under the medium- to low- and high-emission scenarios. This plot indicates that the risk is expected to increase more in winter, particularly for the high-emission scenario; for instance, the West Offaly thermal station location is expected to experience an increase in very wet days in winter of approximately 80% to 100%, depending on the climate change scenario. Overall, it is noted that the above mapping constitutes a very basic risk-screening analysis. A detailed assessment at each location examining catchment areas and power station datum levels, etc., would be required to determine the actual risk of fluvial flooding of the power infrastructure. A probabilistic approach would also need to be employed to provide quantitative risk insight.

Potential climate change impacts on wind-related risks

As previously mentioned, it was not possible to acquire GIS data for the overhead power transmission and distribution networks over the lifetime of this project, meaning that a GIS-based extreme wind risk-screening analysis on these important aspects of the CI network could not be carried out. However, the detailed quantitative risk analysis presented in Part B of this report does explore the vulnerability of power distribution networks to climate change and the feasibility of climate adaptation strategies. This analysis indicates that impacts may be significant. For instance, power pole networks in Cork are expected to experience a 24% increase in pole wind failure by mid-century under RCP4.5. The corresponding value for Dublin was 16%. See Part B for insights into the vulnerability of energy infrastructure to extreme wind and deterioration, and the cost–benefit analysis of possible climate adaptation options.

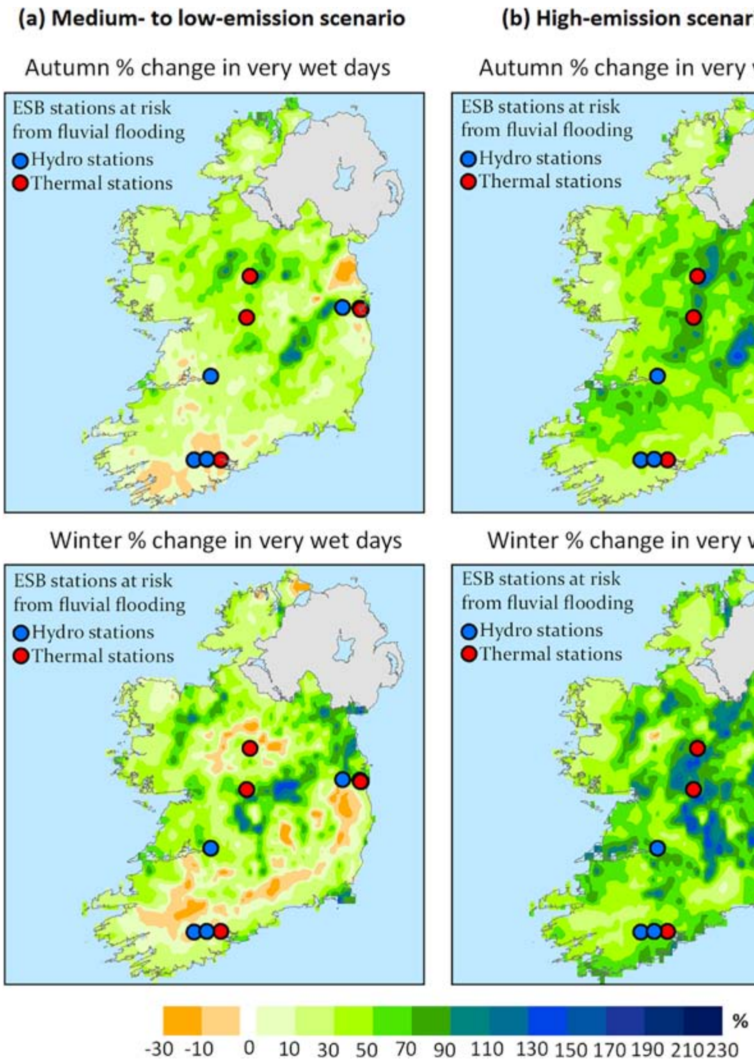

Figure 5.2. Maps of ESB power stations located in areas currently at risk from fluvial flooding overlaid with the projected change (%) in number of very wet days in autumn and winter under (a) the medium- to low-emission and (b) the high-emission scenarios.

Another wind-related risk pertains to the possible changes in future wind energy resource. Figure 5.4 shows the location of ESB wind farms, overlaid with the projected percentage change in the mean annual wind speed at 60 m above ground level. The overall trend is a decrease that reaches –2.4% in the south-east of Ireland, and –2.3% in the north of the country, for the medium- to low-emission scenario. There is a slight increase (< 1%) in the 60 m wind speed in some areas in the east and south of Ireland under the high-emission scenario. Examining the ESB wind farm locations, it is noted that 11 out of 12 of the sites are located in areas with a predicted decrease in annual mean 60 m wind speed, under both medium- to low- and high-emission scenarios. The wind energy resource will also be affected by changes in the variability of wind speeds, i.e. turbines shut down during high wind speed events (cut-out speed ≈ 25 m/s) and low wind speed events (cut-in speed ≈ 3.5 m/s). A report by Nolan (2015) found that the frequency of extreme wind events is projected to increase by mid-century, while the frequency of extreme low wind speeds is also projected to increase in future. Such changes are likely to reduce the overall wind energy resource. This may be an important impact given Ireland's Climate Action Plan target of 70% of electricity generated by renewable sources by 2030 (DCCAE, 2019). It is also important to note that Nolan (2015) states that there is relatively high uncertainty associated with wind change projections. This is not accounted for in this high-level CCRA; however, the uncertainty associated with wind speed projections is

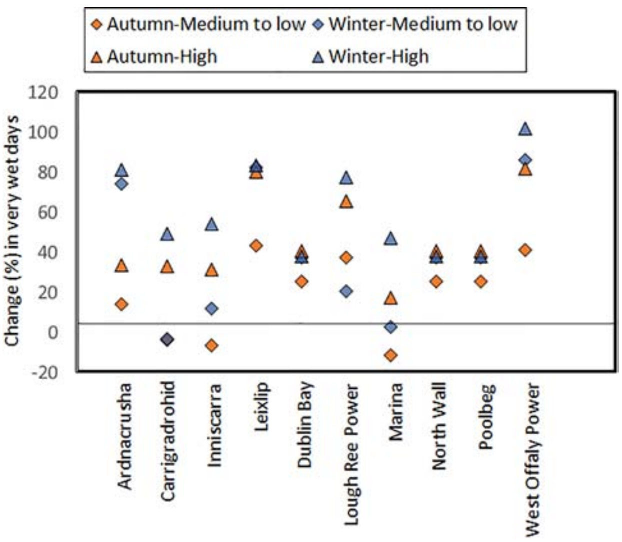

Figure 5.3. Values of the expected change (%) in the number of very wet days in autumn and winter for ESB power stations located in areas currently at risk from fluvial flooding.

incorporated into Part B of this report using detailed probabilistic modelling.

Potential climate change impacts on extreme temperature risk

This assessment was conducted as part of the CIViC project but, in the interests of brevity, is not included in the main report. The analysis can, however, be found in Appendix A4 of the CIViC supplementary material document, which can be obtained from the project's Principal Investigator, Dr P. Ryan.

5.3 Summary of Energy Sector Findings

The ability to conduct the GIS-based high-level risk analysis for the energy sector was limited to an extent by the lack of availability of comprehensive GIS data sets for the sector. The lack of GIS data was primarily due to issues related to security and commercial sensitivities. That said, the energy sector infrastructure owners/operators did engage with the project team to a large extent and some progress was made in terms of obtaining GIS data sets. Over the lifetime of the project, the extent of progress made did not facilitate a full GIS-based analysis. It is hoped that the project team can continue to collaborate with the energy sector in the future in this regard, building on the progress made.

Based on the assessment conducted, the results in Part B and engagement with the sector, the projected change in extreme winds is likely to be the major challenge for the energy infrastructure sector. A projected increase in the frequency of extreme wind events has the potential to have an impact on the above-ground distribution and transmission infrastructure. Failures in the power generation, distribution and transmission systems are particularly important because the reliance of other forms of CI on the energy infrastructure makes it perhaps the most

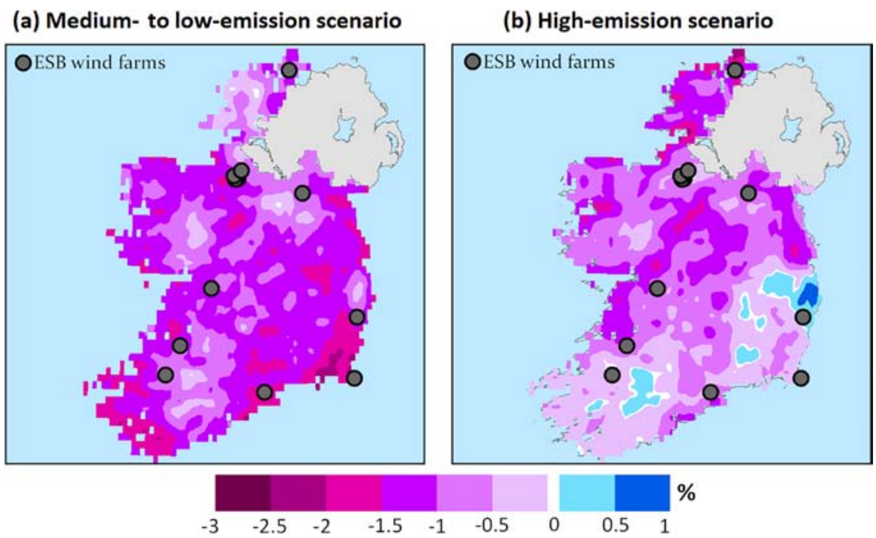

Figure 5.4. Projected change (%) in the annual mean 60 m wind speed and ESB wind farm locations under (a) the medium- to low-emission and (b) the high-emission scenarios.

important component of our modern CI networks. This was exemplified in Ireland by recent power outages caused by Storm Ophelia in 2017, which resulted in cascading failures affecting the wastewater treatment, water treatment and telecommunications sectors (*Irish Independent*, 2017).

Potential changes in wind speeds (extreme, daily means, low wind speed events) may also have impacts on the wind energy sector, with a decrease of between 1% and 3% being projected in the wind energy content under the medium- to low-emission scenario (Nolan, 2015). While this decrease is relatively small, it may be significant in the context of recent government plans to have 70% of Ireland's electricity generated by renewable sources by 2030 (DCCAE, 2017). The projected increase in winter and autumn precipitation may increase the risk from fluvial flooding for some hydro and thermal stations, with Lough Ree Power Station (Co. Longford), West Offaly Power Station (Co. Offaly) and Leixlip Hydro Station (Co. Dublin/Co. Kildare) on the River Liffey among the stations most likely to be adversely affected under the high-end scenario based on the high-level analysis. Finally, it is noted that ESB substations and other energy sector infrastructure may also be at risk of increased flooding in the future; however, it was not possible to investigate this in the CCRA here because of a lack of GIS data.

6 Climate Change Risk Assessment for the Water Sector

6.1 Existing National Assessments for Ireland's Water Sector

The Department of Housing, Planning, Community and Local Government is identified in the NAF as the lead department for developing climate change adaptation plans for (1) the water quality sector and (2) the water services infrastructure sector. To date, outside the NAF, a small number of general studies have been conducted in Ireland to assess the potential impacts of climate change on the water sector. An Environmental Protection Agency (EPA) report (Desmond *et al*., 2009) on the state of knowledge on climate change impacts for Ireland identifies that changing patterns of precipitation will have an impact on water services provision and on levels of pollution and contamination, with significantly wetter winters, particularly in the west, drier summers, particularly in the south-east, and storm occurrences of greater intensity expected. Other national reports (Adamson *et al*., 2009; DECLG, 2012b; EPA, 2016a) also highlighted the potentially significant impacts of climate change on water quality and water supply and infrastructure. An EPA report (Hall *et al*., 2012) presents a framework for supporting adaptation to climate change and a tool for assessing adaptation options in the water sector. All the above studies agree that climate change will increase pressure on water sources, thus increasing the risk of water scarcity and water pollution.

6.2 Application of the High-level Risk Assessment Framework to the Water Sector

6.2.1 *Generate a GIS inventory*

In the present report, the term "water infrastructure sector" refers to both water and wastewater sectors. It is noted that GIS details for the Irish water treatment network could not be obtained for use because of the commercial/security sensitivity of the data, as cited by the relevant state body. This has limited the ability of the project team to conduct the GIS-based CCRA approach for the Irish water sector. It is, however, hoped that these data will be obtained through future collaborations, enabling a climate change risk analysis of this CI network. GIS data were obtained for the wastewater treatment plants in Ireland from the EPA GIS database (http://gis.epa.ie/GetData/Download) and thus the GIS study is limited to these assets.

6.2.2 *Assess the importance level of critical infrastructure assets*

The wastewater system in Ireland includes 1085 treatment plants (Irish Water, 2015a). Figure 6.1 shows the location of the wastewater treatment facilities as reported by the EPA. These plants can be classified by the size of the corresponding agglomeration population equivalent (PE), as shown in the figure. The PE value can be used to classify the plants as large (PE > 10,000), medium (PE between 1000 and 10,000) or small (PE < 1000). Treatment plant importance levels in accordance with Table 3.1 can thus be assigned as follows: large = 3, medium = 2, small = 1.

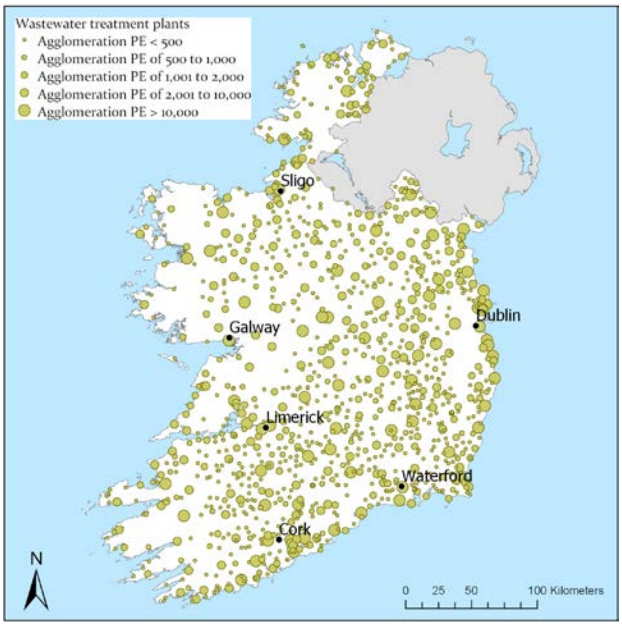

Figure 6.1. Irish wastewater treatment plants.

6.2.3 Identify the key climate threats for each infrastructure asset type

Figure 6.2 represents the relationships between the main critical assets of the water sector and the main climate threats in Ireland under existing conditions (i.e. this step is not focused on climate change). The corresponding vulnerability indices are determined in accordance with the strength of the relationship between the threat and the infrastructure system as discussed in Chapter 4 and presented again in the top panel of Figure 6.2. The matrix in Figure 6.2 (bottom panel) was developed through a review of national government and stakeholders' reports on infrastructure performance and EWEs (EPA, 2016a,b; Irish Water, 2015a,b), as well as European (Dawson, 2017; EEA, 2015; HR Wallingford, 2014; Koutroulis *et al*., 2018) and other international (2030 Water Resources Group, 2009; AFW and CVC, 2017) studies.

6.2.4 Assess the impact of climate change on climate threats

The completion of this step, which is not infrastructure specific, is described in section 3.2.4 (see Table 3.3 for outcomes).

6.2.5 Assess the impacts of climate change on critical infrastructure

Ireland's current water supply infrastructure has somewhat struggled to cope in recent years, with water conservation orders (also known as hosepipe bans) in place in Ireland from 6 July 2018 until 25 August 2018. Climate change predictions indicate that by mid-century summers in Ireland will be hotter and drier, with temperature increases of between 0.9°C and 11.3°C and precipitation decreases of between 1% and 17% expected under the medium- to low-emission scenario, and a 1.1°C to 1.7°C increase in temperature and a 9% to 24% decrease in precipitation expected under the high-emission scenario (Nolan, 2015). These changes are likely to lead to increased pressure on Irish water supply resources in the future. It is noted, however, that Irish Water is already taking positive steps to upgrade the water sector infrastructure, for example through an ongoing leakage reduction programme, which aims to save approximately 166 million litres of water per day. On another positive note, the water distribution network is likely to experience a reduced risk of failure and subsequent supply interruptions due to freezing as winters become warmer. The impact of these

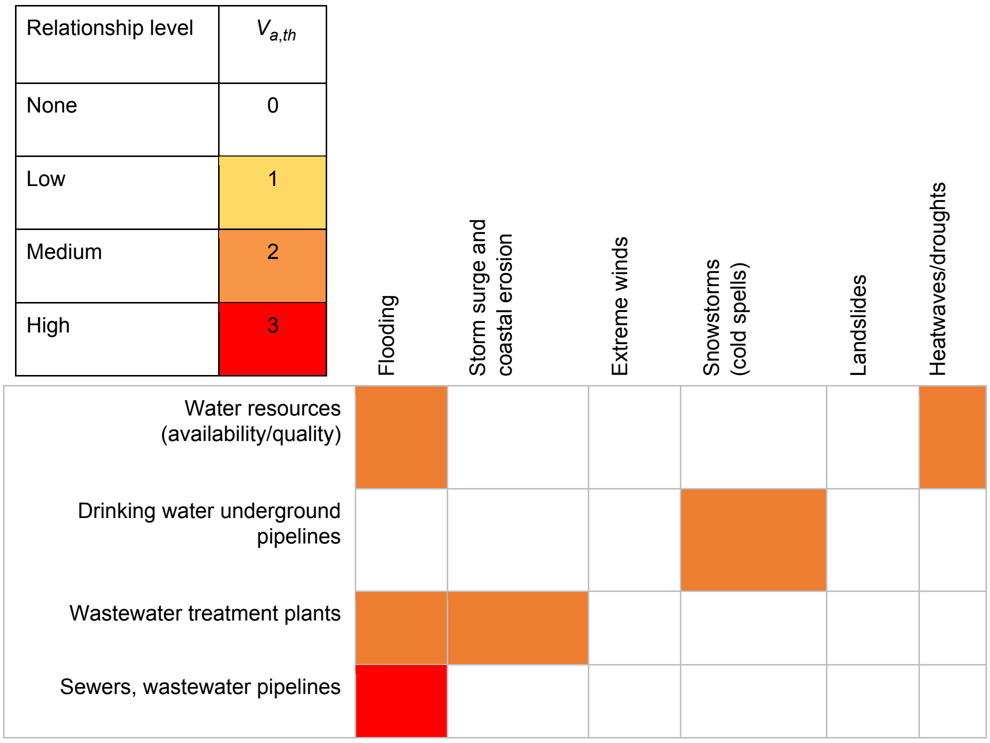

Figure 6.2. Vulnerability matrix for Irish water infrastructure. $V_{a,th}$, vulnerability index of asset *a* to the climate threat *th*. Source: adapted from Hawchar *et al*. (2020).

cold weather events was seen during Storm Emma (in the winter of 2018), when most local authorities experienced difficulties in maintaining normal supplies to the public as a result of the longest period of severe cold weather in almost 50 years. The initial difficulties arose mainly from frozen supplies, but, as the thaw set in, further damage was caused by the moving ground and burst pipes.

The projected increase in heavy rainfall could affect wastewater services through increased risk of sewer flooding, the possible flooding of wastewater treatment plants and the overloading of wastewater treatment plants owing to Ireland's combined sewerage networks. The latter has been a key concern in recent years, with a number of Dublin's southern beaches closed because of overflows from Dublin's Ringsend Wastewater Treatment Plant (O'Sullivan, 2019). This highlights the socioeconomic and environmental implications associated with failures in the water sector. These overflows can occur during or following intense rainfall events, when storm water volumes increase significantly. Ireland's combined sewerage systems mean that increased storm water flows result in significant increases in the inflow volumes into the wastewater treatment plants, meaning that plants can be loaded above capacity. Intuitively, any climate change-induced increases in heavy rainfall events will lead to an increased risk of wastewater treatment plant overflows. Figure 6.3 shows the locations of the large wastewater treatment plants (i.e. in agglomerations with PE > 10,000) overlaid with a map of the projected change in heavy rainfall in winter, under the medium- to low- and high-emission scenarios. These maps indicate that the greatest increases in heavy rainfall, and consequently pluvial flooding risk and plant overflow risk, would affect the treatment plants in the middle of the country. This area is predicted to experience a 126% increase in heavy rainfall in winter under the medium- to low-emission scenario and a 135% increase under the high-emission scenario. Some of the large treatment plants, mainly those located in the south of the country, are expected to experience less intense rainfall under the medium- to low-emission scenario, which would represent a positive effect for the sector, emphasising the regional variability of climate change impacts even in a country the size of Ireland. The Ringsend plant, which treats approximately 40% of Ireland's wastewater, has been subject to a number of overloading incidents in recent years (O'Sullivan, 2019). Heavy rainfall at this plant is projected to increase by 37% by 2050. There are, however, plans to upgrade this plant significantly over the coming years, with permission granted in April 2019 for a €400 million upgrade (O'Sullivan, 2019). Water treatment facilities may also be at risk of climate change-induced flooding and other threats, but this could not be examined because of a lack of GIS data. It is also important to note that the water sector is also vulnerable to failures cascading from the energy sector, as experienced during Storm Ophelia in 2017, when power outages resulted in failures in water treatment systems, with over 100,000 households and businesses cut off from the water supply, and a further

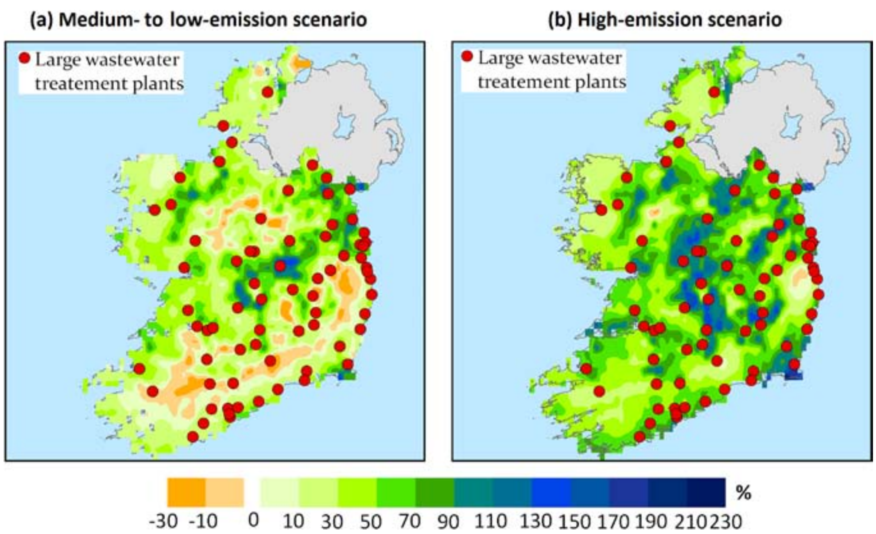

Figure 6.3. Exposure of large wastewater treatment plants to projected increases in heavy rainfall in winter, under (a) the medium- to low-emission and (b) the high-emission scenarios.

260,000 customers at risk of losing water supply during the storm (O'Sullivan, 2017). Approximately 30 wastewater treatment plants were without power during the storm, with these power failures resulting in the discharge of untreated or partially untreated wastewater to receiving waters (O'Sullivan, 2017).

6.3 Summary of Water Sector Findings

The findings of this GIS-based CCRA for the Irish water and wastewater sector were limited to wastewater treatment plants owing to a lack of available GIS data from the sector's infrastructure owners/operators. The high-level analysis identified extreme rainfall events and flooding (fluvial and coastal, depending on the plant location) as the major challenges for wastewater treatment plants. This risk is projected to increase in future as a result of climate change for most of the treatment plants. However, some treatment plants located in the east of the country (i.e. near Dublin) are expected to experience a decrease of between 5% and 14% in the number of heavy rainfall events, under both climate change scenarios. Under the medium- to low-emission scenario, some wastewater treatment plants, mainly located in the south and east of the country, are also expected to experience a decrease in rainfall. These findings emphasise the regional variability of potential climate change impacts in Ireland. Similar regionally variable patterns are likely to affect the water treatment infrastructure; however, these infrastructure assets could not be analysed in detail owing to a lack of access to GIS data.

Future projected reductions in summer rainfall volumes also pose a risk to Ireland's water supply resource. The CCRA also highlighted the reliance of the water sector on energy supply, and the subsequent vulnerability of water sector operations to failures cascading from the energy sector.

7 Climate Change Risk Assessment of the ICT Sector

7.1 Existing National Assessments for the Irish ICT Sector

The DCCAE was identified in the NAF as the lead department for developing the sectoral climate change adaptation plan for the communications sector. The ICT sector includes the fixed phone, mobile phone, internet and data analytics subsectors. The main physical infrastructure assets of the ICT sector are data centres, telecommunication masts and antennae, and overhead and underground wires and cables. It should be noted, however, that a general CCRA of the ICT sector should consider not only the physical assets, but also the service availability and quality (Fu *et al*., 2016). To date, no national assessment of the vulnerability of the ICT sector to climate change has been performed for Ireland.

7.2 Performance of the High-level Approach to the ICT Sector

7.2.1 Generate a GIS inventory

In Ireland, the vast majority of the ICT infrastructure is privately owned and operated, and is therefore subject to commercial sensitivity. For the present study, GIS data for the ICT sector were obtained from Eircom Ltd (eir). The data received were in the form of geospatial locations for 30 key sites that eir considers are possibly at risk from EWEs and climate change. These sites were used in the assessment, but are not shown in this report owing to data publication restrictions. No data for outside these 30 sites were obtained for the Irish ICT sector over the course of this project. This somewhat limited the scope for conducting and presenting a comprehensive GIS-based high-level CCRA for the ICT sector.

7.2.2 Assess the importance level of critical infrastructure assets

The geospatial locations of assets provided by eir primarily correspond to data centres. Any failure of these assets can have a significant impact on Ireland's ICT sector, with cascading failures into other sectors possible. This would have an impact on individuals, businesses and public services. Hence, these assets are deemed of vital national importance (i.e. importance index = 4). It is noted that the increasing reliance on ICT/the digitisation of Irish society will most likely increase the importance of such major ICT assets in the future

7.2.3 Identify the key climate threats for each infrastructure asset type

Figure 7.1 represents the relationships between the main critical assets of the ICT sector and the main climate threats in Ireland under existing conditions (i.e. this step is not focused on climate change). As can be seen, data centres and overhead assets (e.g. masts, antennae, overhead data phone and network cabling) were the key infrastructure aspects identified. The term "data centre" used herein refers to fixed and mobile network switching centres, database and IT information centres, and transmission centres. The corresponding vulnerability indices are determined in accordance with the strength of the relationship between the threat and the infrastructure system as discussed in Chapter 3 and presented again in the top panel of Figure 7.1. The matrix in Figure 7.1 (bottom panel) was developed through a review of international reports (Fu *et al*., 2016; Wong and Schuchard, 2011) and discussions with the ICT industry.

7.2.4 Assess the impact of climate change on climate threats

The completion of this step, which is not infrastructure specific, is described in section 3.2.4 (see Table 3.3 for outcomes).

7.2.5 Assess the impacts of climate change on critical infrastructure

In view of the ever-growing integration of the ICT sector into day-to-day lives, the reliance of society and business on digital and communication services is expected to increase considerably in the future. Investigations and discussions with the ICT industry have indicated that much of the sector's infrastructure

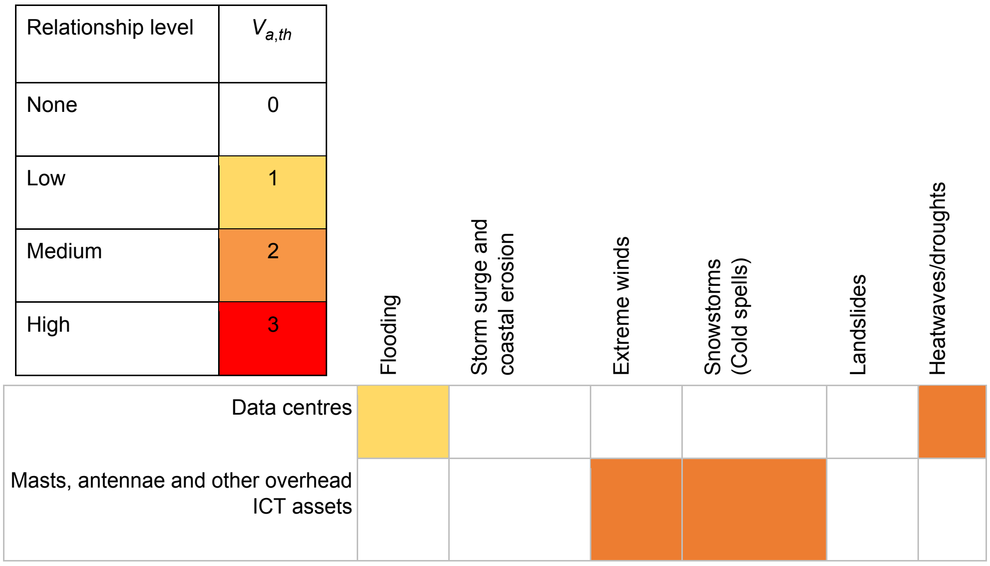

Figure 7.1. Vulnerability matrix for Irish ICT infrastructure. $V_{a,th}$, vulnerability index of asset *a* to the climate threat *th*.

may not be as sensitive to climate change and EWEs as the infrastructure in other CI sectors. However, the ICT sector is vulnerable to cascading failures from the energy sector, as illustrated during recent storms in Ireland, when power outages resulted in ICT service interruptions. In general, the primary climate change risk for the ICT sector's own infrastructure relates to extreme wind events. The vulnerability of the sector to such events was illustrated in 2017 during Storm Ophelia, when an estimated 110,000 people were left without telecommunication services (*Irish Independent*, 2017). The impact of these interruptions are magnified by the fact that the need for voice and data communication services significantly increases during EWEs.

Examining the 30 geospatial locations provided by eir, it was found that none of the sites is currently at risk from coastal flooding. However, two sites were identified using the OPW maps as being at risk of fluvial flooding under current climatic conditions: a site in Dublin city south is located in an area currently exposed to 1-in-100-year fluvial flood events and a site in Donegal is in an area exposed to 1-in-1000-year fluvial flood events. It is predicted that heavy rainfall events for these two sites will increase in the future (Nolan, 2015). In winter, the number of very wet days will increase by 37% at the Dublin site, under the high-emission scenario. The Donegal site is predicted to experience an approximately 90% increase in heavy rainfall under both climate change scenarios (Nolan, 2015). It is noted that discussions with the ICT sector indicate that some adaptation measures are already being put in place, such as the elevation of water-sensitive equipment above floor level, and basic localised flood defence measures are being investigated.

Increased cooling resources for ICT data centres may also be required in the future. An examination of the 30 ICT site locations and geospatial projected climate changes indicates that the site locations will experience an increase in annual maximum temperatures by mid-century of between 1.3°C (in the south) to 1.6°C (in the north) under the medium- to low-emission scenario and 1.4°C (in the south) and 1.7°C (in the north) under the high-emission scenario. On the positive side, ICT infrastructure is expected to experience a reduction in ice loading in Ireland in the future. Figure 7.2 shows the projected percentage change in the number of ice days for Ireland and illustrates that reductions in ice days are expected to be significant throughout the country. For the key site locations, the annual number of ice days is predicted to decrease by 69% (in the midlands) to 78% (in the south) under the medium- to low-emission scenario and by 76% (in the midlands) to 90% (in the north) under the high-emission scenario by mid-century. All 30 ICT sites examined will also experience increases in annual extreme low temperatures by mid-century, ranging from 1.2°C to 1.4ºC under the medium- to low-emission scenario and from 1.4°C (in the south) to 1.6°C (in the north) under the high-emission scenario.

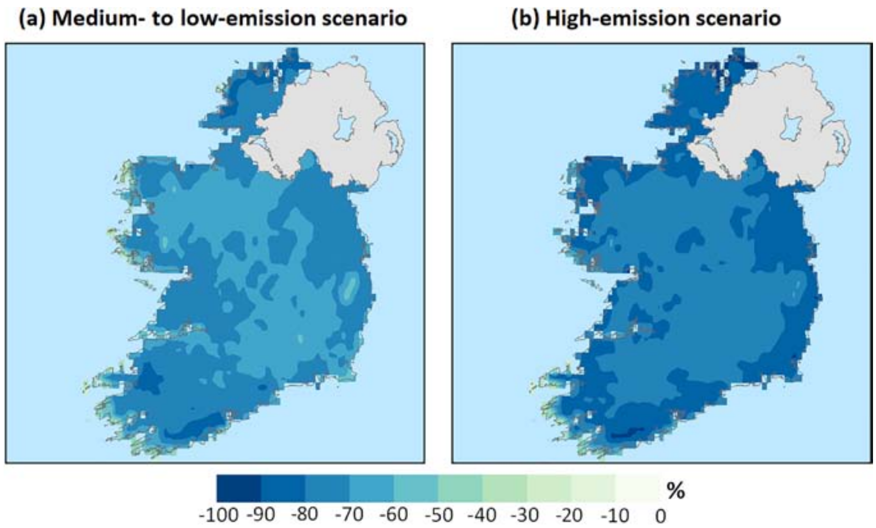

Figure 7.2. Projected change (%) in the annual number of ice days by mid-century under (a) the medium- to low-emission and (b) the high-emission scenario.

7.3 Summary of ICT Sector Findings

The ICT sector is perhaps the most resilient to climate change effects of the four CI sectors considered in this study; however, the sector is still likely to experience climate change-related challenges in the future. The sector has been shown in the past to be particularly vulnerable to extreme wind events (e.g. 110,000 customers were left without service following Storm Ophelia). The GIS analysis also indicates that fluvial flooding risk for a number of key sites may also increase in the future. Increases in the maximum temperatures, notably in summer, and associated increases in the frequency and duration of heatwaves, are likely to present challenges in the context of the cooling of data centres. On a positive note, projected warmer winters with fewer ice days will mean that ICT sector overhead assets (e.g. masts, cables, antennae) will experience less ice and snow loading. Finally, it is important to note that a key vulnerability for the ICT sector relates to cascading failures from the energy sector, as was seen during recent storms in Ireland, such as Storm Ophelia.

8 Cross-sectoral Geospatial Risk Ranking

This chapter represents the results corresponding to step 7 of the high-level approach outlined in Figure 3.1 in Chapter 3. As discussed, fluvial flooding is one of the primary climate threats for a significant portion of Ireland's CI. Thus, for demonstration purposes, gridded ($7 \times 7\,km^2$) cross-sectoral relative risk maps are presented in this chapter for fluvial flooding risk, considering all four CI sectors (transport, energy, water and ICT), under both existing climate conditions (Figure 8.1) and predicted climate conditions (Figure 8.2).

The map presented in Figure 8.1 was developed using the set of relative risk indices obtained from equations 3.1 and 3.2 in section 3.2.6. The dark purple areas represent the grids with the highest calculated relative risk to fluvial flooding under existing conditions considering (1) the density of infrastructure in a given grid located in the fluvial flood extent, (2) the vulnerability of this infrastructure to fluvial flooding and (3) the importance of the infrastructure concerned. Grid squares are included in Figure 8.1 only if the square contains CI and a part of the grid square is within the existing OPW flood risk map extents. It must be noted that this is a high-level assessment and the absolute values of this semi-quantitative risk analysis are not of importance. It is the relative risk that is of interest, indicated by the colour gradients in each $7 \times 7\,km^2$ grid square. As can be seen from Figure 8.1, Ireland's capital, Dublin, exhibits the highest relative risk nationally. This is primarily owing to the density of CI in this area, i.e. rail stations, roads, large wastewater treatment plants, etc. The density of infrastructure in other urban areas such as Cork, Galway and Limerick also plays a key role in their high relative risk levels (Figure 8.1). However, Figure 8.1 also shows that high relative risk levels are not limited to the cities, with a number of areas in the more rural Irish midlands also exhibiting high values under the existing climate. The highlighted grids (A, B and C) are examples of this, where:

$$R^{(A)}_{\text{fluv,flood}} > R^{(B)}_{\text{fluv,flood}} > R^{(C)}_{\text{fluv,flood}} \tag{8.1}$$

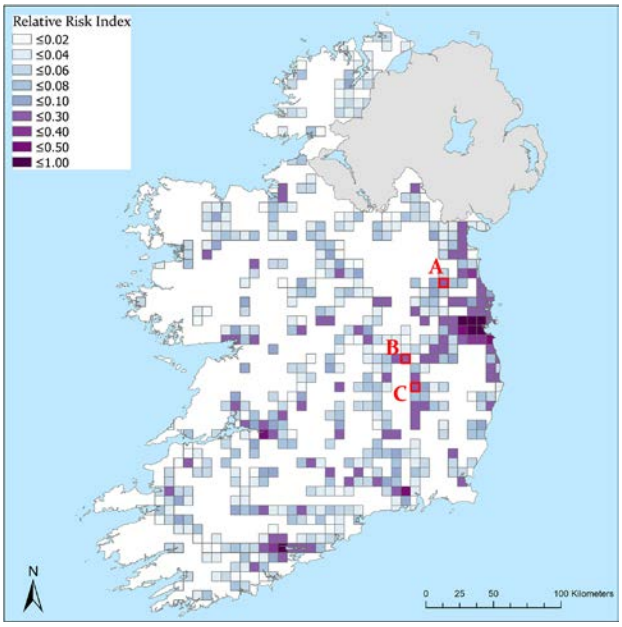

Figure 8.1. Gridded ($7 \times 7\,km^2$) map of relative fluvial flood risk for four Irish CI sectors. Source: Hawchar *et al.* (2020).

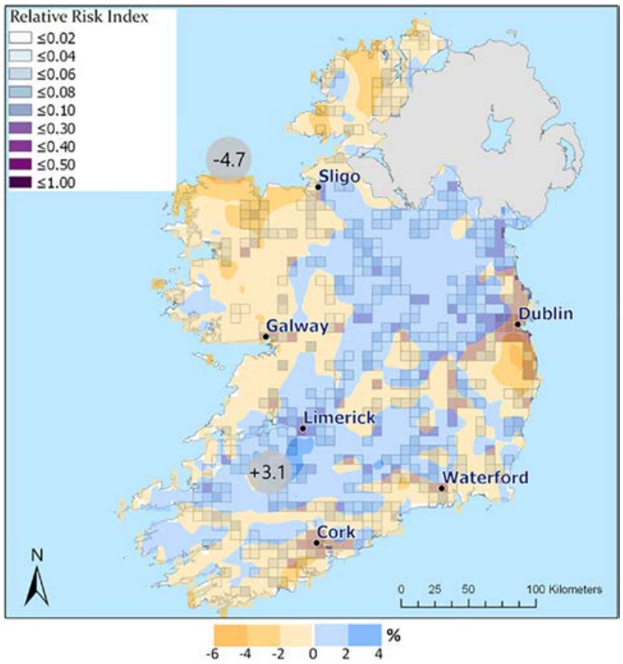

Figure 8.2. Gridded ($7 \times 7\,km^2$) map of relative fluvial flood risk to the four Irish CI sectors and projected change (%) in autumn rainfall, for the high-emission scenario. Source: Hawchar *et al.* (2020).

Examining grid A, the high relative risk score of this 7 × 7 km^2 area is primarily related to the high density of transport infrastructure in this area, i.e. 9.2 km of national roads, 27.9 km of regional roads, three national bridges and nine regional bridges. The importance level of these assets ranges from 2 to 3, with vulnerability indices of 3. Grid A also contains one large wastewater treatment plant (importance index of 3) and some gas network infrastructure. Grid B owes its high relative risk index mainly to the high density of its rail infrastructure, with a total of 7.7 km of rail lines, one small station and 10 rail bridges. This grid also contains 6.9 km of national and 16.6 km of regional roads, 14 road bridges, one medium wastewater treatment plant and a total of 17.2 km of gas pipelines (low vulnerability index of 1). By contrast, grid C's relative risk score is strongly influenced by a high density of wastewater treatment infrastructure, namely one large, one medium and two small plants, all located within the 7 × 7 km^2 grid. This risk score is also affected by the presence of 4.4 km of national and 14.3 km of regional roads, 12 regional road bridges and 7.6 km of rail networks.

To consider the impact of climate change on the future vulnerability of the assets to fluvial flooding, the map of projected changes for total autumn rainfall for the high-emission scenario is overlaid with the gridded map of current relative risk in Figure 8.2. This is in line with the relationship established in section 3.2. The vulnerable areas (i.e. dark purple grids) around Limerick are likely to witness more fluvial flooding events in the future, as the rainfall amount is expected to increase by between 1.7% and 1.8%. Figure 8.2 also shows that some areas currently ranked as highly vulnerable to fluvial flooding, notably in Dublin, Cork and Galway, are expected to witness a decrease in autumn precipitation of approximately 1%, 1.6% and 2%, respectively, under the high-emission scenario. This could lead to a possible reduction in their relative risk ranking, although it is noted that this is a high-level indicative finding, recognising the simplicity of the presumed relationship between probability of fluvial flooding and autumn rainfall. In a more complete study focused on fluvial flood risks, each grid could be assigned to a catchment and consideration could be given to how changes in rainfall in a given catchment would affect river flows, leading to an assessment of the change in climate hazard. However, such an approach is outside the scope of this analysis, which uses a first pass risk-screening approach across a range of hazards and infrastructure types. Despite this, Figure 8.2 is an example of a map that can be used, with other data, in a high-level context to help infrastructure owners/operators to gain an initial understanding of areas where a climate risk across sectors may vary under projected future climate conditions. In the context of Figure 8.2, potential climate change risk hotspots are indicated by areas that have high existing relative risk to fluvial flooding and a projected increase in rainfall.

It is noted that, while this section presents relative risk ranking maps for fluvial flooding for Ireland, its presentation is intended to illustrate the framework that could be applied to any climate threat. The geospatial representation in this ranked risk format has a number of key advantages:

1. In the scope of a high-level analysis, the map is easy to read, given that it incorporates GIS layers for climate threat and many asset types across four different CI sectors.
2. The multi-sectoral approach could help initiate important conversations between CI sectors, which will be key to understanding infrastructure interdependencies and reducing vulnerability to cascading failures across sectors.
3. Presentation of the maps in this gridded format at relatively low spatial resolution protects the commercial sensitivity of the data.

9 Key Messages from the High-level Analysis

Part A of the report has addressed objectives 1 and 2 through the development of the GIS-based high-level CCRA framework, and the implementation of this framework across four of Ireland's CI sectors. The key messages from the high-level analysis are as follows:

- The high-level analysis, which illustrates the regional variability of climate risks for CI, highlights the importance of the development of GIS data sets by CI owners/operators and the sharing of these data sets to enable the assessment of risks associated with climate change and EWEs. It also shows (e.g. Figure 8.1) how sensitive data can be used to assess risk, while also protecting commercial/security sensitivities.
- Continued work is required to promote the sharing of these GIS data sets by infrastructure owners to facilitate research into climate change impacts. As part of this project, GIS data were obtained from industry collaborators from each sector with the exception of the water sector. However, there were incomplete data sets in every sector because of commercial/security sensitivities. This limited the ability of this desk study-scale project to conduct a complete GIS-based high-level climate change risk analysis. However, having established information exchange pathways, there are strong indications from the industry collaborators that greater progress will be made in this regard on future projects.

Having developed a high-level risk analysis framework herein, the implementation of the approach and the results were presented on a sector-by-sector basis and in terms of cross-sectoral risk.

- Fluvial flooding and coastal inundation/coastal flooding are key climate change risks for the transport sector. For instance, the extent of national roads and rail networks in projected flood zones in Ireland for the existing 1-in-1000-year coastal flooding event were found to be similar to those in the 1-in-10-year coastal flood event under the mid-range future climate change scenario. The sector is also likely to experience increased future risk of bridge scour in some areas, most notably in the midlands region, and increased landslide risk in certain areas.
- Climate change risks related to extreme winds are likely to be the major challenge for the energy infrastructure sector. The reliance of other CI sectors on energy supply means that energy sector failures are particularly important, given their propensity to cause cascading failures across networks. Other energy sector risks include reductions in future wind energy and increased risk of flooding (fluvial and coastal) of energy assets. Risks to stations such as West Offaly Power Station may merit further investigation in the context of its proximity to the existing flood plain and a projected increase in very wet days in winter of approximately 80% to 100%.
- The GIS-based CCRA of Irish wastewater treatment plants identified flooding and risks related to extreme rainfall events, such as wastewater treatment overflow, as key risks for the water sector. For instance, Ringsend Wastewater Treatment Plant, which treats approximately 40% of Ireland's wastewater, is projected to experience a 37% increase in heavy rainfall by 2050. However, high levels of regional variability in changes in heavy rainfall events, particularly under RCP 8.5, were identified. Future projected reductions in summer rainfall volumes also pose a risk to Ireland's water supply resource.
- The ICT sector has been shown in the past to be particularly vulnerable to extreme wind events, and thus changes in this threat are among the sector's primary climate change risks. The other main risk relates to the vulnerability of ICT operations to cascading failures from the energy sector. The GIS analysis also indicates that fluvial flooding risk may increase in the future, and increases in maximum summer temperatures and the likelihood of heatwaves will present challenges in the context of the cooling of data centres.
- The analysis of CI highlighted the importance of CI interdependencies, particularly related to energy sector failures, which has also been recognised by the C-Risk project (Flood *et al.*, 2020). The detailed study of this area was

beyond the scope of this project; however, a cross-sectoral geospatial risk-ranking tool, which accounts for only geographical proximity between infrastructure assets from different sectors, was used to highlight potential climate risk hotspots. Although Ireland's main urban areas exhibited the highest relative risk ranking because of the density of infrastructure, some rural areas also had high relative risk ranking values. Plotting relative risk against projected changes in autumn rainfall helped to provide insights into areas where relative risk may increase, such as Limerick.

- Overall, it was recognised that interdependencies between various infrastructure systems and cascading failures are (1) an important element in determining the vulnerability of a society to climate change threats and (2) a complex process that requires a deep level of understanding of the connections between CI systems. This area therefore needs to be examined in future work.
- Finally, it is important to note that the GIS-based CCRA is a high-level risk-screening tool. In general, this level of analysis and the nature of the output obtained are not of sufficient detail to inform actual climate adaptation action for CI. Much more detailed analysis that incorporates uncertainty and variability is required to avoid opportunity costs associated with poorly informed adaptation implementation. This is discussed further in Part B of this report, with an illustrative probability-based analysis case study of the energy sector.

Part B

Quantitative Risk-based Decision Support for Climate Adaptation

Energy Sector Case Study: Irish Timber Power Pole Networks

10 Introduction to Quantitative Risk-based Decision Support for Climate Adaptation

The work presented in this part of the report is an example of the next step following a risk-screening analysis of the type presented in Part A. The GIS-based high-level CCRA aids the identification of CI assets, or parts of CI networks, that are expected to be vulnerable to climate change impacts. Having initially identified these key areas of concern, further, more detailed quantitative risk assessment is required to examine if climate change impacts will actually occur, and what the magnitude of risk or impact actually is. If the impacts are likely to be significant, climate adaptation options can be examined using tools such as cost–benefit analysis. It is vital that these risk assessments take into account the variability and uncertainty associated with the systems examined, i.e. variability and uncertainty associated with EWEs, climate change, long-term performance of infrastructure assets, etc. The high levels of uncertainty and variability are why decision-making concerning climate change impacts is incredibly challenging. It is recognised that the most appropriate tool for modelling processes with high levels of uncertainty and variability is probabilistic analysis (Ryan *et al*., 2014), which is an essential component of all quantitative risk-based approaches. These quantitative risk assessments can facilitate the development of effective climate change adaptation strategies, which optimise the response of built infrastructure to climate threats through risk-based decision support. Such an approach avoids opportunity costs associated with ill-informed adaptation decision-making by avoiding worst-case thinking, probability neglect and risk aversion (Bastidas-Arteaga and Stewart, 2019). Part B of this report illustrates the power of these quantitative risk-based decision support tools in assessing climate change impacts and climate change adaptation using an illustrative case study: timber power pole networks. Prior to examination of the timber power pole networks in Chapter 11, this chapter presents the general framework for quantitative risk-based decision support for climate adaptation. The framework presented utilises the following three-step process:

1. establish existing vulnerability/existing climate risk;
2. quantify climate change risks/impacts;
3. assess the feasibility of different climate adaptation options using probabilistic cost–benefit analysis, thus reducing future climate risk in the most cost-effective manner.

Before predicting how a CI network might perform under conditions in the future, we must first develop a clear engineering-based understanding of the vulnerability of the network under today's environmental conditions. Having established existing vulnerability and subsequent existing climate risk, the second step is to evaluate how changes to the climate in the future may have an impact on risk, examining a range of climate change scenarios. The analysis of impacts across different scenarios, together with the probabilistic approach, helps to avoid worst-case thinking pitfalls. The quantitative climate change risk analysis (also known as climate change impact analysis) will indicate if climate adaptation is necessary, i.e. if there is a potentially significant increase in climate risk. With this knowledge, the feasibility of different climate adaptation strategies can be explored by modelling adaptation effectiveness and conducting a probabilistic cost–benefit analysis of adaptation strategies.

Before exploring these three steps in detail, it is important to first explore the concept of risk itself. Figure 10.1 presents the general concept of climate-related risk as defined in the IPCC Special Report (IPCC, 2012). In this report, the IPCC describes climate risk as "the potential for consequences where something of value is at stake and where the outcome is uncertain, recognising the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of hazard, vulnerability and exposure". Thus, risk can be quantified using the following equation:

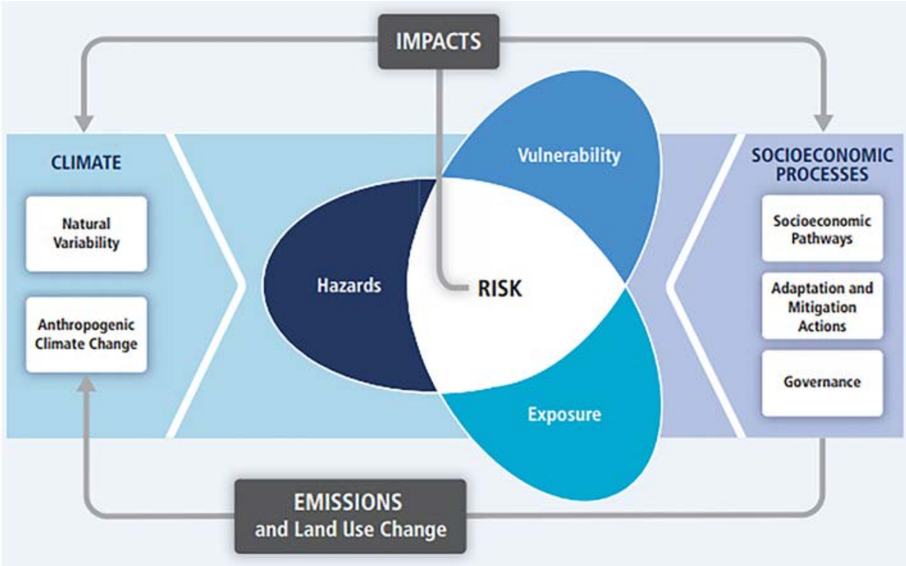

Figure 10.1. Concept of risk by the IPCC (adapted from IPCC, 2012).

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Consequences (or Exposure)} \qquad (10.1)$$

where "Hazard" refers to the probability of occurrence of a climate hazard, "Vulnerability" refers to the probability of damage to the system given the hazard and "Consequences" refers to the loss encountered if the hazard succeeds in causing damage to the system. The term "Consequences" is analogous to the term "criticality", which is often used by industry stakeholders.

Figure 10.2 presents the general framework that can be used for quantitative risk-based decision-making for climate adaptation for infrastructure. The figure expands on the standard definition of risk in equation 10.1, with typical analysis steps for CI classified under the three components of risk, providing examples of what forms of data are required for each assessment step. It is noted that the different steps present different challenges, depending on the infrastructure type and hazard being considered. Importantly, the risk-based decision support framework outlined below is illustrated fully using the case study in Chapter 11.

10.1 Critical Infrastructure Network Vulnerability

Before climate change risk and adaptation analysis can commence, we must first understand the behaviour and performance of the CI system under the existing climate, and identify all the environmental factors (e.g. wind, snow or wave loads, temperature, humidity) that would have an impact on its reliability now and in the future. More than one limit state function (i.e. failure scenario) can be identified at this stage. Given that infrastructure systems are usually intended for long service lives, it is also very important to model infrastructure deterioration over time, using time-dependent reliability analysis. This facilitates more accurate insights into the long-term infrastructure performance through consideration of the ageing process induced by various natural degradation phenomena (timber decay, steel corrosion, reinforced concrete cracking, fatigue, etc.).

The core of the probabilistic time-variant reliability analysis that is used in quantitative risk assessment is the evaluation of the probability of occurrence of a given infrastructure failure event (i.e. a given limit state function), at a given time, through calculation of the time-dependent failure probability $P_f(t)$:

$$P_f(t) = Prob\{G(t) \leq 0\} \qquad (10.2)$$

where $G(t)$ denotes the time-dependent limit state function. The probabilistic approach facilitates consideration of the uncertainties and variability at all levels (material properties, geometry, loadings, model uncertainty, existing climate variability, etc.). At this level of the analysis (without incorporation of climate change impacts), vulnerability curves (see the application in Chapter 11) can be produced. These curves provide information about the vulnerability (i.e.

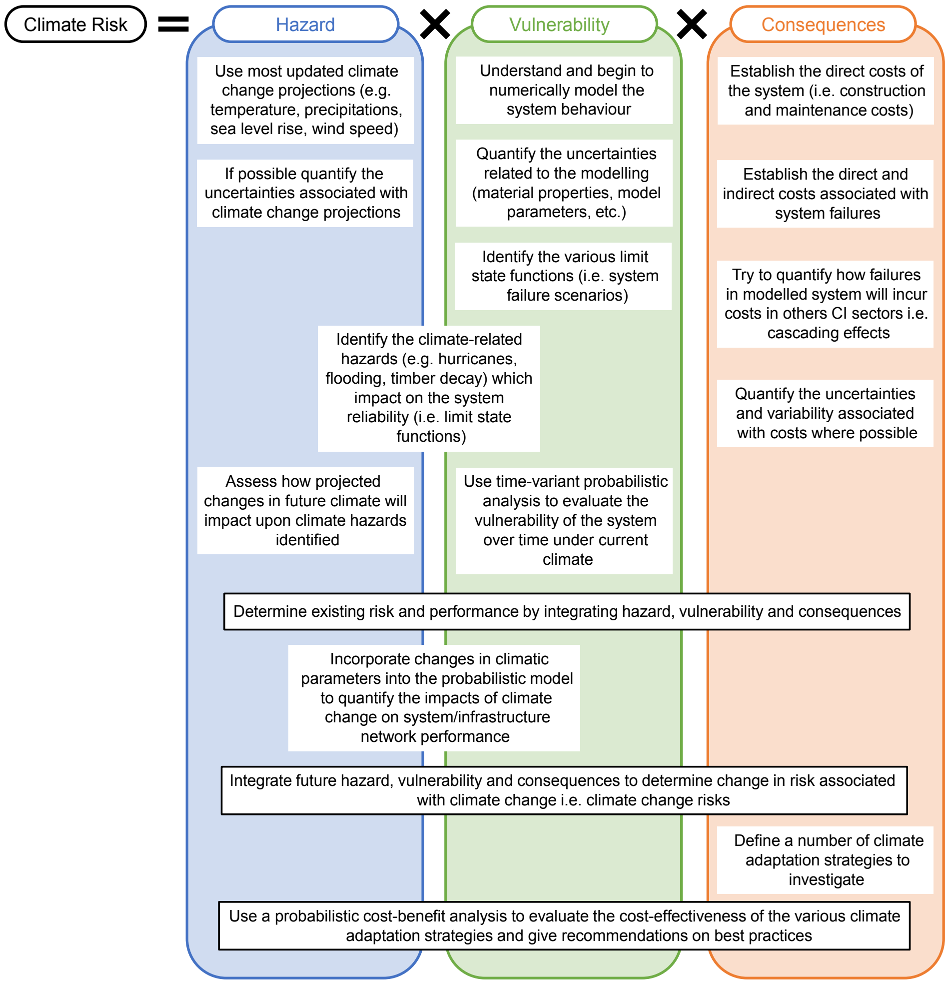

Figure 10.2. Framework for the implementation of quantitative risk-based decision support for climate change impacts and adaptation.

probability of failure) of the CI system under different values of the climate hazard (e.g. values of extreme wind speeds). If integrated with the climate hazards in question, system performance can be quantified. If required, integration of consequences provides values and ranges of risks.

10.2 Climate Change Impacts

Having established an understanding of infrastructure performance under existing climate conditions and modelled this using quantitative risk-based methods, future performance and subsequent changes in future risk can be examined by incorporating projected climate change into the model. Again, the uncertainty and variability associated with climate change projections (e.g. predicted change in wind speeds) can be incorporated using a combination of probabilistic modelling and scenario-based analysis. Statistical properties of projected changes in climate variables can be determined using uncertainty quantification analysis based on a data set of RCM outputs.

It is noted, however, that understanding the extent of climate impacts on CI network performance is not straightforward (Ryan *et al*., 2016). The influence of climate change on infrastructure performance is normally dependent on a relatively complex interaction of a number of different climatic effects (i.e. temperature, rainfall, wind speeds, etc.), manifesting in changes in deterioration rates and loading conditions. Consequently, impacts are often not intuitive, meaning that this detailed quantitative modelling approach is normally required to examine the magnitude of climate change impacts and, importantly, to quantify increases in risk associated with climate change. The IPCC does not assign probabilities or likelihoods to individual RCP scenarios. Therefore, a scenario-based analysis across the main RCPs should be used when examining climate change impacts and adaptation feasibility to ensure that decision-makers are aware of the range of possible futures. It is noted that, often, if a climate adaptation measure has a positive cost–benefit outcome for one climate scenario, it will also have a positive cost–benefit outcome for other climate scenarios, as illustrated in the case study in Chapter 11.

10.3 Adaptation Cost–Benefit Analysis

The ability to implement cost-effective climate change adaptation strategies will be a key factor in determining how well our CI systems cope with a changing climate (Ryan and Stewart, 2017). However, as stated above, climate change impacts are highly complex and not always intuitive, especially for infrastructure networks. This is also true for adaptation feasibility, which adds another layer of complexity to the analysis, i.e. quantifying the effectiveness, and costs and benefits of adaptation. Consequently, detailed and robust analysis is normally required to ascertain if a given infrastructure climate adaptation strategy is effective for a given country or indeed region. Failure to conduct such an analysis could lead to significant opportunity costs, with actions typifying cost neglect being taken after extreme events because of public pressure or other non-scientific forcers (Bastidas-Arteaga and Stewart, 2019)

Probabilistic cost–benefit analysis can be used to assess the impact of different adaptation strategies on monetary risk. The presentation of the results in this form facilitates a robust and quantitative universal metric that infrastructure asset managers, owners and researchers across disciplines can relate to, i.e. mean net present values (NPVs) and benefit-to-cost ratios (BCRs) of a given climate change adaptation strategy indicate that annual monetary risk would vary by implementing the strategy. This constitutes a much more developed risk-based decision support framework than, say, the assessment of climate change impacts alone, which is limited to the consideration of network performance under climate change (i.e. vulnerability integrated with hazard), rather than the effectiveness and cost feasibility of adaptation. The appropriateness of the cost–benefit analysis approach in informing climate adaptation has also been highlighted in the C-Risk project (Flood *et al.*, 2020). Importantly, this analysis should be considered over the life cycle (i.e. life cycle cost – LCC) of the infrastructure asset or network. Further discussion on this can be found in Ryan and Stewart (2017). As outlined by Ryan and Stewart (2017), the NPV for CI over the life cycle can be calculated as:

$$NPV(t) = LCC_{BAU}(t) - LCC_{adapt}(t) \tag{10.3}$$

where $LCC_{BAU}(t)$ and $LCC_{adapt}(t)$ are the LCCs for "business as usual" (BAU) conditions, i.e. existing practice, and under the adaptation measure, respectively, discounted to a present value. The LCC for an infrastructure asset or network of assets could be (but is not limited to):

$$LCC(t) = C_C + C_{IN}(T) + E_{damage}(T) \tag{10.4}$$

where C_C is the construction and materials cost, $C_{IN}(T)$ is the cost of inspections during service life T and E_{damage} is the expected cost of repair or loss during service life T. The expected cost of repair and loss can be described as a present value:

$$E_{damage}(T) = \sum_{j=1}^{DS} \sum_{i=1}^{T} P_{f,i} \frac{C_{damage}}{(1+r_d)^i} \tag{10.5}$$

where $P_{f,i}$ is the probability of damage in year i calculated using time-variant reliability analysis techniques. C_{damage} is the cost of repair, maintenance or replacement and associated user and indirect losses, which, importantly, can include costs of cascading failures in other CI sectors, r_d is the discount rate and DS is the number of different damage states. User costs include monetary losses to users following the failure of the infrastructure system, e.g. extra costs of driving longer routes because of a flooded national road section or bridge collapse, or losses to business and industry following a disruption in energy supply or telecommunication and data services. These costs can be considerable, and for some infrastructure systems user losses are likely to be much greater than direct repair, replacement and maintenance costs.

The BCR of an adaptation strategy over the life cycle can be determined by:

$$BCR = \frac{Benefit_{adap}}{Cost_{adap}} \tag{10.6}$$

The NPV and BCR are not mutually exclusive, but complementary. The “benefit” of an adaptation measure ($Benefit_{adap}$) is the reduction in damages or losses over the life cycle brought about by the adaptation strategy, and the “cost” is the cost of implementation of the adaptation strategy ($Cost_{adap}$). An NPV greater than 0 and a BCR value greater than 1 indicates that an adaptation measure is cost-effective, meaning monetised risk is reduced by adaptation implementation. Importantly, utilisation of a probabilistic approach means that infrastructure owners and operators can be provided with a probability distribution of parameters such as a BCR. This provides insight into the uncertainty of the prediction, meaning, for instance, that the probability ($NPV > 0$) for a given adaptation strategy can be examined. To assist decision-makers in the selection of adaptation strategies, more than one strategy should be investigated using probabilistic cost–benefit analysis, with the best strategy identified as the one with the maximum positive NPV. Finally, it is vital to note that the cost of conducting these detailed quantitative risk-based adaptation feasibility studies is likely to be very small, relative to the opportunity costs incurred if adaptation strategies are implemented without proper investigation. This is particularly true for CI, which tends to consist of vast and valuable networks that have high maintenance and capital costs. The pitfalls associated with adaptation selection without quantitative decision support will be illustrated in Chapter 11, where a number of seemingly good adaptation strategies were found to have negative cost–benefit outcomes, despite being effective in reducing the impact of climate change.

11 Detailed Probabilistic Case Study: Climate Change Impacts and Adaptation for the Irish Power Pole Networks

This chapter aims to present an example of a detailed quantitative risk-based assessment of both climate change impacts and climate adaptation feasibility, implementing the steps presented in the previous section. The illustrative case study selected considers part of Ireland's energy infrastructure. The reliance of other forms of CI on energy infrastructure makes it perhaps the most important component of our modern day CI networks, especially given the ever-increasing dependency on power and power-based IT management and operational systems. As previously mentioned, this was illustrated in Ireland during Storm Ophelia in 2017, when power outages resulted in cascading failures in the wastewater treatment, water treatment and telecommunications sectors (*Irish Independent*, 2017). The effect of power outages on other CI networks has also been highlighted through events internationally. For instance, power disruptions in California in 2001 affected the movement of water from northern to central and southern regions, had an impact on transport operations in the state and in neighbouring states, idled key industries leading to billions of dollars of lost productivity and put stress on the entire western power grid, causing far-reaching security and reliability concerns.

Only one aspect of the energy sector's infrastructure is considered in this illustrative case study, namely the power distribution pole network. These poles undergo far less stringent design and maintenance than other aspects of power infrastructure and consequently are perhaps the most vulnerable aspect of the distribution network. The power pole networks themselves also constitute significant national assets across the globe, i.e. there are over two million power poles in Ireland, five million timber power poles in Australia, worth over AUS$10 billion (Yeats and Crews, 2000), and over 200 million timber power poles in the USA (Bolin and Smith, 2011). The colocation of telecommunications equipment on overhead energy networks (e.g. fibre on ESB lines) means that the specific findings of this case study are also of relevance to ICT asset owners. The analysis constitutes the first use of probabilistic methods and quantitative risk-based decision support to assess the climate change impacts and adaptation feasibility for energy infrastructure in Ireland. Results are presented in the following subsections for both Dublin and Cork.

11.1 Case Study Details: Irish Timber Power Pole Networks

The Irish power distribution network comprises 2.1 million timber power poles and 150,000 km of overhead lines. The network is operated by the ESB. Figure 11.1 presents a typical set-up for an Irish power pole on the medium voltage (MV) distribution network, based on insights provided by the ESB. The most common timber type used for these poles in Ireland is

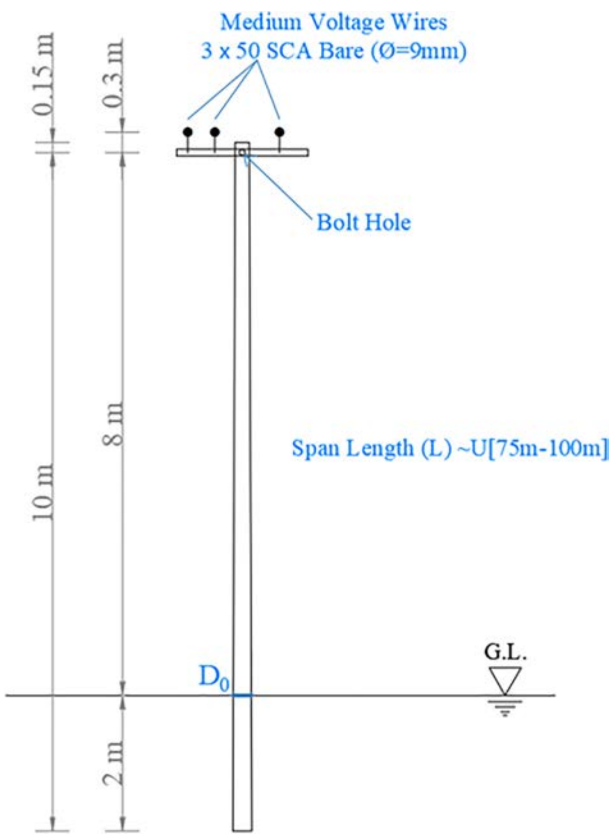

Figure 11.1. Typical Irish power pole loading set-up. G.L., ground level; U, uniform distribution.

Scots pine (*Pinus sylvestris*). The poles were assumed to be creosote treated, in line with common practice in Ireland.

Between 2016 and 2017, the ESB undertook a substantial pole-testing regime, whereby in the region of 700 Scots pine poles underwent full-scale destructive testing. The findings of this experimental study, together with insights provided by the ESB, were used to develop statistical properties for parameters utilised in the probabilistic modelling here. These parameters included pole bending strength, pole diameter, sapwood depth, creosote treatment retention and air dry density. This allows the variability associated with material properties to be incorporated into the analysis.

Inspection intervals in the model were set at 12 years, in line with common historical practice in Ireland. The inspection failure or pole condemning criterion was set at 75% of the original pole capacity, meaning that, if inspection revealed that the pole moment capacity was less than 75% of the original pole moment capacity, the pole would fail the inspection and be condemned and subsequently replaced. This 75% pole condemning criterion is in line with values used in Ireland for the pole set-up shown in Figure 11.1.

11.2 Determining Existing Vulnerability and Network Performance

11.2.1 Detailed probabilistic modelling approach

This section presents the vulnerability assessment of a notional power pole network and the network performance under existing environmental conditions, considering climatic effects in terms of (1) extreme wind events and (2) network deterioration. The basis for this work is discussed in more detail in Ryan *et al*. (2014). Having developed this first-principles mathematical understanding of the network, adjustments to the model can be used to assess climate change impacts and the effectiveness of climate adaptation options. Consequently, the modelling of initial vulnerability and network performance is often the most challenging step of the three-step process presented at the start of Chapter 10.

Probabilistic modelling methodology

The failure risk of a given power distribution pole is evaluated using the following time-variant expression for probability of failure P_f:

$$P_f(t) = Prob\{R(t) - S(t) \leq 0\} \qquad (11.1)$$

where $R(t)$ and $S(t)$ are resistance and load effects at time t, respectively. In this case study, the $R(t)$ term examined will be the bending resistance of a power pole incorporating deterioration, while the $S(t)$ term will be the annual maximum wind load. The impact of climate change on both $R(t)$ and $S(t)$ will be incorporated into the model in section 11.3. The bending failure limit state under extreme wind loading was selected based on the most common failure mode of timber power poles (Winkler *et al*., 2010).

A sequential (i.e. time-dependent) event-based modelling approach was used herein to allow power pole network performance over time to be assessed, considering both maintenance and potential changes in climatic parameters. The sequential nature of the model refers to the fact that each Monte Carlo simulation runs on a year-by-year basis. Each yearly step includes:

- calculation of the resistance of the pole at year t, accounting for deterioration;
- calculation of a load at year t derived from a distribution of maximum annual loads;
- infrastructure element inspection and network maintenance where applicable.

The event-based aspect of the probabilistic model refers to the fact that the occurrence of certain events over the simulation period can influence the course of a given sequential Monte Carlo simulation. The two key events that can occur are (1) violation of the limit state, whereby the annual wind load exceeds the deteriorated pole capacity and the pole fails, and (2) the condemning of a pole as a result of deterioration and the network inspections and maintenance programme. On occurrence of a wind failure or the condemning of a pole, the pole in question is replaced by a new pole in the Monte Carlo simulation. When a pole is replaced in a simulation, it is assigned new properties generated from the appropriate distributions, i.e. pole diameter, pole bending strength, sapwood depth, etc. The process of deterioration then restarts for this new pole and the sequential Monte Carlo process continues for the iteration in question up to the end of the simulation period selected. The following subsections present the modelling approach for $R(t)$ and $S(t)$ for Ireland.

Modelling Irish time-dependent wind load

To capture the time-dependent nature of probabilistic wind load, mathematical expressions incorporating wind speed variability and wind load uncertainty are required. The computation of the wind actions on structures using Eurocode-1 (NASI, 2010) requires the use of the maximum 10-minute mean wind speed, denoted $V_{b,max}$. Parameters for the existing wind field can be derived from wind speed data recorded by the national meteorological service in Ireland (Met Éireann, undated). The Gumbel distribution, given by equation 11.2, is the most commonly used for modelling extreme wind speeds:

$$F(v) = e^{-A}, \text{ where } A = e^{-\left(\frac{v - v_g}{\sigma_g}\right)} \tag{11.2}$$

where v_g and σ_g are the location and scale parameters for the Gumbel distribution (Wang *et al.*, 2013). Having established an expression that probabilistically represents the wind, the Eurocode wind-loading equation for annual maximum wind load W_{max} can be used to calculate the time-dependent wind load $S(t)$ for a given wind speed as follows (Eurocode-1):

$$W_{max} = \frac{1}{2}\rho \cdot C_s C_d \cdot C_a \cdot C_g \cdot (C_r \cdot V_{b,max})^2 \tag{11.3}$$

where ρ is the air density, C_sC_d is the structural factor, C_a is the shape factor, C_g is the gust factor and C_r is the roughness factor. Details of the equation and the various parameters can be found in Eurocode-1 (NASI, 2010). The air density, ρ, is considered deterministic, since its scatter is small at high wind speeds (Kasperski, 2009). However, the C-factors are affected by aleatory and epistemic uncertainties and thus were modelled probabilistically based on JCSS (2001).

Modelling time-dependent pole resistance capacity

The time-dependent resistance of a given power pole is modelled using the equation below:

$$R(t) = f_b \frac{\pi}{32} \frac{D_1(t)^4 - D_2(t)^4}{D_1(t)} \tag{11.4}$$

where f_b is the bending strength of the timber, t is time, $D_1(t)$ is the outer pole diameter allowing for external decay at time t and $D_2(t)$ is the diameter of internally decayed wood at time t. A comprehensive timber decay model developed by Wang *et al.* (2008), based on 35 years of field data for 77 timber species, was used to model internal and external decay depths for this study. The model is in essence a multi-layer timber deterioration model that represents both internal and external decay for timber poles with consideration of pole treatment (i.e. creosote or chromated copper arsenate). The implementation of the model in a probabilistic framework is discussed in detail in Ryan *et al.* (2014). Importantly, in the context of this study, the decay model considers climate through a $k_{climate}$ parameter. This parameter value is determined based on annual average temperature and yearly rainfall at the location considered. The effect of climate change on pole deterioration can thus be captured in the next subsection through appropriate alterations to the input parameters in the Wang *et al.* (2008) model. For this study, values of annual average temperature and yearly rainfall under existing conditions were determined for two locations, Cork and Dublin, based on historical data obtained from the Met Éireann website (Met Éireann, undated). These values, together with the statistical parameters for wind speed at each location, are provided in Table 11.1. Past temperature and rainfall are modelled deterministically in the study, while wind speed is modelled deterministically using the Gumbel distribution.

Table 11.1. Values for climate parameters under existing conditions, i.e. no climate change scenario

			Maximum annual wind speed[a]	
Location	Temperature (°C)	Rainfall (mm)	Mean (m/s)	Coefficient of variation
Dublin	9.73	747	21.8	12%
Cork	9.66	1244	22.5	14%

[a]**Wind speed is a Gumbel random variable.**

11.2.2 Results: existing vulnerability of Irish distribution power poles

The probabilistic approach was implemented utilising Monte Carlo simulation, using 10 million simulations to ensure the stability of the model output. Results are, however, presented herein for a power distribution network of one million poles for ease of interpretation. Figure 11.2 presents wind vulnerability curves for Cork. These vulnerability curves show the probability of failure of a pole in the simulated Irish network across a range of wind speeds. They are in effect a graphical representation of the vulnerability term in Figure 10.1, and in the risk equation (equation 10.1), for Irish power pole networks. The mean annual maximum wind speed for Cork is 22.5 m/s, with a coefficient of variation (CoV) of 14% (Gumbel distribution). Consequently, the key wind speed range in the vulnerability curve is 22 m/s to 40 m/s. The probability of failure up to 40 m/s is very low, indicating a functioning network, i.e. if the probability of failure was 10% for a probable storm event, we would expect 10% of Cork's poles to fail during this storm. This would be an unacceptably high proportion.

Examining the curves in Fig 11.2a more closely, it is noted that vulnerability curves are plotted for a pole in a maintained network 12, 24, 36 and 48 years into the network's service life. As mentioned previously, the ESB network is inspected every 12 years and poles that have less than 75% of their original bending capacity remaining are replaced with new poles. The curves in Figure 11.2a thus show the pole network reliability level right before the first, second, third and fourth inspections. While a slow decrease in pole reliability over the service life is witnessed, the inspection and maintenance interventions ensure that probability of failure under extreme winds is kept at acceptable levels. Figure 11.2b depicts the vulnerability curves of a 48-year-old pole right before and right after the fourth inspection. This shows that the pole reliability is boosted after inspection. As can be seen in the plot, a non-zero probability of failures occurs prior to inspection at low wind speeds; however, after inspection, the probability of failure at all wind speeds below 22 m/s is zero. This is because, after inspection, all poles with advanced decay have been condemned and replaced with new poles, which reduces the overall vulnerability of the network.

Figures 11.3 and 11.4 represent the performance of a simulated Irish power pole network located in Cork under a no climate change scenario, through presentation of the annual wind failure rates and pole condemning rates, respectively. This insight into network performance under existing conditions is obtained through integration of the vulnerability curves with the hazard, extreme wind speed, i.e. the combination of the hazard and vulnerability components of the risk equation. Firstly, considering the condemning rates in Figure 11.3; from initial

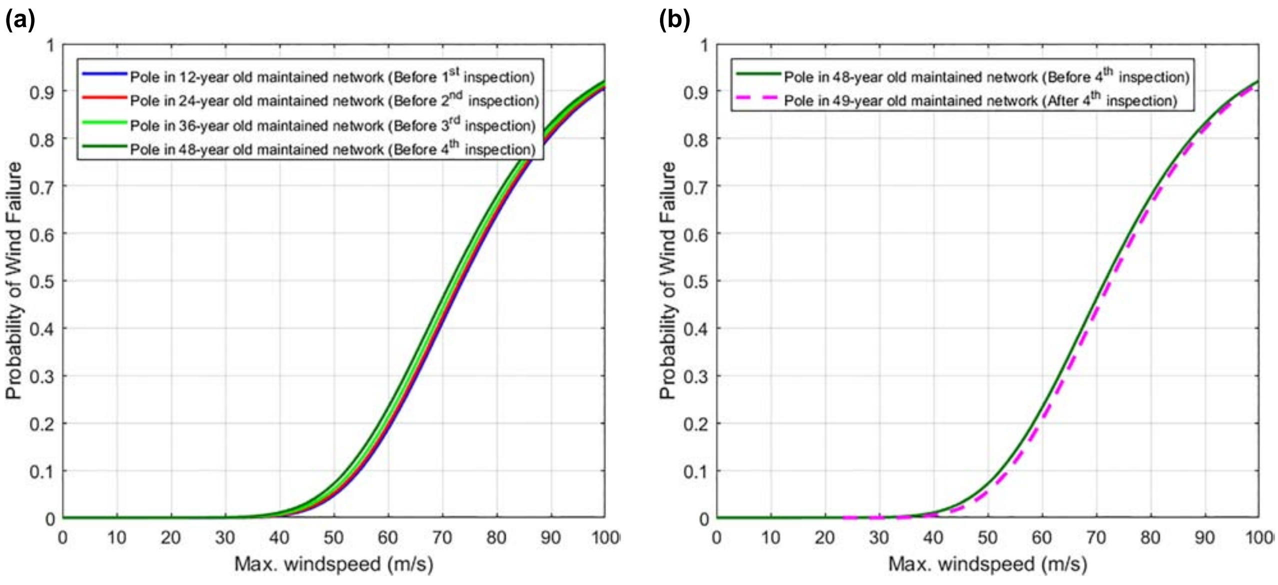

Figure 11.2. Vulnerability curves of a power pole in a maintained network in Cork city: (a) vulnerability curves at pole ages corresponding to the first four inspection years, right before inspection and pole replacement; and (b) vulnerability curves of pole before and after the fourth inspection.

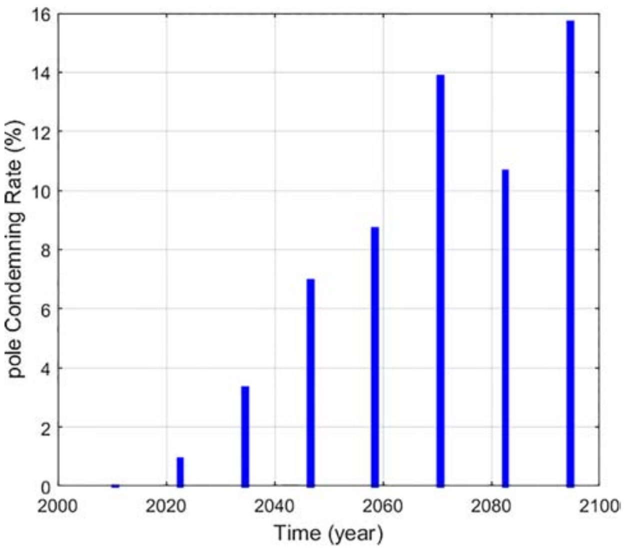

Figure 11.3. Condemning rates at inspection years over the period 2000–2100 under a no climate change scenario for one million poles located in Cork.

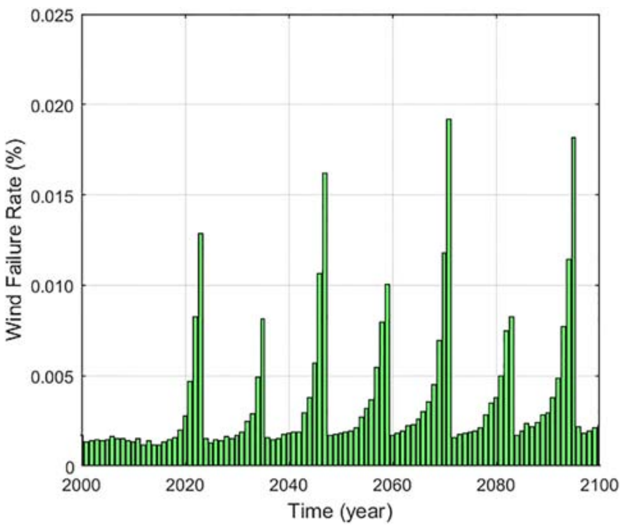

Figure 11.4. Annual wind failure rate over the period 2000–2100 under a no climate change scenario for one million poles located in Cork.

inspection at 12 years, to the 100th year point, rates range from 0.03% to 15.8%, with condemning occurring only every 12 years in accordance with the inspection intervals. A longer interval of 100 years is used here with the aim of exploring the long-term behaviour of the maintained network. The average annual condemning rate for poles over the 100-year monitoring period is 0.6%, meaning on average 0.6% of poles in the network fail inspection and are condemned and replaced each year. This figure is approximately within an order of magnitude of the actual pole replacement rate experienced by the ESB in Ireland. While this is a good reality check for the model, it is noted that the aim of this assessment is not to simulate the existing network, which comprises a mix of poles from the low voltage (LV), MV and 38-kV distribution networks of various ages, treated with various types of treatment.

Figure 11.4 shows very low failure rates ($<2\times10^{-4}$) in the first 1 to 20 years, followed by a steep rise from 20 to 24 years. After this point, the annual failure rate initially drops and then rises to a peak every 12 years. This cyclical nature of wind failures is due to the influence of the maintenance inspection intervals. The inspections every 12 years lead to the replacement of the most decayed poles, which are most vulnerable to wind failure. Thus, the year after an inspection the network is most resilient to extreme wind speeds and the failure rates are low, whereas just before an inspection wind vulnerability is increased as a result of 12 years of deterioration, meaning failure rates are highest. This is a direct result of the changes in vulnerability before and after inspection, shown in Figure 11.2b. The average annual wind failure rate for the treated poles over the 100-year monitoring period was 0.004%. There were insufficient field data available for Ireland for comparison with this figure.

The pole condemning and wind failure rates for a network of one million power poles located in Dublin (not shown in the figure) were found to be lower than for Cork. The annual wind failure rate for Dublin was 0.001% (four times lower than for Cork) and the condemning rate was equal to 0.5% (compared with 0.6% for Cork). The difference in performance is due to the differing climatic conditions in the two locations. Cork has greater annual mean rainfall than Dublin (Table 11.1), resulting is more rapid timber decay, in accordance with the Wang *et al*. (2008) decay model. The annual maximum wind speed is also slightly higher in Cork than in Dublin, and Cork's extreme wind speed has a greater CoV, which is indicative of higher extremes. The difference in simulated performance between the two locations highlights the importance of considering regionally specific data for climate parameters to account for the spatial variability of climate properties. This is further emphasised in the cost–benefit analysis in section 11.4.

11.3 Climate Change Impacts

11.3.1 Modelling climate change impacts

The basis for the approach used herein for assessing the impacts of climate change on power pole distribution networks was developed in a previous publication by the authors (Ryan *et al.*, 2016) that examined Australian power pole networks. The reader is referred to this paper for detailed discussion of the fundamentals of the model development. For this Irish case study, climate change impacts on both timber deterioration and wind speed are incorporated. First, considering timber deterioration, the impact of climate change is incorporated into the adopted decay model of Wang *et al.* (2008) through the $k_{climate}$ parameter. The $k_{climate}$ parameter is calculated using the region average annual temperature T (°C) and the annual rainfall RN (mm/year) through the following equations (Wang *et al.*, 2008):

$$k_{climate} = f(RN)^{0.3} \cdot g(T)^{0.2} \qquad (11.5)$$

with

$$f(RN) = \begin{cases} 10[1 - e^{-0.001(RN-250)}]\left(1 - \frac{N_{dm}}{6}\right) & \text{if } RN > 250 \text{ mm and } 0 \le N_{dm} \le 6 \\ 0 & \text{otherwise} \end{cases} \qquad (11.6)$$

and

$$g(T) = \begin{cases} 0 & \text{if } T \le 5°C \\ -1 + 0.2T & \text{if } 5°C \le T \le 20°C \\ -25 + 1.4T & \text{if } T \ge 20°C \end{cases} \qquad (11.7)$$

where N_{dm} is the number of months per year when the rainfall is less than 5 mm. Possible changes in wind speed are also an important consideration for power distribution infrastructure, as changes in annual maximum wind speed will alter the likelihood of pole wind failures and subsequent power interruptions. To incorporate the impact of projected climate change on extreme wind speed into the model, a modification to the Gumbel distribution (equation 11.2) has been suggested by Stewart (2015) as follows:

$$F(v) = e^{-A}, \text{ where } A = e^{-\left(\frac{\frac{v}{1 + \frac{\gamma_{mean}(t)}{100}} - v_g}{\sigma_g}\right)} \qquad (11.8)$$

where $\gamma_{mean}(t)$ represents the time-dependent percentage change in maximum wind speed for a given Monte Carlo simulation.

11.4 Predicted Climate Change Impacts on Irish Power Pole Networks

The latest available regionally specific climate change predictions for Cork and Dublin locations, developed by the Irish Centre for High-End Computing (ICHEC) and Met Éireann, were used in this analysis. This section presents the findings on the most likely mid-century impacts of climate change on the performance of Irish timber distribution poles, put in service in 2000 and monitored up to 2050. As stated in section 11.2.1, three climate parameters are incorporated into the model: the annual maximum wind speed, the annual mean temperature and the annual total rainfall amount. The projected future changes for these parameters to mid-century were obtained from Nolan (2015) and Nolan *et al.* (2014, 2017). The climate projections were generated using the COSMO-CLM (versions 4.0 and 5.0) and WRF (version 3.6) RCMs. Projections for the future Irish climate were generated based on RCP4.5 and RCP8.5 by downscaling five CMIP5 global data sets: HadGEM2-ES GCM, EC-Earth GCM, CNRM-CM5 GCM, MIROC5 GCM and the MPI-ESM-LR Earth System Model. Data from two time slices, 1981–2000 (the control) and 2041–2060, were used for the analysis of projected changes in the mid-21st-century Irish climate. The historical period was compared with the corresponding future period for all simulations within the same RCM-GCM group. This results in future anomalies for each model run; that is, the difference between past and future climatic parameters.

A total of 24 RCP4.5 and 24 RCP8.5 ensemble comparisons were used to develop statistical parameters for the projected changes in temperature, rainfall and wind speeds for RCP4.5 and RCP8.5 at two locations: Dublin and Cork (Table 11.2). Ideally, a greater number of ensemble comparisons would have been used, but the total number of ensembles available is limited by the computer-intensive nature of the RCM runs. In line with the framework set out by Stewart (2013) and Stewart and Deng (2015), truncated normal distributions were used to represent the uncertainty associated with climatic predictions, whereby the 10th, 50th and 90th percentiles allow the standard deviation of two truncated normal distributions, each with a cumulative probability of 50%, to be calculated. These statistical parameters were used in the probabilistic framework here to help

Table 11.2. Mid-century climate change projections: 1981–2000 versus 2041–2060

	RCP4.5			RCP8.5		
	Percentile			Percentile		
Parameter	10th	50th	90th	10th	50th	90th
Dublin						
Temperature (°C)	+0.9	+1.1	+1.5	+1.2	+1.5	+1.9
Rainfall (%)	–14.0	–6.1	+3.0	–13.7	–7.1	+6.1
Wind speed (%)	–16.0	–1.0	+14.3	–15.9	–0.2	+15.0
Cork						
Temperature (°C)	+0.9	+1.1	+1.5	+1.1	+1.5	+1.9
Rainfall (%)	–15.9	–8.3	+5.0	–15.4	–7.2	+5.0
Wind speed (%)	–14.8	–0.8	+17.9	–15.3	+1.2	+17.3

incorporate the considerable uncertainty associated with projected climate change for a given climate change scenario. The predicted values represent the total change to the year 2050, relative to 1990 levels. A time-dependent linear change in climatic conditions was assumed to determine yearly changes in accordance with practices used by Stewart (2013) and Stewart and Deng (2015).

Figure 11.5 shows the cumulative number of wind failures and the total number of poles condemned across three climate change scenarios: (1) no change in climate, (2) RCP4.5 and (3) RCP8.5. The results are for networks of one million poles over a 50-year period located in both Dublin and Cork. Summary statistics in the form of percentage increase (relative to no climate change) of wind failure rates and pole condemning rates are provided in Table 11.3.

Figure 11.5a and Table 11.3 show that the climate change-related increase in power pole wind failures (which would result in power interruptions) for mid-century is approximately 26% for Cork and 17% for Dublin. The values are not significantly different for RCP4.5 and RCP8.5. Intuitively, one might expect impacts to increase from RCP4.5 to RCP8.5; however, the increase in pole failure risk depends on a complicated interaction between temperature, rainfall and wind speed, the uncertainties associated with climate change predictions and the regions'

(a) (b)

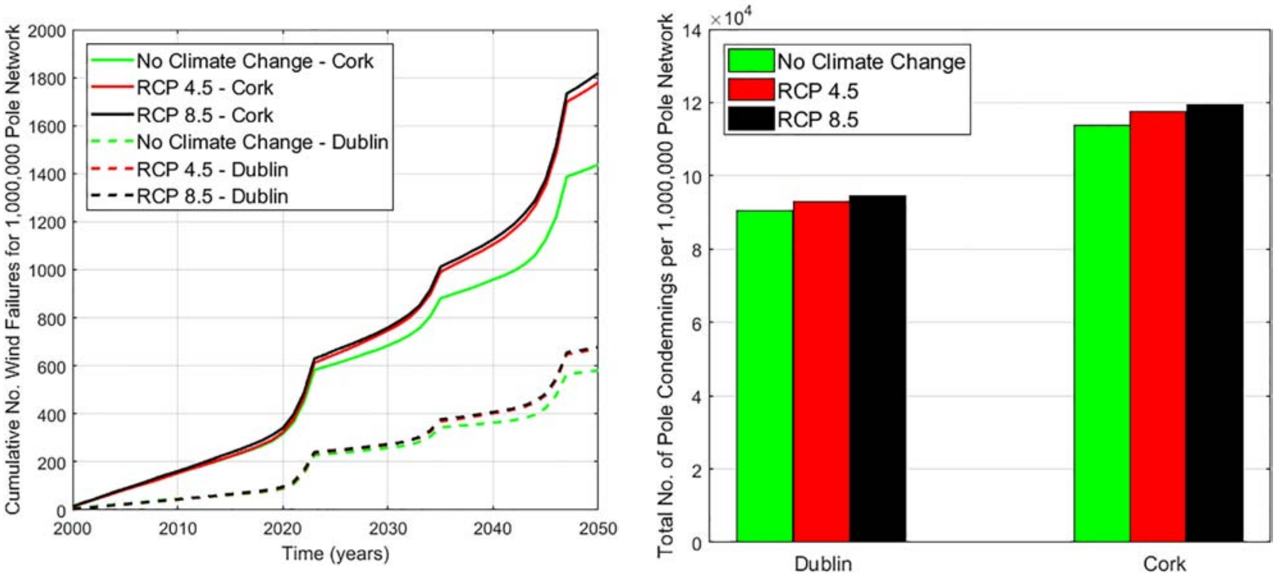

Figure 11.5. Impacts of climate change scenarios on (a) the cumulative number of wind failures and (b) the total number of poles condemned from a network of one million power poles at two locations: Dublin and Cork.

Table 11.3. Mid-century impacts of climate change scenarios on wind failure rates and condemning rates for power pole networks located in Dublin and Cork

	Dublin		Cork	
Climate change scenario	Change in average wind failure rate (%)	Change in average condemning rate (%)	Change in average wind failure rate (%)	Change in average condemning rate (%)
RCP4.5	+16	+3	+24	+3
RCP8.5	+17	+5	+27	+5

baseline climatic conditions. In essence, the lack of a real distinction between the impacts under the two RCPs means, in this case, that the debate over which climate change scenario is more likely is irrelevant. This will make the decision-making process easier for an infrastructure owner.

Importantly, the level of increase in power pole wind failures (≈17% to 26%) is significant in the context of the consequences of failures, which range from loss of power to business and homes, to possible loss of life and wildfire events. The impact of climate change on the numbers of poles condemned is somewhat less, with an increase of between 3% and 5% predicted, depending on the climate change scenario. However, an increase in pole condemnings of up to 5% could result in a significant increase in operating costs for a power pole network stakeholder. Overall, the outcomes of the probabilistic analysis may be used as a decision support tool. An infrastructure owner examining the results might feel that the magnitude of the impacts are of sufficient scale to warrant investigation into climate adaptation. Section 11.5 gives an example of utilising risk-based decision support to inform adaptation strategy selection.

11.5 Climate Change Adaptation Cost–Benefit Analysis

11.5.1 Modelling cost–benefit analysis for Irish power pole networks

This section demonstrates the risk-based decision support methodology for climate adaptation that was presented in general terms in section 10.3. The reader is referred to Ryan and Stewart (2017) for more detailed discussion of probabilistic cost–benefit analysis for timber power pole climate change adaptation. As discussed in section 10.3, one must consider the LCC of the assets or network over a given period when examining climate change feasibility for CI. The LCC of a power pole network includes the cost of pole construction and installation, inspection costs and expected damage costs. In the present case, there are two damage states: power pole condemnings and power pole wind failures. The total damage cost (C_{damage}) at the time of pole wind failure is:

$$C_{damage} = C_{replace} + C_{sales} + C_{users}, \tag{11.9}$$

where $C_{replace}$ represents the cost of pole replacement and C_{sales} represents the cost to the energy company arising from the loss of sale of electricity during the power interruption. These two costs are direct costs, while C_{users} represents the indirect costs incurred by the power user as a result of loss of power supply. The damage cost associated with pole inspection failure (pole condemning) is simply $C_{replace}$, as it is assumed that the other cost implications arising from scheduled replacements are negligible (i.e. minimal or no power interruption). All the above costs would vary according to the adaptation strategy adopted. The benefit of adaptation ($Benefit_{adap}$) is defined as the reduced losses owing to reductions in the numbers of poles condemned, maintenance or pole wind failures, when compared with the BAU case. Similarly, the cost of adaptation ($Cost_{adap}$) includes costs related to the construction of more expensive (e.g. larger) poles, carrying out more frequent inspections, and condemning and replacing more poles, depending on the nature of the adaptation measure employed.

To calculate C_{sales} and C_{users}, we must quantify how much power goes unsupplied in the event of a power outage due to pole wind failure. This is referred to as lost load (LL) in the literature and can be calculated using equation 11.10, whereby OD is outage duration, N_{res} and $N_{business}$ are the number of residential and business customers affected by the outage, respectively, and R_{res} and $R_{business}$ are the power consumption rates for residential and business customers, respectively.

$$LL = OD[N_{res} \cdot R_{res} + N_{business} \cdot R_{business}] \qquad (11.10)$$

Once LL is determined, C_{sales} can easily be calculated by multiplication of the relevant LL figure by the cost of energy. C_{users} is determined by multiplying LL by the value of lost load (VoLL), which, as the name suggests, represents the loss incurred by the customer per unit of electricity unsupplied. This value varies significantly between business customers and residential customers, as can be seen from Table 11.4, which presents all the costs used in the analysis here. The influence of power OD on VoLL for residential customers is incorporated in accordance with Praktiknjo *et al*. (2011). It is also noted that the safety cost, which arises from high-consequence, low-probability events such as bushfires or wildfires, death or injury to people or livestock due to downed power lines, etc., was not considered here owing to a lack of cost data for such events.

It is noted that the binomial distributions used in the table were selected based on the cost data supplied by the ESB. For instance, the inspection programme adopted by the ESB means that, in a given inspection year, every pole is hammer tested and prodded with a soil lever to check for external and internal rot. The cost of this inspection technique is €25/pole. According to the ESB's recorded data, almost 10% of poles fail the hammer test and thus need to be tested using a Mattson borer. This latter technique costs an extra €25/pole. To represent this scenario, a binomial random variable with parameter $p = 10\%$ is used to represent the probability that a pole inspection will require the use of the Mattson borer test. If this is the case, the inspection cost would be €50; otherwise it would be €25. The level of cost detail provided by the ESB greatly enhances the real-world relevance of the output from the risk-based adaptation feasibility modelling. Overall, it is noted that some of the values in Table 11.4 were obtained from the literature, but the majority were derived from databases obtained through collaboration with the ESB. The level of cost detail used here, and network operational data used in the previous sections, emphasises (1) the importance

Table 11.4. Direct and indirect cost parameters for Irish power pole networks

Parameter	Symbol	Unit	Distribution	Mean	CoV	Source
Pole and inspection costs						
Standard pole cost	C_c	€	Deterministic	149	–	ESB
Larger pole cost	C_c^+	€	Deterministic	194	–	ESB
Inspection cost	C_{IN}	€	Binomial (1;10%) (25 or 50)	–	–	ESB
Pole installation cost in new network	–	€	Deterministic	776	–	ESB
Planned pole replacement cost (due to pole condemning)	–	€	Binomial (1;6%) (1046 or 2495)	–	–	ESB
Urgent pole replacement cost (due to wind failure)	–	€	Binomial (1;6%) (1828 or 4848)	–	–	ESB
Lost load for power outage						
Outage duration	OD	Minutes	Lognormal	7	1.5	ESB
Customers affected	–	Number of customers	Lognormal	101	9.4	ESB
Average residential power consumption rate	R_{res}	kWh/h/customer	Deterministic	0.47	–	CRU (2018)
Average business power consumption rate	$R_{business}$	kWh/h/customer	Deterministic	7.16	–	CRU (2018)
Cost of lost load						
Cost of energy unsupplied for residential customers	–	€/kWh	Deterministic	0.22	–	SEAI (2019)
Cost of energy unsupplied for business customers	–	€/kWh	Deterministic	0.13	–	SEAI (2019)
Value of lost load residential customers	–	€/kWh	Lognormal	23.57	1.22	Praktiknjo *et al*. (2011)
Value of lost load business customers	–	€/kWh	Lognormal	54.12	1.22	Praktiknjo *et al*. (2011)

of industry collaboration and (2) the need for CI owners and operators to collect data on operational costs, failure occurrences, levels of deterioration, operational costs, etc. This is particularly challenging during times of EWEs; however, these are perhaps the most important data from a network modelling perspective. Finally, the discount rate used in this study is in line with the values suggested in Annex 6 of the Green Book (Scholar, 2018), which provides guidance on discount rates for appraisal over different timelines. The discount rate used herein is thus equal to 3.5% between 0 and 30 years and 3.0% between 31 and 50 years.

11.5.2 Results of the cost–benefit analysis of climate adaptation strategies

A large number of adaptation strategies were investigated, exploring options to reduce the impacts of climate change, but also attempting to do so in a cost-effective manner. The five adaptation strategies (ADAP1–5) presented in Table 11.5 are a representative sample of the most suitable options.

Under adaptation strategy ADAP1, poles are inspected for the first time right before the steep increase in wind failure rates at 20 years (Figure 11.4). Afterwards, they are inspected more frequently (every 10 years instead of the 12-year interval under BAU conditions), meaning severely deteriorated poles are more likely to be removed before they fail as a result of extreme wind loads, reducing the overall vulnerability of the network. Adaptation strategy ADAP2 adopts a higher condemning criterion, i.e. upon inspection, poles are replaced at 80% capacity instead of 75% under BAU conditions. The strategy then seeks to balance the cost of extra pole replacement with less frequent inspections (every 13 years instead of 12 years under BAU conditions).

While ADAP1 and ADAP2 are based on altering maintenance practices, another option is to make changes to infrastructure asset design practices. To investigate this, ADAP3, ADAP4 and ADAP5 model the use of a power pole one size larger than required under existing design specifications. While this will reduce the vulnerability of the network (i.e. increase resilience), it does so at a cost (a standard pole = €149 and a larger diameter pole = €194). Effectively, ADAP 3–5 consider a new pole network of one million poles that are one size larger than standard poles over the monitoring period 2000–2050. ADAP3 attempts to balance the increase in the network construction cost with a reduction in the network inspection cost, i.e. by changing the inspection interval from the BAU interval of 12 years to 13 years. ADAP4 and ADAP5 represent two other alternatives, which attempt to use alterations to maintenance practices to balance the initial investment cost associated with utilising larger poles (Table 11.5).

Table 11.6 summarises the numerical results, which show both the effectiveness and the cost–benefit outcomes for the five climate adaptation strategies under RCP 4.5 and RCP 8.5 for Cork. The effectiveness of each adaptation strategy is presented in terms of its ability to reduce the percentage of poles condemned and pole wind failures to pre-climate change levels. These metrics are independent of cost and are expressed as a percentage of the condemning rates and pole wind failures rates occurring under the adaptation strategy and RCP scenario, as a percentage of those occurring under the BAU

Table 11.5. Climate adaptation strategy details

Adaptation strategy	Pole size	Condemning criterion	First inspection	Inspection interval
BAU	Ordinary[a]	75%	After 12 years	Every 12 years
ADAP1	Ordinary[a]	75%	After 20 years	Every 10 years
ADAP2	Ordinary[a]	80%	After 13 years	Every 13 years
ADAP3	One size larger[b]	75%	After 13 years	Every 13 years
ADAP4	One size larger[b]	70%	After 20 years	Every 10 years
ADAP5	One size larger[b]	65%	After 20 years	Every 8 years

[a]Ordinary pole corresponding to the prototype developed for the ESB MV network (see Figure 11.1). Diameter at ground level of between 236 mm and 295 mm; cost = €149.

[b]One-size larger poles have the same height as ordinary poles but with a larger cross-section. Diameter at ground level of between 295 mm and 354 mm; cost = €194.

Table 11.6. Climate adaptation results for Cork under RCP 4.5 and RCP 8.5 scenarios

	RCP 4.5				RCP 8.5			
	Effectiveness		Cost–benefit		Effectiveness		Cost–benefit	
Adaptation strategy	Percentage of wind failures	Percentage of condemning failures	Mean NPV (€/pole)	Mean BCR	Percentage of wind failures	Percentage of condemning failures	Mean NPV (€/pole)	Mean BCR
BAU (i.e. climate change impacts)	124	103	NA	NA	127	105	NA	NA
ADAP1 – Insp 20 + 10[a]	93	111	+10	1.11	95	113	+10	1.10
ADAP2 – CC 80% and Insp 13 + 13[a]	96	67	+25	1.31	99	68	+24	1.30
ADAP3 – LP and Insp 13 + 13[a]	47	39	+7	1.06	50	40	+6	1.05
ADAP4 – LP, CC 70% and Insp 20 + 10[a]	31	74	–2	0.98	33	76	–4	0.97
ADAP5 – LP, CC 65% and Insp 20 + 8[a]	35	40	+7	1.07	37	40	+5	1.05

[a]Insp *x* + *n* = first inspection after *x* years, then inspection every *n* years.

CC, condemning criterion; Insp, inspection interval (after first inspection); LP, larger pole; NA, not applicable.

approach under pre-climate change conditions. The cost–benefit results for each adaptation strategy are expressed in terms of mean NPV and mean BCR, defined in section 10.3. A negative NPV and a BCR of less than 1.0 indicate that the investment required to implement the strategy outweighs its financial benefit. They therefore predict whether an adaptation strategy is likely to reduce or increase monetary risk over the life cycle duration chosen. Different time horizons can be investigated to assess the payback period for a cost-effective strategy (Ryan and Stewart, 2017). From an asset owner/operator perspective, the effectiveness values provide information for a risk-adverse asset manager who wants to reduce climate change impacts regardless of cost, while the cost–benefit outcomes provide full quantitative risk-based decision support for adaptation financial feasibility.

The first observation is that the results of both the effectiveness of the adaptation strategies and the cost–benefit outcomes are relatively stable across the two climate scenarios. This can be explained by the small differences in climate change impacts under the two RCPs (between 1% and 3%; Table 11.3). This is important, as it illustrates that the much discussed issue of climate scenario uncertainty can sometimes be ruled out through detailed quantitative multi-scenario analysis, aiding the decision-making process for infrastructure owners. To facilitate assessment of the effectiveness of the adaptation strategies in reducing the effects of climate change on network performance, adaptation effectiveness is plotted for Cork for RCP 4.5 in Figure 11.6. This plot shows the reduction in the number of power poles condemned and wind failures brought about by the adaptation strategies, when compared with the BAU no climate change case. If a point falls below the zero line in the plot, it indicates that the adaptation strategy was unsuccessful in fully reducing the impact of climate change on either the percentage of poles condemned or wind failures. As Figure 11.6 illustrates, it is not difficult to develop climate adaptation strategies that more than mitigate the impact of climate change. The use of larger poles in ADAP3, ADAP4 and ADAP5 reduces the total number of wind failures over the 50-year monitoring period to 47%, 31% and 35% of the pre-climate change level, respectively. These three adaptation strategies also reduce the percentage of poles condemned and replaced to between 39% and 74% of pre-climate change levels. The adaptation strategies using standard pole sizes, but different inspection intervals (ADAP1) or condemning criteria (ADAP2), also reduce the total number of wind failures

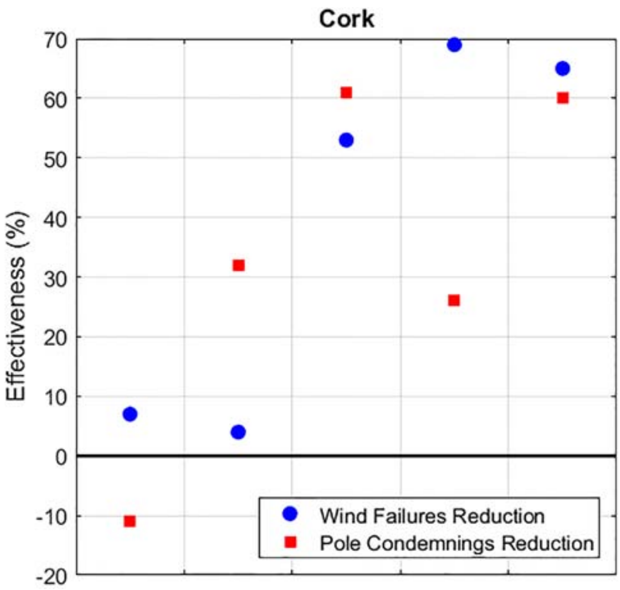

Figure 11.6. Effectiveness of climate adaptation strategies (ADAP1–5) in reducing the impacts of climate change impacts under RCP 4.5 to the year 2050 for a network of one million poles located in Cork.

to below pre-climate change conditions, although ADAP1 does so at the cost of an increase in the percentage of power poles condemned.

Overall, considering Figure 11.6, it is perhaps to be expected that climate change impacts on CI networks can be managed through alterations to maintenance operations or by adopting a more conservative design, i.e. larger power poles, higher flood defences, more frequent inspection and maintenance works on bridges at risk of bridge scour, etc. The more important question is at what cost do these climate change adaptation actions come and do the benefits outweigh these costs, i.e. is the overall reduction in monetary risk achieved through the adaptation greater than the cost of the strategy? The answer to this question for the five power pole adaptation strategies is represented graphically in Figure 11.7, which shows the adaptation NPVs to mid-century under RCP 4.5, based on one million poles in both Cork and Dublin. ADAP2, which involves higher condemning criteria and less frequent inspections than the BAU case, has a mean NPV of between €20 and €25 per pole over the 2000 to 2050 monitoring period. This is a considerable saving in the context of network sizes, i.e. a network of two million poles in Ireland results in savings of approximately €40 million over 50 years. This reduction in monetary risk is coupled with a 28% reduction in power pole failures when compared with the BAU case under RCP 4.5. It is noted, however, that this NPV does include the safety costs, as discussed in section 11.5.1. Inclusion of this cost in the analysis would serve only to increase the cost-effectiveness of the adaptation strategies.

The second key point from Figure 11.7 relates to differences in adaptation NPVs across the two regions examined. ADAP3 and ADAP5 both have positive NPV outcomes for Cork, but have negative NPV

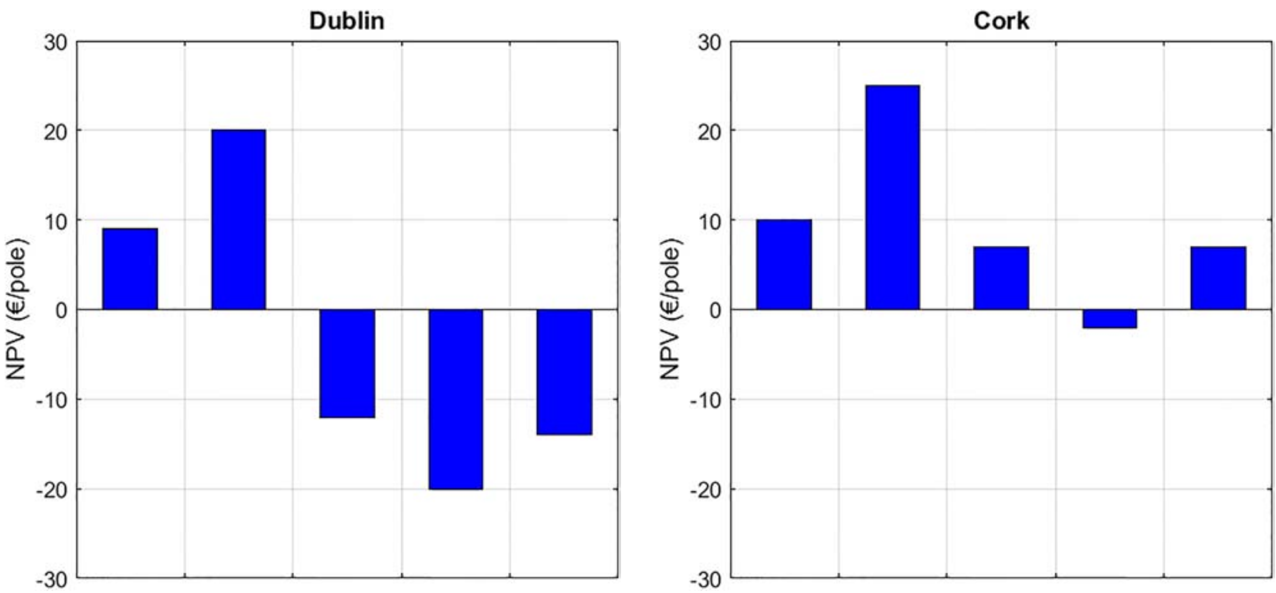

Figure 11.7. NPV of climate adaptation strategies (ADAP1–5) for a network of one million power poles maintained over 50 years, under RCP 4.5, for two locations: Dublin and Cork.

outcomes for Dublin. This regional variability in climate adaptation feasibility is due to a number of factors, but primary among these is the fact that wind failure rates in Cork are higher than in Dublin, as shown in Figure 11.5a. This means that the initial investment in installing larger poles is less likely to be recouped over the monitoring period in Dublin than in Cork, i.e. the installation of larger poles in Cork will prevent more pole failures than in Dublin by virtue of the fact that the probability of pole failure in a given year is higher in Cork. This effect has also been detected in a previous study by the authors that considered Australian power poles (Ryan and Stewart, 2020). This regional variability in climate change feasibility highlights the need to conduct quantitative risk-based decision support analysis at a regional level. It also illustrates the complexity facing CI decision-makers, i.e. implementation of a seemingly good adaptation strategy nationwide based on the analysis in Cork would actually result in a loss (or increased monetary risk) in Dublin, and possibly nationally.

Overall, Figures 11.5 to 11.7 represent the level of insight that can be gained by asset owners/operators from a probabilistic risk-based decision support framework. The results illustrate the advantage of this form of detailed information versus the output from a high-level type assessment (i.e. as described in Part A of the report), where findings are limited to indications that risks may rise in the future for an asset or network. Importantly, the probabilistic analysis incorporates uncertainty and variability, and the relevance of uncertainty and variability in the context of different decisions can also be presented, i.e. the likely payback period, the probability that NPV > 0, etc. The reader is referred to Ryan and Stewart (2017) for a discussion of these additional results. Together, the output of the detailed quantitative risk assessment can help avoid opportunity costs associated with climate adaptation decision-making.

12 Key Messages from a Quantitative Risk-based Decision Support Analysis

Part B of the report has addressed objectives 3 and 4 outlined in Chapter 1 through the development of a quantitative risk-based decision support framework and presentation of an illustrative case study, which uses the framework to quantify projected climate change risks for power pole networks and examines the effectiveness and the feasibility (through probabilistic cost–benefit analysis) of various climate adaptation actions. The key messages from the detailed probabilistic climate risk assessment and adaptation cost–benefit analysis are summarised below.

12.1 Value of the Approach

The aim of the case study was to illustrate the value of a quantitative risk-based decision support approach for climate change adaptation. This is achieved by contrasting the outputs from Part A and Part B of the report. The high-level analysis in Part A provides an indication of possible changes in future risk for an asset or network. The more detailed quantitative risk assessment in Part B can quantify projected increases in future CI risk. Based on this, an adaptation analysis may be deemed appropriate, and probabilistic cost–benefit analysis can then be used as a decision support tool to investigate (1) the effectiveness of the adaptation strategies in reducing climate change impacts and (2) the financial feasibility of their implementation (i.e. monetary risk reduction from adaptation implementation). This level of detail is likely to be required by CI decision-makers to avoid significant opportunity costs when faced with difficult adaptation decisions in the face of considerable uncertainty and variability for vast infrastructure networks.

12.2 Requirements for Implementing the Approach

The case study also illustrates the somewhat complex nature of detailed probabilistic assessment, which requires two elements to be effective in helping to inform adaptation decision-making: (1) sufficient time and resources to develop models that accurately represent the long-term performance of complex infrastructure networks in a changing climate; and (2) significant data, which must be collected and supplied by CI operators/owners. It is vital that owners and operators collect data on operational costs, failure occurrences, levels of deterioration, failure costs, etc. This is particularly challenging during times of EWEs; however, these are perhaps the most important data from a network modelling perspective.

12.3 Analysis Findings

The detailed probabilistic assessment indicates that the impacts of climate change on Irish timber power pole failure risks could be significant. Power pole wind failure rates were projected to increase by 24% in Cork and 16% in Dublin by mid-century under RCP4.5.

It was relatively straightforward to develop climate change adaptation strategies that more than mitigated the impact of climate change on network performance. It was far more challenging to develop cost-effective climate adaptation strategies, with NPVs under RPC4.5 to 2050 ranging from –€20/pole to +€25/pole for five seemingly appropriate adaptation strategies. This highlights the difficulty associated with making adaptation decisions without detailed quantitative information for vast infrastructure networks (i.e. over two million Irish power poles leading to a possible €90 million swing, from projected losses of €40 million to possible savings of €50 million).

Two climate change adaptation strategies were found to have positive cost–benefit outcomes for Cork, but negative cost–benefit outcomes for Dublin. This highlights an additional source of complexity in decision-making in the form of the regional variability of climate change adaptation feasibility.

The analysis herein considers risk from a pole failure due to extreme wind loads, but does not consider risk of power failure from falling trees and debris. Future work should include this failure scenario in the overall risk assessment of the overhead networks.

The climate change predictions used in this analysis are for mid-century (2050). However, as existing CI networks are expected to serve for longer periods, it would be of interest to perform the study considering end-of-century climate change projections for Ireland, which were not available at the time of analysis, but were being developed.

13 Project Conclusions and Recommended Future Work

13.1 Aims and Objectives

Part A of the report addressed objectives 1 and 2 outlined in Chapter 1 through the development of the GIS-based high-level CCRA framework, and the implementation of this framework across four of Ireland's CI sectors. This high-level analysis identified a number of key climate change risks for Ireland's CI, and examined these using GIS data where possible.

Part B of the report addressed objectives 3 and 4 outlined in Chapter 1 through the development of a quantitative risk-based decision support framework and the presentation of an illustrative case study; the latter used the framework to quantify projected climate change risks for power pole networks and to examine the effectiveness and feasibility of various climate adaptation actions. This analysis illustrated the advantages of the detailed approach over a high-level assessment in informing effective climate change adaptation action.

13.2 Conclusions

The regional variability of the climate change impact findings and the difficulties encountered in obtaining GIS data for CI have highlighted the need for continued collaborative research looking at GIS-informed risk screening to (1) build on this desk study-scale project (CIViC budget < €100,000), further exploring areas such as infrastructure failure consequences (criticality), more advanced vulnerability estimation, etc.; and (2) ensure the continued development, gathering and sharing of GIS information.

The high-level GIS-based CCRA described in Part A of the report identified a range of possible regionally specific climate change risks through the mapping of infrastructure, climate change predictions and existing hazards. Primary risks identified for each CI sector were as follows:

- Transport sector: fluvial flooding and coastal inundation/coastal flooding are key climate change risks. For instance, the extent of national roads and rail networks in projected flood zones in Ireland for the existing 1-in-1000-year coastal flooding event were found to be similar to those for the 1-in-10-year coastal flood event under the mid-range climate change scenario. The sector is also likely to experience increased future risk of bridge scour in some areas, most notably in the midlands region, and increased landslide risk in certain areas.
- Energy sector: climate change risks related to extreme wind speeds are likely to be a major challenge; cascading failures into other sectors are also a key consideration. Other risks include reductions in future wind energy and increased risk of fluvial and coastal flooding.
- Water sector: key climate change risks include flooding and wastewater treatment overflow related to extreme rainfall events, e.g. the Ringsend Wastewater Treatment Plant, which treats approximately 40% of Ireland's wastewater, is projected to experience a 37% increase in heavy rainfall by 2050. Future projected reductions in summer rainfall volumes also pose a risk to Ireland's water supply resource, as do cascading failures from the energy sector.
- ICT sector: again, climate change threats related to extreme wind speed risks are a key concern, as are cascading failures from the energy sector. Fluvial flooding risk may increase in the future, and increases in maximum summer temperatures may have an impact on data centre cooling.

While these high-level outputs of risk-screening assessments are useful as a first step in identifying possible future risks across a broad range of infrastructure types and hazards, the approach is limited in terms of informing actual climate change adaptation action, which requires a much more detailed assessment.

The high-level analysis also emphasised the importance of CI interdependencies and cascading effects between sectors, especially the potential for cascading effects from failures in the energy sector, where past failures resulted in breakdowns across all other CI networks, both in Ireland and internationally. This area of research becomes more important in the context of the findings of the detailed probabilistic analysis of an aspect of energy infrastructure in Part B, which predicted that power pole wind failures would increase by 24% in Cork by mid-century under RCP4.5. The probabilistic cost–benefit analysis in Part B went some way to considering cascading failures through consideration of indirect costs, while the analysis in Part A touched on this area using cross-sectoral geospatial risk ranking maps, which considered proximity of infrastructures from different sectors. However, there is a need to explore this area in far more detail, especially given the complex nature of CI sectoral interdependencies, as discussed in the report.

Having identified the possibility of significant climate change impacts for power pole networks in Ireland, a quantitative risk-based decision support approach was used to investigate climate adaptation options. The analysis found that it was relatively straightforward to develop climate change adaptation strategies that more than mitigated the impact of climate change on network performance. It was far more challenging to develop cost-effective climate adaptation strategies, with adaptation option NPVs under RCP4.5 to 2050 ranging from –€20/pole to +€25/pole for five seemingly appropriate adaptation strategies. This highlights the difficultly associated with making adaptation decisions without detailed quantitative information for vast infrastructure networks (i.e. over two million Irish power poles leading to possible projected losses of €40 million or possible savings of €50 million depending on the strategy used and the location).

In the future, it is vital that Ireland moves from GIS-based climate change risk-screening approaches (Part A) to the use of more detailed quantitative risk-based decision support analysis. This is illustrated by the contrasting outputs described in Part A and Part B of the report. The high-level analysis in Part A provides an indication of the possibility of changes in future risk for an asset or network. The more detailed quantitative risk assessment in Part B can quantify projected increases in future CI risk. Based on this, an adaptation analysis may be deemed appropriate, and the probabilistic cost–benefit approach can then be used as a decision support tool to investigate the effectiveness of the adaptation strategies in reducing climate change effects and the financial feasibility of their implementation (i.e. monetary risk reduction of adaptation implementation). This level of detail is likely to be required by CI decision-makers to avoid significant opportunity costs when having to make difficult adaptation decisions in the face of considerable uncertainty and variability for vast infrastructure networks. Failure to obtain this information may result in a lack of significant climate action activity, which can also result in high opportunity costs. For example, as illustrated in section 11.5.2, NPVs indicate that opportunity costs of approximately €20/pole will arise if a BAU strategy (no action) is chosen over adaptation strategy ADAP2. The total opportunity cost to 2050 is thus approximately €40 million.

Finally, it is emphasised that a progression to this more detailed risk-based decision support requires (1) sufficient time and resources to develop models that accurately represent long-term performance of complex infrastructure networks in a changing climate and (2) significant data, which must be collected and supplied by CI operators/owners. This latter point is particularly important and also applies to GIS-based high-level risk analysis. Thus, it vital that infrastructure owners and operators continue (or in some cases begin) to collect and share GIS data for infrastructure and data on operational costs, failure occurrences, levels of deterioration, failure costs, etc.

13.3 Future Work

In line with the concluding remarks above, key areas for future work are as follows:

- It is essential to build on this study by conducting a more in-depth risk-screening analysis across Ireland’s CI networks, exploring issues such as asset importance (criticality), consequences of failures and asset vulnerability in more detail, and subsequent cross-sectoral relative risk ranking across a range of hazards (the scope of the current project was limited somewhat by project scale, i.e. desk study scale with a budget of <€100,000).
- It is important to move towards a more quantitative risk-based analysis in Ireland for studies examining climate change impacts and climate adaptation action. These detailed methods can actually inform effective adaptation action in the face of considerable uncertainty and variability, thus avoiding opportunity costs associated with risk neglect, worst-case thinking and risk aversion.

- CI interdependencies, cascading failures and multi-sectoral risk, particularly in relation to energy infrastructure failures, using detailed quantitative methods should be considered. As an example, enhanced understanding of the impacts of power interruptions on other CI sectors could be integrated into the consequences aspect of a quantitative risk assessment similar to that in Part B, providing a more complete picture of overall climate risks across all CI sectors, with likely improvements in the cost–benefit performance of a given adaptation action.
- While Part B of the report illustrated the power of quantitative risk analysis as a decision support tool for climate adaption, implementation of the approach required detailed information from industry on operations procedures and costs, failure incidents, failure costs, network design, etc. It is vital that all CI sectors gather this information, and share it where possible, to facilitate quantitative risk assessments, aiding effective climate change adaptation action for Ireland, both within and across CI sectors (i.e. multi-sectoral risk).
- Continued efforts are also vital to promote the gathering of GIS data by all industry stakeholders in CI sectors and, perhaps most importantly, the sharing of these data to aid the assessment of single-sector and multi-sectoral risk in Ireland.

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Abbreviations

ADAP	Adaptation strategy
AEP	Annual exceedance probability
BAU	Business as usual
BCR	Benefit-to-cost ratio
CCRA	Climate change risk assessment
CI	Critical infrastructure
CIViC	Critical Infrastructure Vulnerability to Climate Change
CMIP5	Coupled Model Intercomparison Project 5
CoV	Coefficient of variation
DCCAE	Department for Communications, Climate Action and Environment
DTTAS	Department of Transport, Tourism and Sport
EPA	Environmental Protection Agency
ESB	Electricity Supply Board
EU	European Union
EWE	Extreme weather event
GCM	Global climate model
GIS	Geographic information system
GNI	Gas Networks Ireland
HEFS	High-end future scenario
ICT	Information and communications technology
IPCC	Intergovernmental Panel on Climate Change
LCC	Life cycle cost
LL	Lost load
MIROC	Model for Interdisciplinary Research on Climate
MRFS	Mid-range future scenario
MV	Medium voltage
NAF	National Adaptation Framework
NPV	Net present value
NUI	National University of Ireland
OD	Outage duration
OPW	Office of Public Works
PE	Population equivalent
RCM	Regional climate model
RCP	Representative concentration pathway
SRES	Special Report on Emissions Scenarios
TII	Transport Infrastructure Ireland
VoLL	Value of lost load

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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CIViC: Critical Infrastructure Vulnerability to Climate Change

Authors: Páraic C. Ryan, Lara Hawchar, Owen Naughton and Mark G. Stewart

Identifying Pressures

Modern society relies on the effective functioning of critical infrastructure networks to provide public services, enhance quality of life and spur sustainable economic development. Thus, the critical infrastructure constructed today must be capable of operating decades into the future. The Intergovernmental Panel on Climate Change (IPCC) has identified the "breakdown of infrastructure networks and critical services" as a key climate change risk. Consequently, it is vital that we develop a robust understanding of the climate change risks for our critical infrastructure. This is the first step in developing feasible and cost-effective climate adaptation strategies. Failure to do so is likely to result in significant opportunity costs. In this context, the CIViC project developed climate change risk analysis frameworks and conducted analysis for Irish critical infrastructure on two levels: (1) a high-level risk screening approach was used to analyse Ireland's four critical infrastructure sectors and (2) a more detailed fully quantitative risk approach was applied to the energy sector. Results indicate that, while risk screening is useful in identifying potential risks, fully quantitative risk analysis is required to develop cost-effective climate adaptation strategies for Ireland's critical infrastructure.

Informing Policy

Critical infrastructure is identified as one of four key themes under Ireland's National Adaptation Framework (NAF). Vulnerability assessment, risk analysis and adaptation decision support tools are identified in the NAF as key components of "a new framework for delivering climate resilience". The importance of climate risk analysis was highlighted in the IPCC Fifth Assessment Report, and is recognised under the United Nations Framework Convention on Climate Change, including its Paris Agreement. The IPCC defines climate change risk as the integration of hazard, vulnerability and exposure. This definition formed the basis of the climate risk analysis frameworks developed in the CIViC project. It was applied to both the high-level risk screening assessment and the detailed quantitative risk assessment of critical infrastructure. It is hoped that these CIViC risk analysis frameworks and assessments, which were applied in part in the recent Climate Change Adaptation Plan for Transport Infrastructure, will also help to improve future iterations of other sectoral adaptation plans under the NAF.

Developing Solutions

Three main steps are required to help ensure the long-term resilience of Irish critical infrastructure under future climatic conditions: (1) identify potential climate risks, (2) quantify the magnitude of these risks and impacts, and (3) develop cost-effective climate adaptation strategies to mitigate unacceptably high risks. Part A of the CIViC report presents a framework and analysis, aimed at identifying potential risks for the four main critical infrastructure sectors (transport, energy, water and ICT). This was achieved through a GIS-based high-level climate change risk assessment. While this semi-quantitative risk screening is useful, it does not quantify the magnitude of projected impacts, or provide sufficient detail to develop adaptation actions for large-scale infrastructure networks. This can however be achieved through the more informative fully quantitative risk framework developed in Part B of the report, which was applied to part of the energy sector as an illustrative case study. Although much more resource intensive, this analysis was successful in quantifying risks and developing a cost-effective climate adaptation strategy that reduced the projected impact of climate change on timber power pole networks.

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