Report No.360

epa Research
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Methodologies for Financing and Costing of Climate Impacts and Future Adaptation Actions: Transport Networks in Ireland

Authors: Julie Clarke, Enrique Acosta and Heidi Brede

www.epa.ie

Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *We provide high quality, targeted and timely environmental data, information and assessment to inform decision making at all levels.*

Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

Our Responsibilities

Licensing

We regulate the following activities so that they do not endanger human health or harm the environment:

- waste facilities *(e.g. landfills, incinerators, waste transfer stations)*;
- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
- large petrol storage facilities;
- waste water discharges;
- dumping at sea activities.

National Environmental Enforcement

- Conducting an annual programme of audits and inspections of EPA licensed facilities.
- Overseeing local authorities' environmental protection responsibilities.
- Supervising the supply of drinking water by public water suppliers.
- Working with local authorities and other agencies to tackle environmental crime by co-ordinating a national enforcement network, targeting offenders and overseeing remediation.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Prosecuting those who flout environmental law and damage the environment.

Water Management

- Monitoring and reporting on the quality of rivers, lakes, transitional and coastal waters of Ireland and groundwaters; measuring water levels and river flows.
- National coordination and oversight of the Water Framework Directive.
- Monitoring and reporting on Bathing Water Quality.

Monitoring, Analysing and Reporting on the Environment

- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
- Independent reporting to inform decision making by national and local government *(e.g. periodic reporting on the State of Ireland's Environment and Indicator Reports)*.

Regulating Ireland's Greenhouse Gas Emissions

- Preparing Ireland's greenhouse gas inventories and projections.
- Implementing the Emissions Trading Directive, for over 100 of the largest producers of carbon dioxide in Ireland.

Environmental Research and Development

- Funding environmental research to identify pressures, inform policy and provide solutions in the areas of climate, water and sustainability.

Strategic Environmental Assessment

- Assessing the impact of proposed plans and programmes on the Irish environment *(e.g. major development plans)*.

Radiological Protection

- Monitoring radiation levels, assessing exposure of people in Ireland to ionising radiation.
- Assisting in developing national plans for emergencies arising from nuclear accidents.
- Monitoring developments abroad relating to nuclear installations and radiological safety.
- Providing, or overseeing the provision of, specialist radiation protection services.

Guidance, Accessible Information and Education

- Providing advice and guidance to industry and the public on environmental and radiological protection topics.
- Providing timely and easily accessible environmental information to encourage public participation in environmental decision-making *(e.g. My Local Environment, Radon Maps)*.
- Advising Government on matters relating to radiological safety and emergency response.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

Awareness Raising and Behavioural Change

- Generating greater environmental awareness and influencing positive behavioural change by supporting businesses, communities and householders to become more resource efficient.
- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

Management and structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

Methodologies for Financing and Costing of Climate Impacts and Future Adaptation Actions: Transport Networks in Ireland

(2018-CCRP-DS-13)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Gavin and Doherty Geosolutions Ltd

Authors:

Julie Clarke, Enrique Acosta and Heidi Brede

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2014–2020. The EPA Research Programme is a Government of Ireland initiative funded by the Department of the Environment, Climate and Communications. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

The authors would like to acknowledge the members of the project steering committee, namely Dr Tadhg O'Mahony (Consultant), Gaetane Suzenet (International Impact Partners), Seosamh Ó Laoi and Dr Olga Grant (Department of the Environment, Climate and Communications) and Lisa Sheils (Environmental Protection Agency).

DISCLAIMER

This report is based on research carried out/data from December 2018 to March 2020. More recent data may have become available since the research was completed.

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.

EPA RESEARCH PROGRAMME 2014–2020

Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-967-3 January 2021

Price: Free Online version

Project Partners

Dr Julie Clarke (Principal Investigator)
Gavin and Doherty Geosolutions Ltd
Nutgrove Office Park
Rathfarnham
Dublin 14
Ireland
Tel.: + 353 1 207 1000
Email: jclarke@gdgeo.com

Dr Enrique Acosta
Gavin and Doherty Geosolutions Ltd
Nutgrove Office Park
Rathfarnham
Dublin 14
Ireland
Tel.: + 353 1 207 1000
Email: enrique@gdgeo.com

Heidi Schjøll Brede
Gavin and Doherty Geosolutions Ltd
Belfast Office
Scottish Provident Building
7 Donegall Square West
Belfast
United Kingdom
Tel: + 44 289 091 8845
Email: hbrede@gdgeo.com

Contents

Acknowledgements **ii**

Disclaimer **ii**

Project Partners **iii**

List of Figures **vi**

List of Tables **vii**

Executive Summary **ix**

1 Introduction **1**

2 Climate Change and Adaptation Planning **3**

2.1 Global Pressures 3

2.2 Climate Change Adaptation around the World 3

2.3 Projections in Ireland 3

2.4 Climate Change Adaptation Policy for the Transport Sector in Ireland 4

2.5 Barriers to Sustainable Public Transport in Ireland 6

3 Determining the Cost of Climate Change on Transport Networks **7**

3.1 Methods for the Determination of Cost for Transport Infrastructure 8

3.2 Examples for Quantitative Cost and Risk Assessment for this Project 8

3.3 Financial Benefit of Adaptation Plans 13

3.4 QRA as a Method for Costing Climate Adaptation 15

4 Decision-making under Uncertainty **16**

4.1 Participatory Methods 16

4.2 Evaluation Methods 17

4.3 Decision-making Methods 19

4.4 Minimising the Effect of Uncertainty 20

5 Conclusions and Recommendations **21**

References **22**

Abbreviations **25**

Appendix 1 Costing Methodologies **26**

Appendix 2 Example of Workshop 1 Questionnaire **28**

List of Figures

Figure 1.1.	Weather-related losses worldwide 1980–2017	1
Figure 3.1.	Simplified components for a climate change QRA as a tool for adaptation planning	7
Figure 3.2.	Hypothetical flood curve	8
Figure 3.3.	Peak flood depth and M50 stretch	9
Figure 3.4.	Landslide hazard maps for (a) small landslides, (b) medium landslides and (c) large landslides in the study area, including the contribution of climate change	11
Figure 3.5.	The R116 road	11
Figure 3.6.	Landslide risk along a 3000-m stretch of the R116	12
Figure 3.7.	Landslide disruption and alternative route to travel from point 1 to point 2 and vice versa	13
Figure 3.8.	Net benefit of adaptation	14

List of Tables

Table 2.1.	Possible impacts on the transport network in Ireland as a result of climate change	4
Table 2.2.	Possible adaptation measures for the transport network in Ireland	5
Table 3.1.	Travel cost as a function of speed as per Penning-Rowsell *et al*. (2005)	10
Table 3.2.	Calculation of indirect cost due to flooding on a stretch of the M50 (for the year 2020)	10
Table 3.3.	Summary of the cost and risk due to landslides on the R116 road. Monetary values relative to 2020	13
Table 4.1.	Summary of evaluation methods with pros, cons and application suitability	18

Executive Summary

The negative impacts of climate change have become apparent in recent years, with the transport infrastructure network coming under increased stress owing to changing rainfall patterns, extreme storm events and increases in extreme wind speeds. These changing climatic conditions have manifested in flooding of road networks, landslides causing road/railway failures, inundation from coastal flooding and material degradation of structures. Storm events in Ireland in 2009 and the winter of 2015/2016 resulted in repair costs of €225 million and €106 million, respectively. Addressing these impacts and planning for climate change adaptation is now critical, and the development of efficient methods is a vital step in this process. There is a need for the development of methodologies that quantify the social, economic and environmental costs of climate change impacts, as well as the benefits of adaptation planning options. These methodologies should inform transport infrastructure owners, operators, investors, policymakers, decision-makers and governments, as well as other stakeholders interested in climate change adaptation planning for the transport sector.

This report aims to contribute to an improved understanding of the cost of climate change in Ireland owing to the impacts on the transport sector and examines the available methodologies to evaluate various adaptation planning strategies and decision-making tools. These issues are addressed through an existing literature review and two desk studies, as well as stakeholder workshops.

Two quantitative risk assessments (QRAs) were undertaken, including transport infrastructure examples, which were used to assess the cost and risk due to future climate change impacts. An extreme fluvial flood event on a stretch of the M50 motorway in Dublin was assessed, as well as the direct and indirect cost and risk produced by rainfall-induced landslides on a stretch of road in the Wicklow Mountains. The estimation of the costs of climate change in terms of economic, societal and environmental impacts is a key step for any climate change risk assessment and for the implementation of climate change adaptation plans. The application of QRAs showed that they can be used for evaluating the cost of climate change on the transport network. However, QRAs are not without their weaknesses and the output is only as good as the input data and choice of model. There is no "best method" to assess cost and risk. The optimal method is the one that copes best with the uncertainties associated with the availability and quality of information, and the scale of work.

Assessment of the hazard is the most difficult and time-consuming task in a QRA, and the cost or economic losses are strongly controlled by the spatial distribution, frequency, magnitude and intensity of the hazard. Very few hazard maps are available for Ireland at the regional to local scale. Therefore, resources should be put towards mapping out and quantifying climate change-related hazards due to increased rainfall, extreme wind speeds and higher temperatures to enable policymakers to more accurately assess the effect and the cost of climate change in the future.

Two transport stakeholder workshops were organised to identify areas that could be improved in relation to adaptation planning in Ireland. By examining different climate hazard scenarios for specific Irish regions, the following topics were explored: hazard assessment, vulnerability analysis, consequence analysis and adaptation planning. The responses from the participants indicated a lack of high-quality data and a need for improved sharing of existing data across sectors and regions. A lack of reliable data and lack of suitable models make it difficult to quantify the necessary investment in adaptation planning. It is therefore vitally important that future policies address these issues and that standardised data collection is funded nationwide.

During the workshops it also transpired that there was a lack of awareness among the shareholders of the systems and resources already in place to provide information. The benefits of such platforms for the collection and publication of data will only become accessible if shared and used by all stakeholders. A dedicated advertisement campaign is needed to raise awareness and promote the use of tools and resources already in existence among relevant

personnel in the transport sector and regional councils. A co-operative approach among various departments is deemed most beneficial, as this will enable a collective effort rather than a disjointed or fragmented one to tackle the impact of climate change successfully.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) states that human influence on the climate is clear (IPCC, 2013) and that this influence is caused by a significant increase in greenhouse gases having been released into the atmosphere over the past two centuries. Climate change is leading to increasing temperatures, rising sea levels, modified precipitation patterns and increases in the frequency and intensity of extreme weather events (EWEs),[1] including storms, flooding and hurricanes, as well as prolonged periods of cold and hot weather, leading to drought and wildfires.

These changing weather patterns and more frequent EWEs are resulting in significant social, environmental and economic losses, including human casualties and injuries, as well as impacts on infrastructure networks, properties, agricultural systems, natural ecosystems, water resources, food security, human health and coastal zones. Carney (2018) highlighted that the value of registered weather-related loss events worldwide has tripled from approximately US$50 billion annually in the 1980s to US$150 billion annually over the past decade (Figure 1.1). Stern (2007) stated that climate change could cost the world's economy nearly 5% of the global gross domestic product.

Ireland's first transport adaptation plan presented eight case studies where extreme weather caused damage to the Irish transport network. Of these, the most significant financial costs resulted from repairs following severe flooding. After unprecedented rainfall in 2009, the cost was estimated to be in excess of €225 million. For the following two storms in the winter of 2015/2016, the estimated cost of repairs was €106 million. One storm in December 2013 cost the state around €70 million, of which €23.6 million was the cost of direct damage to the transport network. Severe weather in January and February 2014 caused additional damage to infrastructure worth €13.5 million (DTTAS, 2017).

Despite global efforts to mitigate climate change through the reduction of greenhouse gas emissions as agreed at international climate treaties (e.g. Copenhagen 2009, Paris 2015), it is inevitable that countries around the world will be dealing with climate

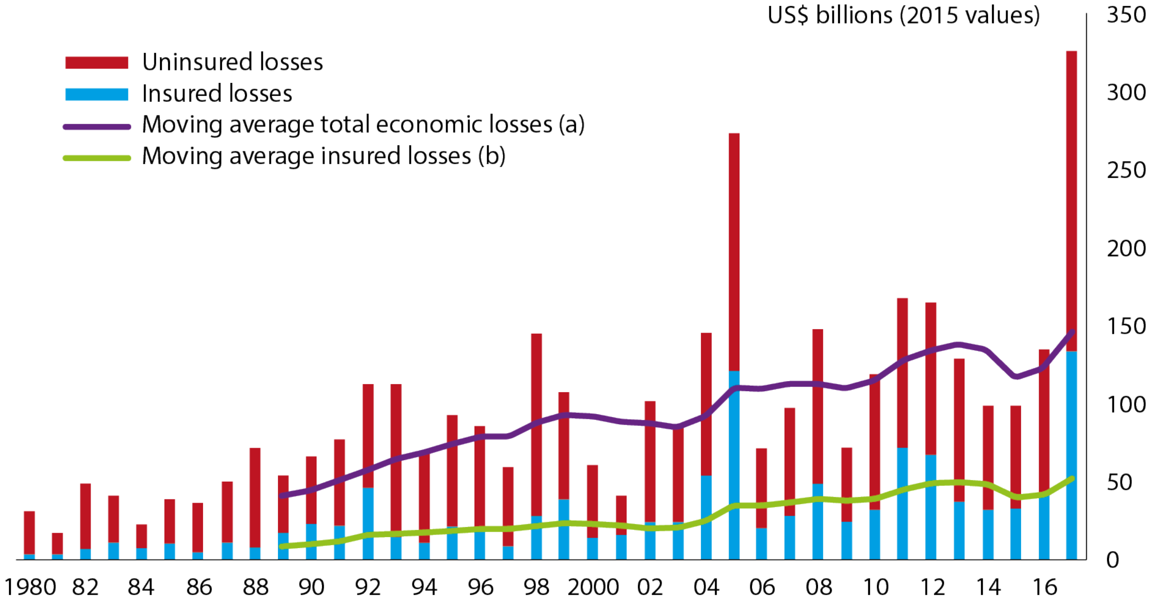


Figure 1.1. Weather-related losses worldwide 1980–2017 (Carney, 2018).

1 Definition of EWE by the IPCC (2012): the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable.

change impacts for the foreseeable decades. In an effort to increase the resilience of regions to the effects of climate change, many countries are now adopting climate change adaptation policies, strategies and sectoral plans. For instance, the European Union (EU) places a strong emphasis on climate change adaptation and resilience (Environmental Impact Assessment – EIA – Directive 2014/52/EU) in an attempt to make transport infrastructure more resilient and climate proof. Decision-makers and infrastructure owners will be obliged to implement cost-effective and reliable adaptation measures to ensure the resilience of the infrastructure networks to climate change impacts.

In Ireland, the government has outlined a plan to transition to a low-carbon, climate-resilient and environmentally sustainable economy by 2050. To support this objective, the National Adaptation Framework (NAF) was established, which specifies the national strategy to reduce the vulnerability of Ireland's environment, society and economy to the impacts of climate change and to increase resilience (DCCAE, 2018a).

Among the different stakeholders in Ireland, this project has identified the need for:

- sectoral (transport sector) adaptation planning at the regional level to determine optimal adaptation planning in terms of measures and timing;
- economic analysis to justify the benefits of such adaptation decisions in terms of their costs;
- a holistic approach to information management to ensure that all parties are fully aware of how to obtain the required information.

To achieve this, the costs of climate change impacts must be determined, and decision-making methods to inform strategic adaptation planning are required. The objective of the TACT project, and in particular this report, is to establish a risk framework that translates climate change impacts for transport networks into costs and to facilitate strategic and financial adaptation planning as well as policymaking for the transport network in Ireland, with the ultimate aim of increasing the resilience of the road, rail and maritime networks. It also aims to identify any shortcomings in the existing process.

These objectives are achieved through a review of the existing literature and two specific desk studies, as well as stakeholder workshops.

2 Climate Change and Adaptation Planning

2.1 Global Pressures

Human-induced climate change is a well-established fact that can no longer be ignored. Higher average temperatures, sea level rise, stronger storms and longer droughts are some of the effects already registered and expected to increase in the future (IPCC, 2014). Exactly how climate change will progress is hard to predict and will depend on future anthropogenic emissions and natural climate variability. Over the past decade, the IPCC has established Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs) that offer plausible future climate scenarios. The RCPs comprise four different pathways describing the effects in the year 2100 related to four different levels of greenhouse gases in the atmosphere, without including any socio-economic narrative. The SSPs, on the other hand, look specifically at the socio-economic aspect of climate change, how the world might evolve in the absence of climate policy and what levels of climate change mitigation can realistically be achieved (Hausfather, 2018).

The RCPs and SSPs are designed to be complementary and provide possible scenarios for the future to be used by policymakers and governments in order to affect their decision-making and adaptation planning.

2.2 Climate Change Adaptation around the World

More and more evidence suggests that the future will bring significant changes to our climate. Countries around the world are implementing adaptation planning strategies and introducing mitigating measures. Examples from Australia (AECOM, 2010), Alaska (Melvin *et al*., 2017) and the Netherlands (de Bruin *et al*., 2009) showed that investing money in solutions today will save significant costs in the future.

The European Commission published an “EU strategy on adaptation to climate change” in 2013 (EC, 2013), stating that climate change mitigation must remain a priority for the global community. The overall aim of the strategy was to contribute to a more climate-resilient Europe and included three main objectives:

1. Promoting action by Member States: encourage and financially support Member States to adopt comprehensive adaptation strategies across sectors and regions.
2. Better informed decision-making: bridge knowledge gaps, fund research and innovation, and improve ease of access to information.
3. Climate-proofing EU action: promote adaptation in key vulnerable sectors and mainstream climate change adaptation into EU policies for all relevant sectors.

2.3 Projections in Ireland

With the climate changing globally, Ireland will also be affected. Climate studies for Ireland have projected an increase in mean temperatures, an increase in length of the growing season, decreases in summer precipitation and increases in winter precipitation, as well as increases in the frequency of heavy (> 10 mm/day) and very heavy (> 20 mm/day) precipitation days (Nolan, 2015; Fealy *et al*., 2018). Furthermore, it has been shown that sea levels around Ireland are rising at a rate of 3.5 cm per decade on average (Dunne *et al*., 2008) and this trend is projected to continue.

To simulate climate variables at regional scale, downscaling of Global Climate Models was employed by Nolan (2015) using regional climate models to provide high-resolution datasets for future climate scenarios. Several future emission scenarios were analysed, as there is uncertainty associated with regional climate predictions owing to the natural variability of climate systems, the complex formulation of the model, the coarse resolution of regional models and atmospheric compositions. The most relevant regional climate projections for the transport sector in Ireland are outlined below.

- mean annual temperature rise:
  - an increase of 1–1.6°C in mean annual temperatures, with the largest increases in the east of Ireland;

   - a rise in temperature at the extremes, with the highest daytime temperatures expected to rise by 0.7–2.6°C in summer and the lowest night-time temperatures anticipated to rise by 1.1–3°C in winter;
- changing precipitation patterns:
   - significant decreases in mean annual, spring and summer precipitation amounts;
   - notable increases in the frequencies of heavy rainfall events of approximately 20% for the winter and autumn months;
   - a substantial increase in the number of extended dry periods during autumn and summer;
- changing wind speed:
   - an overall increase (8%) in the wind intensity for the winter months and a decrease (4–14%) during the summer months;
   - an increase in extreme wind speeds.

In terms of EWEs for Ireland, an increase in the intensity of storms affecting Ireland by 2050 is projected (Nolan, 2015). Furthermore, storm surge events and extreme wave heights are projected to increase in frequency (Dunne *et al*., 2008; Wang *et al*., 2008). Although there is agreement on the direction of these projections, accurate estimates are a challenge owing to the inherent uncertainty associated with predictions.

When the climate changes, so does the environmental impact on buildings, infrastructure and transport networks. Table 2.1 presents some of the challenges that might arise for the transport network in Ireland as a result of the expected climate changes presented previously.

2.4 Climate Change Adaptation Policy for the Transport Sector in Ireland

In accordance with the EU adaptation strategy, Ireland is addressing climate change adaptation at a national level. In 2012, the National Climate Change Adaptation Framework was created and this was the first step in developing national policies for adaptation to climate change. This was followed in 2014 by the establishment of the National Adaptation Steering Committee, consisting of representatives from government sectors, the Environmental Protection Agency (EPA), the Climate Change Advisory Council, the County and City Management Association and the National Standards Authority in Ireland (DCCAE, 2018a). These were later joined by Met Éireann and the Climate Action Regional Offices (CAROs), established in 2018. In the initial phase of the adaptation planning, four sectoral plans were developed, among them "Adaptation Planning – Developing Resilience to Climate Change in the Irish Transport Sector" by the Department of Transport, Tourism and Sport (DTTAS) (2017).

In 2018, the Department of Communications, Climate Action and Environment (DCCAE) – since renamed Department of the Environment, Climate and Communications – published Ireland's first NAF, which includes a chapter on Climate Change Adaptation Planning in Ireland (DCCAE, 2018a). The framework

Table 2.1. Possible impacts on the transport network in Ireland as a result of climate change

Climate change-induced hazards	Impact on the transport network
Mean annual temperature rise	• Concerns regarding pavement integrity, e.g. softening of asphalt layers, traffic-related rutting, embrittlement (cracking), migration of liquid asphalt • Thermal expansion in bridge expansion joints and paved surfaces • Impact on landscaping
Changing precipitation patterns	• Flooding of roadways • Road erosion, landslides and mudslides that damage roads • Overloading of drainage systems, causing erosion and flooding • Traffic hindrance and safety
Changing wind speed	• Threat to the stability of bridges • Damage to signs, lighting fixtures and supports

Modified from Bles *et al*. (2010).

states that Ireland needs to plan for responding to short-term challenges (e.g. floods, rainfall and storms) while also building long-term resilience. The former relates to emergency planning and how Ireland responds to EWEs, whereas the latter requires long-term climate change adaptation planning. Improved coherence between Climate Change Adaptation and Disaster Risk Reduction policies could prove important for supporting emergency planning by reducing risks, enhancing preparedness and improving the ability to recover.

The NAF identified 12 sectors within seven government departments that may be vulnerable to climate change and are encouraged to develop adaptation plans (DCCAE, 2018a). Building on this, several sectoral adaptation plans were published towards the end of 2019, e.g. the adaptation plans for transport infrastructure (DTTAS, 2019) and flood risk management (OPW, 2019).

The 2017 publication from the DTTAS aimed to identify vulnerabilities in the transport system at the national level and provide policies on adaptation strategies for transport in Ireland. The 2019 transport adaptation plan built on this, setting out priorities regarding climate concerns in the transport sector, linking climate impacts with risks to infrastructure, outlining the next steps required to fill knowledge gaps and assessing the adaptability of the transport sector. The flood risk management adaptation plan from the Office of Public Works (OPW) (2019) is also highly relevant to the transport sector, as infrastructure and transport operation will be greatly affected by floods.

In an effort to further support national sectoral adaptation planning, guidelines were developed by the DCCAE with the Irish Climate Information Platform, Climate Ireland. The guidelines aim to ensure coherent and consistent adaptation plans across sectors, by laying out a stepwise approach (in accordance with requirements from the Climate Action and Low Carbon Development Act 2015) (DCCAE, 2018a).

In addition to national and sectoral policies and adaptation plans, steps are being taken at local levels across Ireland. The NAF required local authorities to publish their own local adaptation strategies by September 2019, which should have included strategies on how to plan for and respond to emergency situations on a local level. The four CAROs established in 2018 are to assist local authorities to develop and implement adaptation measures and prepare responses to future climate change (DCCAE, 2018b).

Table 2.2 contains suggestions for adaptation measures in the transport sector based on the expected future climate impacts, which will be discussed in further detail in Chapter 4.

Table 2.2. Possible adaptation measures for the transport network in Ireland

Climate change-induced hazards	Possible adaptation measures for the transport network
Mean annual temperature rise	• Consider the use of asphalt with modified binders that raise the softening point • Paint train tracks in white reflective paint to reduce rail temperatures • Improve the energy efficiency of air conditioning/fridge storage on trains and ships to reduce costs • Review operational procedures for workers operating in hot conditions • Review or introduce firebreaks next to road and rail
Changing precipitation patterns	• Upgrade drainage systems • Upgrade or install flood defence systems • Review and revise design standards for road, rail, bridges, tunnels and port systems • Review land stability and erosion control given increased flooding impacts • Increase maintenance regimes
Changing wind speed	• Assess implications of increased wind on operational efficiencies of railways • Increase the storage capacity of ports to account for weather delays

Sources: Fisk (2017); Moretti and Loprencipe (2018).

2.5 Barriers to Sustainable Public Transport in Ireland

Over the last few years significant progress has been made with regard to adaptation planning in the Irish transport sector. However, there are some challenges that need to be met. An EPA report from 2011 (Browne *et al.*, 2011) found that the most significant barriers to sustainable public transport in Ireland are:

- the legacy of urban sprawl and low-density residential development and the long-term difficulties in retrofitting residential neighbourhoods;
- public acceptability of new fiscal measures and political resistance to introducing potentially contentious fiscal measures;
- the lack of reliable and efficient public transport and cycling facilities, particularly in low-density rural areas and residential neighbourhoods;
- perceptions of safety and distance in relation to cycling and walking;
- existing social norms and lack of awareness of the economic, health and environmental benefits of sustainable transport.

Policy priorities identified include:

- the integration of spatial planning, land use policy and transport investment through measures including:
  - incentives for densification and consolidation in urban centres;
  - restrictions on one-off housing, out-of-town retail centres and ribbon development;
  - retrofitting of residential neighbourhoods;
  - the creation of critical mass in key urban areas;
- improvements in existing public transport services through, for example, network management, reallocation and rationalisation of existing services, improved service quality, integrated ticketing and real-time passenger information, including:
  - promotion of the economic, social, health and environmental benefits of smarter travel through awareness campaigns, market segmentation and customised advertising.

It is widely accepted that climate change will have an impact on the transport infrastructure in Ireland and, although barriers and challenges exist, they must be tackled to ensure solutions that are cost-effective. In order for policymakers to determine the most appropriate adaptation measures, the costs relating to the risk of the hazard as well as to the adaptation measures need to be assessed. This process of costing methodologies needs to be mainstreamed, justifiable and repeatable. The following chapter addresses how this can be done.

3 Determining the Cost of Climate Change on Transport Networks

The estimation of the costs of climate change in terms of economic, societal and environmental impact is a key step for the climate change risk assessment and for the implementation of climate change adaptation plans (Figure 3.1).

The quantification of the other components, hazards and exposure, are also very important because costs are strongly controlled by the spatial distribution, frequency, magnitude and intensity of the hazard and must be based on how many "objects" are affected (or exposed). By quantifying all input parameters to the risk assessment, the risk becomes quantifiable in an objective and reproducible way and the results can be compared from one region to another. In addition, the quantification has the following effects (some of these conclusions are taken from Corominas and Mavrouli, 2011):

- It helps to identify the gaps in the required input data and the resultant weaknesses.
- It allows the performance of cost–benefit analyses for different adaptation measures for transport networks.
- It provides the basis for prioritising mitigation actions and the allocation of resources.
- It contributes to increasing the awareness of the existing risk levels.
- It allows for the implementation of early warning systems.
- It helps to evaluate the efficiency of the adaptation measures undertaken.

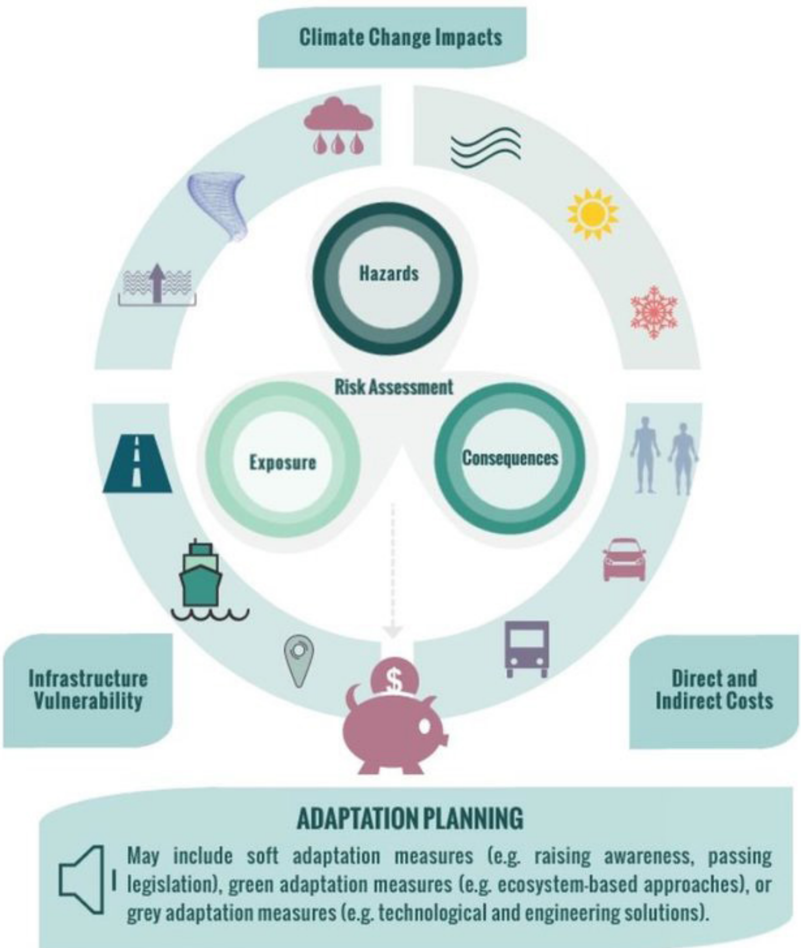


Figure 3.1. Simplified components for a climate change QRA as a tool for adaptation planning.

3.1 Methods for the Determination of Cost for Transport Infrastructure

The determination of cost for the transport infrastructure can be carried out using a variety of methods summarised in Appendix 1, Table A1.1. Methods 2 and 3 in Table A1.1 provide quantitative values of tangible costs. A combination of these two methods has been adopted for the two case studies of quantitative cost assessment for this project.

3.2 Examples for Quantitative Cost and Risk Assessment for this Project

Following the principles for the risk assessment outlined in Figure 3.1, two concrete examples were used to assess the cost and risk as a result of future climate change impacts on the transport network in Ireland. The first exercise estimates the indirect cost and risk produced by the impact of an extreme fluvial flood event on a stretch of the M50 motorway in Dublin. The second exercise calculates the direct and indirect cost and risk produced by rainfall-induced landslides on a stretch of road in the Wicklow Mountains.

3.2.1 Example 1: flooding of the M50 motorway

The following example calculation was originally presented by Julie Clarke at the European Transport Conference 2019 and published afterwards (Clarke and Acosta, 2019). For this example, the hazard is a 1000-year (or 0.1% annual exceedance probability) flood map for a future scenario of climate change. This flood hazard map was previously created by the OPW in its study of Catchment Flood Risk Assessment and Management (CFRAM). Although this hazard map represents the hypothetical peak extent and depth of such a 1000-year flash flood event, it does not provide information on the evolution with time of the flood extent and flood depth (i.e. flood curve), both of which are required for the assessment of the impact of this extreme flood hazard event on the examined road section (the exposed element).

Hazard modelling is the most difficult and time-consuming task in a QRA. As hydraulic modelling is beyond the scope of this work, the curve of the hypothetical flood event was therefore based on expert criteria for small river basins with elongated plan shape, as that of Santry River. It was assumed that the event is 9 hours long and has an asymmetrical Gaussian distribution in terms of flood depth development with time, as shown in Figure 3.2.

The inundation depth along the roadway section was obtained by combining the CFRAM flood hazard map with the LiDAR ground elevations (GSI, 2020), as shown in Figure 3.3.

The speed reduction for vehicles based on the depth of inundation was determined using equation 3.1 (Pregnolato *et al.*, 2017), which is based on empirical data gathered in the UK.

$$v = 0.0009w^2 - 0.5529w + 86.9448 \quad (3.1)$$

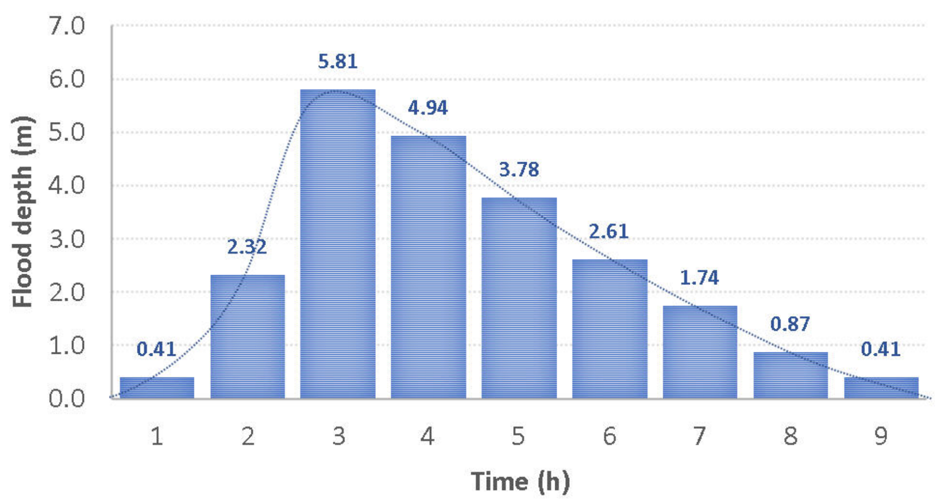


Figure 3.2. Hypothetical flood curve.

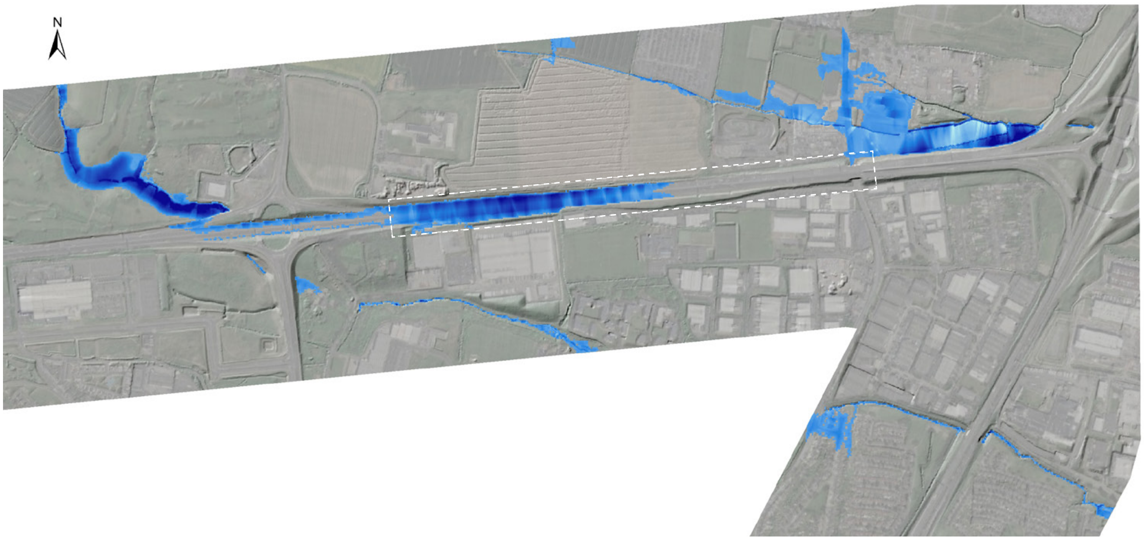


Figure 3.3. Peak flood depth and M50 stretch (dashed white line).

where v is the maximum acceptable velocity (km/h) that ensures safe control of the vehicle given the depth of water (w) in millimetres.

The cost of road traffic disruption was subsequently calculated using equation 3.2 (Penning-Rowsell *et al*., 2005).

$$\text{Cost} = \text{no. of vehicles delayed} \times \text{additional cost per vehicle (€)} \times \text{disruption duration (h)} \quad (3.2)$$

To determine the number of impacted vehicles, measured annual average daily traffic (AADT) values for this section were obtained from Transport Infrastructure Ireland (TII, 2020). Furthermore, travel costs per vehicle were based on values published by Penning-Rowsell *et al*. (2005), which were updated to account for inflation and currency conversion, as outlined in Table 3.1. Note that Penning-Rowsell *et al*. (2005) estimate travel costs as a function of speed only.

The additional cost per vehicle using the road is defined as the difference in the cost of operating the vehicle at normal speed and the actual speed at which this vehicle could travel owing to the presence of the event. Cost is not simply defined as fuel costs but includes other "resource costs".

The annual risk or probability of economic loss due to the 1000-year flood event is obtained by multiplying the hazard in terms of the annual probability of this flooding event (1/1000) and the calculated consequences or cost (equation 3.3).

$$\text{Risk} = \text{hazard} \times \text{consequences} \quad (3.3)$$

Table 3.2 summarises the cost analysis of a traffic disruption on a 1.2-km stretch of the main orbital motorway of Dublin, the M50, due to a 1000-year river flood event. The M50 is flooded during hours 3, 4 and 5 of the hypothetical flood event (Figure 3.2). The accumulated cost of the traffic disruption due to flooding on this stretch of the M50 for 3 hours is €659,160 in 2020 monetary terms.

An annual indirect flooding risk cost of €659.16 is obtained from equation 3.3, multiplying €659,160 and the temporal probability of this extreme flooding event (1/1000).

The total calculated cost is subject to uncertainties related to the determination of the risk components, namely the flood hazard and the cost:

- The flood hazard:
  - Uncertainties of the original CFRAM study.
  - Uncertainties of the climate change projections and how these were included in the flooding hazard map.
  - In this exercise, the flood depth raster was obtained through some 3D geoprocessing that led to inaccuracies in sectors where the official flood extent shapefile (CFRAM) has scarce vertexes.
  - The flood event curve (Figure 3.2) assumed for this exercise is hypothetical. The duration of the flood disruption might be different from 3 h.

Table 3.1. Travel cost (€) as a function of speed as per Penning-Rowsell *et al.* (2005)

Vehicle type	Vehicle speed (km/h)									
	1	2	5	10	20	40	50	80	100	150
Car	16.74	8.39	3.40	1.72	0.90	0.48	0.40	0.27	0.23	0.18
HGV	18.00	9.10	3.75	1.97	1.08	0.63	0.53	0.41	0.35	0.32

Note: values updated for the year 2020 assuming a future inflation rate of 2.8% per annum.
HGV, heavy goods vehicle.

Table 3.2. Calculation of indirect cost (€) due to flooding on a stretch of the M50 (for the year 2020)

Calculation steps	1–2 h	3 h		4 h		5 h		6–9 h	Total
		Car	HGV	Car	HGV	Car	HGV		
No. of vehicles delayed	0	9566	854	9566	854	9566	854	0	31,260
Speed limit (km/h)	100	0	0	0	0	0–1	0–1	100	
Additional cost per vehicle (€/km)	0	16.51	17.65	16.51	17.65	16.51	17.65	0	
Cost/km (€/km)	0	157,935	15,073	157,935	15,073	157,935	15,073	0	
Total cost (€)	0	200,577	19,143	200,577	19,143	200,577	19,143	0	659,160

HGV, heavy goods vehicle.

- The cost:
  - The current calculation of cost is independent of the day during the year and the time of day when the event occurs, as the AADT value is used. The day/date/time will obviously have an effect on the vehicles involved and thus cost. An event at rush hour will have a higher cost impact than one that occurs in the middle of the night. Adaptations for specific times (e.g. day/night, weekday/weekend, summer/winter) are recommended to obtain more accurate values. These could be achieved by applying weights to AADT value.
  - Values chosen for additional cost per vehicle might be low. Table 2 from Penning-Rowsell *et al*. (2005) does not provide cost values for speed values of 0 km/h. Cost values for 1 km/h were used instead. Therefore, €659,160 could be significantly underestimated.
  - The state of the drainage system of the M50 in the study area is unknown, which may affect its effectiveness.
  - The inflation rate might not necessarily be a steady 2.8% per annum.

3.2.2 Example 2: landslide at the R116 road

For this example, the landslide hazard at the R116 road in the Wicklow Mountains is examined using a landslide hazard map created by the project team that expresses the future spatial–temporal probability of landslides of three magnitudes. This landslide hazard map (Figure 3.4) is based on several inputs, namely an updated version of the National Landslide Inventory and the National Landslide Susceptibility Map (GSI, 2016), runout calculations, empirical methods for determining the temporal and magnitude probabilities (Malamud *et al*., 2004; Remondo *et al*., 2005), gauge logs (Met Éireann), future projections of rainfall in mid-century due to climate change (Nolan, 2015), and the expected frequency of landslides for mid-century due to the projected changes in precipitation patterns (Hicks, 1995).

The element exposed to the hazard is the R116 road, which is located south of Dublin in the Wicklow Mountains (Figure 3.5).

The consequences of a 1100-m^2 landslide (average size in the surroundings of R116) reaching the R116 in the year 2034 were estimated in terms of direct and indirect costs.

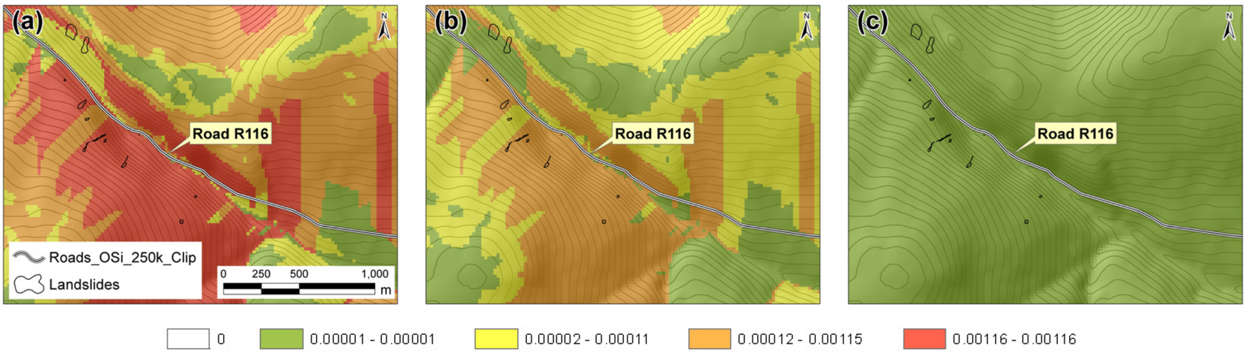


Figure 3.4. Landslide hazard maps for (a) small landslides, (b) medium landslides and (c) large landslides in the study area, including the contribution of climate change. The colour coding indicates the probability of landslides.

Figure 3.5. The R116 road.

Direct cost

Direct cost is an estimation of the budget for 48-h works including a risk assessment of landslide reactivation prior to re-opening and even prior to the road clearance; clearance of the road (≈50 m); clearance uphill; clearance/reconstruction of damaged road ditches; debris transported to a dump site; replacement of damaged traffic signals and fences (≈50 m); and traffic management. Stabilisation design and works are not included. The cost per pixel along the examined stretch of the R116 is obtained by dividing the cost of an average-size landslide of 1100 m^2 by the number of pixels encompassed. In this study, the pixel size of 20 m is determined by the available Digital Elevation Model (DEM). Thus, an average landslide encompasses 2.75 pixels.

The direct cost of a landslide clearance and repairing works in 2020 was estimated as €20,000. Considering that an average-size landside encompasses 2.75 pixels, the present cost per pixel would be €7273. Assuming a future inflation rate of 2.8% per annum, the cost in 2034 would be €27,800 or €10.124 per pixel.

Equation 3.3 is applied to obtain the direct risk in the years 2020 and 2034 along the pixels of the 3-km stretch of the R116. Figure 3.6 illustrates the longitudinal profiles of the risk. The solid line represents the landslide risk in 2020 and the overlying dashed line represents the landslide risk in the year 2034 considering the projections of climate change of Nolan (2015) and the inflation rates. The difference between the two lines is larger in stretches of high risk and smaller in stretches of low risk. Therefore, this simple longitudinal profile provides input for decision-makers and transport infrastructure owners on where to prioritise resources for climate change adaptation plans.

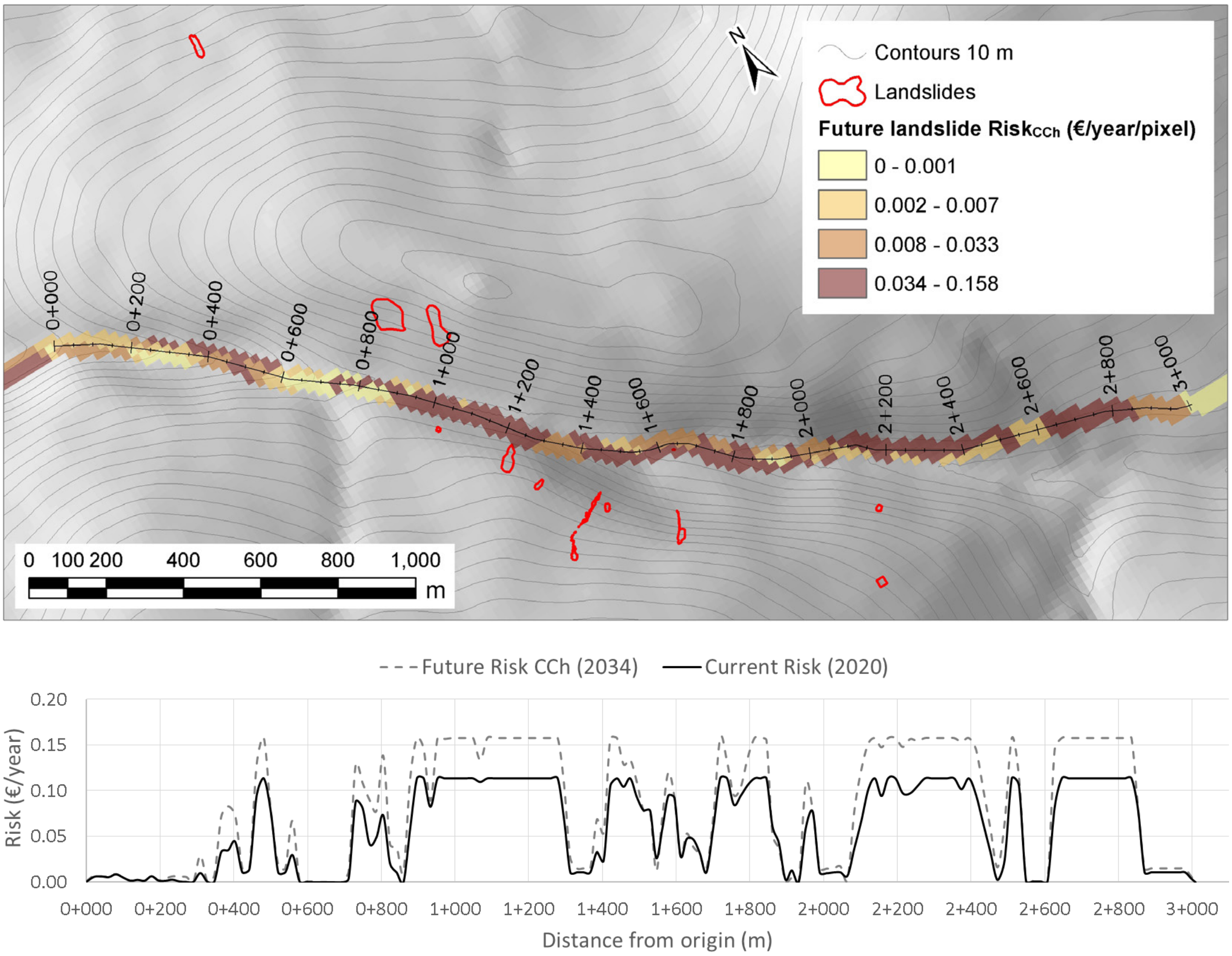


Figure 3.6. Landslide risk along a 3000-m stretch of the R116.

Indirect cost

Indirect cost is an estimation of the cost due to the additional travel distance by car from point 1 in Figure 3.7 to point 2 and vice versa during the 48 h after the landslide event. Google Maps is used here to calculate the alternative route, the additional distance and the average speed. Equation 3.2 and Table 3.1 are used again in this exercise to calculate the additional cost per vehicle. According to Dún Laoghaire-Rathdown County Council, the AADT for this road is 3039 vehicles.

The annual risk or probability of economic loss due to average landslides of 1100 m^2 is obtained with equation 3.3, multiplying the landslide hazard and the calculated consequences or costs, both direct and indirect.

The indirect cost due to additional travel distance during 2 days of traffic disruption is €25,354 in the year 2020. Applying the previously mentioned inflation rates to determine the cost for the year 2034, this would equate to €35,293.

Indirect risk is calculated with equation 3.3. The direct and indirect cost and risk due to landslides in this location are summarised in Table 3.3. The low values of direct and indirect risk are coherent with the lack of information about landslides affecting this road and producing traffic disruption, despite the traffic signal on site.

The annual risk appears low because the annual hazard is low. This low value is attributable to the lack of reported landslides on this road. As in the flood exercise, the landslide costs obtained, and thus the landslide risk, are subject to uncertainties related to the estimation of the landslide hazard and the cost:

- The landslide hazard:
  - Limitations of the landslide susceptibility (failure and runout) (e.g. the DEM).

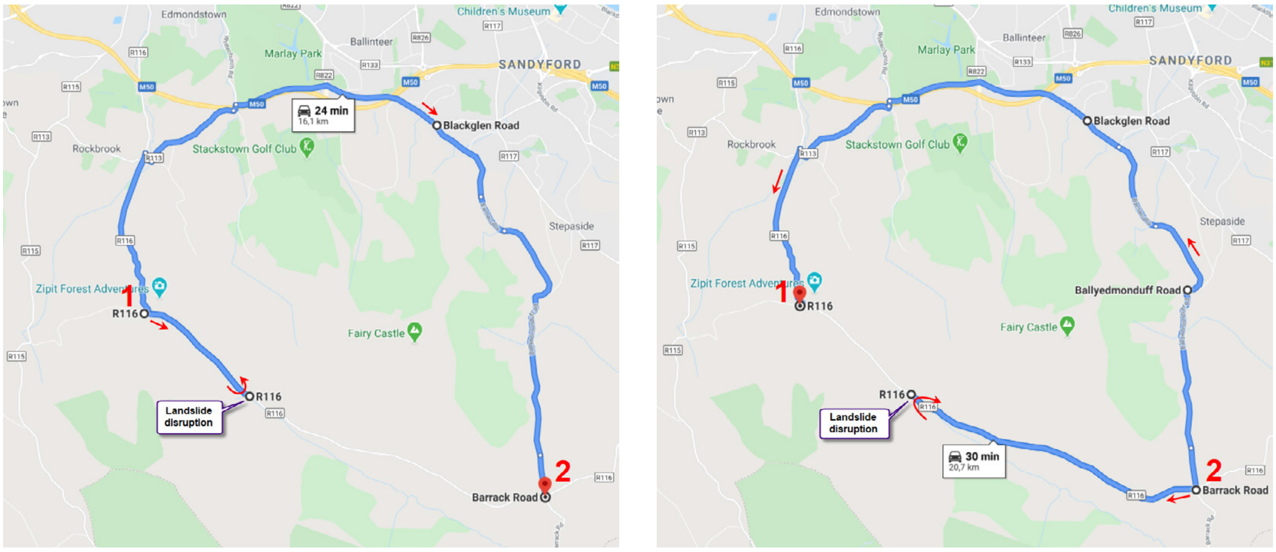


Figure 3.7. Landslide disruption and alternative route to travel from point 1 to point 2 and vice versa (Google Maps).

Table 3.3. Summary of the cost and risk due to landslides on the R116 road. Monetary values relative to 2020

	Present (2020)		Future (2034) climate change	
Cost	Cost (€)	Risk (probability)	Cost (€)	Risk (probability)
Direct	7273/pixel/year	27.5/year (3 km)	10,124/pixel/year	38.13/year (3 km)
Indirect	25,354 (2-day disruption event)	338/year	35,293 (2-day disruption event)	468/year

- – Limitations of the temporal probability (e.g. lack of aerial/satellite imagery in certain periods, inaccurate delineation of landslide polygons).
- – Limitations in the magnitude probability (e.g. underestimated probability for small landslides as many of these are re-vegetated in a time interval that is typically shorter than the time interval of the available aerial/satellite imagery).
- – Limitations of the climate change projections and how these were included in the landslide hazard map.
- The cost:
  - – The direct cost of landslides can vary significantly if stabilisation designs and works are carried out.
  - – The duration of the blockage of the road might be longer than 2 days if the clearance works reactivates the landslide.
  - – The number of vehicles affected might be significantly different if the landslide occurs in working days or during weekends.
  - – The inflation rate might not necessarily be a steady 2.8% per annum.

3.3 Financial Benefit of Adaptation Plans

Experience has shown that the repairs following EWEs can be very costly (DTTAS, 2017). This is one of the reasons why adaptation plans and mitigating measures are of high importance. However, implementing an adaptation strategy can be expensive, and is viable only if the net benefit of adapation is positive (cost of climate change without adaptation > cost of adaptation + residual cost of climate change; see Figure 3.8). Performing QRAs for scenarios with and without adaptation measures can help assess the viability of an adaptation strategy.

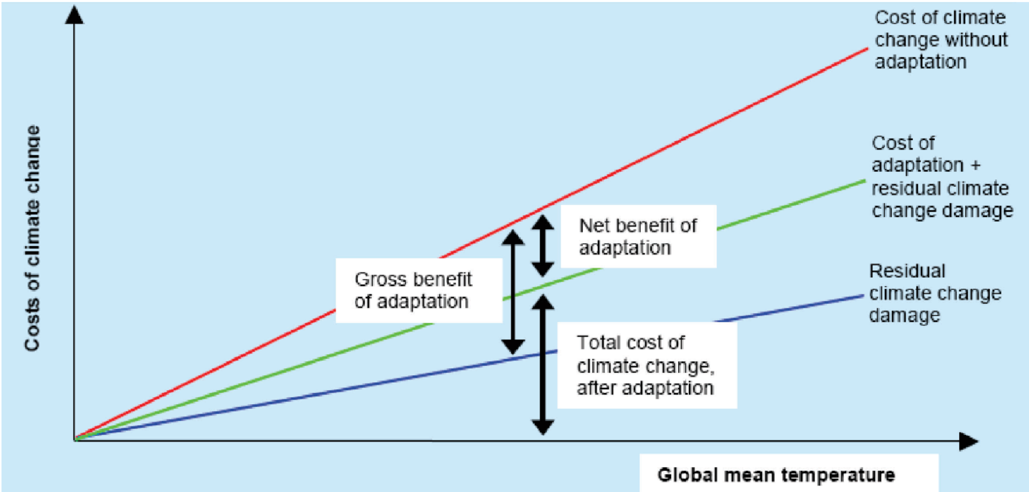


Figure 3.8. Net benefit of adaptation. Source: Stern, 2007. Reproduced with permission of Cambridge University Press through PLSclear.

3.3.1 Discount rates

When assessing the value of the benefit of a potential adaptation solution, the cost savings as a result of avoiding/eliminating a certain hazard need to be determined. However, as these anticipated cost savings occur in the future, there is a need to be able to compare them at any given point in time. For example, a benefit in 10 years' time is valued less than a comparable benefit in today's money, which in economics can be accounted for through the application of a discount rate. Discount rates can help assess the difference between the cost of an investment made today and the anticipated future benefits that accrue as a result of the intervention. This methodology can also be employed for assessing investments in the future and their benefits further down the line.

There is widespread debate surrounding the selection of discount rates, as the chosen rate will greatly affect how we account for future climate effects (Almansa Saez and Calatrava Requena, 2007; IPCC, 2014). For instance, Larsen *et al*. (2008) employed a 7.25% nominal or 2.85% real discount rate in their analysis. However, Neumann *et al*. (2015) used a 3% discount rate and Stern (2007) used an even lower value of 1.4%. The UK and France implement a declining discount rate where all benefits and costs in a given year are discounted at the same rate but the rate decreases over time (Arrow *et al*., 2013). According to a paper from the Irish Department of Public Expenditure and Reform (O'Callaghan and Prior, 2018), a discount rate of 4% should be used across all sectors in Ireland and declining discount rates should be applied to projects with extended time horizons.

As can be seen when comparing the different references, there is a wide range of opinions on what discount rate to apply when it comes to issues of climate change. Discount rates depend largely on the security of the capital, interest rate and risk of the project; however, there is also an ethical component, as the discount rate reflects how society values current welfare against future welfare (O'Mahony, 2018). A high discount rate may prevent socially desirable projects from coming to fruition as their benefit is over-discounted and thus undervalued in present terms. A null discount rate, on the other hand, places equal value on future and present, but may allow for economically inefficient solutions.

It may be argued that adaptation measures for climate change should be treated with a significantly lower discount rate than other investments, as the benefits of the intervention are unlikely to decrease and lose their value over time. In addition, the social benefit for future generations should not be underestimated. This is especially true for transport networks and infrastructure, which often have a long lifespan and play a vital role in the everyday life of most people in Ireland. For this reason as well as the support in literature for low or null discount rates for effects of climate change (Kolstad *et al*., 2014; O'Mahony, 2018), a 0% discount rate was applied to the calculations presented in sections 3.2.1 and 3.2.2.

3.4 QRA as a Method for Costing Climate Adaptation

The estimation of the costs of climate change in terms of economic, societal and environmental impacts is a key step for the climate change risk assessment and for the implementation of climate change adaptation plans. The quantitative assessment of the other risk components (hazard, exposure and vulnerability) is also very important.

Two exercises using empirical determinations of cost including the contribution of climate change for two types of climate change-related hazards were carried out: one for river flooding and another for rainfall-induced landslides. The quantitative assessment of the hazard is the most difficult and time-consuming task in a QRA.

The examples demonstrated that QRA can be used to provide likely estimates of the direct and indirect cost and risk of climate change on the transport network. However, QRAs are subject to a cascade of uncertainties derived from:

- the quality of the input data (e.g. spatial resolution of the DEM, gauge-log with gaps, uncertainties of the climate change model) and the adopted required assumptions to overcome:
  - lack of data (e.g. flood event of 9 hours with asymmetrical Gaussian distribution); or
  - availability of different input data (scenarios); and
- the method used to calculate each risk component (susceptibility, magnitude, intensity, temporal probability, exposure and vulnerability, as well as the direct and indirect costs).

There is no "best method" to assess cost and risk. The optimal method is the one that copes best with the uncertainties associated with the availability and the quality of information, and the scale of work. Taking into account that the scale of most of the input data is typically regional and that detailed input data required for complex physically based methods are often not available, and both expensive and time-consuming to obtain, empirical methods (as used in this project for flooding and landslides) are deemed to be best placed for the objective quantification of cost and risk.

Hazard assessment (i.e. the calculation of the susceptibility, magnitude, intensity, temporal probability) is the most difficult and time-consuming task in a QRA, and the cost or economic losses are strongly controlled by the spatial distribution, magnitude, intensity and frequency of the hazard. Very few hazard maps are available for Ireland at regional to local scale. Therefore, resources should be invested in mapping out and quantifying climate change-related hazards due to increased rainfall, extreme windspeeds and higher temperatures. This task would imply both the creation and the update of existing hazard maps at regional to local scale, ensuring the inclusion of contributions from climate change projections. These new and updated multi-hazard maps would provide valuable input to ensure the provision and implementation of optimised multi-criteria adaptation plans with a reduced degree of uncertainty. The uncertainty can also be reduced by carrying out additional cost determinations at different sites of the transport network. Considering that exposure plays a key role with regard to assessing direct cost, but is irrelevant when determining indirect or macro-economic cost, the recommended areas for additional cost determinations are main transport routes with high values of exposure, areas of low or null exposure but with important economic activity in the surroundings and areas of poor/low density transport network (traffic disruptions leading to long alternative routes).

In this project, only two QRAs, one for flash flooding and one for landslides, were undertaken to demonstrate the methodology on how to carry out QRAs. Given the associated and inherent uncertainty, one QRA is insufficient to provide reliable input into adaptation planning. A suite of likely QRAs should be carried out to examine the effect of additional scenarios and small variations in assumptions. Each QRA would be obtained by:

- adjusting inputs (e.g. hydrograph, inflation rate, slope stabilisation works included in the cost); or even
- applying different methods for obtaining the risk components.

The suite of QRAs would probably exhibit high dispersion (i.e. QRAs with different results). Therefore, uncertainty must be considered and quantified in order to make sustainable decisions about the future.

4 Decision-making under Uncertainty

One of the challenges surrounding adaptation planning in the context of climate change is the inherent uncertainty about the future. Firstly, this relates to the speed and direction of climate change. Although data already exist in vast numbers and continue to be collected, predicting the future is inherently uncertain. In addition, experts often disagree on how the data should be interpreted (Hallegatte, 2009). Secondly, and perhaps more importantly, there is significant uncertainty related to human actions and technological advances for the future. Societies' ability and willingness to limit emissions and fund mitigating technologies will determine the direction of the future climate and are impossible to accurately predict. Thirdly, there is often uncertainty around what information and data are available, which adaptation measures are possible and preferable, and how best to approach finding the optimal solution.

4.1 Participatory Methods

The first two types of uncertainties are highly complex and must be left to scientists and experts in their field. The third type, however, can be addressed by engaging relevant parties through participatory methods. Participatory methods cover a range of approaches to decision-making but generally involve experts, scientists and/or users providing input for the policymakers and stakeholders to consider when deciding on adaptation options. Combining the most recent science and expert information with first-hand policymaking experience has been demonstrated to lead to better assessments (Hanski *et al*., 2018; Toth and Hizsnyik, 2018).

One participatory method is participatory scenario development (PSD). In this approach, a variety of stakeholders discuss preferred future actions based on a given future scenario as developed by experts, such as the IPCC. This process utilises the stakeholders' different experiences, views and resources to map out the potential issues and solutions for adaptation (Bizikova *et al*., 2014). This approach was employed during workshops held by Gavin and Doherty Geosolutions (GDG) and the EPA, where participating stakeholders were asked to consider adaptation options in regions of Ireland under certain future climate scenarios.

4.1.1 Stakeholder engagement and feedback

In an effort to shed some light on the areas in which adaptation planning for the Irish transport sector can improve, GDG and the EPA held two workshops in October and December 2019, respectively. The aim was to gather input from a variety of stakeholders in relation to climate change impacts on and opportunities for the transport networks in Ireland, specifically road, rail and maritime networks. The participants comprised representatives from local county councils, national infrastructure owners, representatives from DTTAS, climatologists, legal professionals, researchers and representatives from the CAROs.

It is important to note that the opinions and beliefs expressed are those of the participants and have been reproduced as a true record of the discussions that took place at the workshops. These opinions repeated below are taken as said and convey the participants' current perceptions of the situation. They do not necessarily reflect the actual state of things.

The format of the first workshop was PSD: the participants were split into four groups and each group was presented with a climate hazard scenario for a specific region in Ireland. The groups then answered questions under the following headings (see Appendix 2 for example questionnaire and answers):

- hazard assessment;
- exposure/vulnerability analysis;
- consequence analysis;
- adaptation planning.

The second workshop took the form of a small focus group to facilitate an interactive discussion regarding some of the key challenges facing the transport sector in Ireland in terms of climate change adaptation. This included current limitations to the implementation of adaptation and how to overcome these in the future.

The responses from the participants point to four main points, indicating that the transport sector in Ireland has a need for:

1. more/higher quality data collection;
2. better use of collected data;
3. improved sharing of the data across sectors and regions;
4. improved approach to climate change adaptation planning.

For example, the flood impact datasets from OPW were considered good but lacking in detail at regional and local level, and a lack of data from flood plains was mentioned. Datasets from Ireland relating to sea level rise were also considered unreliable, and information on coastal erosion and its effect on infrastructure networks is currently missing and not being addressed on a larger scale. Lack of available data and models makes it difficult to justify investment in adaptation planning.

In some sectors the data are available but are not put to optimal use. Inconsistency in terminology, units and approaches make the data hard to use in a unified way, and a national standardised approach to data gathering was suggested as a solution. National co-ordination with international data was also mentioned as a useful step, such as aligning OPW flood maps with IPCC climate hazard scenarios. Several participants seemed unaware of the recently published local adaptation strategies, as they noted that local county councils have an “emergency response plan” but that these are not currently linked to climate change impacts, preventing adaptation planning from being a natural part of regional development. This implies that although the information is available it has not currently reached all the necessary stakeholders.

A recurring opinion voiced by the participants was the need for sharing data between sectors and across regions, as bigger datasets drastically improve the quality and may help local and national decision-making. In recent years, several measures such as forming the CAROs and the development of online resources such as Climate Ireland (www.climateireland.ie) have started to make these changes happen. Fully implementing and making the best possible use of these resources will take time and effort. An important step in this process is to educate stakeholders on the existence and use of such resources.

The participants agreed that climate change adaptation planning in Ireland needs a bigger voice and an improved, unified approach. A cross-sectoral and multi-agency approach with longer timespans was suggested as a solution, which would have to be co-ordinated and enforced at the national level. It was acknowledged that there is good progress being made in Ireland in terms of climate change adaptation planning for infrastructure networks, but perhaps this is not being effectively communicated. The CAROs and the 2019 Climate Change Sectoral Adaptation Plan for the transport sector are important steps in this direction; however, continuous evaluation of the process and education of relevant users is vital. Another suggestion of a way of enforcing and encouraging national co-ordination was to hold an annual national conference dedicated to this cause.

4.2 Evaluation Methods

In order to assess the effect of various adaptation measures, different methods can be used. This comparison will enable the user to make informed decisions. A possible way of comparing the effects is in monetary terms, as any adaptation must be justified by the cost of the adaptation being less than the consequences of doing nothing. These effects might be measured simply as economic gain or loss, or more complex impacts on society and the environment. Several methods exist for the evaluation of adaptation measures, such as cost–benefit analysis (CBA), cost-effectiveness analysis (CEA) and multi-criteria analysis (MCA) (Bullock *et al.*, 2015).

4.2.1 Cost–benefit analysis

A CBA includes, as the name implies, a systematic cataloguing of benefits and costs, valued in monetary units and calculating the net benefit of a proposed measure. A good CBA considers all costs and all benefits to society, not just individuals, and, as such, “CBA is a policy assessment method that quantifies in monetary terms the value of all consequences of a policy to all members of society” (Beardman, 2017). When it comes to assessing climate risk and adaptation measures, CBA is challenging owing to the inherent uncertainty when predicting future impacts.

Despite the challenge of uncertainty, CBA is a useful tool. It converts non-market costs and benefits into monetary units, which allows them to be fully represented in the decision-making process and makes direct comparison between policies possible.

4.2.2 Cost-effective analysis

A CEA is used to identify the least-cost option for achieving a specific objective. As with CBA, it examines the trade-offs between costs and benefits; however, benefits are measured in relative physical units rather than money (Bullock *et al*., 2015). Therefore, solutions can be compared on their cost-effectiveness, i.e. the amount of benefit relative to cost. Given the physical nature of the benefits, CEAs are best used within a specific sector where direct comparison of benefits is possible.

4.2.3 Multi-criteria analysis

An MCA, or multi-criteria decision analysis, can be applied in more complex decision-making scenarios where a stakeholder might have conflicting objectives, or benefits cannot easily be traded off against monetary variables (Bullock *et al*., 2015; Hanski *et al*., 2018). MCA is highly flexible; it allows for the comparison of both qualitative and quantitative variables in different units by scoring and weighing them based on expected performance/consequences and their relative importance and desirability. In addition, MCA allows criteria to be clustered for comparison at different stages, and uncertainties can be explored through sensitivity analyses by varying their weight. In the end, each policy or measure option is given a weighted total score, allowing for easy comparison of the outcome.

4.2.4 Comparison and limitations

Although useful tools, there are shortcomings and limitations to the above methods (see Table 4.1). One challenge is the prediction of variables and their values for the future, as this is near impossible to accomplish with accuracy. This is especially true with relation to climate change, as there are several complex aspects to this uncertainty. As the evaluation methods rely on the value (monetary or otherwise) of the variables, significant error in their estimation may affect the outcome of the analysis. It was also noted in the IPCC's report (2014) that adaptation planning based on tools such as CBA can skew the adaptation evaluation process by discounting future economic

Table 4.1. Summary of evaluation methods with pros, cons and application suitability

	CBA	CEA	MCA
Decision criterion	• Monetary value of all consequences of a policy to all members of society	• Is the least-cost option	• Complex scenarios with multiple (even conflicting) objectives
Pros	• Well-defined framework based on aggregating costs and benefits • Compares and prioritises options based on net monetised benefits	• Costs are easily compared • Intangible benefits (e.g. loss of life) do not need to be monetised	• Enables stakeholder participation • Allows for multiple solutions • Impact assessments retain close links to natural units • Integrates objective measurement with subjective values
Cons	• All costs and benefits have to be monetised and aggregated • Plural values are difficult to represent • Uncertainty is not taken into account • Assumes "marginal" changes	• Only a single solution is produced • Uncertainty is typically not taken into account	• Subjective judgments may be difficult in practice • Multiple solutions may hamper the consensus • Facilitation is required for stakeholder engagement
Typical usage	• Specific interventions with a measurable price for benefits and costs	• Specific interventions with important non-monetary targets	• Multiple interventions involving a range of values derived from participatory processes (e.g. workshops)

Based on Scrieciu *et al.* (2014).

benefits or excluding non-market benefits (human health, biodiversity, quality of life, etc.).

It is also important to note that the role of these economic evaluation methods is to provide decision-makers with information on the impacts of alternative adaptation actions, not to provide a final ranking (IPCC, 2014). None of the methods should be used as a stand-alone solution applied to a specific climate projection, but rather they should be part of a larger approach and be applied to multiple scenarios for comparison and evaluation. Involving stakeholders and decision-makers to frame and value the variables through participatory methods can often be a good approach.

4.3 Decision-making Methods

With the cost and benefit evaluation tools available and feedback from stakeholders taken into account, the next steps are to decide which adaptation measures to adopt and how. However, uncertainties surrounding future climate are still present and cannot be ignored. Therefore, adaptation planning should adopt a decision-making framework that considers uncertainty.

4.3.1 Robust Decision Making

One such framework is Robust Decision Making (RDM), which aims to determine suitable adaptation solutions that are insensitive to uncertainty (Daron, 2014). RDM is an approach that aims to identify the full range of plausible future states and provide a solution that is acceptable and sufficient for as wide a range of the states as possible (Scrieciu *et al.*, 2014). It provides an analytical approach to decision-making for situations characterised by high uncertainty, which is often the case in climate change adaptability. Robust strategies perform well over a range of probability-based scenarios including low-frequency/high-impact events (Wilby and Dessai, 2010) but are likely to provide satisfactory outputs rather than optimum results.

The RDM process is multi-step and iterative, identifying potentially robust alternatives that perform well in many plausible future scenarios. The conditions where the potential solutions perform poorly are identified in a process called scenario discovery.

Stéphane Hallegatte (2009) suggested five strategies within the RDM framework:

1. No-regret strategies that yield benefits even in the absence of climate change.
2. Reversible strategies that are reversible and flexible in order to save cost should the initial assumptions of climate change effects turn out to be inaccurate.
3. Safety margin strategies that reduce the vulnerability of a project to zero or low cost by overestimating safety margins.
4. Soft strategies that involve institutional or financial tools rather than technical and physical solutions. This may force planners to think further ahead than they otherwise would and consider future scenarios they otherwise would choose to overlook.
5. Strategies that reduce decision-making time horizons. Uncertainty regarding climate change increases drastically with time, hence decreasing the timeframe/lifespan of a project reduces uncertainty and may help decision-making.

These strategies, as well as the general RDM framework, are hugely helpful when facing the challenge of adaptation planning. Implementing solutions that follow one or more of these guidelines may make the justification and therefore funding process easier, as they do not rely on accurate predictions of the future climate in order to be advantageous.

4.3.2 Dynamic Adaptation Policy Pathways

Dynamic Adaptation Policy Pathways (DAPP) is a decision-making approach where short-term actions are implemented with a long-term goal in mind. Tipping points and necessary actions are identified from the beginning, and monitoring of the system alerts when a tipping point is reached and new action is required.

This approach to adaptation includes:

- transient scenarios that represent relevant uncertainties and how they develop over time;
- different actions to handle vulnerabilities and take advantage of opportunities;

- adaptation pathways describing a sequence of preferable actions and a monitoring system to keep the plan on track.

The complex process is detailed in Haasnoot *et al*. (2013), but in short it is a reactive plan for the future, where possible and uncertain changes and their necessary responses are accounted for.

4.3.3 Adaptive management

An adaptive management (AM) approach is a way to manage resources that will change over time. Similarly to DAPP, the actions are monitored and adjusted as necessary; however, this is done on a "learn as you go" basis rather than being planned out from the beginning. Policies must be made in the present, based on current knowledge and predictions, but must also be flexible to adaptation for future conditions (Hamilton *et al*., 2013). Therefore, during the planning stages of the project, management objectives are identified to act as steering principles throughout the project. In later stages, the project will be monitored and adjusted to comply with these objectives as variables change. The objectives themselves should regularly be revisited and revised as needed (Wood *et al*., 2017).

4.4 Minimising the Effect of Uncertainty

Climate change is happening and the impacts can already be seen around the world. Science has provided possible future projections, but the future is still uncertain. Making economically justifiable decisions without knowing what the future holds is a challenge. However, there are tools and frameworks that are useful and that can and should be put to use for the Irish transport network. Stakeholders and other relevant parties should be included through participatory methods to ensure, as far as possible, a solution that caters for a wide range of interest, as different knowledge, experience and points of view are considered. In this project, this was done through group discussions and PSD.

Evaluation methods such as CBA, CEA and MCA can be applied to evaluate the cost and benefit of implementing an adaptation plan versus doing nothing. There is no definite best method and the choice of method depends on available information and the nature of the problem to be evaluated. It is important to remember that these techniques are meant to inform decision-makers of the benefits and costs of a situation or adaptation plan. They cannot replace the political process of considering acceptable risk and deciding on the best course of action on a complex socio-economic level.

RDM is a framework that can help to make robust decisions that are cost-effective, flexible and beneficial for a wide range of future scenarios. This approach may not always be ideal, and a more focused but adaptable approach such as DAPP and AM may be adopted. These methods are often complementary, and choice of method(s) relies on the quality and quantity of available information.

5 Conclusions and Recommendations

Climate change is likely to lead to stronger, more frequent storms and heavier rainfall in Ireland in the future. Previous experiences have shown that the costs associated with repairs following severe storm events can be significant, such as the €225 million bill after historically heavy rainfall in 2009, the €106 million required for repairs after storms in the winter of 2015/2016 and the €26.6 million worth of direct damages following a storm in December 2013. The implementation of adaptation measures is likely to lower the future cost of climate change; however, to assess their economic feasibility the potential cost of climate change must be estimated and compared with the price of adaptation.

One method for evaluating the cost of climate change is the QRA, which was applied to two types of climate-related hazards in this study: river flooding and rainfall-induced landslides. These studies showed that QRA can be applied to different climate-related hazards and provide likely estimates of cost and risk for the transport network. However, QRA is not without its weaknesses, and the output is only as good as the input data and choice of risk component calculation method.

The most challenging and time-consuming task of a QRA is the assessment of the hazard, whose spatial distribution, frequency, magnitude and intensity will greatly affect the estimated cost and/or economic losses. Few hazard maps are currently available at regional to local scale in Ireland, and resources should be invested in mapping and quantifying climate-related hazards. Multi-hazard maps with up-to-date information could provide a tool for optimised multi-criteria adaptation plans with a reduced degree of uncertainty. The uncertainty can also be reduced by carrying out several likely QRAs with adjustments to inputs.

The collection of data and research funding will be useful only if the results are made available and shared and their existence is known across sectors and regions of Ireland. The stakeholder workshops revealed a lack of data in certain areas, but also a lack of awareness of the information and systems that are already in place. The workshops resulted in the following recommendations:

- Fund data collection where needed (regional/local rainfall data, coastal processes on a national level, wind speeds, etc.).
- Create a standardised approach to data gathering.
- Continue to develop the adaptation planning approach on national through to local level.
- Consider organising an annual national conference dedicated to climate change adaptation planning on all levels.
- A dedicated advertisement campaign is needed to raise awareness and promote the use of tools and resources already in existence among relevant personnel in the transport sector and regional councils. It is vital to achieve a common denominator of being able to assume that everyone knows where and how to save, store and access relevant data.

Many resources relevant to climate change and adaptation are readily and freely available in Ireland already. However, the workshops showed that this was not common knowledge among the stakeholders, suggesting that the information is not reaching the target audience. A holistic approach is needed to ensure that the available knowledge is suitably shared among all stakeholders. A co-operative approach among various departments is deemed most beneficial, as this will enable a collective effort rather than a disjointed or fragmented one to tackle the impact of climate change successfully.

Climate change is happening, and current effects as well as future projections need to be further addressed. Frameworks for making decisions under uncertainties exist and allow for adaptation planning that can be cost-effective, flexible and beneficial for a wide range of future scenarios. Not having all the facts and knowing that the future is uncertain cannot therefore be an excuse to postpone action. Instead, active knowledge management, i.e. the gathering, sharing and maintenance of data, and its application, is key.

References

AECOM, 2010. *Coastal Inundation at Narrabeen Lagoon – Optimising Adaptation Investment*. Department of Climate Change and Energy Efficiency, Canberra, Australia.

Almansa Saez, C. and Calatrava Requena, J., 2007. Reconciling sustainability and discounting in cost–benefit analysis: a methodological proposal. *Ecological Economics* 60: 712–725.

Arrow, K., Cropper, M., Gollier, C., *et al*., 2013. Determining benefits and costs for future generations. *Science* 341: 349–350.

Beardman, A.E., 2017. *Cost–benefit Analysis: Concepts and Practice*. Fourth edition. Cambridge University Press, Cambridge, UK.

Bizikova, L., Rothman, D.S., Boardley, S., Mead, S. and Kuriakose, A.T., 2014. *Participatory Scenario Development and Future Visioning in Adaptation Planning: Lessons from Experience. Part I*. International Institute for Sustainable Development, Winnipeg, Canada.

Bles, T., Enneser, Y., Fadeuilhe, J.-J., Falemo, S., Lind, B., Mens, M., Ray, M. and Sandersen, F., 2010. *Risk Management for Roads in a Changing Climate: A Guidebook to the RIMAROCC Method*. ERA-NET ROAD. Available online: https://trimis.ec.europa.eu/sites/default/files/project/documents/01_Rimarocc%20Guidebook.pdf (accessed 26 August 2020).

Browne, D., Caulfield, B. and O'Mahony, M., 2011. *EPA Climate Change Research Programme 2007–2013: Barriers to Sustainable Transport in Ireland*. Environmental Protection Agency, Johnstown Castle, Ireland.

Bullock, C., Fealy, R., Clinch, J.P. and O'Shea, R., 2015. *ADAPT: Quantifying the Costs and Benefits Associated with Climate Change Risks and Adaptation*. Environmental Protection Agency, Johnstown Castle, Ireland.

Carney, M., 2018. *A Transition in Thinking and Action.* Speech at the International Climate Risk Conference for Supervisors, Amsterdam, 6 April 2018.

Clarke, J. and Acosta, E., 2019. Determining the cost of extreme flood events to the road network in Ireland: an example application. Paper presented at the European Transport Conference, Dublin, 10 October 2019.

Corominas, J. and Mavrouli, J., 2011. *Living with Landslide Risk in Europe: Assessment, Effects of Global Change, and Risk Management Strategies*. Safeland. 7th Framework Programme Cooperation Theme, 6. Available online: https://cordis.europa.eu/project/id/226479 (accessed 26 August 2020).

Daron, J.D., 2014. Challenges in using a Robust Decision Making approach to guide climate change adaptation in South Africa. *Climate Change* 132(2): 459–473.

DCCAE (Department of Communications, Climate Action and Environment), 2018a. *National Adaptation Framework: Planning for a Climate Resilient Ireland*. DCCAE, Dublin.

DCCAE (Department of Communications, Climate Action and Environment), 2018b. *Local Authority Adaptation Strategy Development Guidelines*. DCCAE, Dublin.

de Bruin, K., Dellink, R.B., Ruijs, A., *et al*., 2009. Adapting to climate change in the Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Climatic Change* 95: 23–45.

DTTAS (Department of Transport, Tourism and Sport), 2017. *Adaptation Planning: Developing Resilience to Climate Change in the Irish Transport Sector*. DTTAS, Dublin.

DTTAS (Department of Transport, Tourism and Sport), 2019. *Transport – Climate Change Sectoral Adaptation Plan*. Government of Ireland, Dublin.

Dunne, S., Hanafin, J., Kynch, P., McGrath, R., Nishimura, E., Nolan, P., Ratnam, J.V., Semmler, T., Sweeney, C. and Wang, S., 2008. *Ireland in a Warmer World: Scientific Predictions of the Irish Climate in the Twenty-first Century.* Community Climate Change Consortium for Ireland. Available online: https://maths.ucd.ie/~plynch/Publications/Ireland_in_a_Warmer_World.pdf (accessed 14 July 2020).

EC (European Commission), 2013. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: "An EU Strategy on Adaptation to Climate Change". COM(2013) 216 final, 16.04.2013, Brussels.

Fealy, R., Bruyére, C. and Duffy, C., 2018. *Regional Climate Model Simulations for Ireland for the 21st Century*. Environmental Protection Agency, Johnstown Castle, Ireland.

Fisk, G.W., 2017. *Climate Risks and Adaptation Pathways for Coastal Transport Infrastructure. Guidelines For Planning And Adaptive Responses*. National Climate Change Adaptation Research Facility, Gold Coast, Australia.

GSI (Geological Survey Ireland), 2016. *Geohazards: Landslides Susceptibility Mapping.* Available online: https://www.gsi.ie/en-ie/data-and-maps/Pages/Geohazards.aspx (accessed 24 April 2020).

GSI (Geological Survey of Ireland), 2020. *Open Topographic Lidar Data.* Data.gov.ie. Available online: https://data.gov.ie/dataset/open-topographic-lidar-data (accessed 15 April 2020).

Haasnoot, M., Kwakkel, J.H., Walker, W.E. and ter Maat, J., 2013. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeeply uncertain world. *Global Environmental Change* 23: 485–498.

Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. *Global Environmental Change* 19: 240–247.

Hamilton, M., Thekdi, S., Jenicek, E., Harmon, R., Goodsite, M., Case, M., Karvetski, C. and Lambert, J., 2013. Case studies of scenario analaysis for adaptive management of natural resource and infrastructure systems. *Environmental Systems & Decisions* 33: 89–103.

Hanski, J., Jaana, K. and Molarius, R., 2018. Tools and methods for supporting regional decision-making in relation to climate risks. In Amini, A. (ed), *Climate Change and Global Warming*. IntechOpen, London, pp. 25–42.

Hausfather, Z., 2018. Explainer: How 'shared socioeconomic pathways' explore future climate change. *CarbonBrief*. Available online: https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change (accessed 27 April 2020).

Hearn, G., Hunt, T., Aubert, J., Howell, J. and Chigira, M., 2008. Landslide impacts on the road network of Lao PDR and the feasibility of implementing a slope management programme. Paper presented at the International Conference on Management of Landslide Hazard in the Asia-Pacific Region, Sendai, Japan.

Hicks, D.L., 1995. A way to estimate the frequency of rainfall-induced mass movements. *Journal of Hydrology (New Zealand)*: 59–67.

IPCC (Intergovernmental Panel on Climate Change), 2012. *Managing the risks of extreme events and disasters to advance climate change adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Field, C.B., V. Barros, T.F., Stocker, D., *et al*. (eds). Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change), 2013. *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change), 2014. *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J.C., Mechler, R., Wouter Botzen, W.J., Bouwer, L.M., Pflug, G., Rojas, R. and Ward, P.J., 2014. Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change* 4: 264–268.

Kolstad, C., Urama, K., Broome, J., *et al*., 2014. Social, economic and ethical concepts and methods. In Edenhofer, O., Pichs-Madruga, R., Sokona, Y., *et al*. (eds), *Climate Change 2014: Mitigation of Climate Change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Kwiatkowski, K.P., Stipanovic Oslakovic, I., ter Maat, H.W., Hartmann, A., Chinowsky, P. and Dewulf, G., 2013. Climate change adaptation and roads: Dutch case study of costs impacts at the organisational level. Paper presented at the Engineering Project Organization Conference, Tabernash, CO, July 2013.

Larsen, P.H., Goldsmith, S., Smith, O., Wilson, M.L., Strzepek, K., Chinowsky, P. and Saylor, B., 2008. Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change* 18(3): 442–457.

Malamud, B.D., Turcotte, D.L., Guzzetti, F. and Reichenbach, P., 2004. Landslide inventories and their statistical properties. *Earth Surface Processes and Landforms* 29(6): 687–711.

Melvin, A.M., Larsen, P., Boehlert, B., *et al*., 2017. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the Academy of Sciences of the United States of America* 114: E122–E131.

Moretti, L. and Loprencipe, G., 2018. Climate change and transport infrastructures: state of the art. *Sustainability* 10: 4098.

Neumann, J.E., Price, J., Chinowsky, P., *et al*., 2015. Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climate Change* 131: 97–109.

Nolan, P., 2015. *Ensemble of Regional Climate Model Projections for Ireland*. Environmental Protection Agency, Johnstown Castle, Ireland.

O'Callaghan, D. and Prior, S., 2018. *Central Technical Appraisals Parameters: Discount Rate, Time Horizon, Shadow Price of Public Funds and Shadow Price of Labour*. Irish Government Economic & Evaluation Service. Department of Public Expenditure & Reform, Dublin.

OECD (Organisation for Economic Co-operation and Development), 2018. *Resilient Infrastructure for a Changing Climate. Input Document for the G20 Climate Sustainability Working Group*. Available online: http://www.g20.utoronto.ca/2018/oecd_-_resilient_infrastructure_for_a_changing_climate.pdf (accessed 26 August 2020).

O'Mahony, T., 2018. *Appraisal in Transition: 21st Century Challenges and Updating Cost–benefit Analysis in Ireland*. Available online: https://www.researchgate.net/profile/Tadhg_Omahony2/publication/328383318_Appraisal_in_transition_21st_century_challenges_and_updating_Cost-Benefit_Analysis_in_Ireland/links/5bc9c4a2299bf17a1c5ff036/Appraisal-in-transition-21st-century-challenges-and-upda (accessed 1 July 2020).

OPW (Office of Public Works), 2019. *Flood Risk Management: Climate Change Sectoral Adaptation Plan*. Government of Ireland, Dublin.

Penning-Rowsell, E., Johnson, C., Tunstall, S., Tapsell, S., Morris, J., Chatterton, J. and Green, C., 2005. *The Benefits of Flood and Coastal Risk Management: A Handbook of Assessment Techniques.* Middlesex University Press, London.

Pregnolato, M., Ford, A., Wilkinson, S.M. and Dawson, R.J., 2017. The impact of flooding on road transport: a depth-disruption function. *Transportation Research Part D: Transport and Environment* 55: 67–81.

Remondo, J., Bonachea, J. and Cendrero, A., 2005. A statistical approach to landslide risk modelling at basin scale: from landslide susceptibility to quantitative risk assessment. *Landslides* 2(4): 321–328.

Scrieciu, S.S., Belton, V., Chalabi, Z., Mechler, R. and Puig, D., 2014. Advancing methodological thinking and practice for development-compatible climate policy planning. *Mitigation and Adaptation Strategies for Global Change* 19(3): 261–288.

Stern, N., 2007. *The Economics of Climate Change: The Stern Review*. Cambridge University Press, New York, NY.

TII (Transport Infrastructure Ireland), 2020. TII traffic data site. Available online: https://www.nratrafficdata.ie/c2/gmapbasic.asp?sgid=ZvyVmXU8jBt9PJE$c7UXt6 (accessed 20 April 2020).

Toth, F.L. and Hizsnyik, E., 2018. Managing the inconceivable: participatory assessment of impacts and responses to extreme climate change. *Climatic Change* 91(1–2): 81–101.

Wang, S., McGrath, R., Hanafin, J., Lynch, P., Semmler, T. and Nolan, P., 2008. The impact of climate change on storm surges over Irish waters. *Ocean Modelling* 25: 83–94.

Wilby, R.L. and Dessai, S., 2010. Robust adaptation to climate change. *Weather* 65(7): 180–185.

Wood, M.D., Thorne, S., Butte, G., Linkov, I. and Kovacs, D., 2017. Adaptive management for climate change. In *Mental Modeling Approach: Risk Management Application Case Studies*. Springer, New York, NY, pp. 57–67.

Wright, L., Chinowsky, P., Strzepek, K., Jones, R., Streeter, R., Smith, J.B., Mayotte, J.M., Powell, A., Jantarasami, L. and Perkins, W., 2012. Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change* 17: 939–955.

Abbreviations

AADT	Annual average daily traffic
AM	Adaptive management
CARO	Climate Action Regional Office
CBA	Cost–benefit analysis
CEA	Cost-effectiveness analysis
CFRAM	Catchment Flood Risk Assessment and Management
DAPP	Dynamic Adaptation Policy Pathways
DCCAE	Department of Communications, Climate Action and Environment
DEM	Digital Elevation Model
DTTAS	Department of Transport, Tourism and Sport
EPA	Environmental Protection Agency
EU	European Union
EWE	Extreme weather event
GDG	Gavin and Doherty Geosolutions
IPCC	Intergovernmental Panel on Climate Change
MCA	Multi-criteria analysis
NAF	National Adaptation Framework
OPW	Office of Public Works
PSD	Participatory scenario development
QRA	Quantitative risk assessment
RCP	Representative Concentration Pathway
RDM	Robust Decision Making
SSP	Shared Socio-economic Pathway

Appendix 1 Costing Methodologies

Costing methods		Examples	Advantages	Disadvantages
1	Qualitative	Wright *et al*. (2012) predicted the impacts of climate change by estimating increased river flooding, combining climate models with a bridge inventory database.	Simple, not many inputs required.	Subjective and not replicable.
2	Based on empirical data from the impact of past climate-related events	Insurance companies (Jongman *et al*., 2014).	Simple and provides values of both direct and indirect cost.	Cost is generally underestimated owing to lack of insurance coverage or insufficient policy coverage.
		Extra time commuting (DCCAE, 2018b).	Provides values of the macro-economic or indirect cost.	Some assumptions are required, e.g. number of vehicles affected and percentage of heavy goods vehicles.
		Loss of revenue in local business after the hazard event (Hearn *et al*., 2008).	Provides additional values of the macro-economic or indirect cost.	The values provided by the business owners might be skewed.
		Cost of repairs (DTTAS, 2017).	Provides real values of the direct cost.	The cost might vary significantly depending on the contracted company and the quality of the materials used in the repairing works. Moreover, the final value of cost might only be known at the end of the works.
3	Based on future predictions of climate change	Clarke and Acosta (2019) estimated the indirect cost of a hypothetical future 1000-year flooding event under a climate change scenario, disrupting a stretch of the M50 in Dublin for a period of 3 hours, to be €660,000. Kwiatkowski *et al*. (2013) assessed pavement degradation due to climate change contribution on future rainfall and temperature.	Allows for the impact of climate change on the magnitude, intensity and frequency of future hazard events (i.e. higher temperatures, heavier rainfall, more severe storms, more frequent landslides). Therefore, expected future cost can be determined not just as a product of inflation rate, but also as change in hazard.	The accuracy of the four variables of a hazard (extent, magnitude, intensity and frequency) is strongly influenced by the spatial resolution of the data used to compute the hazard (e.g. DEM) and by the availability of information on past hazardous events. Only looking at climate change on its own will not provide a reliable answer. Other effects (e.g. uplift of some parts of Ireland) have to be considered to assess the net impact. The quality of the current correlation between climate and hazard affects the ability to accurately predict the contribution of climate change on future hazards. An inaccurate correlation in present terms may lead to significant under- or overpredictions of future cost. There are different climate change scenarios, which can lead to highly variable cost estimates (estimated flooding costs in Paris ranging from US$3 billion to US$30 billion; OECD, 2018). Therefore, the cost assessments provided by this approach should be considered as a mere indicator for decision-makers and would not be appropriate to provide input into detailed or site-specific planning or design measures.

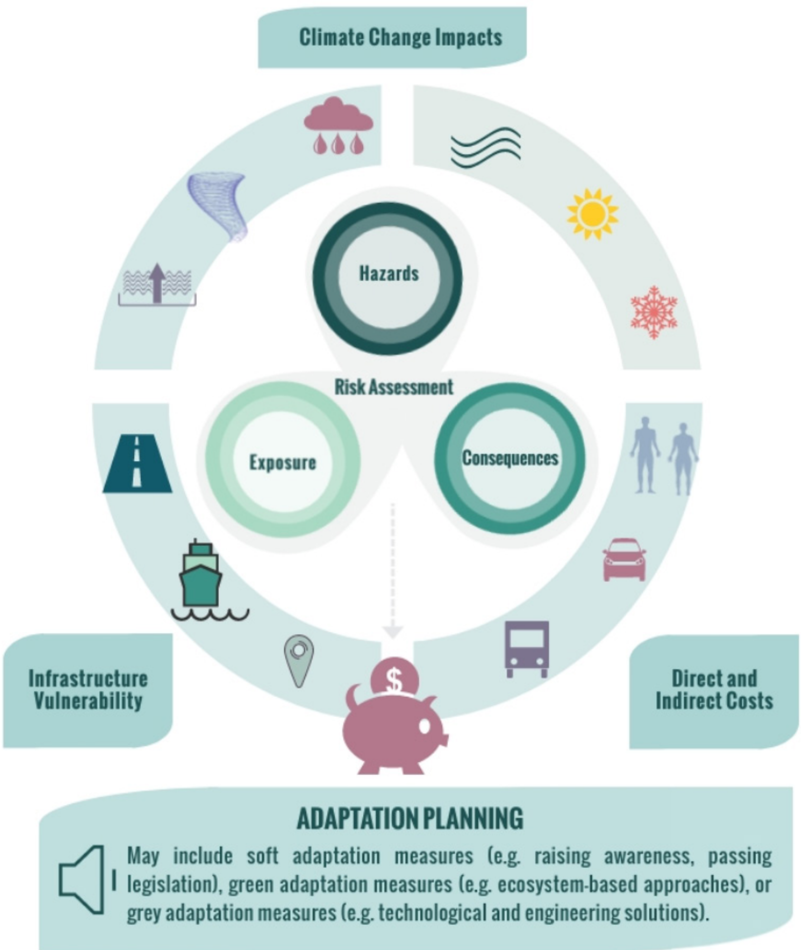
Costing methods		Examples	Advantages	Disadvantages
4	For non-monetised or intangible costs	Bullock *et al*. (2015) outlined a range of methods: *Avoided cost* – the damage that may occur in the absence of an adaptation policy or adaptation measures. *Production function methods* – these methods are employed to determine the contribution provided by an environmental good that contributes to a wider process of final good that has a market price. *Revealed preference* – this is a non-market good that includes expenditure associated with observed behaviour. *Stated preference* – this method involves interaction with stakeholders to determine how much they value an environmental good.	These are complementary methods that provide additional costs.	These methods are highly subjective and depend on personal preferences and circumstances. Considering similar scenarios, it is difficult to reproduce the same values. These methods cannot be used on their own to assess the impact of climate change but must be used in combination with the above three.

Appendix 2 Example of Workshop 1 Questionnaire

Scenario 2	
Hazard	Coastal Storm
Emissions Scenario	RCP8.5 (High emissions scenario)
Period	Up to 2050
Location	Cork

The objective of this exercise is to determine the risk to transport networks in the ***Cork region*** due to an Extreme Weather Event (EWE) comprising of a ***coastal storm***. In this scenario, a high emissions scenario is assumed (RCP8.5) for the period up to mid-century.

Using the framework illustrated below and the questions that follow, participants are asked to conduct a risk assessment for road, rail and maritime networks in this region.



Suggestion: Begin with a round-table introduction to establish what expertise is available with the group (e.g. climatologists, port operators, local county council representatives, etc.).

The group may also wish to consider the information outlined on the following page when performing the risk assessment.

Climate Hazard Information: Coastal Storm

- There is a projected increase in the intensity of storms affecting Ireland by mid-century.[2]
- There is a projected increase in wind speeds during winter for the period 2021–2060 compared to 1961–2000.[3]
- Storm surge heights in the range 50–100 cm are likely to increase in frequency around Irish coastal areas in the future.[2]
- The height of extreme storm surges around Irish coastal areas are projected to increase for the period 2031–2060 compared to 1961–1990.[4]
- The OPW's ICPSS study[5] has predicted the following coastal flood extents in the Cork region for a 1000-year return period (low probability event):

2 Nolan, P., 2015. *Ensemble of Regional Climate Model Projections for Ireland*. Environmental Protection Agency, Johnstown Castle, Ireland.

3 McGrath, R. and Lynch, P., 2008. *Ireland in a Warmer World: Scientific Predictions of the Irish Climate in the Twenty-first Century*. Met Éireann, Dublin.

4 Wang, S., McGrath, R., Hanafin, J., Lynch, P., Semmler, T. and Nolan, P., 2008. The impact of climate change on storm surges over Irish waters. *Ocean Modelling* 25: 83–94.

5 https://www.floodinfo.ie/ (accessed October 2019).

Hazard Assessment
For the identified climate hazard scenario what are the main climate variables to be considered when assessing the impacts on transport networks (e.g. wind speed)?
• Mean sea level pressure (since the lower the pressure, the worse the storm) • Wind speed/duration • Rainfall • Wind direction • Tidal level • Temperature • Season (winter storms are worse; consider foliage, vegetation, tree vulnerability) • Sea level rise
List any specific thresholds/trigger levels currently employed to assess the severity of coastal storms on transport networks (e.g. mean wind speed >50 km/h).
• Met Eireann categories for storms – rainfall amounts, gust wind speeds • Return periods for storms • OPW coastal flood hazard maps • Met Eireann – there is generally a lack of data regarding sea level rise, coastal flooding. Storm surge and sea level data will be available next year. • Consider gust wind speed vs. mean wind speed
Identify any cascading hazard effects for the identified climate hazard scenario (e.g. coastal flooding).
• Coastal flooding • Gusts/high wind speeds
Do you consider existing available datasets in relation to future climate predictions for coastal storms to be satisfactory? Identify data gaps or further information needed to adequately perform a risk assessment for transport networks.
• Atmospheric datasets, Cordex datasets (European) – atmospheric datasets only (pressure). In the future, ocean and coastal data will be incorporated into these models. Cordex is easy to access. • OPW – refer to low, medium and high climate change scenarios but these should be matched with IPCC scenarios. • IPCC global sea level rise – too coarse • CFRAM maps – queries as to whether these have been validated. • OPW gauges • UCC Climate Ireland tool – data portal. Droplet database – Open access has been removed due to GDPR regulations. • Need for central data repository highlighted
Other comments?
• Queries over reliability of data and algorithms used to process data. • Need for continuous updating of OPW flood maps highlighted.

Exposure/Vulnerability Assessment
Which road, rail or maritime networks are likely to be impacted by the identified climate hazard(s) in the Cork region and to what extent?
• Rail: Cork–Dublin line, Cobh line. • Road: ring road, city road, airport road, entire city (especially UCC, Western road) • Maritime: Cobh harbour, Cork harbour
Identify critical locations along these transport networks in terms of potential transport disruption (e.g. critical link that may sever an important transport connection).
• Western road • It was noted that a detailed study has been conducted for Cork and there is a potential for studies in Bandon. However, there is limited to flood hazard only – vulnerability not looked at. • Cobh railway • M7 • N22
For the identified vulnerable transport networks, list the likely physical impacts of the climate hazard(s) on the transport infrastructure (e.g. flooding damage for port/harbour infrastructure).
• Road and rail bridge collapses – severity varies depending on bridge type. • Suggestions to query with TII whether data from previous studies is currently available.
For these transport networks, are there available datasets to indicate the vulnerability of the transport infrastructure assets to the identified climate hazard(s) (e.g. characteristics of port infrastructure that indicate susceptibility to storm surge damage)?
• Sea level data is available in PDF format – there is a lack of data in flood plains (levels are predicted for gauges only at exact points. • Need for OPW maps to be overlaid onto infrastructure. • Further studies needed.
Identify any cross-sectoral vulnerabilities with regard to the transport networks (e.g. power outages affecting rail operations)?
• Power network impacts traffic signals for road network & rail signalling
Other comments?
-

Consequence Analysis
List the direct consequences for road, rail and maritime networks in this region due to the identified future climate hazard scenario (e.g. fines for port operator due to suspended freight transport services).
● Debris accumulation – requires clearing ● Road/railway/port physical infrastructure damage ● Operational disruption to routes ● Silt build-up in harbour – dredging required
Consider how these direct consequences could be quantified in terms of monetary losses. Assign monetary values where possible (e.g. estimate costs of repairing damaged sea wall).
● It was noted that many county councils know how much it will cost to conduct infrastructure repairs. However, this information needs to be shared. For instance, is there data available for Cork based on previous floods? ● Need for open access to data and sharing of information
For the identified physical impacts of the of the climate hazard(s) on the transport infrastructure, rank these in terms of likely traffic disruption. What factors need to be considered in order to perform a ranking (e.g. wind speed)?
● Flood level – general storm surge height. ● Fallen trees on road – may block road. ● Public transport shuts down at a certain Met Eireann warning. ● It was highlighted that wind speeds and coastal flooding very different impacts so it is difficult to directly rank.
List the indirect consequences for road, rail and maritime networks in this region due to the identified future climate hazard scenario (e.g. economic losses due to disrupted freight services).
● Insurance costs ● User delays ● Cost of diesel generators ● Disruption to health supplies ● Inability of people to travel to work ● School closures ● Impacts on crime levels, e.g. Lidl vandalism in Dublin ● Staff costs for inspections following events
Consider how these indirect consequences could be quantified in terms of monetary losses. Assign monetary values where possible (e.g. economic costs of rail line closure for 1 day along important commuter route).
● Data gathered from previous events. ● A query was raised as to who is currently gathering this data.
Other comments?
-

Adaptation Planning
List possible "soft" adaptation measures that could be implemented to reduce the potential losses associated with this future climate hazard scenario. Assign cost estimates where possible.
● Legalisation and policy. It was noted that legislation to allow access to private land (e.g. for infrastructure inspection) is unlikely. ● Improve communication between various groups and experts ● Improved planning, e.g. prevention of infrastructure development in flood plains and coastal areas. ● Use of funds gathered through national carbon tax to conduct studies in relation to climate hazards and sectoral vulnerabilities.
List possible "green" adaptation measures that could be implemented to reduce the potential losses associated with this future climate hazard scenario. Assign cost estimates where possible.
● Upland planting ● SUDS ● Wetlands ● Restore floodplains
List possible "grey" adaptation measures that could be implemented to reduce the potential losses associated with this future climate hazard scenario. Assign cost estimates where possible.
● Flood walls ● Tidal barriers ● Account for climate change in drainage design ● Innovative technologies/materials
Rank the above listed adaptation measures in terms of their effectives with regard to risk reduction (i.e. which adaptation measures are most likely to minimise losses due to the identified future climate hazard scenario)?
● Suggest looking at case studies to see what worked where and if it can be used elsewhere ● Timescale highlighted as being very important
What are the barriers to the implementation of the listed possible adaptation measures?
● Cost ● Lack of expertise ● Maintenance requirements ● Lack of acceptance ● Lack of available data and models to justify investment choices.
Other comments?
● A query was raised in relation to who is responsible for coastal erosion?

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.

EPA Research Report 360

Methodologies for Financing and Costing of Climate Impacts and Future Adaptation Actions: Transport Networks in Ireland

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Authors: Julie Clarke, Enrique Acosta and Heidi Brede

Identifying Pressures

Climate change is happening on a global scale, and Ireland is already seeing its detrimental effects. Rainfall, windspeed and temperatures are expected to increase in intensity and frequency over the next century; this will inevitably affect the transport sector in Ireland. Planning ahead and developing resilient and robust solutions to the challenges at hand is vital to prevent significant economic losses.

Informing Policy

It became evident from stakeholder workshops that information and data relevant to several sectors and regions in Ireland are lacking or not easily accessible. Coherent data collection and use and awareness raising of existing tools and resources should be co-ordinated nationally, with a particular focus on mapping out and quantifying climate-related hazards, as these are key to avoiding potential cost or economic losses in the future. This would assist in improved information provision to policy makers and relevant sectors.

Developing Solutions

There is a need for development of methodologies that quantify the social, economic and environmental costs of climate change impacts, as well as the benefits of adaptation planning options. In order for adaptation planning to be useful, it must be applied correctly. It must also be economically justifiable. Quantitative risk assessments (QRAs) are a useful tool for evaluating the cost of climate change on the transport network, albeit QRAs are not without their weaknesses. However, the future is uncertain and decision-making without knowing all the facts is often inevitable. To overcome this, a robust decision-making framework and other useful tools can be adopted in order to find solutions that are cost-effective, flexible and beneficial for a wide range of future scenarios.

EPA Research: McCumiskey House,
Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie

EPA Research Webpages
www.epa.ie/researchandeducation/research/