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IRELAND'S CLIMATE CHANGE ASSESSMENT

Volume 3: Being Prepared for Ireland's Future Climate

Ireland's Climate Change Assessment 2023

Environmental Protection Agency

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Foreword

This is the first Ireland's Climate Change Assessment (ICCA) and is a major contribution to the national dialogue and engagement on climate change. It tells us what is known about climate change and Ireland. It also provides key insights on gaps in our knowledge. The development of ICCA was modelled on the work of the Intergovernmental Panel on Climate Change and the Sixth Assessment Cycle, completed in 2023, with the use of and localisation of its information for Ireland.

ICCA will support the national response to climate change, ensuring that it is informed by the best available science. It also points to how and where that science can be improved through further investments in innovation, in research and in systematic observations. These collectively form the essential backbone of the science and data required to understand how Ireland is being impacted by and responding to the climate change challenge.

The full Assessment has been developed through a co-creation process between leading academics in Ireland and officials from across state agencies and government departments. Funding was provided by the Environmental Protection Agency, Sustainable Energy Authority of Ireland, Science Foundation Ireland and Department of Transport. The process was collaborative, involving mutual development and agreement of the scope, preparation and review of drafts, wider stakeholder consultation through a series of workshops and meetings, and a detailed sign-off process.

We see the publication of ICCA as a real innovation for Ireland and as a resource for understanding climate change in an Irish context across the underlying science, mitigation and adaptation measures, and opportunities. It is a starting point for further dialogue on the findings and their utility for policymakers, practitioners, researchers, research funders and people. This engagement phase should continue far beyond the publication of this Assessment and support climate action in Ireland.

Dr Eimear Cotter
Director of the Office of Evidence and Assessment, EPA
Chair of the ICCA Steering Committee

Summary for Policymakers

What is adaptation?

The Climate Action and Low Carbon Development Act 2015 provides the legal definition for adaptation as "adjustment to (a) any system designed or operated by human beings, including an economic, agricultural or technological system, or (b) any naturally occurring system, including an ecosystem, that is intended to counteract the effects (whether actual or anticipated) of climatic stimuli, prevent or moderate environmental damage resulting from climate change, or confer environmental benefits". Key to understanding and implementing adaptation are the interrelated concepts of risk, exposure and vulnerability. Risks emerge from the interactions between climate change and related hazards (e.g. heatwaves, floods, droughts), exposure and vulnerability (see Figure SPM.1). Risk is dynamic and in constant evolution as the frequency and intensity of hazards increase and as exposure and vulnerability change through many drivers. Adaptation, therefore, should be seen as iterative risk management (Ara Begum et al., 2022), with emphasis placed on an ongoing process of assessment, action, monitoring, evaluation, learning and improvement.

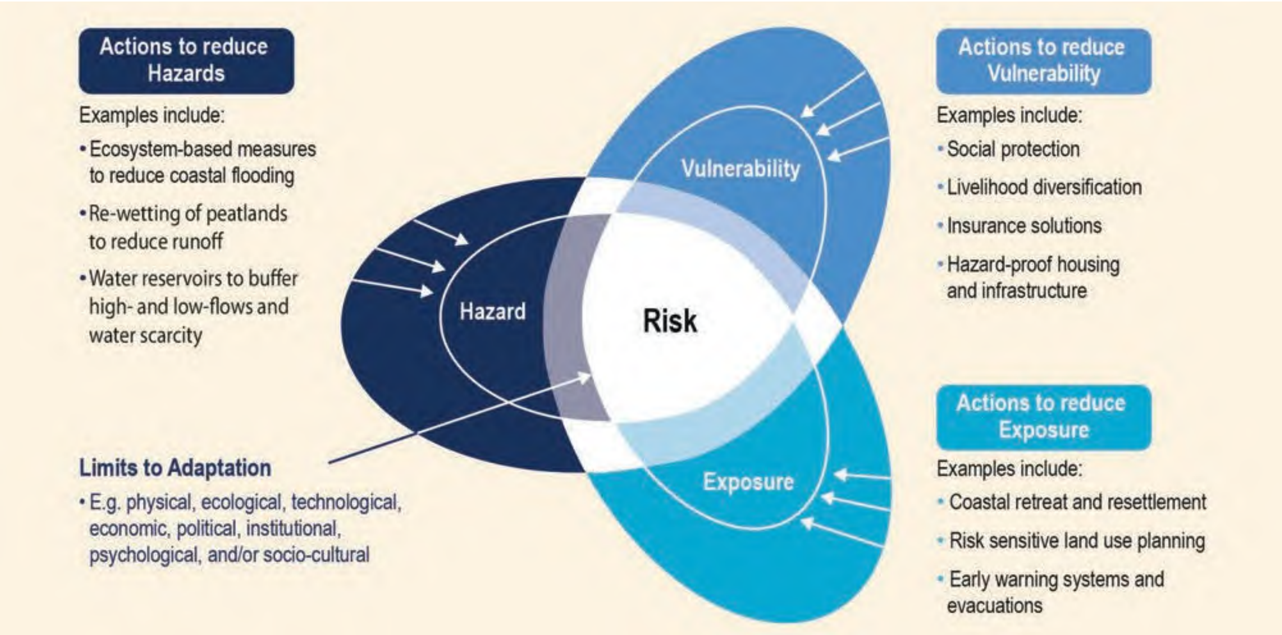

Figure SPM.1 Adaptation can reduce risk by addressing one or more of the three risk factors: vulnerability, exposure and/or hazard. A reduction in vulnerability, exposure and/or hazard potential can be achieved through different policy and action choices over time until limits to adaptation may be reached. Source: IPCC (2019, figure TS.4 (modified with permission))

Adaptation and national policy on climate change

National climate policy establishes the objective of achieving a competitive, low-carbon, climate-resilient and environmentally sustainable economy by 2050. The National Adaptation Framework defines climate resilience as "the capacity of a system, whether physical, social or ecological, to absorb and respond to climate change by implementing effective adaptation planning and sustainable development to reduce negative climate impacts, while also taking advantage of any opportunities". Resilience is closely linked to adaptation as iterative risk management. Adaptation increases resilience by helping us to navigate extremes and surprises, maintaining flexibility and a diversity of responses, learning, and creating and delivering actions that reduce social, ecological and economic vulnerability and exposure.

A. The current state of play on adaptation

A.1 **Climate change is happening now and we need to adapt.** Volume 1 shows that climate change is happening now. Extreme weather events, together with sea level rise and coastal erosion highlight an adaptation deficit in Ireland. Actions taken today to reduce vulnerability and exposure and increase resilience will shape the future and should be seen as an investment rather than a short-term cost. {Chapter 1}

Flooding in Enniscorthy, Co. Wexford, in 2015, just one of many recent extreme events that highlight exposure, vulnerability and the need for adaptation. Source: Reproduced with permission from Wexford Hub (https://wexfordhub.com/enniscorthy-impassable/).

A.2 **Adaptation offers opportunities and multiple benefits.** Climate change impacts will unfold alongside other social, environmental and economic challenges and development objectives. Project Ireland 2040 sets a pathway for realising national priorities for urban renewal, housing, transport, health, critical infrastructure, rural development and more while transitioning to a climate-resilient, biodiversity-rich and climate-neutral economy. Ireland's population is also expected to grow by at least one million people by 2040[1]. Adaptation to climate change will be crucial to the sustainability of these plans and has the potential to offer win–win opportunities, but only if a systematic approach is taken and actions are scaled up and resourced. {Chapter 1}

A.3 **The policy focus of climate action has been on mitigation over adaptation.** Climate action in Ireland has been focused on mitigation, with less attention given to adaptation. The National Adaptation Framework and the Climate Change Advisory Council have emphasised the need to implement climate adaptation measures as a priority in order to build capacity to cope with the impacts of climate change. The timescale left for doing so is short given the timeline of 2050 to realise climate resilience. The Climate Change Advisory Council concludes in its 2022 annual review that the limited number of sectors showing at least good progress on adaptation is "worrying" and needs to be urgently addressed. {Chapter 1}

A.4 **Adaptation and mitigation are inherently linked.** Ambitious global mitigation is critical to the scale and feasibility of adaptation. The more warming experienced, the greater the challenge and costs of adaptation. Even if global mitigation efforts are successful at realising the goals of the Paris Agreement, adaptation is required. At the same time, adaptation actions should not lead to sustained increases in greenhouse gas emissions. Mitigation actions also have trade-offs and benefits for adaptation that need to be understood. For example, afforestation can have benefits for mitigation and flood risk reduction but, if not properly planned, can also increase drought severity and have negative consequences for communities. {Chapter 1}

[1] As detailed in *Project Ireland 2040 – National Planning Framework* (DHPLG, 2018).

A.5	**We are not starting from an ideal position.** Ireland has seen significant and ongoing deterioration in environmental quality, including declines in water quality, biodiversity and ecosystem quality. Together with a growing population and a lack of investment in critical infrastructure, many natural and human systems on which our wellbeing depend have become less resilient. Social and economic challenges, including in energy, health, housing and an ageing population, all increase vulnerability to climate change. {Chapter 1}
A.6	**We are exposed to climate change risks beyond our shores.** A changing climate presents substantial challenges for all sectors. As a small, open economy heavily dependent on imports and exports, Ireland is highly exposed to transboundary climate risks (i.e. the impacts of and responses to climate change experienced elsewhere in the world). Understanding transmission pathways of transboundary risks, including through trade, finance, people and psychological, geopolitical, biophysical and infrastructure pathways, is an important knowledge gap. Assigning governmental responsibilities for managing transboundary risks and facilitating input from the private sector will be crucial to building resilience to transboundary climate risks. {Chapters 1, 10}
A.7	**There are reasons for optimism and foundations are being built.** Despite the challenges and gaps that exist, there are reasons for optimism; foundations for adaptation are being laid, based on robust information, and actions implemented. Investment in research is addressing knowledge gaps. Adaptation is now mandated in national legislation[2] (section 1.2), integrated with EU policy, and governance structures and oversight mechanisms have been established. Many sectors and local authorities have developed their first adaptation plans. Reflection upon and learning from these will underpin advances in adaptation. Investment in climate action regional offices is supporting development of capacity, from local to national level. The importance of effective climate services, community engagement and widening of adaptation actions to include nature-based approaches, and non-structural measures, is being increasingly recognised. Examples of good and bad adaptation outcomes are emerging and provide the foundation for learning and doing better. {All Chapters}
A.8	**But there are challenges we need to confront and improvements to make.** {All Chapters}
	A8.1 Adaptation is not just about technical solutions. Without clear goals that reflect the principles of climate justice, evaluation of adaptation actions and outcomes is difficult.
	A8.2 While many sectors have developed adaptation plans, others are missing, including critical areas such as the built environment, tourism and sport, and financial services; cross-cutting issues such as coastal environments also need addressing.
	A8.3 Adaptation to date has been largely undertaken by national and local government. Widening inclusion of private sector actors and further encouraging and facilitating community involvement can benefit adaptation.
	A8.4 A sectoral focus on adaptation, without opportunities for integrative assessment, increases the prospect of underestimating cascading risks – how risks can transfer or flow from one sector to another. For example how flooding of critical infrastructure such as a water treatment plant can impact water services for businesses and have health impacts for individuals and households.
	A8.5 Socioeconomic vulnerability, community participation in decision making and the concept of just adaptation or just resilience need to be better embedded in adaptation policy and actions.
	A8.6 Developing a climate-resilient Ireland will require sufficient public and private investment and financial support in ways that adequately recognise the value of ecosystem services and the importance of societal wellbeing.

While much is happening, increased ambition, learning and improvement are essential for better adaptation. Section B turns attention to climate change risks and adaptation in key sectors.

[2] The Climate Action and Low Carbon Development Act 2015 and the Climate Action and Low Carbon Development (Amendment) Act 2021 (henceforth Climate Act 2021) constitute Ireland's policy framework to deliver on the national climate objective to pursue and achieve, by no later than the end of the year 2050, the transition to a climate-resilient, biodiversity-rich, environmentally sustainable and climate-neutral economy.

B. Climate change risks and adaptation in key sectors

Climate change risks and adaptation affect all aspects of Irish life. This section presents key findings across eight core sectors ranging from ecosystems to business and finance.

Ecosystems: marine, terrestrial and freshwater

B.1	Biodiversity in Ireland is declining, and continued biodiversity loss will undermine capacity to adapt to climate change across all sectors. Without early and significant adaptation, climate change will result in severe impacts on many species and habitats.
B.2	Ireland's biodiversity has intrinsic value and conservatively contributes at least €2.6 billion annually via ecosystem services to the Irish economy. Despite this, current conservation efforts are not adequately funded. The maintenance of ecosystems in good condition, or their restoration to good condition, enables them to resist pressures and threats, recover from disturbance and reconfigure in response to new conditions. These are all elements of resilience.
B.3	Significant impacts on biodiversity are projected to increase with additional warming. Temperature dictates the timing of growing seasons and ecosystem productivity, while sea level rise impacts our coastal ecosystems. The frequency and intensity of rainfall affects vegetation and crops and indirectly affects ecosystem structure through changes in river flows and lake levels. Projected changes in temperature and precipitation are likely to increase the occurrence and spread of invasive species and the competitive pressures faced by Ireland's native species. Changes in ocean temperature are likely to change the distribution of marine species, from phytoplankton to marine mammals.
B.4	Up to 20% of Ireland's total native flora is estimated to be vulnerable to climate change in the period up to 2050, with more than half of species on the Irish threatened plants list at risk of being adversely affected by climate change (DCHG, 2019a). Observed impacts of climate change on Irish species and habitats include changes in species abundance and distribution, phenology (such as the timing of bird migration and plant flowering), community composition, habitat structure and ecosystem processes. Increases in spring temperatures in recent decades have been demonstrated to impact the timing of key life cycle events in a range of plant, bird and insect species in Ireland.
B.5	There is not yet a clear picture of how offshore marine ecosystems are, and will be, affected by changes in climate. Globally, ocean warming, acidification and oxygen loss are well understood, but regional and local changes in temperature, acidification, salinity, and nutrient and oxygen levels display significant natural variation. The geographical ranges of some species in Irish waters are predicted to shift northwards to cooler waters. Fish stocks of commercial interest to Ireland may be adversely impacted by climate change. This could have implications for quota sharing and fisheries management. Key adaptation actions for marine ecosystems include protection from overfishing, and the development of refuges for species recovery. Ireland's current network of protected areas in the marine needs to be more coherent, representative and connected[3].
B.6	It is vital that all sectors recognise their role in reducing pressures on biodiversity and contributing to adaptation measures. Actions to protect and restore biodiversity are valuable adaptation strategies for other sectors that either rely on ecosystems or work with nature through the deployment of nature-based approaches. Examples of synergistic nature-based actions include restoration of peatlands and native woodlands, rewetting grasslands on peat soils, salt-marsh and sea-grass meadow restoration, urban greening, landscape regeneration, climate-integrated land use planning and regenerative agriculture. Central to all these are funding, education and capacity building, together with stronger community participation so that actions can be mainstreamed and benefits distributed fairly.

[3] A bill for the designation and effective management of marine protected areas is currently being drafted, taking into account the findings of the Marine Protected Area Advisory Group (2020) report.

Agriculture, forestry and land use

B.7	Irish agriculture is changing in response to climate change mitigation and biodiversity objectives. Among the farming community, an ageing profile, the pattern of smallholdings and changing access to services and payments are factors to consider as part of a just transition for agriculture. While climate change is likely to impact all forms of agriculture, opportunities for adaptation are emerging around the integration of local knowledge, stewardship of ecosystem services, agroforestry, horticulture, organic farming and urban food systems.
B.8	Climate change is likely to result in increases in productivity for some crops but decreases for others. Increases in humidity will increase the vulnerability of potato crops to blight. Other pests and pathogens (current and novel) are likely to have an increased impact due to warming winters resulting in a lack of die-off. Pests and pathogens are also likely to gain an increased geographical range, gaining a foothold where current climate conditions are not favourable. At present, irrigation is applied to a relatively small proportion of land, but that is expected to increase in future. Changes in precipitation may result in increased nutrient washout from land. Warming is expected to lead to an increase in growing season length; however, any productivity gains may be offset by increases in extreme rainfall events or in drought frequency, magnitude and duration. Risk-sharing instruments can help buffer the negative effects of extreme events on crop yields.
B.9	Soil management will be impacted by climate change, with projected increases in both wet and dry conditions. Wetter conditions will increase compaction and degradation from vehicles and livestock. In response to droughts, peatland and wetland restoration, together with better grassland and cropland management, could increase soil organic carbon content, which has benefits for adaptation and mitigation through an increased capacity for water storage and retention of nutrients in soils, with additional benefits for water quality. Agricultural practices and their timing will change in response to climate change.
B.10	Increasing rainfall can lead to increases in the prevalence of liver fluke and other diseases in cattle and sheep, as well as increasing the risk from exotic pests and diseases. More frequent and prolonged periods of higher temperatures will increase the potential for animals to experience heat stress, affecting fertility, milk production and growth rates. Heat risks can be reduced through silvopasture, i.e. blending pasture and woodland, to provide shelter for animals.
B.11	For forestry, increased yields are projected for some species such as Scots pine, beech, lodgepole pine and birch. Conversely, decreased yields are projected for others including Sitka spruce and other conifers, oak and most other deciduous trees. Agroforestry has the potential to provide multiple benefits, including shelter for livestock, water and carbon retention, and biodiversity, but adoption rates are low. Additional incentives are required to address barriers and increase the uptake of agroforestry.
B.12	Existing studies on climate change impacts on agriculture, forestry and land use are fragmented. A systematic programme of research to assess climate impacts on agriculture, forestry and land use is needed to support adaptation. The emergence of a new generation of tools and decision support systems has value for developing a more resilient sector.

Coastal environments

B.13	Ireland is highly exposed to climate change impacts on coastal environments, with all major cities and many regional population centres located by the sea. Global sea level is projected to rise under all future scenarios and will continue to do so for hundreds to thousands of years. Locally, sea level rise is more complex (see Volume 1). Currently there are no standardised, locally tailored, sea level rise projections available for Ireland. For adaptation, it is important to consider projections of sea level rise up to and beyond 2100 to avoid increasing exposure. Significant increases in sea level out to 2300 are already inevitable, even in the most optimistic mitigation scenarios.
B.14	The impact of climate change on storm surges and wave heights is unclear, related primarily to uncertainty in changes in storminess, emphasising the importance of robust decision making in coastal areas. Approximately 20% of the Irish coastline is exposed to erosion, with low lying, relatively densely populated coastal zones in the east particularly exposed. In Irish coastal environments, sensitive ecosystems include cliffs, beaches, lagoons, dunes and machair, salt marshes, mudflats and other wetlands.
B.15	Sea level rise and changes in storm surge present large flood risks for urban areas. Superimposed on the current 100-year flood, mid-range estimates of sea level rise are estimated to quadruple the number of properties affected by flooding in coastal locations. For Limerick city alone, the cost of extreme floods under a high-end scenario of sea level rise may increase up to 12.5-fold, amounting to over €1 billion for a single event. Such estimates do not account for future urban expansion and emphasise the importance of adaptation to coastal flood risk.
B.16	Approximately 98% of trade by volume comes through our ports, and they are key gateways for tourism. Climate hazards for Irish ports include sea level rise and changes in wind, wave and tidal extremes and storminess, with risks differing by port location. Currently there is little guidance on how adaptation in ports should be managed. The National Development Plan (2021–2030) sets out over €340 million of infrastructural investment at Irish ports. It is critical that investment is stress tested to the risks posed by climate change.
B.17	Bathing water quality is essential for human health and is an important recreational and tourism asset for local and regional economies. Climate change will affect bathing water quality through increased heavy rainfall on land and associated storm water overflow, warmer ocean temperatures and associated changes in the frequency and extent of harmful algal blooms.
B.18	Our coasts are home to a rich cultural and natural heritage. Cultural heritage includes historical buildings, archaeological sites and monuments. Climate change may increase the rates of physical and chemical erosion affecting the structure and composition of heritage assets, while changes in the frequency and magnitude of events such as droughts, floods and extreme rainfall will impact our cultural heritage. Sand dunes are an important part of our natural coastal heritage, are sensitive ecosystems and play an important role in protecting low lying coastal areas from flooding and erosion. In addition to existing pressures from erosion and human impacts from grazing, recreation, trampling and sand extraction, climate change is likely to increase pressure on dune systems through sea level rise and changes in storminess. This is particularly so for westerly oriented dunes along the Atlantic coast.
B.19	There is currently no clear governance structure for coastal adaptation. There are also challenges for adaptation in terms of private and public land ownership in coastal areas and the designation of many vulnerable locations as protected areas. The Inter-Departmental Group on Managing Coastal Change is considering approaches for the development of an integrated, whole-of-government coastal change management strategy.

B.20	Coastal adaptation responses can be categorised as (1) protect, (2) accommodate and (3) retreat. Protection can take the form of hard engineering (e.g. sea walls, dikes, groynes and revetments) and/or nature-based approaches (e.g. beach nourishment, dune creation and wetland restoration) that seek to keep sea water out and/or reduce erosion rates. Accommodation seeks to increase the ability of humans to live with risks and includes insurance schemes, early warning systems, the design and/or retrofitting of infrastructure and the use of regulatory approaches such as building codes and land use/planning regulations. Where protect and accommodate are not feasible or sufficient responses and coastal loss is inevitable, managed retreat may be necessary. Appropriate actions depend on the nature of impacts experienced, the local physical and social context, exposure and vulnerability and economic constraints.
B.21	The procedural and distributive justice aspects of managed retreat should be carefully considered, including supports for those having to relocate. Minimising the negative impacts of relocation for individuals and communities will require the co-creation of relocation plans and community-centred approaches. Managed retreat raises complex governance issues for adaptation in coastal zones.

Water

B.22	In Ireland, climate change impacts on the hydrological cycle are happening in the context of increasing water demands, decreases in water quality and a lack of resilience in our water supply infrastructure. Impacts are likely across multiple sectors, including critical infrastructure, settlements, biodiversity, land use and health, raising the importance of cross-sectoral collaboration for adaptation.
B.23	Identifying a clear signal of climate change in observed precipitation and river flows is difficult because of natural variability. Observational records show that the magnitude and timing of floods are changing; however, there is uncertainty in attributing the cause of these changes, whether due to climate change, natural climate variability, data quality or internal catchment modifications (e.g. land use change, arterial drainage).
B.24	Rainfall and river flow projections for mid-century and end of century are uncertain, but suggest increases in flood magnitude and frequency, increases in spring and summer drought magnitude and frequency (future changes in drought duration are uncertain), and increases in river flows in winter and decreases in summer. Ambitious global mitigation measures resulting in less warming are associated with less severe low flows.
B.25	Future changes in temperature, relative humidity and wind speed will lead to changes in evapotranspiration. Increases in evapotranspiration would have significant implications for drought impacts, water resources and agriculture, especially during the spring and summer months. The impact of vegetation responses on evapotranspiration remains open to scientific debate.
B.26	The impacts of climate change on groundwater are strongly influenced by local hydrogeological settings. Some aquifers are projected to experience increases in drought impacts, while the incidence of flooding may increase in others[4].
B.27	Water quality is influenced by air and water temperature, precipitation amounts and intensity, and the occurrence of extreme events. Changes in rainfall amounts, timings and intensities have implications for nutrient washout, erosion, suspended sediment and sediment yields, with sensitivity varying by catchment. Climate change impacts on water quality in urban areas are also dependent on the design and construction standards of water infrastructure. Changes in land use/management are likely to interact with and amplify the impacts of climate change on water quality. Land use management is a critical adaptation pathway for alleviating pollution and improving water quality in catchments.
B.28	Adaptation in the water sector should account for the range of plausible changes in climate variables. Frameworks for decision making under uncertainty, including the development of adaptation pathways, together with integrated catchment management as part of river basin management plans, offer valuable approaches for reducing existing vulnerability and addressing adaptation needs.
B.29	Water supplies face growing pressures resulting in increased water demand. Climate change is likely to further increase water demand from households, businesses and agriculture. A large portfolio of supply and demand side adaptation options are available for water resources management. However, effective adaptation options and appropriate adaptation pathways remain to be devised and assessed. Some supply side options, such as the development of new sources, may involve significant trade-offs and encounter adaptation limits via social or environmental acceptability, technical feasibility or excessive cost.
B.30	The implementation of adaptation actions for flood risk reduction can be categorised as defending against risk, living with risk, and relocation or withdrawing from risk. For defending against risk, actions include retrofitting existing infrastructure, building new infrastructure and integrating safety margins to accommodate climate change into designs. Living with risk includes land use planning and flood zoning, insurance, deployment of nature-based approaches and recognising the important role of flood plains in attenuating floods. Relocation in response to flooding has been rare in Ireland to date but has happened and may become more commonplace in future.

[4] Groundwater aquifers with low storage capacity are thought to be more vulnerable to extremes, particularly rainfall amount, intensity and timing. Aquifers with high recharge coefficients and sufficient recharge acceptance capacity will be impacted by the amplification of rainfall seasonality. Groundwater flooding is likely to increase in scale, frequency and duration.

Built environment, heritage and rural communities

B.31	Flooding from rainfall, rivers and the sea is a major hazard for the built environment. These are expected to increase in future. Increases in rainfall intensity are expected with implications for existing buildings and building design. Sea level rise, in combination with changes in storms and tidal surges, will challenge the management and planning of coastal settlements. Cities and larger urban areas tend to have a higher temperature than the surrounding rural areas due to the urban heat island effect, such that increases in average and extreme temperature will be amplified in dense urban settings.
B.32	Buildings, both domestic and public, such as workplaces, hospitals, schools and care homes, need to be resilient to future climate. Building regulations need to be updated to reflect future changes in climate. Newly available climate maps for key design parameters (wind-driven rain (section 6.2.3), maximum and minimum temperature (Volume 1, Chapter 3), rainfall intensities (Volume 1, Chapter 4) and overheating risks (section 6.2.2) are important for guiding design into the future. A significant amount of Ireland's urban and rural heritage is already at risk because of vacancy and dereliction and will be more vulnerable to changes in climate.
B.33	The role of planning and architectural design will be critical to adaptation in urban and rural settlements. Planning for an increasing and urbanising population demands coherence across spatial scales. It is crucial that exposure to flooding is not increased and that flood risk management guidelines are followed. There is abundant evidence for the value of nature-based approaches to reduce climate change impacts in urban areas. These include urban trees which can, with careful choice of species and planting, provide cooling, water retention, shading and some absorption of pollutants. The thoughtful siting of parks and green and blue spaces improves thermal comfort and general quality of life for inhabitants. Sustainable urban drainage systems offer potential for managing pluvial flooding. Planning based on local climate zones, which have already been developed for Dublin, can further aid spatial planning at the city scale by tailoring policies and guidelines to the typologies of local climate.
B.34	Ireland's long-sustained trend of dispersed rural settlement, highly dependent on transport-intensive and dispersed services, is a form of 'lock-in' that will present challenges for ensuring climate resilience. Ensuring that our goals for adaptation, rural development, housing, infrastructure, heritage protection and biodiversity are complementary rather than contradictory will require a greater degree of coordination and calibration of expectations than currently exists.

Critical infrastructure

B.36 Ireland depends on the resilience of its critical infrastructure for delivering public services, economic growth and a sustainable environment. Approaches to risk screening have been developed to examine vulnerabilities across four critical infrastructure sectors, namely transport, energy, water and communications infrastructure. Risk screening is useful for high-level assessment and identifying assets and locations for further analysis. This will need to be complemented with standardised quantitative approaches for stress testing critical infrastructure and identifying potential failure points, adaptation options and cascading risks.

B.37 Without effective adaptation, damage costs at the European scale to critical infrastructure from extreme events attributed to climate change are likely to increase from 2018 levels of €3.4 billion per year to triple that amount during the 2030s, six times by 2050 and 10 times by 2100. The main hazards causing these damages are expected to be heatwaves, droughts and coastal flooding, but also inland (fluvial, pluvial and groundwater) flooding, windstorms and wildfires.

B.38 For transport, sea level rise and flooding are key climate change risks. For energy, the key risks are extreme wind speeds, increased precipitation and saturated soils, given their impacts on the electricity distribution network, with flooding also of concern. Cascading of failures from the energy sector into other sectors is a key multi-sectoral risk. For water infrastructure, key climate change risks include flooding, wastewater treatment overflow and reductions in water quality related to extreme rainfall events, together with possible decreases in summer rainfall and droughts. For the ICT (information, communications and technology) sector, climate change risks related to extreme wind speeds are a key concern.

B.39 Some current infrastructural risks may reduce as the climate warms. For example, pipe bursts due to water freezing is a major weather-related operational issue for the water sector, but such bursts may become less frequent in a warmer future climate, as the number of frost and ice days is projected to decrease. However, gains could be offset by drought impacts through cracking and drying of the soil.

Health and wellbeing

B.40 Projected changes in extreme events are likely to have direct and indirect impacts for health and wellbeing. The number of people exposed and vulnerable to heatwaves will increase. To date, the number of flood-related deaths and rates of injury are low, but there is extensive evidence that floods have significant impacts on health and wellbeing, including mental health, across populations. Loss of and changes in valued places as a result of climate impacts have been related to the experience of solastalgia, a psychological grief experienced because of environmental loss. An ageing Irish population will pose additional challenges for public health in a changing climate. Without adaptation, projected changes in floods and droughts and associated impacts on water quality are likely to impact public health.

B.41 As a country with a high rate of excess cold-related deaths, warmer winters may have a positive effect in reducing this risk in Ireland. But climate change may also aggravate existing public health pressures on respiratory diseases such as asthma through increased circulation of aeroallergens in a longer growing season and changes in air quality. Shifting geographical ranges of vectors and associated pathogens, but also human behaviour, may have consequences for exposure to vectors and vector-borne diseases.

B.42 Responses to extreme events through emergency management and recovery affect direct and indirect health outcomes. The responses of governments and insurance companies have a significant impact on the wellbeing of populations following flood events, with information and financial support from public agencies contributing meaningfully to the wellbeing of affected populations.

B.43 Climate change is also likely to increase the exposure of critical health infrastructure. Overheating in hospitals and residential care settings has been identified as a public health concern in the UK during heatwaves, with hospitals reaching dangerous temperatures and a lack of capacity to cool older, less efficient buildings. There is evidence that similar conditions were experienced in Ireland during the heatwave of 2018. Flooding poses a significant risk to health care infrastructures both in direct damage and in preventing provision of care. Development of a register of at-risk infrastructure and services is needed to inform adaptation.

B.44 Systemic approaches to adaptation planning for public health are needed to develop effective strategies to reduce climate risks. The health and wellbeing outcomes of adaptation actions across all sectors should be monitored and used to evaluate the success of adaptation interventions. It cannot be assumed that interventions will do no harm or be equally successful across populations.

Business, industry and tourism

B.45 Climate change is likely to bring risks and costs to the Irish economy amounting to billions of euros per year by 2050. In 2020, Ireland experienced the third highest climate-related economic losses per inhabitant in Europe (Eurostat, 2022). Climate change adaptation in business and industry in Ireland is limited to date, and significant efforts are required to coordinate effective adaptation efforts with actors in the private sector.

B.46 As a highly globalised country, Ireland is vulnerable to shocks to supply chains, but these risks are yet to be sufficiently systematically assessed. Further research is needed to identify the vulnerabilities of business and industry to supply chain risks. In addition, important local direct and indirect risks for businesses, employees and customers emanate from flooding and storms, sea level rise, coastal erosion, heat extremes, water scarcity and drought.

B.47 Currently, the scale of climate change risks to the banking and financial sector in Ireland has yet to be quantified. Climate risks are not well reflected in the pricing of insurance, investment and lending. As these risks become more fully integrated into financial processes, they will affect access to capital and insurance.

B.48 Tourism, a key sector in the Irish economy, is highly exposed and vulnerable to climate risks and extreme events. While warmer summers are often held up as an opportunity for Irish tourism through increasing visitor numbers, without careful management this could create damaging and unsustainable pressures on sensitive heritage sites and environments. Careful and integrated adaptation planning that values heritage protection and ecosystem services is needed.

C. Realising the benefits of a climate-resilient Ireland

Following the assessment of climate change impacts and adaptation across sectors, this section reflects upon and presents the key steps necessary to build momentum on adaptation and to develop a pathway for realising a climate-resilient Ireland.

C.1	**Define objectives.** The success of adaptation is contingent on negotiating and defining goals around what success looks like and that account for competing values and worldviews. Without a clear definition of goals, it is difficult to monitor both the progress and the outcomes of adaptation. {Chapters 1, 10}
C.2	**Ensure just adaptation/resilience.** The decision-making process of selecting and implementing actions and their associated outcomes should reflect the principles of distributive (fair distribution of the benefits and burdens of adaptation), procedural (fair participation in decision-making processes) and recognitional (fair consideration of diverse values, cultures, perspectives and worldviews) justice. {Chapter 1}
C.3	**Recognise adaptation as an iterative process.** In the context of climate change, risks emerge from the dynamic interactions between climate-related hazards (e.g. heatwaves, floods, droughts), exposure and vulnerability. Risk is dynamic and in constant evolution as the frequency and intensity of hazards change and as exposure and vulnerability change through many drivers. {Chapter 1}. Therefore, adaptation is a process that responds to the dynamics and evolution of risk. This is the idea of adaptation as iterative risk management, whereby emphasis is placed on adaptation pathways as ongoing cycles of assessment, prioritisation, action, monitoring and evaluation, reassessment and response. {Chapters 1, 10}
C.4	**Place greater focus on monitoring and evaluation.** In Ireland, and internationally, monitoring and evaluation of adaptation are limited as the focus is primarily on progress in implementation. Greater focus needs to be placed on process and outcomes, including elements of justice and wellbeing. An all-purpose and globally acceptable set of indicators that comprehensively measures adaptation does not exist. Learning requires knowledge of how and why adaptation has or has not happened, which cannot be accomplished by quantitative metrics alone. Opportunities for institutional feedback, peer learning and knowledge sharing, with adaptation built on a culture of learning, collaboration and sharing insights, need to be further developed. {Chapter 10}

Figure SPM.2 Climate-resilient development pathways consolidate climate action and adaptation towards long-term sustainable development – the adapting towards what question. Source: Werners et al. (2021). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

C.5	**Understand social dimensions.** Successful adaptation depends on reducing vulnerability. This necessitates a better understanding of the spatial, temporal and socioeconomic nature of vulnerability. Consideration should be given to how assessments of vulnerability can inform the development of adaptation plans and the evaluation of outcomes. {Chapters 1, 10}
C.6	**Work with people and nature.** Widening adaptation actions to include nature-based approaches opens opportunities for multiple co-benefits for people and nature. Implementation of nature-based approaches can have positive outcomes for environmental quality, biodiversity, health and wellbeing. A greater focus on non-structural measures and opportunities for better governance will help open pathways to transformation. {Chapters 1, 10}
C.7	**Increase participation and cooperation.** Successful adaptation requires collaborative planning efforts and co-production. Methods that facilitate adaptation across sectors need to be further developed and integrated into policy processes. The role of the private sector and individuals/communities in adaptation also needs to be further developed. Communities will need support for adaptation and need help to generate leadership in collaboration with local government. {Chapter 10}
C.8	**Minimise response risks.** Adaptation actions themselves can entail risks, termed 'response risks', which may result in maladaptation. These include the risk of adaptation actions being ineffective and/or unjust or resulting in unintended adverse effects. Feedback opportunities for those affected by adaptation need to be created to evaluate and learn from experience in order to avoid maladaptation. {Chapters 1, 10}
C.9	**Recognise cross-sectoral and cascading risks.** Ireland takes a sectoral approach to adaptation. Increased coordination across sectors is required to ensure that joined-up opportunities are not lost and that efficiencies of scale are achieved while minimising cross-sectoral risks and cascading impacts. Ireland's national climate change risk assessment, the new National Adaptation Framework and revised national sectoral adaptation guidelines can be important additions in this regard. {Chapters 1, 10}
C.10	**Tailor climate services to needs.** Effective climate services should be based on scientifically credible information and expertise, have appropriate engagement from and between users and providers, and have effective access mechanisms to meet user needs. Important for the development of effective climate services in Ireland is the opportunity to provide ongoing dialogue and learning about how climate research and model outputs can be best tailored to decision needs, contexts and decision-making frameworks. The National Framework for Climate Services is a beneficial mechanism to support adaptation planning and action. {Chapters 1, 10}
C.11	**Integrate uncertainty into decision making.** Future projections of climate change impacts contain, sometimes large, ranges of change. It is critical that adaptation decision making recognises this. Numerous frameworks exist to support decision making under uncertainty but are under-deployed in Ireland. This is even more important where adaptation decisions concern critical infrastructure and/or where exposure and vulnerability are high. Frameworks for decision making under uncertainty and for evaluating adaptation actions are needed to support adaptation in Ireland. {Chapters 1, 10}
C.12	**Avoid lock-in and maintain flexibility.** Adaptation action taken today may lock us into resource allocations and decision pathways that limit future choices to adapt, increasing the risk of creating lock-in effects that limit future resilience. Climate resilience requires integrating flexibility and diversity into climate adaptation. {Chapter 1}
C.13	**Invest in adaptation.** Adaptation needs to be seen not as a cost but as a necessary investment. Adaptation is about placing Ireland in a position to prosper in the decades ahead. Resourcing of adaptation needs to move beyond the limits of traditional cost–benefit analysis. Aside from the material impacts, climate change threatens cultural heritage, sense of place, wellbeing and nature – all non-economic losses that are rarely captured in traditional economic assessments. {Chapter 10}

D. Knowledge gaps

In performing this assessment, a range of knowledge gaps have been identified. Specific gaps are detailed at the end of each chapter in the underlying report. Here, broad priorities are identified to improve the basis for future assessment activities and to enhance the knowledge base for adaptation.

D.1	**Address knowledge gaps on impacts for sectors.** A key challenge in compiling this assessment, and for adaptation more generally, is that there is a very uneven distribution of climate change impact assessments across different sectors. To date, there has been no programmatic funding of research to assess impacts across different sectors using a consistent set of climate model projections. This results in considerable gaps in our knowledge in key sectors. For coastal and flood risks, it is important that locally tailored sea level rise projections that extend beyond 2100 are developed for informing adaptation. Research is also needed on how to strategically integrate such long-term projections into spatial planning and the siting of critical infrastructure, for example.
D.2	**Increase capacity.** Adapting to climate change presents new challenges, and success will depend on capacity in research, training, upskilling and retention of existing and new professionals, together with engagement with and learning from communities. Irish research takes a leading role internationally. However, further investment is needed to grow the enduring human capacity, skills and infrastructure necessary to consolidate and sustain this contribution and address core gaps in knowledge. This will require investing in and leveraging knowledge from all disciplines and the local knowledge held by communities themselves. Developing capacity and leveraging the insight of the private sector into key vulnerabilities and exposures will be necessary to realising a climate-resilient Ireland.
D.3	**Understand adaptation processes and outcomes.** International research shows that barriers to adaptation emerge from neglect of place-based values, a lack of engagement with affected communities, shortcomings in, and failures of, governance and a lack of financial resources. Climate modelling and impact assessment needs to be supplemented with research into adaptation processes and outcomes. This has salience in informing adaptation that is just and equitable.
D.4	**Relocation and managed realignment.** Understanding the negative impacts of relocation and how to avoid or minimise them and the potential opportunities and trade-offs of managed realignment need be further understood. Consideration needs to be given to understanding the justice dimensions of relocation and the policy tools necessary to navigate such issues in the fairest way possible. Approaches to adaptation that consider managed realignment can reduce flood and erosion risk, reduce maintenance costs, mitigate coastal squeeze, and create new habitats and biodiversity benefits, while minimising relocation, depending on site-specific constraints. The potential opportunities and trade-offs of managed realignment need be further understood.
D.5	**Sustaining and enhancing monitoring networks.** Sustained and enhanced monitoring is essential for tracking emerging signals of change, the changing nature of risk and the attribution of impacts, and for tracking the success of adaptation outcomes. It is critical that monitoring across sectors is enhanced and supported, such as monitoring of invasive species, wildfires and coastal change. Collation of the impacts from extreme events is limited in Ireland presently. For evaluating the success of adaptation actions, further efforts at quantifying losses from extremes would be valuable.
D.6	**Ireland's islands.** A key gap in knowledge is how climate change is likely to affect Ireland's islands and their communities. Little research has been undertaken to examine climate change impacts and adaptation in these important locations. Ireland's islands face unique climate change pressures from land and ocean and often have unique challenges and cultural heritage, both tangible and intangible.

D.7	**Nature-based approaches.** Given their many potential co-benefits, the potential for nature-based approaches for climate action, including adaptation and mitigation, across all sectors needs to be more fully explored and assessed. This includes their potential effectiveness across local contexts, development of capacity for design and implementation, and opportunities to scale up successful interventions.
D.8	**Transboundary climate risks.** In an increasingly interconnected world, transboundary climate risks can flow through shared ecosystems and resources, trade links, financial interdependencies and people (through migration or forced displacement). Ireland's open economy and trade and finance links make it vulnerable to climate change impacts and adaptation responses in other parts of the world. Research is required to better understand transboundary risks.

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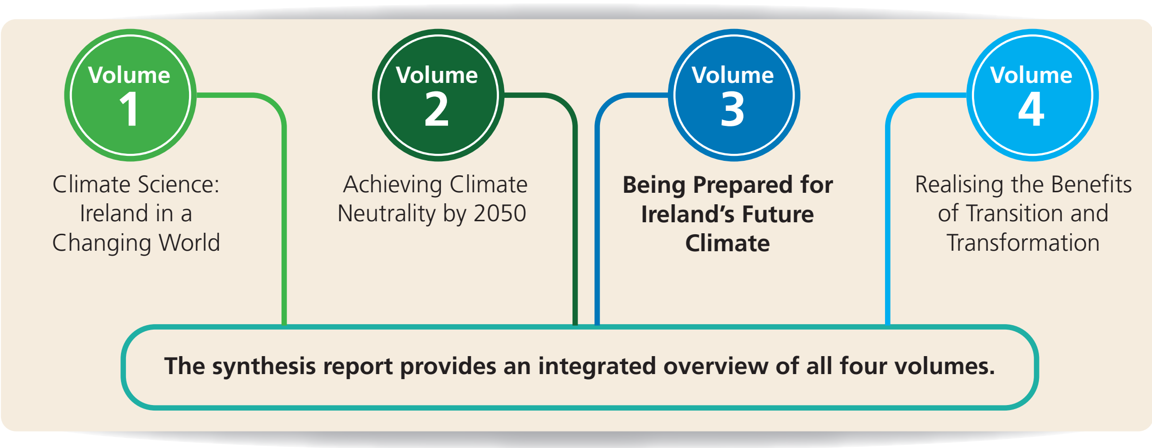
Preamble

The UN Framework Convention on Climate Change (UNFCCC, 1992) has the objective of preventing 'dangerous anthropogenic interference with the climate system', and the Paris Agreement (2015) established the long-term goals of 'holding the increase in global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels' and of achieving 'a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century'. Ireland's Climate Change Assessment (ICCA) delivers a comprehensive, Ireland-focused, state of scientific knowledge report on our understanding of climate change, its impacts on Ireland, the options to respond to the challenges it poses, and the opportunities from transitions and transformations to a climate-neutral, climate-resilient and sustainable economy and society. This serves to complement and localise the global assessments undertaken by the Intergovernmental Panel on Climate Change (IPCC) reports (see www.ipcc.ch). The findings presented build upon these global assessments and add important local and national context.

The report is presented in a series of four thematic volumes accompanied by an overarching synthesis report. The volumes are as follows:



Volume 3 provides a state of knowledge assessment of climate change impacts and adaptation for Ireland. Irish climate policy establishes the objective of achieving a competitive, low-carbon, climate-resilient and environmentally sustainable economy by 2050. Central to realising this objective will be understanding and adapting to the impacts of climate change over the coming decades and beyond. The volume is organised around ten chapters.

Chapter 1 frames adaptation, providing an overview of the policy context, a definition of key terms and entry points. It highlights the urgency of adaptation, drawing on the fact that climate change is happening now and that recent extreme events show the clear need for adaptation. The chapter evaluates progress on adaptation to date in Ireland and distils key opportunities and challenges for adaptation.

Chapters 2 to 9 focus on synthesising climate change impacts and adaptation across eight key sectors for the Irish society, the economy and environment. Chapter 2 considers Ecosystems: Marine, Terrestrial and Freshwater, Chapter 3 looks at Agriculture, Forestry and Landuse, Chapter 4 examines Coastal Environments, Chapter 5 deals with Water, Chapter 6 synthesises findings for the Built Environment, Heritage and Rural Communities, Chapter 7 looks at Critical Infrastructure, Chapter 8 turns attention to Health and Wellbeing, while Chapter 9 considers Business, Industry and Tourism. Each chapter takes a similar structure by considering the current context and pressures, observed and future changes and impacts, distils key risks and vulnerabilities, before examining adaptation responses, cross cutting issues and priorities for future research.

Chapter 10 draws from across each chapter to identify key focus areas for progressing adaptation. In particular, it highlights how issues such as governance, transboundary climate risks, understanding vulnerability and exposure, decision making frameworks, working with nature, and monitoring and evaluating adaptation outcomes can enhance adaptation actions and result in better and more just outcomes in preparing for and meeting the challenges posed by Ireland's changing climate.

1

Framing Adaptation

Key messages

1. Adaptation in human systems is the process of adjustment to actual or expected climate and its effects, to moderate harm or exploit beneficial opportunities. In natural systems, adaptation is defined as the process of adjustment to actual climate and its effects. There are strong interdependencies between adaptation in natural and human systems.

2. Volume 1 shows that climate change is happening now. Extreme weather events, together with sea level rise and coastal erosion highlight an adaptation deficit in Ireland. Actions taken today to reduce vulnerability and exposure and increase resilience will shape the future and should be seen as an investment rather than a short-term cost.

3. Climate action in Ireland has been focused on mitigation, with less attention given to adaptation. The National Adaptation Framework and the Climate Change Advisory Council have emphasised the need to implement climate adaptation measures as a priority in order to build capacity to cope with the impacts of climate change.

4. Ambitious global mitigation is critical to the scale and feasibility of adaptation. The more warming experienced, the greater the challenge and costs of adaptation. Even if global mitigation efforts are successful at realising the goals of the Paris Agreement, adaptation is required.

5. The decision-making process of selecting and implementing actions and their associated outcomes should reflect the principles of distributive (fair distribution of the benefits and burdens of adaptation), procedural (fair participation in decision-making processes) and recognitional (fair consideration of diverse values, cultures, perspectives and worldviews) justice.

6. In the context of climate change, risks emerge from the dynamic interactions between climate-related hazards (e.g. heatwaves, floods, droughts), exposure and vulnerability. Risk is dynamic and in constant evolution as the frequency and intensity of hazards change and as exposure and vulnerability change through many drivers.

7. Adaptation is not a single intervention fixed in time, but a process that responds to the dynamics and evolution of risk. This is the idea of adaptation as iterative risk management, whereby emphasis is placed on adaptation pathways as ongoing cycles of assessment, prioritisation, action, monitoring and evaluation, reassessment and response.

8. Adaptation actions themselves can entail risks, termed 'response risks', which may result in maladaptation. These include the risk of adaptation actions being ineffective and/or unjust or resulting in unintended adverse effects. Feedback opportunities for those affected by adaptation need to be created to evaluate and learn from experience in order to avoid maladaptation.

9. It is critical that decision making recognises the uncertainties in future impacts, with decision making based on the range of plausible changes. Beyond the use of climate model projections, catalogues of past extreme events could be better integrated into adaptation decision making and used to stress test adaptation decisions, portfolios of adaptation options and the performance of critical infrastructure.

10. A key challenge in compiling this assessment, and for adaptation more generally, is that there is a very uneven distribution of climate change impact assessments across different sectors. To date, there has been no programmatic funding of research to assess impacts across different sectors using a consistent set of climate model projections.

1.1. The current urgent moment

1.1.1. A changing climate and a changing world

The atmosphere, oceans and the frozen and living planet are changing at rates not seen in hundreds to many thousands of years. Global surface temperatures rose by 1.15°C between 1850–1900 and the most recent decade, 2013–2022. Volume 1 of this assessment report shows that we are already living in a changed climate. The effect of climate change is increasingly apparent in the changing occurrence and intensity of extreme weather events and impacts on natural systems, including the health and wellbeing of terrestrial, freshwater and marine ecosystems (see Chapter 2). The effects of human influence on climate are increasingly apparent in these changes, with impacts likely to worsen with continued global warming.

In Ireland, and in line with global patterns, annual average temperatures are now approximately 1.0°C higher than in the early 1900s. Sixteen of the top 20 warmest years since 1900 have occurred since 1990 (Volume 1, Summary for Policymakers, A.5). At regional scales such as Ireland, it is more difficult to extract the climate signal from natural variability for variables such as precipitation, but evidence shows that since the 1980s we have seen an increasing tendency towards wetter winters and higher annual rainfall totals (Cámaro García and Dwyer, 2021). In Ireland, median annual precipitation was 7% higher in the period 1991–2020 than in the 30-year period 1961–1990 (Volume 1, Summary for Policymakers, A.7). Increases in precipitation extremes are in line with expectations of heavier rainfall events in a warming world (Cámaro García and Dwyer, 2021).

Changes in climate are unfolding alongside other social, environmental and economic challenges that point towards an increase in vulnerability, making Ireland more sensitive to changes in climate. In recent decades, Ireland has seen a significant and ongoing deterioration in water quality (see Chapter 5), while declines in biodiversity on our island are a source of concern (see Volume 1 and Chapter 2). In many domains, a lack of investment in critical infrastructure has meant that many systems upon which our wider wellbeing depend have become less resilient, resulting in reduced ability to cope with surprise events or extremes. In addition, ongoing inflation, associated cost of living challenges and the housing crisis all serve to increase vulnerability to climate change and extreme weather events.

Climate action (see Figure 1.1) refers to efforts to reduce greenhouse gas emissions, known as mitigation, and the implementation of actions to deal with climate change impacts, known as adaptation. While much of the dialogue on climate action in Ireland has focused on mitigation (see Volume 2), less attention has been given to how we can adapt to the impacts of climate change. However, climate change is happening now; we already see the impacts. It is therefore essential that we see a step change in efforts to adapt to climate change. Both mitigation and adaptation are inherently linked. The less successful we are at mitigation, the more challenging adaptation will be. However, even if we are successful at limiting global warming to no more than 1.5°C or 2°C, in line with the Paris Agreement, we will still need to adapt to the impacts of climate change.

	Mitigation	Adaptation
What it means	Reduce our emissions and enhance sinks that sequester and store greenhouse gases – net zero	Adjust to expected and actual effects of climate change to reuce vulnerability
What it does	Address the root cause	Addresses the effect
Goals	Avoid the negative impact of climate change	Reduce risk and increase the ability to prepare, absorb and recover from adverse climate events (resilience). Increase our capacity to thrive under adverse climate conditions
Focus	Global impact	Local, start with the specific local situation
Geographies	Global north that has the highest emissions	Global south already experiences the effects and is more vulnerable to climate change
Examples	Clean energy, energy efficiency, sustainable transportation etc.	Disaster management, flood projection, infrastructure upgrades etc.

Figure 1.1 Climate action comprises both mitigation and adaptation. The figure highlights the key focus of both threads of climate action. Adaptation to the impacts of climate change is the focus of this volume. Source: Graf (2022; https://www.lilligraf.com).

This volume assesses climate change impacts and adaptation for key sectors in Ireland. We consider observed and projected impacts for marine, terrestrial and freshwater ecosystems (Chapter 2), agriculture, forestry and other land use (AFOLU) (Chapter 3), coastal environments (Chapter 4), water (Chapter 5), the built environment, heritage and rural communities (Chapter 6), critical infrastructure (Chapter 7), health and wellbeing (Chapter 8), and business, industry and tourism (Chapter 9). The range and breadth of these chapters alone point to how all aspects of Irish life are likely to be impacted by climate change and that adaptation needs to be systematic and integrative, coordinated and ambitious. In this chapter we provide the entry points for thinking about adaptation. We start by considering what recent extreme events tell us about vulnerability to climate change in Ireland, before outlining the policy landscape and introducing key concepts and terminology. Following our assessment of individual sectors in subsequent chapters, in Chapter 10 we consider how to better enable adaptation in Ireland to realise the step change in action required.

1.1.2. Recent extreme events evidence the need for adaptation

Recent extreme events highlight the vulnerability of individuals, communities, sectors and ecosystems to climate variability and change, emphasising the urgency of adaptation. The heatwave and drought of summer 2018 (Met Éireann, 2018), following on from Storm Emma and 'the Beast from the East', exposed the fragility of the agricultural system to weather extremes, with cereal yields down 20% on the previous year and significantly increased production costs in the dairy sector associated with poor summer grass growth and increased fertiliser inputs (Dillon et al., 2018). Overall, 2018 saw a 34% drop in average net margins for dairy farmers, with expenditure on animal feed nearly 50% higher in 2018 than in 2017 (Dillon et al., 2018; Falzoi et al., 2019). Drought conditions also exposed the vulnerability of the water sector, with widespread hosepipe bans, reliance on water tankers to meet potable water needs in some locations and degraded water quality with impacts for many ecosystems and species, while the National Emergency Coordination Group was convened to manage the situation. Despite such widespread impacts, the drought of 2018 was not as severe or as protracted as many other droughts in historical records (e.g. Noone et al., 2017). Subsequent drought in spring 2020, although more spatially restricted to the east of the country, brought the risk of water restrictions during the height of the COVID-19 pandemic and focused attention on water as a critical public health issue (Figure 1.2).

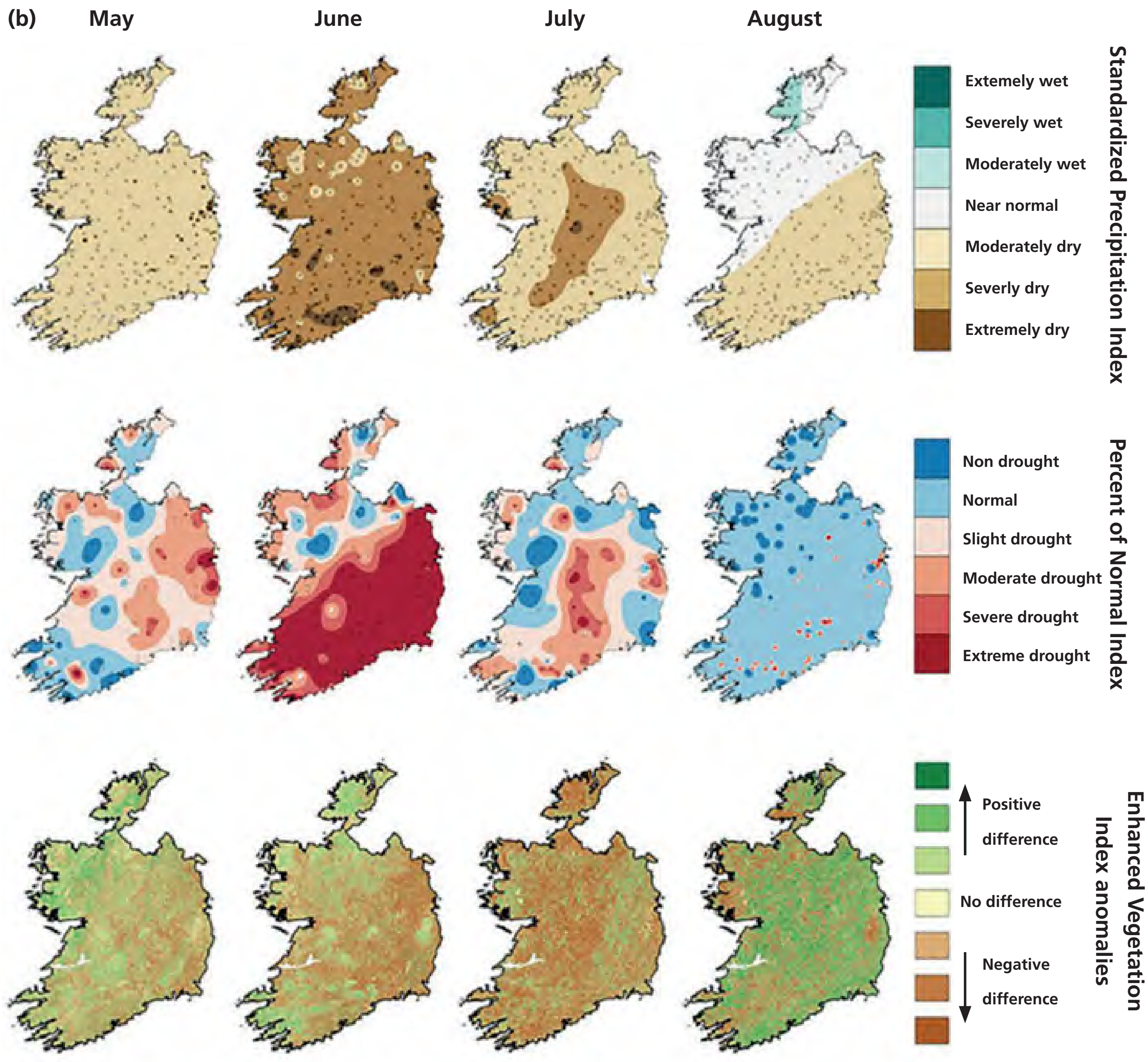


Figure 1.2 Overview of the 2018 drought from different metrics, including the monthly Standardised Precipitation Index (SPI) and per cent of normal index for precipitation, both of which indicate how different from normal precipitation conditions during summer months in 2018 were. Also included is an assessment of vegetation responses using MODIS satellite data, showing the reduction in vegetation growth as the drought progressed. Source: Reproduced from Falzoi et al. (2019) with permission from the Royal Meteorological Society.

The heatwave and extreme temperatures during summer 2018 resulted in challenges for the transport sector because of melting roads and the buckling of railway tracks. Soil moisture deficits created challenges for forestry and wetlands, with widely reported wildfires. Human health was also affected, with patients in hospitals and nursing homes highlighting the unbearable indoor temperatures and a lack of appropriate air conditioning. Research has shown that mortality rates in Ireland are temperature dependent (Goodman et al., 2004; see Chapter 8), with numerous heatwaves in the past 50 years associated with a discernible excess mortality (Pascal et al., 2013). With an ageing population and rising temperatures, such impacts are likely to increase in future without appropriate adaptations to building designs and the health system, and changes at the individual level.

Recent decades (2000 onwards) have also highlighted Ireland's vulnerability to floods and windstorms. Over the period 2000–2014, total insured losses from flooding exceeded €1 billion, with the 2009 floods alone resulting in costs of more than €244 million (Insurance Ireland, 2010). For 2009, Insurance Ireland estimates that the largest proportion of insured losses were associated with commercial properties, followed by households and motor claims. Storm Darwin in February 2014 occurred during the stormiest winter on record for Ireland (Matthews et al., 2014) and resulted in > €110 million in damages, with more than 260,000 homes left without power. Darwin exposed vulnerability within the electricity network to saturated ground conditions and the integrity of pylons. It is estimated that up to 7.5 million trees were felled, representing almost 1% of total forestry in Ireland. The impact of fallen trees and damaged infrastructure on transport networks was compounded by lorries being overturned on busy motorways by high winds. Widespread flooding in winter 2015/16, Ireland's wettest winter in more than 300 years, resulted in extensive and prolonged river and groundwater flooding, affecting agriculture, private homes and business, and human health through contamination of water sources (Boudou et al., 2021; Figure 1.3). Together these events highlight national vulnerability to extremes, any associated increases in their magnitude and frequency with climate change and the importance of adaptation.

Figure 1.3 Aerial image of the extent of flooding around Athlone in January 2016. Source: Irish Times/Irish Air Corps.

1.2. The policy context

1.2.1. International

The United Nations Framework Convention on Climate Change Paris Agreement (2015) and the 2030 Agenda for Sustainable Development (2015) provide the overarching goals and strategy for climate action (both mitigation and adaptation) globally. The Paris Agreement frames local, national and private sector actions, addressing both mitigation and adaptation. For mitigation, the Paris Agreement "reaffirms the goal of limiting global temperature increase to well below 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees" (UNFCCC, 2016). For adaptation, the Paris Agreement establishes a global goal of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change in the context of the temperature goal of the Agreement. It aims to significantly strengthen national adaptation efforts, including through support and international cooperation. It recognises that adaptation is a global challenge faced by all. All Parties should engage in adaptation, including by formulating and implementing national adaptation plans, and should submit and periodically update an adaptation communication describing their priorities, needs, plans and actions (UNFCCC, 2016). The United Nations 2030 Agenda for Sustainable Development sets out 17 Sustainable Development Goals (SDGs) that frame policies for achieving a more sustainable future. SDG 13 (Climate Action) aligns with the Paris Agreement's objective of strengthening the global response to the threat of climate change, in the context of sustainable development, while effective climate action will be critical to realisation of other SDGs, given the inherent connection between environment and human development. Climate compatible development (Mitchell and Maxwell, 2010) and climate-resilient pathways (Denton et al., 2014) combine adaptation and mitigation to realise the goal of sustainable development.

The Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) also recognises that some disasters are exacerbated by climate change, impeding progress towards sustainable development. Realisation of climate resilience globally will be determined by the success of these three important conventions (see Figure 1.4). International policy also recognises the close links and feedbacks between climate change and biodiversity. The Convention on Biological Diversity (CBD), one of the key legal instruments for the conservation of biodiversity, recognises that biodiversity is affected by climate change, with negative implications for human socioeconomic and environmental wellbeing, while biodiversity is also critical to both climate change mitigation and adaptation.

1.2.2. Europe

The European Commission's 'Forging a climate-resilient Europe – the new EU Strategy on Adaptation to Climate Change' outlines a long-term vision for the EU to become a climate-resilient society, fully adapted to the unavoidable impacts of climate change by 2050. Central to the strategy is reinforcing and developing adaptive capacity and minimising vulnerability to the impacts of climate change in line with the Paris Agreement and the proposal for a European Climate Law (for achieving climate neutrality by 2050), the Sendai Framework for Disaster Risk Reduction and the Sustainable Development Agenda, as represented by the European Green Deal. The new EU strategy aims to build a climate-resilient society by improving knowledge of impacts and adaptation solutions, stepping up adaptation planning and climate risk assessments, accelerating adaptation action and helping to strengthen climate resilience globally. Four objectives underpin the new EU strategy:

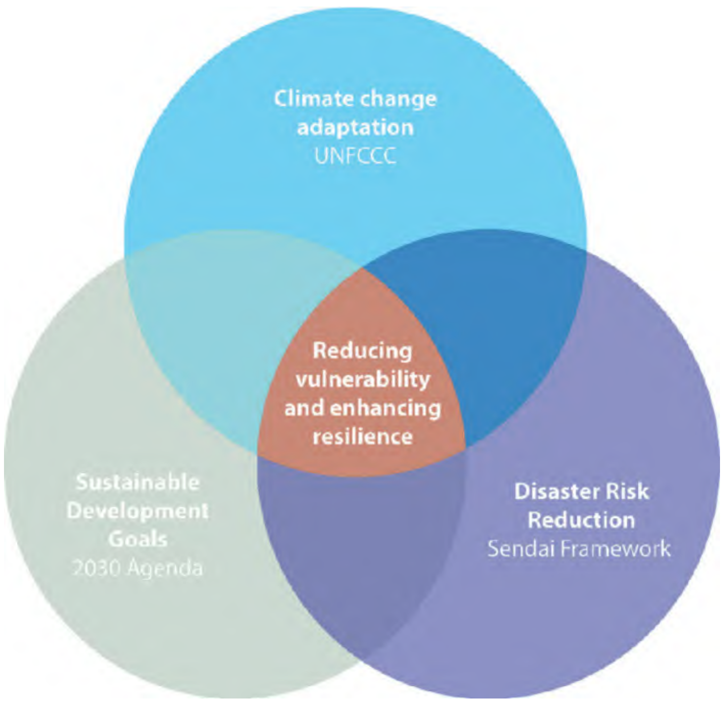


Figure 1.4 Opportunities and options for integrating climate change adaptation with the SDGs and the Sendai Framework for Disaster Risk Reduction 2015–2030. Source: UNCCS (2017).

Smarter adaptation: improving knowledge and managing uncertainty through advancing the frontiers of adaptation knowledge, more and better climate loss data and enhancing and expanding climate services platforms (e.g. Climate-ADAPT) for adaptation knowledge.

Systematic adaptation: advancing adaptation policy development at all levels of governance and related policy fields, including integration of adaptation into fiscal policy, nature-based approaches and local adaptation actions.

Faster adaptation: speeding up implementation of adaptation actions across the board.

Stepping up: international action on adaptation to climate change

1.2.3. Ireland

The Climate Action and Low Carbon Development Act 2015 (henceforth Climate Act 2015) and the Climate Action and Low Carbon Development (Amendment) Act 2021 (henceforth Climate Act 2021) constitute Ireland's policy framework for delivering on the national climate objective to pursue and achieve, by no later than the end of the year 2050, the transition to a climate-resilient, biodiversity-rich, environmentally sustainable and climate-neutral economy. Climate change adaptation, which will play a crucial role in successfully achieving the national climate objective, is underpinned by the National Adaptation Framework (NAF; DECC, 2018), which provides the strategic policy focus to ensure that adaptation measures are taken across all levels of government. The NAF places a statutory requirement on government departments to develop adaptation plans for key sectors of the Irish economy and on local authorities to develop local-level adaptation strategies, both of which are central to the development of the national climate action plan.

Ireland's first statutory 5-year NAF was published in January 2018 and identifies 12 key sectors requiring sectoral adaptation plans. These sectoral adaptation plans, developed in line with the *Sectoral Planning Guidelines for Climate Change Adaptation* (DCCAE, 2018a), were approved by the government and published in October 2019 (see Table 1.1). The completed plans identify and assess the extent of risks presented by climate change to each sector and the plans put in place to address these risks, and ensure the resilience of the sector. Each sectoral plan also identifies actions to mainstream adaptation policy at sectoral levels and improves cooperation and coherence across other sectors and with local government. In accordance with the Climate Act 2021, sectoral plans were also subject to statutory consultation processes with the public, the Minister for the Environment, Climate and Communications, the Minister for Finance and Public Expenditure and Reform, the Climate Change Advisory Council (CCAC) and the EPA. The National Adaptation Steering Committee, chaired by the DECC, also facilitated discussion and identification of wider cross-sectoral issues of importance to adaptation.

Table1: *Adaptation and themes as per2018 NAF*

Theme	Sector level	Lead department for sectoral adaptation plans[a]
Natural and cultural capital	Seafood	Department of Agriculture, Food and the Marine
	Agriculture	
	Forestry	
	Biodiversity	Department of Culture, Heritage and the Gaeltacht
	Built and archaeological heritage	
Critical infrastructure	Transport infrastructure	Department of Transport, Tourism and Sport
	Electricity and gas networks	Department of Communications, Climate Action and Environment
	Communications networks	
Water resource and flood risk management	Flood risk management	Office of Public Works
	Water quality	Department of Housing, Planning and Local Government
	Water services infrastructure	
Public health	Health	Department of Health

[a] Note that department names may have changed since publication of the NAF.

In addition to sectoral adaptation plans, and in recognition of the importance of local authorities in delivering climate action, the NAF and the Climate Act 2021 require each local authority to develop, on a 5-year basis, a local authority climate action plan outlining the mitigation and adaptation measures to be adopted. In 2019, all local authorities developed and published their local adaptation and mitigation (climate action) strategies in line with the *Local Authority Adaptation Strategy Development Guidelines* (DCCAE, 2018b). These strategies are to be used to inform development and other statutory plans of the local authority to help ensure mainstreaming of adaptation into local government systems over the medium and long term. The development of new local authority climate action plans is currently under way and due for delivery in 2024. To support development of coordinated efforts on climate action across local authorities, the Department of the Environment, Climate and Communications (DECC) established four climate action regional offices in 2018 led by Mayo (Atlantic Seaboard North), Cork (Atlantic Seaboard South), Dublin (Dublin Metropolitan Region) and Kildare (Eastern and Midlands) County Councils.

In 2022, DECC undertook a review of the 2018 NAF in line with the requirements of the Climate Act 2021 (DECC, 2022a). This review took account of feedback from key stakeholders, adoption of the new 2021 EU Adaptation Strategy, policy advances nationally since 2018 and the views of the CCAC. The key outcome from this review was recognition of the need for a fundamentally new NAF, structured to take account of changing knowledge, legislative environments and feedback that embodies learning from the 2018 NAF. The development of a new NAF will be an intensive project and is due to be completed in 2023. Priority areas for revision include:

- defining a distinct vision of Ireland's climate resilience, expanding on that contained in the 2018 NAF, together with the resourcing needs for its achievement, alongside better understanding of the societal and economic implications of not addressing current and future vulnerabilities;
- revision of key sectors required to produce sectoral adaptation plans, including extension of adaptation planning to finance and financial services, tourism, coastal areas and urban areas (built environment), nature-based approaches and disaster risk reduction;
- the necessity of an overarching national climate change risk assessment to identify common priority areas and adaptation actions that also consider pressures in addition to climate change;
- the need for additional guidance on the selection and implementation of adaptation indicators;
- extension of adaptation planning to the private sector, including business, communities and individuals;
- increased clarity on the relationship between mitigation and adaptation, sustainable development and disaster risk reduction;
- a greater need for consideration of socioeconomic vulnerability and just resilience in the context of adaptation policy and planning;
- increased emphasis on the importance of nature-based approaches and how they can increase climate resilience;
- increased recognition of the importance of transboundary and cross-border climate risks;
- updating of sectoral adaptation planning guidelines and alignment of sectoral plans with local authority climate adaptation plans.

A significant development for Irish adaptation was government approval in June 2022 to establish the Irish National Framework for Climate Services (NFCS) (see Chapter 10). The primary aim of the NFCS is to support Irish national adaptation initiatives, including the NAF, sectoral adaptation plans, local authority climate action plans, as well as agency, semi-state and private adaptation planning. The NFCS objective is to provide standardised, user-tailored, co-created climate data and information. The NFCS standardised outputs, led by Met Éireann, will be disseminated via Climate Ireland, led by the EPA, which will also work to put guidance in place to ensure that information is used in a consistent manner within and across sectors.

1.3. Key concepts and entry points

1.3.1. Defining adaptation

The Climate Act 2015 provides a legal definition for adaptation as "adjustment to (a) any system designed or operated by human beings, including an economic, agricultural or technological system, or (b) any naturally occurring system, including an ecosystem, that is intended to counteract the effects (whether actual or anticipated) of climatic stimuli, prevent or moderate environmental damage resulting from climate change or confer environmental benefits". This maps closely to Intergovernmental Panel on Climate Change (IPCC) definitions, which also distinguish adaptation in natural and human systems and highlight their interconnected nature and co-dependency. IPCC Working Group II (WGII) Sixth Assessment Report (AR6) defines adaptation in human systems as the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, adaptation is defined as the process of adjustment to actual climate and its effects (Ara Begum et al., 2022). For natural systems, human intervention may facilitate adjustment to expected climate and its effects. According to the IPCC (2022), adaptation is often associated with five general stages: awareness, assessment, planning, implementation, and monitoring and evaluation (Ara Begum et al., 2022). Responsibility for adaptation falls to a range of actors, including governmental, non-governmental, private sector, community and individual actors. In Ireland, adaptation actions have tended, thus far, to be focused on governmental actors; however, the realisation of a climate-resilient Ireland will require adaptive action from all actors.

1.3.2. Risk, hazard, exposure and vulnerability

Key to understanding and implementing adaptation are the interrelated concepts of risk, exposure and vulnerability. Risk signifies the potential for adverse consequences for human or ecological systems (Ara Begum et al., 2022) and originates from a combination of social processes and their interaction with the environment (Cardona et al., 2012). In the context of climate change, risks emerge from the dynamic interactions between climate change (changing average conditions and variability) and related hazards (e.g. heatwaves, floods, droughts, etc.), exposure and vulnerability (see Figure 1.5). Importantly, climate change is not the sole driver of risk, with adverse outcomes in good part determined by the vulnerability and exposure of societies, infrastructure and ecosystems (Birkmann, 2006; Cardona et al., 2012). Moreover, risk is not fixed but is dynamic and in constant evolution, as the frequency and intensity of hazards change with climate change and as exposure and vulnerability change through many drivers. Both exposure and vulnerability are also highly context specific. As a result, adaptation needs to be seen as not as a single intervention fixed in time, but a process that responds to the dynamics and evolution of risk. This is the idea of adaptation as iterative risk management (Ara Begum et al., 2022), whereby emphasis is placed on adaptation as an ongoing process of learning and improvement, with assessment, action, monitoring and evaluation, learning and improvement.

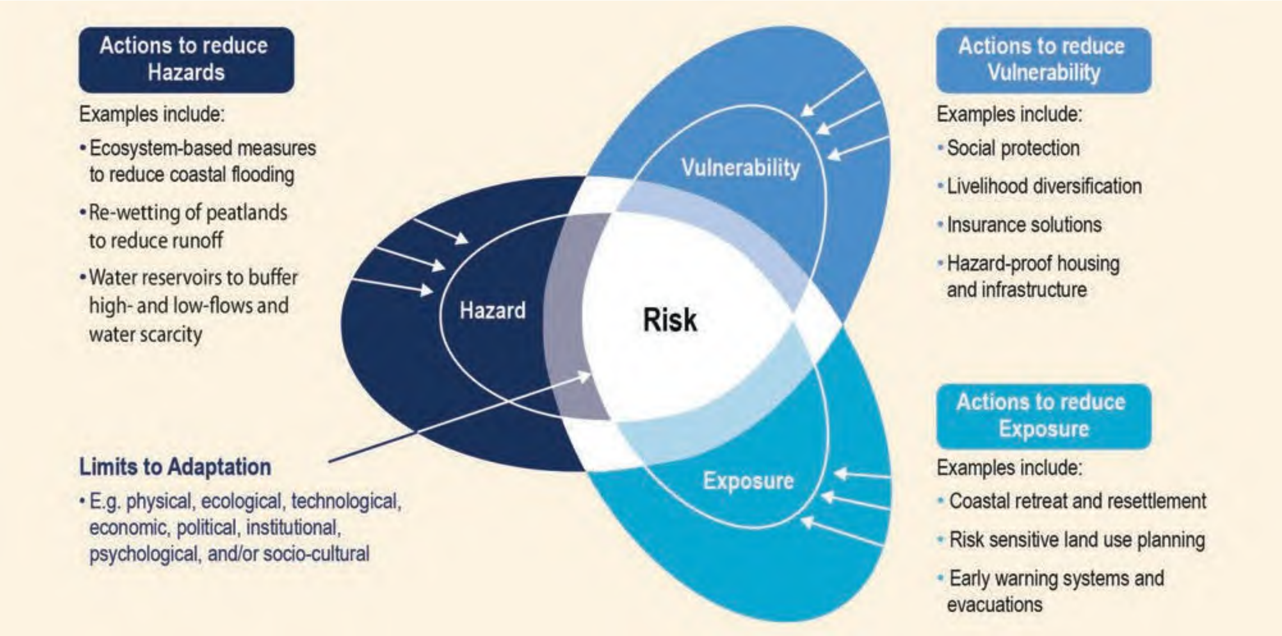


Figure 1.5 Adaptation can reduce risk by addressing one or more of the three risk factors: vulnerability, exposure and/or hazard. The reduction of vulnerability, exposure and/or hazard potential can be achieved through different policy and action choices over time until limits to adaptation might be reached. Source: IPCC (2019; their figure TS.4; modified with permission).

Exposure refers to the presence of people, species or ecosystems, resources, services, infrastructure, or economic, social or cultural assets in places and settings that could be adversely affected by climate hazards. Exposure is a necessary but insufficient determinant of risk. For example, it is possible to be exposed but not vulnerable. Vulnerability refers to the propensity of exposed elements to suffer adverse effects when impacted by hazard events. It is therefore related to predisposition, fragilities, susceptibilities and lack of capacities that favour adverse outcomes. While vulnerability can be hazard specific, issues such as poverty, gender, lack of social networks and support mechanisms aggravate or amplify vulnerability, irrespective of hazard. For natural systems, a critical component of vulnerability may be the inability to adapt, considering the temporal and spatial impacts and disturbances. Vulnerability is therefore intrinsically tied to social, cultural and environmental processes (Adger, 2006), and to deficits in risk communication (Cardona et al., 2012). Critical for adaptation is that poor decisions, maladaptation or evolving conditions (social, political, economic, environmental, etc.) can also undermine the effectiveness of existing adaptation measures, resulting in increasing vulnerability.

1.3.3. Resilience

IPCC AR6 defines resilience as "the capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure" (Ara Begum et al., 2022). Resilience therefore is a positive attribute focused on maintaining capacity for adaptation, learning and transformation (see section 1.3.5). Given the importance of resilience as part of the national objective on climate change (see section 1.3.3), it is important to recognise its links to vulnerability, exposure and risk. The 2018 NAF defines resilience as "the capacity of a system, whether physical, social or ecological, to absorb and respond to climate change by implementing effective adaptation planning and sustainable development (including governance and institutional design) to reduce negative climate impacts while also taking advantage of any positive outcomes. This will allow the system to either return to its previous state or to adapt to a new state as quickly as possible." (DECC, 2018). However, resilience is about more than speed of recovery following disturbance. Such a narrow framing can result in maladaptation, reducing resilience to maintenance of the status quo, with the assumption that current systems are sustainable with existing vulnerabilities and their root causes being ignored. Therefore, resilience overlaps with concepts of risk and vulnerability; it is about creating a society, economy and environment that can undergo change and maintain function (i.e. the services and supports that people rely upon) while retaining the capacity to adapt and transform into the future.

A resilience-based approach is founded on the understanding that the natural state of any system is one of ongoing and dynamic change rather than equilibrium. Consequently, adaptation within a resilience framework means managing for flexibility, avoiding being overly adapted to a narrow set of conditions, preparing for navigating extremes and surprises, avoiding decisions that create lock-in and reduce the capacity for future flexibility, maintaining a diversity of responses, and developing and maintaining adaptive capacity (see next section) in designing and implementing adaptation strategies to reduce vulnerability (Nelson et al., 2007). The success of adaptation in a resilience framework is contingent on negotiating and defining goals around what a desirable state (considering the socioecological changes under way) looks like and that accounts for competing values and worldviews, sometimes recognising that the maintenance of the status quo may not be feasible or desirable. A balance must be negotiated between what is an acceptable level of risk and the breadth of flexibility necessary to respond to future change.

1.3.4. Adaptive capacity

The IPCC defines adaptive capacity as the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences (Ara Begum et al., 2022). Adaptive capacity is reflective of the ability to undertake adaptation and can be influenced by managerial ability, access to financial, technological and information resources, infrastructure and institutional context (Smit and Wandel, 2006). Adaptive capacity is highly context specific and varies from sector to sector, from community to community, among social groups and individuals and over time. While adaptation is a realisation of adaptive capacity, higher degrees of adaptive capacity do not mean that adaptation action will follow automatically, nor that it will succeed in terms of equity and effectiveness in reducing vulnerability to climate change and enhancing wellbeing (Ara Begum et al., 2022). To date in Ireland little research has formally evaluated adaptive capacity for key systems. Moreover, the adaptive capacity of natural systems should also be considered and recognised as a legitimate and important area where further research is required.

1.3.5. Types of adaptation

There are a range of ways to conceptualise adaptation, including anticipatory and reactive approaches and incremental and transformational adaptation, with each approach drawing on particular values and rationales (see Volume 4). Proactive adaptation reflects action taken in anticipation of climate change risks and events, embedded in longer-term planning horizons and policy directions, and often focused on collective action for the public good, and to date is often carried out by governments rather than individuals (Berrang-Ford et al., 2011). Reactive adaptation reflects actions taken after extreme events or in response to incremental climate-driven change. Here the time frames are shorter and the drive is often to return to status quo and to restore welfare (Quinn, 2014). It should be noted that recent extreme events show an adaptation deficit,

and that reactive adaptation has not kept pace with changing hazards, exposure or vulnerability. Planned adaptation draws on resources now to avoid negative impacts in the future, while reactive adaptation uses resources now to respond to events as they occur. The reality is that these types of adaptation happen concurrently; we are now adapting to climate change, but we also are anticipating increasing risks going forward and the adaptation strategies that are required. The type of adaptation strategies that we engage with can be incremental, where communities maintain current social–ecological systems and can also become increasingly transformative by changing the fundamental attributes of a social–ecological system and often the associated institutions and governance structures. It is possible for incremental changes to collectively contribute to transformational change when they are coordinated within a longer-term adaptation plan (Magnan et al., 2020).

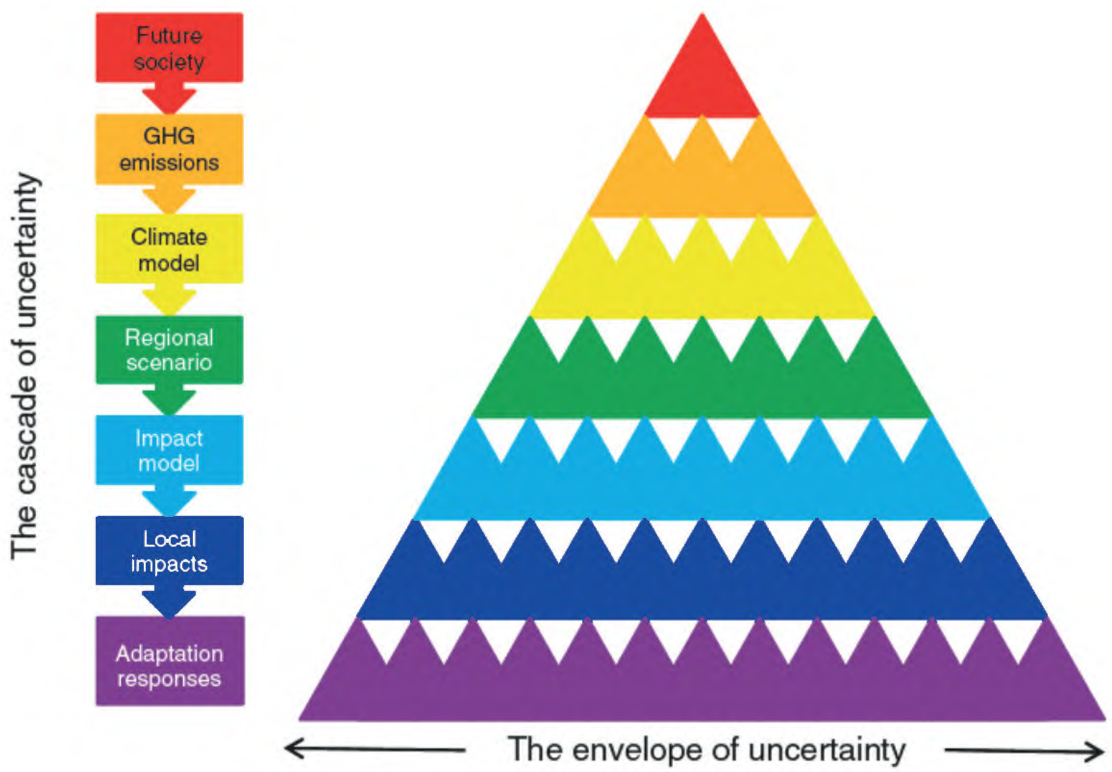
1.4. Information for informing adaptation

The most common approach to informing adaptation is by climate model projections to assess future impacts in the sector/location of interest. This involves complex modelling chains, typically implemented by researchers/scientists, with results provided to decision makers. Box 1.1 provides an overview of the steps involved in using climate models to assess future impacts for informing adaptation. While decision makers often look for a precise answer or most likely outcome, it is important to realise that future projections of impacts are not deterministic and contain, sometimes very large, uncertainties. For successful adaptation, it is critical that decision making recognises this and is based on the range of plausible changes. This is even more important where adaptation decisions concern critical infrastructure and/or where exposure and vulnerability are high. Chapter 10 further explores how climate services and decision making frameworks can help decision makers grapple with uncertainty.

A key challenge in compiling this assessment and for adaptation more generally is that there is a very uneven distribution of climate change impact assessments across the different sectors considered in each chapter. To date, there has been no programmatic funding of research to systematically assess impacts across sectors using a consistent set of climate model projections. Rather, available information is more contingent on the activities of individual researchers in different areas of study. This results in considerable gaps in knowledge in key sectors and is also evident in many adaptation actions put forward in the recent sectoral adaptation plans, which call for more research on future risks to inform adaptation. As Ireland progresses to establishing a coherent set of climate model projections for informing adaptation via the TRANSLATE project (see Volume 1), it is important that these projections capture the plausible range of change in future impacts and are used systematically to inform assessments of future impacts across key sectors. This will require considerable funding support to ensure that assessments of future impacts are available for informing the next iteration of adaptation plans. Furthermore, while the appropriate use of climate change projections is important, if adaptation is to consider vulnerabilities and exposure, then focusing only on future hazards is insufficient and needs to be supplemented with assessments of exposure and vulnerability.

Box 1.1 Evaluating future climate impacts using climate models

How do scientists assess what climate change impacts may be for different receptors such as cities, river catchments, ecosystems and agriculture? Methods have been developed over many decades and rely on modelling chains (see Box 1.1, Figure 1) that begin with the development of scenarios of what future global society might look like in terms of demographics, economic development pathways, technological developments, global governance, etc. These aspects of the future are unknowable; thus, scenarios are used to develop plausible and consistent storylines of an uncertain future. From these visions of future society, integrated assessment models are used to develop trajectories of greenhouse gas concentrations and/or emissions scenarios, which allow scientists to develop understanding of climate forcing consistent with future development pathways.



Box 1.1 Figure 1 The modelling chain and associated cascade of uncertainty in climate change impact assessments. Source: Wilby and Dessai (2010).

In the IPCC Fifth Assessment Report, representative concentration pathways (RCPs) were used to represent future concentrations of greenhouse gases in the atmosphere. The four key RCPs (RCP2.6, RCP4.5, RCP6 and RCP8.5) were defined by their total radiative forcing (expressed in watts per square metre) and level by 2100.

More recently, RCPs have been replaced by shared socioeconomic pathways (SSPs) in the IPCC AR6 to explore how societal choices will affect greenhouse gas emissions and the realisation of the Paris Agreement targets. SSPs offer five broad pathways that the world might take, ranging from a business-as-usual world without implementation of climate policy (SSP5) to a world that shifts to a sustainable path and realises the Paris Agreement targets (SSP1) (see Volume 1 for a summary of RCPs and SSPs and their relationships).

Greenhouse gas emissions are then used to force climate models to derive simulations of future climate. Climate models are complex tools that represent our best understanding of how the climate system works. The complexity of the climate system means that different climate models have slightly different representations of key processes, and therefore there are many different climate models available. Best practice for assessing future climate change impacts is to use a broad selection or ensemble of available models. To facilitate this, the international modelling community has developed the Coupled Model Intercomparison Project (CMIP) (see Volume 1, Cross-volume Box 1), which provides projected changes in global climate, forced by different emissions scenarios for many climate models.

Despite increasing computing resources, global climate models still operate at too coarse a resolution to be useful for most local-scale impacts assessment, and thus some form of regionalisation or downscaling is required to link local climate with the output from global climate models. There are many different approaches to regionalisation, each with their own assumptions, advantages and limitations. Common approaches that have been employed in Ireland include statistical methods and/or the application of regional climate models (climate models that operate at a much higher resolution over a region of interest (domain) and take the 'parent' global climate model as input).

Once regionalised, projections of future climate for different emissions scenarios are used as input to impact models at the local scale. For assessing changes in water resources or floods, this might be a hydrological model representing the river catchment of interest. Again, different impact models are available, each giving different outputs depending on the model used. These impact models are used to assess changes in the impact of interest (e.g. crop yield, drought, flood events, etc.) from an ensemble of climate models for different emissions scenarios, and inform adaptation responses at the local scale.

This modelling chain is associated with subjective decisions along the way, such as which emissions scenarios, climate models, regionalisation approaches and impact models to use and how to deploy them. These decisions result in different outputs regarding the impact of interest. In addition, plausible ranges of change (termed uncertainty) widen and cascade, moving from one step in the modelling chain to the next, resulting in a wide range of plausible impacts at the local scale. This can be challenging for adaptation, where decision makers would like a single value or narrow range of change on which to base decisions. This cascade of uncertainty in future climate impacts is well known by researchers (and represented in Box 1.1, Figure 1), but often less appreciated by decision makers. Ensuring a climate-resilient Ireland must mean that we take the full range of uncertainty (plausible ranges) into account when developing adaptation solutions.

While climate model projections and associated impact assessments are important for informing adaptation, other types of information are also of utility. Ireland has a rich history of weather observing, extending back over centuries, and many academics have made significant contributions to understanding historical climatology. There is also a rich history of paleoclimate and documentary-based research that could be useful for adaptation planning. Far from being of academic interest only, catalogues of past extreme events can be used to stress test adaptation decisions, portfolios of adaptation options and the performance of critical infrastructure. Such datasets (e.g. the Irish drought catalogue in Figure 1.6) provide decision makers with information about extreme events that may be well outside recent experience, allowing them to identify vulnerabilities and how systems would succeed or fail if such events were to reoccur. These historical datasets could also be used in combination with climate model projections to evaluate how likely their occurrence would be in a climate-changed future or used as analogues to develop storylines to assist the discussion of key vulnerabilities and adaptation options. IPCC AR6 has emphasised the utility of such approaches, but they remain undeveloped in Ireland.

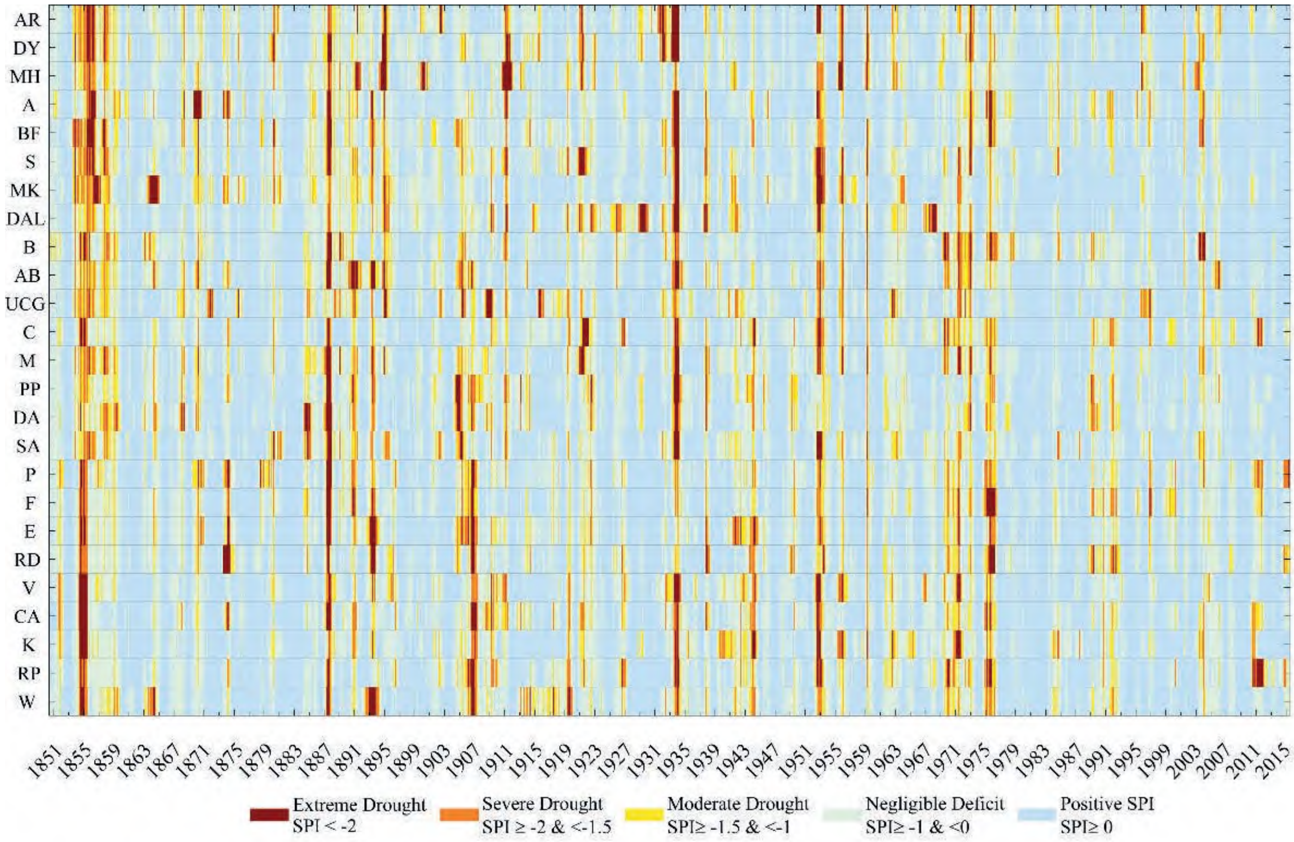


Figure 1.6 A history of Irish drought showing severe (orange) and extreme (brown) drought conditions for 25 precipitation stations across Ireland from 1850 to 2016. Recent decades have been relatively drought poor, highlighting the value of historical records and extremes for stress testing adaptation decisions using events outside the range of recent experience. Source: Reproduced from Noone et al. (2017) with permission from the Royal Meteorological Society.

Given that climate risks are a product of hazards, exposure and vulnerability, climate change adaptation also needs to be informed by assessments of vulnerability. In addition, climate action in Ireland is framed within the concept of just transition. To date, the national debate on a just transition has focused on mitigation and transition to a climate-neutral Ireland. However, there are important aspects of justice in adaptation (see section 1.6.1). Moreover, the development of adaptation plans, and the assessment of outcomes, depends heavily on success in reducing vulnerability. This is difficult, if not impossible, without a better understanding of the spatial and temporal dynamics of vulnerability. Recent work has sought to advance the assessment of Irish social vulnerability to environmental hazards (Fitton et al., 2021); however, this work needs to be expanded and consideration given to how such vulnerability assessments can be operationalised to inform the development of adaptation action plans and the evaluation of outcomes. Chapter 10 returns to the importance of monitoring and evaluation for progressing adaptation in Ireland.

1.5. Progress on adaptation in Ireland

Under the Climate Act 2015 the NAF mandates 12 priority sectors and local authorities to develop adaptation plans to assess climate change risks, identify adaptation actions, prioritise actions, mainstream adaptation policy and implement actions to advance climate resilience. Following publication of the first set of adaptation plans in 2019, the CCAC developed and refined an adaptation scorecard to measure the progress of adaptation plans against the NAF objectives and monitor implementation of the NAF itself (CCAC, 2021, 2022). The adaptation scorecard evaluates progress via three primary criteria:

Risk, prioritisation and adaptive capacity: which assesses whether sectors are identifying and monitoring risks, addressing key knowledge gaps and building adaptive capacity.

Resourcing and mainstreaming: which assesses whether sectors are taking climate change into account in decision making and if adaptation is being mainstreamed and resourced appropriately.

Governance, coordination and cross-cutting issues: which assesses whether sectors are ensuring good coherence with other policies and if systemic coordination is in place, both within the sector and across other sectors.

In its 2022 annual review (CCAC, 2022), the CCAC reports that, despite existing vulnerabilities and significant exposure to climate change, most sectors demonstrate only moderate or limited progress towards adaptation, with some sectors demonstrating no progress and others failing to engage sufficiently with the review process for an evaluation to be undertaken. Only two sectors (flood risk management and local government) showed good progress towards adaptation, with no sector achieving advanced progress. Across sectors, the greatest progress in adaptation is evident within the criteria of risk, prioritisation and adaptive capacity. However, while actions for addressing knowledge gaps are in place for most sectors, certain research areas remain underrepresented, while knowledge sharing across and between sectors could be improved. There is also a need for improved translation and dissemination (climate services – see Chapter 10) of research to ensure that research better informs policy.

The 2022 annual review also highlights limited evidence for the permeation of adaptation into decision making or the integration of climate change into policy development. While each sector identifies numerous adaptation actions, efforts at prioritisation were found to be lacking. Moreover, the 2022 annual review reports a lack of detail with regard to risk monitoring across most sectors, while resourcing remains a key constraint across the board, especially in the context of the COVID-19 pandemic, which has created a barrier to achieving adaptation policy goals and restricted progress, most notably in the health sector. Governance, coordination and cross-cutting issues was the weakest area of adaptation assessed, with an evident need for strengthening leadership on adaptation across sectors to drive ambition and govern action. Overall, in its assessment of progress on adaptation in Ireland, the CCAC concludes that the limited number of sectors showing at least good progress is "worrying". Given the scale of risks facing Ireland, this is an issue that needs to be addressed urgently (CCAC, 2022).

1.6. Opportunities and challenges for adaptation

Adaptation aims to reduce the exposure and vulnerability of humans and ecosystems to climate risks. However, there is no universally accepted way of measuring adaptation success. What might be viewed as successful at one place and time might not be at another. In addition, the benefits and costs of adaptation may be unequally distributed. In this section, we identify challenges and opportunities for adaptation, including a focus on outcomes, avoiding maladaptation, overcoming limits, adopting a systematic approach through climate-resilient development, widening the solution space and monitoring and evaluating progress and outcomes.

1.6.1. Outcomes: effective, feasible and just adaptation

Successful adaptation is associated with multiple positive outcomes, including a reduction in climate risks and vulnerabilities for humans and ecosystems, increased wellbeing and co-benefits with other sustainable development objectives (New et al., 2022). IPCC AR6 highlights successful adaptation 'solutions' as an *effective*, *feasible* and *just* means of reducing climate risk, increasing resilience and facilitating other climate-related societal goals (e.g. mitigation) (New et al., 2022). It should be noted that while the term 'solution(s)' suggests finality, that a problem is solved, and often denotes a narrow set of technical solutions, adaptation should be viewed as iterative, dynamic, ongoing and encompassing a broad set of knowledge, including both technical and non-technical approaches. Climate change risks and vulnerability are ever changing, and so adaptation is an ongoing process of learning and improvement. Adaptation is just when the decision making process of selecting and implementing actions and their associated outcomes recognises the principles of distributive (fair distribution of the burdens and benefits of adaptation), procedural (fair participation in decision making processes) and recognitional (fair consideration of diverse values, cultures, perspectives, and worldviews) justice (Ara Begum et al., 2022). Adaptation can be evaluated as effective to the extent that it achieves its intended outcome of reducing risk within a stated time frame. Measures of effectiveness can be broad ranging, from economic effectiveness through assessment of costs and benefits to wider multidimensional measures of societal wellbeing. The feasibility of an adaptation action concerns the extent to which it is desirable or possible within the context of its implementation. The IPCC AR6 and Special Report 1.5 (SR1.5) (IPCC, 2018) reports consider different dimensions of feasibility: geophysical, environmental–ecological, technological, economic, and sociocultural and institutional (IPCC, 2018; Ara Begum et al., 2022). Feasibility is context dependent, and so an adaptation action may be feasible in one context but not in another and may also vary over time. Context-specific aspects vary according to governance capacity, financial resources and public opinion/acceptability (Ara Begum et al., 2022). It is worth noting that a lack of feasibility may signal the need for transformative adaptation, indicating that action is needed on addressing underlying constraints or soft limits to adaptation (see Figure 1.7).

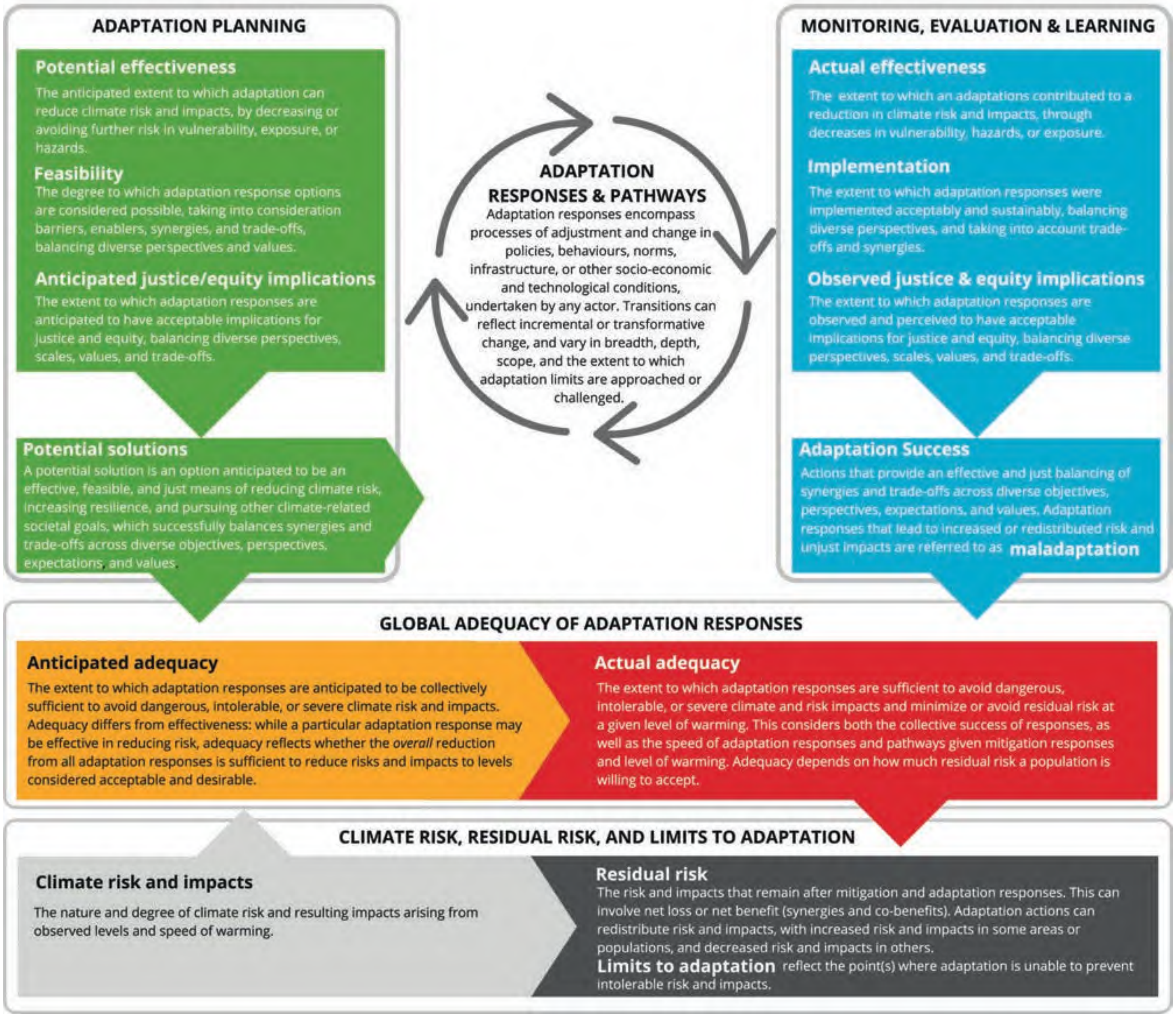


Figure 1.7 Assessing adaptation solutions and success. A solution is defined as an adaptation option that is effective, feasible and conforms to principles of justice. These attributes can be assessed ex ante during adaptation planning. During implementation, the overall success of a response can be judged via monitoring and evaluation of these attributes. Adaptation unfolds as an iterative learning process of assessment, implementation, monitoring, adjustment and learning. A set of responses is adequate to the extent that they sufficiently reduce climate risk to levels considered tolerable. Adaptation may not fully avoid residual risks, but the more adequate the response, the less residual risk remains. Adaptation also has limits beyond which it is no longer possible to avoid intolerable risks and impacts. Source: Ara Begum et al. (2022; their figure 1.7).

1.6.2. Avoiding maladaptation: adaptation as a response risk

Adaptation actions themselves can entail risks, termed response risks by the IPCC AR6. These include the risk of adaptation actions being ineffective and/or unjust, or resulting in unintended adverse effects on individuals, constraining their ability to meet other societal objectives or the ability of others to adapt to climate change. Maladaptation is a response risk and refers to the potentially adverse outcomes of certain adaptation actions, such as an increase in greenhouse gas emissions (e.g. air conditioners powered by fossil fuels to adapt to heat extremes), increases in vulnerability to climate change and reductions in welfare and/or wellbeing, or increases in vulnerability for certain parts of the population now or in the future (Ara Begum et al., 2022). Adaptation action taken today may set in train resource allocations and decision pathways that limit choices for future generations to adapt, increasing the risk of creating lock-in effects that limit future resilience. Maladaptation has been widely studied and tends to be associated with human, financial and technical resource constraints, lack of transparency and/or capacity in decision making and governance, lack of key policy guidance, entrenched institutional, legal and technical worldviews, exclusion of vulnerable groups or those affected by adaptation from the decision-making process, and where top-down planning approaches are not connected to local dynamics and needs (Ara Begum et al., 2022). Not all adaptation actions reduce risk, and some may have negative consequences. Maximising the likelihood of successful adaptation requires focusing on ideas of just adaptation, maintaining flexibility and response options to avoid lock-in and increase resilience, and ensuring satisfactory wellbeing outcomes for those affected (Quinn et al. 2023). Understanding the sustainability of adaptation measures is critical to avoiding maladaptation, and requires assessments of current and future vulnerabilities, together with monitoring programmes and subsequent evaluations of adaptation interventions. Such aspects should be a priority for future research into learning for adaptation.

1.6.3. Recognising limits

The effectiveness of adaptation is dependent on several factors, including the speed and magnitude of climate change impacts and the constraints and limits that human and natural systems face when confronted with increasingly higher levels of climate risk. Adaptation limits refer to the point at which adaptive actions no longer suffice and result in the inability of those affected to derive needs (e.g. resources, ecosystem services, health and wellbeing) from the impacted sector/system. Adaptation limits have been defined as hard or soft. Hard limits occur when the speed and/or magnitude of change is such that no adaptive actions can be taken to avoid intolerable risks (Dow et al., 2013). For resilience, limits to hard adaptation represent a level of change within a system that negates its ability to maintain essential functions and structure. Ecosystems and many species have been widely associated with environmental thresholds beyond which they cannot adapt.

Soft adaptation limits occur when adaptive options exist but are unavailable or cannot be deployed (for many reasons, including finance and social acceptance). Adaptation limits can arise from complex interactions between social, cultural, ecological, technological and climate factors that have thresholds beyond which adaptation can be infeasible (Ara Begum et al., 2022). For soft limits, thresholds tend to be endogenous to society and therefore are contingent on ethics, knowledge, culture, governance, institutions and policies (Tschakert et al., 2017). Constraints on adaptation, including financial, governance and institutional barriers, can lead to soft adaptation limits. O'Brien (2009) argues that adaptation limits may also be encountered in the form of the irreversible loss of place and identities that people value, raising important questions about the role of social values in adapting to climate change. In essence, many of the limits to adaptation that are likely to be encountered relate to social values, culture and risk perceptions. These areas are understudied in the Irish literature, and insights would be beneficial to ensuring the success of adaptation actions. Where limits are encountered, they may only be overcome by transformational adaptation. Adaptation and mitigation are closely linked in understanding limits to adaptation. The less successful mitigation is at reducing greenhouse gas concentrations, the greater the rate and magnitude of climate change and thus the greater the likelihood of encountering adaptation limits. Less mitigation makes adaptation harder or even impossible.

1.6.4. Climate-resilient development

Development decisions in a changing climate need to include choices and actions that reduce emissions and adapt to climate risks to sustain development over time – development processes can enhance vulnerability, while poorly designed climate action and maladaptation can deflect from sustainable development (Werners et al., 2021). Climate-resilient development is a process of implementing mitigation and adaptation to support sustainable development for all. It emphasises the integrative solutions within sectors or regions that address the socially and spatially uneven distribution of climate risks and extend the goals of climate action beyond risk reduction to improving social, economic and ecological outcomes (Schipper et al., 2022). By taking a systematic approach, climate-resilient development strengthens sustainable development and aims to promote fair and equitable approaches to mitigation and adaptation, promoting multiple co-benefits for society and nature. Climate-resilient development pathways emerge from the choices of multiple actors across scales including government, business, civil organisations, communities and individuals, and represent the results of negotiation, cooperation and competition among actors (Figure 1.8). Rather than identifying single adaptation solutions, climate-resilient pathways enable a mix of adaptation, mitigation and development appropriate to development contexts and shared goals, and they unfold in ways that are consistent with the principles of equity and social justice, thereby expanding the solution space. They also avoid fragmentation of adaptation efforts. Crucially, the idea of pathways is that resilience is not a fixed outcome, but a process of negotiation and management that can be achieved through a combination of incremental and transformative changes that improve livelihoods, social and economic wellbeing, and responsible environmental management.

Figure 1.8 Climate-resilient development pathways consolidate climate action and development decisions towards long-term sustainable development. Source: Werners et al. (2021). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

1.6.5. Widening the solution space

To date, most adaptation actions have been technically focused (e.g. flood walls, coastal defences). Existing adaptation gaps suggest that technical solutions on their own will not be sufficient to reduce climate risks. The concept of the solution space – defined as the space within which opportunities and constraints determine why, how, when and who adapts to climate risks – helps expand the set of effective, feasible and just solutions (Haasnoot et al., 2020). A larger solution space indicates people and organisations with more options for adapting to and reducing their risk from climate change. Schipper et al. (2022) highlight that widening the solution space requires leveraging interdisciplinary knowledge, bringing new ways of thinking and knowledge systems to the table to inform action that embraces plurality and complexity and avoids reductionist approaches. In addition to traditional scientific, engineering and economic approaches, working with nature through so-called nature-based approaches and integration of local knowledge are important but underimplemented approaches to widening the solution space.

The concept of nature-based approaches is broad and has increased in prominence in recent decades in both the scientific literature and international policy. Underpinning nature-based approaches are actions that benefit people and biodiversity while reducing climate risks. Nature-based approaches can range from restoration of degraded ecosystems to restore function, with multiple co-benefits for risk reduction, mitigation and biodiversity (e.g. the role of rewetting peatlands for flood management, carbon uptake and enhancing biodiversity), to implementation of nature-based approaches in heavily modified environments such as cities, where such approaches have been used for sustainable drainage systems to reduce flooding, to the use of green roofs and walls to promote cooling effects and air quality improvements in cities. Effective nature-based climate change adaptation stems from inclusive decision making and adaptive management pathways that deliver climate-resilient systems serving multiple sustainable development goals (Schipper et al., 2022). However, as with any adaptation solution, poorly conceived and designed nature-based efforts can result in maladaptation with potential for multiple negative impacts, reducing human wellbeing and a lack of sustainability (Schipper, 2020).

Increasingly, adaptation research is recognising the importance of diverse forms of knowledge, including scientific (natural and social sciences) as well as indigenous and local knowledge, in realising effective and just outcomes in reducing climate risks. Enhancing knowledge on risks, impacts, vulnerabilities and adaptation options promotes societal and policy responses. Embracing top-down, bottom-up and co-produced and collaborative knowledge production processes can deepen capacity building, widen the solution space and ensure justice in adaptation outcomes (Ara Begum et al., 2022).

1.7. Priorities for research

1.7.1. Social aspects and outcomes of adaptation

Adaptation takes place in society, yet comparatively little research has been undertaken to understand the social dynamics of adaptation. Research shows that soft barriers to adaptation emerge from neglecting place-based values, a lack of input from affected communities, shortcomings and failures in governance, and a lack of financial resources. Without considering these important social aspects of adaptation there is a risk that adaptation can become contested and result in maladaptation or unwanted outcomes or that adaptation will not take place. Most research in Ireland to date has focused on modelling and assessment of future climate impacts. This needs to be supplemented with research into the social science dimensions of adaptation. This also has salience in ensuring that adaptation is just and equitable.

1.7.2. Knowledge for informing adaptation

No systematic assessment of climate change impacts has been undertaken across sectors using the same climate change projections or the same socioeconomic or socioecological scenarios. While advances in the development of a consistent set of climate projections for Ireland are forthcoming from the TRANSLATE project (O'Brien and Nolan, 2023), it is essential that these projections are used to assess climate change impacts across sectors in advance of the next cycle of climate adaptation plans. The implications of this lack of systematic assessment are evident throughout Volume 3, in that little research has been undertaken for some sectors and considerably more for others.

In addition to climate change impact assessments, novel approaches to informing adaptation are emerging in the international literature. Key among these is the development of adaptation storylines, which take advantage of memorable historical extremes, together with process understanding and climate model projections, to leverage insight into discussions of vulnerability, risk and adaptation responses. Such approaches have much to offer, especially in understanding cascading risks and interdependencies, which are an underexplored aspect of adaptation in Ireland to date.

Adaptation, at its core, is about reducing vulnerability. In addition, the outcomes of adaptation need to be tracked relative to their impact on vulnerability. Little research has explored current and future vulnerability, and this should be highlighted as a core component of the knowledge necessary to inform adaptation. If adaptation reduces climate risks, then knowledge of how hazards and disruptions are likely to change is just one part of the equation, as we also need a fuller understanding of vulnerability and exposure. In addition, how to deploy these tools for evaluating adaptation actions and options, rather than simply impact assessments, needs development and support.

Lastly, little research has been conducted to understand the adaptive capacity of sensitive ecosystems. Given the strong coupling between human and natural systems, research that advances understanding of the adaptive capacity of critical ecosystems is urgently required.

1.7.3. Decision making under uncertainty

Climate change projections are associated with large uncertainties for future changes in precipitation and extremes. For successful adaptation, it is critical that adaptation accounts for the range of plausible change. There is no guidance available for decision making under uncertainty at a national level. Such frameworks are important for adaptation for critical infrastructure, and in situations where exposure and vulnerability are high and the costs of adaptation large. Research and guidance are urgently required on the implementation of frameworks to support decision making under uncertainty.

1.7.4. Governance and cross-cutting issues

Governance, coordination and cross-cutting issues was the weakest area of adaptation assessed by the CCAC, with an evident need for strengthening leadership on adaptation across sectors to drive ambition and govern action. Working with adaptation practitioners to understand the barriers to and opportunities for adaptation in these areas should be an important priority, and the need for better engagement with the private sector and non-governmental organisations, beyond government departments, has been highlighted by the CCAC.

2

Ecosystems: Marine, Terrestrial and Freshwater

Key messages

1. Biodiversity in Ireland is declining, and continued biodiversity loss will undermine capacity to adapt to climate change across all sectors. Without early and significant adaptation, climate change will result in severe impacts on many species and habitats.

2. Ireland's biodiversity has intrinsic value and conservatively contributes at least €2.6 billion annually via ecosystem services to the Irish economy. Despite this, current conservation efforts are not adequately funded. The maintenance of ecosystems in good condition, or their restoration to good condition, enables them to resist pressures and threats, recover from disturbance and reconfigure in response to new conditions. These are all elements of resilience.

3. Significant impacts on biodiversity are projected to increase with additional warming. Temperature dictates the timing of growing seasons and ecosystem productivity, while sea level rise impacts our coastal ecosystems. The frequency and intensity of rainfall affects vegetation and crops and indirectly affects ecosystem structure through changes in river flows and lake levels. Projected changes in temperature and precipitation are likely to increase the occurrence and spread of invasive species and the competitive pressures faced by Ireland's native species. Changes in ocean temperature are likely to change the distribution of marine species, from phytoplankton to marine mammals.

4. Up to 20% of Ireland's total native flora is estimated to be vulnerable to climate change in the period up to 2050, with more than half of species on the Irish threatened plants list at risk of being adversely affected by climate change (DCHG, 2019a). Observed impacts of climate change on Irish species and habitats include changes in species abundance and distribution, phenology (such as the timing of bird migration and plant flowering), community composition, habitat structure and ecosystem processes. Increases in spring temperatures in recent decades have been demonstrated to impact the timing of key life cycle events in a range of plant, bird and insect species in Ireland.

5. There is not yet a clear picture of how offshore marine ecosystems are, and will be, affected by changes in climate. Globally, ocean warming, acidification and oxygen loss are well understood, but regional and local changes in temperature, acidification, salinity, and nutrient and oxygen levels display significant natural variation. The geographical ranges of some species in Irish waters are predicted to shift northwards to cooler waters. Fish stocks of commercial interest to Ireland may be adversely impacted by climate change. This could have implications for quota sharing and fisheries management. Key adaptation actions for marine ecosystems include protection from overfishing, and the development of refuges for species recovery. Ireland's current network of protected areas in the marine needs to be more coherent, representative and connected.

6. It is vital that all sectors recognise their role in reducing pressures on biodiversity and contributing to adaptation measures. Actions to protect and restore biodiversity are valuable adaptation strategies for other sectors that either rely on ecosystems or work with nature through the deployment of nature-based approaches. Examples of synergistic nature-based actions include restoration of peatlands and native woodlands, rewetting grasslands on peat soils, salt-marsh and sea-grass meadow restoration, urban greening, landscape regeneration, climate-integrated land use planning and regenerative agriculture. Central to all these are funding, education and capacity building, together with stronger community participation so that actions can be mainstreamed and benefits distributed fairly.

2.1. Introduction

Biodiversity is understood as the variability among living organisms from terrestrial, marine and other aquatic ecosystems and the ecological complexities of which they are part; this includes diversity within species, between species and of ecosystems (UNEP, 1992). Biodiversity is central to the healthy functioning of ecosystems, their continued resilience and their ability to provide ecosystem services (MEA, 2005; IPBES 2019). Without early and significant action, climate change will result in severe impacts on many of the Earth's species and habitats, as well as on their capacity to provide adaptative capacity and other benefits to humanity (O'Higgins et al., 2020).

Ireland's biodiversity holds intrinsic value as well as being estimated to contribute approximately €2.6 billion each year via ecosystem services to the economy (Bullock et al., 2008)[5]. Ireland's marine, freshwater and terrestrial environments include a wide range of habitats (NPWS, 2019). Habitats including active peatlands, dune and machair systems, limestone pavements, turloughs and offshore reefs are of special significance due to their scarcity in both Ireland and the rest of Europe.

As a result of climate and topography, wetland and aquatic habitats are very well represented in Ireland (NPWS, 2019). Because of this, Ireland is home to internationally significant populations of several aquatic species, including the otter, Atlantic salmon, freshwater pearl mussel and white-clawed crayfish, many of which are vulnerable to changes in climate (Wyse-Jackson 2007; DCHG, 2019a; NPWS, 2019). Ireland is also relatively well populated with algae, lichens and bryophytes. Most species in Ireland are invertebrates, accounting for over 18,000 of Ireland's *c.* 19,122 species of animals (Ferriss et al., 2009), with at least 11,260 insect species. Fifty nine per cent of all animals in Ireland are insects. Ireland maintains important populations of butterfly species, including the country's only legally protected insect species, the marsh fritillary butterfly (NPWS, 2019). Two hundred and eleven bird species regularly call Ireland home, of which 26% are on the International Union for Conservation of Nature (IUCN) Red List (high conservation concern) (Gilbert et al. 2021), and 40 Irish bird species are included in Annex I of the EU Birds Directive. There are 952 native plant species that occur in Ireland together with 987 non-native plant species (BSBI, 2023).

Ireland's marine territory is 10 times greater than its terrestrial territory and covers a variety of habitats encompassing open water (pelagic), deep-sea continental shelves and canyons with seafloor (benthic) habitats, including vulnerable cold-water coral reefs (Wall et al., 2020) (see Box 2.1). Some 7,300 resident and visiting faunal species have been recorded in Irish waters, which are also the site of crucial spawning grounds and nurseries for important commercial fish species (Ocean Research & Conservation Association, 2021). The EU Marine Strategy Framework (MSF) Directive (EU, 2008) employs an ecosystem-based approach to ensuring the sustainable use and management of human activities at sea. An assessment carried out under the MSF found that Irish marine waters are clean, healthy and biologically diverse but that some marine habitats and several bird and fish species are in poor condition or under threat (NPWS, 2019; Wall et al., 2020). There is also concern over increasing pressures such as overexploitation and climate change (Marine Protected Area Advisory Group, 2020).

The environmental status of Ireland's marine food webs is unknown. Although there is evidence that components are changing, it is not clear how those changes affect the food web or which human-induced pressures are causing these changes (e.g. overexploitation, habitat destruction, climate change and pollution) (DHPLG, 2020). Loss of biodiversity is not just an issue for marine ecosystems, it also has further impacts on fisheries, aquaculture, tourism, recreation, energy, shipping and biotechnology (Marine Protected Area Advisory Group, 2020). Enhancing biodiversity through the protection and restoration of marine ecosystems can restore productivity, avoid future degradation (Kenchington et al., 2003), enhance resilience and adaptability within these systems, and bring substantial health, social and economic benefits to those communities that rely upon them.

The ecological processes and services that these habitats and their species provide underpin human survival and wellbeing

[5] This relatively early figure from 2008 of €2.6 billion per annum has since been considered a significant underestimate by the authors, with new calculations likely to be significantly higher (C. Bullock, University College Dublin, 2023, personal communication). For example, further research at the Socio-Economic Marine Research Unit at the University of Galway estimated the value of Ireland's marine ecosystem services at €3.4 billion per annum (Norton et al., 2018), while Teagasc research through the ECOVALUE project estimated Irish forest biodiversity to contribute €68 million per annum, with forestry contributing a further €22.9 million per annum through carbon sequestration and €179 million per annum through recreation. Other relevant figures may be found in the National Biodiversity Expenditure Review (Morrison and Bullock, 2018).

and all economic sectors, and are impacted by changes in climatic drivers such as temperature, precipitation and extreme climatic events (Scheffers et al., 2016; DCHG, 2019a). The frequency and intensity of rainfall affects vegetation and crops and directly and indirectly affects streamflow in lakes and rivers through ecosystem structure. Temperature dictates the timing of growing seasons and ecosystem productivity, and sea level rise impacts our coastal ecosystems (O'Higgins et al., 2020). Projected changes in temperature and precipitation are likely to increase the occurrence of invasive species and the competitive pressures on Ireland's native species. Habitats that are highly vulnerable to invasive species include freshwater river systems, native woodlands, ponds, lowland heath, coastal floodplains, coastal salt marshes and coastal sand dunes (Kelly et al. 2013). Changes in ocean temperature are likely to alter the distribution of marine species, from phytoplankton to marine mammals (Bindoff et al., 2019).

2.2. Context – social and environmental

At the local scale, human development is supplanting natural environments, with local environmental impacts (O'Higgins, 2020). The summation of these local actions has resulted in a global-scale biodiversity and climate crisis (IPBES, 2019; IPCC, 2022). We are currently facing the triple interlocked threat of climate change, unsustainable land use and the sixth mass species extinction (Flood et al., 2020a). Climate change has significant current and future impacts for many species and habitats in Ireland and across the globe (Coll et al., 2013; DCHG, 2019a; Flood et al., 2020a). Without bold and ambitious action, climate change will have severe impacts on our shared natural heritage (CBD Secretariat, 2009; Scheffers et al., 2016).

Biodiversity change and loss are projected to be among the most important climate change impacts globally, with 5% of species at risk of climate-related extinction at 1.5–2°C warming (IPBES, 2019). Significant impacts on biodiversity are set to occur even if we keep climate change to 1.5°C above pre-industrial levels (IPCC, 2018). The Earth is currently losing biodiversity at a rate last seen during mass extinctions (WWF, 2018). The *Living Planet Report 2018* finds that global losses in populations of vertebrate species – mammals, fish, birds, amphibians and reptiles – averaged 60% between 1970 and 2014 (WWF, 2018). Overexploitation of species, agriculture, land conversion, pollution and climate change are the main drivers of biodiversity decline, with climate change a growing threat.

Under the CBD, which Ireland is a party to, the Irish Government must report on progress towards implementation of the Strategic Plan for Biodiversity 2011–2020, which seeks to "take effective and urgent action to halt the loss of biodiversity in order to ensure that by 2020 ecosystems are resilient and continue to provide essential service, thereby securing the planet's variety of life, and contributing to human well-being, and poverty eradication" (CBD Secretariat, 2010). The Kunming–Montreal Global Biodiversity Framework was adopted in 2022 and outlines four overarching goals and 23 targets, including the protection of 30% of Earth's lands, oceans, coastal areas and inland waters, the restoration of 30% of degraded land and sea areas, and the reduction of government subsidies harmful to biodiversity (CBD, 2022). Ireland must also report under the new EU Biodiversity Strategy for 2030, which is closely aligned with the European Green Deal and aims to build societies' resilience to future threats such as the impacts of climate change, forest fires, food insecurity and disease outbreaks – including by protecting wildlife and fighting illegal wildlife trade (EC, 2020a). A key element of the proposed EU Biodiversity Strategy is the Nature Restoration Law, due to be finalised late 2023, which is likely to set binding restoration targets across a range of ecosystems.

National biodiversity strategies and action plans are the principal instruments for implementing the CBD at the national level, including Ireland's National Biodiversity Action Plan (NBAP) 2017–2021 (DCHG, 2017). An assessment of the NBAP (2017–2021) by the National Biodiversity Forum found that "although public awareness of biodiversity has increased, and cross-sectoral engagement in biodiversity action has improved, the status of biodiversity in protected areas, seas and the wider countryside is in poor condition and continues to decline" (Buckley et al., 2020). Several recommendations were made for the next NBAP (Ireland's fourth), which is under development. The fourth NBAP will set the national biodiversity agenda for the period 2023–2027 and aims to deliver "the transformative changes required to the ways in which we value and protect nature" (DHLGH, 2022a). However, significant action, supported by adequate funding, is needed to deliver on this vision.

While the NBAP and biodiversity adaptation plans recognise the need for all sectors to consider biodiversity in decision making, how to do so is debated. There is a need to enable just and equitable access to benefits from biodiversity across society (Pörtner et al., 2023). Traditional approaches to valuing and protecting the environment tend towards a single metric of monetary valuation when considering the 'value' of ecosystems and biodiversity (Flood, 2012). However, the question of substitutability is key, such as whether different elements of biodiversity are substitutable and whether biodiversity values can be given economic values.

2.3. Climate change impacts on biodiversity

The main observable direct impacts of climate change on Irish species and habitats are changes in species abundance and distribution, phenology (such as the timing of bird migration and plant flowering), community composition, habitat structure and ecosystem processes (DCHG, 2019b; NPWS, 2019). It must be noted that the timing of these impacts will vary, with some biological responses taking decades to materialise and others occurring rapidly. Moreover, some species may be able to move location if conditions become less favourable and suitable alternative locations are in proximity. Evolutionary change and adaptation are thought to occur at a slower rate than current and predicted rates of climate change (Hoffman and Sgro, 2011). Therefore, if species do not have the capacity to move at a rate dictated by climate change, they may become locally extinct.

An ecosystem consists of relationships between species in various functional groups and with the abiotic elements of the environment. A functional group consists of species that perform similar functions in an ecosystem. These might include pollinators, herbivores and insectivores or litter decomposers. There is a significant risk that key representatives of functional groups, or perhaps entire functional groups, will be degraded locally because of persistent extreme weather events such as flooding. This would result in impaired ecosystem functioning where, as a by-product of the redistribution of species in response to changing climate, existing interactions among species are being disrupted and new interactions are emerging (Scheffers, 2016).

Climate change impacts on Irish plant and animal phenologies have been documented (Donnelly et al., 2006, 2013; Wingler et al., 2022). Increases in spring temperatures in recent decades have been demonstrated to impact the timing of key life cycle, or phenology, events in a range of plant, bird and insect species in Ireland (Donnelly et al., 2004, 2006, 2008, 2009, 2016; Carroll et al., 2009; O'Neill et al., 2012; Stirnemann et al., 2012; Gleeson et al., 2013; Wingler et al., 2022). For example, Arctic wading birds have suffered from a shift in suitable habitats, including habitat decline and contraction (Wauchope et al., 2016), the arrival of migratory birds has advanced over time, and start-of-season in deciduous woodlands has advanced by > 2.5 days since 1990 (Wingler et al., 2022). Timing mismatches between chick hatching and peak food abundance have also been noted (McKinnon et al., 2012; Reneerkens et al., 2016).

Up to 20% of Ireland's total native flora is estimated to be vulnerable to climate change in the period up to 2050 (Wyse Jackson, 2007), with more than half of species on the Irish threatened plants list at risk of being adversely affected by climate change (DCHG, 2019a). A 40% decline in water bird species in less than 40 years has been documented, with climate change identified as a significant factor (Burke et al., 2018).

Projected changes in temperature and precipitation along with other climate variables are likely to increase the occurrence of invasive species and the competitive pressures on Ireland's native species. Habitats with particular vulnerabilities to invasive species include freshwater river systems, native woodlands, ponds, lowland heath, coastal floodplains, coastal salt marshes and coastal sand dunes (Kelly et al., 2013). Although most invasive species in Ireland are currently plants, the future trend is likely to be towards invasive animal species (O'Flynn et al., 2014). The threat from high-impact invertebrates is of greatest concern for freshwater environments.

The preparation and publication of IUCN Red Lists for species groups across the island of Ireland is ongoing, coordinated by the National Parks & Wildlife Service. Thirteen Red Lists (see https://www.npws.ie/publications/red-lists) have been published to date, covering vertebrate and invertebrate groups, vascular plants and mosses. The potential impacts of climate change have been highlighted as a significant cause for concern in several of those groups. Further work is required to assess the potential impacts of climate changes on other taxonomic groups.

The following sections explore climate change impacts on key elements of Irish biodiversity through changes in atmospheric temperature, insolation, precipitation, ocean warming, acidification and other changes.

2.3.1. Temperature

Temperature (see Volume 1, Chapter 3) plays a key role in phenological process timing in the annual cycle of plant species, including the start of the growing season and the timing of bud burst. Shifting annual cycles of plants and animals can lead to so-called mismatches in the interactions between species (Wingler et al. 2022), for example in the relations between predators and their prey and between plants and their pollinators. This can cause structural changes in the functioning of ecosystems (O'Higgins et al., 2020).

An increase in temperature will also impact the geographical range of species. Lewis et al. (2019) noted that, due to Ireland's position at the western edge of the wintering range for many waterbird species that breed in Northern Europe, Scandinavia

and Arctic Russia, it is likely that the effects of climate change, including increasing winter temperatures, are making Ireland a less hospitable migration destination for many species. Moreover, bioclimatic modelling (of species and habitat distributions) shows that under future climate scenarios many species in Ireland are likely to experience changes in their ranges (Walmsley et al., 2007; Coll et al., 2013). In general, fern, liverwort and moss species will experience contraction of their ranges. Species most vulnerable to climate change are those included in Arctic, boreal and boreo-Arctic montane biomes (Coll et al., 2013; Coll and Sweeney, 2013). The habitats indicated as most vulnerable to climate change impacts in Ireland include upland, peatlands and coastal habitats, the last of which have the additional threat of sea level rise and associated coastal squeeze, as habitats are prevented from extending landwards because of the presence of a fixed or artificial boundary (Coll et al., 2013; Wall et al., 2016).

2.3.2. Solar radiation

Smith et al. (2007) compared biodiversity in Ireland directly with solar radiation data and found that "solar radiation influences at least some aspects of biodiversity in open spaces, but its effects are frequently obscured by variation in other environmental factors, particularly soils. In general, higher light levels increase vascular plant species richness and decrease bryophyte species richness." Other studies for Ireland (Mullen et al., 2003) and Britain (Sparks et al., 1996; Buckley et al., 1997) have found similar results. Regional climate projections for Ireland show small projected changes (–1% to 0%) in solar radiation by mid-century, even under Middle and Late action scenarios (Nolan and Flanagan, 2020).

2.3.3. Precipitation

Coll et al. (2014) indicate that the distribution of Irish active blanket bog is regionally sensitive to climate change, particularly in the lower-lying areas in the south and west of the country. Coll et al. note that increasing temperatures along with precipitation changes may reduce the area suitable for active blanket bog. This is projected to have potentially major implications for lowland blanket bog distribution along the western Atlantic seaboard, where the projected losses are greatest. The projected decline in the climate space associated with active blanket bog areas can be expected to have significant implications for the ecology of these complex wetland ecosystems and associated plant and animal species adapted to living in wet, nutrient-poor conditions. Seasonal drying, for example, may affect surface micro-topography and hydrology. This, in turn, will influence plant composition and habitat suitability for birds and other species. Loss of unprotected high-quality wetlands, such as active blanket bogs, will result in the direct loss of wetland biodiversity by physical removal of the habitats and most plant and invertebrate species, while degradation may cause reduced species diversity and local extinction of rare or sensitive species (Coll et al., 2014). The combination of drier summers and more intense rainfall events (see Volume 1) may result in an increased number of bog bursts and landslides, as well as creating cascading impacts on other habitats such as lakes (Kiely et al., 2010). Increasing winter precipitation has the potential to increase nutrient runoff and sediment loads that can negatively impact water quality (Desmond et al., 2017) and salmon and trout spawning areas.

2.3.4. Ocean warming, acidification and other changes

Changes in global ocean temperature are causing changes in the distribution of marine species, from phytoplankton to marine mammals, changing the structure of ecosystems and interactions between species, as well as phenology (Bindoff et al., 2019). Studies documenting the changes in temperature, salinity, stratification, acidification and the availability of oxygen and other essential nutrients in the Atlantic and the Irish Sea are available (see Volume 1) (Nagy et al., 2021; McCarthy et al., 2023; Nolan et al., 2023). Apart from recent biogeochemical modelling of marine ecosystems that explores the European waters of the Iberian–Biscay–Ireland zone (Gutknecht et al., 2019), there is little biogeochemical or marine food web modelling in the offshore marine environment around Ireland. There is not yet a clear picture of how offshore marine ecosystems are, or will be, affected by changes related to climate.

In the global open ocean, observations are used to understand changes that have already occurred, and Earth system models (ESMs) are used to predict future trends (Bindoff et al., 2019). Both observations and modelling have led to the detection of changes on a global level. Globally these changes, including ocean warming, acidification and oxygen loss, are scientifically well understood (Bindoff et al., 2019). Regional and local changes in temperature, acidification, salinity, and nutrient and oxygen levels display significant natural variation (for examples in the Irish context, see Volume 1). These scales, for which we do not have sufficiently detailed information, are the most relevant for marine ecosystems and the Irish communities that depend on them (Bindoff et al., 2019).

In general, temperature changes will affect both metabolic rates, such as respiration, and ecological processes, such as productivity and species interactions. As the concentration of atmospheric carbon dioxide increases, the concentration in the ocean also increases, lowering ocean pH, causing the ocean to become more acidic and changing ocean carbonate chemistry. This affects marine species that use calcium carbonate to build shells or skeletons. Changes in wind, temperature and salinity can alter water circulation patterns and increase stratification. This can change the availability of nutrients and oxygen, which has knock-on effects for marine species and fisheries. Different species will react in different ways to changes, and changes may be positive for some species. The biogeographical ranges of some species in Irish waters are predicted to shift northwards to cooler waters. Those species that are unable to migrate or those that can no longer compete for resources are at risk of extinction (Bindoff et al., 2019). Not only will there be changes in the distribution of species, there may also be changes in the productivity and variability of ecosystems and fisheries (Cheung et al., 2012; Heath et al., 2012).

Fish stocks of commercial interest to Ireland may be adversely impacted by climate change in ways that are not yet fully documented in the literature. This could have implications for quota sharing and fisheries management systems. For example, cold-water species such as cod and herring, for which Ireland holds a significant quota share, may reduce significantly in number, while warm-water species, for which Ireland currently holds only a small quota share, such as bluefin tuna, sardine and hake, may increase in numbers in Irish waters (Marine Institute, 2009; Payne et al., 2021).

A combination of sea level rise, coastal erosion and increasing frequency of storm surge events may lead to significant coastal habitat loss (Devoy, 2008; Crowe et al., 2013). Habitats most at risk include low-lying coastal lagoons, salt marshes and estuaries (Wall et al., 2016; Chapter 4 of this volume).

2.3.5. Modelling climate impacts on individual species

Modelling the impact of climate change on complex biological communities is challenging. Restricting models to relatively small geographical regions such as Ireland often fails to account for the range of environmental conditions tolerated by Irish species elsewhere within their global ranges. Thus, modelling often requires inclusion of data from throughout Europe or beyond. Two examples where Europe-wide modelling has provided context for Ireland are recent studies on bats (of which Ireland has nine species) and natterjack toads (Ireland's only toad, which is regionally listed as endangered).

Modelling suggests that eight of the nine Irish bat species should maintain their ranges under climate change, with only the whiskered bat projected to undergo range contraction by the end of the 21st century, perhaps disappearing from the west (McGowan et al., 2021). In addition to maintaining stable ranges, five species (the common pipistrelle (Figure 2.1), soprano pipistrelle, Nathusius' pipistrelle, Leisler's bat and the brown long-eared bat) are predicted to increase their population sizes throughout the 21st century due to increased favourable (milder) weather conditions. Daubenton's bat and the lesser horseshoe bat are predicted to maintain their present ranges but, within those, populations are predicted to decrease in number largely due to increasingly mild winters interfering with their necessary overwinter hibernation. These predictions contrast with recent population trends derived from long-term monitoring programmes, which indicate stable (Daubenton's) and increasing (lesser horseshoe) populations (Aughney et al., 2022).

Figure 2.1 Pipistrelle bat (Pipistrellus sp.). The common pipistrelle, soprano pipistrelle and Nathusius' pipistrelle bats are predicted to maintain their ranges and increase their population sizes due to milder weather conditions under climate change. Reproduction licensed under the Creative Commons Attribution CC BY-SA 2.0 licence (https://creativecommons.org/licenses/by-sa/2.0/deed.en).

The natterjack toad is at the edge of its distribution range in Ireland and is found only at a small number of sites in west Kerry (Reyne et al., 2019). Natterjack toad egg laying is favoured by mild spring conditions, warm, dry summers and wet winters; as a consequence, it is predicted to be a climate change 'winner' with conditions throughout Europe, and Ireland, becoming more favourable (Figure 2.2; Reyne et al., 2021). However, in recent decades the species has declined markedly in Ireland due to the deterioration of its terrestrial and aquatic habitats. Thus, whether its fortunes are turned around by climate change will depend on effective species conservation efforts to improve existing habitat quality and connectivity and prevent any more of its sand dune home in County Kerry being converted to intensive farmland, golf links courses or other recreational uses.

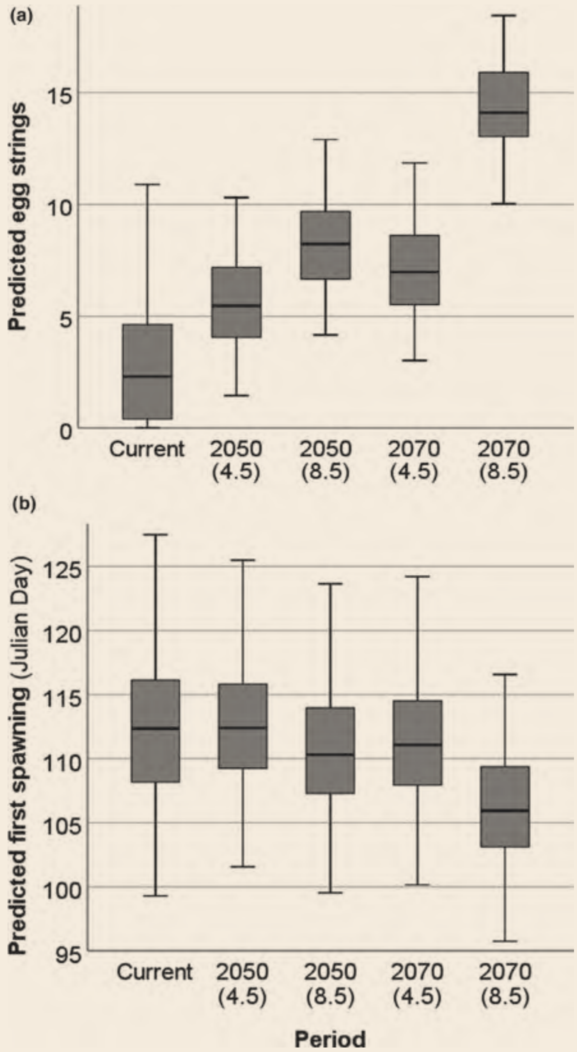


Figure 2.2 Modelled projections suggest that in Ireland may benefit from warmer conditions later this century, laying more eggs strings (a) and spawning earlier (b) under low (RCP4.5) and high (RCP8.5) greenhouse gas emission scenarios. Source: Reyne et al. (2021). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/); image of the toad added by the authors.

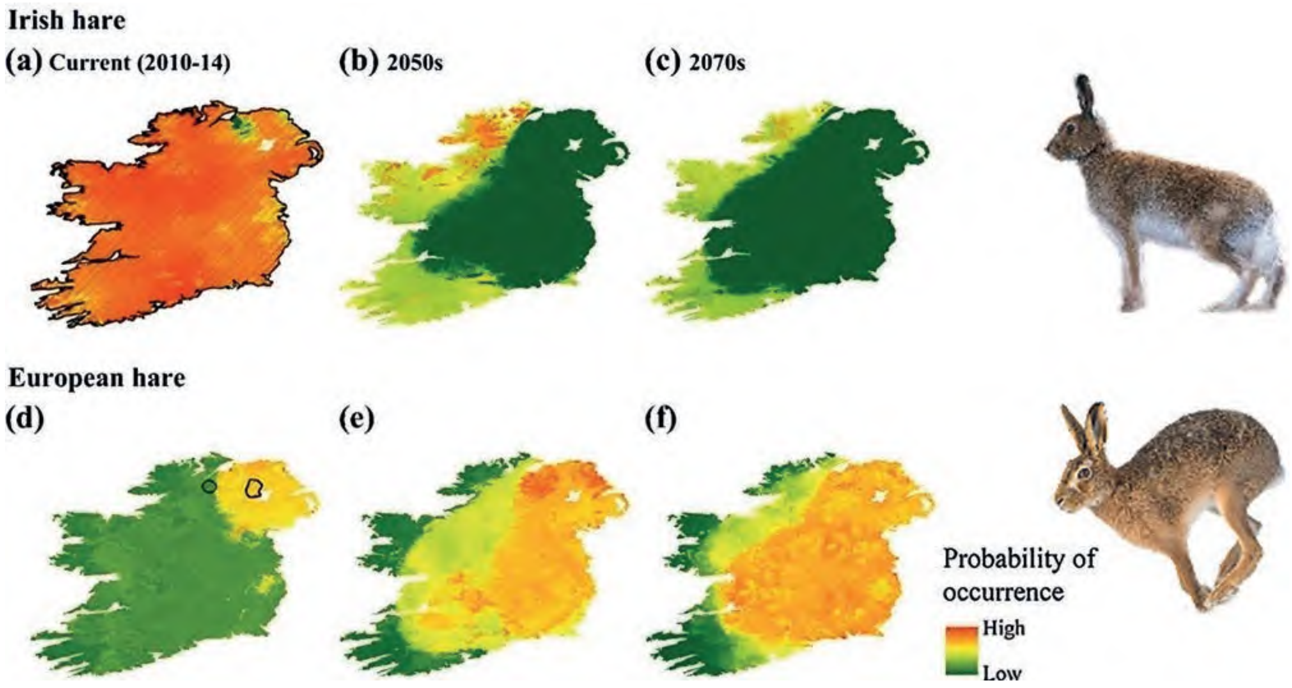


Figure 2.3 Bioclimatic model projections for the cold-adapted native hare species (a–c) show substantial range contraction, while projections for the non-native European brown hare show range expansion (d–f). Source: Caravaggi et al. (2017). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/); image of the hares added by the authors.

Bioclimatic model projections suggest that cold-adapted species native to Ireland such as the endemic Irish hare (Lepus timidus hibernicus) may fare poorly under climate change, contracting their range, while non-native species such as the European brown hare are likely to find future conditions more suitable, giving them a competitive advantage over the native species, which they seem set to replace over the long term (Figure 2.3; Caravaggi et al., 2017).

The effects of climate change on Irish wildlife are highly variable depending on the conditions that favour each species, with potential winners, losers, and those for which the impacts in terms of their range and population size may vary across space and time. Bioclimatic drivers are likely to interact with other biodiversity threats and pressures, leading to more uncertainty in future projections. Modelling of threat complexes and climatic and socioeconomic 'storylines' is needed to adequately assess climate change impacts to inform government and conservation organisations when creating future conservation policy.

Box 2.1 Unique Irish places and pressures: cold-water coral habitats

Cold-water coral habitats are found, as the name suggests, in colder, higher-latitude waters than the tropical coral habitats that are more familiar in public imagination. They occur in deeper, darker waters and have been found at depths of 2,000 metres. Along the Irish margin these habitats, in the form of mounds, can be tens or hundreds of metres high. They are formed by the skeletal remains and living structures of stony reef-building corals such as *Lophelia pertusa* and *Madrepora oculata* (Wheeler et al., 2005; Davies et al., 2017). Associated with hard substrates and topological features such as slopes of banks, submarine canyons and seamounts (Davies et al., 2017), these habitats are unique biodiversity hotspots in the deep sea with over 1,300 associated species (Roberts, 2009; Rengstorf et al., 2013; Bindoff et al., 2019), providing refuge, nursery grounds and physical support for other organisms (Davies et al., 2017; Portilho-Ramos et al., 2022).

Alongside current vulnerability to human pressures, including overexploitation (fishing) and pollution, cold-water corals are expected to be severely affected by changing nutrient distribution associated with climate change (Portilho-Ramos et al., 2022). Despite their importance as biological hotspots and their vulnerability, little is known about their ecological functioning or their geographical distribution (William et al., 2006; Conti et al., 2019). Understanding the distribution of vulnerable habitats such as cold-water corals is essential when the design of marine protected areas (MPAs) is being considered, but gaps remain (Rengstorf et al., 2013). Mapping has been carried out by Infomar and the Marine Institute to understand the distribution of these important and vulnerable habitats so they may be protected as special areas of conservation, and in order to map vulnerable fisheries resources for which Ireland is responsible (O'Sullivan et al., 2018). This work will create a baseline from which policy and research related to the management and protection of these deep-water resources can be developed. Ireland has seven offshore MPAs, six of which are reef areas and protect cold-water coral habitats in the Rockall Trough and the Porcupine Seabight. In these areas, bottom trawling and demersal fishing are prohibited, while long-line pelagic fishing and oil and gas exploration are allowed.

2.4. Adaptation strategies

A climate change sectoral adaptation plan for biodiversity has been prepared under the NAF (DCHG, 2019a), which outlines six objectives:

1. protect, restore and enhance biodiversity to increase the resilience of natural and human systems to climate change;
2. improve understanding of the impacts of climate change on biodiversity;
3. improve landscape connectivity to facilitate mobility in a changing climate;
4. engage society and all sectors to protect biodiversity to enhance resilience;
5. ensure that sufficient financing is available to implement the Biodiversity Climate Change Adaptation Plan;
6. put adequate monitoring and evaluation measures in place to review the implementation of the Biodiversity Climate Change Adaptation Plan.

The biodiversity sectoral plan is in the implementation phase and, while several of the objectives may be covered in the fourth National Biodiversity Action Plan, the CCAC (CCAC, 2022) rate progress on adaptation in the sector as showing no progress/insufficient evidence of progress.

Adaptation strategies for biodiversity should be designed for the adaptation of biodiversity itself to climate change and for leveraging biodiversity for adaptation within other sectors. Biodiversity is at the heart of healthy ecosystems, which support sustainable ecological and evolutionary processes and can be thought of as natural assets or natural capital with intrinsic value as well as supporting the flow of ecosystem services or nature's contributions to people. The maintenance of ecosystems in good condition, or their restoration to good condition, enables them to resist pressures and threats, recover from disturbances and reconfigure in response to new conditions, all of which are elements of resilience. For example, if one species in an ecosystem is negatively affected by temperature change, ecosystem function may be maintained if there is a wider variety of species; that is, another species may take over the functional role of the species that has been negatively affected. Similarly, for any particular species, the greater the genetic diversity and variability the more likely it will be able to adapt to new conditions through evolution. For example, if a species is adversely affected by changing temperatures but can move to an area with similar characterises to the one from which it originated, high genetic diversity and variability may make it better able to adapt to its new surroundings.

Healthy biodiversity is at the heart of healthy and vibrant Irish environments, human wellbeing, food systems, carbon sinks and the economy (Flood et al., 2020a). Actions to protect and restore biodiversity will be valuable adaptation strategies for other sectors that either rely on ecosystem services from sustainable functioning ecosystems (e.g. pollination services for food production) or leverage biodiversity in nature-based approaches (e.g. green roofs for climate change adaptation in building design) (see section 6.3) (O'Higgins et al., 2020). The concept of biodiversity action underpinning multi-sectoral climate change adaptation is particularly compelling if an ecological economics framework is used in which a healthy environment underpins society and the economy.

When considering nature-based approaches it is important that clear connection is established between adaptation and mitigation actions and between climate change and biodiversity actions with reciprocal co-benefits. Some actions, such as protection and restoration of carbon-rich biodiversity habitats can have climate change mitigation and adaptation benefits as well as biodiversity benefits. Examples of synergistic actions include restoration of peatlands and native woodlands, rewetting grasslands on peat soils, and salt marsh and seagrass meadow restoration (Figure 2.4; IAP, 2021; Gorman et al., 2023).

Other synergistic climate and biodiversity actions include urban greening, landscape regeneration, climate-integrated land use planning and regenerative agriculture. Central to all these actions is education and capacity building, together with integrated and stronger communities, so that the actions can be mainstreamed and benefits distributed fairly.

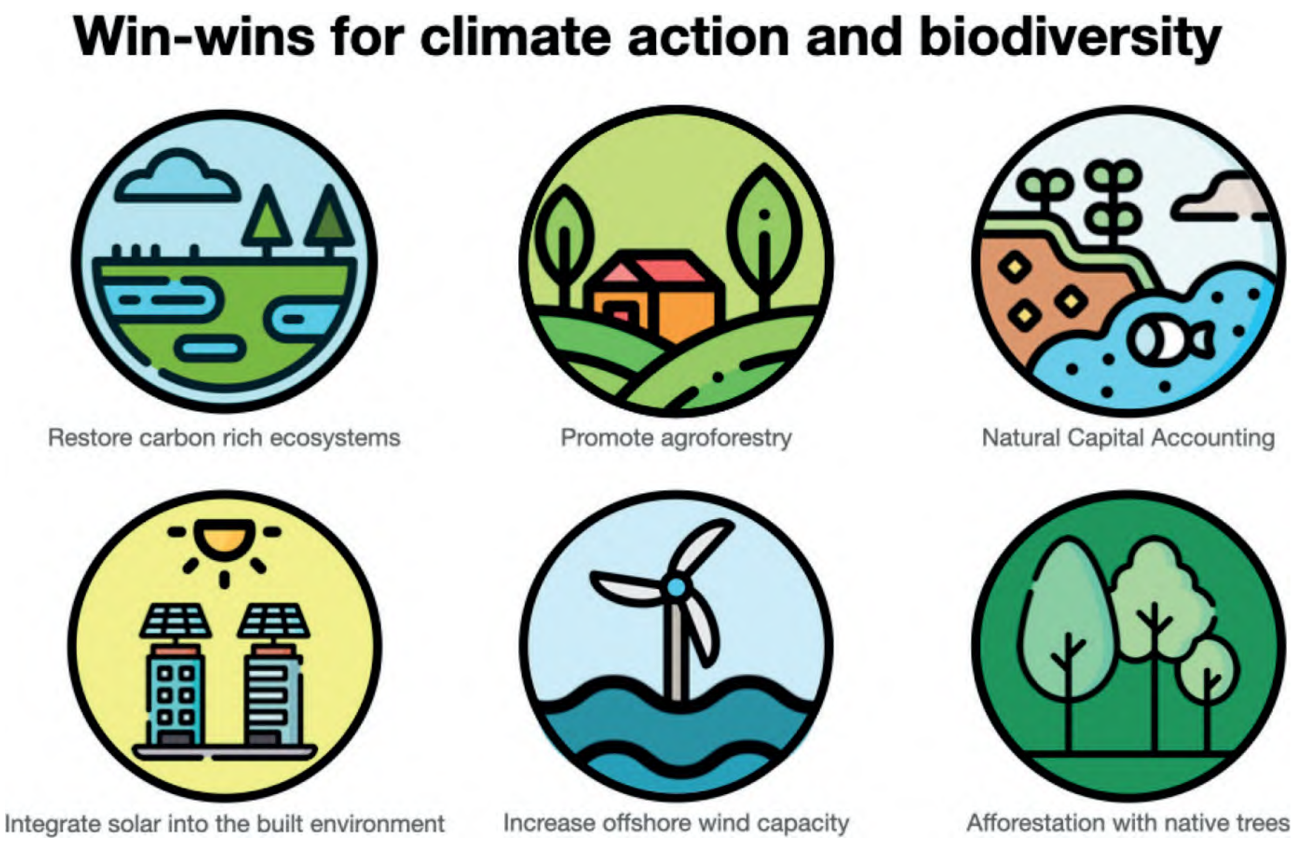


Figure 2.4. Examples of synergistic actions for climate change and biodiversity. These actions include climate mitigation and adaptation with co-benefits for biodiversity. Source: Gorman et al. (2023).

"Biodiversity benefits of climate actions are dependent on a 'right action – right place' framework, as biodiversity impacts are locally and context dependent (Gorman et al., 2023)."

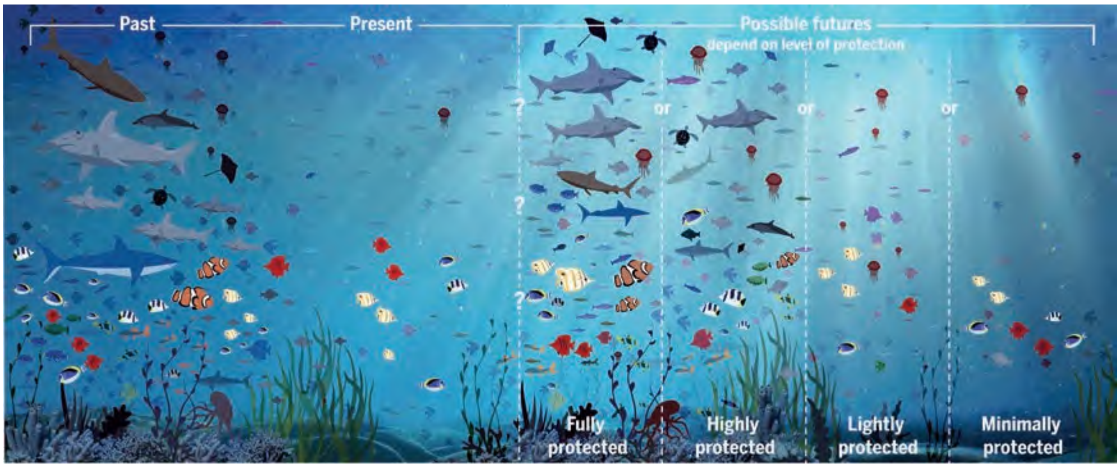
Biodiversity benefits of climate actions are dependent on a 'right action – right place' framework, as biodiversity impacts are locally and context dependent (Gorman et al., 2023). For example, sensitivity mapping of vulnerable biodiversity components can be used to appropriately site onshore or offshore wind farms to minimise biodiversity impacts (Burke, 2018).

Box 2.2 Adaptation in marine ecosystems

Marine ecosystems can reduce the impacts of climate change, with benefits for nature and people (Pörtner et al., 2021). The changes occurring in the marine environment because of climate change, such as temperature increases, are occurring too quickly for the normal process of species adaptation to keep pace (Bindoff et al., 2019).

There are two key strategies to help marine ecosystems maintain, improve and restore biodiversity and enhance resilience, which work in similar ways. The first strategy protects from overexploitation, a significant cause of loss of marine genetic variability, which damages the adaptive capacity of a species. The second offers species and ecosystems a refuge from overexploitation and climate change. Once species are protected from overexploitation or find a refuge from climate change, both the species and the ecosystem can recover quickly if they have not already been irrevocably damaged. Moreover, this recovery can spill over into adjacent areas, which is good for ecosystems and also good for production in sustainable fisheries (Grorud-Colvert et al., 2021) (see Box 2.2, Figure 1).

MPAs are marine areas that are managed in the long term, and their primary concern is protecting habitats or other natural features (Marine Protected Area Advisory Group, 2020). The conservation and management of marine ecosystems is covered by several international agreements and legal obligations. Despite this, Ireland's current network of protected areas is not yet considered coherent, representative, connected or resilient, and does not meet international or legal commitments (Marine Protected Area Advisory Group, 2020). A Marine Protected Areas Bill has been proposed for Ireland, in parallel with the Maritime Area Planning Act (2021), to identify, designate and manage MPA sites. Only a small proportion of Ireland's total maritime area, 10,420km^2 or 2.13%, is protected, and only a fraction of these protected areas can be found offshore (Marine Protected Area Advisory Group, 2020). Ireland has committed to protecting 30% of its total maritime area by 2030 (see Volume 4 for further information) under the Global Biodiversity Framework (CBD, 2022). The level of protection that MPAs receive is important, as greater levels of protection allow ecosystems to recover to a greater extent, increasing their resilience (Grorud-Colvert et al., 2021).



Box 2.2 Figure 1 The effectiveness of MPAs and the level of protection they provide will influence the future state of the ocean. Biodiversity can be conserved and restored, helping ecosystems to become more resilient and benefit human wellbeing. Source: Grorud-Colvert et al. (2021).

2.5. Cross-cutting issues

Biodiversity crosses many domains and has relevance across the areas of agriculture, coastal environments, critical infrastructure, health, forestry, marine and fisheries, tourism and cultural heritage, water management and our local authorities. Biodiversity is not so much a sector per se, as it is a cross-cutting issue with implications for all sectors and all levels of decision making. Effective biodiversity adaptation requires bottom-up and top-down planning across all sectors based on coordination and cooperation (DCHG, 2019a).

Flood et al. (2022) highlight the policy coherence building opportunity between the SDG, disaster risk reduction and climate change adaptation agendas. Biodiversity is central to all three agendas and is articulated particularly clearly within the SDG agenda under Goals 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), 11 (Sustainable Cities and Communities), 13 (Climate Action) 14 (Life below Water) and 15 (Life on Land).

It is vital that other sectors recognise their role in reducing the pressures on biodiversity and contributing to adaptation measures. For example, the permeability of the landscape and potential avenues for the spread of invasive species should be considered by the transport sector; local and national planning authorities should incorporate green infrastructure into future development plans; and agriculture, forestry and fisheries should evaluate measures undertaken in government programmes to ensure that no further degradation of biodiversity occurs (DCHG, 2019a).

Adaptation and mitigation options from other sectors can have positive and negative impacts on biodiversity. The development of sea wall defences, for example, is a climate change adaptation addressing rising sea levels, but one that can have negative effects on biodiversity and not offer an optimal long-term defence against climate change. Likewise, flood defence schemes may alter water flows and habitat characteristics, with impacts on biodiversity. Therefore, each sector needs to actively consider its interaction with biodiversity, with joined-up thinking being essential.

2.6. Priorities for research

2.6.1. Lack of knowledge and monitoring needs

Irish biodiversity has been highlighted as having low adaptive capacity compared with other sectors (Coll and Sweeney, 2013; Donnelly, 2018). Despite the evidence of climate change impacts on biodiversity in Ireland, there remains significant uncertainty about how individual species and ecosystems will respond to future changes in climate (Donnelly, 2018). Uncertainty stems from (1) challenges associated with isolating climate change impacts on biodiversity when relying on data not specifically collected for that purpose, (2) a limited number of organisms with sufficient data to determine trends and (3) a lack of historical data on the spatial extents of key habitats, which further undermines the ability to analyse species' interdependencies. To address these limitations, Donnelly (2018) highlights the importance of identifying key species and habitats, both vulnerable and resilient to climate change, to establish a multi-trophic monitoring programme. This type of programme could also be adapted to incorporate direct and indirect impacts of climate change, such as determining how rising temperature may impact phenology and range shifts directly, and how changes in the physical environment resulting from climate change may feed back to organisms.

2.6.2. Research and modelling of marine food webs

Research and modelling of marine food webs is necessary to understand their level of vulnerability and how they are responding to climate change and to establish a baseline for MPAs.

2.6.3. Land use management for biodiversity

As covered in more detail in Chapter 3 (sections 3.4 and 3.5), land use management options to increase biodiversity on farmland and forestry can improve the outlook for Ireland. This includes more species-rich grasslands, improving the biodiversity of hedgerows, agroforestry and increasing soil carbon storage. This increased focus is needed to better understand trophic interactions and tackle the threat of phenological mismatches. The importance of healthy plant biodiversity to reduce phenological mismatches should be recognised.

2.6.4. Baseline monitoring of invasive species

The National Biodiversity Data Centre provides national coordination and management of information on Ireland's non-native invasive species through maintaining Ireland's National Invasive Species Database. Bord Iascaigh Mhara (BIM) has set up a cross-department and inter-agency working group to examine invasive alien species in the context of aquaculture and developed reporting guidelines for alien invasive species risk assessment. BIM's aim is to develop a marine baseline for alien species to provide a means for managing them effectively. Research gaps exist in assessing the risk of new invasive species incursions and the potential for non-native species already present to become problematic if climatic conditions become more suitable for them. There are also likely to be changes in non-native species introduction pathways as direct and indirect consequences of climate change. For example, the sources of agricultural and horticultural imports may change.

2.6.5. Next-generation analytical tools

The use of new and emerging technologies such as complex ecological models capable of incorporating a wide range of biotic and abiotic interactions, together with remote-sensing products with the ability to observe landscape-scale features, can help make reliable future projections (Donnelly, 2018). The combination of remote-sensing products with site-specific phenology cameras (phenocams) can be used to track phenological changes (Wingler et al., 2022). However, the effectiveness of these techniques will require direct in situ long-term monitoring at a local level to allow the identification of changes in biodiversity attributable to climate change, to parameterise and validate ecological models, and to corroborate and validate remotely sensed biodiversity observations.

The ability to model interacting threats to and pressures on biodiversity, together with climate change, is needed, together with social and economic 'storylines' that can be used to explore potential future scenarios. The new land use data (from Tailte Éireann) will contribute important products for exploring how different land use configurations will impact on biodiversity, but additional spatial modelling capacity is needed to understand the impacts on biodiversity of changes in land and sea use.

3

Agriculture, Forestry and Land Use

Key messages

1. Irish agriculture is changing in response to climate change mitigation and biodiversity objectives. Among the farming community, an ageing profile, the pattern of smallholdings and changing access to services and payments are factors to consider as part of a just transition for agriculture. While climate change is likely to impact all forms of agriculture, opportunities for adaptation are emerging around the integration of local knowledge, stewardship of ecosystem services, agroforestry, horticulture, organic farming and urban food systems.

2. Climate change is likely to result in increases in productivity for some crops but decreases for others. Increases in humidity will increase the vulnerability of potato crops to blight. Other pests and pathogens (current and novel) are likely to have an increased impact due to warming winters resulting in a lack of die-off. Pests and pathogens are also likely to gain an increased geographical range, gaining a foothold where current climate conditions are not favourable. At present, irrigation is applied to a relatively small proportion of land, but that is expected to increase in future. Changes in precipitation may result in increased nutrient washout from land. Warming is expected to lead to an increase in growing season length; however, any productivity gains may be offset by increases in extreme rainfall events or in drought frequency, magnitude and duration. Risk-sharing instruments can help buffer the negative effects of extreme events on crop yields.

3. Soil management will be impacted by climate change, with projected increases in both wet and dry conditions. Wetter conditions will increase compaction and degradation from vehicles and livestock. In response to droughts, peatland and wetland restoration, together with better grassland and cropland management, could increase soil organic carbon content, which has benefits for adaptation and mitigation through an increased capacity for water storage and retention of nutrients in soils, with additional benefits for water quality. Agricultural practices and their timing will change in response to climate change.

4. Increasing rainfall can lead to increases in the prevalence of liver fluke and other diseases in cattle and sheep, as well as increasing the risk from exotic pests and diseases. More frequent and prolonged periods of higher temperatures will increase the potential for animals to experience heat stress, affecting fertility, milk production and growth rates. Heat risks can be reduced through silvopasture, i.e. blending pasture and woodland, to provide shelter for animals.

5. For forestry, increased yields are projected for some species such as Scots pine, beech, lodgepole pine and birch. Conversely, decreased yields are projected for others including Sitka spruce and other conifers, oak and most other deciduous trees. Agroforestry has the potential to provide multiple benefits, including shelter for livestock, water and carbon retention, and biodiversity, but adoption rates are low. Additional incentives are required to address barriers and increase the uptake of agroforestry.

6. Existing studies on climate change impacts on agriculture, forestry and land use are fragmented. A systematic programme of research to assess climate impacts on agriculture, forestry and land use is needed to support adaptation. The emergence of a new generation of tools and decision support systems has value for developing a more resilient sector.

3.1. Introduction

The IPCC Special Report on climate change and land (Shukla et al., 2019, p. 5) emphasises the centrality of land to human livelihoods and wellbeing and biodiversity, and notes how human use directly affects more than 70% (likely 69–76%) of the global ice-free land surface. Soil erosion is currently estimated to be 10–20 times (no tillage) to more than 100 times (conventional tillage) higher than the soil formation rate. Land use and land use change form a critical nexus between many facets of human life and biodiversity, which is covered in Volume 2 in relation to climate neutrality and in Volume 4 in terms of the transformative action required to meet our commitments. Therefore, the decisions we make on land use will have repercussions for how we respond to all dimensions of climate change. Land use is at the heart of multiple SDGs (particularly SDGs 12, 13 and 15), with sustainable consumption policies playing an important role in mediating between the conflicting demands of land use at the global scale (Obersteiner et al., 2016).

AFOLU has large crossover connections with other chapters in this volume and other volumes, such as biodiversity, managing urban sprawl, planning critical infrastructure, carbon sequestration and water. However, even with the intensification of pasture usage for dairy exports, land use patterns in Ireland are broadly stable, with moderate decreases in wetlands and grasslands matching a slowing rate of afforestation.

Agriculture is a major Irish industry, which in 2021 accounted for almost 6.6% of modified gross national income, 10% of exports in value terms, approximately 170,400 jobs representing 7.1% of total employment, and €15.4 billion of exports (DAFM, 2022a). The agricultural sector has strong cultural resonance in the Irish context and is experiencing increasing pressures to reduce greenhouse gas emissions and incorporate new practices to support biodiversity and carbon sequestration. A new forestry strategy and increased funding to support forestry (DAFM, 2022b), the Agri-Climate Rural Environment Scheme (ACRES) and other policies (section 3.2.1), are gradually laying the basis for a 'just transition' for the agricultural and forestry sectors, while land use has been covered in detail in the national land use review (Haughey et al., 2023).

3.1.1. Changing trends in agricultural policy and land use decision making

The challenges facing AFOLU are multidimensional. Living within a safe margin of the productive capacity of our land while safeguarding biodiversity will provide a sustainable blueprint for the future. The IPCC notes that more than 70% of ice-free land globally is directly under human influence, and thus our use of it shapes global and regional climate (Shukla et al., 2019, p. 5). Climate change and land degradation are closely entwined, with climate change being both a result of land degradation and a further driver of degradation. Climate change impacts on land use include increases in precipitation, flooding, heavier precipitation events, droughts, sea level rise and coastal erosion (Shukla et al., 2019, p. 347). In Ireland, a first round of mandatory sectoral adaptation reports has captured how present-day climate (and its changing characteristics) has impacted agriculture, forestry and ecosystem services. A priority assessment of impacts and vulnerabilities was completed for the *Agriculture, Forest and Seafood Climate Change Sectoral Adaptation Plan* (DAFM, 2019). The report highlights a broad series of impacts, both present and future, reflecting the changing state of agriculture, new practices in land use and a greater concern for the marine environment.

3.1.2. A changing policy context for agriculture and farming communities

Ireland's biodiversity is already at risk from direct human practices, as well as from climate change. These practices include the runoff of nutrients into water bodies due to, for example, the excessive use of nutrients or spreading during unsuitable conditions. In part, this is related to the rapid expansion of Ireland's food exports, particularly in the dairy sector, and associated pressures on the environment (Kleijn et al., 2009). A continued decline in the quality of water bodies (Figure 3.1) is mirrored in biodiversity indicators (Chapter 2). The National Parks and Wildlife Service reports that 85% of EU protected habitats are in unfavourable status, with 46% demonstrating ongoing declines, noting that "[t]he main drivers of this decline are agricultural practices which are negatively impacting over 70% of habitats, particularly ecologically unsuitable grazing, abandonment and pollution" (NPWS, 2020). Further studies from the Irish Butterfly Monitoring Scheme and BirdWatch Ireland support this outlook of decline (BirdWatch Ireland, 2021; National Biodiversity Forum, 2021; National Biodiversity Data Centre, 2022).

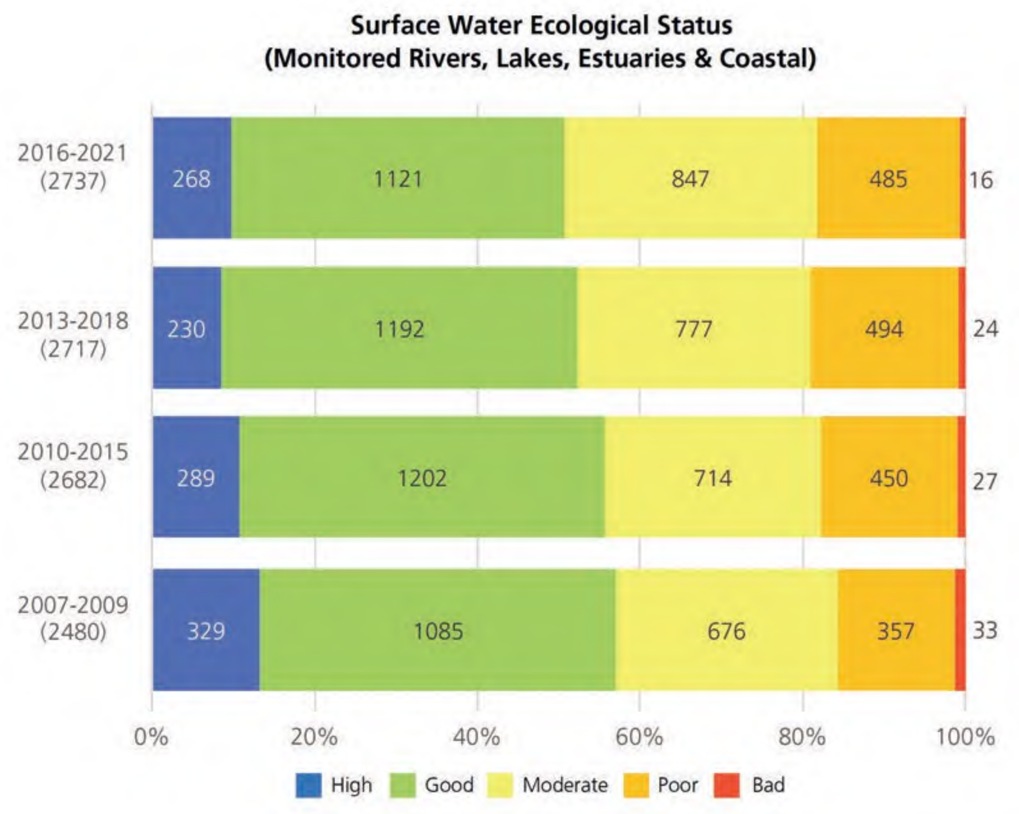


Figure 3.1 Continuous decline in surface water ecological status, 2007–2009 to 2016–2021. Source: Trodd et al. (2022).

There are negative externalities associated with present-day farming practices, in terms of environmental quality, emissions and biodiversity. The trend reflects the assessment in the 2020 state of the environment report (Wall et al., 2020, p. 347), where it was concluded that "economic growth in the agri-food sector in recent years is happening at the expense of the environment, as evidenced by trends in water quality, emissions and biodiversity all going in the wrong direction."

Therefore, it is problematic to build a set of adaptation practices to preserve a status quo of agriculture that is already out of kilter with mitigation objectives, biodiversity and SDGs 14 (Life below Water) and 15 (Life on Land), as well as the national biodiversity policies discussed in Volume 1 and in Chapter 2 of this volume. Given the scale and pace of change in European and Irish agriculture, it is likely that the combination of pressures to restore and protect biodiversity, while becoming a zero-carbon economy, will mean that climate adaptation policies will be reflective of these broader goals. This implies a greater sense of custodianship and management of land use than has hitherto been the case, with climate adaptation policies integrated into long-term planning and management practices to balance a range of environmental and socioeconomic goals (see Haughey et al., 2023).

Teagasc and the farming community are responding to the climate crisis, and the arrival of the new Common Agricultural Policy (2023–2027) (EC, 2022) presents a hopeful picture through its coordination of Pillar 1 direct payments and the Pillar 2 national programmes of ACRES and the Organic Farming Scheme (see section 3.4). The prior trajectory has placed farming communities under pressure, as they are associated with environmental decline, even though they have arrived at this juncture by responding to past drives of intensification and productivity gain, including greater representation in world markets. The EU Farm to Fork Strategy seeks to better reconcile agriculture with biodiversity and climate resilience through progressive reductions in pesticide inputs and excess nutrients, with a target of 25% organic farming across the EU by 2030. Further down the chain, it also seeks to reinforce sustainable consumption practices and minimise food waste (EC, 2020b).

An ageing profile (Conway et al., 2021, 2022; Citizens' Assembly, 2023), a pattern of smallholdings and an increasingly complex system of farm-based assessment and access to services and payments are further factors to take into account as part of a just transition for agriculture. The psychological impact of the burden and blame attached to farming practices requires sensitive treatment and support, and, above all, conjoined policies that avoid individual sectors and leadership organisations going it alone without consideration of their linkages to other policy objectives.

The Ag Climatise roadmap (DAFM, 2020) attempts to create a holistic framework for development of the AFOLU sectors in Ireland, incorporating targets for emissions and afforestation and establishing a 'Future of Farming in Ireland Dialogue' to manage a just transition (Action 29). Adaptation actions include greater genetic diversity in forestry (Action 14 on afforestation generally) and highlighting the role of Signpost farms from Teagasc (Action 23). The subsequent Food Vision 2030 document was formed in partnership with stakeholders and presents a comprehensive framework for the agricultural sector, but it was formed prior to the 25% emissions ceiling target agreed for agriculture in 2022. Despite somewhat contradictory goals of meeting broad emissions targets for methane and other greenhouse gases, while also growing the dairy and beef industries (as discussed in Volume 2, section 6.1), it marked a progression towards a framework for lowering greenhouse gas emissions and supporting biodiversity through schemes such as a national study of hedgerows and the land cover set, which have since been completed. Action 10 (Goal 1, 'Climate Neutrality and Resilience') calls for a risk analysis of climate impacts on food production and food safety. The limited published literature on climate impacts available at the time of writing is discussed in section 3.5.

3.1.3. Land use change objectives and climate change adaptation

Food Vision 2030 contains an action (Action 3) as part of Goal 2 'Restore and Enhance Biodiversity', committing the government to "[u]ndertake a national land use review and support the DECC led development of a land use strategy" (DAFM, 2021). The international importance of land use, land use change and forestry for climate change was made clear in the IPCC's landmark report on land use (Shukla et al., 2019). A similar national-scale research report was commissioned for Ireland (Haughey, 2021). Until March 2023, Ireland lacked a high-resolution land cover set, which will be needed as a baseline tool to track progress on key climate change and biodiversity indicators, and which can now be acquired from Tailte Éireann (https://www.tailte.ie/). Hitherto, research was reliant on the general European land cover map, CORINE (https://land.copernicus.eu/en/products/corine-land-cover), with its 25-hectare resolution. In contrast, the new land cover set has a minimum mapping unit of less than 0.1 hectare and will provide a platform for future research and policy implementation.

Based on Central Statistics Office (CSO) data (CSO, 2021), Haughey provides an overview of land use change in recent decades, showing the stable dominance of grassland and relatively small proportion of forestry and tillage crops (Figure 3.2).

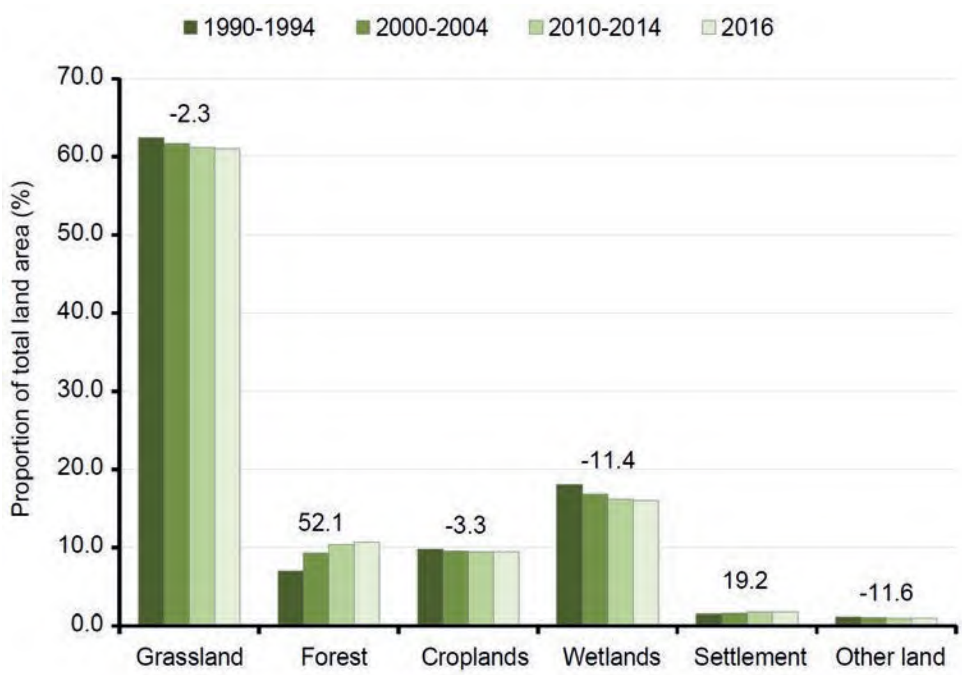


Figure 3.2 Land use in Ireland from 1990 to 2016 and for six land use categories, derived from 2018 data. Source: Haughey (2021).

A more complete overview of landscape diversity, rather than land use, can now be derived from the landscape classification map (GSI, 2018; Carlier et al., 2021) (Figure 3.3).

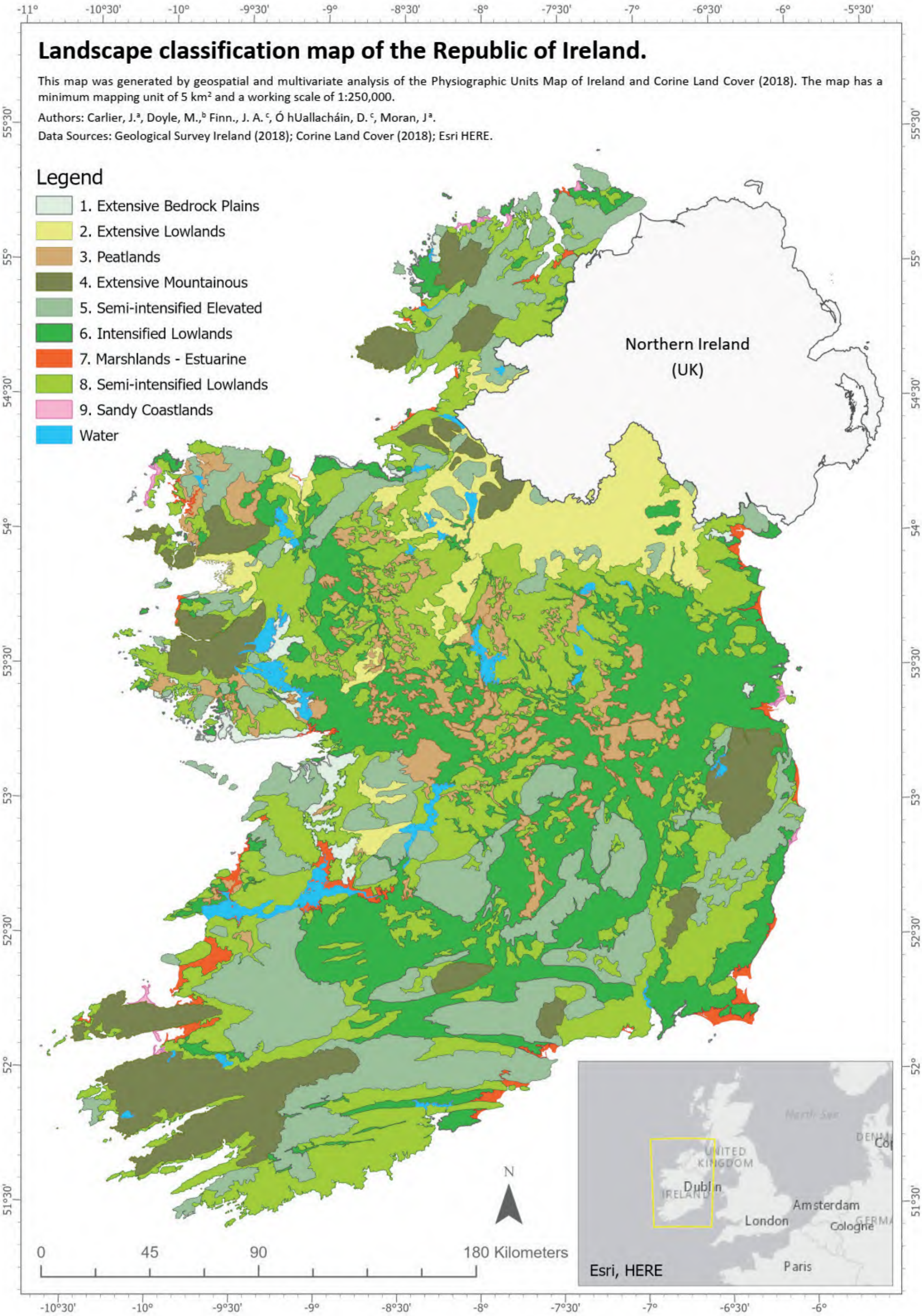


Figure 3.3 Landscape classification of the Republic of Ireland. Source: Carlier et al. (2021). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

Given the low baseline of continuous cover forestry and mature native woodlands compared with other European countries, hedgerows form an important reservoir for multiple plant and animal species in Ireland. They also offer further services by providing shelter, absorbing runoff, and together with riparian woodlands (next to streams or rivers) help water quality. Afforestation and restoration of peatlands are given prominence across rural policies, including in further actions within *Our Rural Future – Rural Development Policy* 2021–2025 (DRCD, 2021).

3.2. Climate change risks

Research on climate impacts on Ireland's AFOLU sectors is advancing, but there are several areas where further attention is needed (see section 3.5). A systematic programme of assessing climate impacts on agriculture and forestry will be needed to support these assessment cycles with consistent evidence over time. While new programmes, including a partnership with Teagasc covering climate impacts on agriculture, are under way, coordination among research programmes will be required to enable periodic and systematic assessment of climate change impacts for land use, agriculture and forestry that utilise standardised climate scenarios.

Previous assessments of climate impacts on Ireland conclude that more information is needed on the impacts of climate change on agricultural land, water stress, soil quality, crops, pests, pathogens and invasive species (Desmond et al., 2017, p. 21). Research since then has not substantially added to the general picture outlined there and elsewhere (Robbins et al., 2020; Sweeney, 2020), although successive refinements of growth models have the potential to be linked with Irish climate projections (Cucak et al., 2019, 2021; Upreti et al., 2022).

The general outlook is increased productivity for many crops, such as grass and maize, reduced growth for others susceptible to drought and pests (e.g. potatoes and wheat), and potentially increased instability in global supply chains. Currently, irrigation is applied to only a very small proportion of land in Ireland (Vicente-Serrano et al., 2019), but this is expected to increase in the future (Haughey, 2021). There is a knowledge gap regarding the impact of such increases on overall national water demand (Irish Water, 2021a).

Changes in precipitation along with increased temperatures in critical periods can lead to increased soil erosion, while loss of soil water retention capacity may have implications for the suitability of pasture and grazing areas (DAFM, 2019; Wreford and Topp, 2020). Moreover, loss of coastal land due to sea level rise and coastal erosion may increase the salinity in coastal aquifers and result in less productive pasture (Corwin, 2021).

3.2.1. An increased growing season partially offset by drought

While partly offset by risks to global supply chains and extreme weather events (Campbell et al., 2016), the growing season is projected to increase in Ireland by the middle of the century, with a "clear south-to-north gradient, with increases ranging from 5% to 18% and from 6% to 23% for the mid (RCP4.5) and late (RCP8.5) action scenarios, respectively" (Figure 3.4; Nolan and Flanagan, 2020, p. 20).

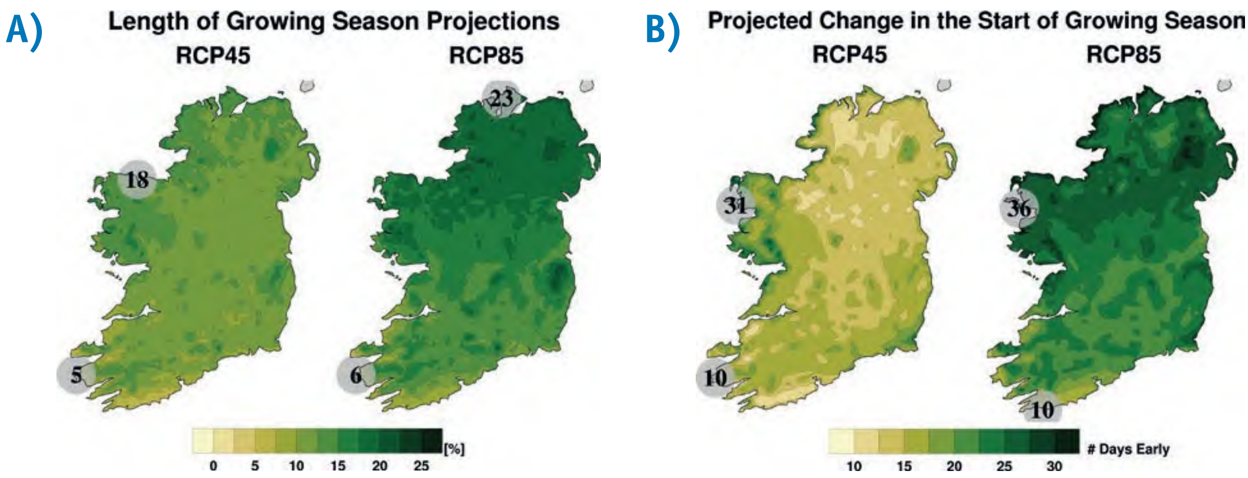


Figure 3.4 Mid-century projected changes in (a) the length of the growing season (%) and (b) the start of the growing season (number of days early). In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations. Source: Nolan and Flanagan (2020).

Similarly, the grazing season, crop heat units and growing degree-days for a range of crops are projected to increase substantially by the middle of the century (Table 3.1). An increase in the frequency and magnitude of droughts may offset this increase in growing season length for certain crops in Middle to Late action scenarios. Shrestha et al. (2015) show that a reduction in yield is projected for barley and wheat, and is larger in the south-east than in the border region. In contrast, maize and grass are projected to increase substantially in all regions. The increase in maize is strongest in the border counties, while for grass the increase is broadly similar in all regions. For the most part, permanent grassland in Ireland is associated with relatively low soil erosion risks but with large variation (Mullan, 2013). Specific risks for cropland and peat soils are likely to be exacerbated by climate change.

Table 3.1 *Growing degree-days base temperature for various crops and pests, and mid-century projected change averaged over all land points of Ireland*

Crop or pest	Base temperature (°C)	Projected change (all Ireland) (%)	
		RCP4.5	RCP8.5
Crops			
Wheat, barley, rye, oats and lettuce	5.5	+23	+30
Sunflower and potato	8	+32	+42
Maize, rice and tomato	10	+45	+59
Pests			
Stalk borer	6	+25	+32
Corn rootworm[a]	7	+28	+36
Lucerne weevil	9	+38	+49
Black cutworm, European corn borer and standard baseline for insect and mite pests of woody plants	10	+45	+59

Notes: In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. Base temperature refers to the threshold below which development does not occur for a given species.

[a]Reported in the UK but currently not present in Ireland (as at 2020).

Source: Based on Nolan and Flanagan (2020).

Increasing annual or seasonal precipitation will have impacts on soil management, as wetter soil will be more vulnerable to compaction and degradation from vehicles and livestock. Livestock can cause poaching and increase vulnerability to erosion (Haughey et al., 2023). Research on climate change impacts on soil management have called for improvements in data quality and consistency, better alignment to EU policies and a more even geographical coverage, including non-agricultural soils (Haughey, 2021, p. 201; McNamara et al., 2022).

3.2.2. Greater potential for pests and invasive species

A warming climate will increase risks from pests due to an increase in pest growing degree-days (Table 3.1) and a decrease in frost and ice days, as cold conditions are a key control mechanism for the survival of pests (Nolan and Flanagan, 2020). Desmond et al. (2017) called for more research on the impacts of climate change on pests, pathogens and invasive species presenting risks to Irish agriculture. High relative humidity and temperature combine to provide the warm, wet conditions in which the Phytophthora infestans fungus (the cause of potato blight) thrives (Cucak et al., 2019). Specific humidity is projected to increase substantially for all seasons by the middle of the century (Figure 3.5), while relative humidity is projected to increase slightly for all seasons except summer (Nolan and Flanagan, 2020).

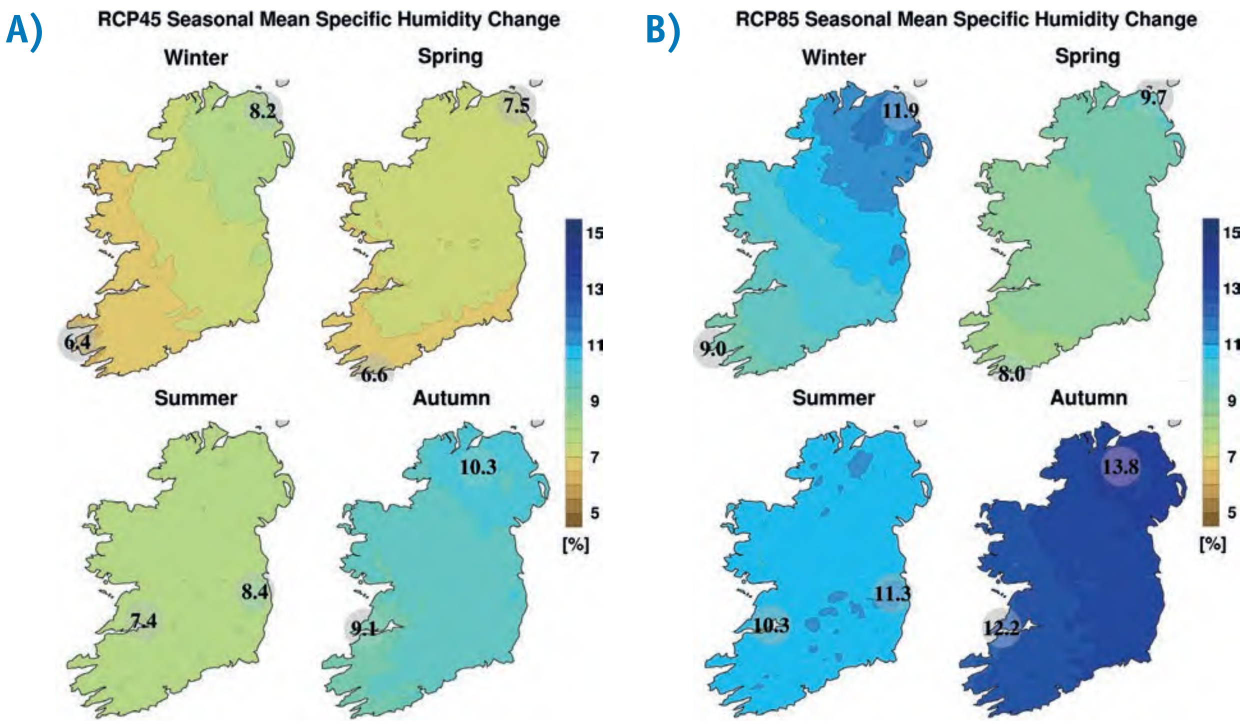


Figure 3.5 Mid-century seasonal projections of specific humidity (%) for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations. Source: Nolan and Flanagan (2020).

Wet conditions can lead to increases in the prevalence of liver fluke, *Fasciola hepatica*, and hence increase the risk of disease in cattle and sheep (Wreford and Topp, 2020). Moreover, there is a risk of exotic pests and diseases due to enhanced favourable conditions induced by climate change (DAFM, 2019). Several active invasive plant species in Ireland pose a threat to biodiversity and ecosystem functioning (Baars, 2011), and control of these could help stabilise and reduce pressure on protected habitats and species. The results from a series of horizon scanning workshops on invasive species indicated that many future risks are also likely to be aquatic (Lucy et al., 2021).

3.2.3. Impacts on livestock

In a global study of climate change impacts on livestock, Rojas-Downing et al. (2017) differentiate between impacts from temperature increases, higher carbon dioxide and precipitation. Temperature and carbon dioxide levels interact to affect the composition of pasture, while temperature and precipitation interact by altering susceptibilities to pests and invasive species. Impacts on the wellbeing of livestock such as cattle can have further impacts on food consumers, such as levels of aflatoxin M1 in milk, although a recent study found no exceedance of maximum levels under Middle (RCP4.5) and Late action (RCP8.5) scenarios (Chhaya et al., 2023).

Wreford and Topp (2020) distinguish broad categories of climate impacts for livestock for the UK. They consist of animal heat stress, pests and diseases, variable precipitation and climate extremes, and changes in pasture area, forage quality and quantity (Table 3.2).

Table 3.2 *Potential impacts of climate change on livestock systems and four categories of impacts to which they relate (heat stress, variable precipitation and climate extremes, pests and diseases, pasture area, and forage quality and quantity changes)*

Impacts identified in the literature	Broad categories
Increasing carbon dioxide levels, resulting in changes in herbage growth and quality	Forage quality and quantity
Changes in temperature, rainfall, radiation and humidity	Pasture area: forage quality and quantity; pests and diseases; variable precipitation and extremes
Extreme events (e.g. heat waves, hail, drought and flooding)	Pasture area; heat stress; variable precipitation and extremes
Shifts in crop suitability	Pasture area; forage quality and quantity; variable precipitation and extremes
Changes in plant nutrition and increasing incidence of weeds, diseases and pests	Forage quality and quantity; pests and diseases
Degradation of resources (e.g. soil erosion)	Pasture area; variable precipitation and extremes
Increased flooding	Variable precipitation and extremes; pests and diseases
Increased risk of drought and water scarcity	Variable precipitation and extremes; pasture area; forage quality and quantity; pests and diseases
Deterioration of soil quality	Pasture area changes
Saltwater intrusion in coastal agricultural areas	Pasture area changes
Increased risk of agricultural pests, diseases and weeds	Pests and diseases
Deterioration of livestock conditions – heat stress with implications for production, reproduction and health	Heat stress

Source: Wreford and Topp (2020).

More frequent and prolonged periods of higher temperatures will increase the potential for animals to experience heat stress (Wreford and Topp, 2020). Dairy cattle are particularly susceptible to heat stress caused by higher temperatures and humidity. This can affect fertility, milk production and cattle growth (DAFM, 2019). These impacts can be at least partly assuaged through silvopasture, a form of agroforestry that blends pasture and woodland to provide shelter for animals from extreme weather events and also an increase carbon and water storage (Klumpp and Fornara, 2018).

There is only limited research on livestock and climate change in Ireland, with Shrestha et al. (2015) basing their assessment upon localised impacts on grass production and switches to and from concentrate feed. A representative sample of farm types and region, derived from the National Farm Survey Report 2008 (Connolly et al., 2009), was used to assess responses to increases in costs or shifts in profit margins. Impacts varied according to region, with border regions and the south-east having relative decreases in profit margins according to the size and type of livestock, and other regions able to increase their profits (see Table 8 in Shrestha et al. (2015)). However, the study does not consider external shocks from food supply chains, or the costs of increasing stocking rates in relation to climate mitigation goals. Further research might consider the broader-scale economic modelling of impacts to supply chains and integrate that into agricultural pathways compatible with climate and biodiversity goals across a range of climate scenarios. For instance, bottom-up adaptation pathways have been trialled in New Zealand, considering climate uncertainties, local farming cultures and climate profiles (Cradock-Henry et al., 2020).

The 2012 fodder crisis exposed the potential vulnerabilities of the Irish livestock sector to adverse changes in weather and climate (Flood, 2012). A poor growing season in 2012 combined with a long winter period gave rise to a severe shortage of fodder on many farms. The regional climate impact resulted in economic costs conservatively estimated at €900 million by the Irish Creamery Milk Suppliers Association. Similarly, the 2018 fodder crisis resulted from a cold period followed by an extended dry period during the grazing season, which created a strong demand for supplemental feed (O'Mara et al., 2021, p. 38). The 2019 sectoral adaptation report on agriculture (DAFM, 2019) recommends incorporating winter feed budgets into the PastureBase tool (see section 3.4).

3.2.4. The forestry sector

Irish forestry is mostly coniferous species (69%), with commercial plantations of spruce being the dominant species, comprising 45% of the total forested area. Broadleaved forest comprises 31% and mixed forest the remainder. The primary broadleaved species are willow and birch, followed by ash, oak and alder (DAFM, 2022d, p. 4). Ambitions to plant 8,000 hectares of trees annually have stalled at around 2,000 hectares per year (DAFM, 2023).

The impacts of climate change on forestry are highly varied by species, regional climate, topography, rainfall, soil type, moisture content and management strategy. Irish research is limited to long-term projections of productivity and species choice, with a commercial focus through the CLIMADAPT project. Lundholm et al. (2019) provide projections of climate change impacts on Irish forestry by combining a forestry decision support system (CLIMADAPT), Irish forestry data, climate projections from HadGEM2-ES and industry-specific scenarios matched to Early, Middle and Late action scenarios for the middle and end of the century. In agreement with earlier studies (Sweeney et al., 2003), the authors find that forests in eastern Ireland are likely to suffer more droughts, as the area is expected to experience the highest temperature increase and largest reduction in precipitation (Figure 3.6; Lundholm et al., 2019, p. 2). Increased yields by the end of century are projected for species such as Scots pine, beech, lodgepole pine and birch, and decreased yields for others, including oak, Sitka spruce, other conifers and most other deciduous trees.

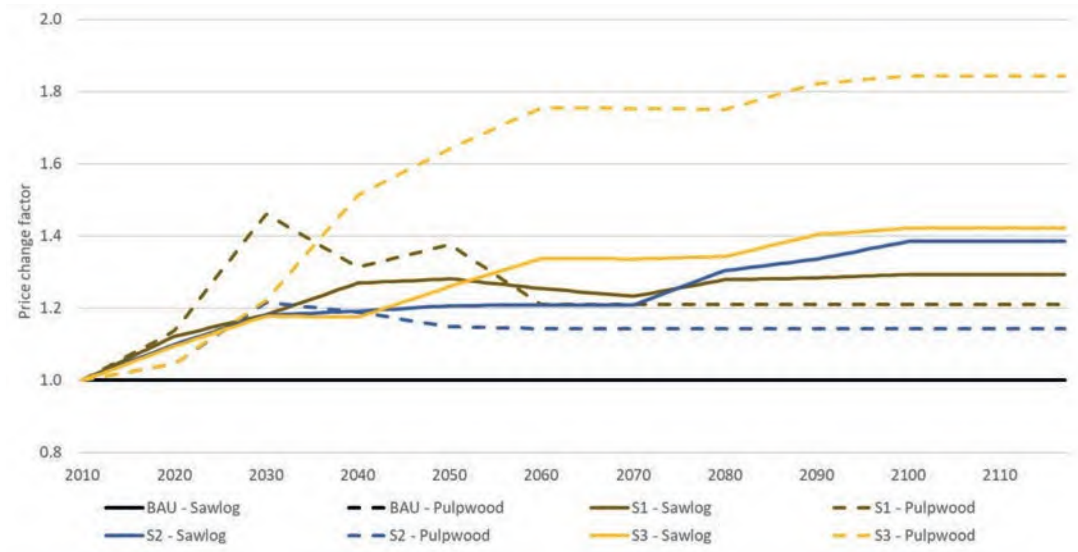


Figure 3.6 Net present value (NPV) development throughout a 100-year planning horizon for the business-as-usual (BAU) and three global scenarios, where S_1, S_2 and S_3 correspond to RCP8.5, RCP4.5 and RCP2.6, respectively. The NPV in each year is the sum of all discounted costs and revenues in the preceding years and the current year, discounted to the start year 2016. An initial divergence between scenarios commences around year 2035. Source: Lundholm et al. (2019). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

Under these scenarios, spruce stocks are likely to be impacted by changing precipitation patterns, with a reduction of 28% by 2080, due to increased drought in eastern regions and waterlogged soil in western regions (Lundholm et al., 2019, p. 3). However, these climate projections are based on a single climate model. As in other sectors, pest control will likely be a concern for forestry, driven in large part by increased international trade over recent decades (Ramsfield et al., 2016).

Wildfire (see also Volume 1, section 7.6) impacts on forestry and other biomass have been explored in a historical context (Jeffers, 2021) and in terms of remote sensing of biomass burning events and land cover data (Hawthorne and Mitchell, 2018; Vilar et al., 2019). However, projections of future wildfire risk are not yet available, and will be dependent upon better land cover data and integration with the latest climate projection data for Ireland. In a German case study, using a Late action climate scenario, findings changed greatly according to species and species mix (Albert et al., 2018). Similarly, for a Finnish case study, the authors conclude that a careful selection of the subset of general circulation models is crucial, as it may greatly affect the interpretation of the results and may result in costly and sub-optimal (adaptation) to climate change (ALRahahleh et al., 2018).

3.3. Adaptation strategies

There is a wide range of potential adaptation response options in the land system. These include options that seek to enable actions through data collection and processing, such as mapping geographical features of concern, and early warning systems for extreme events. Such information can also be deployed for land use planning, cognisant of increasing climate risks and enabling a longer-term perspective on sustainability. Other options focus on decreasing risks in relation to extreme events in managed and natural systems, including the redesign of agricultural or forestry systems, or installation of adaptive supporting infrastructure.

Haughey (2021) assessed the potential of 40 integrated adaptation options for the land system in Ireland. These options were selected based on the analysis conducted as part of chapter 6 of the IPCC Special Report on climate change and land (Smith et al., 2019). A selection of these land-based options with the greatest relevance for climate change adaptation in Ireland is summarised below.

3.3.1. Supply chain and risk management

Enhanced urban food systems. Improving access to nutritious food in urban areas can have co-benefits for food security and human health. Examples include urban or peri-urban agriculture, market gardens and farmers' markets, as well as the provision of allotments. This may include the use of novel technologies such as vertical farming and the use of controlled environments. Due to their multifunctional nature, urban food systems are likely to provide social, economic and environmental co-benefits (Lucertini and Di Giustino, 2021). These aspects are discussed further in Volume 4.

Improving soil organic carbon content. Grassland and cropland management can be improved to increase the soil organic carbon content, which has benefits for climate adaptation through an increased capacity for water storage and retention of nutrients in soils. This is critical in the face of extreme events such as droughts and floods. Soils already high in carbon content may have limited capacity for further increases (Klumpp and Fornara, 2018; Haughey, 2021), but site-specific exceptions can be expected. The capacity to contribute to adaptation requires further research.

Disaster risk management and wildfire alerts. Alerts and risk management systems can be used to minimise the negative outcomes resulting from climate-related disasters and impacts on socioeconomic systems. Examples include hazard and risk mapping, hydrological and meteorological monitoring and early warning systems, and related education and outreach.

Flooding, drought, wildfire and climate change-related landslides are of particular concern for Ireland under future climate conditions. Despite a relatively small area of land being subject to wildfire annually in Ireland (EFFIS, 2020), this is likely to increase due to climate change and land management trends. This includes probably greater 'fuel loads' across the landscape in the future due to increased afforestation rates and biodiversity spaces (Haughey, 2021).

Landslides represent a significant risk across Europe (Herrera et al., 2018), likely to increase due to climate change, with peatlands being especially vulnerable (Long et al., 2011). High-quality historical data are available (GSI, 2016), but systematic and active disaster risk management is lacking. Actions to manage landslide risk include vegetation management, such as afforestation or physical/engineering solutions, and soil stabilisation methods.

Risk-sharing instruments. Risk-sharing instruments can help buffer the negative effects of extreme climate events on society. In agriculture, a prime example of this is commercial crop insurance, which can help manage the risks associated with crop failure or price fluctuations. There are currently only limited private sector options available in Ireland (Vladimir and Nataša, 2014).

3.3.2. Agriculture and land management

Improved cropland and grazing management. Cropland management approaches are typically region and crop specific and can also reduce greenhouse gas emissions by increasing soil carbon. Adaptation-relevant actions include breeding more resilient crops and optimising soil management to retain water and nutrients.

Grazing management is a collection of practices that focus on the management of grasslands and aim at reducing greenhouse gas emissions and increasing soil carbon and resilience to climate change. Increased production and utilisation of grass on farms in Ireland has been identified as key for efficiency (O'Donovan et al., 2021). Multi-species swards have been shown to have significant adaptation potential for resilience in the face of drought events (Hofer et al., 2016; Finn et al., 2018; Haughey et al., 2018).

Improved livestock and soil management. Adaptation-relevant actions in livestock management include breeding more climate-resilient livestock and the use of traditional breeds, with livestock suitability tailored to local soil and climate conditions. Active livestock management approaches can help avoid soil degradation (e.g. through poaching or erosion). Much current knowledge is focused solely on increasing production efficiency (Lanigan et al., 2019). There is a significant gap in relation to livestock and climate adaptation for Ireland, such as in relation to extreme weather events.

Soil compaction can have a significant negative impact on soil health and functioning. Options to reduce it include the control of agricultural traffic (avoiding traffic during periods of soil water saturation), adapted farm machinery and appropriate management of livestock density. The negative impacts of soil compaction are likely to be exacerbated for Ireland under more variable climate conditions, with operational limitations on soil trafficability for animals and machinery when soils are wet (Posthumus et al., 2009; Bondi et al., 2020).

Agroforestry. Agroforestry encompasses a range of approaches to sustainable forest management, including continuous cover forestry and a greater share of broadleaved species. More diverse forestry systems are expected to have increased resilience to climate change. The IPCC defines agroforestry as "[l]and-use systems and technologies where woody perennials (trees, shrubs, etc.) are deliberately used on the same land management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence" (Shukla et al., 2019, p. 805). Agroforestry can (potentially) increase carbon sequestration in soils and biomass, with co-benefits for climate change resilience.

Forestry in Ireland is dominated by fast-growing non-native species, but the proportion of broadleaved species being planted annually has increased in recent decades from a baseline of less than 5% in 1980s to more than 45% in 2021 (DAFM, 2022b). There is a relatively low uptake of agroforestry in Ireland to date (McAdam, 2018), despite significant grant aid opportunities (Teagasc, 2020). Only 51 hectares of land have been planted under the present agroforestry subsidies, which is just over one-quarter of the targeted land area of 195 hectares that was to be planted between 2015 and 2020 (Irwin et al., 2022). The perception of the risks associated with adopting agroforestry as well as the time taken for return on investment in the case of timber or tree crops have been identified as barriers. However, Irwin et al. (2022) found that farmers are generally well disposed to agroforestry but that they are not well informed about what the term 'agroforestry' means nor are they aware of the subsidies that are available.

Livelihood and agricultural system diversification. Diversification encompasses a range of approaches that aim to increase the resilience of farms to climate variability and climate change and the associated economic risks. The general approach is to shift the farming system away from a single, typically low-value, agricultural output to a more diverse set of

outputs, including those with higher or added value. This could include organic produce or other value-added products (e.g. artisanal food). Research indicates that diversification of farming systems in Ireland is not viewed favourably by many farmers, with many preferring livelihood diversification through off-farm work rather than agricultural diversification (Meredith et al., 2015; Moroney et al., 2016). A review of these barriers has been recommended elsewhere (Haughey, 2021), and will be necessary for facilitating a 'just transition' for large parts of the Irish farming community.

Restoration of peatlands and coastal wetlands. The restoration of our wetlands and peatlands is imperative for achieving Ireland's climate goals. This involves a range of actions undertaken to restore degraded peatlands and avoid further human conversion of peatland areas. Restoration provides benefits in relation to water storage (including flood regulation, mitigation of peak flow and groundwater recharge) and water quality, with positive interactions with climate adaptation (Andersen et al., 2017; Pschenyckyj et al., 2021; Tanneberger et al., 2021). For a more detailed discussion see Volume 1 (section 7.4 and Box 7.1) and Volume 2 (section 6.4) on restoration efforts, links to biodiversity and associated greenhouse gas emissions.

For wetlands, conservation involves actions undertaken to avoid further conversion to other land uses and restoration of degraded coastal wetlands, including salt marshes and seagrass ecosystems. Salt marshes and mudflats in Ireland are recognised for their important contribution to biodiversity (Sheehy-Skeffington and Curtis, 1998), with contributions to carbon sequestration increasingly recognised. Recent studies indicate that saltmarsh and seagrass habitats in Ireland store 9.2Mt of carbon over an estimated area of 162km^2 (Cott et al., 2021).

3.4. Cross-cutting issues

Adaptation policies for agriculture, biodiversity and forestry will ideally be coordinated within an overall framework for land use for Ireland. These are discussed below, covering the role of climate services, biodiversity and ecosystem services, and landscape- or catchment-scale coordination of land use.

3.4.1. Supporting agriculture and forestry with climate services

Ireland has a long tradition of active farming communities that have helped shape the agricultural policy environment (Smyth, 1975; Lapping and Scott, 2019). Organisations such as Muintir na Tíre, Macra na Feirme and the Irish Farmers' Association have played an important role in advocating for the farming community, while state extension services such as Teagasc have driven modernisation and training. Having in place training and advice services (Warner, 2008), and boundary organisations that mediate between and indeed combine science and practice, improves the capacity of all parties to provide climate data that are timely, relevant and usable (Cash, 2001; Cutts et al., 2011). As an exemplar, the Teagasc Signpost series of talks and discussions has shown how farmers, through research and Signpost farms, can co-design and participate in scientific research.

The continued advancement of participatory science programmes will be essential to develop and disseminate best practices among Ireland's farming community. Examples at present include the National Organic Training Skillnet, and its annual BioFarm conference, and Farming for Nature, which looks at improving the environmental credentials of farming practices. European innovation partnerships have strongly supported environmental advances in farming practice through training and support programmes, while the present agri-scheme ACRES further supports a network of skilled advisers on the ground that support change in Irish farming.

Climate services tools are being successfully used to guide land use decision making in Ireland and could be progressively amended or superseded with further tools that enable broader decisions across multiple sectors. The CLIMADAPT tool was adapted specifically for the Irish forestry sector and links Coillte's land use geographical information system (GIS) information (Keenan et al., 2017) with projections of climate impacts on yield and pricing (Lundholm et al., 2019). It was developed by Forest Research UK in collaboration with Forest, Environment Research & Services Ltd and Met Éireann. The forestry sector is undergoing change and incorporating its role of ecosystem services provider through continuous cover forestry (as opposed to clear-felling) (Wilson et al., 2018), greater use of native and broadleaved species, biodiversity and provision of space for recreation.

CLIMADAPT could be further developed in the future to inform broader-scale land use strategy. Forthcoming research funded by the EPA on land use scenarios, as well as existing major research projects such as Terrain-AI, can inform broader decisions on forestry objectives that go far beyond simple productivity projections. These might include carbon sequestration and maximising carbon retention in peaty soils, forestry planting to mitigate flood risk, biodiversity reserves and corridors (which obviously excludes clear-felling crops), and landscape enrichment through the continued reversal of medieval and early modern destruction of native forestry. For example, at the federal scale in Germany, Gutsch et al. (2018) examined the trade-offs and synergies between different choices in terms of timber production, water, carbon storage and habitats. In addition to covering the national land mass, it also links projections to three different management strategies: 'baseline management', following present-day recommended rotation cycles; 'nature protection', with longer rotation cycles and higher biomass stock as well as more deciduous trees; and 'biomass production', with higher timber harvests, faster growing species such as Douglas fir and shorter rotation cycles.

A further example of climate services aiding decision making is the grassland management tool, PastureBase, albeit operating on much shorter meteorological timescales. The tool incorporates data from Met Éireann for a 7-day window, and from the farmers themselves who share data on their farms within the tool, which further informs the model with a view to more efficient predictive growth modelling (Hanrahan et al., 2017).

3.4.2. A greater space for ecosystem services and biodiversity

The direction of policy in Europe is that of increasing local stewardship of our natural resources in the face of a climate and biodiversity crisis. The Common Agricultural Policy (2023–2027) advances the stated ambitions of the EU's Farm to Fork Strategy and biodiversity strategies, with at least 25% of direct payments linked to ecoschemes. The Basic Income Payment is now the Basic Income Support for Sustainability, and the present flagship programme, ACRES, successor to the GLAS (Green, Low-Carbon Agri-Environment Scheme) and the REPS (Rural Environment Protection Scheme), is funded to €1.5 billion. It contains the following ecoschemes, with their relevance for adaptation shown in Table 3.3.

Table 3.3 *Ecoschemes in place for ACRES and their adaptation relevance*

Ecoscheme	Adaptation relevance
Space for Nature	Create further resources to harbour and restore biodiversity, making it more resilient against climate change
Extensive livestock production	As opposed to intensification, creating more opportunities for high nature value farmland to thrive
Limiting chemical nitrogen usage	Improving sustainability of soil
Planting of native trees/hedgerows	Carbon sequestration; biodiversity; silvopasture providing shelter from heat or rain
Use of a GPS-controlled fertiliser spreader/sprayer	Improving sustainability of soil
Soil sampling and appropriate liming	Improving sustainability of soil
Planting of a break crop	Pest control; improving sustainability of soil
Planting of a multi-species sward	Improving sustainability of soil and reducing need for fertilisers

ACRES and programmes such as the Burren Programme could be further integrated into broader discussions on afforestation, biodiversity habitat evaluation and monitoring, and energy infrastructure. This is likely to involve a higher tier of coordination at the landscape and catchment scale, aligned with national and regional objectives.

3.4.3. Landscape planning

Article 5 of the European Landscape Convention asks that nation-states recognise landscapes in law and "establish policies aimed at landscape protection, management and planning" (CETS, 2000). The National Landscape Strategy for Ireland 2015–2022 (DAHG, 2015) committed the state to providing characterisation of Irish landscapes and to integrating this into land use planning. Once completed, subsequent county and city development plans have referenced their landscape character assessment in terms of varied sensitivities to development from agriculture, rural housing, urbanisation and infrastructure.

There is further potential in Ireland to move from farm-level considerations and link up with landscape-scale programmes and design, building on the new landscape classification, the new land cover data and the work that will follow to build a habitats map of Ireland. From a biodiversity perspective, Rotchés-Ribalta et al. (2021) argue that agricultural policy needs reform to go beyond minimal share of high nature value farmland and build a more progressive system that rewards conservation and restoration of quality habitats. This is particularly prominent for Ireland, given the contrast between the intensive land use practices in the east and south of the island and the more extensive farming practices in the west and border areas.

The development of results-based payments for ecoschemes is largely celebrated in Ireland in terms of its capacity to reconcile mandated directives and targets with locally led participative programmes (Moran et al., 2021). The combination of a network of advisers and flexible payment options that ease the burden of administration and risk for farmers is creating better conditions for coordinated approaches to ecoschemes at the landscape level. Landis (2017) argues that greater gains in basic and applied ecology, and thus in climate resilience, can be gained by moving to larger-scale coordinated 'design' of landscapes to reduce fragmentation of habitats (Figure 3.7).

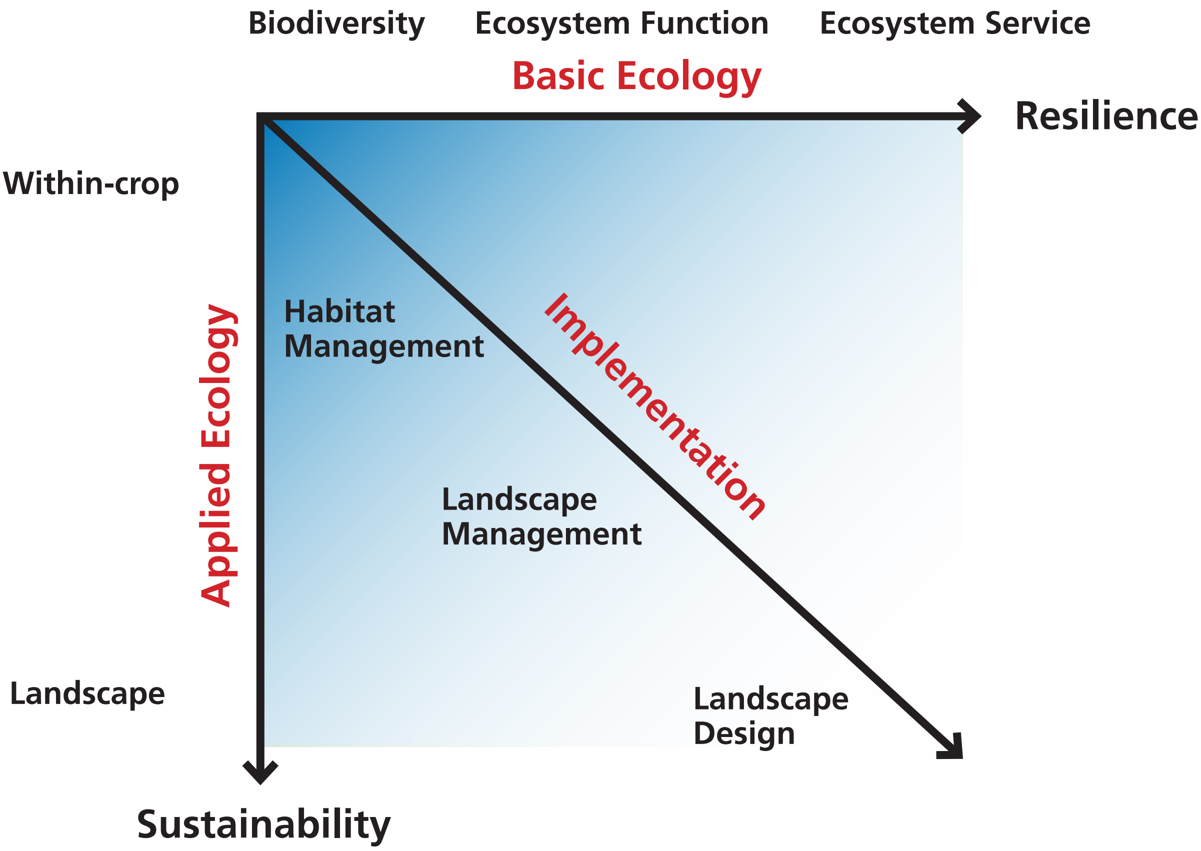


Figure 3.7 Landis' framework for integrating basic and applied ecology in the context of agricultural landscape management and design. Research and knowledge are considered to be stronger in the darker shaded area towards the top left of this conceptual diagram. Source: Landis (2017). Reproduction licensed under the Creative Commons Attribution CC BY-NC-ND 4.0 licence (https://creativecommons.org/licenses/by-nc-nd/4.0/).

Carlier et al. (2021) provide an example of how science can inform the design of landscape features such as greenways to minimise fragmentation of habitats. At the farm level, the existing cooperative zones for ACRES (Figure 3.8) might also serve as a basis for broader landscape-level coordination of landscape that combines multiple landowners, and thus might also reinforce spatial planning policies at the county level.

Landscape design and catchment-scale land use planning can incorporate adaptation options alongside biodiversity and climate neutrality objectives to create connected biodiversity corridors, to thoughtfully incorporate renewable energy infrastructure into landscapes and to plant suitable species, and mixes of species, of trees into woodlands and forests. These landscapes under human custodianship provide more than commercial plantations or centres of aesthetic enjoyment for recreation, as they also return to the land the vitality it once held for other species to thrive and balance each other alongside human activity (see Volume 4 for further discussion on landscapes and ecosystem services).

Landscape design may require additional resources commensurate with the extra responsibilities acquired from the demands of a rapidly growing and developing state. It will also require research to co-produce an evidence base for landscape decisions based on various land use scenarios that are themselves measured against our climate and biodiversity objectives. These objectives include our afforestation goals, which alongside peatbog and wetland restoration form a nexus of adaptation and mitigation goals. Lastly, in the context of a climate emergency, these high-level decisions will need to be made with a reasonable degree of urgency to meet our climate goals, with expediency occasionally outweighing our traditional multi-decadal timescales for large land use changes. Precedents exist in terms of the Land Commission and state-led afforestation, but the scale of the challenge is significant and will demand much human ingenuity until at least the latter part of this century.

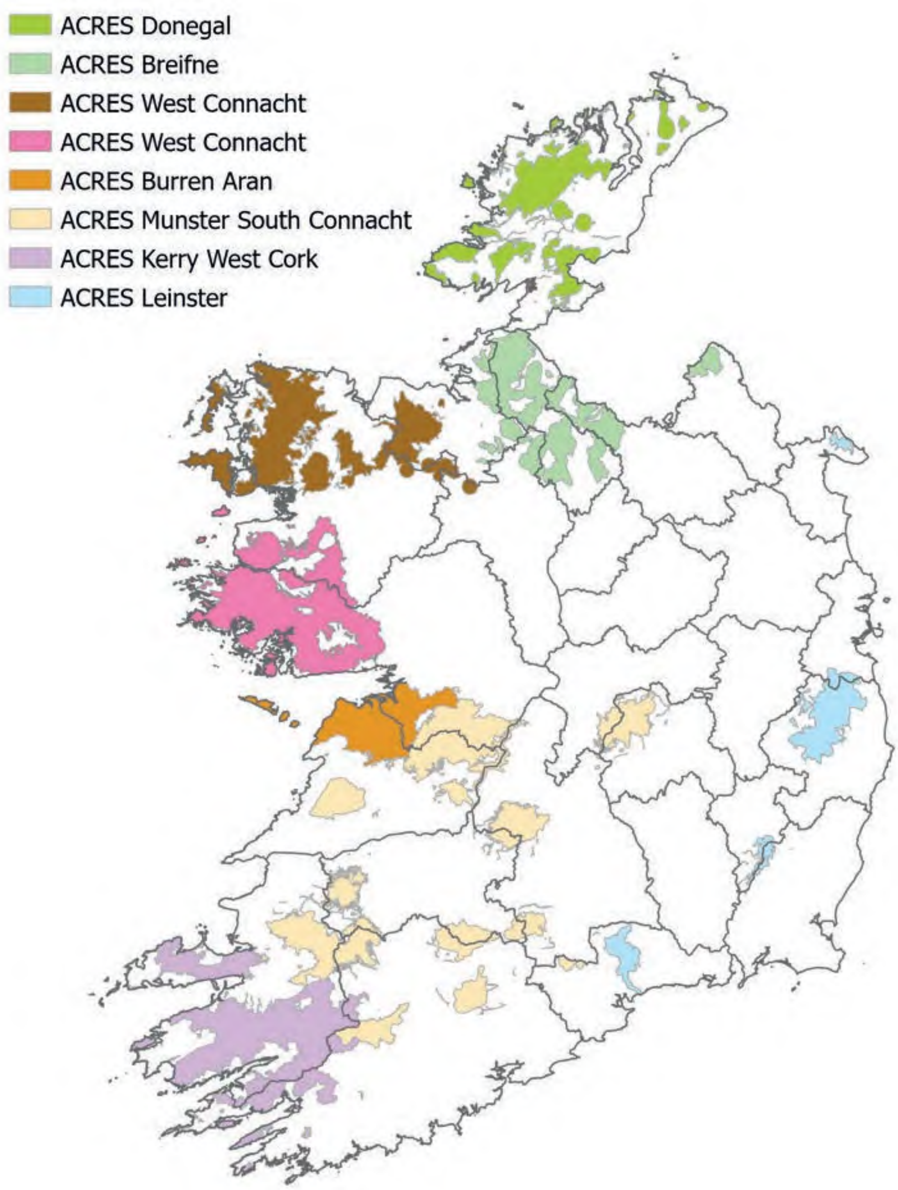


Figure 3.8 ACRES cooperative zones for coordinated ecoschemes across catchment areas. Source: DAFM (2022d).

3.4.4. Evidence-based land management

Following on from the land use review (Haughey et al., 2023), a new suite of research projects on land use data and land use scenarios funded by the EPA and directly by the Department of Agriculture, Food and the Marine (DAFM) will address part of the evidence needs, while it then falls on government and broader society to enact change on a democratic basis. The land use review report notes that guided land use management could bring substantial benefits for biodiversity and water, but that, conversely, poorly targeted land use change with inappropriate management could have significant trade-offs.

The draft Forest Strategy for 2022–2030 (DAFM, 2022d) recognises that this requires a whole-of-society and whole-of-government response and that there needs to be a significant shift in land use change and a regulatory and licensing system in place that can facilitate efficient and effective forest expansion and management. A recognised 'preference' for a plan-led approach at catchment, landscape, local authority or county level, expressed in the draft strategy and on the basis of the land use review, is arguably an essential basis for land management in Ireland. Haughey et al. (2023) conclude that to achieve the levels of land use change outlined, while minimising negative externalities, an overall integrated land use management strategy for the country is needed.

Box 3.1 Unique Irish places and pressures: the Burren

The Burren Programme (http://burrenprogramme.com/) is credited with further developing and proving a model of results-based payments for ecoschemes (Moran et al., 2021). The Burren, Co. Clare, covers 72,000 hectares of thin soils, limestone pavements, calcareous heaths, Atlantic hazel woodland and grasslands (Box 3.1, Figure 1). As a case study of an area under pressure from intensification and abandonment, it provides a template for many areas along coastal and border areas that have an extensive farming tradition but are experiencing depopulation.

Box 3.1 Figure 1 Local farmers contracted to remove encroaching hazel scrub as part of efforts to restore grazing to areas of species-rich grassland as part of the Burren Programme. Photo credit: Brendan Dunford.

In the mid-1990s, 33,000 hectares were designated as a special area of conservation, which although halting decline also generated resistance among people in the area. EU LIFE nature funding provided a basis for a scaled-up programme by 2016, with 328 farmers on 23,000 hectares. The success of the programme is attributed to a well-developed scoring system and results linked to payment, the support of a local office and trained advisers, a farmer-centred approach with simple two-page plans, minimised private risk with simple reference costs for recouping expenditure, and a 'freedom to farm' concept, meaning that farmers choose what and where to implement measures if they wish to participate (Moran et al., 2021).

3.5. Priorities for research

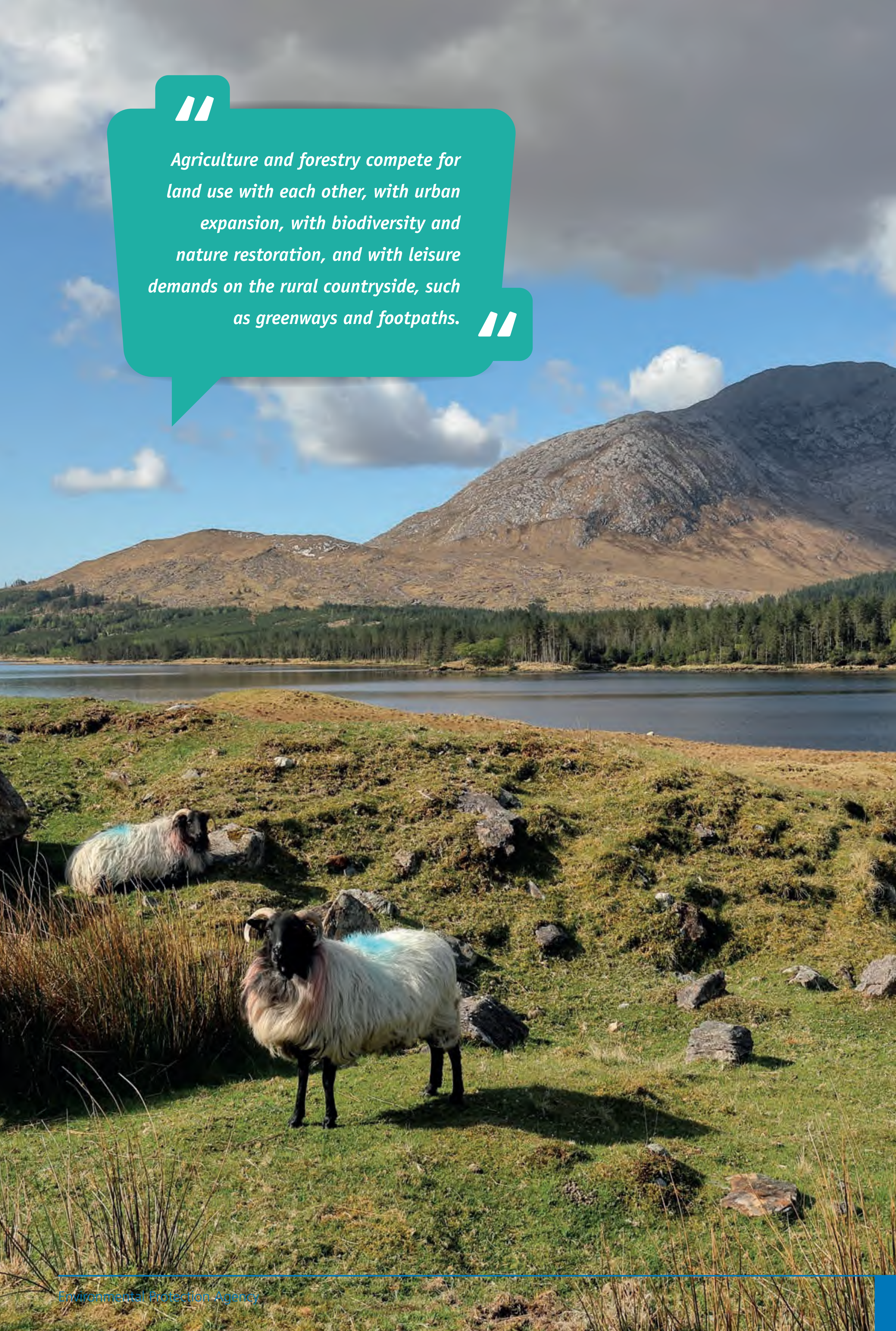
3.5.1. Update of climate impacts assessments

The number and relevance of recent climate impact studies for AFOLU sectors in Ireland are very limited. While the general picture from successive impact studies is largely consistent, the studies nevertheless embody different modelling assumptions, use different baseline scenarios, and use different approaches to link domain-level data and models to climate data. The studies in Table 3.4 are papers published over the past decade and cited elsewhere in this chapter, using climate model-derived scenario data and linking these to impact models of their respective domains.

Table 3.4 *Downscaled climate impacts studies from 2013 to 2023 for Ireland and Northern Ireland, incorporating climate projections and agricultural, forestry or soil management modelling.*

Sector	Impacts	Scenarios	Climate models	Agri-models
Agriculture	Regional projections of future growth for winter wheat, spring barley, forage maize and grass biomass (Shrestha et al., 2015)	A1B (SRES)	HadCM3, RCA3 (McGrath et al., 2008)	CERES, Johnstown castle grass model, FLLP
	Projections of future levels of aflatoxin M1 in milk in Ireland (and France) (Chhaya et al., 2023)	SSP2–4.5, SSP5–8.5	Global temperature change average derived from IPCC AR6 on baseline Met Éireann data (2011–2022) for temperature, humidity and saturated vapour pressure	Excel addon-based probabilistic study; equations detailed
	Projections of future grazing season, crop heat units and growing degree-days (Nolan and Flanagan, 2020)	RCP4.5, RCP8.5	COSMO-CLM (v4.0 and v5.0) and WRF (v3.8) RCMs, CMIP5 datasets	Equations derived from literature for crops, growing season, etc.
	Projections of future grazing and growing season, crop heat units and growing degree-days for a range of crops and pests (Nolan, 2023)	SSP1–2.6, SSP2–4.5, SSP3–7.0, SSP5–8.5	COSMO-CLM and WRF RCMs, CMIP6 datasets	Equations derived from literature for crops, growing season, etc.
Forestry	Projections of impacts on Irish forestry (Lundholm et al., 2019)	RCPs 2.6, 4.5 and 8.5 derived from A2 (SRES) and a time period of 2050 to 2080	HadGEM2-ES	Woodstock model
Soil management	Projections of soil erosion for Northern Ireland (Mullan, 2013)	A2 B2 (SRES)	HadCM3, CGCM2 CSIROMk2	WEPP model

"Agriculture and forestry compete for land use with each other, with urban expansion, with biodiversity and nature restoration, and with leisure demands on the rural countryside, such as greenways and footpaths."



A considerable policy research task remains to create peer-reviewed studies of AFOLU sectors and other sectors in this report for Ireland using comparable climate data. Current efforts at generating a consistent set of climate change projections for Ireland from the TRANSLATE project (O'Brien and Nolan, 2023) need to be used to assess impacts and adaptation options across sectors, especially land use, agriculture and forestry. This will require a concerted programme of research for the next 5-year assessment and will ensure a stronger baseline of evidence going forward.

3.5.2. Key knowledge gaps

Agriculture: Important knowledge gaps that hamper rapid progress across multiple sectors include the need for more detailed data on land cover/land use and soil carbon fluxes, uncertainty with regard to climate impacts on the land system, and the contribution of areas of semi-natural vegetation to climate mitigation. There is also a need for more effective knowledge sharing and innovation development with land managers, to enable effective and timely climate actions.

Wildfires: Gaps exist for wildfire projections, for which the FLARES project and its successor FLARES-PPLUS will provide baseline data for 1990–2024, as well as for future climate scenarios using TRANSLATE data. As in other areas, research was hampered by the lack of a detailed land cover dataset, which was not available until 2023 (using 2018 baseline data). However, these land cover data will now open up avenues in this and other sectors to provide more detailed risk assessment. An assessment of fire risk in Ireland under current and future climate change scenarios, similar to the UK fire danger rating system (Arnell et al., 2021), would help inform land management decisions and indicate hotspots for potential biodiversity loss.

Sea level rise and loss of land: Loss and deterioration of coastal land and groundwater due to saltwater intrusion requires consideration, even if the timelines for mass intrusion of saltwater extend beyond this century.

Land use interactions: Agriculture and forestry compete for land use with each other, with urban expansion, with biodiversity and nature restoration, and with leisure demands on the rural countryside, such as greenways and footpaths. A new suite of research projections including the ongoing Terrain-AI project and EPA/DAFM projects on land use scenarios open up more holistic approaches to land use decision making that is holistic and applicable at regional, landscape and catchment scales.

Invasive species: An updated evidence-based list of alien species for the island of Ireland under varying temperature scenarios would provide important information to the relevant statutory agencies in both Ireland and Northern Ireland. This would prioritise targeted biosecurity in both jurisdictions and help manage the pathways and vectors of arrival that are vital to maintaining native biodiversity on the island of Ireland (Lucy et al., 2020).

4

Coastal Environments

Key messages

1. Ireland is highly exposed to climate change impacts on coastal environments, with all major cities and many regional population centres located by the sea. Global sea level is projected to rise under all future scenarios and will continue to do so for hundreds to thousands of years. Locally, sea level rise is more complex (see Volume 1). Currently there are no standardised, locally tailored, sea level rise projections available for Ireland. For adaptation, it is important to consider projections of sea level rise up to and beyond 2100 to avoid increasing exposure. Significant increases in sea level out to 2300 are already inevitable, even in the most optimistic mitigation scenarios.

2. The impact of climate change on storm surges and wave heights is unclear, related primarily to uncertainty in changes in storminess, emphasising the importance of robust decision making in coastal areas. Approximately 20% of the Irish coastline is exposed to erosion, with low lying, relatively densely populated coastal zones in the east particularly exposed. In Irish coastal environments, sensitive ecosystems include cliffs, beaches, lagoons, dunes and machair, salt marshes, mudflats and other wetlands.

3. Sea level rise and changes in storm surge present large flood risks for urban areas. Superimposed on the current 100-year flood, mid-range estimates of sea level rise are estimated to quadruple the number of properties affected by flooding in coastal locations. For Limerick city alone, the cost of extreme floods under a high-end scenario of sea level rise may increase up to 12.5-fold, amounting to over €1 billion for a single event. Such estimates do not account for future urban expansion and emphasise the importance of adaptation to coastal flood risk.

4. Approximately 98% of trade by volume comes through our ports, and they are key gateways for tourism. Climate hazards for Irish ports include sea level rise and changes in wind, wave and tidal extremes and storminess, with risks differing by port location. Currently there is little guidance on how adaptation in ports should be managed. The National Development Plan (2021–2030) sets out over €340 million of infrastructural investment at Irish ports. It is critical that investment is stress tested to the risks posed by climate change.

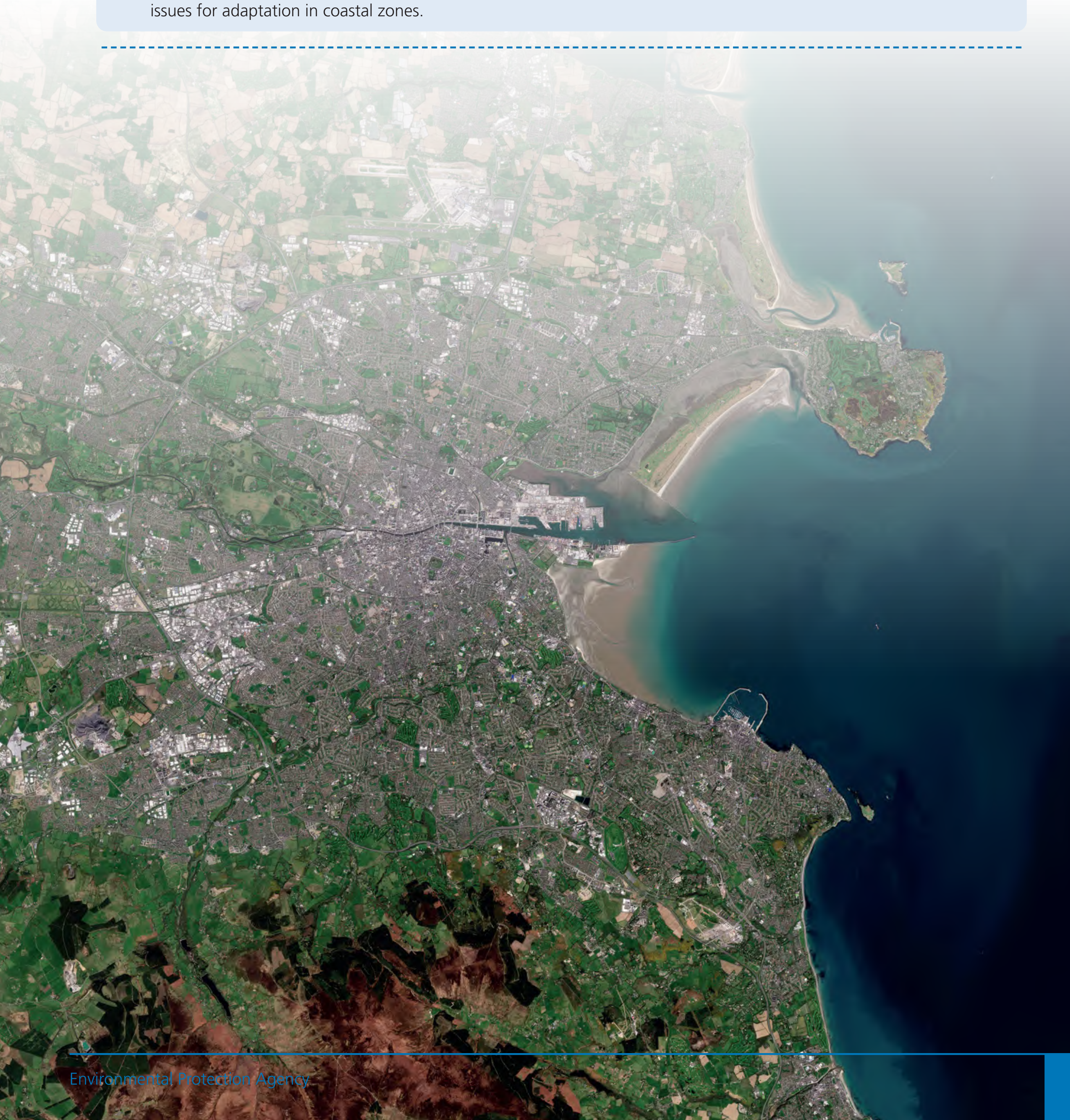
5. Bathing water quality is essential for human health and is an important recreational and tourism asset for local and regional economies. Climate change will affect bathing water quality through increased heavy rainfall on land and associated storm water overflow, warmer ocean temperatures and associated changes in the frequency and extent of harmful algal blooms.

6. Our coasts are home to a rich cultural and natural heritage. Cultural heritage includes historical buildings, archaeological sites and monuments. Climate change may increase the rates of physical and chemical erosion affecting the structure and composition of heritage assets, while changes in the frequency and magnitude of events such as droughts, floods and extreme rainfall will impact our cultural heritage. Sand dunes are an important part of our natural coastal heritage, are sensitive ecosystems and play an important role in protecting low lying coastal areas from flooding and erosion. In addition to existing pressures from erosion and human impacts from grazing, recreation, trampling and sand extraction, climate change is likely to increase pressure on dune systems through sea level rise and changes in storminess. This is particularly so for westerly oriented dunes along the Atlantic coast.

7. There is currently no clear governance structure for coastal adaptation. There are also challenges for adaptation in terms of private and public land ownership in coastal areas and the designation of many vulnerable locations as protected areas. The Inter-Departmental Group on Managing Coastal Change is considering approaches for the development of an integrated, whole-of-government coastal change management strategy.

8. Coastal adaptation responses can be categorised as (1) protect, (2) accommodate and (3) retreat. Protection can take the form of hard engineering (e.g. sea walls, dikes, groynes and revetments) and/or nature-based approaches (e.g. beach nourishment, dune creation and wetland restoration) that seek to keep sea water out and/or reduce erosion rates. Accommodation seeks to increase the ability of humans to live with risks and includes insurance schemes, early warning systems, the design and/or retrofitting of infrastructure and the use of regulatory approaches such as building codes and land use/planning regulations. Where protect and accommodate are not feasible or sufficient responses and coastal loss is inevitable, managed retreat may be necessary. Appropriate actions depend on the nature of impacts experienced, the local physical and social context, exposure and vulnerability and economic constraints.

9. The procedural and distributive justice aspects of managed retreat should be carefully considered, including supports for those having to relocate. Minimising the negative impacts of relocation for individuals and communities will require the co-creation of relocation plans and community-centred approaches. Managed retreat raises complex governance issues for adaptation in coastal zones.



4.1. Introduction

The Irish coast comprises a range of landforms, marine environments and coastal communities. The west coast is a high wave energy 'crenellated' coastline composed of high relief and low-lying bays, with the east and south-east coasts consisting mainly of low-lying, loosely consolidated sediments and glacial tills (Devoy, 2008). Landforms consists of cliffs, gravel beaches and barriers, lagoons, salt marshes, wetlands and mudflats, along with a range of land uses, including artificial structures such as sea walls and urban areas such as Dublin, Cork, Galway and Limerick, along with many other low-density population centres (Devoy, 2008). There is significant variation in the wave and wind climate along the Irish coastline due to the complicated geomorphology of the Irish coast combined with Ireland having one of the highest wave energy climates in the world (Nolan et al., 2023).

Ireland's coast provides important cultural, recreational and economic benefits to society, not least the tourism sector, as well as providing important habitats for plant and animal species. Coastal margin natural environments provide a minimum of €2.57 billion in ecosystem goods and services to the Irish economy annually (Farrell and Connolly, 2019). There are just under 11,000 people employed in the marine and fisheries sector, while the seafood industry in Ireland was estimated to be worth €700 million as of 2013 (Desmond et al., 2017). Therefore, adaptation to climate change in coastal environments is at the core of realising a climate-resilient Ireland.

4.2. Key impacts

Climate change exposes coastal and marine environments and ecosystems to multiple impacts, including ocean warming, sea level rise (SLR) and erosion, along with other climatic impact drivers (Pörtner et al., 2022). Section 2.1 outlines observed and projected changes in key impacts for Irish coasts, before key vulnerabilities and risks are considered in section 4.3.

4.2.1. Sea level rise

The rate of global mean SLR was 1.35mmyr–1 [0.78–1.92mmyr–1] during 1901–1990, faster than during any century in at least 3,000 years (IPCC, 2022). Global mean SLR accelerated to 3.25mmyr–1 [2.88–3.61mmyr–1] during the period 1993–2018 (Pörtner et al., 2022). For Ireland, sea levels have risen on average by 2–3mm per year since the early 1990s (Cámaro García and Dwyer, 2021), with local variations. For example, long-term records for Dublin suggest that, over the period 1953–2016, the rate of SLR in Dublin Bay has been 1.1mm per year (95% range 0.6–1.6mm), but with an accelerated rate of 7mm per year during 1997–2016 (95% range 5–8.8mm per year) (Shoari Nejad et al., 2022). This increased rate is likely to be due to accelerated global SLR together with multi-decadal variability (Volume 1, section 5.3). Ongoing work that leverages historical records is attempting to better estimate rates of historical SLR around the Irish coast (McCarthy et al., 2023).

The sea level around Ireland is projected to rise under all future scenarios and will continue to do so for hundreds to thousands of years. Regional patterns of SLR in Ireland will differ from the global mean due to (1) local patterns of glacial isostatic adjustment (GIA) following the retreat of the ice sheet at the end of the last glacial period and (2) the balance of ice sheet melting between Greenland and Antarctica. Projected changes in sea level out to 2100 for Ireland are expected to be lower than global mean sea level estimates if melt from Greenland dominates over melt from Antarctica. Ireland is sufficiently close to Greenland that melting from that source results in the country having a lower than global rate of SLR, as locations close to Greenland experience a sea level drop due to changing mass loading and geoid adjustments (Hsu and Velicogna, 2017). By 2100, Dublin mean sea level is projected to rise by 0.6m at the 50th percentile (1.0m at the 95th percentile) under a Late action scenario and by 0.3m at the 50th percentile level (0.6m at the 95th percentile level) under an Early action scenario (Shoari Nejad et al., 2022). For adaptation it is important to consider long-term commitments to SLR beyond 2100 as it may take many hundreds of years for the cryosphere and deep ocean to adjust to rising temperatures. The UK Climate Projections 2018 project (UKCP18) produced projections of mean SLR to 2300, indicating that limiting global temperature increases to 1.5oC would avoid increases in sea level of about 0.37m by 2100 but up to 4.0m by 2300 compared with unmitigated emissions (Palmer et al., 2018).

4.2.2. Storm surge

Ireland is exposed to significant waves and storm surges, with risks modulated by a complex coastline (Volume 1, section 5.4). Changes in wave characteristics, including height, period and direction, are strongly correlated with the phase of the North Atlantic Oscillation (NAO), with a positive NAO associated with increased wave activity. Storm surges, associated with local increases in sea level from intense low-pressure systems, have resulted in overtopping and flooding in Irish cities in recent years (McCarthy et al., 2023). Future changes in storm surges are uncertain, being dependent on changes in the intensity of storms and the location of future storm tracks. However, SLR will exacerbate flood risks from storm surges and significant waves and increase erosion risks, particularly for sandy shorelines. As highlighted in Volume 1, the combined impacts of SLR and storm surges are likely to be considerably more acute under Late action emissions scenarios. The impact of climate change on wave heights is unclear, with studies showing both increases and decreases in wave heights, related primarily to uncertainty in changes in storminess in the region (Dabrowski et al., 2023).

4.2.3. Coastal erosion

Coastal erosion is shaped by site-specific factors, with soft/hard coastlines experiencing a range of erosion processes. Approximately 20% of the Irish coastline is exposed to erosion, with softer, sediment coastlines most vulnerable (Eurosion, 2004). Erosion rates are expected to increase with SLR, changing wave heights and surge events (Masselink and Russell, 2013). Low-lying coastal zones in the east of Ireland are particularly exposed, with SLR already impacting areas composed of soft boulder clay deposits (Devoy, 2008; Flood and Sweeney, 2012; Paranunzio et al., 2022). Coastal erosion presents challenges for coastal squeeze as land, ecosystems, infrastructure and other assets become threatened (Desmond et al., 2017; Figure 4.1). Sensitive coastal ecosystems include cliffs, beaches, lagoons, dunes and machair, salt marshes, mudflats and other wetlands (Devoy, 2008). Coastal erosion rates for soft, sediment-dominated coasts have typically been 0.2–0.5myr–1, often rising to 1–2myr–1 on southern and eastern coasts (Devoy, 2008). Little is known about erosion rates on hard-rock coasts; however, erosion rates are likely to increase into the future (Masselink and Russell, 2013; Masselink et al., 2020).

Projections for future coastal erosion rates are difficult to establish without a clear understanding of dominant coastal change processes (including past coastal change and causes of coastal erosion). The default position has been to assume that present-day processes of coastal change will persist (Masselink and Russell, 2013). It is more than likely that coastlines that are currently experiencing erosion will experience increased erosion rates. For hard-rock environments recession is likely to remain low except for very localised areas (Masselink and Russell, 2013). The effect of climate change on embayed beaches is likely to be more severe, as beaches backed by cliffs or higher ground generally have very limited back-beach accommodation space (Masselink and Russell, 2013). SLR will push these beaches further landward with coastal squeeze resulting from a progressively shrinking beach volume until no beach is left (Masselink and Russell, 2013).

Figure 4.1 Coastal squeeze at Burrow Beach, Co. Dublin. Photo credit: Syran Bruen/Alamy.

4.2.4. Ocean warming and chemistry

Global mean sea surface temperature has increased by 0.88°C (very likely range 0.68–1.01°C) since the beginning of the 20th century (Pörtner et al., 2022). The rate of warming is estimated to have doubled since the 1990s. As highlighted in Volume 1 (section 5.2), the heat content and sea surface temperatures in Irish waters are influenced by ocean currents and exhibit substantial interannual and interdecadal variability. Sea surface temperatures and ocean heat content of Irish waters are presently substantially elevated relative to mid-20th century records. Future sea surface temperature and ocean heat content is likely to be dominated by global responses to greenhouse gas emissions and climate variability (Volume 1, section 5.2). Temperature is responsible for seasonal stratification and consequently for circulation patterns (Olbert et al., 2012), with the potential to change in response to future climate changes, which may have significant effects on local coastal environments and ecosystems (Olbert et al., 2012). Nutrient concentrations are critical for marine ecosystems and are strongly influenced by stratification (see Volume 1, section 5.5). Sea surface temperatures in Irish waters could increase by several degrees Celsius, with ocean heat content taking centuries to reach a new equilibrium (Volume 1, section 5.2). Changes in ocean–atmosphere carbon exchanges are resulting in more acidic ocean waters, with evidence of changes documented in both Irish coastal waters and the deep ocean (Volume 1, section 5.5). Ocean acidification impacts on the ability of marine organisms to form shells and skeletons.

4.3. Key risks and vulnerabilities

With these observed and projected changes in mind, the following sections outline key risks and vulnerabilities for Ireland. Many of the risks identified have relevance to other chapters in this volume, including critical infrastructure, flooding (Chapter 5) and ecosystems.

4.3.1. Coastal and marine ecosystems

Changes in the physical and chemical characteristics of the ocean are altering the timing of seasonal activities, and the distribution and abundance of oceanic and coastal organisms, from microbes to mammals and from individuals to ecosystems, in all regions globally (Cooley et al., 2022). Changes in the geographical range of marine species generally follow the pace and direction of environmental change. Warming, acidification and deoxygenation have driven habitat loss, population declines, increased risks of species extinctions and rearrangement of marine food webs (Cooley et al., 2022). Ireland has not been exempted from these climate-driven changes, which have impacted ecosystems on the coast around the island.

Many plant species will find it difficult to adapt to projected climatic changes, which may result in major changes in coastal ecosystem structure and function and how different species react to their environment, along with shifts in the geographical ranges of species (Hodd and Skeffington, 2011). Some species are likely to be more adaptable than others. For example, it is possible that dune grasses will grow more rapidly as temperatures rise, increasing the effects of nitrogen deposition, leading to denser vegetation and stabilised dunes, along with causing further loss of the bare sand habitat that is important for many dune species (Jones et al., 2013). Rates of recent soil development in dunes have been linked to climatic variation over the last 60 years, with faster soil development associated with warmer periods (Jones et al., 2013). Warmer, wetter conditions as evidenced from the Holocene stratigraphic dune record favour stabilisation and soil development; however, this could be offset or even reversed by a higher frequency of summer droughts and storm events (Jones et al., 2013).

Coastal upland plant species are also likely to be impacted by climate change. Projected temperature increases and reduction in frost days may affect montane habitats in western Ireland. Coastal mountain species are particularly vulnerable to rises in temperature, as they are adapted to colder conditions (Hodd and Skeffington, 2011). Projected temperature increases may cause lowland species to expand their range to higher altitudes, resulting in lowland species coming into direct competition with arctic–montane species (Hodd and Skeffington, 2011).

Phytoplankton are a key element of marine ecosystems, accounting for approximately 50% of primary production on Earth; however, when the abundance of phytoplankton increases above background concentrations, 'algal bloom' events develop (Bresnan et al., 2013; Clarke et al., 2023). Algal blooms are a natural part of the phytoplankton seasonal cycle, but some can have a negative impact on marine ecosystems, fish and shellfish (Bresnan et al., 2013). These 'harmful algal blooms' or HABs (Bresnan et al., 2013) have impacted ecosystem services in Irish waters in two distinct ways. High-biomass HABs can cause mortality of farmed fish and the marine benthos through clogging of gills, anoxia and, in some instances, the production of ichthyotoxins (Bresnan et al., 2013). Other HAB species can have a negative impact through the production of potent toxins that can accumulate in filter feeding shellfish (Bresen et al., 2013). While these toxins are not harmful to shellfish, they can pose a high risk to human health if consumed (Bresnan et al., 2013). In 2012, a HAB resulted in large fatalities among

Figure 4.2 A plankton bloom off the west coast of Ireland in 2009. Source: European Space Agency (https://www.esa.int/ESA_Multimedia/Images/2009/12/Plankton_bloom_off_the_Irish_coast).

certain fish, including turbot, flounder, scorpion fish and shore rockling. Other affected species included worm pipefish, lesser weever, grey gurnard, shanny, sand goby, pollock, sole, plaice, flounder and dab (Bresnan et al., 2013). The most impacted area was the north-west of Ireland, where beaches were closed in Rossnowlagh and Murvagh due to the quantity of dead fish washing up on shore (Bresnan et al., 2013).

In the last decade there has been a noticeable extension of the abundance and growth season of some species of phytoplankton in Irish waters (Figure 4.2; Clarke et al., 2023). Examples of species that may become established in Irish waters are Gymnodinium catenatum, a paralytic shellfish poison producer frequently observed in Spanish waters, and Ostreopsis spp., a toxin-producing benthic dinoflagellate which is now known to have a European distribution outside the Mediterranean (Bresnan et al., 2013). Given the complex interactions that determine the occurrence of HAB species and that control bloom development, it is difficult to determine the probability of more southerly species becoming established in Irish waters (Bresnan et al., 2013). Variables such as temperature, pH, light, nutrient supply and water movement/turbulence can affect algal bloom dynamics and their toxicity (Bresnan et al., 2013). Climate change is expected to impact these variables to differing extents in different regions. A recent study combining downscaled climate model data with data from the national HAB monitoring programme found that most of the HAB taxa examined are likely to have an increasing presence in Irish waters in the coming decades (Clarke et al., 2023). The 2023 Marine Institute report (Nolan et al., 2023) contains a number of recommendations for managing the impact of HAB events, including improving risk management tools and forecast systems to support the seafood sector in adapting to climate change, increasing data collection at sentinel sites and developing models to better estimate the likelihood of future HAB events.

Climate change is also likely to pose challenges for marine and coastal animals. Recent warming of Irish seas has been associated with a northward shift in the distribution of zooplankton along with other fish species (Evans and Bjorge, 2013). The change in distribution is most evident near the northern or southern borders of the species' initial range (Evans and Bjorge, 2013). It is the same for certain cetacean species, such as the typical warmer water dolphins, the short-beaked common dolphin and the striped dolphin, all of which have extended their shelf sea range further northwards in the Irish Sea (Evans and Bjorge, 2013). The UK has also seen a similar phenomenon to that observed in Ireland, where in recent years numerous warm-water species have been recorded for the first time. These species include Blainville's beaked whale (1993), Fraser's dolphin (1996) and dwarf sperm whale (2011). It is also worth noting that between January and April 2008 there were 18 strandings of the Cuvier's beaked whale (which is another typically warm-water species) in Ireland, Scotland and Wales (Evans and Bjorge, 2013). Conversely, species that prefer colder waters north of Ireland and Britain have not been recorded with increased frequency; for example, the bowhead whale has not been recorded for the last 100 years and the narwhal has not been recorded since 1949 (Evans and Bjorge, 2013).

Evidence shows that certain animal species may be indirectly affected by changes in the distribution of other animals on the Irish coast. Numerous bird species (such as the ruddy turnstone) can be found along Ireland's rocky shoreline. These species of bird feed on small molluscs and crustaceans that live underneath stones, on macroalgae and inside cracks and crevices in rocks (Kendall et al., 2004). The changes that certain species of waterbirds will experience due to climate change will also have an impact on coastal invertebrates. Species such as the common eider might move northwards and, as a result, their predation on mussel beds may be reduced, which may lead to an expansion of these invertebrates (Kendall et al., 2004).

4.3.2. Fisheries

Fisheries and fishing communities are a key part of the Irish economy and cultural heritage. An average of 500 fishing vessels are active each day within Ireland's exclusive economic zone, catching approximately €382 million worth of quota fish and shellfish each year (€128 million by Irish vessels; Vaughan et al., 2023). Some coastal communities are heavily reliant on fisheries for income; for example, 82% of regional economic activity in the Killybegs region of Donegal is attributed to the fisheries sector (Macfayden et al., 2010). Climate change has several implications for Irish fisheries going forward.

Ireland has some of the most biologically sensitive marine areas in EU waters, containing major spawning grounds for the Atlantic mackerel, horse mackerel, blue whiting, hake and cod (Vaughan et al., 2023). Climate change affects fish range, abundance, productivity, mortality, maturity and growth (Pinnegar et al., 2017). A common response to changing water temperatures (both sea surface temperatures and near-bottom temperatures) is for fish to move to cooler temperatures (polewards). With sea surface temperature and near-bottom temperature projected to increase off the south-west of Ireland in the coming decades (Nagy et al., 2021), several fish species may move to cooler waters.

It is difficult to accurately attribute changing fish distributions to climate change (Vaughan et al., 2023) as fishing levels are a key driver of the health of stocks; however, there are changes in fish stocks in Irish seas that correlate with changing sea temperatures and salinity. Herring and cod are currently at the southern limit of their range, with both showing declines in spawning stock biomass (largely due to overexploitation). Herring in the Celtic Sea ecoregion have shown a decline across all fish ages since the mid-1980s, which can be partly explained by rising sea temperatures (Lyashevska et al., 2020). Mackerel stocks in the north-east Atlantic are relatively stable (Vaughan et al., 2023), with mackerel catches landed in Irish ports between 2010 and 2019 averaging €46 million per year, making it the financially most important fished species. Hake and anchovy are warm-water species and under warming ocean scenarios are projected to move polewards. Hake stocks have improved through better management, and Nolan et al. (2023) note that an increase in appropriate habitats through ocean warming is likely to enable expansion of this species. Going forward, the warming of Irish waters may provide hospitable environments for previously peripheral species; for example, anchovies have not to date been a significant stock in Irish waters, but recent evidence suggests that they may be increasing in number, as noted in the annual groundfish survey of Irish waters.

Ocean acidification and deoxygenation caused by climate change are theorised to be influencing fishing and aquaculture harvests, but limited evidence prevents an assessment of their present global impact on harvests (Cooley et al., 2022). Ocean acidification alters larval settlement and metamorphosis of fish in laboratory studies, suggesting possible changes in fish survival and thus fishery characteristics (Cooley et al., 2022). Deoxygenation can decrease the size and abundance of marine species and suppress trophic interactions, decreasing diversity within marine ecosystems while temporarily increasing catchability and the risk of overfishing, thereby decreasing the ecosystem services provided by specific fisheries (Cooley et al., 2022). The impacts of climate change on wild fish are complex and highly interactive, with many different drivers of and ecosystem responses to these changes. While there are extensive management practices in place through EU and national processes, Nolan et al. (2023) highlight the lack of data currently available for the management of fisheries in Ireland.

Nolan et al. (2023) emphasise the importance of adaptive management for the sustainable management of Irish fisheries. Overexploitation remains the primary driver of change in stock abundance, and climate change is likely to compound existing risks. Current management approaches that focus on single species stock assessments and on maximum sustainable yields may not be appropriate for capturing the fluctuations that occur in ecological processes. Nolan et al. (2023) suggest that a more holistic, ecosystem-based approach to fisheries management may be needed, recommending long-term scientific monitoring of fish stocks, more research into best practice in fisheries management, and international coordination.

4.3.3. Ports

In Ireland, ports are critical infrastructure, acting as key sites in the maritime transport system. As an island, 98% of trade by volume comes through our ports (O'Keeffe et al., 2020), amounting to 53 million tonnes of cargo in 2022, with Dublin Port managing 59% of all vessel arrivals (CSO, 2023). Alongside the goods trade, ports are key gateways for tourism. Potential climate-related risks for Irish ports include SLR and increases in wind, wave, swell and storminess, with risks differing by port location. On the east and south coast, ports are relatively sheltered from the high-wave environment of the Atlantic that impacts maritime traffic and port operations on the west coast. In Dublin Port SLR has been higher than expected since the 1990s (Shoari Nejad et al., 2022), increasing at a higher rate than the global average. As O'Keeffe et al. (2020) outline, wind has an impact on the berthing of ships and the unloading and loading of cargo. Given the amount of reclaimed land in Irish ports, management of ports to limit erosion is an issue for port managers going forward.

Ireland's 25 ports are governed by both private and public sector organisations. The 2013 National Ports Policy outlined three groupings of Irish ports. Tier 1 ports represent 15–20% of national throughput of tonnage and include Dublin, Cork and Shannon Foynes. Tier 2 ports represent at least 2.5% of tonnage and include Waterford and Rosslare Europort. The final grouping of regionally significant ports includes Galway, Drogheda, Dún Laoghaire, Bantry Bay, New Ross and Wicklow. Research by O'Keeffe et al. (2020) involving 70 senior managers in the maritime sector found that there is a lack of awareness and understanding of the impacts of climate change for Irish ports.

Currently there is no reference in the National Ports Policy to climate change risks and adaptation, with little guidance on how adaptation in ports should be managed. The Transport Sectoral Adaptation Plan outlines the main risks for the maritime sector, which include risks to both operations and facilities. Heavy rainfall can reduce the ability of radar to work, can impact storage facilities if they become flooded and can impact dredging and natural scouring in port locations. The impacts of storms and associated high winds and storm surges can damage port infrastructure, vessels in port and navigational aids. Such conditions can also pose risks to passengers embarking and disembarking from ships. Potential prolonged and more intense periods of hot weather may impact working conditions at ports; in particular, glass boxes in cranes may become too hot to work in. SLR exacerbates processes of flooding and erosion, presenting a long-term risk for all ports. More generally, these risks will have consequences for supply chains if services are cancelled, cause economic damage to vessels and other infrastructure, and impact tourism if sailings are cancelled and the health and safety of port workers, vessel operators and passengers on ferries.

The economic and social significance of ports, alongside the communities that are often established in adjacent areas, means that they are key sites for climate change adaptation. Additionally, the drive for port expansion, as evident in Dublin Port's redevelopment plan, means that these sites are likely to continue to experience increasing coastal squeeze, requiring coordinated management of land use and attention to the vulnerability and exposures of different coastal users. O'Keeffe et al. (2020) suggest key interventions to improve adaptation planning in ports, including:

- training and skills to assess risk and vulnerability within port management organisations and the need to broaden engagement with the issue of climate change;
- introducing scenario planning and modelling capabilities to deal with climate risk and uncertainties;
- learning from best practice and facilitating knowledge transfer from other ports or other economic sectors;
- accessing better scientific data and information on long-term trends in weather and climate;
- engaging with other stakeholders, including the public;
- including climate change adaptation in strategic business planning.

Project Ireland 2040 (DHPLG, 2018) sets out the government's long-term vision for the development of an environmentally sustainable transport system for Ireland. The National Development Plan (NDP) sits under this vision and commits €230 million of infrastructural investment at Dublin Port to accommodate larger vessels, €90 million for the redevelopment of port facilities at Ringaskiddy and €27 million for capacity extension of Shannon Foynes Port. It is critical that investment in the future of Irish ports is stress tested for the range of risks posed by climate change.

> *"All major Irish cities, together with many larger towns, are located by the sea and at the outlet of major rivers. Many hundreds of smaller harbours, often important tourist and fishing locations, are also exposed to coastal hazards (Devoy, 2008; Falaleeva et al., 2011)."*

4.3.4. Settlements by the sea

All major Irish cities, together with many larger towns, are located by the sea and at the outlet of major rivers. Many hundreds of smaller harbours, often important tourist and fishing locations, are also exposed to coastal hazards (Devoy, 2008; Falaleeva et al., 2011). Considering such high exposure, the Geological Survey of Ireland is developing a coastal vulnerability index (CVI), focused on understanding and mapping the relationships between SLR, local geology and coastal responses. The first phase of the CVI project has focused on County Dublin and will allow local geomorphology, significant wave heights, relative SLR and long-term shoreline erosion and accretion rates, among other variables, to be quantified to inform adaptation planning. Potential flood extents for the end of the century have been mapped using an extreme event consistent with a 0.5 annual exceedance probability (AEP) superimposed on a projected 1.98m SLR as a worst-case scenario (Figure 4.3). Such toolkits will allow planners to identify the areas most physically vulnerable to SLR and coastal flooding for informing adaptation plans.

Figure 4.3 Potential flooded areas in Dublin from a 0.5 AEP event and 1.98m SLR worst-case scenario, projected by 2100. Source: Geological Survey of Ireland Coastal Vulnerability Index Mapping Project (https://www.gsi.ie/en-ie/programmes-and-projects/marine-and-coastal-unit/projects/Pages/Coastal-Vulnerability-Index.aspx).

Flood and Sweeney (2012) explored the potential economic impacts of SLR on the Irish coast, with a focus on cities. As a first pass exploratory assessment, their analysis found that approximately 350km^2 of land is vulnerable to a 1m rise in sea level, increasing to 600km^2 at 3m. While the latter sounds extreme, it is not inconsistent with longer-term (i.e. out to 2300) projections of SLR, which are committed to even under a 1.5°C warming scenario (Palmer et al., 2018). Potential economic costs related to insurance claims were found to be approximately €1.1 billion under the 1m scenario. Counties Wexford, Dublin, Louth, Kerry, Cork, Clare, Galway, Mayo and Donegal were found to be most vulnerable.

As the agency responsible for coastal flooding, the Office of Public Works (OPW) has also assessed the potential impacts from coastal and fluvial flooding as part of the Catchment Flood Risk Assessment and Management (CFRAM) Programme. To this end mid-range and high-end future scenarios were adopted, with SLR assumed to increase by 0.5m under the mid-range and by 1m under the high-end scenario. As part of the sectoral adaptation plan for flood risk, the scenarios highlight that the potential impacts of future increases in coastal flooding are significantly greater than for fluvial flooding. For rare flood events (those with 1% chance of occurrence in any given year, or the 100-year flood), the number of properties at risk of flooding under the mid-range scenario approximately doubles for fluvial floods, but approximately quadruples for coastal flooding, assuming no implementation of additional adaptation interventions (OPW, 2019). Moreover, the assessment does not include future changes in exposure through intensification of development in urban areas and increasing property prices, both of which are likely to increase future loss and damage estimates. An assessment of coastal flood risk undertaken for Limerick city and environs using the current 200-year flood event, superimposed on the high-end scenario of 1m SLR, shows large increases in flood extent, with a doubling of residential and business properties inundated in comparison with current exposure. Overall, the costs of flood damage for Limerick from such an event are estimated to rise from over €83 million presently to over €1 billion under the high-end scenario, corresponding to a 12.5-fold increase (OPW, 2019). Table 4.1 shows the estimated damages from the present-day scenario associated with a 200-year flood event and the equivalent under the high-end scenario of SLR for Limerick city and environs.

Table 4.1 *Estimated risks and damages for Limerick city and environs associated with a 200-year flood event under the present-day scenario and with an additional 1m SLR under the OPW high-end future scenario*

Type of risk	Present-day scenario	High-end future scenario
Event damage (€)	83,149,253	1,035,710,958
No. residential properties at risk	1,122	2,636
No. business properties at risk	248	510
No. utilities at risk	0	2
No. major transport assets at risk	49	69
No. highly vulnerable properties at risk	4	6
No. social infrastructure assets at risk	6	12
No. environmental assets at risk	4	6
No. potential pollution sources at risk	0	1

Source: Adapted from OPW (2019).

A recent study by Paranunzio et al. (2022) assessed the risk of coastal flooding associated with climate change for County Dublin, accounting for changing flood hazards, exposure and social vulnerability. Their approach, undertaken as part of the EPA-funded Urb-ADAPT project, used two future emissions scenarios, namely a Late action (RCP8.5: mean SLR of 0.81m) and Middle action (RCP4.5: mean SLR of 0.45m) scenario for the end of the century to quantify future risk based on inundation depths, combined with land cover changes and assessment of current socioeconomic vulnerability. Vulnerability was assessed using the demographic and socioeconomic characteristics of exposed populations, in addition to urban development intensity, the presence of transport systems, industrial facilities, and service infrastructure, including electricity, water and communications systems, hospitals and health and emergency services. The derived vulnerability index was categorised into five classes ranging from very low to very high (Figure 4.4). By simulating a recent storm event from 2013 with associated increases in sea level, the results suggest significant challenges for adaptation, with increases of c. 26% and 67% in the number of administrative areas considered at very high risk by the end of the century under Middle and Late action scenarios, respectively. The study highlights that inundation risk is not limited to the coast, with areas bordering the lower Liffey also highly exposed and requiring adaptation. New building developments in recent decades have increased coastal flood risk in towns such as Balbriggan, Malahide and Howth.

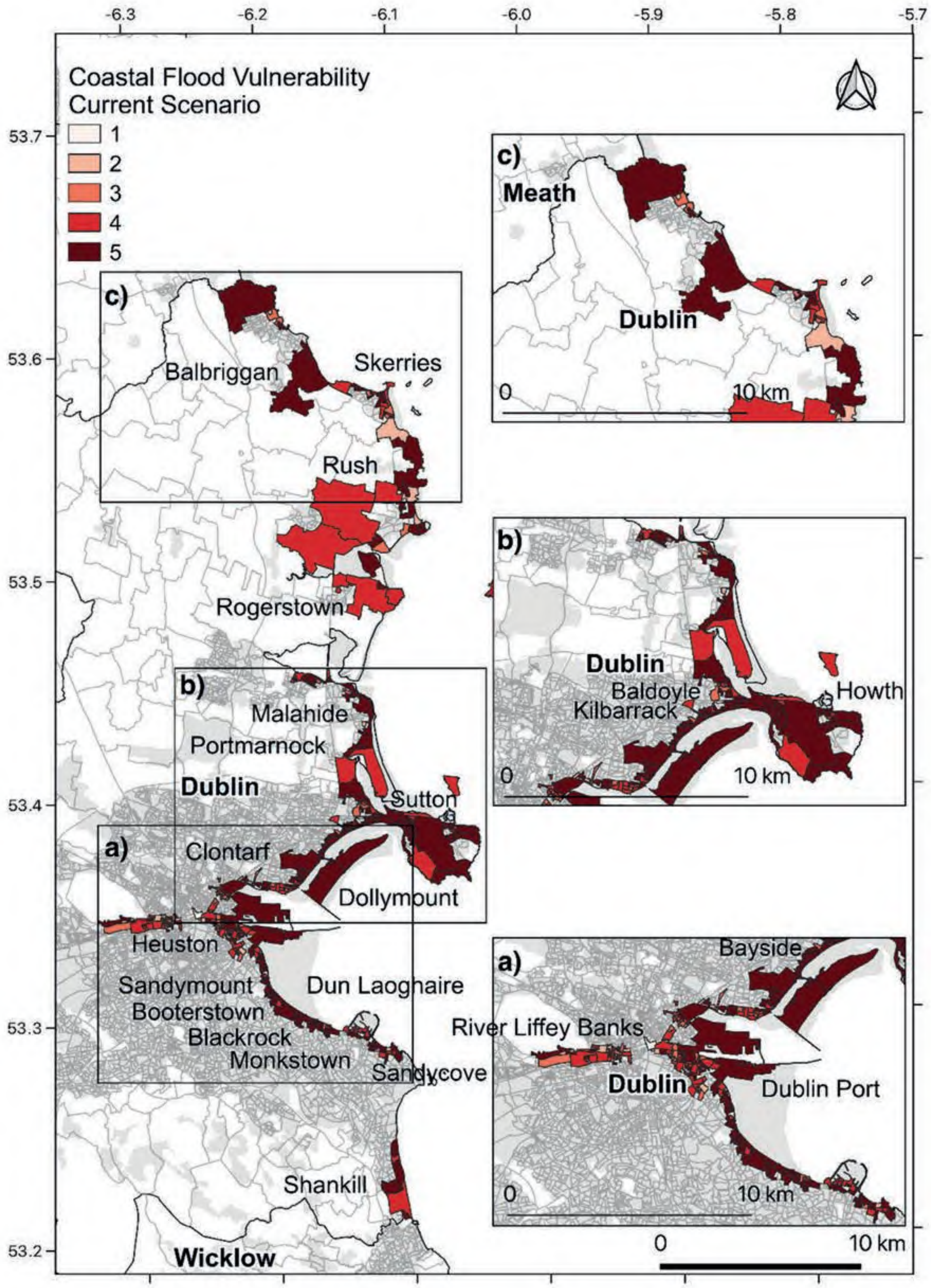


Figure 4.4 Vulnerability index across Dublin County for the current period. The index ranges from 1 (very low vulnerability) to 5 (very high vulnerability). Source: Paranunzio et al. (2022). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

4.3.5. Coastal heritage

Our coasts are home to a rich cultural heritage, with assets including historical buildings, archaeological sites and monuments. In addition to their heritage importance as a legacy of our past, such assets underpin a sense of place, identity and wellbeing for local populations (Sesana et al., 2021). While heritage sites have always undergone change and will continue to change due to natural weathering processes, climate change presents additional challenges that may exacerbate rates of decay or give rise to new pressures (Bertolin, 2019). Climate change may increase rates of physical and chemical erosion, affecting the structure and composition of heritage assets, while changes in the frequency and magnitude of events such as droughts, floods and extreme rainfall will impact cultural heritage. In coastal areas the impacts of SLR, storm surges, erosion and flooding present additional risks. As an example, coastal neolithic and early Christian monastic sites such as Dunbeg (Dún Beag) and Illauntannig (Oileán tSeanaigh) on the Dingle Peninsula are highly vulnerable to coastal erosion, while other unroofed structures such as tower houses and abbeys can be vulnerable to storm damage (CHERISH Project; https://cherishproject.eu/en/author/edwardpollard/).

In recognition of the vulnerability of coastal heritage to climate change, the CHERISH project, led by the Geological Survey of Ireland, has supported the development of new technologies to assist in the assessment of the vulnerability of key archaeology and heritage sites to coastal erosion, storms and SLR. The project facilitated the development of baseline data and maps to enhance the protection of heritage assets and inform site-specific adaptation plans. An example of one of the CHERISH project sites in north Wexford is Killincooley Beg, home to a circular rath situated precariously over 20m-high cliffs of soft glacial till (Figure 4.5).

Figure 4.5 Erosion at Killincooley Beg Ringfort, near Kilmuckridge, Co. Wexford. Photo credit: CHERISH Project (CHERISH Project on X: "Killincooley Beg Ringfort, near Kilmuckridge, Co. Wexford. #picoftheweek https://t.co/rbXZsTKo11" / X)

The Sustainable Resilient Coasts project is also deploying remote sensing technologies to collect data on coastal geology and local heritage sites to inform assessments of the exposure and adaptation of coastal heritage sites to climate change. For example, through collaboration with the community of Rathlin Island, off the coast of Antrim, it has developed high-resolution 3D models of the site that, when used longitudinally and in conjunction with field visits and inspections, can provide detailed data to monitor and anticipate structural issues requiring action (COAST, 2022).

4.3.6. Bathing water quality

Good bathing water quality in coastal areas is essential for ecosystems, human health and tourism. Bathing sites are important assets for local and regional economies given their importance for tourism, health and wellbeing and for the social and cultural benefits they provide (Alamanos et al., 2022). Each year numerous bathing sites are closed or receive water quality warnings for certain periods (Figure 4.6). The need for systematic monitoring and tracking of bathing water quality has been noted by the EPA (2022). Discharges from urban land use and wastewater treatment plants, sewage, agricultural runoff and overflows after heavy rainfall events are typical causes of degraded water quality at bathing sites, highlighting important connections to climate change and land-based water management practices (Alamanos et al., 2022). Pressures from human activities include nutrient enrichment of transitional and coastal waters, 16% of which are potentially eutrophic (Bermejo et al., 2019). Overall, water quality in coastal waters and estuaries is deteriorating, especially along the south-east and southern seaboards (EPA, 2023).

While assessments of climate change impacts on coastal bathing water quality are limited in Ireland, research in other European countries highlights that climate change is likely to affect bathing water quality through increased heavy rainfall on land and associated storm water overflow, and warmer ocean temperatures and associated changes in the frequency and extent of harmful algae and cyanobacteria (Roijackers and Lurling, 2007). The development of integrated catchment–coastal modelling systems for real-time water quality forecasts offers opportunities for better management of bathing water quality (Bedri et al., 2014).

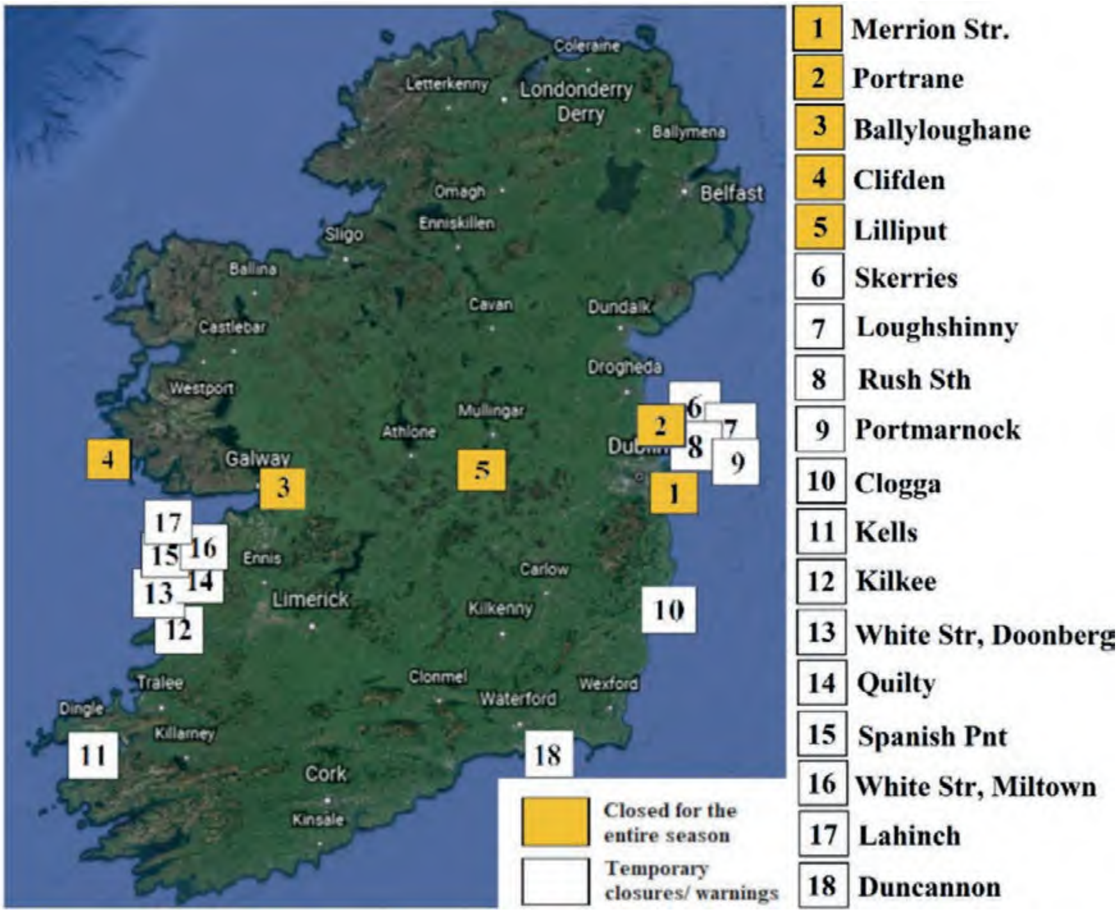


Figure 4.6 Bathing sites with swimming restrictions in 2020. Source: Alamanos et al. (2022). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

4.3.7. Loss of natural heritage: dune systems

Beach dune ecosystems are a significant part of our natural heritage and represent an important component of coastal margin natural environments that provide an estimated €2.57 billion in ecosystem goods and services to the Irish economy annually (Farrell and Connolly, 2019). Dune systems cover a total area of 76.2km^2 in Ireland, with counties Donegal, Mayo and Kerry accounting for 74% of the total dune area. Coastal dunes are sensitive ecosystems that are home to diverse plant communities, often endemic species, with many, especially dune wet depressions, protected under the EU Habitats Directive. Aside from their value as habitats and as a source of ecosystem services, coastal dunes play an important role in controlling coastal erosion through stabilisation of sediment and the promotion of soil retention through vegetation growth. They also play an important role in protecting low-lying coastal areas from flooding (Figure 4.7; Farrell and Connolly, 2019). The sediment provided by dunes is critical to nourishing sandy beaches during erosion events, providing the first line of defence against storms and storm surges for tourist-related businesses, agriculture and wildlife habitats (Barbier et al., 2011).

Figure 4.7 Dune erosion near Castletown, Co. Wexford. Photo credit: Prof. Conor Murphy

Historically, only intermittent surveys of dune health have been undertaken. The most recent and comprehensive assessment, the Sand Dune Monitoring Project 2011–2013 undertaken by the National Parks & Wildlife Service (NPWS), serves as a baseline for the assessment of dune health. This survey highlights that most dune systems are in a largely unsatisfactory condition, with no dune system in Ireland classed as having 'favourable' status (Delaney et al., 2013). Key pressures facing dunes include natural erosion from storms and high tides and human-caused impacts from land use management, including grazing, recreation, trampling and sand extraction. Data from lidar surveys, aerial photography and oblique imagery are playing an important part in monitoring dune health and the impacts of erosion and storms. A changing climate through SLR, changes in storminess and associated winds and surges is likely to increase pressure on dune systems, particularly westerly oriented dunes along the Atlantic coast (Farrell and Connolly, 2019). The long-term vulnerability of these important coastal ecosystems needs to be assessed, while their management needs to include coastal communities in identifying risks and designing and implementing short- and long-term solutions (Farrell and Connolly, 2019). Valuable lessons on how best to approach this challenge have been learned from the Maharees in Co. Kerry, where work undertaken with the local community and academics at the University of Galway through the Maharees Conservation Association is highlighting the enablers of and barriers to sustainable dune management (Farrell and Farrell, 2023). Key enablers include the availability of scientific expertise, governance arrangements and policy coherence, and empowerment of local communities. Key barriers include competing values and priorities, lack of recognition and support for community actions at government level, and a perceived lack of expertise within local authorities tasked with implementing adaptation actions (Farrell and Connolly, 2019; Farrell et al., 2023b).

4.4. Adaptation responses

4.4.1. Governance and integrated coastal zone management

The CCAC has highlighted that sectors identified in the NAF do not fully address coastal change and SLR due to climate change and that the lack of clear governance and responsibility for coastal adaptation is currently a barrier to realising a climate-resilient Ireland. There are also challenges for coastal adaptation in terms of private and public land ownership in coastal areas and the designation of many vulnerable locations as EU protected sites and special areas of conservation. Ownership issues are particularly challenging in the context of local coastal roads, infrastructure and cultural heritage located on private land.

In recognition of the complex governance challenges facing coastal areas, the Inter-Departmental Group on Managing Coastal Change (formed in 2020 and jointly chaired by the Department of Housing, Local Government and Heritage and the OPW) is currently considering approaches for the development of an integrated, whole-of-government coastal change management strategy. This includes developing recommendations on future structures and roles of government departments in dealing with coastal change and delivering a national coastal change policy, including adaptation strategies, resource implications, and legislative and regulatory change requirements. Such an integrated coastal zone management (ICZM) approach, characterised by national coordination, data-driven decision making, and extensive consultation and public

participation (Flannery et al., 2015), has long been advocated in Ireland, with the National Marine Planning Framework giving ICZM new emphasis. However, O'Mahoney et al. (2020) and Tubridy et al. (2022a) report that attempts to progress implementation of ICZM are characterised by locally focused effort and typically conducted within time-bound projects. An audit of the coastal policy space by researchers from University College Cork (Cronin et al., 2017) notes the divergence between individual local authorities in terms of resources and policy implementation, highlighting the need for national guidelines to coordinate risk-based assessment of coastal erosion as part of a cohesive marine planning approach. The recent EPA report Building Coastal and Marine Resilience (Farrell et al., 2023a) identified key institutional and technical barriers to building coastal resilience to climate change (see Table 4.2).

Table 4.2 *Institutional and technical barriers to developing coastal and marine resilience to climate change*

Institutional barriers	Technical barriers
Weak governance. Too many government departments or public bodies (> 40) with a remit for the coastal area have different policy objectives that do not align with each other.	**Measuring climate adaptation.** There is confusion over which NAF adaptation actions are to be considered and/or prioritised and how their impact will be measured.
Confusion over legal responsibility for the coast. Local authorities do not have jurisdiction in coastal areas or lack guidance, expertise and resources to design and deliver climate actions.	**Are our coastal assets losing/gaining value?** Identifying and valuing coastal natural capital will highlight the financial benefit of capital investments in coastal projects.
No coastal stakeholder forum. Unlike other sectors that have publicly funded organisations to support resilience building (e.g. Local Authority Waters Programme), there is no equivalent structure to coordinate actions for coastal communities.	**EU protected sites.** The NPWS management of Natura 2000 sites is viewed as exclusively top-down and disproportionately balanced between biodiversity preservation and economic, social, cultural and regional requirements.
Seasonal tourism. Successful marketing initiatives such as Fáilte Ireland's Wild Atlantic Way are increasing the number of visitors to the coast with no equivalent increase in amenities, leading to pressure on sensitive environments during the summer season.	**Erosion and flooding.** Coastal erosion and flooding are critical factors in the vulnerability of coastal communities and rely on underfunded local authorities (rural counties) for funding and prioritisation. The implementation of nature-based approaches also requires a planning framework.

Source: Adapted from Farrell et al. (2023a).

4.4.2. Approaches to adaptation

Adaptation to climate change in the coastal zone is critical given the exposure and vulnerability to coastal risks. Even under the most ambitious reductions in greenhouse gas emissions, sea levels will continue to rise for many hundreds of years. Several studies have categorised adaptation responses as (1) protect, (2) accommodate and (3) retreat (e.g. Masselink and Russell, 2013; Mallette et al., 2021; see Table 4.3). Others have highlighted additional distinctions, including adoption of hard and soft protection, and accommodate, retreat and no action, to define approaches to adaptation in the coastal zone (Mallette et al., 2021). In essence, 'protect' refers to approaches that seek to defend land and reduce the risk of coastal hazards. Protection can take the form of hard engineering approaches or physical infrastructure, including sea walls, dikes, groynes and revetments, etc. that seek to keep sea waters out and/or reduce erosion rates. Soft protection responses include the deployment of nature-based approaches (see section 3.3), including beach nourishment or dune and wetland restoration that seek to work with nature to provide protection from coastal risks. 'Accommodate' recognises the increased likelihood of coastal risks and seeks to deploy socioeconomic and/or technical measures to reduce impacts (Mallette et al., 2021). In many cases such approaches seek to increase the ability of humans to live with risks and include measures such as development of insurance schemes, early warning systems for inundation and storm events, the design and/or retrofitting of infrastructure to accommodate projected changes and use of regulatory approaches such as building codes and land use/planning regulations. Finally, 'retreat' may include recognition of the inability to protect or accommodate change and involves the relocation of people and/or infrastructure and prevention of new developments in high-risk locations. Such approaches can be supplemented through information measures, including early warning systems, and flood hazard and erosion susceptibility mapping (Linham and Nicholls, 2012).

Table 4.3 *Commonly deployed coastal adaptation approaches*

Adaptation approach	Technology	Purpose
Hard protection	Sea walls/revetments	Erosion reduction
	Dikes	Flood reduction
	Groynes	Erosion reduction
	Land reclamation	Creation of new land areas
	Raise land areas	Flood reduction
Soft protection	Beach nourishment	Erosion reduction
	Dune construction	Erosion reduction/flood reduction/creation of habitats
Accommodate	Flood-proofing	Avoid/reduce flood impacts
	Wetland restoration	Flood reduction/habitat restoration
	Enhanced drainage systems	Flood reduction
Retreat	Managed realignment	Flood reduction/erosion control/creation of new habitat
	Coastal setback	Flood reduction/erosion control

Source: Adapted from Linham and Nicholls (2012) and Masselink and Russell (2013).

While categorisation of adaptation responses is useful, it is most likely that adaptation actions will involve some combination of each strategy. Ultimately, which combination of approaches is selected will depend on the economic, ecological, technological and social pros and cons of each. Appropriate actions will also depend on the nature of impacts experienced, the local physical and social context, exposure, vulnerability and economic constraints. As cost–benefit analysis will be critical to informing adaptation decision making, it is important that the methods deployed recognise the value of ecosystem services and allow for the avoidance of potential future damages to be seen as benefits (otherwise integration of allowances can increase costs without associated benefits). A further challenge for adaptation in response to SLR is the timescales involved, with significant increases in sea level out to 2300 already committed to, even in the most optimistic mitigation scenarios. It is therefore important that the shorter adaptation time frames often considered in policy (i.e. 2050s or even end of century) keep this longer-term perspective in mind to avoid lock-in.

In a review of the literature on social preferences for coastal adaptation, Mallette et al. (2021) highlight that, across 90 studies evaluated, hard protection options were most frequently preferred by affected communities given their perceived effectiveness and the desire to maintain the existing shoreline and associated uses, recreational spaces and private property. However, it is not realistic to expect that even under hard protection options the coastline will remain as it is. Soft protection strategies and accommodation of risks were the next most preferred option, with retreat or relocation being the least desirable. Despite the low desirability of retreat as an adaptation option, the ability to protect all places or to accommodate all changes will not be possible everywhere. As such, managed retreat will be inevitable in some locations, and the procedural and distributive justice aspects of such adaptation options should be carefully considered. As highlighted by Tubridy et al. (2022b), managed retreat initiatives often have negative social, economic and cultural implications for those affected, with negative impacts tending to be most acutely felt by low-income and marginalised groups. Moreover, the literature shows that managed retreat is often imposed through top-down models of planning that can suffer from a reductive view of adaptation with a focus on costs and benefits (Tubridy et al., 2022b). For low-income populations, cost–benefit analysis, given the typically lower value of housing and assets among these groups, can predispose them to unfavourable decision-making outcomes, resulting in distributive injustice. There are also important non-financial losses that should be considered in the context of relocation, including loss of social and family ties, together with the cultural and psychological impacts associated with loss of identity and attachment to place (Agyeman et al., 2009). Given the complex nature of land ownership around the coast, development of legislation and protocols around potential supports for those forced to relocate, together with approaches to land acquisition, will need to be considered, with such debates likely to be politically sensitive, particularly given the high density of holiday homes in coastal locations. Given the challenges of retreat as an adaptation option, Tubridy et al. (2022b) highlight key planning and governance approaches to be integrated, including the incorporation of local knowledge, the co-creation of relocation plans and facilitating community-led approaches to ensure a more socially just approach to relocation as adaptation.

4.4.3. Nature-based approaches for coastal adaptation

There is increasingly a trend towards the incorporation of nature-based approaches into more holistic coastal protection strategies, rather than solely a hard engineering-dominated approach. This trend towards more holistic coastal protection strategies acknowledges the role of nature-based approaches, particularly their potential capacity for adaptation interventions and positive implications for biodiversity. Nature-based approaches focus on the ability of natural or semi-natural ecosystems to reduce the impacts of climate change in a way that also helps ecosystems to thrive. This includes approaches such as protecting or cultivating naturally occurring landforms, including beaches and dunes, and hybrid approaches, including marsh–levee systems, through to 'green' structural approaches such as vegetated engineering (Farrell et al., 2023a; Farrell and Farrell, 2023).

Policies at the European scale are placing nature-based approaches more centrally in adaptation efforts, with the European Green Deal and the Green Infrastructure Strategy emphasising the potential of nature-based approaches for reducing climate change risks. At the national scale, Ireland's sixth National Report to the Convention on Biological Diversity states that 85% of Ireland's listed habitats are considered as having 'unfavourable' or 'bad' status and calls for transformative change to achieve the targets set out in the NBAP. The twin policy aims of climate change adaptation and improving biodiversity (particularly in coastal environments where a large proportion of coastal habitats are within designated Natura 2000 sites) means that nature-based approaches are gaining significant attention, with research under way to examine the effectiveness of such approaches.

Work by the local community in the Maharees in County Kerry is an example of ongoing, community-driven coastal adaptation employing nature-based approaches. This low-lying, sandy-soiled tombolo in south-west Ireland is a popular tourist destination, hosts diverse coastal habitats and connects the villages of Fahamore and Kilshannig to the mainland. The compounding impacts of Atlantic storms and pressure from tourism are impacting the dune system, with both pressures likely to increase into the future. These pressures have led to degradation of the dune system, threatening access to the villages on the tombolo (e.g. the road had to be cleared 17 times in 2015–16 (Farrell et al., 2023a)). The local community formed the Maharees Conservation Association in 2016, engaging in a range of nature-based approaches to stabilise the dunes, including the planting of marram grass and tourist management activities, which have helped to stabilise the dunes and protect surrounding wildlife.

Box 4.1 Maladaptation: the case of Courtown, Co. Wexford

As with other sectors covered in this report, it is important to ensure that adaptation actions do not result in negative outcomes (maladaptation; see Chapter 1) for the communities affected. The case of Courtown, Co. Wexford, where the installation of rock armour to protect against coastal erosion resulted in unintended consequences for the community, is a case in point (Box 4.1, Figure 1). Courtown is an area which has proven to be vulnerable to the impacts of coastal erosion (Philips et al., 2022). Over the last number of decades Courtown's North Beach has been severely diminished by coastal erosion (Philips et al., 2022). To protect against ongoing erosion Wexford County Council employed coastal protection works in the form of rock armour to protect the coast (Philips et al., 2022). Surveys undertaken with the community in Courtown show that loss of the beach and the addition of rock armour as an adaptation action have had a negative psychological impact on many residents in the community (Philips and Murphy, 2021). Residents reported experiencing solastalgia – a sense of loss of identity and of grief associated with loss of the beach, together with emotions of sadness and disappointment (Philips and Murphy, 2021). Importantly, many associate these feelings more with the addition of hard infrastructure rather than the loss of the beach per se. These findings highlight the importance of co-producing adaptation interventions with communities, especially where place attachment is high.

Box 4.1 Figure 1 Left: North Beach at Courtown, 1967. Right: North Beach at Courtown, 2015, including rock armour. Source: Phillips and Murphy (2021). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

4.4.4. Climate-resilient adaptation pathways

Adaptation to coastal risks is hampered by high uncertainty in the rate and magnitude of SLR, changes in storminess and rates of erosion. Subsequently, adaptation decisions carry strong risks of under- or overinvestment, and could lead to costly retrofitting or unnecessary high margins. To better allocate timely and effective resources, and achieve long-term sustainability, planners could utilise adaptation pathways to evaluate feasible adaptation options and their timing and to consider the path dependencies of adaptation options (Haasnoot et al., 2019a,b). Such approaches help to identify low-regret, short-term decisions that preserve options in an uncertain future while monitoring to detect signals that adaptation is needed. As indicated by Haasnoot et al. (2019a), the time horizon for adaptation planning in coastal areas needs to be long term and should consider when adaptation tipping points emerge, i.e. when a move to transformative options may be needed, such as planned retreat. Given the inevitability of SLR and the importance of engagement with communities, coastal adaptation needs to start earlier than anticipated, especially given the time required for local debate and implementation of measures (Haasnoot et al., 2019a).

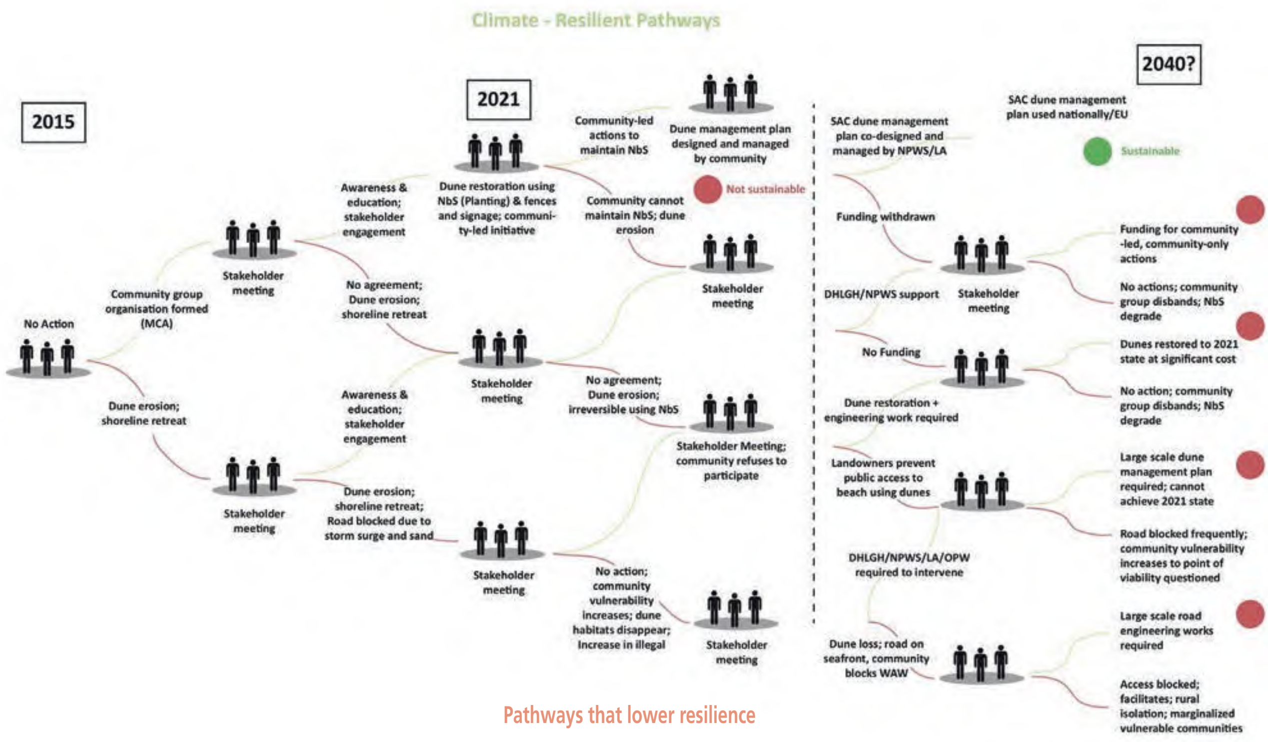


Figure 4.8 Opportunity spaces and climate adaptation pathways for community-led action to mitigate coastal erosion and dune habitat degradation in the Maharees, Co. Kerry. The filled red circle labelled 'not sustainable' represents the current state (2015–2021). LA, local authority; NbS, nature-based solution; WAW, Wild Atlantic Way. Source: Farrell et al. (2023a).

An important asset for coastal adaptation in Ireland is the lessons being learned from the development and implementation of adaptation pathways in specific case study locations. For instance, Sánchez-Arcilla et al. (2016) highlight the identification and implementation of robust short-term measures to protect against coastal erosion while envisaging future pathways as climate change unfolds in Portmarnock in Dublin. Farrell et al. (2023a) show how an adaptation pathways approach can provide a collaborative structure to help coastal communities engage in a long-term process of resilience building using two case studies (see Figure 4.8 for an example of an adaptation pathway to manage dune erosion in the Maharees out to mid-century). Farrell et al. (2023a) emphasise how such an approach can provide a forum for integration of diverse stakeholder views, sharing of knowledge on science, governance, management approaches and local knowledge, providing opportunities for consensus building and identification of preferred futures and critical points for adaptation interventions. Such case studies offer rich opportunities to learn from and expand implementation of similar approaches to other challenges (e.g. SLR), other locations and scales of deployment.

4.5. Priorities for research

4.5.1. Monitoring and understanding coastal change

Projections of coastal change require consideration of local, regional and global factors driving processes of erosion and localised estimates of sea level change. Information is often lacking on rates of coastal change, drivers of coastal change, sediment budgets and response and/or recovery to/from storm impacts. Increasing, and improving access to, knowledge is key to informed decision making in coastal areas. Ongoing and recently completed work is seeking to address some of these gaps, including those listed below; however, expansion and integration of data into decision making will be key to informing adaptation.

- The OPW Pilot Coastal Monitoring Survey Programme (CMSP) is a 5-year pilot project designed to regularly survey coastal locations in Ireland to quantify and identify coastal change.
- The OPW is reviewing methodologies and data requirements available for estimating long-term coastal erosion, to enable estimation of the future positions of the Irish coast for a range of SLR scenarios.

"An important gap in our understanding is how climate change is likely to impact Ireland's islands and how adaptation should proceed in these important places. Ireland's islands are very much a product of land and ocean dynamics. Climate change will present challenges for transport links, livelihoods, ecosystems, tourism, water and agriculture, while existing pressures such as depopulation, cultural heritage and governance processes will need to be accounted for in adaptation planning."

- The OPW Coastal Aerial LiDAR Survey 2022 covers most of the urban and coastal areas across Ireland.
- Ireland's Marine Atlas, compiled by the Marine Institute, includes data such as administrative boundaries, protected sites, oil and gas, ocean features, fisheries and aquaculture, marine monitoring, seabed habitats, tourism and leisure, transport, infrastructure, discharge point sources, International Maritime Organization-protected areas and current/historical dump sites.
- INFOMAR, a joint programme between the Geological Survey of Ireland and the Marine Institute, conducts surveys of the physical, chemical and biological features of the seabed.

4.5.2. Projections of sea level rise

Local rates of SLR are likely to differ from the global mean because of isostatic adjustment and differential melt rates of major ice masses. It is important that locally tailored SLR projections are developed for informing adaptation. From the research reviewed in producing this chapter, there is a lack of consistency in SLR estimates used in impact assessment to inform adaptation planning and in the nature of extreme events that SLR is superimposed upon to estimate future flood inundation. As progress is made in standardising climate projections through the TRANSLATE project (O'Brien and Nolan, 2023), climate services for coastal environments would also benefit from standardisation. Sea levels will continue to rise over centennial timescales. At present we do not have projections of SLR for Ireland out to 2300. While such scenarios go beyond present adaptation policy horizons, they are critical to avoiding expensive decisions that may increase exposure and result in lock-in of adaptation decisions. Research is also needed on how to strategically integrate such long-term projections into urban planning and siting of critical infrastructure, for example.

4.5.3. Ireland's islands

Most research on climate change impacts and adaptation has focused on mainland communities. An important gap in our understanding is how climate change is likely to impact Ireland's islands and how adaptation should proceed in these important places. Ireland's islands are very much a product of land and ocean dynamics. Climate change will present challenges for transport links, livelihoods, ecosystems, tourism, water and agriculture, while existing pressures such as depopulation, cultural heritage and governance processes will need to be accounted for in adaptation planning.

4.5.4. Understanding retreat and managed realignment

Understanding the negative impacts of relocation as an adaptation option and how to avoid them is a critical research gap. Consideration needs to be given to understanding the procedural and distributive justice aspects of relocation and the policy and legislative tools necessary to navigate such issues in the fairest way possible. Discussions about what is valued about our coasts, together with the limited resources available for approaches that seek to protect against or accommodate climate change impacts, will be challenging politically and for individuals and needs to be engaged with sooner rather than later. As highlighted by Haasnoot et al. (2021), implementing managed retreat constitutes a multi-decadal sequence of actions, including community engagement, vulnerability assessment, land use planning, active retreat, compensation and repurposing. Approaches to adaptation that consider managed realignment can reduce flood and erosion risk, reduce maintenance costs, mitigate coastal squeeze, sequester carbon, create new habitats and biodiversity benefits, and compensate landowners for the permanent loss of land – all without relocation of properties (or with minimal relocation), depending on site-specific constraints. The potential opportunities for managed realignment should be further investigated.

5

Water

Key messages

1. In Ireland, climate change impacts on the hydrological cycle are happening in the context of increasing water demands, decreases in water quality and a lack of resilience in our water supply infrastructure. Impacts are likely across multiple sectors, including critical infrastructure, settlements, biodiversity, land use and health, raising the importance of cross-sectoral collaboration for adaptation.

2. Identifying a clear signal of climate change in observed precipitation and river flows is difficult because of natural variability. Observational records show that the magnitude and timing of floods are changing; however, there is uncertainty in attributing the cause of these changes, whether due to climate change, natural climate variability, data quality or internal catchment modifications (e.g. land use change, arterial drainage).

3. Rainfall and river flow projections for mid-century and end of century are uncertain, but suggest increases in flood magnitude and frequency, increases in spring and summer drought magnitude and frequency (future changes in drought duration are uncertain), and increases in river flows in winter and decreases in summer. Ambitious global mitigation measures resulting in less warming are associated with less severe low flows.

4. Future changes in temperature, relative humidity and wind speed will lead to changes in evapotranspiration. Increases in evapotranspiration would have significant implications for drought impacts, water resources and agriculture, especially during the spring and summer months. The impact of vegetation responses on evapotranspiration remains open to scientific debate.

5. The impacts of climate change on groundwater are strongly influenced by local hydrogeological settings. Some aquifers are projected to experience increases in drought impacts, while the incidence of flooding may increase in others. Groundwater aquifers with low storage capacity are thought to be more vulnerable to extremes, particularly rainfall amount, intensity and timing. Aquifers with high recharge coefficients and sufficient recharge acceptance capacity will be impacted by the amplification of rainfall seasonality. Groundwater flooding is likely to increase in scale, frequency and duration.

6. Water quality is influenced by air and water temperature, precipitation amounts and intensity, and the occurrence of extreme events. Changes in rainfall amounts, timings and intensities have implications for nutrient washout, erosion, suspended sediment and sediment yields, with sensitivity varying by catchment. Climate change impacts on water quality in urban areas are also dependent on the design and construction standards of water infrastructure. Changes in land use/management are likely to interact with and amplify the impacts of climate change on water quality. Land use management is a critical adaptation pathway for alleviating pollution and improving water quality in catchments.

7. Adaptation in the water sector should account for the range of plausible changes in climate variables. Frameworks for decision making under uncertainty, including the development of adaptation pathways, together with integrated catchment management as part of river basin management plans, offer valuable approaches for reducing existing vulnerability and addressing adaptation needs.

8. Water supplies face growing pressures resulting in increased water demand. Climate change is likely to further increase water demand from households, businesses and agriculture. A large portfolio of supply and demand side adaptation options are available for water resources management. However, effective adaptation options and appropriate adaptation pathways remain to be devised and assessed. Some supply side options, such as the development of new sources, may involve significant trade-offs and encounter adaptation limits via social or environmental acceptability, technical feasibility or excessive cost.

9. The implementation of adaptation actions for flood risk reduction can be categorised as defending against risk, living with risk, and relocation or withdrawing from risk. For defending against risk, actions include retrofitting existing infrastructure, building new infrastructure and integrating safety margins to accommodate climate change into designs. Living with risk includes land use planning and flood zoning, insurance, deployment of nature-based approaches and recognising the important role of flood plains in attenuating floods. Relocation in response to flooding has been rare in Ireland to date but has happened and may become more commonplace in future.

5.1. Introduction: current pressures

Water is central to a sustainable environment and economy and underpins human health and wellbeing. Climate change will result in an intensified hydrological cycle, with associated changes impacting water quantity and quality in all parts of the hydrological cycle. These changes will also impact on hydrological extremes, including floods and droughts. Changes in the hydrological cycle with climate change are unfolding in the context of increasing water demands and decreases in water quality and within a legacy of a lack of investment in water infrastructure. Therefore, successfully adapting to changes in water and the hydrological cycle are likely to be critical to obtaining Ireland's climate objective of realising climate resilience. Moreover, changes in water are likely to have an impact across multiple sectors, including critical infrastructure, settlements, biodiversity, land use and health, raising the importance of cross-sectoral collaboration for adaptation to meet many of Ireland's social and ecological goals, especially those related to the Water Framework Directive. This chapter assesses key risks, vulnerabilities and impacts from climate change for water and hydrology in Ireland and considers adaptation responses in the areas of water resources and flood risk management.

5.2. Observed and future changes in the hydrological cycle

In the following subsections, changes in observed and projected components of the hydrological cycle are assessed. In each case, a brief overview of wider European changes is provided before evaluating observed and projected changes for Ireland.

5.2.1. Changes in average precipitation

Precipitation is the major input to the land-based hydrological cycle and is critical to understanding changes in water resources and extreme hydrological events. Annual precipitation totals in Ireland, consistent with northern Europe generally, indicate an increasing trend since the 1980s (Volume 1, section 4.1). Long-term records of precipitation, representing the island of Ireland and dating back over 300 years (Murphy et al., 2018), reveal large variability, with recent decades being among the wettest on record (Noone et al., 2016; Wilby et al., 2016). Seasonally, winter precipitation reveals an increasing trend for records commencing after 1860; however, this may be due to changes in measurement techniques and challenges in measuring snow in early records (Murphy et al., 2020a). Summer precipitation in Ireland is also highly variable, but decreasing trends are evident in long-term records, with the largest decreasing trends evident for July (Leahy and Kiely, 2011). No clear trend can be seen in spring and autumn totals.

Globally, mean precipitation is constrained by Earth's energy budget to increase at around 1–3% per degree of global warming (Fowler et al, 2021a), meaning that the signal of change for mean precipitation is expected to be less than that for precipitation extremes. Annual and seasonal precipitation in Ireland in different seasons and regions is strongly influenced by climate variability, particularly the NAO, the East Atlantic Pattern and variations in Atlantic sea surface temperatures (Kiely, 1999; McCarthy et al., 2015; Comas-Bru et al., 2016). Therefore, identifying a clear signal of human-driven climate change in observed annual and seasonal mean precipitation is difficult presently. This is to be expected given the amount of warming experienced to date.

Volume 1, section 4.2, details future changes in precipitation. In summary, uncertainty in the magnitude and even direction of future precipitation is likely to persist, and decision makers should be aware that there is substantial uncertainty in precipitation projections for the island as a whole, which become more acute locally. Differences in projections between climate models and the significant role of natural variability means that large ranges of plausible changes in precipitation are to be expected. In broad terms, annual precipitation totals are projected to increase over the course of the century. The spatial distribution of changes depends on the climate models used, with the ensemble mean of the TRANSLATE projections (Volume 1) indicating greatest relative increases in the east. Changes in annual mean precipitation are least for Early action mitigation scenarios.

Winter (December–February) precipitation is expected to increase with climate change; however, the magnitude and spatial distribution of increases depends on the climate models used. The ensemble mean from the TRANSLATE projections indicates an increase of up to 20% in winter precipitation for much of the island by the end of the century under a Late action scenario (Volume 1, Figure 4.5). Early action on emissions is associated with more modest increases.

For summer (June–August), the direction of change in seasonal totals from large ensembles such as Coupled Model Intercomparison Project Phase 6 (CMIP6) indicate ranges of change that span increases and decreases; however, most models indicate a drying trend, some substantially. The TRANSLATE projections suggest that summers are likely to get drier (Volume 1, Figure 4.6), with decreases of up to 20% using the ensemble mean under a late action scenario. Reductions in summer precipitation are less extreme under early action scenarios.

The direction of change in autumn (September–November) and spring (March–May) precipitation is uncertain, with both increases and decreases projected by different models. These are important seasons for groundwater–surface water interaction dynamics. Overall, the precipitation regime for Ireland is likely to become increasingly seasonal, with relatively modest increases in annual totals, representing the balance between wetter winters and drier summers. However, uncertainties in all aspects of future precipitation changes are large and should be fully explored to avoid maladaptation in the water sector.

5.2.2. Changes in extreme precipitation

Short-duration rainfall extremes (sub-daily) can be especially hazardous, resulting in fatalities, pluvial floods, flash floods (especially in small upland rivers), landslides and pollution instances (either through contaminated runoff to rivers or coastal bathing areas, or through overwhelming the capacity of sewerage/drainage systems or waste water treatment plants (WTPs)), with associated public and ecological health consequences. Urban areas are highly vulnerable to heavy, short-duration rainfall due to impermeable surfaces, resulting in very high proportions of runoff.

Changes in extreme precipitation are driven by thermodynamic (warmer atmosphere) and dynamic (atmospheric circulation) changes. In general, warming increases the water holding capacity of the atmosphere following the Clausius–Clapeyron (CC) relation (around 6–7% per degree of global warming). The CC relation can be used as a first-order approximation to indicate how rainfall extremes may change with warming. However, extreme precipitation is further modulated by dynamic changes, including changes in modes of climate variability, such as the NAO, which can amplify or dampen extreme precipitation. Future projections of NAO response to warming remains a major source of uncertainty in our understanding of precipitation (and hydrological) responses to climate change. Other drivers of change may give rise to changes in extreme precipitation at rates exceeding the CC relation, including increased latent heating of convective cells, temperature stratification of the atmosphere, and changes in cloud micro-physics that increase efficiency at converting atmospheric moisture into precipitation. However, such drivers remain poorly understood (Sui et al., 2020; Fowler et al., 2021b, 2021c; Seneviratne et al., 2021). Urbanisation and land use change at local scales can also result in feedback that may amplify changes in sub-daily extremes.

As assessed in Volume 1, there is high confidence that heavy precipitation has intensified at the global scale over land, and it is likely that anthropogenic influence is the main cause. In Europe, there is robust evidence that the magnitude and intensity of extreme daily precipitation has increased since the 1950s. In an analysis of daily precipitation records from Ireland from the 1950s onwards, Harrigan (2016) found increases in precipitation intensity consistent with the CC relation in the east and south-east, especially in summer. Ryan et al. (2022) evaluated changes in annual precipitation extremes for rescued daily observational records extending to the early 20th century (Ryan, C. et al., 2021) and found significant increasing trends in rainfall intensity, again predominant in the east and south-east, while the contribution of heavy and extreme precipitation events to annual totals was also found to be increasing.

Volume 1, section 4.4, evaluates future changes in extreme daily precipitation. In summary, climate model projections from the TRANSLATE ensemble indicate a broad pattern of increase in maximum daily precipitation. Late action scenarios show that precipitation totals for the wettest day of the year may be 30–50% greater by the end of the century. Heavy rainfall days (> 20mm) are also likely to increase in frequency. Under a Late action scenario, some simulations indicate up to a doubling of the frequency of heavy rainfall days. Uncertainty in precipitation extremes is also large and heavily influenced by natural climate variability.

Understanding of changes in sub-daily precipitation extremes is hampered by a lack of long-term records, the low spatial density of stations and variations in study designs, metrics and different methods of analyses. In one of the few Irish studies to examine changes in sub-daily precipitation extremes, Leahy and Kiely (2011) analysed different return periods for 1- to 24-hour rainfall totals from 13 stations. They found that, while some stations show increases in the frequency and magnitude of short-duration extremes, there is no clear spatial pattern to changes, with local variations in site exposure or orography likely to be responsible for differences between stations. Importantly, they also show that increases in the frequency and magnitude of sub-daily extreme rainfall do not always coincide with increases in annual total rainfall. Therefore, changes in sub-daily rainfall extremes remain poorly understood and are highlighted as a future research priority, given their importance to engineering design and adaptation. Understanding of projected changes in sub-daily precipitation changes is limited. Recent international research is moving towards very high-resolution convection-permitting models to better understand sub-daily extremes (e.g. Fowler et al., 2021a), especially in summer, but this is an important gap in knowledge in the Irish context. Given the impact of heavy rainfall events (both daily and sub-daily) on infrastructure and the risks posed by pluvial flooding, it is important that adaptation accounts for the range of change projected for these extremes. Rainfall extremes also have the potential to impact crop growth and land management, landslide susceptibility and groundwater recharge.

5.2.3. Changes in evapotranspiration

Evapotranspiration includes direct evaporation of moisture from the Earth's surface, together with water vapour exchange via vegetation (transpiration). Enhanced atmospheric evaporative demand (AED) promotes enhanced water fluxes to the atmosphere, predominantly via plant transpiration, but also via direct evaporation from soils (when available), streams, reservoirs and lakes. Globally, annual evapotranspiration from land has increased since the early 1980s, driven by increased atmospheric water demand and vegetation greening, and can be partially attributed to anthropogenic greenhouse gas forcing and also to irrigation and land cover change (Douville et al., 2021).

Few studies have evaluated observed changes in evaporation for Ireland. In a study of evaporative losses from Class A evaporation pans across Britain and Ireland for the period 1963–2005, Stanhill and Moller (2007) reported increasing evaporation from three of four Irish series, with Irish data showing a small but significant increase in evaporation over the past 40 years. Changes in sunshine duration, used as a proxy for global radiation, were found to be a major factor in understanding the spatial and temporal changes in evaporation, while long-term changes were closely correlated with those found for air temperature. Vicente-Serrano et al. (2019) examined changes in AED for catchments across Europe, finding increasing (but non-significant) trends for catchments in eastern Ireland and decreases (non-significant) in the Midlands and south-west.

Future changes in evapotranspiration will be driven by changes in temperature, relative humidity and wind speed. Climate models project increases in AED and evapotranspiration over most land areas where moisture limitation is not a factor. However, considerable uncertainty remains in understanding regional and seasonal variations that are influenced by changes in soil moisture and vegetation and complex feedback processes (Douville et al., 2021). The role of vegetation responses in modulating losses from evapotranspiration remains open to debate. Some argue that increases in plant water use efficiency will limit losses from evapotranspiration, while others suggest that transpiration increases due to the impact of climate change on growing season length, leaf area and evaporative demand will increase losses from evapotranspiration (Douville et al., 2021). The CMIP6 ensemble projects changes in evapotranspiration that vary in magnitude and sign across individual models but show a median increase in evapotranspiration of approximately 25% in the mid-/high latitudes, with the upper range of 50% for a Late action emissions scenario (Caretta et al., 2022).

For Ireland, Gharbia et al. (2018) evaluated future potential evapotranspiration (PET) changes for the Shannon catchment under different emissions pathways, finding that PET is likely to increase over the course of the century, with the largest losses under a Late action scenario of up to 13.5% annually. Such changes would have significant implications for water resources, agriculture and ecosystems, especially during spring and summer months. They also found that the results are sensitive to the method used to estimate PET. The projections of evapotranspiration are in broad agreement with Nolan and Flanagan (2020), who used an ensemble of dynamically downscaled regional climate datasets to assess the impact of climate change on evapotranspiration (using the FAO 56 Penman–Monteith method) under a range of emission scenarios (see Figure 5.1). For reference, observed annual evapotranspiration, derived from a high-resolution (1.5-km) downscaled ERA-Interim climate simulation, is presented in Figure 5.2.

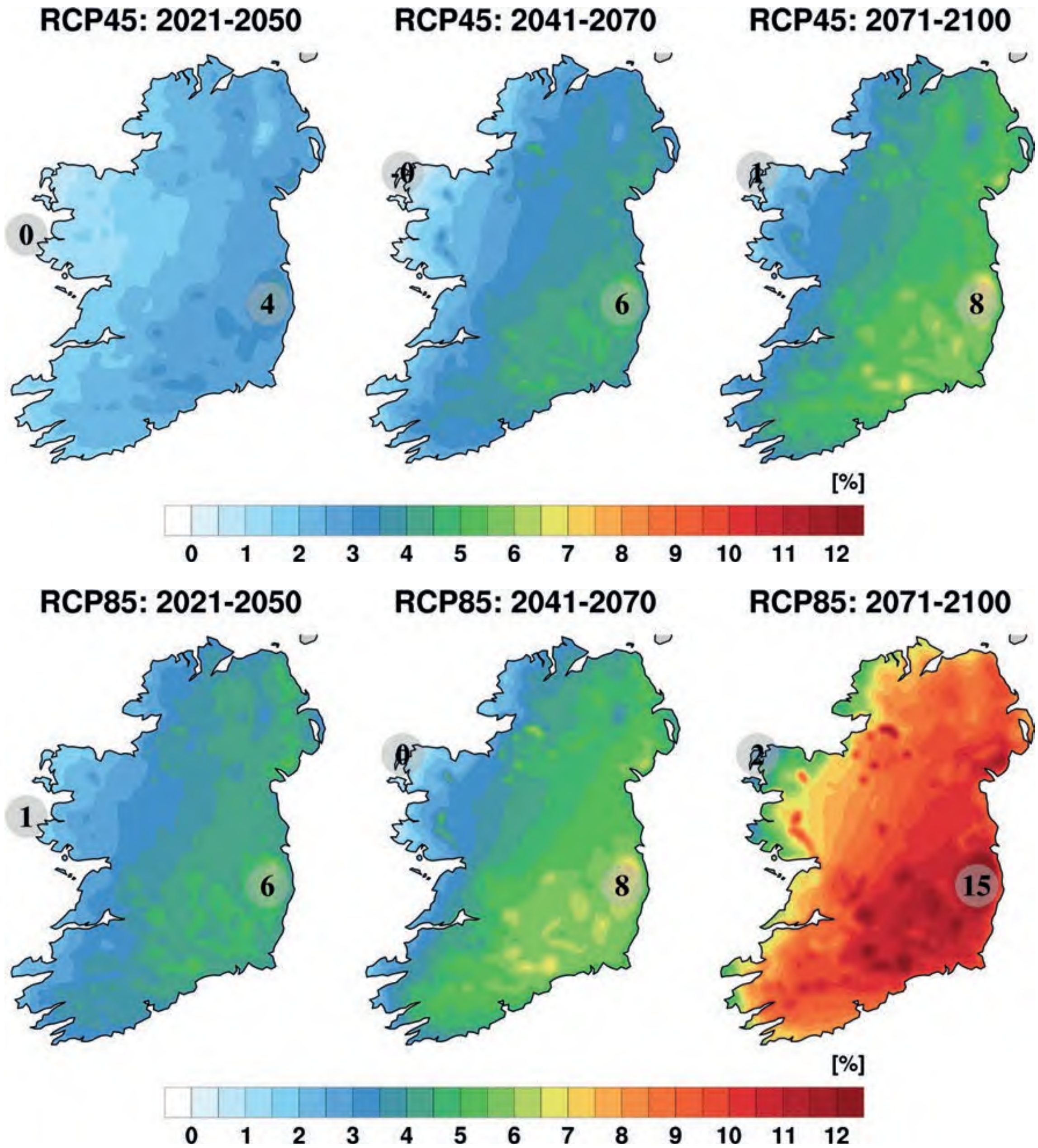


Figure 5.1 Regional climate projections of annual evapotranspiration (%) for the RCP4.5 and RCP8.5 scenarios. In each case, the future period is compared with the past period, 1976–2005. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations. Source: Authors' original.

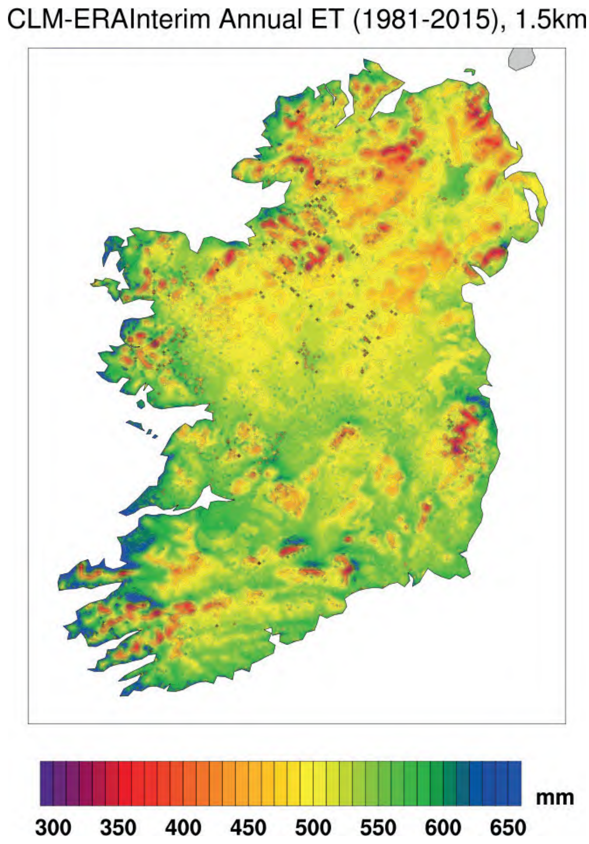


Figure 5.2 Observed annual evapotranspiration (1981–2015), derived from a high-resolution (1.5-km) downscaled ERA-Interim climate simulation using the FAO 56 method. Source: Werner et al. (2019).

In summary, there are considerable gaps in our knowledge concerning observed and future estimates of PET, the sensitivity of results to the methods used, the uncertainty in future plant responses and the multiple variables (especially wind speed) used to estimate PET. Furthering understanding of PET and climate change will be critical to understanding impacts in various sectors, especially water, agriculture and ecosystems, and should be a priority for future research.

5.2.4. Changes in river flows

Analysis of the Irish Hydrometric Reference Network for monitoring and detecting climate change in Irish river flows shows increases in annual flows for the period 1976–2009, particularly for catchments in the west and north-west (Murphy et al., 2013). Winter flows also show increasing trends in the north-west but decreases in the east and south-east. In summer, island-wide increasing trends have been found; however, this is likely to be due to the relatively short length of flow records, with many series commencing during drought conditions in the mid-1970s. River flows are strongly influenced by natural climate variability, with winter flows in the west being strongly influenced by the NAO. Even summer flows in the south show significant negative correlation with the previous winter's NAO (Murphy et al., 2013).

To contextualise changes from short observed records, O'Connor et al. (2021) reconstructed river flows for more than 50 Irish catchments, with analysis of trends in annual flows since 1900 revealing increases in the west, north-west and south-west (O'Connor et al., 2022a). Seasonally, increases in winter and autumn flows were found, particularly in the west and north-west. The pattern of change in spring and summer is less clear. Weak decreasing trends predominate in summer, especially to the south, while in spring weak increasing trends are found in the north, west and south-west, with weak decreasing trends in the east and south-east (see Figure 5.3). Both observed and reconstructed flows show large variability in Irish river flows, meaning that any trends will be dependent on the period of record analysed. The largest change in river flows over the past 120 years has been a step change towards increased annual, winter and spring flows in the late 1970s, attributed to a shift towards a more positive phase of the NAO at that time (Kiely, 1999; Murphy et al., 2018).

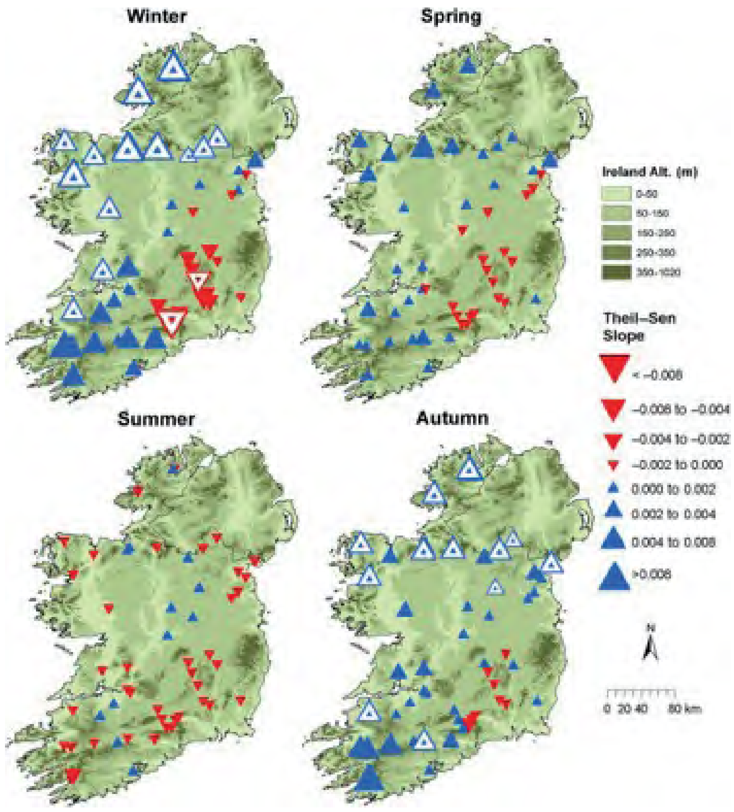
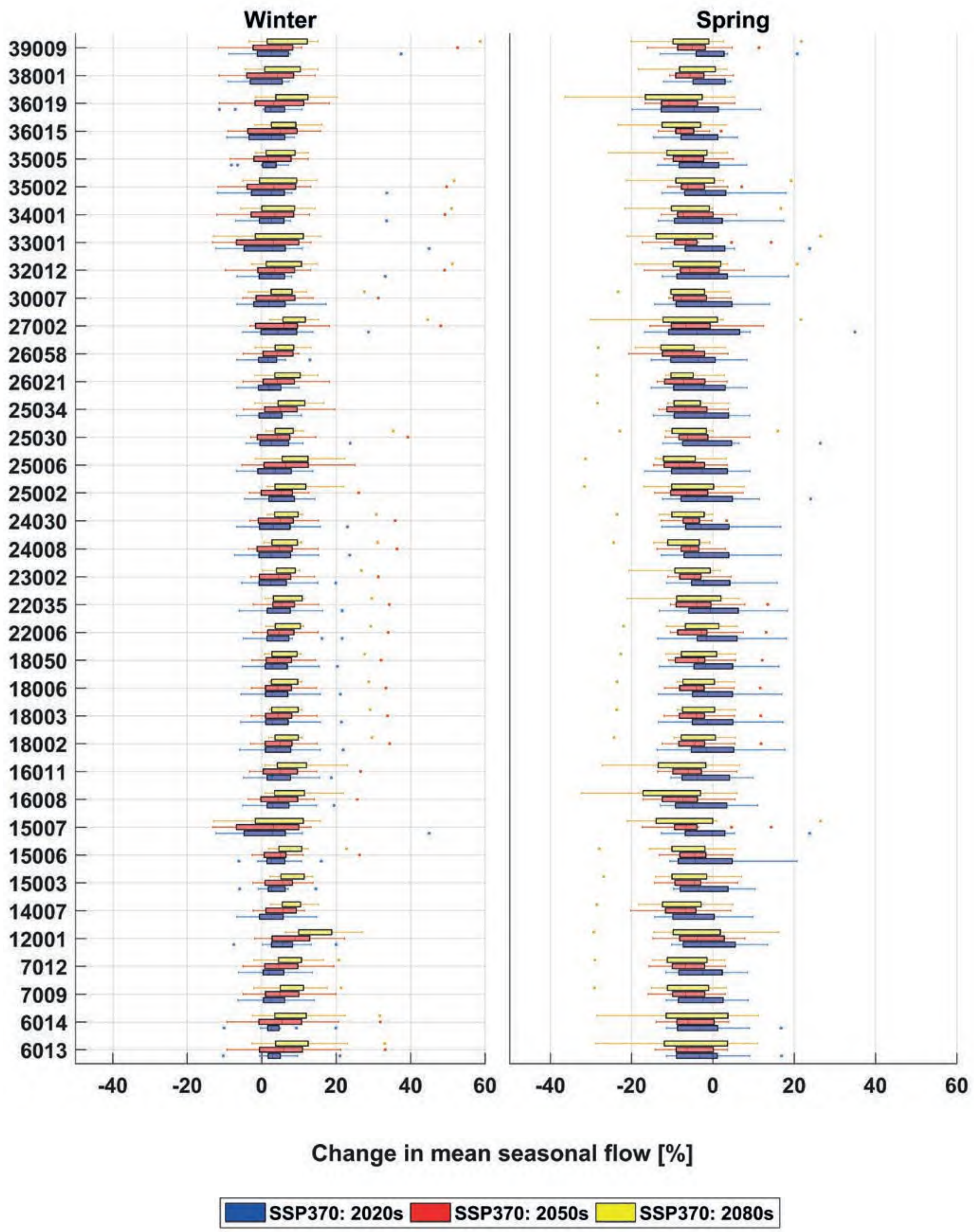


Figure 5.3 Trends in reconstructed seasonal mean flows for 51 catchments for the period 1900–2016. Trend directions are indicated by arrow direction and colour (blue: increasing; red: decreasing), with arrow size indicating the magnitude of change. Statistically significant trends (0.05 level) are indicated using white triangles. Source: O'Connor et al. (2022a). Reproduction licensed under the Creative Commons Attribution CC BY-NC-ND 4.0 licence (https://creativecommons.org/licenses/by-nc-nd/4.0/).

Several Irish studies have evaluated possible future changes in river flows (Charlton et al., 2006; Steele-Dunne et al., 2008; Meresa et al., 2022; Murphy et al., 2023) but use different study designs. The most comprehensive study by Meresa et al. (2022) investigated changes in future river flows for 39 Irish catchments, examining changes in seasonal (winter (DJF), spring (MAM), summer (JJA), autumn (SON)), mean and annual low flows (Q95, the flow exceeded 95% of the time) from an ensemble of 12 climate models from the CMIP6 ensemble under Early, Middle and Late action scenarios. They also evaluated changes from two different hydrological models. Their results show a wide range of change in seasonal and low flows across catchments (Figure 5.4). However, the overall distribution of changes derived suggests increases in winter flows and decreases in summer flows. Under a Middle action scenario, by the 2080s, changes in summer flows of 4.8% to –36.9% are simulated across catchments, while for winter simulated changes in flows across catchments range from –1.8% to 32.2%. The range of change in low flows (annual Q95) across catchments ranges from –2.5% to –38.2%. For spring and autumn, the overall direction of change is more uncertain. These findings are broadly consistent with recent studies in Northern Ireland (Kay et al., 2021), where large reductions in low flows were identified in simulations driven by the UKCP18 project's regional climate projections. These projected changes would have significant implications and require substantial adaptation effort. This is particularly the case for Middle and Late action scenarios by the 2050s and 2080s, where increases in winter flows and decreases in summer flows could prove problematic for water resources management, freshwater ecosystems and water quality.

Wide ranges of change in river flow projections are associated with uncertainties in precipitation simulations from global climate models and the addition of hydrological models to the impact assessment modelling chain (see Chapter 1, Box 1.1). To ensure resilience in the face of adaptation, decision making in the water sector should account for the wide range of plausible changes simulated. Importantly, Meresa et al. (2022) show that early action to reduce greenhouse gas emissions would be likely to have a large impact on the magnitude of reductions in summer flows (although the extent depends on hydrological model used) and low flows.



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Change in mean seasonal flow [%]
SSP370: 2020s
SSP370: 2050s
SSP370: 2080s

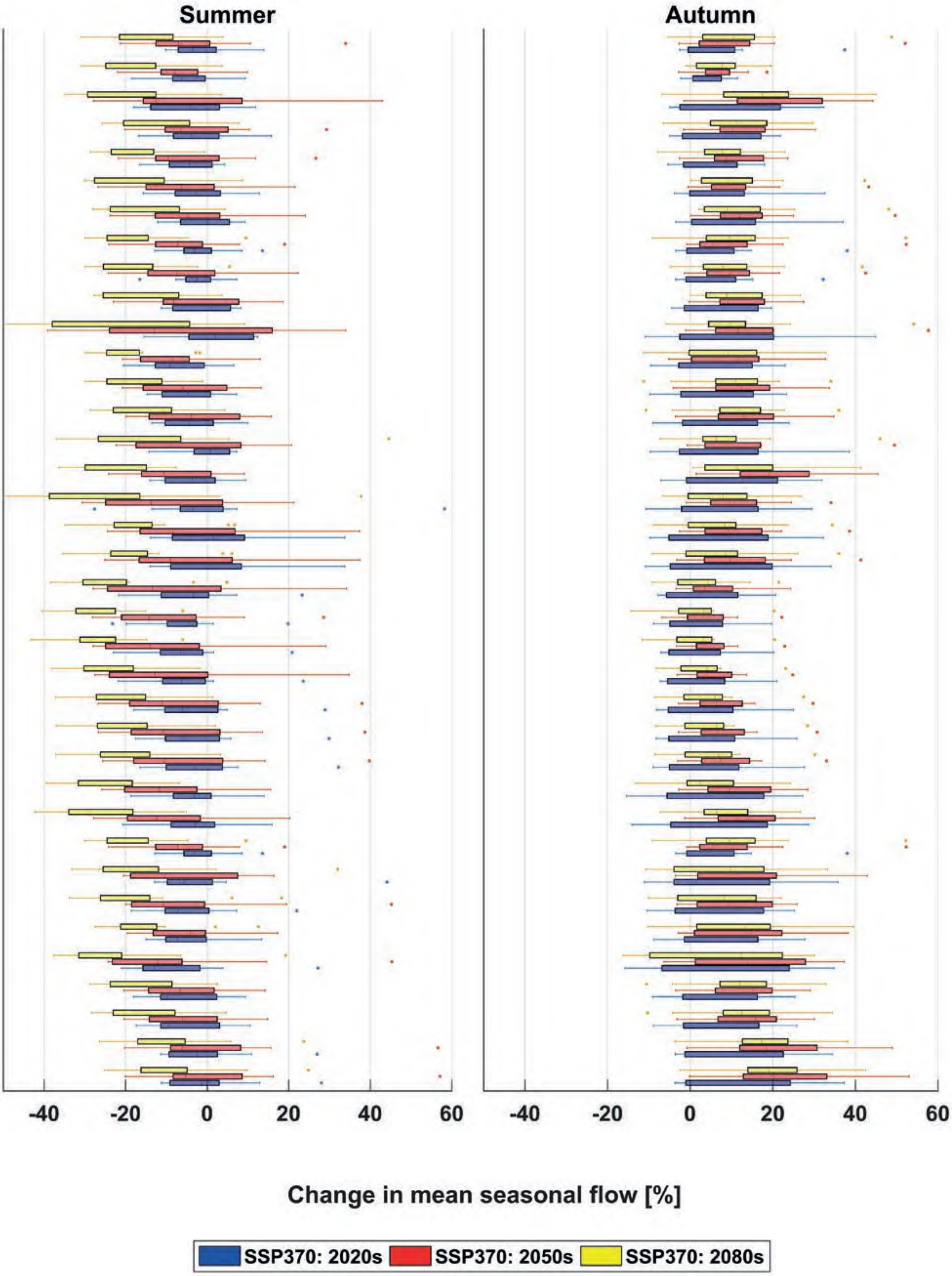


Figure 5.4 Simulated changes in seasonal river flows (per cent change) for 37 Irish catchments (catchment numbers given on y-axis), as simulated by 12 CMIP6 climate models and the GR4J hydrological model for three future time periods (2020s, 2050s and 2080s) under a Middle action scenario (SSP370). Source: Meresa et al. (2022). **Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).**

5.2.5. Changes in groundwater

Climate change is expected to impact groundwater resources over the coming decades, with potentially exacerbated seasonal flooding and drought increasing pressures on maintaining water supply, quality and biodiversity. However, projections of climate change impacts on groundwater are subject to significant uncertainty, as the climate parameters most relevant to recharge – precipitation and evapotranspiration – show large variations within climate models (Riedel and Weber, 2020; Wunsch et al., 2022). Additional uncertainties relate to terrestrial responses to changing precipitation (Taylor et al., 2013), changes in the growing season (Holman, 2006) and changes to soil properties in response to more intense precipitation (Burt et al., 2016). Increased evapotranspiration would cause less infiltration beyond the root zone, and hence less groundwater recharge (Kløve et al., 2014; Wunsch et al., 2022), while groundwater resources would be under greater stress due to increased abstraction.

In Ireland, it is expected that large parts of the country will see limited changes in the average annual recharge volumes to the 'deep' groundwater system, since the poorly productive aquifers that cover over two-thirds of the country are not likely to accept significantly more recharge, unless there is intervention such as drainage to create additional space. The extensive cover of limited permeability glacial till subsoils is already a limiting factor to groundwater recharge (Hunter Williams and Lee, 2010). Aquifers with low storage capacity are thought to be more vulnerable to extremes, as they have no 'buffer' against extreme events (Charlton et al., 2006). Aquifers with high recharge coefficients or those not affected by constrained recharge acceptance capacity may be impacted by the amplification of rainfall seasonality. Overall, the impacts of climate change on Irish aquifers are expected to be strongly influenced by the local hydrogeological settings (Cantoni et al., 2017). Changes in the timing of the onset and cessation of the recharge period, rainfall intensity and overall rainfall volumes are likely to cause the following alterations to aquifer behaviour:

- In low storage capacity, poorly productive aquifers, earlier groundwater recession may reduce spring/summer groundwater levels, although groundwater levels are likely to recover quickly (potentially within one season) once recharge commences.
- In higher storage capacity sand and gravel aquifers, multiannual trends in recharge volumes will have a potentially significant impact. These aquifers are more resilient to 1- or 2-year droughts, but will take longer to recover to 'typical' levels after a run of lower or higher than average recharge years.
- In areas with moderate infiltration rates through soil and subsoils layers, recharge may decrease, even if total effective rainfall amounts stay the same over the recharge period, due to the infiltration capacity being exceeded during higher intensity but shorter duration rainfall events.
- Increased sea levels are likely to impact high permeability coastal aquifers, such as karst limestones, by increasing seawater intrusion, particularly during summer months.
- In low-lying areas, increased rainfall may result in increased surface flooding due to 'rejected recharge' from poorly productive aquifers, or localised groundwater flooding due to increased groundwater levels in aquifers.

Projected changes to recharge and aquifer functionality may lead to detrimental impacts. Abstractions may come under pressure due to increasingly long uninterrupted groundwater recessions during the spring and summer (in addition to increased water demand). This may cause growth in zones of contribution to compensate (Hunter Williams and Lee, 2010). Growth in the zones of contribution may result in intersection with sources of pollution, affecting groundwater quality. Reductions in river baseflows during dry periods could lead to a deterioration in river water quality due to a higher concentration of pollutants, while changes in rainfall patterns and intensity could alter the mobilisation of pollutants in the soil towards groundwater. Groundwater flooding is likely to increase in scale, frequency and duration (Morrissey et al., 2021; see Box 5.1). Increased flows into the near shore zone may impact shallow marine and intertidal fauna, due to decreased salinity, and increase the risk of nutrient, chemical and microbiological pathogens transport into that zone.

Box 5.1 Climate change and turloughs: a unique Irish pressure

Turloughs are a form of seasonally flooded wetland and characteristic features of the Irish karst landscape. They are virtually unique to Ireland and typically vary in size from less than 1 hectare to over 250 hectares. There are over 500 recorded examples of turloughs across the country, with the majority located in the limestone lowlands of counties Roscommon, Galway, Mayo and Clare. The prevalence of groundwater flooding in western counties is fundamentally linked to bedrock geology. Groundwater flow systems in these areas are characterised by high spatial heterogeneity, low storage, high aquifer diffusivity and extensive interactions between groundwater and surface water, which leaves them susceptible to groundwater flooding (Naughton et al., 2017). During intense or prolonged rainfall, the subterranean flow paths are unable to drain recharge, and available sub-surface storage rapidly reaches capacity. This causes groundwater to temporarily rise above the land surface and flood the low-lying topographic basins of turloughs (Box 5.1, Figure 1).

Box 5.1 Figure 1 Groundwater along the western railway corridor near Gort, Co. Galway, in winter 2020. Photo credit: Galway County Council.

Most turloughs are filled by rising groundwater levels through estavelles or springs, in addition to direct precipitation and some surface runoff, and ultimately empty through estavelles and swallow holes (Skeffington et al., 2006). Filling normally occurs in late autumn due to periods of intense or prolonged rainfall, with emptying typically occurring from March onwards, although the timing and extent of flooding can vary significantly between sites, depending on the nature of and connections to the karstic groundwater system. This flooding promotes a biodiverse habitat, as flora and fauna adapt to survive the oscillation between terrestrial and aquatic conditions. As such, turloughs tend to support a variety of wet grassland and fen-type vegetation but are notably absent of trees or shrubs (Praeger, 1932). Characteristic species of invertebrates include some aquatic species – often benefiting from the absence of fish – and many wetland terrestrial species, including carabid beetles that are rare in Europe (Skeffington et al., 2006). Due to their diverse habitats, turloughs are protected under the EU Water Framework Directive (Directive 2000/60/EC) and designated as a priority habitat under Annex 1 of the EU Habitats Directive (Council Directive 92/43/EEC). Numerous sites supporting ecological communities of national and international importance have been designated as special areas of conservation and afforded the highest level of protection available under EU conservational law.

Under normal hydrological conditions, inundation within turloughs does not represent a flood hazard; in fact, it is an ecohydrological-supporting condition for flood-dependent turlough ecosystems (Naughton et al., 2017). However, water levels can exceed normal bounds under extreme conditions and inundate surrounding buildings, agricultural land and infrastructure. It is in this context that turloughs represent the principal form of recurrent, extensive groundwater flooding in Ireland (Naughton et al., 2017). Flood risk management at turloughs poses a unique set of technical and environmental problems that differentiate it from other forms of flood management. Groundwater flooding is primarily driven by cumulative rainfall over a prolonged period. It is this accumulation of water over a period of weeks or months that determines flood severity and duration. Furthermore, the long-term hydrometric data required for traditional flood frequency analysis does not exist for groundwater flooding, impeding the calculation of flood risk.

The last 15 years have seen the worst groundwater flooding in living memory. Floods during the winters of 2009/2010, 2015/2016 and 2019/2020 caused widespread damage and disruption to communities across the country, particularly in the extensive karstic limestone lowlands in the west. As the climate changes, it is likely that extensive flood events such as these will become more common with wetter winter conditions. In a study of climate change impacts on groundwater flooding at a series of turloughs in south Galway, Morrissey et al. (2021) found that, even though there is significant uncertainty, the underlying trend for future flood behaviour is increases in mean annual flood levels (groundwater levels) and, most significantly, in flood duration, particularly at higher (and more extreme) flood levels. Furthermore, Morrissey et al. (2021) also suggest a shift in the seasonality of flooding, whereby peak flood levels will occur later in the year. These changes in flood patterns would have detrimental impacts for ecosystems within turloughs. Habitats within turloughs have developed in conjunction with the hydrological regime. Altering the flood patterns is likely to cause associated changes in the location and extent of habitat zones. In addition, a shift in the seasonality of flooding may cause disruption to the early growing season for wetland grasses and flora. The research of Morrissey et al. (2021) is a critical first step in the study of potential climate change impacts on turloughs. The Geological Survey Ireland GWClimate project is continuing this research theme with a national focus.

5.2.6. Changes in fluvial floods

Floods are complex events, with the link between rainfall and flooding dependent on soil wetness or antecedent conditions, land cover use/change and adaptation measures. While increases in the frequency and magnitude of extreme precipitation have been observed across the globe, linking changes in precipitation extremes and fluvial flooding is more complex (Sharma et al., 2018). Previous IPCC reports have reported low confidence in linking climate change to floods due to limited spatial and temporal coverage of high-quality gauges in catchments that are free from confounding factors. That remains the case in the most recent AR6 report.

Analysis of observations for river gauging stations across Europe show a complex picture of change in the magnitude and timing of floods (Blöschl et al., 2017, 2019). For western Europe, including Ireland, changes in the timing of floods over the period 1960–2010 have been related to changes in soil moisture and the NAO, resulting in floods occurring later/earlier in the winter season in the west/east of the country. However, it is unclear whether changes in the NAO are a result of natural variability or driven by anthropogenic climate change (Blöschl et al., 2017). Research examining changes in the magnitude of floods in Europe has found some evidence of regional patterns of change consistent with climate model projections for the coming century. Over the last five decades, increases in winter precipitation and soil moisture have led to increasing flood magnitude in parts of north-western Europe, including Ireland (Figure 5.4; Blöschl et al., 2019). In a study of climate-driven trends in major floods across North America and Europe, Hodgkins et al. (2017) found that changes over time were dominated by multi-decadal climate variability rather than anthropogenic climate change. Therefore, the attribution of changes in floods remains uncertain.

For Ireland, Murphy et al. (2013) examined observed trends in high flows from the Irish Hydrometric Reference Network over the period 1976–2009, finding that changes in annual maximum flows were dominated by increasing trends (at 77% of stations), with statistically significant increases at 19% of stations. While trends are evident and likely to be climate driven (due to the use of high-quality reference-like stations), attribution of trends to natural or anthropogenic-driven climate change was not possible. Increasing trends were largest in the south-west, west and upper Shannon basin. Significant increasing trends were also found for other high-flow indicators, including the maximum consecutive 10- and 30-day flows. Correlations between the NAO and high flows were found to be strong and significant, indicating the importance of understanding how climate change is likely to impact the NAO in deciphering changes in floods. Other studies that have investigated trends in floods for Ireland (though not based on reference-type networks) have found significant increasing trends at 26% of stations (Faulkneret et al., 2019), particularly in the Midlands and north-west. An important research priority over the coming years must be attribution of changes in flood characteristics in Ireland and the development of approaches for dealing with non-stationarity in flood risk. This will also require collation of datasets on plausible drivers of change, including land use change and arterial drainage.

In summary, observational records show that the magnitude and timing of floods are changing; however, there is uncertainty in attributing the cause of these changes, i.e. whether these are due to climate change, natural climate variability, data quality or internal catchment modifications (e.g. land use change, arterial and land drainage, etc.). At larger scales, increasing trends in floods are consistent with climate model projections; however, consistency is not causality.

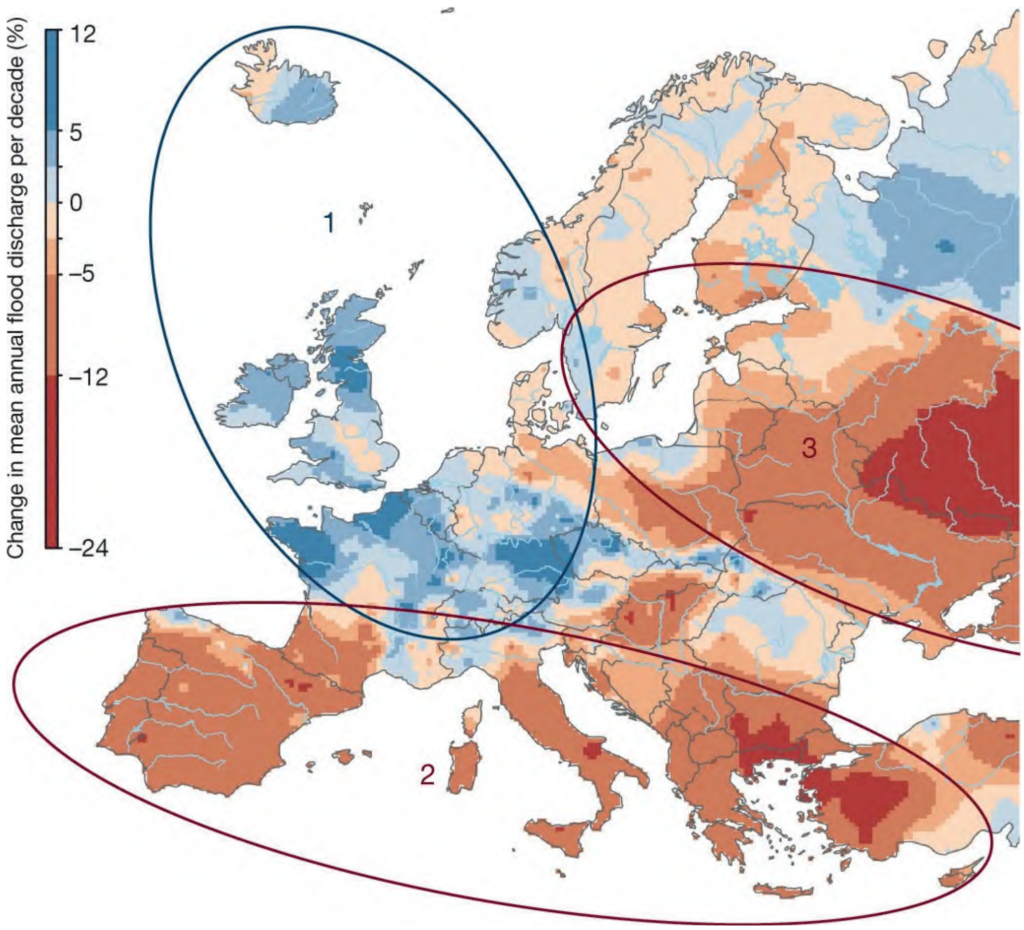


Figure 5.5 Observed trends of river flood discharges in Europe (1960–2010). Blue indicates increasing flood discharges and red indicates decreasing flood discharges (percentage change per decade of the mean annual flood discharge). 1–3 indicate regions with distinct drivers: 1, north-western Europe, increasing rainfall and soil moisture; 2, southern Europe, decreasing rainfall; 3, eastern Europe, decreasing and earlier snowmelt. Source: Reproduced from Blöschl et al. (2019) with permission from Springer Nature.

Changes in future flooding with climate change have been evaluated by several Irish studies. Meresa et al. (2021) examined the impacts of climate change on flood magnitude for four Irish catchments, using 12 models from the CMIP6 ensemble forced with three different emissions pathways. They found increased flood magnitude under each emissions scenario considered. While only using a single climate model, Steele-Dunne et al. (2008) found increases in floods at all return periods analysed in south-western catchments. Sarkar Basu et al. (2022) assessed changes in flood magnitude for the urbanised Dodder river using three regional climate model projections forced by different emissions pathways. They found that the magnitude of peak flows associated with floods of 50- and 100-year return periods increased by up to 12% and 16%, respectively, again with projected changes being greater for the late action scenario. Murphy et al. (2023) examined changes in floods with a current 20-year return period for 27 Irish catchments under Late and Middle action emissions scenarios, and found increases in flood magnitude across catchments (see Figure 5.6).

In summary, Irish research to date indicates an increase in the magnitude of fluvial flooding with climate change, particularly for the middle and end of the century. However, large ranges of change are projected, with the magnitude of increases dependent on the ensemble of climate models used, the emissions scenario considered and the hydrological model used.

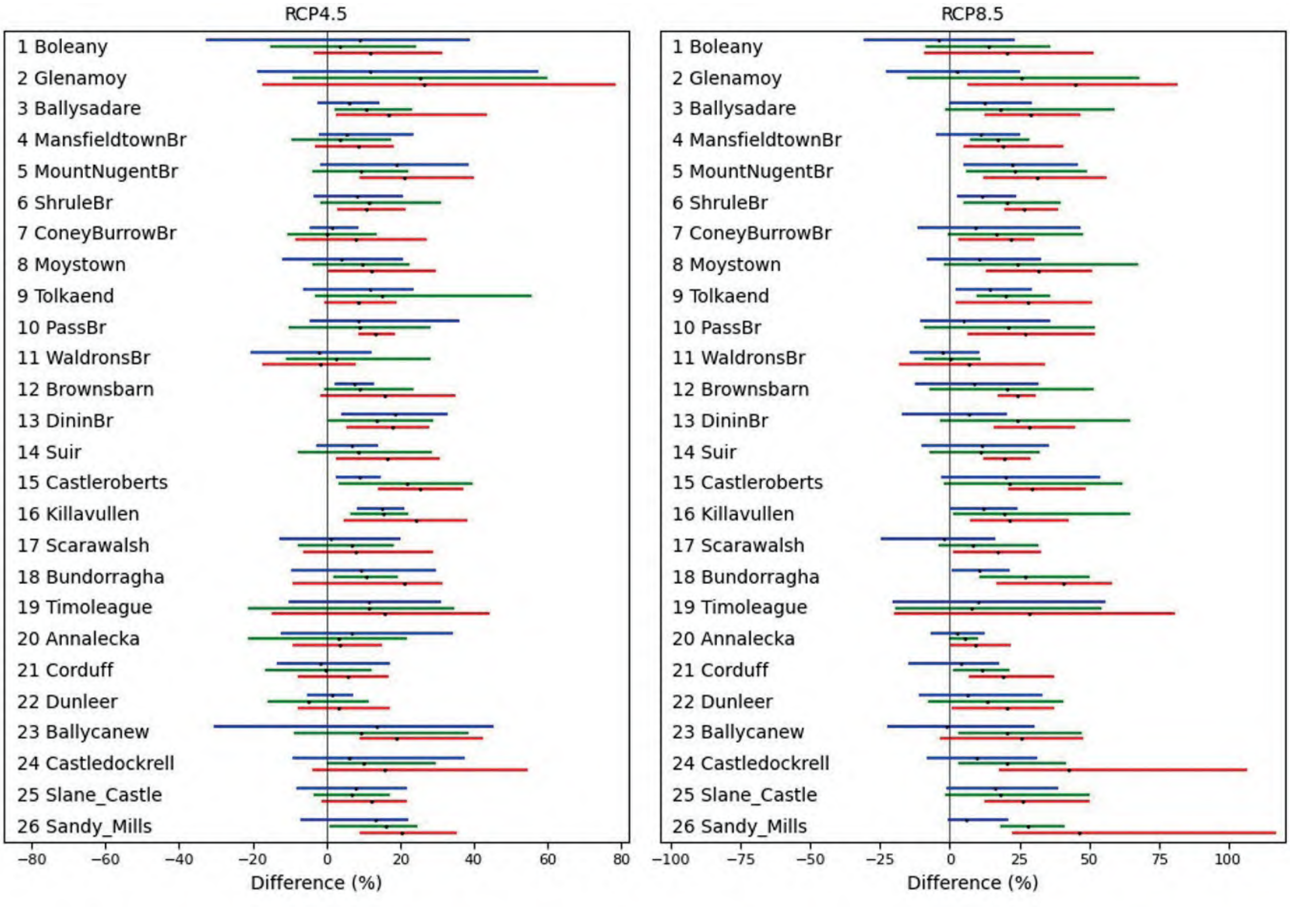


Figure 5.6 Changes in 20-year return period flows projected for 27 catchments for the 2020s (blue), 2050s (green) and 2080s (red) under RCP4.5 (left) and RCP8.5 (right). The black dots represent the ensemble mean for each catchment/period. Source: Murphy et al. (2023). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

5.2.7. Changes in drought

Droughts refer to periods of abnormally dry weather that persist for long enough to cause hydrological imbalance (Cook et al., 2018). Most droughts begin with a precipitation deficit (meteorological drought) and propagate over time into soil moisture deficits (agricultural drought) and streamflow and groundwater deficits (hydrological drought), which can lead to reductions in water supply. The distinction between different drought types is not absolute and they can occur at the same time (Brunner and Talaksen, 2019). Over time, droughts give rise to environmental and socioeconomic impacts (see Figure

5.7). Climate change can affect drought through changes in precipitation, increases in evaporative demand and changes in plant responses to evaporative demand (see section 5.2.2). Droughts can span a large range of spatial and temporal scales and can be amplified or alleviated by different biological and physical processes. Because of these complexities, droughts cannot be characterised by a single universal definition (Lloyd-Hughes, 2014) or directly measured based on a single variable (Douville et al., 2021) and are often analysed using various indices that measure severity, duration and frequency using single variables (e.g. precipitation, evapotranspiration, streamflow deficits) or indices combining different atmospheric variables (e.g. precipitation minus evapotranspiration).

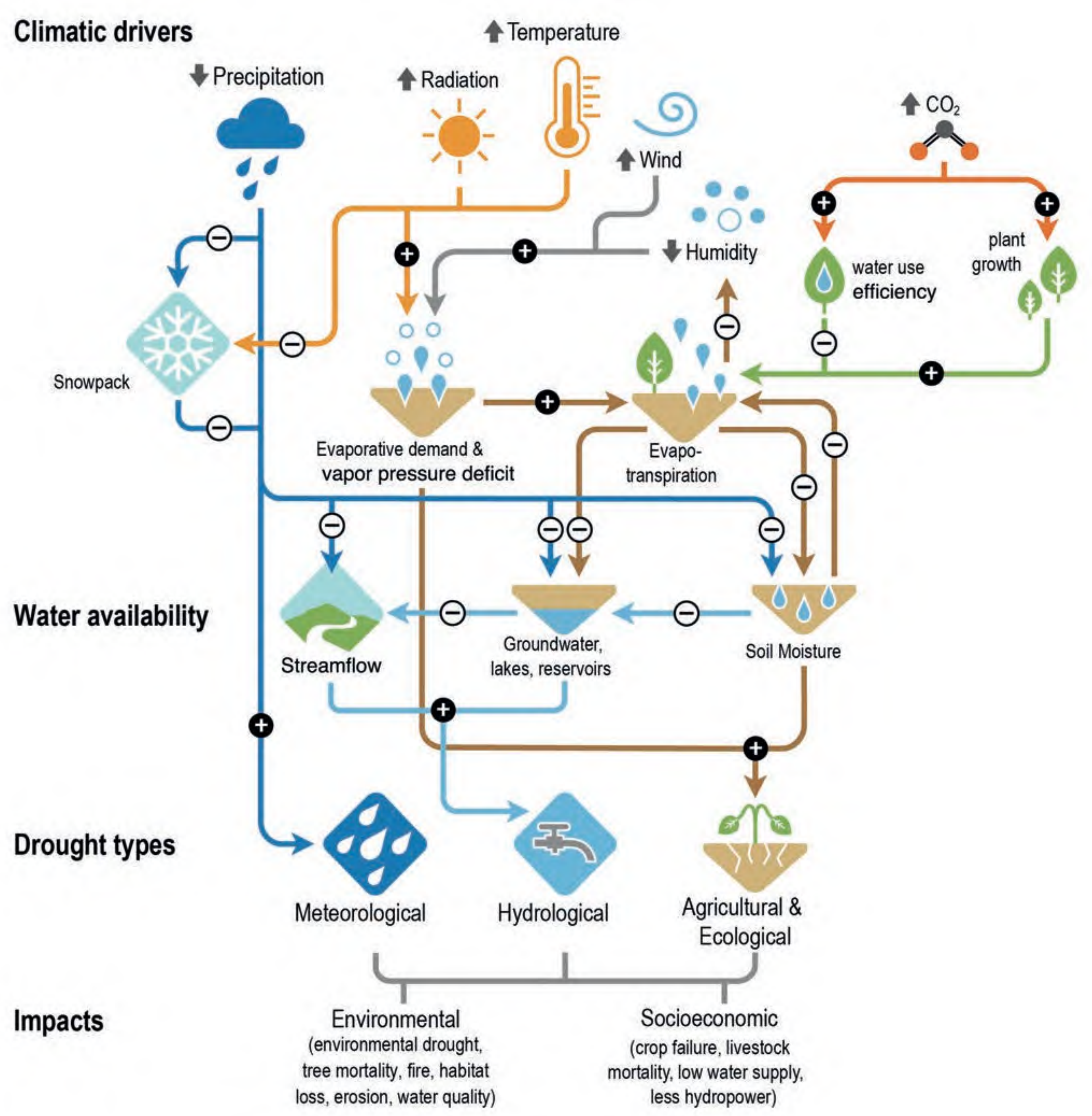


Figure 5.7 Climatic drivers of different categories of drought, effects on water availability and impacts. Plus and minus signs denote the impact that changes in climate drivers have on factors such as precipitation, evapotranspiration, soil moisture and water storage. The three main types of droughts are listed, along with some possible environmental and socioeconomic impacts of drought (bottom). Source: Caretta et al. (2022; their figure 8.6).

Droughts occur through a combination of thermodynamic and dynamic processes (Parry et al., 2023). The former relates to heat and moisture exchanges that affect temperature, radiation and AED, while the latter relate to larger-scale weather patterns that influence precipitation. There is high confidence that thermodynamic changes are the main driver of drought changes in a warming climate, with lower confidence in the effects of greenhouse gas forcing on changes in atmospheric dynamics (Seneviratne et al., 2021). Assessments of meteorological drought using the widely deployed Standardised Precipitation Index show no significant trends at the global scale (Spinoni et al., 2014, 2019), with few regional exceptions. Some regions show a decrease in meteorological drought over annual timescales, including northern Europe, with results dependent on the period analysed. In western Europe, there is no evidence of changes in hydrological droughts since the 1950s based on flow reconstructions and observations (Stahl et al., 2010; Vicente-Serrano et al., 2019). Assessment of changes in drought indices that combine precipitation deficits with evaporative losses tend to show increases in drought severity, compared with those that just consider precipitation. Given the lack of long-term observations, few studies nationally or internationally have evaluated drought changes in groundwater. Some studies suggest an increase in drought frequency and severity in groundwater droughts in northern Europe (Bloomfield et al., 2019); however, local conditions are important (see section 5.2.4).

In Ireland, Noone et al. (2017) and Murphy et al. (2020b) have developed long-term records of observed and reconstructed meteorological droughts from precipitation records. These studies show that recent decades have been relatively drought poor. Significant drought-rich episodes include the periods 1890–1910, 1921–1922, 1933–1934, the 1940s and the 1970s. Analysis of trends in meteorological droughts for western Europe from quality-assured long-term precipitation records finds that the largest trends towards increased drought magnitude were found for summer in the British and Irish Isles (Vicente-Serrano et al., 2021). However, the role of natural variability in western Europe is strong, indicating the difficulty of attributing an anthropogenic climate change signal.

O'Connor et al. (2022b) examined changes in reconstructed meteorological and hydrological droughts for Irish catchments for the period 1767–2016, finding that changes in drought characteristics reveal a complex picture with the direction, magnitude and significance of trends dependent on study design, including the definition of drought and the period of record analysed. However, of note from their findings is a tendency towards shorter, more intense meteorological and hydrological droughts, especially during summer, over the period analysed.

In terms of future drought projections, climate models show a tendency to overestimate drying in mid- to high latitudes (Knutson and Zeng, 2018; Vicente-Serrano et al., 2022). The latest generation of CMIP6 models show better performance in reproducing long-term precipitation trends, but important limitations of climate models for assessing future drought risk include a tendency to underestimate drought persistence at monthly to decadal scales in the mid-latitudes and the large spread in simulated precipitation deficits (Seneviratne et al., 2021). Moreover, uncertainties in drought projections are affected by plant physiological responses to increasing atmospheric carbon dioxide, soil moisture–atmosphere feedbacks (Ishola et al., 2023) and statistical issues related to different drought timescales (Seneviratne et al., 2021).

Nonetheless, the IPCC concludes that the likelihood of drought is projected to increase in many regions over the 21st century even with strong climate change mitigation, and more severely in the absence of this (Caretta et al., 2022). The frequency of agricultural drought is projected to increase over wider areas than that of meteorological drought (Caretta et al., 2022). The IPCC also highlights that the choice of drought definition can affect the magnitude and even the sign of the projected drought change. For example, if adaptation is tailored to agricultural (soil moisture) drought changes, projected changes in meteorological (precipitation) drought metrics may not provide the necessary information. In addition, importantly, projected changes in drought in many regions depend on the season and may not be evident in annual mean changes.

Few studies have assessed projected changes in drought for Ireland. Meresa et al. (2023) evaluated future changes in drought at the catchment scale using 12 climate models, finding increases in the frequency and magnitude of summer meteorological and hydrological drought for the six catchments analysed. Changes in the duration of drought events were unclear, with model simulations covering a wide spread. Using the Coordinated Regional Climate Downscaling Experiment (CORDEX) ensemble of 11 dynamically downscaled regional climate model projections, Meresa and Murphy (2023) evaluated changes in meteorological and agricultural drought for Ireland by the end of century under Middle (RCP4.5) and Late action (RCP8.5) scenarios. They find that increases in PET together with changing seasonal rainfall patterns (wetter winters and drier summers) increase aridity, especially in the east and Midlands, by the end of the century. Increases in drought frequency and magnitude were also found, especially for late action on emissions reductions. Critically, increases were considerably greater for the Standardised Precipitation Evapotranspiration Index than for the Standardised Precipitation Index, emphasising the importance of using metrics that capture PET in monitoring and assessing future drought risk (Figure 5.8). Summer and spring returned the greatest increase in drought magnitude and frequency, most marked in the east of the island. By contrast, multi-seasonal droughts show more modest changes in magnitude and duration (Figure 5.8).

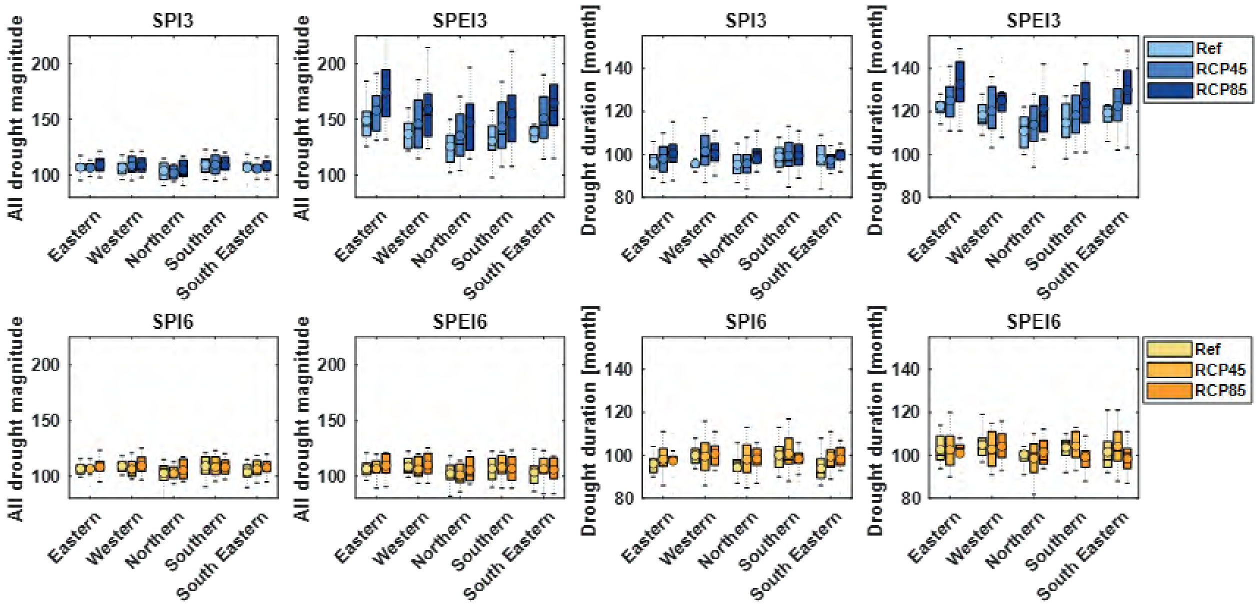


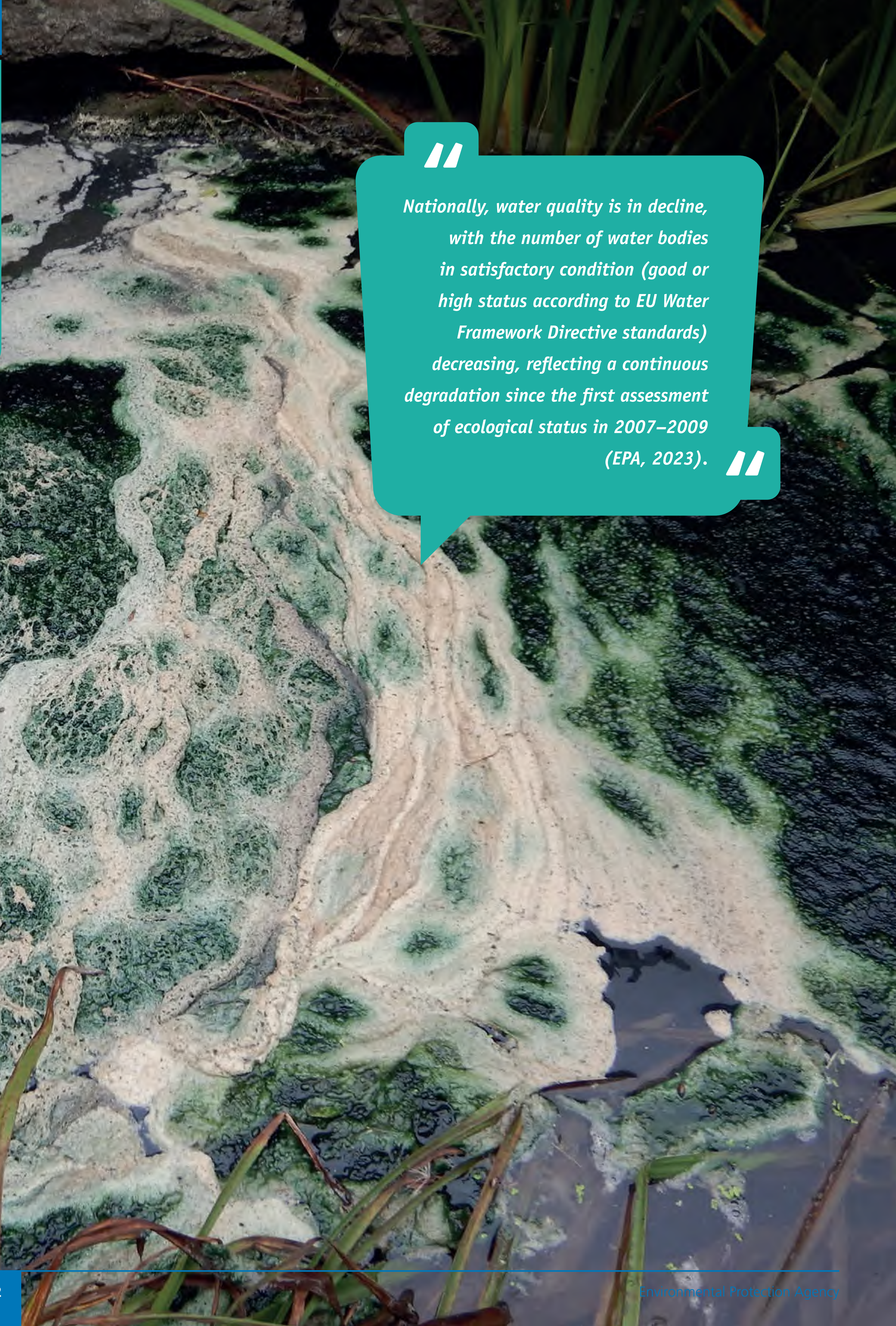
Figure 5.8 Changes in the magnitude and duration of drought events identified using the Standardised Precipitation Index/ Standardised Precipitation Evapotranspiration Index at 3- (blue) and 6-month (orange) accumulation periods for each RCP and region of Ireland for the end of century (2080s), relative to current conditions (reference). Each box shows the interquartile range simulated from 11 CORDEX ensemble members for that region. The circles indicate the ensemble mean, and the horizontal line the median. Source: Meresa and Murphy (2023). **Reproduction licensed under the Creative Commons Attribution CC BY-NC-ND 4.0 licence (https://creativecommons.org/licenses/by-nc-nd/4.0/).**

5.2.8. Changes in water quality

Nationally, water quality is in decline, with the number of water bodies in satisfactory condition (good or high status according to EU Water Framework Directive standards) decreasing, reflecting a continuous degradation since the first assessment of ecological status in 2007–2009 (EPA, 2023). Declines in quality are evident for all water body types (rivers, lakes, groundwater, estuaries and coastal waters). Key drivers of this decline in water quality are (1) increases in nutrient, sediment and pesticide runoff from agricultural land, farmyards and forestry activities, (2) land drainage, navigational dredging and the presence of barriers such as dams, weirs or culverts in water courses that damage physical habitats and ecology, disrupt natural flow and create migration barriers to critical fish species, and (3) discharge of poorly treated sewage from urban wastewater treatment plants, domestic treatment systems and storm water overflows in urban areas that have led to increased organic pollution and large declines in dissolved oxygen, affecting microinvertebrates and inducing fish kills (EPA, 2023).

Most freshwaters are affected by multiple stressors, leading to impacts that are sometimes greater than the sum of the individual stressors and often generating unpredictable outcomes (Beermann et al., 2018). Therefore, water quality in Ireland is highly sensitive to climate change. Water quality can be impacted by climatic factors such as air and water temperature, precipitation amounts and intensity, and the occurrence of extreme events. Changes in water quality during storms, heatwaves and droughts can cause conditions that exceed thresholds for ecosystem tolerance and lead to degraded water quality. Future changes in water quality should therefore be considered in the context of changes in temperature, precipitation and flow regimes (Whitehead et al., 2009). Changes in rainfall amounts, timings and intensities have implications for nutrient washout, erosion, suspended sediment and sediment yields, with sensitivity varying by catchment. Climate change impacts on water quality in urban areas are also dependent on design standards of critical infrastructure.

Increases in air temperature are closely associated with increases in water temperature, biological oxygen demand and suspended solids, and decreases in dissolved oxygen. Warming is also known to accelerate nutrient cycling (Kundzewicz and Krysanova, 2010). Climate change can impact water quality through physical, chemical and biological changes brought about by changes in water temperature, turbidity, pH, pollutant concentrations, and aquatic biodiversity and species abundance.



"Nationally, water quality is in decline, with the number of water bodies in satisfactory condition (good or high status according to EU Water Framework Directive standards) decreasing, reflecting a continuous degradation since the first assessment of ecological status in 2007–2009 (EPA, 2023)."

Delpla et al. (2009) highlight that dissolved organic matter, micropollutants and pathogens may increase in concentration because of temperature increases (in air, water and soil) and heavy rainfall events. Changes in the magnitude and duration of droughts, rainfall and temperature are known to affect stream pH through higher maximum values and increases in average pH. Increased flooding can exacerbate contaminant transport to water bodies from both floodplains and overland flows and from overloading of urban storm drainage (Vorobevskii et al., 2020) and wastewater treatment systems (Hughes et al., 2021). The projected increase in surface water temperatures combined with increased pollutant loading from agricultural land could increase the presence of algal blooms in rivers and lakes (Coffey et al., 2019; Paul et al., 2019). More extreme summer low flows are also likely to decrease the amount of water available for dilution of pollutants during sensitive times of the year for aquatic ecosystems. This is particularly important for point source pollutants from industry, agriculture (e.g. farmyards) and urban locations.

Climate change is also likely to alter the delivery of dissolved organic matter (Creed et al., 2018), and in combination with nutrient, sediment and other pollutants may impact the delivery and quality of essential ecosystem services. Elevated levels of dissolved organic carbon (DOC) have the potential to impact human health and the costs of drinking water treatment (Whitehead et al., 2009) and are susceptible to higher concentrations due to extreme rainfall events (Delpla et al., 2009), particularly in peat-dominated catchments. Elevated DOC levels can also affect the mobility of contaminants and toxic compounds, in addition to increased problems of microbial growth. Climate change is likely to increase DOC levels in surface waters (Naden et al., 2010; de Wit et al., 2016).

Numerous Irish studies have highlighted the sensitivity of water quality to climatic drivers. Coffey et al. (2016) examined the sensitivity of water quality to climate and land use change for the Black and Fergus rivers in western Ireland, finding that future changes in microbial load typically followed changes in precipitation and streamflow. Increases in the frequency and intensity of winter precipitation was found to impact significantly on microbial transport, representing increased risk to water quality. They also found that future changes in land use/management may be as important as changes in climate for water quality, highlighting land use management as a critical adaptation pathway over the coming decades. Ryder et al. (2014) found that variation in DOC for a forested peat catchment in Ireland was largely determined by variations in soil temperature, river discharge and rainfall. For the Boyne catchment in the east of Ireland, O'Driscoll et al. (2018) found that years with higher precipitation showed greater DOC export, with lowest values typical after dryer summer periods. However, considering future climate change projections, they found moderate impacts of climate change on total DOC load, with changes in extreme precipitation being the main driver of change. They also highlight the interaction of climate and land use change as a driver of DOC pressures in Irish surface waters.

Agricultural intensification and climate change present challenges for achieving desired water quality standards in Ireland, particularly in relation to diffuse contamination from phosphorous and nitrogen pollution. Temperature and precipitation are important variables for nutrient mobilisation and transfer to water courses. Large winter rainfall events, when soils are already saturated, are likely to cause surface runoff events that cause loss of phosphorous stores (Haygarth et al., 2005). Increased soil temperatures and drought conditions have been linked to increased mineralisation rates (Morecroft et al., 2000). Rainfall events following prolonged dry periods are likely to increase leaching and transfer of nitrogen stores to water courses (Mosley, 2015). Summer droughts can lead to a build-up of soil nitrogen due to limited grass growth and reduced nitrogen uptake, enhanced mineralisation and nitrification rates, and in certain situations the application of additional nitrogen-based fertilisers to encourage growth. Moreover, soil cracking during drought conditions can result in the development of preferential flow paths, increasing the efficiency of nitrogen transport during subsequent rains.

Mellander and Jordan (2021) show that nutrient concentrations in agricultural catchments are influenced by natural climate variability, particularly the NAO, while extreme weather events can induce pollution episodes and nutrient fluxes that can exceed annual average rates in just a few days. These observed changes illustrate the risks to water quality posed by climate change. Winter storms in the Ballycanew catchment (Wexford) were shown to be the key driver of long-term phosphorous increases (Mellander and Jordan, 2021). Summer drought in 2018 was also shown to increase nitrogen losses in the catchment, well above regulatory standards, because of the build-up of the catchment nitrogen pool during the drought and its mobilisation at drought termination (Mellander and Jordan, 2021). Notably, the study also raises the possibility of pollutant risk switching during extreme weather, whereby a catchment predominantly affected by phosphorous losses can switch to becoming at risk of nitrogen losses. Critically, Mellander and Jordan (2021) highlight that the links between climate and water quality heavily depend on catchment characteristics (e.g. soil types), land management and cropping patterns, with catchments responding differently to climate variability and change and extreme events, highlighting the importance of additional investment in monitoring and modelling to better understand climate change impacts on water quality.

5.2.9. Lakes

Critical to ecology, biodiversity, water supply and tourism, lakes are an important component of Irish hydrology in the context of climate change. Irish lakes tend to be relatively shallow for their surface area, with the deepest lakes located in upland regions to the south and west and along the Shannon. Temperature is a fundamental lake property that can influence mixing patterns, phenology and the structure of biotic communities (Woolway and Merchant, 2019). Summer surface temperatures of lakes have increased progressively over the past 40 years. George et al. (2010) examined the impact of climate change on lakes in Britain and Ireland, with a focus predominantly on relatively deep lakes that become stratified during summer. They highlight that in winter lake surface temperature is closely correlated with air temperature, with the relationship influenced by site-specific factors such as depth and wind exposure. Therefore, with warming air temperatures, lake surface temperatures are also likely to increase, with the largest increases likely for shallow lakes with short residence times. Deep lakes with longer residence times tend to show less warming (George et al., 2010).

Recent research examined the impact of weather extremes, including heatwaves, droughts and storms, on lakes (Jeppesen et al., 2021). Woolway et al. (2020) examined the impact of the 2018 heatwave on lake surface water temperature across Europe, demonstrating that maximum lake water temperatures were 2.4°C warmer than average during the event. This large impact was found to be driven by increases in air temperature and solar radiation and a decrease in wind speeds. Heatwaves can affect lake thermal and oxygen dynamics, changes in phytoplankton communities and the frequency of cyanobacteria blooms, in addition to greenhouse gas emissions from lakes. Lake heatwaves are expected to become more intense and longer lasting over the coming century. However, the extent and nature of impacts were found to depend on the timing of extremes and lake and catchment characteristics. Jeppesen et al. (2021) highlight that storms can impact lakes by decreasing light availability, depressing surface temperatures, increasing mixing and deepening the lake thermocline. Increases in extreme rainfall and river flows can increase lake levels and decrease lake stability, with lakes with shorter residence times being more sensitive. In addition, flood waters typically contain high loads of particulate matter, sediments and dissolved substances, with increased turbidity. In summer, floods can cause an influx of colder waters. Catchment droughts can also increase exports of dissolved organic matter and sediment to lakes, affecting important biogeochemistry processes.

Quantifying the impact of extremes and longer-term climate change on lakes requires intensive monitoring and modelling. While current generation models can capture the impacts of increased temperature on lake stratification, the response of lake biogeochemistry can be complex and dependent on the nature of the surrounding catchment, interaction between species and antecedent conditions within lakes, resulting in a large degree of uncertainty. Increased monitoring is critical to developing improved process understanding for individual lakes, particularly given the risk of tipping points in such complex systems, especially in shallower lakes with short residence times, as is the case in Ireland.

5.3. Risks and vulnerabilities from changes in the hydrological cycle

Changes in the hydrological cycle present challenges for water management. In this section we evaluate current and future vulnerabilities and risks for water resource and flood risk management.

5.3.1. Water resources management

Drinking water in Ireland is derived from public supplies, overseen by Irish Water (now known as Uisce Éireann); privately sourced group water schemes; publicly sourced group water schemes, in which networks are developed by community groups and treated water provided by Irish Water; private wells in areas with no piped supply; and small private supplies (Rolston and Linnane, 2020). Approximately 80% of Ireland's public water supply is abstracted from surface waters, and despite significant resource investment more than half of surface waters are in unsatisfactory condition in terms of water quality (EPA, 2023). Moreover, group water schemes provide treated drinking water to c. 69,000 rural households in Ireland, typically from abstraction points in small catchments with contributing areas of between 5km^2 and 100km^2 that are often highly vulnerable to extreme events and deteriorating water quality (Rolston and Linnane, 2020).

Public water supplies are abstracted from approximately 1,090 individual sources and treated in 749 WTPs, with the size and capacity of plant varying significantly across the country. The 72 largest WTPs produce 73% of the water supplied, with the smallest 500 producing on average about 6% of the total supply (Irish Water, 2021a). The WTPs feed water into supply areas known as water resources zones. There are 539 water resources zones in Ireland, serving populations ranging from fewer than 30 people up to 1.7 million people (Greater Dublin Area). Due to long-term underinvestment in water services, many water supply assets need upgrading, or additional infrastructure is required to meet existing demand and/or environmental requirements (Irish Water, 2021a). Many water resources zones rely on a single source of supply, increasing vulnerability to supply interruptions, and/or abstract from small local rivers, increasing risks from drought and reduced water quality.

Rapid growth in some areas, coupled with underinvestment, has meant that some WTPs are undersized and treat water in quantities that exceed the original design capacity of these facilities.

The performance of Irish water distribution networks does not meet European norms, and leakage and distribution losses are unacceptably high, primarily due to the age of the water mains infrastructure in Ireland (Irish Water, 2021a). These challenges mean that public water supplies have a low level of service (LoS) or reliability of supply compared with international norms under present-day conditions. Figure 5.9 shows the LoS for each water resource zone with expected failure rates, whereby for an LoS of 1 in 30 a user would expect to experience a water outage or severe limitation of supply on average once in every 30 years. It should be noted that these LoS standards are conservative and are calculated for a normal year rather than for a dry year, where the LoS would be expected to be lower.

On top of considerable existing challenges, public water supplies face considerable future pressures, even in the absence of climate change. The population is expected to increase by 21% or 1.2 million people over the next 25 years, increasing water demand. Project Ireland 2040 (DHPLG, 2018) estimates that at least 50% of future population growth will be focused in the five cities of Dublin, Cork, Galway, Limerick and Waterford and their suburbs. Continued intensification of agriculture is likely to amplify the already concerning decline in water quality nationally, while increases in irrigation water demand may be expected from agriculture (see Chapter 3). Water quality pressures are likely to be further increased through emerging contaminants and higher quality/supply standards required under the EU Drinking Water Directive. In addition, forthcoming abstraction legislation, required to ensure that Ireland can meet its obligations under the Water Framework Directive, may reduce the amount of water that can be abstracted from individual sources in the future.

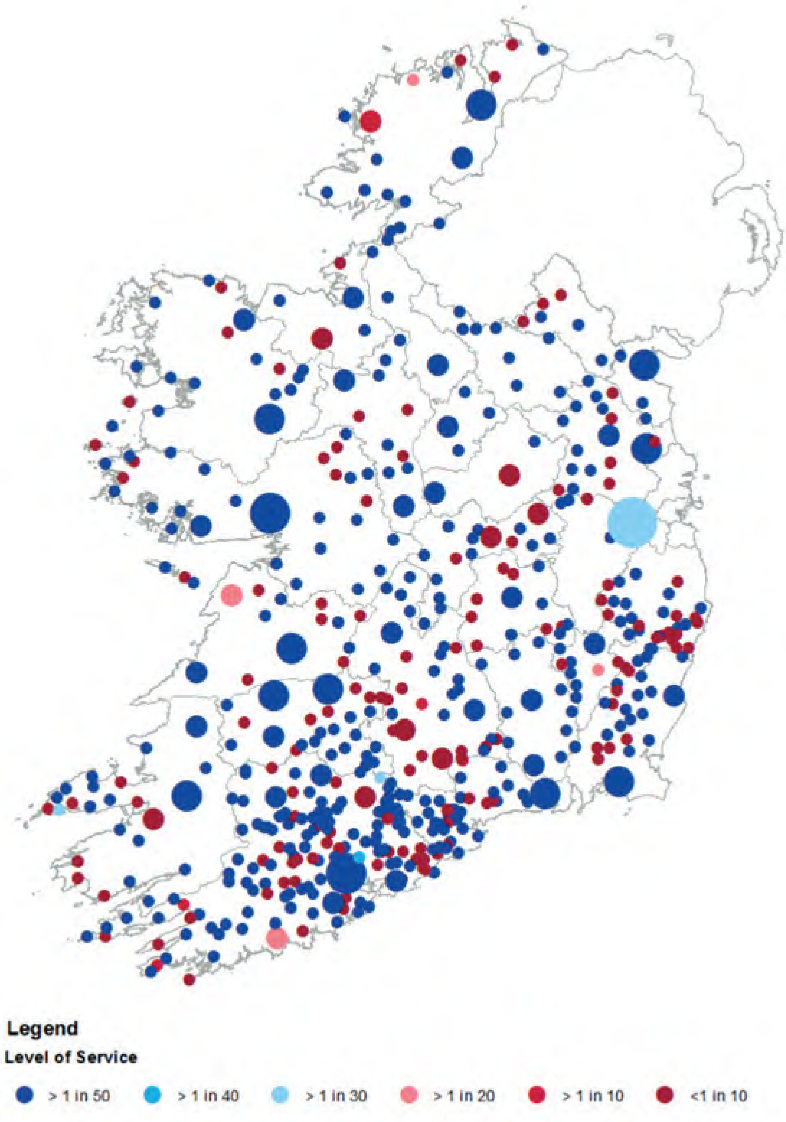


Figure 5.9 LoS for water resource zones in Ireland for a normal year. Source: Irish Water (2021a).

As part of the sectoral adaptation plan, key impacts and consequences for water resource management were identified and are summarised in Table 5.1 for water quality and water service infrastructure. The potential for cascading impacts from water services to public health (see Chapter 9) and environmental consequences is evident.

Table 5.1 *Climate change impact matrix for the water quality and water services infrastructure sectors presented in the Water Quality and Water Services Infrastructure – Climate Change Sectoral Adaptation Plan*

Impact chain/sectoral consequences	Public health	Environmental	Security of supply	Asset damage/loss	Service provision	Business continuity
Water quality						
Increased surface and sewer flooding leading to mobilisation of pollutants	✓	✓			✓	
Reduced dilution of contaminants	✓	✓			✓	
Spread of/increased viability of pathogens	✓	✓			✓	
Changes in species distribution and phenology		✓		✓	✓	
Drying of peatland	✓	✓			✓	
Water service infrastructure						
Hot weather-related changes in demand (e.g. higher daily and peak demand)		✓	✓		✓	
More frequent water/wastewater asset flooding, asset loss and potential for environmental pollution (high precipitation)	✓	✓		✓	✓	✓
Increased drawdown in autumn/winter for flood capacity, leading to resource issues in the following spring/summer			✓		✓	
Reduced availability of water resources (surface water and groundwater)	✓	✓	✓		✓	
More frequent water/wastewater asset flooding, asset loss and potential for environmental pollution (increased storminess)		✓		✓	✓	✓
Business continuity impacts/interruptions					✓	✓

Source: DHLGH (2019).

As part of the development of Ireland's first National Water Resources Plan (for Irish water assets only), Irish Water has derived estimates of future water available for use (WAFU) by considering how climate change may affect the hydrological yield of water supply sources and using seasonal climate change factors. Presently, for a normal year, the maximum WAFU is 1,723Ml (million litres) per day nationally. This will increase in the short term to 1,751Ml per day from delivery of projects to increase WAFU during Irish Water's current investment cycle. By 2044, however, the maximum WAFU may be reduced back to 1,725Ml per day, due to the impacts of climate change. For a dry year (dry year annual average), the maximum WAFU is 1,631Ml per day, rising to 1,654Ml per day in 2023. This reduces to 1,622Ml per day by 2044 with climate change. The WAFU is less in a dry year than in a normal year, as dry weather conditions reduce the amount of raw water (hydrological yield) that can be abstracted. It should be borne in mind that these are annual assessments and may necessitate increased storage of water to balance the impacts of wetter winters and drier summers. In addition, climate change allowances were derived from nine catchments using climate impact assessments conducted in 2008. It is critical that assessments of future WAFU are updated using contemporary climate change projections. Assessments of WAFU for dry years are also based on the 2018 drought year. While drought conditions in 2018 stressed water resources, that drought has been frequently surpassed in terms of magnitude and duration according to the long-term records (Noone et al., 2017).

Even for public water supplies, most research has focused on climate change impacts on catchment hydrology, with only limited publicly available research focusing on water management and the evaluation of adaptation options to build resilience in the sector. Depending on the characteristics of water supply systems, the same change in climate can have different effects. For example, a resilient water supply system can be thought of as one with large available headroom: the difference between WAFU and peak demand (Dessai and Hume, 2007). In such cases, the system has a high degree of resistance, and even a large change in inputs of raw water through changes in rainfall, or an increase in demand through warmer temperatures, will have little effect on the system. In contrast, in a system that is precarious and operating towards the limits of its capacity, with little available headroom, even a small change in climate or a relatively modest extreme event can push it past a critical threshold and result in failure of the supply system. During the heatwave conditions in 2018, national average water demand increased within 10 days by 15% from 1,650Ml per day to 1,900Ml per day, resulting in high water stress across multiple water supply networks (Irish Water, 2021a).

5.3.2. Flood risk management

Ireland is affected by a range of different types of flooding, the most significant being fluvial (river), coastal (see Chapter 4), groundwater and pluvial flooding. The most recent national risk assessment by the Office of Emergency Planning identifies flooding as a significant risk facing Ireland today. Recent flood events such, as winter 2015/2016, have shown the extent of risks and vulnerabilities nationally. Current flood risk management practice is coordinated by the OPW and focuses on prevention (through avoiding flood-sensitive development in high-risk areas), protection (through flood relief schemes and maintenance of arterial drainage schemes) and preparedness (though the development of non-structural measures, including public awareness, flood warning and emergency response). Climate change adaptation is integrated into prevention in The Planning System and Flood Risk Management: Guidelines for Planning Authorities (OPW, 2009), which provides guidance on land use zoning based on existing risk but with a recommendation that a precautionary approach be taken to potential future risk given the impacts of climate change on floods. The inclusion of climate change measures in the design and construction of flood relief schemes has been considered since 2009. Notably, with increases in flood magnitude, the standard of protection offered by flood relief schemes will reduce over time as the impacts of climate change unfold. Arterial drainage schemes were implemented to improve land drainage and agricultural productivity. Little is known about the impact of climate change on the effectiveness of these schemes, nor on how arterial drainage is likely to modify or amplify the impacts of climate change, for both floods and droughts/low flows. Harrigan et al. (2014) show how arterial drainage in the Boyne catchment served to amplify high flows associated with a shift to a more positive NAO in the late 1970s; however, beyond the study, there is a general lack of understanding on the interaction of arterial drainage works with climate change. On preparedness, the establishment of Met Éireann's National Flood Forecasting Service is an important resource to help improve all aspects of community and emergency resilience and response.

Detailed assessment of the potential impacts of climate change on flood risk nationally have been undertaken through the Catchment Flood Risk Assessment and Management (CFRAM) programme conducted by the OPW. This work adopted two representative climate futures, a mid-range future scenario (MRFS) and high-end future scenario (HEFS) (see Table 5.2), as plausible future storylines to evaluate flood risk for 300 high-risk locations across Ireland that are home to over 3 million people. Results from this national assessment show clearly that, without significant ongoing and future investment in flood risk reduction, the impacts of climate change would result in very significant increases in flood damages. For relatively frequent flood events (those with 10% or a 1 in 10 chance of occurring or being exceeded in any given year), the number of properties at risk of flooding would increase significantly, with a commensurate rise in potential damages. For rarer flood events (those with a 1% or 1 in 100 chance of occurring or being exceeded in any given year), the number of properties at risk also increases significantly. On the whole, the number of properties that could become at risk of flooding under the MRFS doubles for fluvial (river) flooding and quadruples for coastal flooding. However, the impact of climate change on both the hazard and risk is site specific and varies from community to community, with no clear geographical trends. Furthermore, the intensification of development in urban areas and increases in the value of properties and their contents can further increase potential future damages due to climate change.

Table 5.2 *OPW allowances in flood parameters for the MRFS and HEFS*

Parameter	MRFS	HEFS
Extreme rainfall depths	+20%	+30%
Peak flood flows	+20%	+30%
Mean sea level rise	+500mm	+1,000mm
Land movement[a]	$-0.5\,\mathrm{mmyr}^{-1}$	$-0.5\,\mathrm{mmyr}^{-1}$
Urbanisation	No general allowance – review on case-by-case basis	No general allowance – review on case-by-case basis
Afforestation	–1/6 Tp[b]	–1/3 Tp[b] +10% SPR[c]

[a]Applicable to the southern part of the country only (Dublin–Galway and south of this).

[b]Reduction in the time to peak (Tp) to allow for potential accelerated runoff that may arise as a result of drainage of afforested land.

[c]Add 10% to the standard percentage runoff (SPR) rate; this allows for temporarily increased runoff rates that may arise following felling of forestry.

Source: OPW (2019).

5.4. Adaptation responses

5.4.1. Adaptation options for water resource management

The Water Quality and Water Services Infrastructure – Climate Change Sectoral Adaptation Plan (DHLGH, 2019) identifies categories of adaptation options for water quality and water services infrastructure. These are organised into 15 categories of measures (Table 5.3) and range from operational and strategic actions to ongoing monitoring and research to develop adaptive capacity. Links are evident between water quality, water supply and biodiversity.

Table 5.3 *Overview of categories of adaptation measures identified in the Water Quality and Water Services Infrastructure – Climate Change Sectoral Adaptation Plan*

Adaptive measure	Summary
Asset management	Includes coordinated and optimised planning, asset selection, asset acquisition/development, asset utilisation, asset maintenance, asset life extension and asset decommissioning/renewal
Biosecurity measures	Measures cover steps to make sure that good hygiene practices are in place to reduce and minimise the risk of spreading invasive non-native species
Business continuity planning	Planning to mitigate risks to the normal operation of a business/organisation
Communication	Outreach to citizens, customers (household and industrial) and owners and operators of private schemes and private operators. This includes warnings, (local-level) awareness raising and behavioural change campaigning as part of demand management, as well as information and messaging as part of normal business operation
Ecosystem and habitat restoration	Restoration of degraded ecosystems helps improve freshwater water quality and catchment hydrology
Flood risk assessment and defences	The undertaking of studies to quantify flood risk to inform the requirement for and design of flood defences. 'Flood defences' refers to the infrastructure in place to reduce the extent, severity and duration of flooding. This can include hard engineering solutions (e.g. flood walls) or more nature-based approaches (e.g. using leaky dams to slow the flow of water in headwaters). This also includes flood risk assessments, to inform the requirement for and design of defences
Improved aeration and circulation	Mechanical aeration or changes to circulation of a water body, not wastewater treatment asset, predominantly to reduce stratification and improve water quality
Improved water/wastewater treatment	Infrastructure new builds, upgrades or other improvements to increase the effectiveness and level of treatment of both raw water and wastewater and to reduce the impact of such on the environment and public health
Integrated catchment management	Integrated catchment management (ICM) measures may be implemented at the scale of a whole catchment or may be more localised, for example actions taken by one landowner. ICM includes consideration of other interacting sectors that are likely to be involved in catchment-based measures, such as agriculture and forestry
Monitoring and research	Implementation of a programme of monitoring to understand the performance of a system (e.g. in-river water quality). This may also include numerical modelling to predict impacts. The focus of this research should be on water sector-related research to enhance the adaptive capacity of the sector and reduce uncertainty to inform decisions of key stakeholders
Operational and maintenance improvements	Improvements to operation and maintenance programmes (risk based), for example increased maintenance frequency or storage of increased quantities of chemicals for wastewater treatment
Drought planning	A plan setting out the actions water service providers will take during a drought to maintain public water supply, including temporary restrictions on water use, leakage control, drought permit applications and publicity campaigns encouraging water conservation

Adaptive measure	Summary
Asset upgrades	Improvements to water and wastewater infrastructure (capital expenditure only), for example an increase in pipe diameter or improved design standards to inform upgrades. This also includes local-/private asset-level measures
Water resource planning	Long-term and strategic planning involving all relevant stakeholders to ensure that the long-term balance between water supply and demand is maintained. This includes demand management and supply-side options
Water and wastewater network improvements	Improvements to raw water mains and sewerage networks, for example to increase the capacity or resilience to leakage/bursts

Source: Adapted from DHLGH (2019).

In broad terms, options to adapt water supply to climate change can be categorised into demand- and supply-side options (Arnell and Delaney, 2006). However, limits to adaptation are often set by technical feasibility, cost, social acceptability and environmental trade-offs. Supply-side options aim to augment supplies and include developing new or enhanced reservoirs, aimed at storing water collected during wetter times of the year and distributing during drier periods. Increasing abstractions from existing sources or developing new abstraction points from surface or groundwater are also aimed at increasing supply, as are bulk water transfers from one water resource zone to another. However, such options often have high costs and large trade-offs for ecosystems and local communities. Other supply-side options include improvements to supply network linkages to increase resilience during drought or periods of peak demand, and improvements to water treatment and distribution capacity. Demand-side options include leakage reduction, adoption of more water-efficient equipment and fittings in buildings, greater conservation efforts among water users, including the public, use of tariffs to promote conservation, water use and recycling, and rainwater harvesting.

Integrated catchment management is key to the development of sustainable and acceptable adaptation in the water sector, offering benefits and opportunities for multiple stakeholders and situating adaptation in this sector within the goals of the EU Water Framework Directive. This is particularly important given the deterioration of water quality in Ireland over recent decades. Integrated catchment management views the catchment system as the basic unit of analysis and governance in relation to water management. It involves building partnerships, creating and developing a vision of outcomes, characterising and understanding pressures and risks within the catchment, collaboratively identifying and evaluating possible management strategies, and designing and implementing measures to address them, and implementing, monitoring and evaluating outcomes, and making adjustments if necessary (Daly, 2013; Daly et al., 2016). This overarching framework has much in common with the development of robust adaptation solutions and adaptation pathways in the climate adaptation literature, bringing opportunities to widen the solution space to include nature-based approaches (see below) and important stakeholders, such as group water schemes and members of the public. However, consideration needs to be given to the different timelines and policy cycles of sectoral and local adaptation plans and wider directives such as the Water Framework Directive, together with the 25-year planning horizon of the National Water Resources Plan.

The assessment of climate change risks and adaptation in the sectoral water plan is based on qualitative risk profiling and the development of impact chains identified based on expert judgement and stakeholder workshops. While valuable at a high level for risk screening, additional work is necessary to evaluate the sensitivity to and risks posed by climate change to water resources zones and critical infrastructure. For example, what would the consequences be for water supply in the Greater Dublin Area should a drought of similar magnitude to historically extreme droughts recur? (Wilby and Murphy, 2018). While there is a large portfolio of potential adaptation actions available within the water sector, quantitative evaluation of the effectiveness of different actions and the development of adaptation pathways to assess how to combine them (see also section 10.6) need to be prioritised.

In one of the few studies to assess adaptation options for water supply systems, Hall and Murphy (2011) evaluated the effectiveness of adaptation options, including leakage reduction, to reduce water stress under a wide range of future climate change projections. For the abstraction points assessed, they found that, while leakage reduction serves to reduce the occurrence of water stress in future, additional adaptation options would need to be considered. Research that examines adaptation options in the context of existing water systems would serve to reveal vulnerabilities and move analysis towards the evaluation of adaptation actions. In addition, little research has examined how water demand in Ireland is likely to increase with climate change, particularly under drought conditions, with learning from past drought events and drought management in other jurisdictions important for better drought management (Jobbová et al., 2023a).

5.4.2. Adaptation options for flood risk management

Wilby and Keenan (2012) conducted an international review of enabling conditions and specific measures implemented to adapt to flood risk in the international policy and research literature. Development of enabling conditions and adaptive capacity can be strengthened through collection of information such as baseline data, assessment of existing risk, scenarios of long-term drivers of risk and greater understanding and mapping of vulnerability (including gender, social groups, etc.). In Ireland, the OPW, the lead agency responsible for flood risk management, has been approaching these issues through national programmes such as CFRAM (see section 5.3.2), the maintenance of a national hydrometric monitoring network and the development of key storylines of climate change for informing future assessment of climate change risks for flooding (see Table 5.2).

At the institutional level, enabling conditions can be strengthened through cross-sectoral planning and cooperation, information exchange, the development and implementation of planning guidelines to avoid exposure of people and assets in high-risk locations, public participation in decision making and the implementation of adaptive management strategies (Wilby and Keenan, 2012). The private sector, particularly insurance, can play a key role in building capacity to adapt to climate change. Enabling conditions for preparedness include continuous improvement of emergency response, including before, during and after events, and closer integration of disaster risk management and climate adaptation (Medway et al., 2022). Enhancing preparedness can extend beyond government agencies to include contingency planning at the household level and communication of roles and responsibilities for actions during flood emergencies. Research in Ireland has shown that, without clear agreements on the roles and responsibilities between government agencies and households in emergency events, perceptions of fairness, or a lack thereof, in terms of outcomes can reduce the willingness of individuals to adapt to future floods (Adger et al., 2013).

Implementation of adaptation actions for flood risk can be categorised into three broad approaches: defending against risks through engineered or hard infrastructure, living with risk and relocation or withdrawing from risk (Figure 5.10). For defending against risk, actions include repairing or retro-fitting existing infrastructure, building new infrastructure and integrating safety margins to accommodate climate change into designs. In these instances, it is important that such critical infrastructure is 'stress tested' against the range of plausible future changes in climate. For Ireland, Broderick et al. (2019) evaluated the OPW allowances for fluvial flooding in the design of flood relief schemes (Table 5.2) against the range of changes in flooding in 215 catchments, as simulated by a large ensemble of climate models. They found that a 20% allowance for climate change, as determined by the OPW's MRFS, accommodates between 48% and 98% of uncertainty in future flooding, depending on the catchment analysed. The study also highlights the type of catchments for which safety margins greater than the MRFS may be required. Aside from technical design issues, implementing engineering approaches to defend against the risk may encounter limits to adaptation because of social acceptability or unacceptable trade-offs. Clarke et al. (2018) detail how issues of social acceptance have hampered adaptation in Clontarf, Dublin, and highlight the importance of integration of local perspectives and knowledge to ensure procedural justice in developing adaptation interventions. Jeffers (2019) highlight similar challenges for flood relief schemes in Cork city. Historically, arterial drainage has been widely deployed for flood risk management. However, given environmental impacts and trade-offs for other sectors, including biodiversity, arterial drainage could be considered as maladaptation (see Chapter 1) (Kelly et al., 2021). Furthermore, arterial drainage schemes, through changes in rainfall runoff responses, may interact with changes in rainfall to amplify increases in river discharge (e.g. Harrigan et al., 2014). Recently, the potential for nature-based approaches (see below) to help defend against the risk of flooding has been increasingly recognised, with potential win–wins for adaptation across other sectors.

Adaptation actions that prioritise living with risk include land use planning and flood zoning, insurance, integration of green spaces into urban areas sensitive to pluvial flooding, deployment of nature-based approaches aimed at slowing the flow and moderating flood risk downstream, and allowing certain areas to flood, recognising the important role of flood plains in attenuating floods and reducing damage potential downstream. An important component of living with risk is the operationalisation of flood warning systems to assist preparation for floods to reduce adverse impacts and losses. Ireland still does not have a national-scale flood warning system, but progress is being made between Met Éireann and OPW (among other stakeholders) in the development and deployment of such a service. There is much room for innovation and scaling up of living-with-risk approaches in Ireland, with historical emphasis placed on defending against the risk. However, this is changing, as outlined in the flood risk sectoral adaptation plan (OPW, 2019).

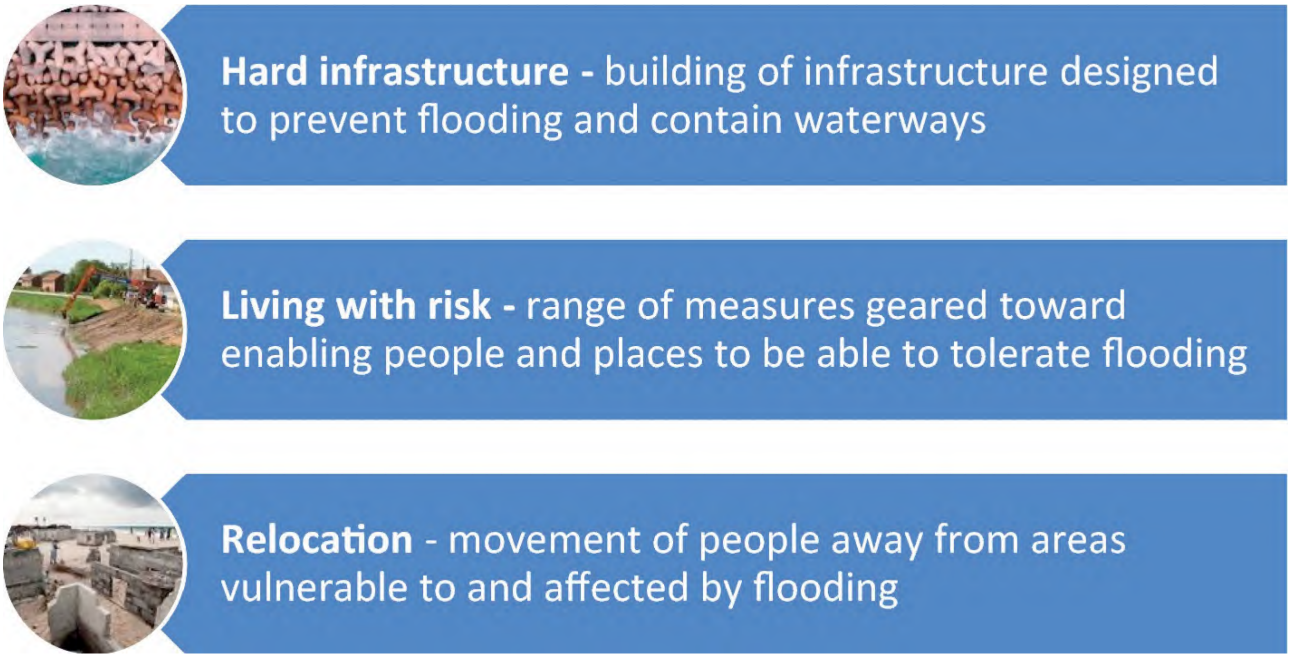


Figure 5.10 Strategies for flood adaptation. Source: Quinn et al. (2023). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

Adaptation actions that concern withdrawing from risk and the relocation of people and assets are becoming more commonplace globally. In Ireland, such approaches to adaptation are rare but may become more commonplace in future. Learning from historical cases of relocation and from international experience is vital. To this end, Tubridy et al. (2021) offer valuable insights into relocation as a response to flooding after the 1954 floods in the Shannon, highlighting the importance of place attachment, land reform and maintenance of family, social and livelihood connections for those affected. Moreover, for such transformative adaptation, Tubridy et al. (2022b) highlight the necessity of co-production and deep engagement with affected communities in ensuring just outcomes.

Key aspects of adaptation planning for all sectors concern the prioritisation of risks, deciding on the right portfolio of adaptation actions and the timing of their deployment in specific contexts. To this end, the flood risk sectoral adaptation plan has been commended for its approach to risk screening and prioritisation, with a focus on identifying and reducing existing vulnerabilities, while creating opportunities for scaling up adaptation as risks increase. Monitoring and the identification of risk-based indicators is important in this regard. Flood risk adaptation is also taking an adaptive approach and integrating decision making under uncertainty (e.g. through the sensitivity testing of design allowances). The development of adaptation pathways for the Midleton Flood Relief Scheme (Buckley et al., 2021), which links the implementation of flood adaptation measures to the ongoing evolution of risk, offers a prime example of adaptive management for other sectors to learn from (including water resources management and critical infrastructure (Chapter 7)). Such approaches demonstrate learning from international adaptation efforts, including management of flood risk in the Thames basin (Ranger et al., 2013) and urban and transport critical infrastructure adaptation (Marchau et al., 2008; Wall et al., 2015) (see also Chapter 10 on decision making under uncertainty).

5.4.3. Nature-based approaches

Nature-based approaches view nature and natural processes as having high potential to address societal challenges and achieve the SDGs, while providing multiple co-benefits (including for human wellbeing and biodiversity). In many instances, such approaches can be integrated with, and at times provide alternatives to, traditional hard engineering approaches to adaptation. Numerous studies have evaluated the potential for nature-based approaches in the context of water quality management and flood risk reduction and as a tool for deployment in adapting to climate change. In evaluating their potential for water quality protection in Ireland, Heneghan et al. (2021) highlight that constructed wetlands, sustainable drainage systems and nature-based interventions in the riparian zone can improve water quality to varying degrees, with co-benefits in terms of cost savings, enhanced biodiversity, carbon sequestration and recreational opportunities. However,

challenges exist regarding performance and roll-out, with long-term monitoring required to establish effectiveness in different contexts. Barriers to implementation include cross-sectoral cooperation, legislation and policy, financial support, capacity and public participation.

Similarly, Collier and Bourke (2020) make the case for mainstreaming nature-based approaches into integrated catchment management in Ireland for both flood risk management and water purification purposes. They highlight the co-benefits for flood risk adaptation and the potential to complement engineered/technical solutions. While nature-based approaches offer much, the absence of evidence for their efficacy for flood mitigation remains a significant obstacle (e.g. Dadson et al., 2017). Studies of 'on the ground' approaches for flood management, such as that under way in Inishowen, Co. Donegal, offer a space for innovation, experimentation and mainstreaming of such approaches. Given their many co-benefits, the potential for nature-based approaches as an adaptation strategy, either on their own or in combination with traditional measures, should be further supported and investigated. Future research should also investigate the potential of nature-based approaches for drought risk reduction within Irish contexts.

5.5. Cross-cutting issues

Clean, reliable and sustainable water and effective adaptation to flood risk are central to a climate-resilient Ireland and therefore are cross-cutting issues for all sectors, while adaptation in the areas of flood risk and water services can have benefits and trade-offs for other sectors. Failures in critical infrastructure (water supply systems and flood defences) can cause cascading risks in other sectors (including linked critical infrastructure), emphasising again the importance of stress testing existing water services infrastructure to the range of climate change projections to identify exposure to failure points. As highlighted above, nature-based approaches to adaptation can have multiple co-benefits within the water sector, whereby, for example, restoring wetland function can serve to increase water quality, and WAFU, while serving to attenuate flooding. This example also highlights the potential benefits of considering flood and drought risk in integrative ways.

Given the sensitivity of water to land use changes, it is important that consideration be given to how changes in land management associated with mitigation (e.g. increased afforestation) may impact water availability and quality and flood risk. Evidence in the literature suggests that increases in hydrological drought in southern Europe may be amplified by revegetation and afforestation of upland areas in recent years (e.g. Vicente-Serrano et al., 2019). Therefore, it is important to examine the interactions of mitigation and adaptation strategies for the water sector, while it is vital that efforts at adaptation do not increase greenhouse gas emissions, making the mitigation challenge more difficult.

As highlighted in the flood risk sectoral adaptation plan, other sectors can contribute positively to flood risk adaptation by reducing runoff, attenuating floods and damages through avoiding increased exposure in high-risk areas, effective land use and urban planning, and through deployment of flood-resilient design such as sustainable urban drainage systems. Flooding can cause negative impacts in other sectors, with a comprehensive list of impacts per sector provided in Appendix F of the flood risk sectoral adaptation plan. Integrated catchment management approaches to adaptation, especially via the development of river basin management plans as part of the Water Framework Directive, holds significant opportunities for addressing cross-cutting issues and developing win–win adaptation actions.

Recent research has shown that adaptation to flood risk via hard engineering, living with risk and relocation can each have positive and negative health and wellbeing outcomes for those affected, beyond reducing the direct impacts of flooding. It is therefore important that evaluation of adaptation outcomes include health and wellbeing indicators so that interventions do not result in maladaptation. Table 5.4 highlights the domains of life that can be affected by adaptation to flood risk and the key impacts of adaptation strategies that directly or indirectly shape health and wellbeing outcomes. The latter provide a potential starting point for the development of metrics for tracking the health outcomes of adaptation interventions (Quinn et al., 2023).

Table 5.4 *Summary of key impacts of adaptation strategies on health and wellbeing structured by material-, social- and environment-focused pathways. Pathways were identified from studies in Ireland, the UK and Ghana as part of a Wellcome Trust-funded project on healthy adaptations*

Domains of life impacted by adaptation	Key impacts of adaptation strategies that directly and indirectly shape health outcomes
Material/economic: What a person or organisation owns or has access to for meeting their everyday needs. For example, housing, income, food and infrastructure	• Livelihood: loss/gain of land, effect on employment • Food security: change in crops, change in diet, malnutrition • Public infrastructure: access to health care, protection of key health care assets such as hospitals • Insurance coverage: percentage of people with coverage, cost of insurance, price of excess
Social: The elements of personal and relational life that a person has or can have. For example, access to decision making, security and community connections	• Personal resilience: sense of security, anxiety, sense of continuity, happiness, sense of coherence • Process/equity: perception of procedural and distributional justice in decision making processes, use of commons • Community resilience: relational capital, active belonging, social capital • Identity: social identity, place identity
Environment: The aspects of a person's local environment, including the physical aspects and the social and cultural meanings that people attach to it. For example, availability of blue/green space and memories associated with a place	• Place: place meaning, place safety, place attachment, solastalgia • Human/nature relations: access to green/blue space, changes to natural environment, e.g. wildlife

Source: Adapted from Quinn et al. (2023).

5.6. Priorities for research

5.6.1. Seasonal hydrological forecasting

While attention nationally is currently focused on developing near real-time flood forecasting, opportunities exist for leveraging recent scientific advances in seasonal hydrological forecasting (e.g. Slater et al., 2023). Seasonal forecasts offer probabilistic information on likely hydrological conditions weeks to months in advance, assisting policymakers in developing management strategies. Such approaches are operational in other countries. Recent research, funded by Science Foundation Ireland, has shown that skilful forecasts at these timescales can be obtained for Irish catchments (e.g. Foran-Quinn et al., 2021; Donegan et al., 2021). Golian et al. (2022) also show that seasonal precipitation totals for Ireland can be skilfully forecast months in advance using hybrid dynamical/statistical approaches. These tools offer potential for water resources management, drought planning, flood risk management and management of reservoirs. Further research is required into how best to leverage these skills for operational purposes.

5.6.2. Enhanced monitoring

Monitoring is essential to track emerging signals of change, the changing nature of risk (including losses from extreme events and changing vulnerability), the attribution of detected changes and the success of adaptation outcomes. While Ireland has an extensive hydrometric network for monitoring water levels and discharge, networks for other key variables need to be developed and maintained. For example, investment in the Agricultural Catchments Programme by Teagasc has led to new insights into how climate, catchment characteristics, land management and agricultural practices affect water quality. Expansion of such intensive monitoring programmes to other locations would be of high value to adaptation for a range of sectors. Monitoring of key variables for water quality is often of short duration and linked to the duration of research projects. Continuous, high-quality observations of all components of the hydrological cycle are vital for adaptation.

5.6.3. Quantifying impacts and losses

Collation of impacts from extreme events is limited in Ireland presently. For evaluating the success of adaptation actions, further efforts at quantifying losses from extremes would be valuable. Such datasets would also be of value for linking hydrological indices with impacts, for example calibrating the selection of drought indicators and the identification of thresholds that result in socioeconomic and environmental impacts, thereby better informing monitoring and management.

5.6.4. Process understanding

Key knowledge gaps remain as to how climate change will impact certain hydrological variables, including extreme rainfall, potential and actual evapotranspiration, groundwater and lakes, and further research is required to advance this knowledge. Quantifying plausible changes in extreme precipitation is a priority given the impact on urban flooding, risks to ecosystems and critical infrastructure. New generations of very high-resolution modelling, large ensemble approaches (e.g. Kelder et al., 2022) and novel statistical methods (e.g. Kent et al., 2022) offer opportunities, while updated guidance is needed to inform adaptation in areas such as building regulations, adaptation of critical infrastructure and flood risk management for sewers and urban drainage systems.

5.6.5. Stress testing existing systems and developing adaptation pathways

Research is also needed into developing methods for stress testing water resource systems to the range of plausible future changes. Most research to date has examined climate change impacts for hydrological variables, without linking these to assessments of supply systems themselves. Such studies will be vital to identifying failure points, the evaluation of adaptation actions and the timing of their implementation (e.g. Wilby and Murphy, 2018). Opportunities for learning from and extending the application of the adaptive pathways approach to flood risk management developed by the OPW to water resource management would be valuable, as would exploration of other frameworks for decision making under uncertainty.

5.6.6. Nature-based approaches

Given their many potential co-benefits, the potential for nature-based approaches for adaptation across the water sector needs to be more fully explored and assessed, including their potential in the context of water quality, resource management and flood risk reduction.

6

Built Environment, Heritage and Rural Communities

Key messages

1. Flooding from rainfall, rivers and the sea is a major hazard for the built environment. These are expected to increase in future. Increases in rainfall intensity are expected with implications for existing buildings and building design. Sea level rise, in combination with changes in storms and tidal surges, will challenge the management and planning of coastal settlements. Cities and larger urban areas tend to have a higher temperature than the surrounding rural areas due to the urban heat island effect, such that increases in average and extreme temperature will be amplified in dense urban settings.

2. Buildings, both domestic and public, such as workplaces, hospitals, schools and care homes, need to be resilient to future climate. Building regulations need to be updated to reflect future changes in climate. Newly available climate maps for key design parameters (wind-driven rain (section 6.2.3), maximum and minimum temperature (Volume 1, Chapter 3), rainfall intensities (Volume 1, Chapter 4) and overheating risks (section 6.2.2)) are important for guiding design into the future. A significant amount of Ireland's urban and rural heritage is already at risk because of vacancy and dereliction and will be more vulnerable to changes in climate.

3. The role of planning and architectural design will be critical to adaptation in urban and rural settlements. Planning for an increasing and urbanising population demands coherence across spatial scales. It is crucial that exposure to flooding is not increased and that flood risk management guidelines are followed. There is abundant evidence for the value of nature-based approaches to reduce climate change impacts in urban areas. These include urban trees which can, with careful choice of species and planting, provide cooling, water retention, shading and some absorption of pollutants. The thoughtful siting of parks and green and blue spaces improves thermal comfort and general quality of life for inhabitants. Sustainable urban drainage systems offer potential for managing pluvial flooding. Planning based on local climate zones, which have already been developed for Dublin, can further aid spatial planning at the city scale by tailoring policies and guidelines to the typologies of local climate.

4. Ireland's long-sustained trend of dispersed rural settlement, highly dependent on transport-intensive and dispersed services, is a form of 'lock-in' that will present challenges for ensuring climate resilience. Ensuring that our goals for adaptation, rural development, housing, infrastructure, heritage protection and biodiversity are complementary rather than contradictory will require a greater degree of coordination and calibration of expectations than currently exists.

5. A key gap in knowledge is how climate change is likely to affect Ireland's islands and their communities. Little research has been undertaken to examine climate change impacts and adaptation in these important locations. Ireland's islands face unique climate change pressures from land and ocean and often have unique challenges and cultural heritage, both tangible and intangible.

6.1. Introduction: changing context and current pressures

As society mobilises to meet the challenge of rapid and large-scale decarbonisation of both society and the economy, we also need to rethink how cities, towns, rural areas and homes adapt to climate change. The impacts of climate change on our built environment, built heritage and rural communities are multiple and interconnected. While this chapter necessarily considers climate impacts on areas where the population is concentrated, it also discusses impacts on villages, dispersed rural settlements and island communities. Actions to bring forward climate neutrality are heavily interlinked with resilience and climate adaptation. Consequently, the social and environmental resilience of settlements of all scales is bounded by the conditions required to deliver climate neutrality by 2050. The synergies and co-benefits of mitigation and adaptation are explored in this chapter, as well as potential conflicts between them. Planning for climate change implies continued changes to how we plan our future settlements, informed by better environmental data, broad social resilience principles and stronger buy-in from communities, which new legislation and funding initiatives affect.

Ireland's modernisation and industrialisation in the mid- to late 20th century delivered considerable economic growth, allowing the country to leapfrog into developed status with net immigration and population growth, while retaining legacy issues of its underdeveloped status. Legacy issues in the built environment sector include poor enforcement of building regulations, as seen in the 2022 building defects report (DHLGH, 2022b), widespread urban sprawl extending into rural areas and, during the Celtic Tiger years, a severe disconnect between forecasted demand and reality on the ground. The legacy of these years remains with us in terms of a slow post-pandemic recovery of the construction sector and a severe housing shortage, in addition to ongoing issues related to building materials (including mica and pyrite). The 2022 census now places the population of Ireland at 5.1 million, which means that the island of Ireland now has a population of 7 million people for the first time since the 1840s. Ireland, while neither numerically nor geographically large, is now a mid-tier country in European terms.

6.1.1. The historical basis of urbanisation in Ireland

To understand Ireland's housing stock, it is pertinent to understand its settlement history and trends of growth in recent decades. Ireland's settlement history is readable in its towns, cities, villages and rural areas through place names, architectural styles and settlement patterns across the island.

During the Early Middle Ages, Ireland followed a steady path of nucleation around ecclesiastical settlements. The Norman invasion took place on an island already subject to early urbanising forces common to the north of Europe and left a lasting legacy of manorial towns and villages that largely remain in situ across counties such as Kilkenny (Smyth, 2007; McAlister, 2019). The early modern period of Ireland's history is one increasingly shaped by central control from London and enrolment into the imperial project of controlling and administering vast overseas territories. Architectural and planning styles (and their proponents) are shared with the island of Britain, yet comparable industrialisation was limited to the north-east of the island where the population of Belfast eventually eclipsed that of Dublin in the late 19th century. Following the establishment of the Free State in 1921 (and the Republic in 1949), mass emigration and a relatively closed economy kept the urban influence subdued until liberalisation of the economy in the 1960s. The influx of foreign investment and expansion of the services industries paved the way for the present panorama of high-end technology and global services, which has provided the economic backbone for rapid urbanisation and demographic growth. In addition, the major land reforms of the late 19th and early 20th centuries created a propertied middle class in rural Ireland. This democratic empowerment of a new farming class, including many smallholders, positioned them as major actors in rural development. A localised culture of political clientelism (Fox-Rogers and Murphy, 2014) and underdevelopment of forward planning has left us with a fractured urbanisation pattern of suburban edge development, dispersed rural housing and relative depopulation of preceding cities, towns and villages.

6.1.2. Decline of rural settlements in favour of dispersed 'one-off' housing

'Rural' is defined by the CSO as all areas outside urban centres of 1,500 or more inhabitants. This broad definition further breaks down rural areas into three additional categories as a function of their dependency on urban centres of employment: areas under high urban influence (16.1% of national population), areas with moderate urban influence (12.5% of national population) and remote rural areas (8.8% of the national population) (Scott and Heaphy, 2021). The European Commission's Atlas of the Human Planet 2019 (European Commission and Joint Research Centre, 2020), which largely bypasses national classification schemes, characterises Ireland as having a relatively low level of urbanisation, at 54% of the national population. This is comparable to central European countries such as Slovenia (50%), Slovakia (52%) and Austria (58%), and Nordic countries such as Norway (54%) and Finland (59%).

Detached houses in the open countryside comprise 70% of dwellings in rural areas, with the remainder being in small rural clusters, villages and rural towns (Keaveney, 2007). The CSO defines these 'one-off' houses as occupied detached houses with their own sewerage systems, totalling 442,699 dwellings (26% of national housing stock) in 2016 (Scott and Heaphy, 2021). They amounted to 40% of new construction in the 2011–2016 period. Keaveney (2007) notes how such houses have become more concentrated in peri-urban, accessible rural areas or in coastal areas of scenic interest. During the Celtic Tiger period, these houses grew in size and have continued to grow post-recession (Heaphy and Scott, 2021). This indigenous growth within rural communities is helped by the increasing potential of working from home, allowing people to return to their rural areas and broad social networks (Scott and Heaphy, 2021).

The growth of rural one-off housing contributes to what can be characterised as sprawl in an Irish context (Ahrens and Lyons, 2019). This tendency of dispersal is increasing, with "robust evidence that low-density areas exhibit a higher growth in population density and building stock than high-density areas, implying that the population structure is becoming more dispersed over time" (Ahrens and Lyons, 2019, p. 12). At the same time, Ireland has high levels of vacancy in urban areas due to decades of extra-urban and edge development and a lack of people willing to relocate and revitalise traditional town and village centres. These issues have been further exacerbated through the global trend towards out-of-town retail parks, which have been allowed to convert, over time, into car-based civic centres, frequently leaving older main streets the preserve of hostelry and services such as takeaways and betting shops.

6.1.3. Ireland's existing housing stock

Ireland's housing stock of 2,124,590 dwellings (2022 census; CSO, 2022) is relatively young, with 45% constructed since 1991 (see Table 6.1). The anomalous 2011–2016 period has been followed by a moderate recovery of the housing sector, with 120,945 further dwellings counted on the census night of 2022 (CSO, 2022). Currently, built dwellings are highly concentrated in the Greater Dublin Area and to a lesser extent in the Cork and Galway catchment regions (see Figure 6.1).

Table 6.1 *Housing stock relative to population (CSO census data from 2022 and 2016)*

Census year	Housing stock	Population	Housing stock change	Population change	Dwellings per 1,000 population
1991	1,160,249	3,525,719			329
1996	1,258,948	3,626,087	98,699	100,368	347
2002	1,460,053	3,917,203	201,105	291,116	373
2006	1,769,613	4,239,848	309,560	322,645	417
2011	1,994,845	4,588,252	225,232	348,404	435
2016	2,003,645	4,761,865	8,800	173,613	421
2022	2,124,590	5,123,536	120,945	361,671	415

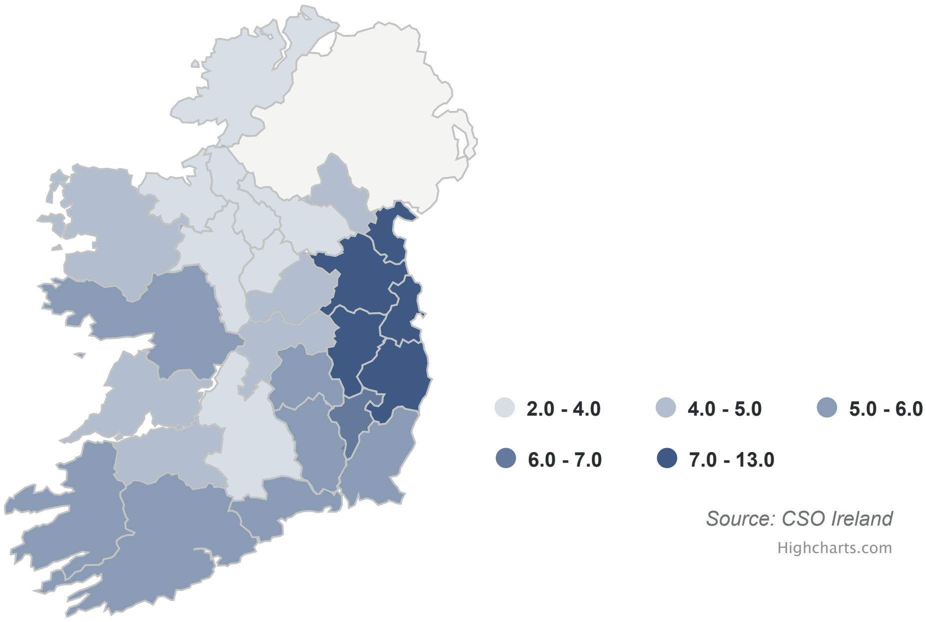


Figure 6.1 CSO (2022) preliminary findings, noting the percentage change in the total stock of available housing from 2016 to 2022 for each county in Ireland. Source: CSO (2022). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

6.1.4. Distribution of heritage sites in Ireland

'Built and archaeological heritage' is a recognised sector for climate adaptation and has a sectoral adaptation plan. It presents definitions for 'built heritage' and 'archaeological heritage' that encompass our material heritage and can be consulted in the report (DCHG, 2019c). Figure 6.2 provides a high-level view of recorded archaeological monuments from Ireland (Republic), in part reflecting the predominance of relatively intensely studied sites such as the Dingle Peninsula/Corca Dhuibhne in Co. Kerry, the Burren in Co. Clare and Lough Gur in Co. Limerick.

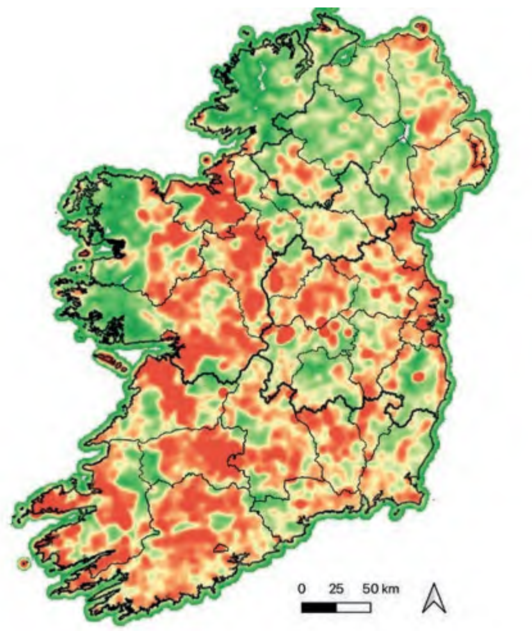


Figure 6.2 Heatmap showing the distribution of heritage sites on the island of Ireland from the Archaeological Survey of Ireland and Northern Ireland Sites and Monuments Record. Source: Recreated by the authors with 2023 data following Clutterbuck (2018).

Among the headline sites are the UNESCO-listed Sceilg Mhicíl off the coast of Co. Kerry and Brú na Bóinne in Co. Meath, which form part of a global initiative, 'Preserving Legacies: A Future for our Past', on safeguarding heritage sites from climate impacts (DHLGH, 2023). Heritage sites subjected to coastal erosion are examined in section 4.3.5.

6.2. Risks, vulnerabilities and impacts

This section assesses the direct impacts of climate change in the form of flooding, heatwaves and the urban heat island (UHI), and storm damages (see Chapter 4 for coastal erosion) for Ireland's built environment, heritage and local communities.

6.2.1. Flood risk to property

Flooding from rainfall (pluvial) and from rivers overspilling their banks (fluvial) is a major concern for climate change adaptation and is explored further in Chapter 5. As part of a coordinated European approach, Ireland's implementation of flood risk mapping and management has been assessed as being of high standard (Adamson, 2018; OPW, 2018), and forms part of a coordinated, data-informed approach that informs our development and engineering decisions. It is built on an extensive modelling of flood risk that takes account of both present and future flood risk and is tied to the planning system on a statutory basis.

The flood risk sectoral adaptation plan provides assessments of exposure of properties to flooding with future climate change (under MRFSs and HEFSs), finding that for frequent flood events (those with a 10% annual exceedance possibility, or 1 in 10 chance of occurring or being exceeded in any given year) the number of properties would increase very significantly in percentage terms. Protection from floods in Ireland is heavily dependent on engineered flood relief schemes. It was reported in 2018 that the 42 flood relief schemes completed protect around 9,500 properties, while a further 12,500 properties were to be protected by 33 future works. In addition, 11,500 properties were to be considered under proposed flood relief schemes, while 500 properties were to be the subject of further analysis. Around 500 properties were deemed at relatively low risk or unsuitable for structural works (OPW, 2018, p. 28). The response to flood risk is covered in section 6.4, while a more extensive consideration of flooding impacts is present in Chapter 5 and not repeated here.

6.2.2. Heat risk and the urban heat island

The UHI describes the fact that cities are generally warmer than surrounding 'natural' areas; the UHI magnitude is measured as the difference in temperature. The drivers of the UHI are well known and include:

- The replacement of natural cover by paved surfaces and buildings. This reduces cooling by evapotranspiration and enhances surface warming.
- The types of materials used in construction (asphalt, concrete, bricks, glass, etc.). These materials absorb and retain heat effectively.
- The geometry created by building dimensions and layout. This reduces airflow near the surface, creates areas of shade and sunlight and inhibits night-time cooling.
- The concentrated human activities in cities that emit waste heat into the near-surface atmosphere.

These urban drivers create different types of thermal effects. The surface UHI is the result mainly of heating of pavements, walls and roofs. The canopy UHI is based on the near-surface air temperature (about 2m above the ground), which lies below roof height (within the urban canopy) and is highest at night as urban surfaces cool. The surface UHI exhibits great spatial and temporal variation and is highest in the daytime over areas with large impervious cover and is lowest over well-watered green spaces. The canopy UHI exhibits highest values in the city centre where the canopy is deepest and the sky view factor is smallest. Both UHI types are greatest in calm and sunny weather associated with anticyclones; in these circumstances the rates of daytime warming and night-time cooling are accentuated and the urban–rural differences are greatest. As a result, thermal stress associated with hot weather is greater in cities; this impact will be enhanced under global warming scenarios.

The magnitude of the UHI is greatest for larger cities and for neighbourhoods with high built densities; smaller towns and villages experience lower temperature differences. In Ireland, where airflow is strong and skies are often cloudy, the normal magnitude of the UHI is considerably less than the potential. As part of the Urb-ADAPT project, Paranunzio et al. (2020) created projections of the future UHI of Dublin under the RCP4.5 and RCP8.5 scenarios for July in the 2050s (Figure 6.3).

These projections were further linked to a social vulnerability index to create integrated maps of heat risk (Figure 6.4). The authors note that under RCP4.5 and RCP8.5, the number of areas particularly vulnerable to heat (levels 4–6) will increase by 70% and 96%, respectively, between the 2020s and the 2050s (Paranunzio et al., 2021). While limited to current CSO-derived calculations of social vulnerability, the study finds an intensification of heat risk particularly in the northern and south-western peripheries of the city and northern central areas.

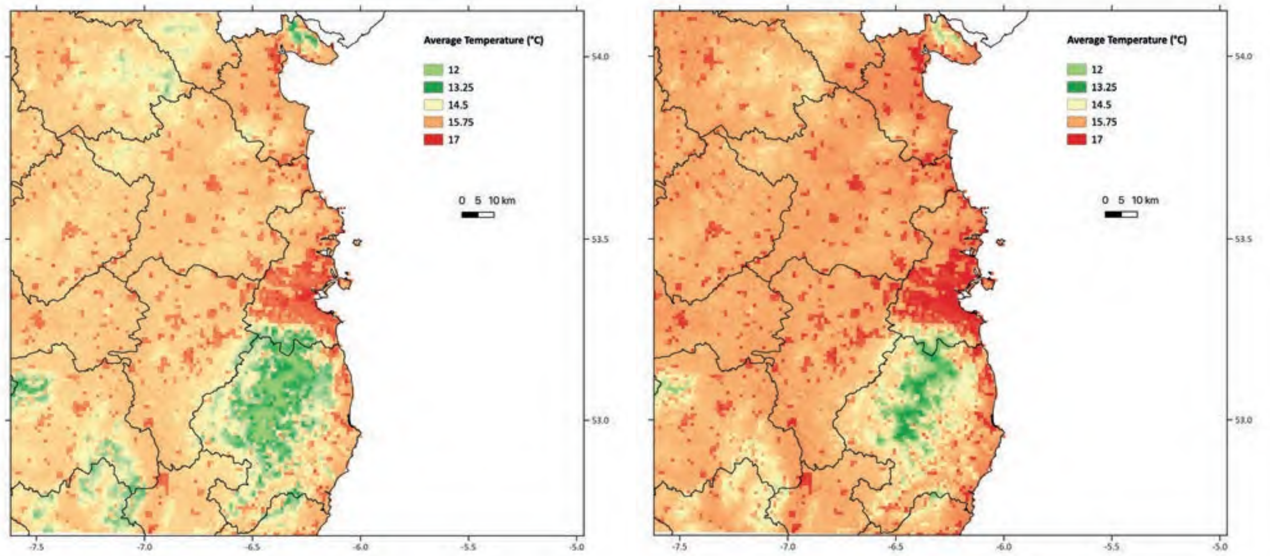


Figure 6.3 Monthly average temperature for the 2050s under RCP4.5 (left) and RCP8.5 (right), with climate projections from Nolan (2015) that are further downscaled using a finely resolved urban climate model. Source: Paranunzio et al. (2020).

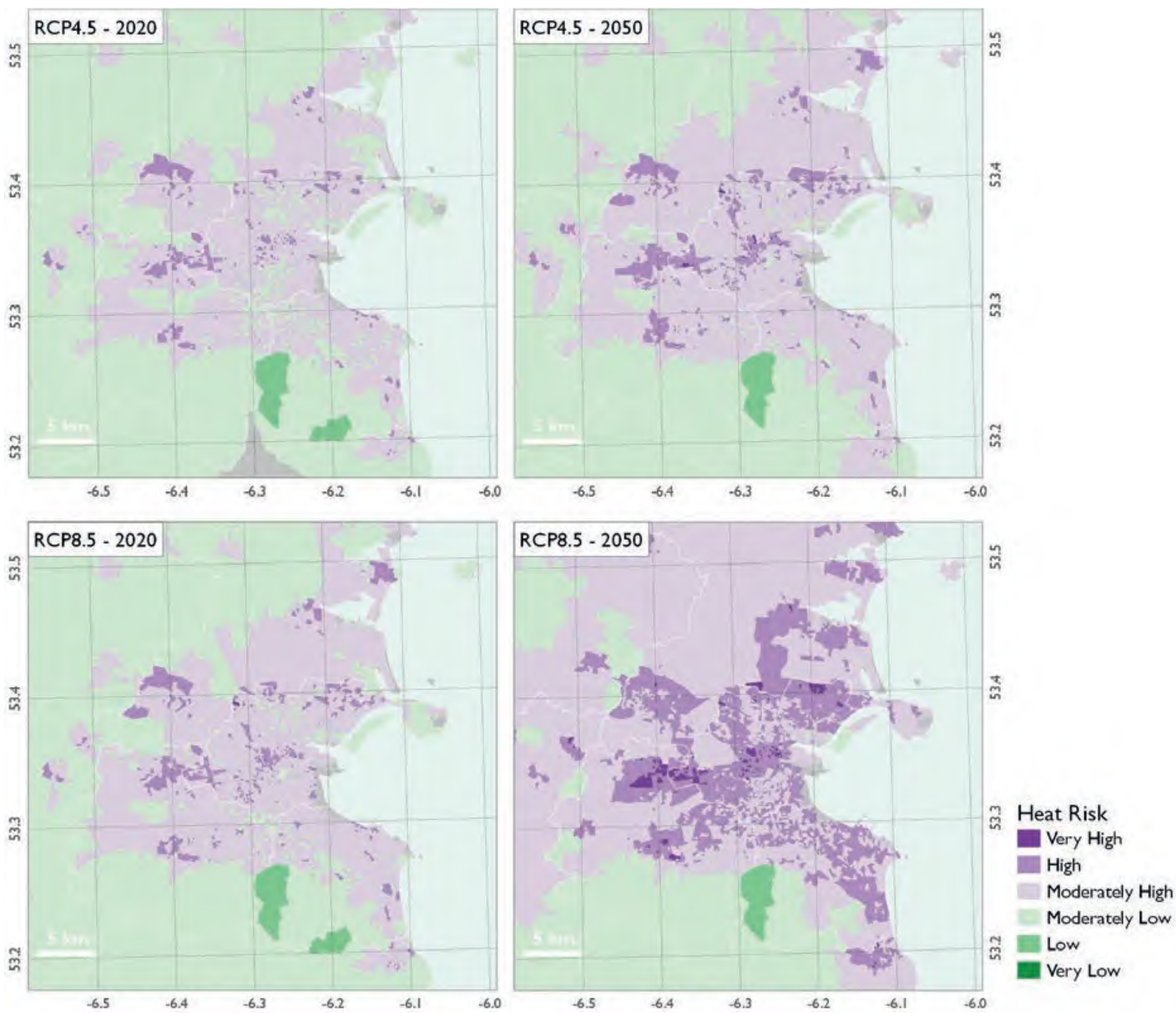


Figure 6.4 Heat risk vulnerability mapping of Dublin with downscaled urban climate model projections linked to a social vulnerability index. Projections include RCP4.5 and RCP8.5 for the 2020s and 2050s during the month of July. Source: Paranunzio et al. (2021). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

6.2.3. Storm damage and sea level rise

As detailed in Volume 1, changes in storm activity and associated wind speeds remain uncertain. An increase in windspeed would increase the danger of structural damage to roofs, or from trees collapsing, and damage through driving rain (Scott and O'Neill, 2022). Storm surges can combine with tidal and sea level rises to bring greater damages to coastal cities and towns. Rare events of short duration, such as Storm Ophelia, can result in breaches of coastal defences and cause extensive flooding in urban areas (Moore, 2021). Smyth (2012) outlined a methodology for evaluating present and projected wind-driven rain, providing maps that have since been further developed by Met Éireann (Mateus and Coonan, 2022).

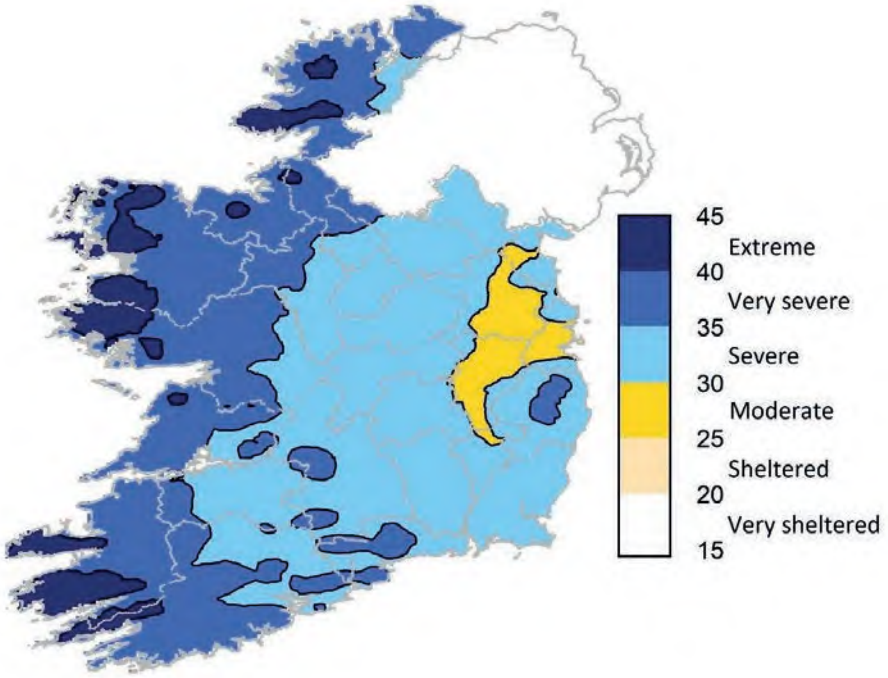


Figure 6.5 Met Éireann's Driving Rain Index for Vertical Surfaces (I.S. EN ISO 15927-3:2009) for the period 1991–2020 for the Republic of Ireland. Illustrated classes of exposure: very sheltered (< 20), sheltered (20–25), moderate (25–30), severe (30–35), very severe (35–40) and extreme (40–45). Source: Mateus and Coonan (2022).

Traditionally, Irish vernacular homes were adapted to regional differences in climate through adapted roof types, such as weighted-down thatch and thoughtful siting in relation to shelter from prevailing westerlies and maximised solar gain (O'Reilly, 2011; Stevens, 2015). Modern construction techniques have rendered homes less vulnerable to external factors; however, the risks are still manifest, and due consideration should be given to regional variations in climate, such as the variation in wind-driven rain, as mapped in Figure 6.5.

Sea level rise is a further consideration for the management and planning of coastal settlements in combination with storm and tidal surges. While we cannot prevent sea level rise, to which we are already committed through historical and present greenhouse gas emissions (see Volume 1, section 2.5.1), our collective global action now marks the difference between being able to adapt cities and effectively abandoning low-lying urban areas (Jackson et al., 2018; Rasmussen et al., 2018; Aschwanden et al., 2019).

6.2.4. Special considerations for built and material heritage

Among vulnerable properties are many buildings in the National Inventory of Architectural Heritage, including settlements at risk of future flooding in parts of Dublin Bay (Ringsend, Docklands, Clontarf) and Cork city centre. Much of our urban heritage is already at risk due to vacancy and dereliction, and therefore climatic events such as floods and storm damage may push such properties deeper into dereliction, with implications for restoration viability. Schemes such as Town Centre First and the Heritage Council's Collaborative Town Centre Health Check programme can address this baseline vulnerability of underutilised heritage assets, particularly in the case of non-listed structures (DRCD, 2020; Harvey, 2020). Furthermore, circular economy considerations mean that significant carbon savings are possible by revitalising and reusing heritage buildings instead of constructing new builds (Cabeza et al., 2013; Foster, 2020). In such cases, a streamlined process of revitalisation will be needed that balances energy performance and fire safety requirements with the heritage fabric of these buildings and with the practical need to keep these buildings in use (Purcell, 2018).

The development of a digital building renovation passport for all retrofitting work, as trialled by the Irish Green Building Council in line with current trends for the European Green Deal (IGBC, 2020), will be important for the sharing of best practices and coordination. This will be critically important for heritage assets maintained in active use, such as residential buildings, public buildings and commercial premises (Figure 6.6).

Figure 6.6 Vacant terraced home with flat roof annex for sale in Ballyporeen (Béal Átha Póirín), Co. Tipperary. Photo credit: Liam Heaphy.

OPW heritage sites that are preserved in a semi-ruinous state, such as abbeys and tower houses, due to cost limitations or cultural preferences to maintain them unaltered, may suffer water incursion or structural failure without the more immediate monitoring and response that occurs in used or lived-in active buildings, such as restored religious buildings and castles used for a variety of regular public events (e.g. Kilkenny and Cahir castles, Ballintober and Holy Cross Abbey). Where possible, data from the National Inventory of Architectural Heritage should be linked to Tailte Éireann (formerly OSI) building information, the GeoDirectory and the Building Energy Rating (BER) system to avoid data and policy silos and consequent maladaptation of heritage assets. Combined, these would form a common standard of digital passport for all buildings in Ireland.

6.3. Adaptation strategies

The Irish planning system has a tiered hierarchical framework, from national policy and guidelines to the detailed plan-making of local authorities at multiple scales and the planning application system for individual developments (Haughton, 2010). County or city development plans, as well as smaller-scale plans and applications, are subject to statutory oversight from a range of bodies, including the OPW, the Office of the Planning Regulator and An Taisce. The system has an independent appeals body, An Bord Pleanála, that has been further utilised of late to largely bypass part of the appeals and oversight process for fast-tracking strategic housing developments (Lennon and Waldron, 2019). Consequently, in the context of a rapid drive to accelerate the rate of new building after the recession and pandemic, it has a rather powerful role in terms of Ireland's climate goals.

Section 10(2)(n) of the Planning and Development (Amendment) Act 2010 requires that development plans reduce anthropogenic greenhouse gas emissions and address the necessity of adaptation to climate change. Further leverage is attained through the building regulations, voluntary industry standards above the regulations, and forward planning at the master planning scale. For example, in strategic development zones such as the Dublin Docklands (North Lotts and Grand Canal Dock), the local authority (or bespoke body in the case of the former Dublin Docklands Development Authority) provides very detailed requirements for individual buildings and infrastructure in advance of developer submissions (Moore, 2008; Doyle, 2015; Lawton, 2018; Heaphy and Wiig, 2020). In each case, whether for flood management or for a healthy environment, the role of planning and architectural design is critical for the provision of sustainable urban and rural communities (and discussed further in Volume 4).

6.3.1. Planning and flood risk management

Increasing urbanisation combined with severe flooding events in the 1980s and 1990s drove a change in flood management policy towards one that not only sought to provide relief works and restrict new development in risk areas, but also sought to live with and adapt to flooding events. A review in the early 2000s for the OPW created the scope for river catchment-scale analyses of flood risk, aligning with the EU Floods Directive, which in 2009 was transposed into national law in Member States, including Ireland. Each Member State conducted a preliminary flood risk assessment (by the end of 2011), created flood hazard and risk maps (by the end of 2013) and then formed flood risk management plans (Adamson, 2018). The technically sophisticated analysis conducted for the CFRAM programme was completed in 2018 for Ireland, along with the aforementioned preliminary flood risk assessments and flood risk management plans, and provides the basis for flood risk assessments created by each local authority as part of their development plan cycle.

The existing flood risk management guidelines for planning authorities, dating from 2009, establishes a set of principles that inform county and city development plans (OPW, 2009):

- avoid inappropriate development in areas at risk of flooding;
- avoid new developments increasing flood risk elsewhere, including that which may arise from surface water runoff;
- ensure effective management of residual risks for development permitted in floodplains;
- avoid unnecessary restriction of national, regional or local economic and social growth;
- improve understanding of flood risk among relevant stakeholders;
- ensure that the requirements of EU and national law in relation to the natural environment and nature conservation are complied with at all stages of flood risk management.

The guidelines provide a sequential approach to flood risk management, building on the flood risk assessment's zonal classification in relation to development management (Figure 6.7).

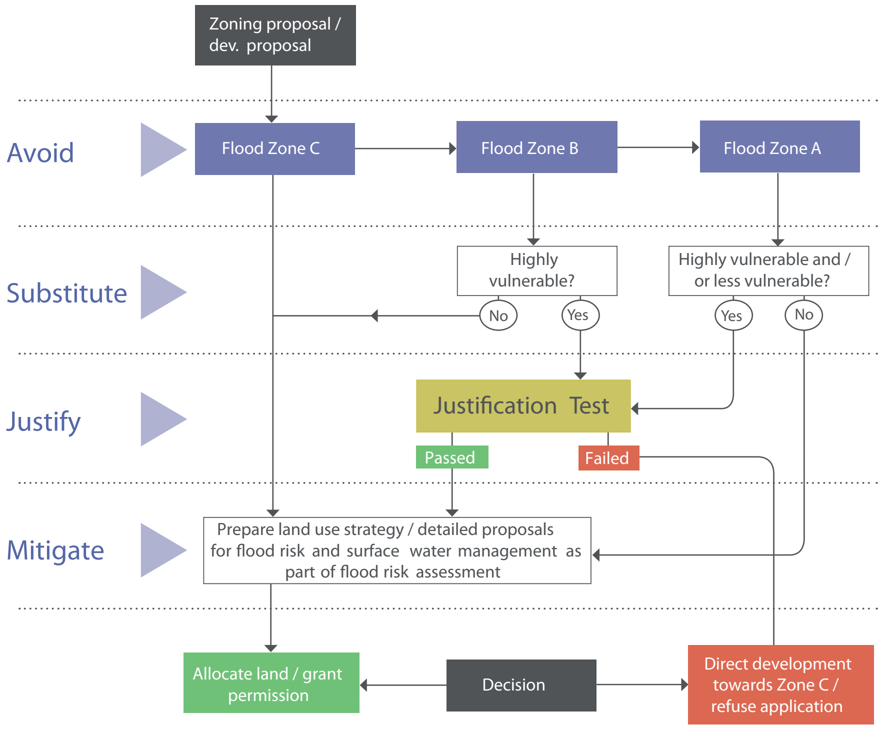


Figure 6.7 The justification test and sequential approach used by local authorities for responding to zoning and development proposals. This decision making aide provides clarity to all parties in relation to flood risk and planning decisions based on the three differentiated flood risk zones. Source: OPW (2009).

The move towards a risk-based approach with prioritisation of resources has been a significant change in how government approaches individual petitions to increase flood protection. To avoid a 'winners and losers' characterisation, or an over-reliance on hard infrastructure, Clarke and Murphy (2019) recommend a greater degree of co-production of knowledge with communities. Similarly, Revez et al. (2017) examine the case study of the Kinvara catchment area, prone to periodic flooding, in terms of how the transition to risk-based management was considered to have not addressed the needs of the community.

The case of the Clontarf sea wall is emblematic of a failure in building consensus, leading to wasted resources and time in the preparation of plans, the construction and subsequent deconstruction of protective barriers, and the absence of sea walls that has followed (Clarke and Murphy, 2019). Agencies can avoid such scenarios by providing a clear outline of the pathways available to communities to reduce flood vulnerability, in addition to guidelines and support for attaining these outcomes. This is particularly important for nature-based approaches and social adaptation measures, where policymakers must be aware that appraisal of risk varies enormously from place to place and is often at variance with official expert-driven risk assessment (O'Neill et al., 2016; O'Neill, 2018; Clarke and Murphy, 2019). Managed retreat, either collectively or on a case-by-case basis, may also constitute a viable response, as shown in the case of the Shannon Callows in the 1950s (Tubridy et al., 2021).

The past 10 years have seen a rapid pace of change in planning, with a plethora of GIS tools now available to help with decision making (e.g., https://www.myplan.ie, https://www.floodinfo.ie, https://airomaps.geohive.ie/ESM/). For the future planning of homes and communities, development management and environmental impact assessments can avoid future conflicts over flood prevention and control by adhering to decision making based on mapped flood zones. However, such tools are emerging from a prior planning practice where there was much further scope for negotiated outcomes and trading of interests.

The counterpart to data-informed choices and established procedures is the need for a greater consultation with communities prior to establishing procedures and plans. The continuing transition from reactive case-by-case planning to evidence-based strategic planning requires political backing so that the wider environmental benefits are recognised. Development management and forward planning are considered among practising planners to be under-resourced, with a perception that there is a general lack of political support (BE-Resilient, 2021).

6.3.2. Strategic spatial planning for urban climate at the city scale

At the city region and city scales, planning can work together with public health objectives and carbon budgeting to create healthy, safe and secure urban environments. Spatial planning at the city scale can contribute to cleaner air through ventilation corridors protecting prevailing winds that disperse concentrations of pollutants. The thoughtful siting of parks and green and blue spaces improves the thermal comfort and general quality of life of inhabitants (Katzschner, 2011; EEA, 2020).

The National Planning Framework has a progressive vision of denser, better-connected and better-serviced urban communities, combining both affordable, social and market-priced housing, and commercial and social services (DHPLG, 2018). Denser urban communities will require more input from design and evidence-based spatial planning than we are accustomed to in order to offset the increased UHI and potential for overheating in indoor and outdoor spaces (Dodoo and Gustavsson, 2016; Fosas et al., 2018; Caparros-Midwood et al., 2019). More concentrated urban settlements will offer greater flexibility for biodiversity initiatives such as green corridors that further SDG 15 on protecting and enhancing terrestrial ecosystems (see Chapters 2 and 3).

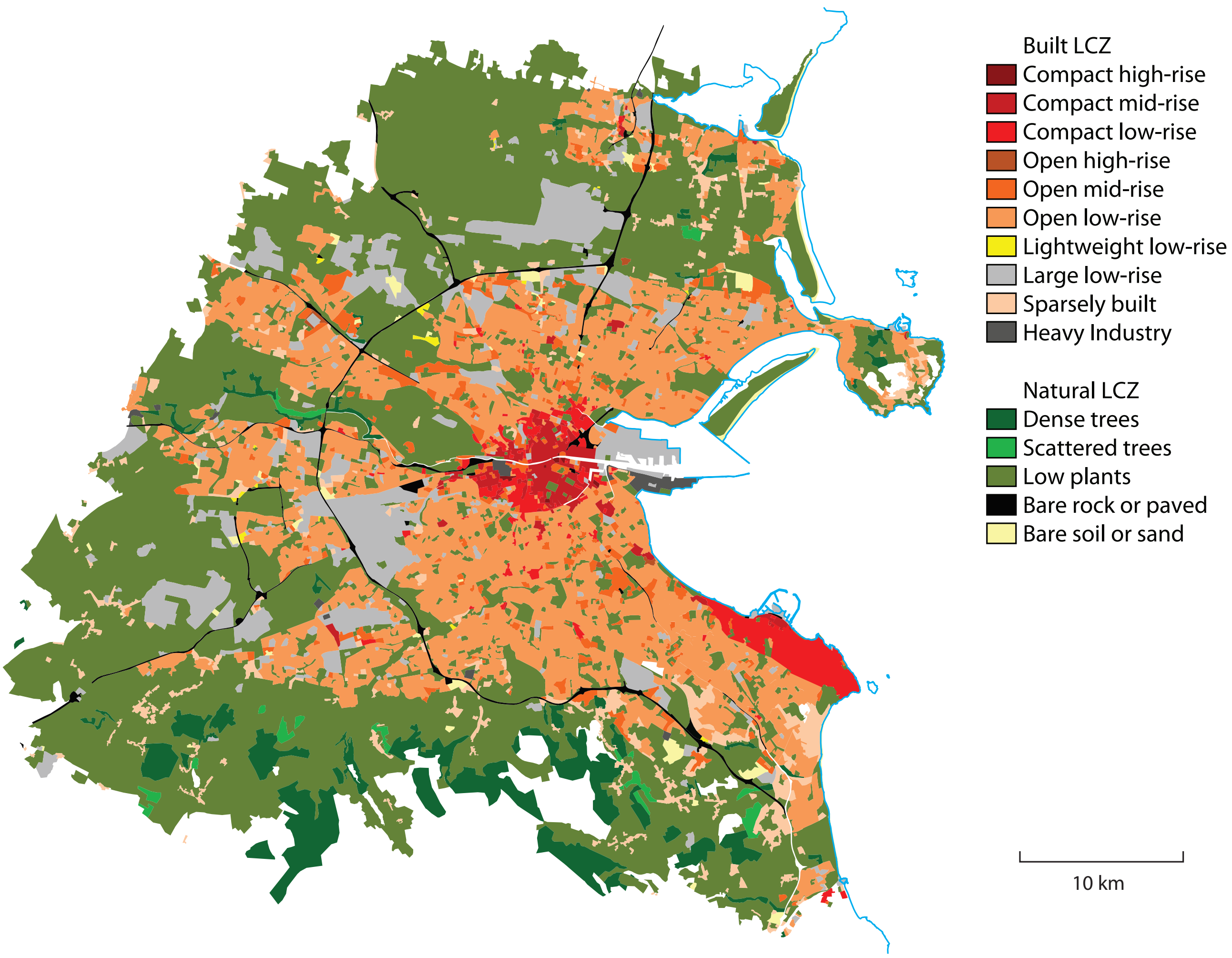


Figure 6.8 Local climate zone map of Dublin, which can form the basis for risk assessments and planning measures at finer scales. Image credit: Paul Alexander; reproduced in Oke et al. (2017).

Planning for an increasing and urbanising population demands coherence across spatial scales and their respective plans, such that interventions at small scales do not undermine or contradict those at larger strategic scales. This is particularly important for urban climate (Heaphy, 2017; Oke et al., 2017), where levels of thermal comfort and air quality are contingent upon building and neighbourhood design and above that upon strategic spatial planning. Best practice in urban climate is that city spatial plans and local-scale master planning be conducted with reference to data-informed analytical and decision making maps indicating areas of climate vulnerability, such as is long established in Germany (Hebbert and Webb, 2011;

Hebbert, 2012) and has since been adapted in various guises throughout Europe in the development of tools and processes to aid planning decision making (Lorenz et al., 2017; Eichhorn et al., 2021; Wright et al., 2021). However, as with flood risk, this form of specialist planning is heavily contingent on sufficient resourcing to understand these technically complex considerations and put them into practice in a consistent and publicly transparent manner.

Flood risk management provides a model of how to integrate technical risk-based frameworks into forward planning and development control. The recognition of local climate zones (Figure 6.8), such as those already developed in a research context for Dublin (Alexander; reproduced in Oke et al., 2017), can further aid spatial planning at the city scale by tailoring policies and guidelines to the typologies of local climate as experienced in different areas of the city, largely shaped by density and urban morphology (Stewart and Oke, 2012; Alexander and Mills, 2014).

Mitigating the UHI means modifying the drivers listed in section 6.2.2, especially vegetative cover. An effective UHI strategy is to identify places and people at risk of overheating to refine actions. Moreover, as the UHI is correlated with other urban effects, actions should be designed to meet multiple objectives, such as enhancing biodiversity and reducing rainfall runoff. The most effective strategy is to increase the extent of green space in cities (green infrastructure), as this will reduce surface heating and enhance cooling. Increasing the number of landscaped green spaces within densely built-up urban areas reduces the magnitude of the UHI (mitigation) and provides a thermal refuge (adaptation) for the local population.

In built-up and paved parts of the city, trees can be used to shade streets and buildings. Green walls and roofs can also help limit energy gain by buildings and reduce heat stress in outdoor gathering places. Adding water features in these places (such as fountains) will also contribute to thermal comfort. Changing construction materials to limit heat gain can be effective measures, but these need to be applied carefully, for example conventional paving with permeable cover can be used for lightly trafficked areas. Changing geometry to increase night-time cooling is not really an option for existing built-up areas and does not fit with other climate change goals, such as increasing built density. The heat added by humans and their activities is a relatively minor contributor to the UHI, although in combination with other actions will enhance urban environmental quality.

6.3.3. Neighbourhood design: designing public space around nature

There is abundant evidence for the value of nature-based approaches to reduce climate change impacts in urban areas (Geneletti and Zardo, 2016; Kabisch et al., 2016; Scott et al., 2016; Depietri and McPhearson, 2017). Since the spatial design and physical implementation of measures falls into the purview of architecture and design, frameworks such as the Project for Public Spaces have been adapted to incorporate climate comfort (see Figure 6.9).

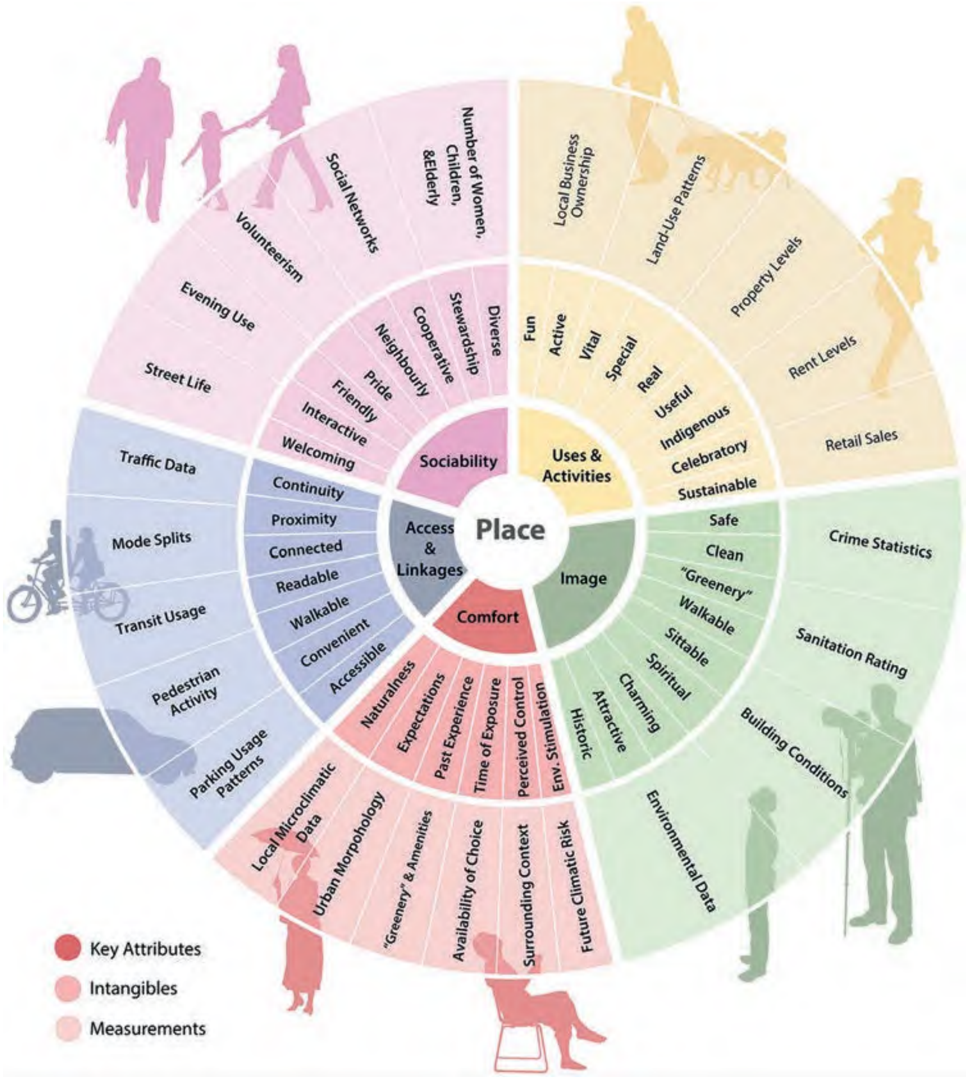


Figure 6.9 Adaptation of the Project for Public Space diagram (PPS, 2003) by Santos Nouri and Costa (2017), which includes future climate considerations in relation to urban design and place-making. Source: Santos Nouri and Costa (2017). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

Nature-based approaches can either complement or substitute for hard infrastructure solutions for flooding and overheating and can comprise a wide range of measures. These include urban trees, which, with careful choice of species and planting, can provide cooling, water retention, shading and some absorption of pollutants (Zölch et al., 2019; Rahman et al., 2020). A second well-established measure is that of public gardens, particularly when scaled and distributed to ensure that they are accessible to a broad public. Forming part of sustainable drainage systems, 'rain gardens' combine the trend towards creating green spaces to retain storm water within parks (Karvonen, 2011; Zhou, 2014). More recently, rain-friendly playgrounds have also been designed (Orange, 2021). Further measures include green roofs, green corridors, open culverts with planting and green verges. There is abundant guidance for planners in Ireland (OPW, 2009; Woods Ballard et al., 2015), but practitioners converge on the opinion that the benefits and implementation of nature-based approaches are poorly understood in Ireland (Igoe et al., 2021), depending on the communities and local authorities in question (e.g. Clarke and Murphy, 2019).

6.3.4. Rural settlements and hinterlands

Our Rural Future – Rural Development Policy 2021–2025 makes commitments to improve rural Ireland's infrastructure and services, housing and settlements, economic development and social cohesion, in the context of carbon neutrality (DRCD, 2021). However, our long-sustained trend of dispersed settlement and high dependency on transport-intensive services is a form of 'lock-in' that will present particular challenges for ensuring climate resilience (Scott et al., 2010; CCAC, 2020; Heaphy and Scott, 2021). These include maintaining service provision to remote populations without a significant service centre and creating space for key infrastructure such as wind energy farms, forestry, green corridors for biodiversity and the safe treatment of waste from one-off housing (EPA, 2021).

Recent efforts to provide a more sustainable form of rural development include the promotion of guidelines for providing sites for clustered development in established settlements (see Tipperary County Council, 2018) plus the adoption of the Town Centre First Policy from Scotland into Irish policy (Crowe, 2019; DRCD, 2021). However, as with flood risk, choices will have to be made on where new development is permitted to ensure that these policies and guidelines are successful. Permissive development policies in favour of the status quo, while politically palatable in the short term, will have significant repercussions for both mitigation and adaptation in the medium to long term that should be costed now.

Ensuring that our goals for rural development, housing, infrastructure and biodiversity are complementary rather than contradictory will require a greater degree of coordination and calibration of expectations than currently exist. Further research is required on climate-sensitive solutions for the fulfilment of rural housing needs in terms of energy use, service provision costs, social cohesion and waste treatment, to ensure sustainable rural futures (Scott et al., 2010). The environmental costs of different scenarios of rural development are currently under-studied. Similar forms of rural settlement and land ownership exist in other regions such as Scandinavia (e.g. Finland, Norway) and central Europe (e.g. Slovenia, Slovakia), which may provide a basis for pan-European research funding applications.

6.3.5. Islands and rural communities

Island communities have lost a greater share of their population and services than their mainland rural counterparts (Baldacchino and Starc, 2021). However, after a 20th century history of island abandonment, many have started to grow again thanks to changes in technology and increased desirability. Of late, Árainn in the Aran Islands and the Dingle Peninsula/Corca Dhuibhne have served as testbeds for energy independence, low-carbon development and social resilience (Heaslip and Fahy, 2018; Clercq et al., 2019; Boyle et al., 2021; Torabi et al., 2021).

While frequently considered peripheral or marginalised, such communities have long-standing self-organisation in relation to Irish language services, economic development and cultural initiatives (Bradley and Kennelly, 2009; O'Keeffe and O'Sullivan, 2017). Technology has brought communities closer, while physical isolation delimits boundary conditions for trialling new initiatives. The European Commission's Smart Rural project (https://www.smartrural21.eu/, 2019–2022) also brought new funding for rural development in Ireland and elsewhere, in addition to LEADER programmes and national rural development funding, with Daingean Uí Chúis/Dingle as the Irish case study. A smart villages project has also been completed for North Kerry (https://nkwlsmartvillages.ie/).

6.3.6. Building for a future climate

Our buildings will need to be resilient to future climate. This includes both domestic and public buildings, such as workplaces, hospitals, schools and care homes. As we advance our retrofitting programme (see Volume 2, Chapter 5), we will need to ensure that our existing, retrofitted and new buildings are adapted to handle projected climate impacts and future energy constraints.

Depending on materials, design standards and concern for heritage, buildings may continue their functions from decades to centuries into the future. Irish homes are projected to have lower heating bills due to both rising average temperatures and, more importantly, the construction of highly insulated buildings (Finegan et al., 2020) and a retrofitting programme. The present building regulations have been updated over the last decade to reflect increasing energy efficiency goals and zero carbon targets, corresponding primarily to Part L. In contrast, other sections such as Part A on structure and Part D on materials and workmanship have received less attention than merited in relation to climate adaptation. Recent research that has been conducted on building regulations primarily relates to energy efficiency, highlighting long-standing issues with assuring compliance through certification and inspection, and sociotechnical barriers (Lewis and Goulding, 2002; Goggins et al., 2016; Ahern et al., 2018; Raushan et al., 2022; Souaid et al., 2022). Earlier research by Smyth (2012) recommended a series of actions, reproduced in Table 6.2.

Table 6.2 *Adaptation actions for the building regulations recommended in Smyth (2012)*

Part	Recommendation	Impact concerned
Part A	Include 'climate change' as an action in IS EN 1997-1:2005 Section 2.4.2, Actions (4)	Precipitation and temperature
	Employ higher wind values in the order of 10% in design wind calculations	Wind
	Update wall loading classification requirements in the light of higher design wind loads	Wind
	Revise the National Annex to IS EN 1996 Eurocode 6 using the latest wind data	Wind
	Update driving rain map in Irish Standard ICP 2:2002	Wind and precipitation
Part C	Increase minimum recommended water table distance to ground floor with respect to BS 8102:1990	Precipitation
Part D	Climate change data to be utilised in CE certification	Wind, precipitation and temperature
Part F	Continual review of values with respect to airtightness versus ventilation	Wind and relative humidity
Part H	Investigate increasing the minimum depth to water table in the Code of Practice for Wastewater Treatment Systems for Single Houses (EPA, 2009)	Precipitation
Part L	Review acceptable construction details (2008) to align with Technical Guidance Document L (2011) to ensure compliance with current U-value aims	Wind, precipitation and temperature

Further revision of the building regulations is advisable in relation to future climate. A case in point is in relation to overheating in highly insulated homes, on which there has been more research than on the impacts of wind-driven rain and storms.

As discussed in Volume 1, section 3.4, Ireland will experience more heatwaves in the future. Ensuring that our buildings operate at safe temperatures for vulnerable populations, particularly in residential settings without cooling systems, is dependent on design and construction. Heatwaves at present are experienced differently according to location, building design, time of day or night, and human state of health. Older homes that have not been retrofitted to a higher BER typically have high thermal mass and greater ventilation and heat exchange, meaning that they retain their coolness during warm daytime periods and can be cooled quickly during sleeping periods. In contrast, research shows that newer, highly insulated and retrofitted buildings are more susceptible to overheating because heat gains acquired during the day are not so easily dissipated during the cooler periods in the evening and night (Dodoo and Gustavsson, 2016; Mulville and Stravoravdis, 2016; Din and Brotas, 2017; Taylor et al., 2023).

In many neighbouring northern European countries, such as Denmark, Sweden and Germany, there are existing regulations to ensure that new and retrofitted buildings do not surpass potentially dangerous internal temperature thresholds (Dodoo and Gustavsson, 2016; Rahif et al., 2021; Velashjerdi Farahani et al., 2021). In the UK, the existing building regulations (Part L) are also being reviewed to incorporate a more substantial consideration of overheating thresholds (Heaphy, 2017; Mylona, 2020). As overheating concerns seem to be common to all of northern Europe, including Scandinavia and northern Scotland (Morgan et al., 2017; Velashjerdi Farahani et al., 2021), it can be expected to occur in Ireland as well.

Research conducted by Finegan et al. (2020) simulated and empirically measured overheating hours for a Passive House-compliant 2015-built detached house in Cork. The Passive House standard has climate-specific metrics for simulating overheating frequency and includes relevant recommendations for glazing and thermal bridging. Real-world measurements of overheating during 2013 (greater than 25°C) reported 13 days where overheating occurred and 69 days where overheating occurred in bedrooms (Finegan et al., 2020, p. 697). In contrast, the simulations anticipated zero days above this threshold. As per a Scottish study by Morgan et al. (2017), there was a significant gap between simulations and real-world measurements, and between different zones within buildings (see Figure 6.10). This indicated the importance of developing further zone-sensitive methods for simulating overheating frequency, which will be relevant for nearly zero energy homes in Ireland.

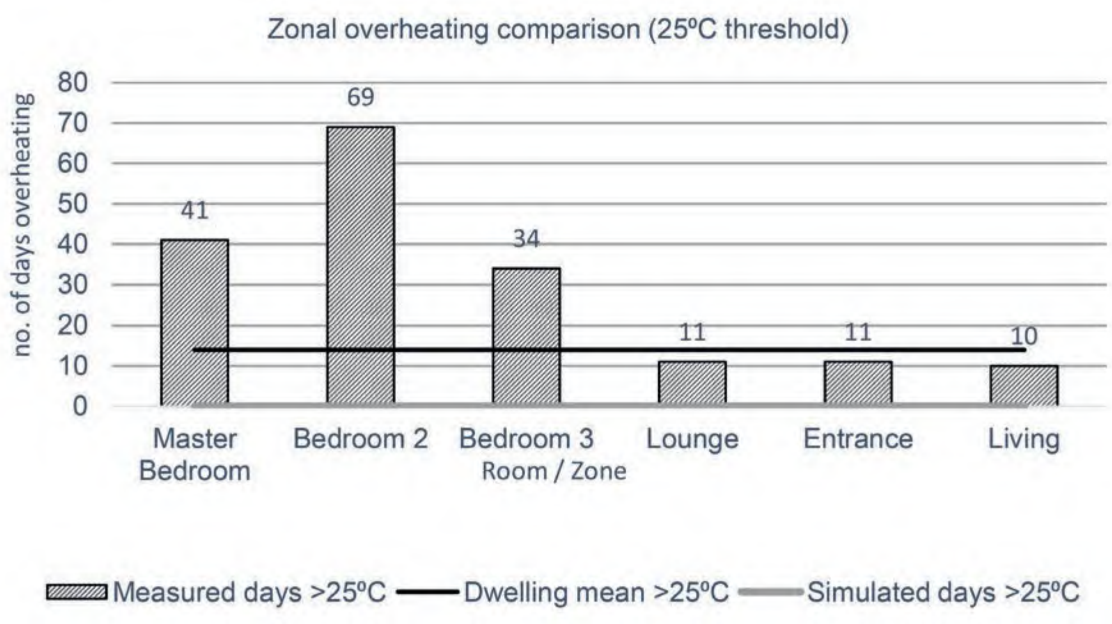


Figure 6.10 Results from an Irish study (Finegan et al., 2022) monitoring temperature thresholds in a Passive House-compliant dwelling in Cork. The chart records the number of days where measured temperature exceeds 25°C on a zonal basis. Source: Finegan et al. (2022). Reproduced with permission.

There is presently no legislative requirement in Ireland to account for future overheating in buildings, although guidelines by the Chartered Institution of Building Services Engineers (TM59 on thermal comfort and TM37 on building design measures for overheating) are recommended (Finnegan, 2008; Mulville and Stravoravdis, 2016). The Dwelling Energy Assessment Procedure from the Sustainable Energy Authority of Ireland is used for new buildings and provides a method for calculating overheating, assuming a constant external temperature of 15°C. It does not account for future temperatures and heatwaves. The emerging picture is that overheating is a key concern for highly insulated buildings and that the pace of change in building technology is outstripping our capacity to address overheating sufficiently through regulations. As in the UK, 'design for compliance' (Pan and Garmston, 2012; Ahern et al., 2018) contrasts with the measured real-world performance of buildings. Ireland would benefit from further research to inform policy cycles and retrofitting programmes based on both measured and simulated performance of new and retrofitted buildings. Further research has been conducted around the world to measure the effect of various modifications to decrease overheating frequency, with findings showing the benefits of a moderate use of glazing, addition of external solar shading, effective ventilation, orientation of building and insulation applied externally rather than internally (van Hooff et al., 2014; Fosas et al., 2018; Taylor et al., 2018). Place-sensitive design, with larger developments showing consideration for each individual unit, will reduce overheating frequency for new and retrofitted buildings, as will careful vetting at the planning stage alongside clearer guidelines and regulations.

6.4. Cross-cutting issues

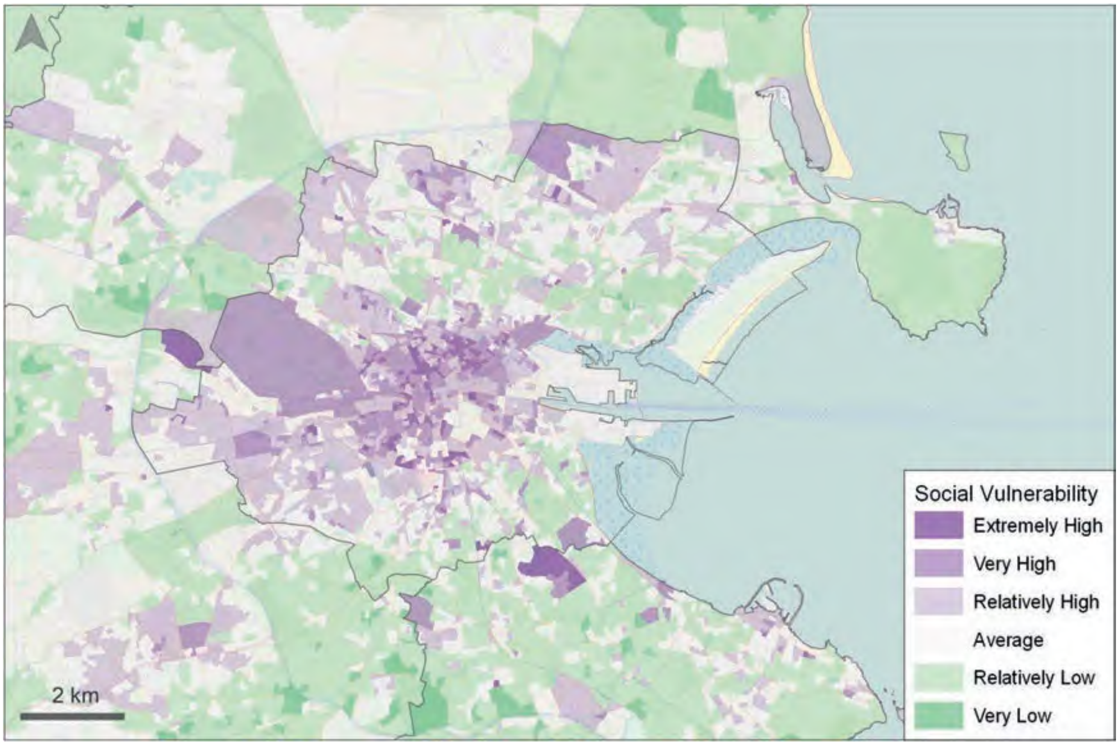
This chapter covers the built environment, settlements and heritage. Connecting these is the influence of our workplaces and homes on our health. Questions arising from the overheating potential of retrofitted homes, or from flooding of buildings, relate strongly to human health and wellbeing (Chapter 8). Adaptation for settlements is heavily place based and shaped by interaction with local communities. This discussion continues in Volume 4, Chapter 3, where the balance between established guidance and solutions and realities on the ground are discussed with further examples. Among rural communities across Europe, there are changes occurring in relation to provision of services, migration to urban areas and vacancy plus dereliction. Further work could be undertaken towards rational data-based reassessment of key settlement approaches in response to the actual amount of new one-off homes that exist (Ferreira et al., 2010; Scott, 2017; Scott and Heaphy, 2021).

Box 6.1 Unique Irish places and pressures: inner-city wards and dense urban cores

Ireland's international image is that of open landscapes, coastal areas, picturesque townscapes and villages. A very small proportion of the State consists of densely populated urban areas, which are in turn surrounded by low-to-medium density housing, with the exception of more recent plan-led developments such as Adamstown, Tallaght's new urban core and Pelletstown in the Greater Dublin Area. The rarity of dense urban areas in Ireland, plus the exceptional pressures to which they are subjected, makes them unique Irish places for consideration of climate change impacts.

Given Ireland's distributed population and general low-density settlements, housing and planning discourse is shaped by the political values of our public representatives. Particular care should be shown in our policymaking on housing and planning for denser urban core areas, which historically have lacked political resources, given the overwhelming rural character of the post-independence Republic (Kearns, 1983; Kincaid, 2006; Hanna, 2013). This has resulted in tensions between national and local government, where more advanced regulations for apartments and energy-saving policies pushed by local authorities such as Dublin City Council and Dún Laoghaire Rathdown have been rejected or scaled down. This is attributed to the market-based and neoliberal ideologies of successive national governments (Kitchin et al., 2015; O'Callaghan et al., 2015; Hearne, 2020; O'Callaghan and Cesare, 2021), yet it is also tied to the rural legacy of the State following partition from the industrial and more urban north-east.

Communities in inner-city Dublin have frequently had to protest to acquire the ear of national government as the limited resources of local government failed to address housing needs, crime and poor living environments (Moore, 2008; Doucet and Duignan, 2012). They have further come under gentrification



Box 6.1 Figure 1 Social vulnerability to environmental hazards classification using small areas for Dublin City. Source: Fitton et al. (2021). Reproduction licensed under the Creative Commons Attribution CC BY 3.0 licence (https://creativecommons.org/licenses/by/3.0/).

pressure as Ireland's housing crisis reached levels unprecedented since the age of tenements, rendering housing in central urban areas inaccessible to the middle ground between the very rich and the very poor. A small area scale mapping of social vulnerability (Fitton et al., 2021) correlates strongly with denser urban areas in Dublin and Cork, as well as areas in border and western counties (Box 6.1, Figure 1).

Although established as a strategic market-oriented regeneration effort incorporating a free trade area, the docklands redevelopment under the Dublin Docklands Development Authority combined strong social inclusion policies alongside material and physical interventions in the urban fabric of a long-depressed area of the city (Swyngedouw et al., 2002). As a bespoke well-resourced agency with community representation, it was able to bring tangible improvements to inner-city communities while at the same time gentrifying these same areas as part of a concerted urban renewal programme (Heaphy and Wiig, 2020).

Measures to address climate change impacts in these areas, whether in terms of flood risk mitigation, public spaces or building design, will need to be integrated into area plans, ideally with ringfenced resources and political backing. The concept of adaptive social protection, defined in IPCC AR6 as a resilience-building approach by combining elements of social protection, disaster risk reduction and climate change adaptation, may be useful in this context to link climate resilience with social resilience (IPCC, 2022).

This may go beyond present trends of time-limited task forces and programmes, which are not sustained across the decadal timescales over which such programmes can be measured. Opportunities to integrate climate measures into programmes to improve access to education and employment should be sought.

6.5. Priorities for research

6.5.1. Mitigation and adaptation in urban planning

Research on land use scenarios for urban development would be useful for comparing the various trade-offs between denser development and the higher emissions associated with low-density development and sprawl. These trade-offs include an increased UHI and localised unit-scale overheating for denser development versus the emissions trajectories and land use implications of continued sprawl. These objectives also link strongly to other land use functions, including biodiversity, agriculture, infrastructure and carbon sequestration. Many of the increased risks or even inconveniences associated with medium-to-high density development can be reduced or eliminated through better urban design with a greater input from urban planners and architects. Better design can create a comfortable microclimate for denser developments (as further discussed in Volume 4).

6.5.2. Urban heat island

Planners and architects require training and resources to move forward on the research already carried out on urban climate and social vulnerabilities. This could be coordinated with the climate action regional offices and the climate officers in each local authority to ensure that urban climate is understood by planners for planning control decisions, and better integrated into the master planning of new developments. Better resourced forward planning for local authorities can ensure comfortable microclimates for denser urban developments.

6.5.3. Buildings

The building regulations and retrofitting programme require attention to ensure that the regulations, certification process and skill sets match the combined demands for energy-efficient and climate-resilient homes. Targeted research on the building regulations can build on recent studies to ensure greater climate resilience to storms, wind-driven rain and overheating. Research in Ireland (Finegan et al., 2020) and Scotland (Morgan et al., 2017) shows that people can be at risk if night-time temperatures stay consistently high even in our temperate Atlantic climate. While the Chartered Institution of Building

Services Engineers' TM59 on thermal comfort and TM37 on building design measures for overheating are recommended, the task of making this or similar bespoke guidelines mandatory will need greater oversight from planning and enforcement.

Coastal planning is an area in flux as the policy landscape changes due to the Marine Planning Act. Where defences, whether hard or nature based, are deemed necessary, they should be informed by a study of the specific geomorphological properties of the coast in question where possible. As in the case of the Clontarf sea wall (Clarke and Murphy, 2019) and Kinvara Bay area (Revez et al., 2017), communities will require support to understand the processes in question and to deliberate on responses that are reality based and cognisant of natural processes and risk factors.

7

Critical Infrastructure

Key messages

1. Ireland depends on the resilience of its critical infrastructure for delivering public services, economic growth and a sustainable environment. Approaches to risk screening have been developed to examine vulnerabilities across four critical infrastructure sectors, namely transport, energy, water and communications infrastructure. Risk screening is useful for high-level assessment and identifying assets and locations for further analysis. This will need to be complemented with standardised quantitative approaches for stress testing critical infrastructure and identifying potential failure points, adaptation options and cascading risks.

2. Without effective adaptation, damage costs at the European scale to critical infrastructure from extreme events attributed to climate change are likely to increase from 2018 levels of €3.4 billion per year to triple that amount during the 2030s, six times by 2050 and 10 times by 2100. The main hazards causing these damages are expected to be heatwaves, droughts and coastal flooding, but also inland (fluvial, pluvial and groundwater) flooding, windstorms and wildfires.

3. For transport, sea level rise and flooding are key climate change risks. For energy, the key risks are extreme wind speeds, increased precipitation and saturated soils, given their impacts on the electricity distribution network, with flooding also of concern. Cascading of failures from the energy sector into other sectors is a key multi-sectoral risk. For water infrastructure, key climate change risks include flooding, wastewater treatment overflow and reductions in water quality related to extreme rainfall events, together with possible decreases in summer rainfall and droughts. For the ICT (information, communications and technology) sector, climate change risks related to extreme wind speeds are a key concern.

4. Some current infrastructural risks may reduce as the climate warms. For example, pipe bursts due to water freezing is a major weather-related operational issue for the water sector, but such bursts may become less frequent in a warmer future climate, as the number of frost and ice days is projected to decrease. However, gains could be offset by drought impacts through cracking and drying of the soil.

7.1. Introduction

'Critical infrastructure' refers to the array of physical assets, functions and systems that are vital to ensuring the health, wealth and security of a nation (Forzieri et al., 2018). Critical infrastructure provides services considered necessary for the routine functioning of a modern society. While slow degradation or depreciation of critical infrastructure may not immediately lead to degradation in the associated services, it increases the probability of a sudden failures within these key networks.

The definition above is largely carried through in the strategic emergency management guidelines for critical infrastructure, which consider how such issues would have a significant impact in the State as a result of failure to maintain those functions (Government Task Force on Emergency Planning, 2021). The NAF lists the water, energy, communications, transport and emergency services as critical infrastructure sectors at risk from sea level rise, flooding and climate extremes (DECC, 2018, p. 29). While attentive to broader pictures of critical infrastructure, this chapter examines solely transport, energy, and information and communications technology (ICT). Water provision and wastewater are covered in Chapter 5, and flooding is covered further in Chapters 5, 6, 8 and 9.

A characteristic of critical infrastructure is that it is possible to identify and list each individual piece. For Ireland, this is done by Hawchar et al. (2020), focusing on the four key sectors of transport, energy, water and ICT. These same four sectors were also taken to be the main repository of critical national infrastructure by the CIViC (Critical Infrastructure Vulnerability to Climate Change) project (Ryan, P. et al., 2021), which is the most substantial research project in Ireland to date on climate change and critical infrastructure.

Climate-related risks to critical infrastructure assets are a function of hazards, vulnerability and exposure. Some assets may be highly critical, meaning that the consequences of failure are significant. They may, however, have low vulnerabilities to climate hazards, meaning that their overall climate risk is low. This emphasises the importance of considering the three essential components of risk. It is also important to note that many pieces of critical infrastructure are dependent on other infrastructure to operate (Dawson et al., 2018). Consequently, seemingly resilient infrastructure can be vulnerable to cascading failures from other critical infrastructure sectors. Thus, it is important to consider interdependencies between sectors when assessing critical infrastructure risks. The Irish Academy of Engineering (2009) report on critical infrastructure adaptation focused on water supply, flood alleviation and energy, and recommended a series of planning, management, information and engineering measures that are broadly consistent with the thrust of this report.

A much more expansive concept of key infrastructure was taken by the IPCC WGII AR6, chapter 6 (Dodman et al., 2022), to include social institutions and networks and nature-based amenities, as well as physical, engineered assets. This chapter focuses exclusively on the climate change risks to the four key critical infrastructure sectors in Ireland and on how such infrastructure may be adapted to make it more resilient. It also attempts to identify specific gaps in monitoring, research and adaptation planning for critical infrastructure.

7.1.1. Adapting critical infrastructure

Critical infrastructure should be routinely maintained, frequently upgraded and ideally engineered to have sufficient resilience to operate within the full range of weather situations that are likely to arise in both current and future expected climates. The phrase 'likely to arise' can be quantified by choosing specific percentiles or occurrence frequencies for weather parameters such as temperature, precipitation and wind. More detailed assessment can also be completed using a quantitative risk analysis that incorporates uncertainty and variability at each assessment phase, as will be discussed later in this chapter. Weather and climate data are available (Nolan, 2015; Nolan and Flanagan, 2020) to assess the occurrence frequency of weather parameters with a quantifiable confidence level. Note, however, that the overall risk to any infrastructure asset depends on the vulnerability of the asset as well as on weather hazards.

Climate change, whether in the form of more extreme weather events or simply a shift in average conditions, is now a reality that needs to be factored into the overall design of critical infrastructure, including its location, capacity, versatility and operational range, and other resilience features. Quantitative projections out to 2100 by Forzieri et al. (2018) found that the cost of infrastructure damage within Europe caused by extreme events attributed to climate change is likely to increase from 2018 levels of €3.4 billion per year to triple that amount during the 2030s, six times by 2050 and 10 times by 2100. The main hazards causing these damages are expected to be heatwaves, droughts and coastal flooding, but also inland flooding, windstorms and forest fires. These increased hazards (and consequent infrastructural damage) are expected to be concentrated in southern and eastern Europe. Moreover, those projections were based on 'business-as-usual' or Late action on greenhouse gas emissions scenarios, which are not necessarily the most likely. While the semi-quantitative analysis by Forzieri et al. (2018) provides a useful high-level assessment of projected European-scale infrastructure damage, it cannot substitute for full quantitative analysis of asset-level vulnerability.

Dawson et al. (2018) list four strategies to manage climate change risks to critical infrastructure:

1. protect the infrastructure to reduce likelihood of failure;
2. improve component performance, so assets can operate under a wider range of conditions;
3. provide redundancy (back-up systems, increased capacity, more diverse components, alternative routings);
4. train people and provide the technology needed to respond to, and recover from, infrastructure disruption.

For Ireland, the CIViC report (Ryan, P. et al., 2021) highlighted the need to better understand critical infrastructure networks and the importance of moving towards a more quantitative risk-based analysis for examining climate change impacts and climate adaptation. Quantitative risk analysis can inform effective adaptation in the face of considerable uncertainty and variability, thus avoiding the opportunity costs associated with risk neglect, worst-case thinking and risk aversion. Resilient infrastructures may be characterised by their ability to anticipate and absorb disruption, adapt and transform themselves in response to external changes, recover quickly and learn from past experiences (Mehvar et al., 2021).

7.2. Risks, vulnerabilities and impacts

Forzieri et al. (2018) conducted a comprehensive high-level semi-quantitative assessment of risk to critical infrastructure across Europe due to climate change under a 'Late action' future emissions scenario. Risk was quantified as a combination of hazard, asset exposure and sensitivity. Future risks were extrapolated from costs and damage caused by recent extreme weather events. Seven primary hazards were identified (heatwaves, cold waves, droughts, coastal floods, river floods, windstorms and wildfires), with risks calculated over four infrastructural sectors (energy, transport, industry and social). Of the hazards listed, only cold waves (and their associated costs) are projected to decrease in the coming decades. Damage caused by windstorms, river floods and wildfires is projected to increase (from 10% to 100%, relative to the 1981–2010 baseline period). Specific estimates are for windstorm costs to critical infrastructure to increase from about €900 million per annum to €1,100 million throughout Europe by the 2080s; river flood costs to increase from €1,500 million to €2,500 million and wildfire costs to increase from €55 million to €79 million. However, damage caused by coastal floods, droughts and heatwaves is projected to increase by very large factors, including up to 20 to 50 times the present damage costs. Damage to critical infrastructure from coastal flooding was almost negligible during the baseline period (approximately €15 million per annum) but is projected to increase to €500 million per annum by the 2080s. Damage caused by droughts is projected to increase from about €450 million per annum to €15,000 million, while heatwave damage is projected to increase from about €370 million per annum to €18,000 million (Forzieri et al., 2018).

Some current infrastructural risks should be significantly reduced as the climate warms. For example, pipe bursts due to water freezing is currently a major weather-related operational issue for Irish Water, but such bursts should become less frequent in any warmer future climate (Irish Water, 2021a; section 2.3.3) as the number of frost and ice days is projected to decrease substantially (Nolan and Flanagan, 2020). More speculatively, an increase in surface solar radiation due to cleaner air (by about 3% per decade since 1990) (Wild et al., 2005; Müller et al., 2014) may enhance opportunities for infrastructural developments related to solar power generation. Increased total rainfall rates could similarly provide better opportunities for hydroelectric power generation.

7.2.1. Floods

Several studies of infrastructural exposure in the UK to current and projected climate risks provide relevant information for Ireland too. For example, under a scenario of 4°C global temperature rise by the 2080s, HR Wallingford (2014) projected that the fraction of the UK rail network vulnerable to flooding (about 2,400km currently) would double.

Across the UK and Ireland, van Leeuwen and Lamb (2014) reported that flooding caused or contributed to 138 bridge collapses between 1846 and 2013, corresponding to an annual probability of approximately 40% that a flood event will cause one or more bridges to fail (of a current total of approximately 12,900 main bridges). Many bridge collapses are triggered by relatively minor flood events, with other factors contributing too, such as the slow undermining effects of scour, which leads to a gradual weakening of structural foundations. According to HR Wallingford (2014), approximately 5% of the UK main road and railway bridges will be highly exposed to increased scour, while 26% will be moderately exposed – an increase from 0% in both exposure categories currently. Those 5% of bridges will be vulnerable to a projected 8% increase in river scour by the 2080s in a 4°C warmer climate. Small increases like this could be enough to exceed the tipping point for failure of many vulnerable structures. It is the nature of scour to remain undetected until it leads to a major incident, as occurred when a section of the Broadmeadow viaduct, north of Malahide, collapsed in 2009 (see Figure 7.1).

Figure 7.1 Aerial image of the section of the Broadmeadow viaduct near Malahide that collapsed on 21 August 2009. Source: https://cdn.ca.emap.com/wp-content/uploads/sites/9/2009/09/0908230099.jpg

Although difficult to quantify, sewer flooding and sewer overflow events are both likely to become more frequent as rainfall becomes more intense and pluvial flooding more frequent (Dawson et al., 2018). These overflows can affect popular swimming beaches and water quality more generally, as well as lead to more intangible reputational damage, e.g. to tourism. This is particularly true in Ireland where urban drainage systems predominantly consist of combined foul and storm networks, increasing the pressure on wastewater treatment plants from intense rainfall events (Saikia et al., 2022).

Forzieri et al. (2018) project the cost of expected annual damage to critical infrastructure due to coastal flooding across Europe to increase by a factor of 20–30 by 2100, relative to 2018. Ireland's main cities are coastal and on the outlet of major rivers, and they contain infrastructure that is highly exposed and vulnerable to this hazard – as well as to compound flooding due to heavy rain, high river levels and storm surges all occurring together (see Chapter 6). In the same report, Forzieri et al. project the cost of expected annual damage due to river flooding across Europe to increase by a factor of about two by 2100.

7.2.2. Droughts

Currently in Ireland, 15 consecutive days without rain formally constitutes a drought. Given current infrastructure, supply stresses can occur almost anywhere, depending on the vagaries of weather patterns that may remain quasi-stationary for several weeks. However, current imbalances in the water supply infrastructure make some regions such as the Greater Dublin Area and the Midlands particularly vulnerable (McGuire, 2018; Irish Water, 2021a). Seasonal demand changes play a role too: people moving from cities to holiday destinations at certain times of the year tend to put pressure on supplies there. However, it is widely acknowledged that extra capacity and resilience are already badly needed in Irish water supplies (Irish Water, 2021a). Drought-related stresses on water supplies will increase in the future as demand increases and as extended dry spells become more common.

Forzieri et al. (2018) projected the cost of expected annual damage to critical infrastructures caused by droughts across Europe to increase by multiples of 20–30 by 2100. The specific drought-related number for Ireland was not provided, but aggregated over the range of seven different climate hazards considered, Ireland was projected to experience damage increases in the low to middle part of the European-wide range. Of those seven climate hazards, droughts and heatwaves (which frequently occur together) were highlighted as causing the most damage to critical infrastructures now, especially in the energy, industry and social sectors, such as health and education. Their costs were also projected to increase the most dramatically (by up to 300 times or more to about €18 billion per year) out to the end of the century.

7.2.3. Windstorms

Assets at risk from windstorms (and associated incidents such as tree falls) include overhead cables used for electricity, phone and broadband internet distribution. Projections of future wind speeds suggest a reduction in mean wind speed but an increase in variability (Ranasinghe et al., 2021). Over northern and western Europe, a slight increase in the frequency and amplitude of windstorms is projected, particularly if global surface temperature increases exceed 2°C (Ranasinghe et al., 2021).

Using the same analysis as described above for droughts, Forzieri et al. (2018) project an approximate 10% increase in the cost of expected annual damage due to windstorms by 2100 across Europe, to approximately €1 billion per year. This is under the relatively high future emissions scenario, which assumes little or no climate mitigation. Along with cold waves (which are projected to decrease) and wildfires, windstorms are one of the three least damaging of the seven climate hazards considered at the European scale; however, this is unlikely to be the case for Ireland. Hawchar et al. (2020) report that the greatest risks to the approximately 2 million timber power poles in Ireland are windstorms and wood decay. As reported in Volume 1, increased moisture and heavy rain events, both projected for future climates in Ireland, are likely to accelerate the decay of timber poles.

7.2.4. High temperatures

The frequency of rail-buckling events is expected to quadruple in a climate that is 2°C warmer than present (Dobney et al., 2009). Tracks can be re-tensioned to suit prevailing temperatures, so the greater risk is probably from an increased range of temperatures rather than from a simple shift in temperature (i.e. a uniform absolute change). Some countries with regular swings in temperature extremes may adjust their rails between summer and winter, but, currently in the UK, this is considered neither practical nor cost-effective (Network Rail, 2023). As cited above for droughts and windstorms, and using the same Late action emissions scenario, Forzieri et al. (2018) project the cost of expected annual damage due to heatwaves to increase by factors of 20–40 by 2100 across Europe. While those costs are based on the relatively strong emission scenario responses analysed by Forzieri et al., it is reasonable to assume that proportionately lower costs and less risk would apply under lower emissions scenarios.

7.2.5. Geohazards (fires, landslides, subsidence)

Any future increase in the frequency or duration of dry spells or heatwaves increases the risk of fire proportionately. Insofar as most wildfires are in relatively remote locations (e.g. hillside gorse or forest fires), they usually pose little threat to critical infrastructure. However, wind farms and power transmission networks will be increasingly located in places vulnerable to wildfires, and under most plausible future climate scenarios heatwaves are projected to be more frequent and longer lasting, further raising the fire vulnerability of those installations. Forzieri et al. (2018) project only marginal increases by the end of the century in the expected annual damage due to wildfires across Europe. That risk is distributed almost equally among energy, transport and social infrastructure, with industrial infrastructure at relatively lower risk.

Landslide susceptibility maps for Ireland are provided by Geological Survey Ireland (McKeon, 2016). Hawchar et al. (2020) combined these maps with infrastructure information to assess risk. Their analysis indicated that no major change to the landslide or subsidence risk profile is expected as a direct result of climate change. However, intensification of the changes in weather from dry to wet conditions under future climate scenarios may amplify the soil shrinking and swelling cycle, leading to greater risk of landslides.

7.3. Adaptation strategies

7.3.1. Transport and logistics infrastructure

Following the approach of avoid–shift–improve (IPCC, 2014, p. 603; Müller and Reutter, 2022), climate impacts on transport can be reduced through minimising journeys and improving connectivity and reliability. Future transport, if suitably tied to land use planning and urban design, will become less dependent on private transport. To further Ireland's climate neutrality targets, investment is increasing in both active travel (self-propelled means of travel such as walking and cycling) and public transport, both of which are reliant on combined strategic planning of both housing and transport to create a critical mass and density of population. In the present, being an island nation with a dispersed population, Ireland is highly dependent on its road network of approximately 96,000km (DPER, 2021, p. 72). Only Dublin has a light rail and tram network for urban public transport. Other regional cities are far smaller in size and are serviced by buses and commuter rail services. Smaller cities and towns have limited bus and rail services, while rural areas are reliant on private cars and infrequent bus routes.

Future impacts (heat, extreme weather events, flood, SLR, erosion). A GIS-based analysis of transport climate vulnerabilities in Ireland completed by P. Ryan et al. (2021) highlights the importance of fluvial and coastal flooding events to road, rail, bridges and airports (and more specifically Shannon Airport) (see Figure 7.2).

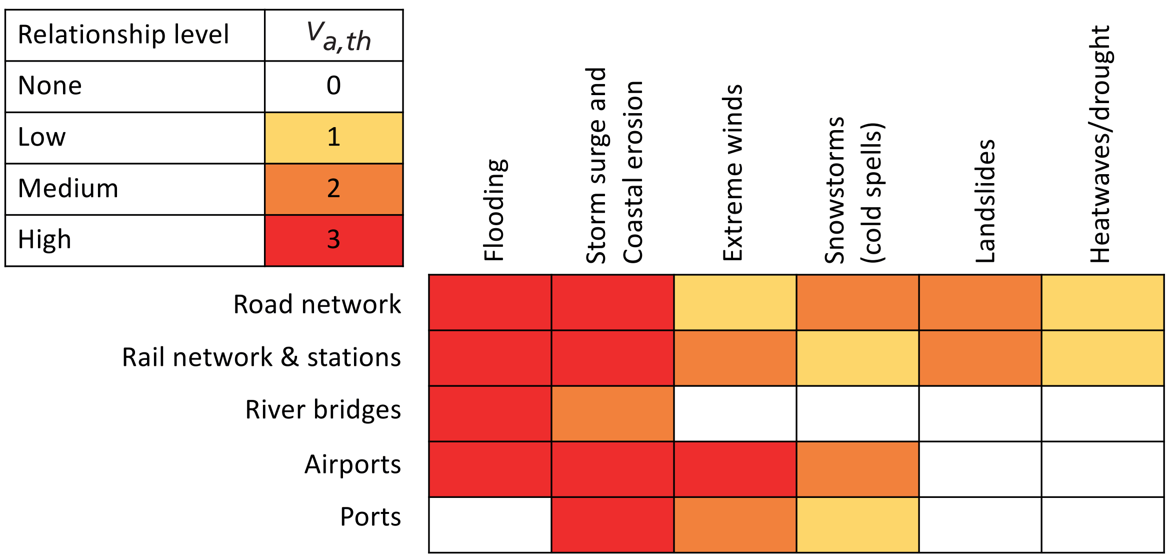


Figure 7.2 A vulnerability matrix for Irish transport infrastructure systems. Source: Hawchar et al. (2020). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

The CIViC project assessed the four main critical infrastructure sectors using semi-quantitative climate risk approaches in addition to a detailed quantitative assessment of a component of Ireland's energy infrastructure (Ryan, P. et al., 2021). The semi-quantitative approaches utilised in the CIViC project and by Hawchar et al. (2020) were based on established methods for spatial risk assessment (Dawson et al., 2018; Koutroulis et al., 2018) used in the UK Climate Change Risk Assessment. These impacts, and measures to address them, can be further investigated by partnerships between research and infrastructure owners so that specific asset information can be shared and analysed. For instance, the CIViC project did not integrate data directly from the Local Government Management Agency's pavement management system, which has empirical information on the degradation and works scheduling for all roads in Ireland. Once data on road assets are shared, changes to road materials and drainage solutions can be evaluated and screened against future climate impacts in much more detail.

Alterations to roads can be to road structure and design standards, maintenance schedules or traffic management (Enríquez-de-Salamanca, 2019). Projected increases in rainfall and flooding events will mean that sections of road may be impacted by both short-term flooding events and long-term increases in mean precipitation. Further specific research will be needed to elaborate what climate adaptation actions are needed in an Irish context for each particular asset type.

Monitoring and knowledge gaps. Future research will need to build climate change into design standard revision cycles and maintenance schedules. It is noted, however, that some Irish transport bodies have commenced this process already for some of their infrastructure. While these advances are encouraging, there is a recognised need to progress to fully quantitative risk assessment as a form of risk-based decision support. This was one of the key findings of the CIViC project, which presented a high-level semi-quantitative analysis, showing how these studies could indicate possible impacts but were limited in informing climate adaptation actions for valuable and expansive critical infrastructure assets. However, the study also presented the results of a detailed fully quantitative risk assessment of energy infrastructure (timber power poles), assessing the effectiveness and cost–benefit outcomes of adaptation actions. The authors conclude that these detailed methods can inform effective adaptation action in the face of considerable uncertainty and variability, thus avoiding the opportunity costs associated with risk neglect, worst-case thinking and risk aversion (Ryan, P. et al., 2021, p. 66).

A strategic and selective protection of key assets requires asset-specific information as a baseline for planning. Data sharing will be essential for coordinated adaptation, given the interdependencies of critical infrastructure (see section 7.4). This will allow climate adaptation actions to be costed and implemented into climate-readiness plans that extend beyond the present first- and second-pass screening stages (Tonmoy et al., 2019; Flood et al., 2020b) of adaptation evident in the 2018/2019 sector plans. On this basis, adaptation indicators (Flood et al., 2021) can be formulated in detail and climate actions monitored and reviewed.

Smart technologies and modelling future transport planning. The implementation of real-time passenger information in the last decade has greatly improved the efficiency of journeys for bus services in Dublin and regional cities (NTA, 2018; Heaphy, 2019). Similar efficiencies have been delivered to road users through variable pricing of tolls, centralised road management traffic centres and improvements to traffic junctions based on the dynamic analysis of real-time traffic (McCann, 2014; Coletta and Kitchin, 2017).

The issues that matter to transport providers depend on their responsibilities and needs. Wang et al. (2019) examined how transport professionals prioritise road and rail climate impacts in the UK, which shows consensus concern around traffic delays and rerouting, and their attendant costs. Safe, secure and free circulation of goods and people is a priority for transport providers and engineers, yet long-term decisions beyond day-to-day operations may also benefit from integrated modelling of future impacts (Jin et al., 2017; Ford et al., 2018; Müller and Reutter, 2022).

Integrated assessment models incorporating transport, the economy and land use, among other sectors, can inform incremental and radical changes in relation to climate impacts (Ford et al., 2018, p. 87), providing surrogate experimental and control environments for a sector that is not amenable to large-scale experimentation. Smart city programmes, such as Cork's participation in the European Commission's Intelligent Cities Challenge (https://www.intelligentcitieschallenge.eu/cities/cork), the many projects led by or coordinated with Smart Dublin (https://smartdublin.ie/) and Limerick's participation as a lighthouse city in the Horizon 2020-funded +CityxChange (https://cityxchange.eu/), can provide a basis for projects where stakeholders form part of applied research from inception through to results dissemination. Furthermore, these programmes communicate findings and identify collaborative opportunities through the All Ireland Smart Cities Forum.

7.3.2. Energy infrastructure

The main energy infrastructure in Ireland consists of power stations and wind farms, along with the pylons, poles, cables and control centres of the power distribution network, and the gas network. Currently, solar energy installations constitute relatively minor, non-critical components of the energy infrastructure, but are likely to become increasingly important within the next decade or even sooner. Oil importing and storage facilities and the Whitegate refinery in Cork are also critical energy infrastructure. Hawchar et al. (2020) considered the energy infrastructure to be among the most important of all critical infrastructure due to its essential role in the provision and operation of other critical infrastructure. As with ICT infrastructure, the most vulnerable part of the energy infrastructure is the overhead electricity network, which is susceptible to failures during storm events.

Forecast development and shift to carbon neutrality. The direct response of the energy sector to climate change risks is likely to be to harden its infrastructure and make it more resilient. That direct response, however, will be dwarfed by the process of transitioning from an energy infrastructure built on burning fossil fuels to an infrastructure built on renewable energy sources. This infrastructure will consist of a much more distributed power generation network (much of it in remote places), along with major upgrades to the power distribution network (involving new pylons and cables) and an increasingly sophisticated network management and control system. Centralised control systems qualify as critical infrastructure. The development of new energy infrastructure will provide a low-cost opportunity to develop climate-resilient infrastructure that will last into the future. However, to take full advantage of this opportunity, detailed quantitative risk analysis should be conducted to help understand what the potential future risks are and the cost-effectiveness of any climate adaptation strategies. Almost certainly, the energy infrastructure will need to accommodate significant amounts of localised power or 'micro-generation' at the very fine-grained level of individual houses or farms.

Along with changes to power generation, power consumption patterns will also transition from fossil fuels to electricity as a source of energy, as is the case with battery electric vehicles and heat pumps. Regional power blackouts are a regular occurrence in the wake of code red or even code orange winter storms. These dependencies may be reduced by more distributed power storage capabilities (such as batteries in the home), but such capabilities do not currently exist at scale. Greater energy efficiency measures can also help, not by making critical infrastructure any less critical but by placing less stress on it, thus making it more resilient. In all these ways, changes to the national energy infrastructure in response to climate change will involve fundamental reorganisation and transformation.

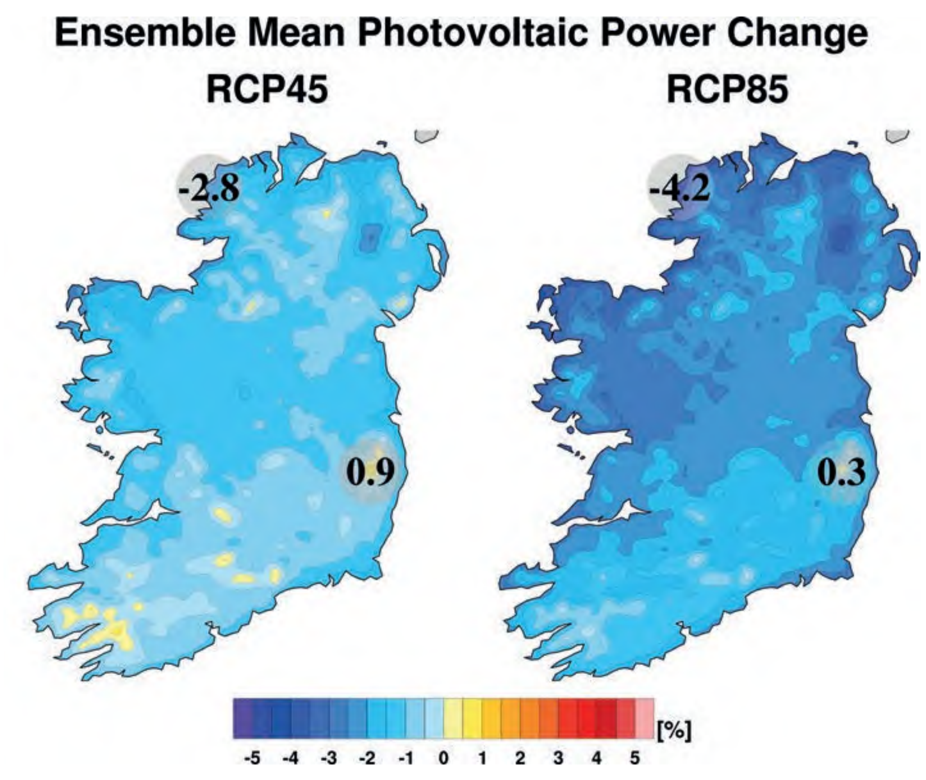


Figure 7.3 Mid-century projected changes (%) in mean annual solar PV power. Source: Nolan and Flanagan (2020).

Impacts on energy supply. Nolan and Flanagan (2020) used an ensemble of regional climate model datasets, under a range of emission scenarios, to assess the impact of climate change on solar photovoltaic (PV) power in Ireland. The projected change in PV power, presented in Figure 7.3, shows a small decrease by the middle of the century, ranging from approximately 0% to 4%. The largest decreases are noted in the north of the country and for a Late action scenario. The results are consistent with Jerez et al. (2015), who analysed the effects of climate change on PV in Europe using an ensemble of EURO-CORDEX models. The reductions in PV and surface solar radiation (Nolan and Flanagan, 2020) are likely to be attributed to increasing atmospheric absorption in line with an increase in water vapour content (Bartók et al., 2017). Projections such as those in Figure 7.3 can be used to set expectations for the productivity of future PV installations.

A warming climate is projected to decrease heating requirements in Ireland, which has the potential to alleviant stresses on the power transmission network. Figure 7.4 shows projections of heating degree-days (HDDs) as simulated by an ensemble of regional climate models, indicating that by the middle of the century HDDs are projected to decrease by 12–17% and 15–21% for Middle and Late action scenarios, respectively (Nolan and Flanagan, 2020). A clear north-to-south gradient is evident, with the largest decreases in the south. The projections show that cooling degree-days are expected to slightly increase, suggesting a small increase in air conditioning requirements by the middle of the century. However, the amounts are small compared with HDDs and therefore have a negligible effect on the projected changes in the total energy demand.

Along with the vulnerability of the power transmission network due to windstorms (section 7.2.3), P. Ryan et al. (2021) detail further risks in Ireland from flooding and coastal erosion, such as where power stations and other critical infrastructure may be more vulnerable to flooding events (see Figure 7.5). However, the study also presented the results of a detailed fully quantitative risk assessment of energy infrastructure (timber power poles), assessing the effectiveness and cost–benefit outcomes of adaptation actions (Ryan and Stewart, 2021). Further research should determine actions to protect and minimise damage to these assets with specific actions. As the DCCAE (2019) sectoral report notes, redundancy built into the network means that outages caused by the flooding, say, of substations should affect only a limited number of customers, depending on the extensiveness of the flood event.

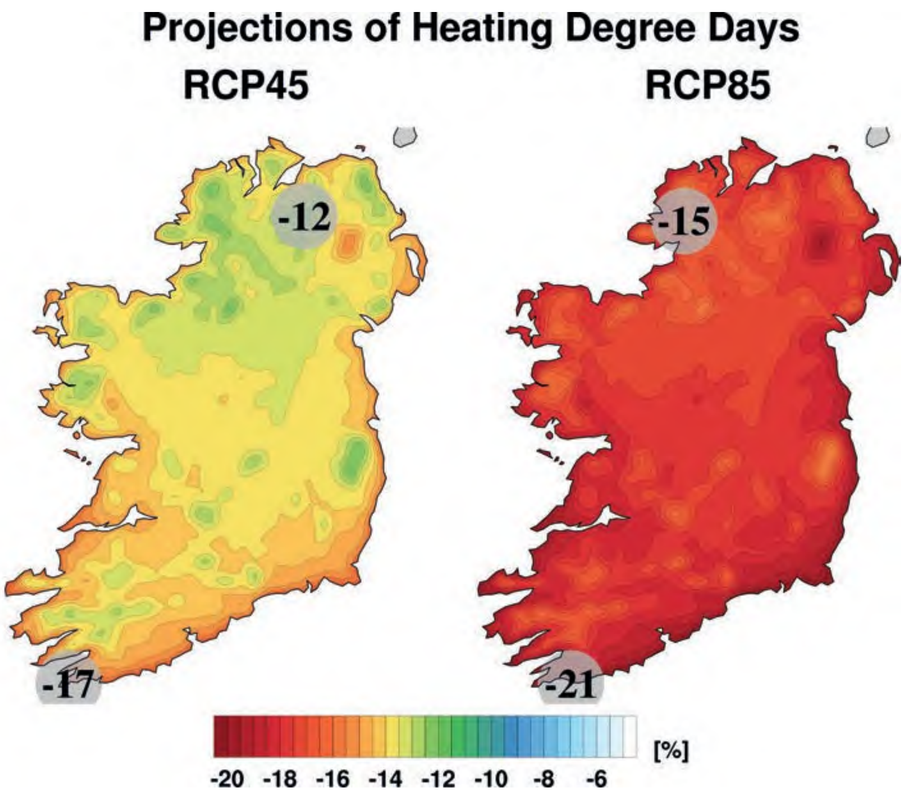


Figure 7.4 Mid-century projected changes (%) in HDDs for the (a) RCP4.5 and (b) RCP8.5 scenarios. Source: Nolan and Flanagan (2020).

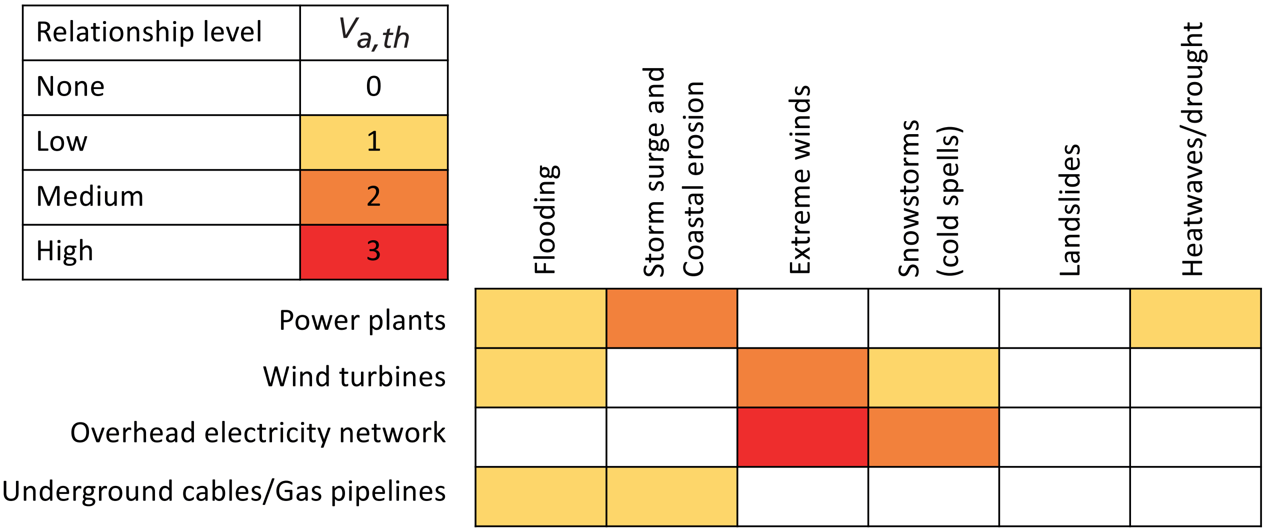


Figure 7.5 A vulnerability matrix for Irish energy infrastructure. Source: Hawchar et al. (2020). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

Distribution networks are normally very extensive geographically and consist of many near-individual connections, so that climate change is more likely to affect multiple independent clusters of customers through breakdown of their connection to the networks. Flooding of larger stations is another potential risk, although distribution stations are normally limited in size to 2 × 10MVA (say up to 10,000 domestic customers) and standby arrangements may be available for up to 50% of this load from adjoining substations.

Monitoring and knowledge gaps. P. Ryan et al. (2021) highlight several limitations of their high-level analysis work on the four critical infrastructure sectors, which will need to be resolved to advance both on-the-ground measures and adaptation progress reporting. First, they note that the "the overhead electricity lines are not included in the GIS-based high-level risk analysis, as the GIS data for the overhead electricity transmission and distribution grids could not be obtained from the corresponding energy companies for commercial sensitivity reasons." To implement climate risk assessment, such data will have to be procured and utilised to build concrete adaptation actions beyond the broad first-pass screening commitments in the DCCAE (2019) report.

In future, however, the increasing dependence of both private and public mobility on electricity and charging facilities (e.g. Beheshtian et al., 2018) will need at least equal consideration. The expansion of battery storage and local (or 'micro') power generation at the level of individual buildings may provide further resilience to small-scale outages (Ghanem et al., 2016). Vehicle-to-grid technologies are advancing and, with the expected widespread adoption of electric vehicles, will become broadly accessible to many homes as a convenient means of storing excess energy during off-peak times (or from PV panels). Such battery-stored power can then be returned to both home and grid as needed, albeit with some fractional loss during each conversion. These interdependencies, along with quantitative risk analysis to inform concrete asset-specific adaptation actions rather than general aspirational goals, should add overall resilience and provide a further platform for climate readiness. The more expensive the adaptation, the more robust the justifying quantitative risk analysis needs to be to make it happen.

7.3.3. Communications infrastructure

Communications infrastructure comprises fixed and mobile networks. In September 2020, the European Commission adopted a recommendation calling on Member States to boost investment in very high-capacity broadband connectivity infrastructure, including fibre and 5G. In Ireland, as part of an EU-wide plan, copper-based services are currently earmarked for replacement with fibre-optic based networks[6], and in some cases fixed-line networks are being extended by wireless ones. Eircom's own infrastructure is now being supplemented by the National Broadband Plan, implemented by National Broadband Ireland network. Together, these will provide a comprehensive fixed broadband service to all of Ireland.

Key impacts. From a climate perspective, however, the fibre-optic-based broadband delivery infrastructure has many of the same characteristics as fixed telephone lines, via overhead and underground connections all connected to an access network consisting of roadside cabinets and exchanges that are then connected to a core network. The Communications Sector Climate Adaptation Plan (DCCAE, 2019) identifies the most 'distributed' elements of the access network (i.e. overhead lines and underground cables) as more vulnerable than other 'access' network elements (radio base stations, transmission nodes, exchanges). Overhead cables are vulnerable to wind, snow, rainfall and even a prolonged growing season – effectively anything that increases the threat to cables from falling or growing trees or failure of the poles or cables themselves.

HR Wallingford (2014) reports that approximately 15% of all telecommunications masts (of all sizes) in the UK are in areas vulnerable to shrink–swell subsidence. Such exposure has not been assessed for Ireland. Underground cables are vulnerable to both flooding and droughts (along with coastal erosion), due to the direct risk of water damage, and also due to physical stresses from saturated soil expanding and dry soil contracting.

In December 2022, ComReg published a report Climate Change and its effect on Network Resilience – A Study by Frontier Economics (ComReg, 2022). This study considered the 2019 Communications Sectoral Adaptation Plan and presented findings on:

- electronic communications networks' (ECNs) and electronic communications services' vulnerability to climate change;
- preparation for the effects of climate change and the subsequent adaptation measures implemented across ECNs;
- the potential future steps to further adapt ECNs to climate change.

The principal network vulnerabilities identified in the report are listed in Table 7.1.

Table 7.1 *Network vulnerabilities*

Wireless networks	Fixed networks
Wind damage of overhead infrastructure and misalignment of antenna	Wind damage to cables and poles, e.g. by falling trees
Flooding of underground infrastructure	Flooding of underground infrastructure or street cabinets can cause corrosion or short circuits that degrade the service
Signal loss caused by heavy precipitation ('rain fade')	Overheating of street cabinets
Signal loss by ice build-up on dishes	Damage to overhead infrastructure by heavy snow
Lightning damage to electrical components	Power outages
Power outages	

Source: Compiled from ComReg (2022; figure 1).

Monitoring and knowledge gaps. By and large, the risks to critical communications infrastructure due to climate change are primarily enhancements of the risks that exist today. The large, nationwide distributed network of overhead lines, underground cables and radio base stations inevitably have weak points that will eventually be exposed by some extreme weather event (storm, flood, drought, heatwave). It is possible that future climate conditions will warrant the selection of higher standards in specifications, maintenance and deployment of cables, poles and radio base stations, which warrants further research as part of sectoral strategies and overall network hardening programmes.

[6] https://digital-strategy.ec.europa.eu/en/policies/connectivity-toolbox; https://www.openeir.ie/wp-content/uploads/2021/03/White-paper_Leaving-a-Legacy.pdf; https://www.comreg.ie/media/2022/04/ComReg-2213R.pdf

In the aforementioned ComReg report, actions and inconsistencies in reducing vulnerabilities to communications infrastructure were identified:

- Few operators specifically consider climate change as a risk to their ECN, and instead design their ECN to be resilient to a range of environmental conditions. Only one operator had commissioned a specific climate change risks report.
- All operators monitor upcoming weather, although operators have different approaches to codifying their response to severe weather. Some operators have a clear and detailed 'storm plan'; similarly, another operator has a storm protocol that defines how it responds to severe weather events.
- Some operators provide back-up power (with batteries and or generators) of up to 2 days in some parts of their network, whereas others have back-up power for as little as 10 minutes in parts of their network (enough time for equipment to power down safely – but not to maintain service).
- Electronic communications service providers or other ECN operators that rely on the physical infrastructure of another operator noted that they had very limited information about the physical state of the host ECN, which made assessing weather-related risks to the network difficult.

7.4. Cross-cutting issues: interdependencies and compound events

Just as climate-related hazards can be compounded by two or more of them occurring together or in a cascade of closely related events (see Volume 1) (Pescaroli and Alexander, 2018; Girgin et al., 2019), climate-related risks to critical infrastructure can also be compounded by interdependent links between two or more critical infrastructure sectors. Such interdependencies are especially important if infrastructure is considered more broadly as a coupled set of interdependent social–ecological–technical systems (Mehvar et al., 2021; Dodman et al., 2022).

Every infrastructure sector can identify failure of another infrastructure sector as a primary risk to its own operations (Defra, 2013). One clear interdependency is the requirement that all sectors have for electrical power. Electrical power failures or outages immediately disrupt wastewater treatment, water supply and telecommunications (see also Government Task Force on Emergency Planning (2021)). Communications infrastructure is also now vital to the smooth operation of many other infrastructure networks, including power stations and transport systems. Much infrastructure also depends on transport networks to deliver fuel, spare parts, food and other supplies. The co-siting of cables and pipes for multiple utilities also represents a compounding of risk should those sites be subject to unplanned disruptions, whether by floods, wind or accidental human activity.

Tsavdaroglou et al. (2018) proposed a methodology for analysing the risk associated with interdependent infrastructure assets to extreme weather events (whether single or compound). They showed that a single infrastructure failure or a common cause event may give rise to a cascading set of infrastructure failures, the combined effects of which depend on the recovery time of each asset. Even after recovery from an extreme event, risks actually increase. A relatively straightforward dependency cascade occurred when Storm Ophelia made landfall in Ireland in 2017: power failures caused by the storm winds led to water supply cut-off and wastewater treatment shutdown, leading in turn to waterway pollution.

The Strategic Emergency Management Guideline 3 – Critical Infrastructure Resilience (Government Task Force on Emergency Planning, 2021) provides metrics for defining the extent and severity of impacts across various scales. Furthermore, the EPA 2021 report on disaster risk reduction (Medway et al., 2022) provides a more general perspective on managing risks, building on the Horizon 2020-funded ESPREssO (Enhancing Synergies for Disaster Prevention in the European Union) project. It provides a series of recommendations for integrating climate change adaptation and disaster risk reduction around the project's 'SHIELD' model (see Figure 7.6). At its core, SHIELD has the three objectives of preventing new risk, reduction of existing risk and management of residual risk. The SER guidelines and EPA disaster reduction report (Medway et al., 2022) provide a framework for further, more localised responses to impacts in specific sectors or groups of interdependent sectors.

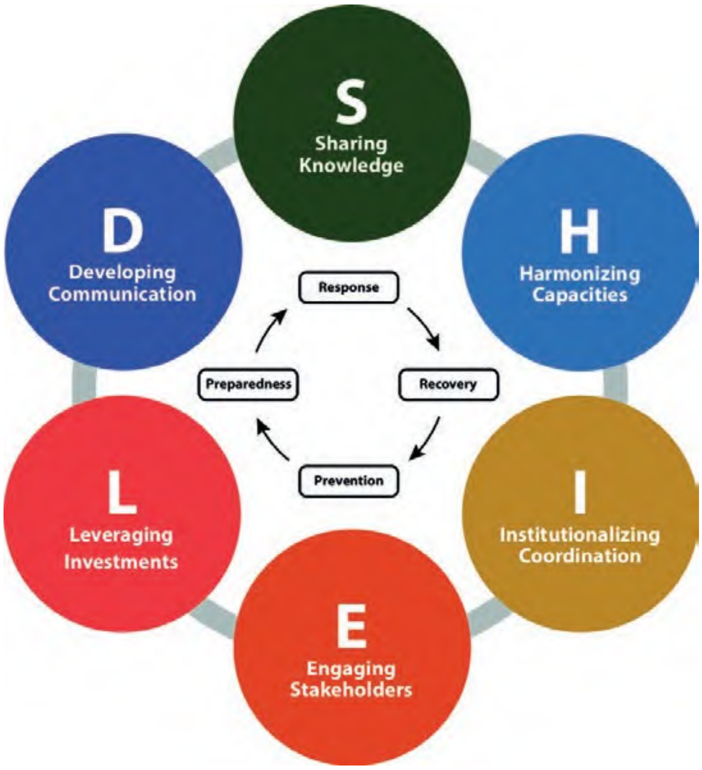


Figure 7.6 SHIELD model for disaster risk reduction from the EU H2020 project ESPREssO. Source: Medway et al. (2022).

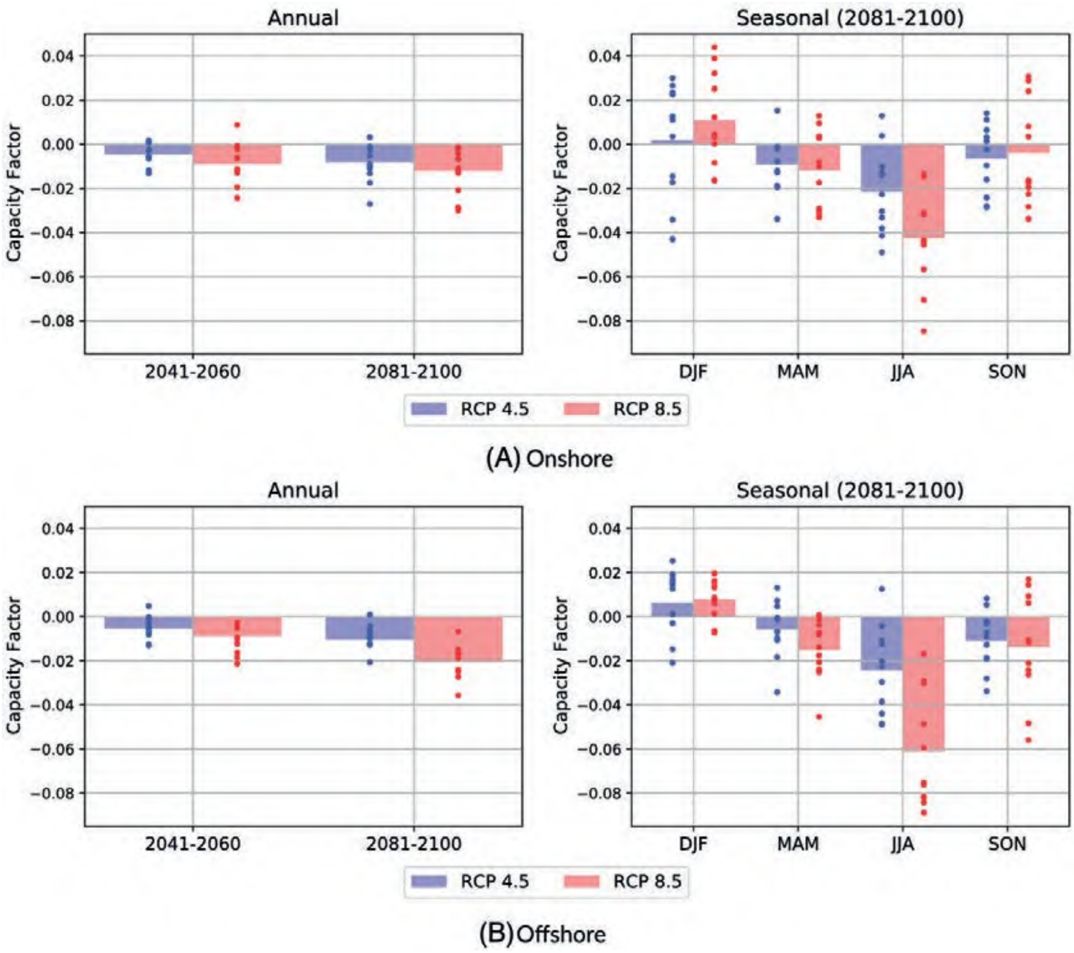
Box 7.1 Unique Irish pressures and places: wind farms

Wind farms are an essential part of Ireland's plan to reduce greenhouse gas emissions. We already have a lot of wind farms in Ireland, and wind generation capacity has increased from around 115MW in 2000 to over 4,300MW in 2021 (EirGrid, 2021). However, we need to increase this substantially if we are to achieve the government targets set out in the Climate Action Plan 2021, with an additional 5GW of both onshore and offshore wind capacity planned by 2030 (DECC, 2021). As we build more wind farms and reduce our reliance on fossil fuels, wind farms will become responsible for a larger part of our overall energy generation. This will make them a more critical part of Ireland's energy infrastructure. We will need to build a lot of the new wind farms at sea as offshore wind farms. Such wind farms are more challenging to build than their onshore equivalents, but they offer the advantage of more consistent generation.

To efficiently manage the increased role that wind farms will play in our future electricity generation, it is essential that we have an accurate idea of how much electricity wind farms will generate, and when. We need this knowledge of wind generation on two timescales. The first, from a few hours to a few days into the future, is called short-term forecasting. This allows us to manage the existing energy infrastructure efficiently. If the wind is going to be strong and consistent, wind farms can generate a lot of electricity. However, if there are periods of low winds, we will need to ensure that electricity can be generated from other sources during those times. We generate forecasts using computer models of the atmosphere. Advances in research have improved the way these models represent the atmosphere. Supercomputers have also become more powerful. This means that we can run forecast models at higher grid resolutions, as well as running a collection of forecast models, called an ensemble. This allows us to calculate the probability of different events occurring during the forecast period. All of these advances have led to increased accuracy of our short-term wind power forecasting in recent years.

The second timescale is on the scale of decades. The lifetime of a wind farm is typically around 20 years. We need to know how much electricity it will generate over that period to ensure that the investment is worthwhile. However, we also need to know more details, such as how generation is expected to vary during different months of the year and at different times of the day. To answer questions like these, we use decades of historical wind data from reanalysis datasets, which represent our best estimate of what the atmosphere has done over recent decades. We also need to investigate the impact that climate change may have on the wind farms of our future. We do this by using wind data up to the year 2100 from different climate models.

One recent example of this type of research (Doddy Clarke et al., 2022) has indicated that changes in wind energy generation in Ireland are evident by mid-century and are more pronounced by 2100, particularly for high emissions scenarios. Seasonally, wind energy is projected to decrease by less than 6% in summer and to increase slightly in winter (Box 7.1, Figure 1). The frequency of low wind energy events is projected to increase, especially during summer. The research suggests that developing offshore wind energy generation could allow the national energy system to maintain more stability, as low winds in one region of the future wind farm network may be compensated by a different region with higher wind speeds.



Box 7.1 Figure 1 Future changes in (a) onshore and (b) offshore wind generation capacity for the end of century, relative to 1981–2000. Seasons are winter (DJF), spring (MAM), summer (JJA) and autumn (SON). Dots are individual climate model results; shaded bars are ensemble means. Source: Doddy Clarke et al. (2022). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

7.5. Priorities for research

Foundations for future research have been laid through the EPA report on disaster risk reduction (Medway et al., 2022), the CIViQ project and corresponding EPA report (Ryan, P. et al., 2021), and the work of the Government Task Force on Emergency Planning (2021). Moving forwards, the task force can work with infrastructure providers and research agencies to advance asset-level resilience studies across a range of climate scenarios.

7.5.1. Standardised projections and baseline data

As discussed in Chapter 10, a consolidated and definitive or official set of climate projections covering key variables on both mean changes and extremes can provide a baseline for asset-level tolerance modelling. The Government Task Force, meanwhile, can assist in the data-sharing complications highlighted in the CIViC report, perhaps brokering access to data and allowing infrastructure companies to share data without compromising their position vis-à-vis competitors.

7.5.2. Quantitative risk assessment

A key knowledge gap is a lack of quantitative risk-based assessments of climate change impacts on critical infrastructure assets. Studies of climate change impact in an Irish and international context tend to focus on qualitative and semi-quantitative assessment. These forms of assessment require less time and monetary investment than detailed fully quantitative assessments; however, in most cases, they lack the numerical justification required to bring about meaningful climate change adaptation for our critical infrastructure networks. This is largely due to the vast nature of our critical infrastructure networks and the resulting high cost of adaptation, which necessitates robust quantifiable justification prior to adaptation action. Thus, as highlighted by the CIViC report (Ryan, P. et al., 2021), there is a need to move towards detailed quantitative understanding of climate impacts on critical infrastructure, and probabilistic cost–benefit analysis of adaptation actions to bring about adaptation on the required scale.

7.5.3. Stress testing of critical infrastructure

Such exercises are naturally limited by irreducible uncertainties and the possibility of low-probability high-impact events (Volume 1 section C), and perhaps more importantly unknowns surrounding the nature of our critical infrastructure networks themselves decades into the future. Ongoing research to develop a semi-quantitative climate risk assessment for local authorities by the MaREI institute in University College Cork is trialling the use of ISO 14092 (ISO, 2020) for climate change adaptation and the GIZ/EURAC guidelines (GIZ et al., 2018) for conducting climate change risk assessments. These methods are initially being conducted with trial data but could later be developed as the baseline for further impact studies for critical infrastructure, whether at the local authority level (as is the case with roads) or national agency level. Research is also under way to expand the use of fully quantitative risk-based decision support tools into the water and transport sectors to inform climate change adaptation. Importantly, this work will incorporate probabilistic modelling, facilitating incorporation of the considerable uncertainty and variability associated with vast and varied critical infrastructure networks, and their long-term performance in a changing climate.

8

Health and Wellbeing

Key messages

1. Projected changes in extreme events are likely to have direct and indirect impacts for health and wellbeing. The number of people exposed and vulnerable to heatwaves will increase. To date, the number of flood-related deaths and rates of injury are not well recorded, but there is extensive evidence that floods have significant impacts on health and wellbeing, including mental health, across populations. Loss of and changes in valued places as a result of climate impacts have been related to the experience of solastalgia, a psychological grief experienced because of environmental loss. An ageing Irish population will pose additional challenges for public health in a changing climate. Without adaptation, projected changes in floods and droughts and associated impacts on water quality are likely to impact public health.

2. As a country with a high rate of excess cold-related deaths, warmer winters may have a positive effect in reducing this risk in Ireland. But climate change may also aggravate existing public health pressures on respiratory diseases such as asthma through increased circulation of aeroallergens in a longer growing season and changes in air quality. Shifting geographical ranges of vectors and associated pathogens, but also human behaviour, may have consequences for exposure to vectors and vector-borne diseases.

3. Responses to extreme events through emergency management and recovery affect direct and indirect health outcomes. The responses of governments and insurance companies have a significant impact on the wellbeing of populations following flood events, with information and financial support from public agencies contributing meaningfully to the wellbeing of affected populations.

4. Climate change is also likely to increase the exposure of critical health infrastructure. Overheating in hospitals and residential care settings has been identified as a public health concern in the UK during heatwaves, with hospitals reaching dangerous temperatures and a lack of capacity to cool older, less efficient buildings. There is evidence that similar conditions were experienced in Ireland during the heatwave of 2018. Flooding poses a significant risk to health care infrastructures both in direct damage and in preventing provision of care. Development of a register of at-risk infrastructure and services is needed to inform adaptation.

5. Systemic approaches to adaptation planning for public health are needed to develop effective strategies to reduce climate risks. The health and wellbeing outcomes of adaptation actions across all sectors should be monitored and used to evaluate the success of adaptation interventions. It cannot be assumed that interventions will do no harm or be equally successful across populations.

8.1. Health and wellbeing: a cross-cutting issue

The breadth of impacts of climate change on individuals, communities, infrastructure and services has significant implications for the health and wellbeing of the Irish population. Managing climate risks and adapting to climate change in ways that will improve wellbeing requires wide-ranging, coordinated planning efforts across sectors and stakeholders to address vulnerabilities as well as exposure to extreme weather events.

A healthy and happy population is a key societal objective that drives much policy and planning and is becoming more central in adaptation policy and planning. There is a rich body of research that seeks to define health and wellbeing, with the two terms often used interchangeably or with considerable overlap (Cisse et al., 2022). The World Health Organization (WHO) definition of health includes physical, mental and social wellbeing, expanding the scope beyond a focus on morbidity and mortality. Definitions of wellbeing often include positive emotions and satisfaction with life, together with opportunities and capabilities to achieve life goals. Collective processes of social inequality and cohesion matter for levels of subjective wellbeing (Delhey and Dragolov, 2016).

In recent years there has been increasing policy recognition of the systemic nature of health and wellbeing and the need to consider the social and environmental systems that people live within to understand health outcomes in social–ecological systems. These broader approaches to health, looking beyond clinical and public health settings, bring a focus onto the role of wider social processes. The social determinants of health model made popular by Professor Sir Michael Marmot provides a useful lens to understand how social contexts shape health outcomes – i.e. the non-medical factors that influence health outcomes (Figure 8.1 reproduced from Dahlgren and Whitehead, 2021; Delhey and Dragolov, 2016;). The social determinants of health model illustrates how individuals are embedded within communities and broader societal dynamics, emphasising health as an emergent process across these contexts. Ireland's health sector adaptation plan (DOH, 2019) recognises this wider basis for health and highlights the role of other sectors in supporting a healthy population. Indeed, the growing attention on the mind–body connection and on systemic understandings of health suggest that more holistic approaches to health and wellbeing can lead to greater diagnostic power and more effective policymaking (Berry et al., 2018; Haslam et al., 2018). Using this framing, effective adaptation to climate change is rooted in reducing vulnerability by addressing socioeconomic, cultural and environmental determinants of health as well as risk-specific interventions.

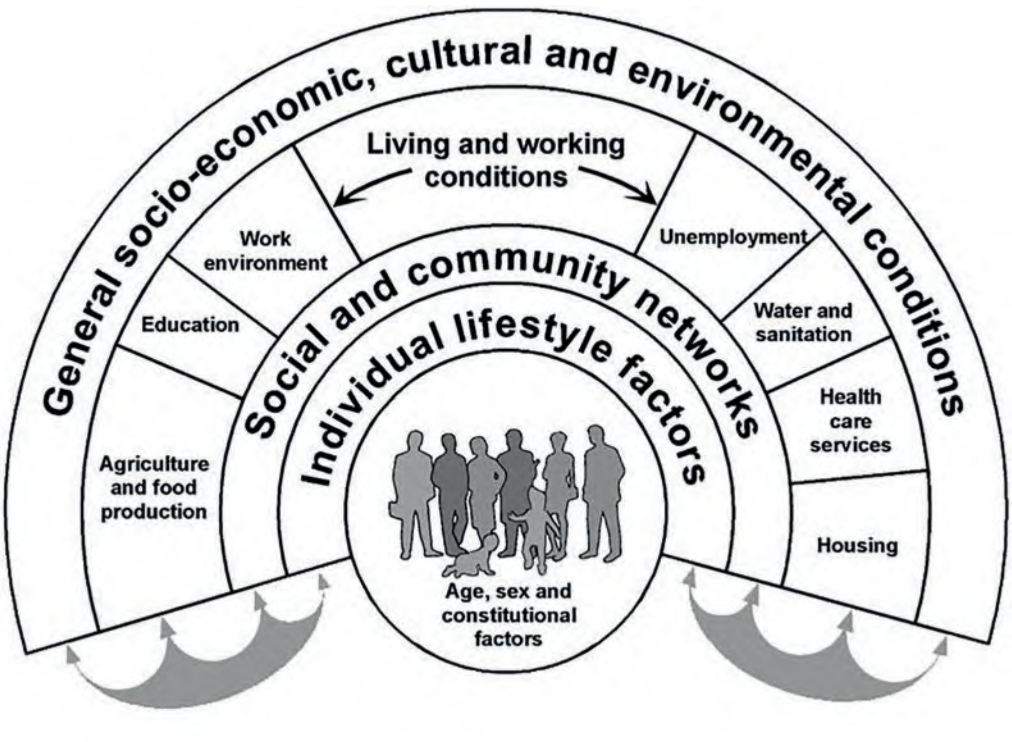


Figure 8.1 The social determinants of health model. Source: Dahlgren and Whitehead (2021).

Broader systems-based conceptualisations of health such as the 'One Health' approach provide a framework to consider how human, animal and environment health processes are co-dependent and continuously interacting across scales. The One Health approach highlights the complex health challenges that societies are facing and shows that the health of humans cannot be separated from the health of animals and plants (Figure 8.2). In examining health through these interconnecting systems, it becomes possible to identify trade-offs, co-benefits, risks and opportunities, with implications for how health policies are developed across sectors. The One Health approach is increasingly being embedded in institutional approaches to health, with the recent United Nations One Health Joint Plan of Action launched in 2022 (WHO, 2022). More recently, the Irish government has mobilised a One Health approach to address the growing risk of antimicrobial resistance in humans and animals.

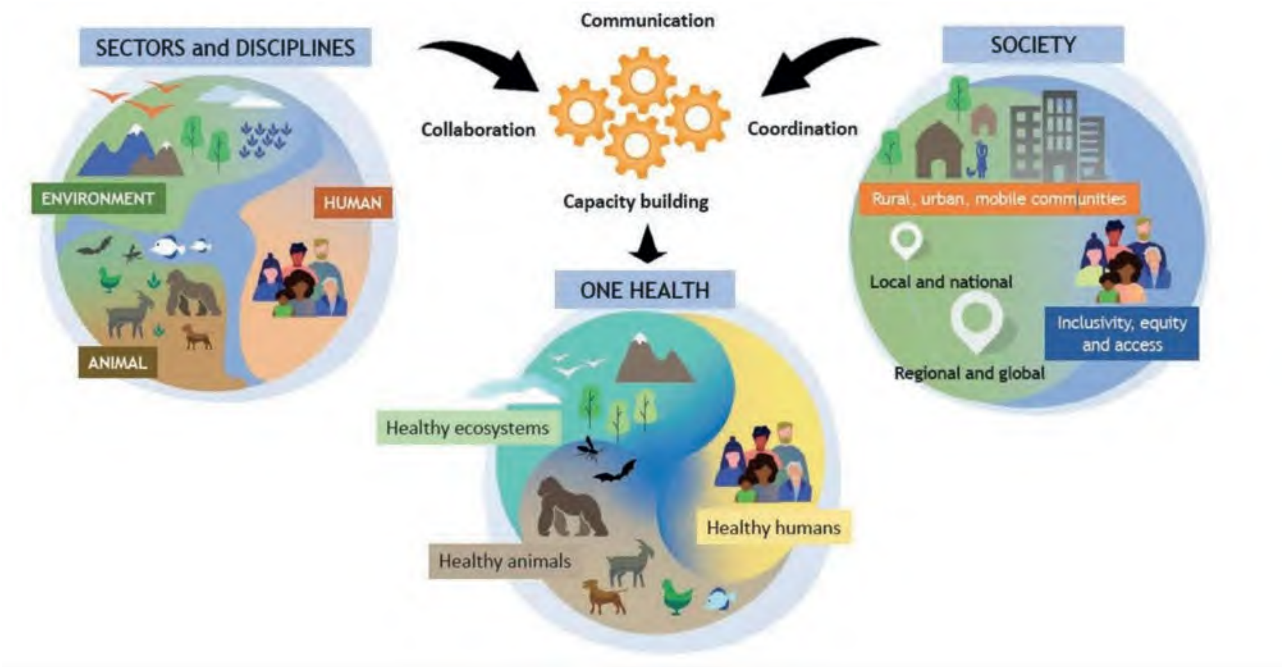


Figure 8.2 The World Health Organization's conceptualisation of One Health, showing the connections between sector-specific specialist concerns and different scales of governance and collaboration in managing the collective health of ecosystems, animals and humans. Source: One Health High-Level Expert Panel et al. (2022). Reproduction licensed under the Creative Commons Attribution CC0 1.0 licence (https://creativecommons.org/publicdomain/zero/1.0/).

In this chapter we draw on these models of health to examine how social–ecological systems and socioeconomic conditions shape health outcomes (Cisse et al., 2022). We take this broad view to capture more fully what makes people and groups vulnerable to climate change risks, through examining both direct health and wellbeing impacts on populations and impacts on broader socioeconomic conditions. As the health sector adaptation plan (DOH, 2019) outlines, making clearer how climate change will affect the quality of everyday lives provides the opportunity for new types of public engagement, drawing attention to the immediacy of climate change in everyday life.

8.1.1. Health inequalities in adaptation to climate change

Adaptation planning requires consideration of who benefits from and who is disadvantaged by an intervention. While many adaptations will reduce risks, it cannot be assumed that interventions will be equally beneficial across populations. There are well-established health inequalities in terms of the distribution of diseases across populations, including exposure to risks and ability to recover from ill health and, although there are indications that Ireland has relatively low levels of inequality compared with other European countries, they are increasing (Pascual et al., 2018).

Ireland's ageing population will pose challenges for public health in a changing climate. In Ireland there are currently approximately 696,300 people aged 65 and over, and this group is projected to grow to almost 1.6 million by 2051, with life expectancy expected to improve from 78.4 years to 85.6 years for men, and from 82.8 years to 88.3 years for women between 2011 and 2051 (Sheehan and O' Sullivan, 2020). While Ireland has been a relatively young country in Europe in recent years, by 2028 it is projected that there will be more people aged 65 and over in Ireland than those aged 0–14 (Sheehan and O'Sullivan, 2020). While increased longevity is a positive reflection of public health, the quality of life in those extended years is also an important public health objective, and so disability-free life expectancy at age 65 is used to measure good health in older adults. In 2017 in Ireland, the disability-free life expectancy at 65 was 13.4 years for women and 12.5 years for men (Sheehan and O' Sullivan, 2020). There are several chronic health conditions that are associated with ageing, including arthritis, diabetes, hypertension, cancer, chronic obstructive pulmonary disease and dementia, that require focused treatment plans and public health support. Several of these chronic diseases are climate sensitive, based on the methods of exposure, including the impacts of heat, cold, dust, small particulates, ozone, fire smoke and allergens (Cisse et al., 2022).

In Ireland there are urban and rural inequalities in health, with sharp health inequalities within Irish cities, particularly in Dublin (Rigby et al., 2017). Multimorbidity (the presence of two or more chronic diseases) is twice as likely to be experienced by people in lower socioeconomic groups than people in higher socioeconomic groups in Ireland (Sheehan and O'Sullivan, 2020). The IPCC's 2018 Health and Climate report suggests that, until mid-century, climate change is expected to primarily exacerbate existing health challenges, with socioeconomic factors determining the severity and extent of climate-sensitive health risks. Broader determinants of health such as access to safe housing and transport and proximity to health facilities will shape how climate change impacts health in Ireland, bringing focus to the need for coordinated planning in public health for equitable adaptation to climate change. The trend of increasing inequity does itself have negative impacts on health, and adaptation interventions can aim to not only avoid exacerbating inequity but also reduce it. (Cisse et al., 2022)

8.1.2. Climate change adaptation in the health sector

The health sector adaptation plan (2019–2024) (DOH, 2019) was informed by international literature and adopts Public Health England's approach to health sector adaptation, which is three-fold:

1. Supporting population health and wellbeing, paying attention to vulnerable populations and anticipating different volumes and patterns in healthcare demand;
2. supporting health care continuity and ensuring that services and operations can be maintained during severe weather events;
3. building infrastructure resilience to severe weather events, including built infrastructure, as well as maintaining supply chains.

The health sector adaptation plan (DOH, 2019), developed by the Irish Medical Organisation, highlights the need for the expertise of consultants in public health in conducting baseline and ongoing public health risk assessments for a joined-up approach in adapting to climate change risks.

8.1.3. What are healthy adaptations?

Given the scale and number of adaptation interventions that will need to be rolled out in coming years and decades, sustainable adaptation planning will have to consider how interventions impact people's health and wellbeing to ensure that action taken is not maladaptive in the long term. Indeed, the broader move towards more transformative climate action in Ireland, as outlined in Volume 4, requires adaptation efforts to address deep-rooted socioeconomic vulnerabilities.

A review of adaptation to flood risk by Quinn et al (2023) shows that different intervention types (e.g. sea walls, nature-based approaches, etc.) all act to reduce risk but have different profiles of impacts on local communities. Indeed, adaptation interventions affect people across most areas of their life and have the potential to impact, both positively and negatively, on individual and community wellbeing. Included in this is emergency response and how public agencies are perceived by communities. Increasingly, research is highlighting how societal, organisational and governmental response to disaster events has consequences for health outcomes (Williams et al., 2021; Quinn et al., 2023).

A broader set of metrics is needed for assessing how health and wellbeing will be impacted by adaptations. Quinn et al. (2023) outline metrics that can be used in adaptation planning that focus on material, social and environmental dimensions of wellbeing affected by different interventions. In public health settings the need to understand the health consequences of adaptation becomes more acute, and further research can help in considering how different suites of interventions are likely to affect the health of patients and staff.

8.2. Vulnerabilities, impacts and adaptation strategies

In this section we review the risks and impacts associated with specific climate-related hazards and adaptation strategies to date. Drawing on the academic and policy literature, we identify possible directions for adaptation planning as well as identifying research gaps going forward.

8.2.1. Warmer summers and winters

Current risks and impacts. Heat acts directly on physical health by causing stress to individuals who are less able to keep their body temperature stable and has implications for the broader provision of public health. Definitions of a heatwave vary between countries; in Ireland the HSE defines a heatwave as 5 consecutive days when the maximum temperature exceeds 25°C. The HSE outlines a broad demographic that is vulnerable to extreme heat, including babies and children, pregnant people, people aged over 65, people with underlying conditions related to their breathing, heart and kidneys and to diabetes, and people with Alzheimer's disease and dementia. The physiological vulnerability of older adults is particularly pertinent given that the Irish population aged over 65 is expected to rise to almost 1.6 million by 2051, as shown in Figure 8.3, increasing the number of people living with a range of chronic diseases.

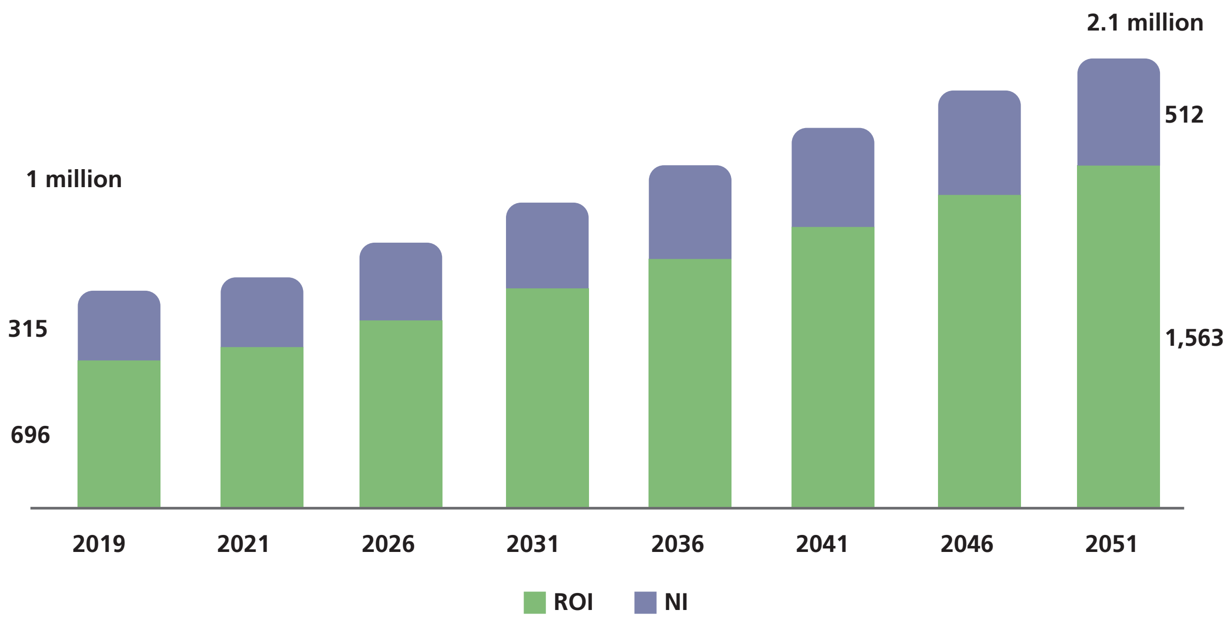


Figure 8.3 Projected number of people aged 65+ in thousands, 2019–2051. Source: Sheehan and O'Sullivan (2020).

There is a lack of detailed information on the impact of heatwaves on health and wellbeing in Ireland (Paterson and Godsmark, 2020); however, 294 deaths were attributed to heatwave events between 1981 and 2006 (Pascal et al., 2013). Looking forward, trends in urbanisation and population growth suggest that the number of people in Ireland exposed to heatwaves will increase. Vulnerability to the impacts of hot weather is also determined by how and where we spend our time, with people who live in urban areas (where the UHI effect is significant) and people who work outdoors are particularly exposed to sustained hot weather periods (Patersmen and Godsmark, 2020). The risk to health from heatwaves occurs during the summer months in Ireland. It is important to note that Ireland is a country with a high rate of excess cold-related deaths (Zeka et al., 2014), and warmer winters should have a positive effect in reducing this risk. However, excess winter mortality is a function of temperature and seasonal infections, alongside quality of housing, etc., so cold-related deaths will remain a significant public health issue. As noted in the UK third Climate Change Risk Assessment, an ageing population may offset the benefit of milder winter temperatures (Kovats and Brisley, 2021).

A significant risk associated with heatwaves and hot weather days is the impact of UV radiation on the incidence of skin cancers as people spend increasing amounts of time outside, with the HSE rating this risk as high in likelihood and impact. People with white skin are the most vulnerable to skin cancer (especially those of Celtic descent; Thomas et al., 2012), and it is the most common form of cancer in Ireland, with 11,000 cases diagnosed each year (National Cancer Registry Ireland, 2014) and projections for 2040 suggesting a potential increase in melanoma skin cancers of up to 175% in women and up to 327% in men (National Cancer Registry Ireland, 2014).

Prolonged hot weather poses a risk to people working outdoors and in poorly ventilated conditions, who may experience heat stress driven by working conditions. As well as air temperature, heat stress is also influenced by humidity and clothing type in the workplace. The most severe examples of heat stress are found in countries with already high average temperatures , but it is also a concern in Ireland, where temperature regimes, and summer temperature ranges, are projected to change. There is also increasing evidence on the impact of heat and drought on the mental health of people whose livelihood relies on favourable weather patterns, with national and international studies on the farming community detailing these challenges (Murphy and Grainger, 2023), and adverse mental health impacts associated with periods of heat and drought (Ellis and Albrecht, 2017).

Heatwaves can be challenging for several aspects of the health care system, with higher levels of patient engagement during periods of extreme heat (Scalley et al., 2015; Smith et al., 2016). The Urb-ADAPT project examined the exposure of hospitals, creches, general practices and primary care centres in urban areas in Ireland to climate change risks. It singled out the sensitivity of the children's hospital in St James' Street, and maternity hospitals including the Coombe, Rotunda and Holles Street hospitals, in Dublin, to heat risk (Paranunzio et al., 2020). Evidence from the UK outlines the particular vulnerabilities of people in care homes during heatwaves (Walker et al., 2016). The exposure and vulnerability of the public health infrastructure in Ireland to extreme heat events is not well understood, but overheating in hospitals and residential care settings has been identified as a public health concern in the UK during heatwaves, with hospitals reaching dangerous temperatures and a lack of capacity to cool older, less efficient buildings (Kovats and Brisley, 2021). Work by Brooks et al. (2023) shows that hot weather in the UK in 2019 caused significant disruption to hospital facilities and equipment and staff and patient levels of comfort, alongside a significant rise in hospital admissions. The response to the heatwave put pressure on infection control, electric fan usage and patient safety. There is evidence that heatwaves significantly impacted healthcare provision in Irish hospitals in the summer of 2018.

Adaptation strategies. Going forward, heat is a moderate but real risk in Ireland (Pascal et al., 2013) and, combined with an ageing population, presents an important challenge for public health. Currently there is a lack of a comprehensive plan for hot weather events, with the government recognising the need for a new heatwave action plan, as highlighted in the Climate Action Plan 2023 and the health sector adaptation plan (DOH, 2019).

Public awareness around heat risk is a key component in adapting to hot weather periods, as changes in individual behaviour and daily routines can reduce exposure to heat stress. Research has demonstrated that vulnerable people do not always self-identify as being at risk (Abrahamson et al., 2009). Targeted campaigns are therefore required, as well as further research into cultural risk perception and perception of vulnerability to help inform appropriate communication strategies and to more effectively communicate the advice available on the HSE website. Climate services can also play a role in providing information for communicating seasonal and short-range weather alerts for the general population. There is also the opportunity to build on current information campaigns targeted at vulnerable groups that advise them to avoid being outside in the hottest part of the day, e.g. actions included in the National Skin Cancer Prevention Plan (2019–2022) (National Cancer Control Programme, 2020).

Reducing the impact of heatwaves in workplaces requires adaptation of working practices (including more rest breaks), temperature control, hydration and protective equipment – as set out under temperature guidance on the HSE website. Efforts to reduce working hours in direct sunlight, increased ventilation and, potentially, air conditioning (ideally powered by renewable energy) will reduce the risk of heat stress for employees (Gao et al., 2018). Again, communication about and training on heat risk is key for organisations to keep their workforces safe. Further research is needed on occupational health during heatwaves in Ireland; in particular, the development of occupational heat stress indexes can help to identify when management plans should be triggered during extreme events. Climate services can play a role in producing tailored heat warnings for industries and workplaces particularly exposed to heat stress (Gao, 2018), which, in coordination with heatwave plans, can provide timely and joined-up advice in the face of increasing heat stress risk.

Adaptation strategies for managing health services during hot weather include a range of behavioural and technical strategies, such as providing thermometers within buildings, adjusting diets of patients, cooling mechanisms, managing rostering of staff in heatwaves, identifying vulnerable people and their appropriate treatment, and allocation of vulnerable patients to morning clinics (Matthies et al., 2008; Gough et al., 2019). Pascal (2011) recommends that surveillance systems for heatwaves in Ireland move beyond a focus on specific symptoms such as hospital admissions to also consider housing conditions, deprivation and the UHI effect. More immediately, the HSE can incorporate climate change adaptation into risk registers, as suggested by the health sector adaptation plan, formalising heat risk into existing risk management strategies. As Paranunzio et al. (2020) suggest, ultimately each hospital will have to develop a plan to manage climate change risks depending on the services they provide. A longer-term view that considers the sustainable design of built infrastructure can encourage the design of buildings limited to three to four storeys that have thick walls and courtyards facilitating ventilation (Curtis et al., 2017), and avoid the use of lightweight, modular buildings (Iddon et al., 2015). There is extensive research globally on how to improve the resilience of public health provision in heatwaves, learnings from which can be built on in the proposed new heatwave plan (e.g. Casanueva et al., 2019; Linares et al., 2020).

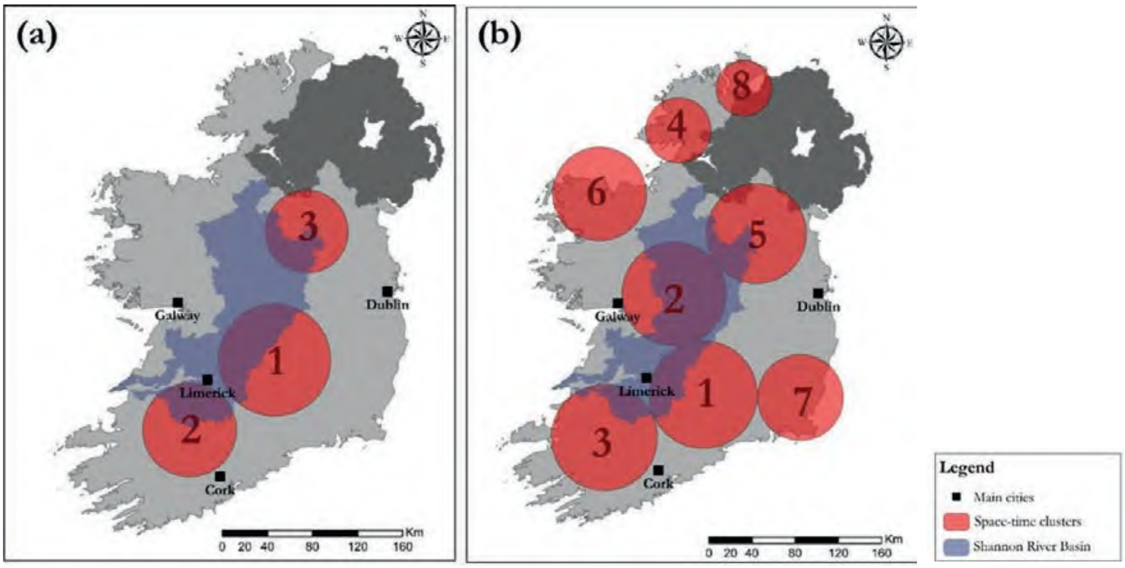
8.2.2. Flooding and storms

Current risks and impacts. Flooding impacts on health and wellbeing through (1) the anticipation of risk, (2) direct experience of flood events and (3) the period of recovery following an event. To date the number of flood-related deaths and rates of injury secondary to flooding in Ireland are not well recorded (DOH, 2019); however, there is extensive evidence that floods have significant impacts on health and wellbeing across populations. The immediate concern during a flood event is risk to life and injury (including as a result of contaminants in the water). In the period after flood events, residents often have to relocate or remain living in damp conditions. Damp living conditions bring the risk of mould and fungus (Crowley, 2016), and the risk of carbon monoxide poisoning after flood events increases due to the use of portable heating equipment and dehumidifiers, and the restarting of damaged boilers (Waite et al., 2014; Saulnier et al., 2017).

A distinctive aspect of the Irish water supply system is a significant reliance on private groundwater supplies and domestic wastewater treatment in rural areas, with an estimated 720,000 people getting their water from a private, unregulated, supply (Hynds et al., 2012; Naughton and Hynds, 2014). This creates vulnerabilities for health, as private systems cannot be regulated to national standards, with no obligation for testing or maintenance. Ireland has the highest rate of Escherichia coli in Europe, with the use of domestic wells a major transmission route, and private well users up to six times more likely to experience a gastrointestinal infection (Hynds et al., 2014). High rainfall events put pressure on the water supply system and can undermine the integrity of private wells, with the flood risk management sectoral plan highlighting the potential risk of pathogen and chemical contamination during floods, identifying overflowing sewers, storm water floods and landfill sites as potential sources of contamination. Research into the preparedness and behavioural adaptation of 405 private well users in Ireland found that over 70% of respondents who had experienced flooding have not undertaken protective measures, with rural, non-agricultural well users the least likely to have acted (Musacchio et al., 2021). Water sources are also threatened by mismanagement of individual septic tanks, which can pose contamination risks to wells and local streams. In 2021, over half of septic tank systems in Ireland failed inspection; 75% have been fixed but delays in resolving older failures is still a concern (EPA, 2021).

Box 8.1 Waterborne infections and floods

A recent study by Boudou et al. (2021) investigated the impact of the 2015/2016 flood events in Ireland on the epidemiology of two waterborne infections: verotoxigenic E. coli (VTEC) and *Cryptosporidium*. Winter 2015/2016 is now synonymous with some of the most widespread and severe flooding ever recorded across Ireland. To assess the impacts of these events on incidence of waterborne infections, weekly spatially referenced disease data (July 2015 to June 2016) were analysed relative to weekly time series of cumulative antecedent rainfall, surface water discharge and groundwater levels, as well as high-resolution flood risk mapping. Models show a clear association between rainfall, surface water discharge, groundwater levels and infection incidence, with lagged associations from 16 to 20 weeks particularly strong, thus indicating a link between infection peaks (April 2016) and the flood event, which began approximately 18 weeks earlier.



Box 8.1 Figure 1 Space–time clusters of infection from July 2015 to July 2016. (a) VTEC (83 cases) and (b) Cryptosporidium, with Shannon Basin indicated in blue (238 cases). Source: Boudou et al. (2021). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

The results demonstrate that the incidence of waterborne infections post flooding should be closely monitored for several months following the event. Likewise, environmental monitoring (i.e. surface water and groundwater sampling) campaigns are required to fully understand the spatiotemporal dynamics of waterborne pathogens both during and after incidents of flooding.

The projected increase in the number of intense storm events and associated flooding will have implications for bacterial infection, particularly by multidrug-resistant bacteria, and is a risk factor in the aftermath of high-rainfall events. Flood events carry two major risk pathways for antibiotic resistance emergence and spread. The first is in the spreading of bacteria and their resistance genes into the wider environment through increased rainfall and overflow of rivers, reservoirs and estuaries. The second is through the flushing of fertilisers, sewage and heavy metals from farms and industries into the water systems (Burgmann et al., 2018). Fertilisers and sewage can harbour resistant bacteria, and flood events can release these into the wider environment, but such flooding also increases the number of metals and compounds that lead to cross-resistance in bacteria – i.e. bacteria adapt to the presence of heavy metals, and the same adaptations enable them to resist antibiotics (Yazdankhah et al., 2018). There is a lack of empirical evidence of a link between climate change and antibiotic resistance; however, the Irish government has outlined a One Health approach to tackle the rise of antimicrobial resistance in humans and animals in the coming years (HSE Antimicrobial Resistance Infection Control Action Plan, 2022-2025). Such an approach must be integrated with initiatives such as the national climate action plan, to survey and monitor bacteria and antimicrobial resistance under changing climate conditions in Ireland and plan for the risks associated with flooding and heat events.

There is substantial evidence globally that floods have negative consequences for the mental health of affected populations, and researchers have explored the stressors associated with such events. Work in the UK on the 2013/2014 winter floods demonstrates that the effects of floods are felt for years afterwards. For example, after 1 year, flooded populations are more likely than non-flooded populations to experience depression, anxiety and post-traumatic stress disorder (PTSD). Mental ill health is more severe among flooded residents who experienced disrupted utilities, while higher flood depth is also associated with negative health outcomes (Waite et al., 2017). After 2 years, psychological morbidity, although reduced from year 1, remains higher for flooded householders. For people who report persistent damage in their home, mental health outcomes are lower than for other affected populations, and those without household insurance experience significantly higher levels of PTSD (Jermacane, 2018). However, those who have insurance but experience stress due to interactions with insurance agencies are more likely to experience PTSD, depression and anxiety than households that do not report stress (Mulchandani et al., 2019).

Increasingly, research indicates the significant role that the responses of governments and insurance companies have in the wellbeing of populations following disaster events, with information and financial support from public agencies contributing meaningfully to the wellbeing of affected populations (Walker-Springett et al., 2017). There has been criticism that properties in Ireland have been unfairly identified as uninsurable, and increasingly there are areas where premiums are becoming unaffordable or with deductibles that make insurance unviable for homeowners (Surminski, 2017). More broadly, flood-

Figure 8.4 Letterkenny hospital after floods in 2013, when 40% of hospital services had to be taken out of clinical use. (Source: McGinley (2014), Photo Declan Doherty)

affected communities can experience a sense of isolation and stigma, with research in the UK identifying depressed house prices for 4–7 years after a flood event, with lower-priced properties experiencing a post-flood price discount relatively longer (Beltrán et al., 2019), contributing to a very real experience of being 'stuck', with implications for mental health (Tapsell and Tunstall, 2008). The impact of broader, secondary stressors in shaping health outcomes indicates that the consequences of climate change on health and wellbeing will be driven both by the direct impact of climate risks and by the response of societal actors in managing climate risks.

Flooding also poses significant risk to health care infrastructure, both in terms of direct damage and by preventing provision of care. Public health infrastructure on floodplains or areas at risk of surface water flooding are at present a significant risk for health provision in times of a flood event – because of both the need to evacuate sites and difficulties in sustaining levels of care. There is no inventory of at-risk public health infrastructure in Ireland, but the example of flooding in Letterkenny hospital in July 2013 and August 2014 (see Figure 8.4) demonstrates the significant disruption to health care that can occur in areas surrounding at-risk hospitals, with up to 40% of the hospital's services taken out of clinical use (Lavin et al., 2014; DOH, 2019). The health sector adaptation plan notes the risk of loss of paper-based notes, loss of electrical power and loss of laboratory systems that support care. Longer journey times and lack of access to health care and medicine can be longer-term impacts, especially where roads or bridges are structurally damaged.

Adaptation strategies. There is a range of adaptation strategies to mitigate the risk of flooding, as detailed in Chapters 4 and 5. Here we focus on adaptation strategies that specifically mitigate the health impacts of floods on populations. The impact of floods on water quality, particularly through the mismanagement of wells, requires a targeted long-term communication strategy. Evidence suggests that people in non-agricultural areas are less likely to adapt their wells and that women are less likely to know about post-flood management actions than men (McDowell et al., 2020; Musacchio et al., 2021). A recent study by Musacchio et al. (2021) shows that there is a general low level of well stewardship, with only around 10% of well users in Ireland treating water and carrying out regular testing, highlighting the need for information campaigns that focus on targeted interventions in well management behaviour. The contamination risk from septic tanks is highlighted in the recent EPA (2021) systems inspection report, and the new National Inspection Plan for Domestic Waste Water Treatment Systems 2022–2026 proposes an increase in inspections from 2023 onwards that will focus on sites near rivers, and in poorly draining soils, where there is greater risk to household wells (DHLGH, 2021).

Long-term, collaborative efforts are needed for sustainable flood risk management. Formally integrating mental health impacts into flood risk planning can help to better anticipate the consequences of adaptation responses. The Environment Agency in England, for example, has developed a method for assigning a value to the mental health impacts of flooding, which can now be used in financial flood appraisals and allows this impact of flooding to inform decision making on adaptation strategies. The private sector can also play a role in reducing the negative mental health impacts of flood risk; for example, actions by government, in tandem with the insurance industry, to provide affordable insurance coverage can reduce the health impacts of poor coverage. A focus on collaboration and fair process in flood risk planning can support more effective outcomes, and it is important that the evolving role of the insurance industry is integrated into planning to reduce the risk of stigmatised communities and uninsured households.

Longer-term support for flood-affected communities can help to mitigate some of the health impacts of floods and maintain the integrity of health care and social support systems in response to flood crisis events. There are possible synergies with Sláintecare, a government programme that is helping people stay healthy in their homes and communities (as per general advice in the sectoral plan). Focusing directly on physical risk, a register of at-risk infrastructure and services can help to inform future adaptation strategies (and could be gathered in conjunction with a review of other climate risks). In the months following a flood, there is often a surge in government and community support that drops off after the initial response (Medd et al., 2015; Butler et al., 2018). This 'recovery gap' has implications for mental health, and coordination is required between emergency response and longer-term care plans for flood-affected communities.

8.2.3. Air quality

Climate change and accompanying changes to weather patterns will contribute to air quality in several ways, primarily by shaping the formation and dispersal of air pollutants such as ozone and particulate matter and by increasing the localised risk of wildfire. Warmer summers are likely to lead to both the environmental conditions associated with the risk of ignition of fire and the increased likelihood that people will spend more time outdoors, which in turn increases the possibility of accidental fire ignition. Wildfires emit both harmful gases and particulate matter, with direct consequences for air inhaled and risk to water quality where ash and organics enter the water supply (Kettridge et al., 2019). In Ireland, over 1,380 deaths annually are attributable to PM2.5, NO_2 and O_3 air pollution (EEA, 2019). Particulate matter that can be generated by wildfire events

(Aguilera et al., 2021) has been linked to headaches, dementia, preterm births and respiratory conditions, but the biggest health impact is on cardiovascular systems. In Ireland it is estimated that over 500,000 people over the age of 40 living with chronic obstructive pulmonary disease (DOH, 2019), increasing their vulnerability to wildfire-driven deterioration in air quality.

Climate change is likely to change the growing season and distribution of plants in Ireland, altering the number of aeroallergens circulating throughout the year. Driven by changes in global temperatures, spring pollen seasons are starting earlier in the northern hemisphere, by about 15 days over the last 30 years, a process linked to changing global temperatures and, going forward, growing seasons in Ireland are projected to lengthen by approximately 35 days by 2050 (WHO, 2008; Nolan and Flanagan, 2020). This has implications for respiratory diseases, including asthma, and can increase the use of health services. Older adults, those with chronic diseases and children are most vulnerable to poor air quality, with approximately 450,000 people in Ireland living with asthma, and the number is rising (NPSO, 2018). In 2011 the HSE reported that approximately 20,000 emergency department visits were related to asthma, as were 50,000 hours of GP consultations (DOH, 2019).

Adaptation strategies. Key to the management of climate-driven changes in air quality will be efforts in mitigating emissions and improving housing standards to reduce the combustion of fossil fuels and ensuring that building regulations support ventilation alongside energy efficiency. In general, the reduction of pollutant emissions will benefit both mitigation and healthy adaptation. Given the large contribution of combustion of solid fuels within households, communication strategies focusing on transition to cleaner fuels will also have significant health co-benefits.

Where localised zones of poor air quality develop due to weather patterns, namely in urban areas, congestion zone strategies offer opportunities to reduce direct emissions from vehicles, and, at the same time, active travel can be encouraged, having the additional benefit of positively contributing to health. Poor air quality is a highly unequal risk, mostly affecting urban residents and in particular those who live along busy roads, especially when considering NO_2 levels (Tonne et al., 2018). At the same time, households with a low income are also more likely to have lower-quality housing and to experience higher levels of indoor air pollution (Ferguson et al., 2020). The compounding effects of the socioeconomic drivers of vulnerability mean that interventions to improve air quality should incorporate broader social considerations to try to ensure just and equitable outcomes (Ferguson et al., 2021), with interventions focused on building quality also having implications for reducing vulnerability to air pollution and exposure to other risks such as mould. However, it is important to note that adapting buildings to be more energy efficient and better insulated can have implications for indoor air pollution if there is not appropriate circulation of air. Mapping of Irish-specific climate change epidemiology relating to air pollution and vulnerable groups (as outlined in the sectoral plan) will help in the development of air quality-related adaptations, and this can be supported by additional monitoring stations and reporting processes.

8.2.4. Vector-borne diseases

Changing temperature and rainfall patterns associated with climate change are likely to result in shifting geographical ranges of vectors and the pathogens that they carry. Changing weather patterns are also likely to affect human behaviour and how people interact with environments, with further consequences for exposure to vectors and vector-borne diseases. These changing interactions were identified in an assessment by the Health Protection Surveillance Centre (2016), which highlights the potential for increased density of the vectors of diseases including malaria. Such changes in disease are currently not forecast as one of the significant health risks for Ireland, but the potential for extended ranges of disease vectors needs to be monitored going forwards.

Lyme disease, transmitted by ticks, is a bacterial disease that can affect joints, the heart and nervous system and is associated with woodland areas and high humidity. In Ireland, neuroborreliosis (a symptom of Lyme disease) is recorded at a rate of 0.08 cases per 100,000, with the highest incidence in the south-west of the country (HPSC, 2021). Although the rate is low, there is evidence that it is getting higher in nearby countries, e.g. the UK (UKHSA, 2022).

There are a range of mosquito-borne diseases, and, while they are currently not present in Ireland, they have been flagged as future risks in a changing climate, with warmer weather affecting the home range of mosquitoes, their development time, biting rates and the incubation time of disease. While climate change is likely to enable the spread of malaria-carrying mosquitos, health care and socioeconomic systems in Europe can reduce the vulnerability of populations, and the chance of re-emergence is limited (Semenza and Suk, 2018). Similarly, there is no evidence of West Nile virus in Ireland, other than imported cases (Raleigh et al., 2012); however, it should be noted that there have been recent cases of the Culex modestus mosquito, the vector of the West Nile virus, in southern England, indicative of an expanding range of vectors previously located in tropical regions.

Adaptation strategies. Key to the management of vector-borne diseases is long-term surveillance, as carried out by the Irish Health Protection Surveillance Centre on a quarterly basis. This will be important in managing existing diseases and potentially newly arriving diseases amid changing climate conditions. For diseases such as Lyme disease that are also driven by behaviour, e.g. spending time in long grass, communication campaigns and signage in public spaces can help to manage exposure.

8.2.5. Foodborne diseases

Foodborne illness poses a significant risk to the modern, complex, food production system and is a significant cause of morbidity in Ireland, with acute gastroenteritis one of the most common reasons for visiting a family doctor (Cullen, 2009). Ireland's mild climate has contributed to the agri-food industry's significant growth (by international standards), increasing the need to identify how changing direct and indirect impacts of climate will impact the industry.

Climate change is likely to extend the seasonality and range of foodborne disease pathogens, with extreme events also acting to drive surges in disease occurrence. Climate change will have both direct and indirect impacts on foodborne pathogens. The microflora of food is made up of microorganisms from the raw materials, the environment the food is handled and processed in, and exposure during preservation and storage (Stewart and Elliot, 2015). In Ireland, warmer temperatures are associated with increased risks of certain foodborne pathogens, providing more hospitable conditions for bacterial and viral growth (DOH, 2019). Flooding can also impact food safety where contaminated water can indirectly introduce infection into the food production system.

Foodborne diseases can be mitigated by refrigeration of food, but hotter ambient temperatures may challenge the ability of cooling systems to keep food at a safe temperature, and those systems will be increasingly vulnerable to power cuts or interruptions in distribution systems. Prolonged periods of hot weather also increase the risk of contamination by food handlers (Stewart and Elliot, 2015). A clear seasonal pattern has been observed in European cases of Salmonella (ECDC, 2023), with the highest rates in the summer and the lowest in the winter. We also know that Campylobacter-related illness is increasing in Ireland (Stewart and Elliott, 2015). The health sector adaptation plan highlights the need to consider mycotoxin contamination of cereal grains. Less common but more deadly, the number of reported cases of listeriosis in Europe stabilised in 2019, but the increases in preceding years give cause for concern (ECDC, 2019). Wet weather events and poor water quality management can have consequences for foodborne diseases when fruit or vegetables come into contact with contaminated flood water or poor-quality irrigation water (Lake and Barker, 2018).

Adaptation strategies. There are guides at the national and EU level on good hygiene practice for foodstuffs, as listed on the Food Safety Authority of Ireland's website. Going forwards, further advice on risk assessment and hygiene practices in response to climate risks – i.e. the risk of warmer ambient temperatures and threat to the cold chain – can help to systematise adaptation in this sector.

Stewart and Elliott (2015) emphasise the need for an expanded surveillance system to monitor pathogens (including monitoring water supplies), targeting interventions in the early part of the food chain. Such an expanded system will help to improve detection and identification and should aim to reduce under-reporting of pathogens. More generally, robust long-term climate projections, coupled with short-term weather forecasts, will help with planning for resilience of the Irish food system, with information sharing of surveillance data supporting integrated plans. Given the number of entry points for contamination, an integrated approach to monitoring is needed to underpin responses to crisis events as well as bringing tools together for longer-term management.

As highlighted in the health sector adaptation plan, more research is needed on the impact of climate change on mycotoxin contamination of cereal grains, how algal blooms will be affected by changing temperature regimes and how aquaculture safety needs to address the new risks that climate change will bring.

8.2.6. Climate change and mental health

The mental health impacts of climate change are being increasingly experienced and recognised, and not just by people affected directly by disaster events, with 96% of people in a large-scale survey in Ireland (4,000 respondents) agreeing that climate change is happening, 85% of people responding that they are worried about climate change and 37% of respondents reporting being very worried (Leiserowitz et al., 2021). The tangible and intangible impacts of changing towns and landscapes, of seeing the news of disaster events and of the collapse of ecological systems, are affecting psychological health across populations.

Figure 8.5 Left: North Beach at Courtown in Wexford in 1967. Right: North Beach at Courtown in 2015, including sea defence. Source: Phillips and Murphy (2021). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

Cunsolo and Ellis (2018) describe ecological grief as a response to climate change, and research carried out in County Wexford by Phillips and Murphy (2021) and Phillips et al. (2022) illustrates the emotional impacts of losing a valued local beach to coastal erosion (shown in Figure 8.5), and they echo the concept of 'slow violence' to describe the experience of slow-onset environmental change. In their research they find that members of the local community are experiencing solastalgia, a psychological grief caused by environmental change. The authors also find that community members experiencing solastalgia report a negative outlook for the future and for future generations. The negative impacts of place loss can be experienced beyond impacts on local places, with work by Marshall et al. (2019) identifying communities locally, nationally and internationally that feel an attachment to a common location experiencing grief as a result of climate impacts (in this instance the Great Barrier Reef in Australia). The nuanced relationships people have with places and people near and far means that the psychological consequences of climate change are likely to be experienced across distances, and this may be particularly meaningful for a country with such an extensive diaspora and links to communities worldwide. Berry et al.

(2018) suggest that to fully understand the impacts of climate change on wellbeing it is necessary to take a broad systems approach (outlined in Figure 8.6) that considers the role of government, business and community as well as disaster events in understanding how climate change elevates risk to mental health and wellbeing, echoing the social determinants of health model and findings on the impacts of secondary stressors described earlier in this chapter.

While there is limited evidence for the consequences of increased awareness of climate change trends on mental health (Ma et al., 2022), the negative impacts of climate change are increasingly part of public consciousness. In Ireland, of 4,000 people surveyed, 95% believed that future generations of people, and plant and animal species (94%), will be harmed by climate change (Leiserowitz et al., 2021). Recent research in Australia outlines the direct and indirect impacts that climate change is having on the psychological health of children (Burke et al., 2018).

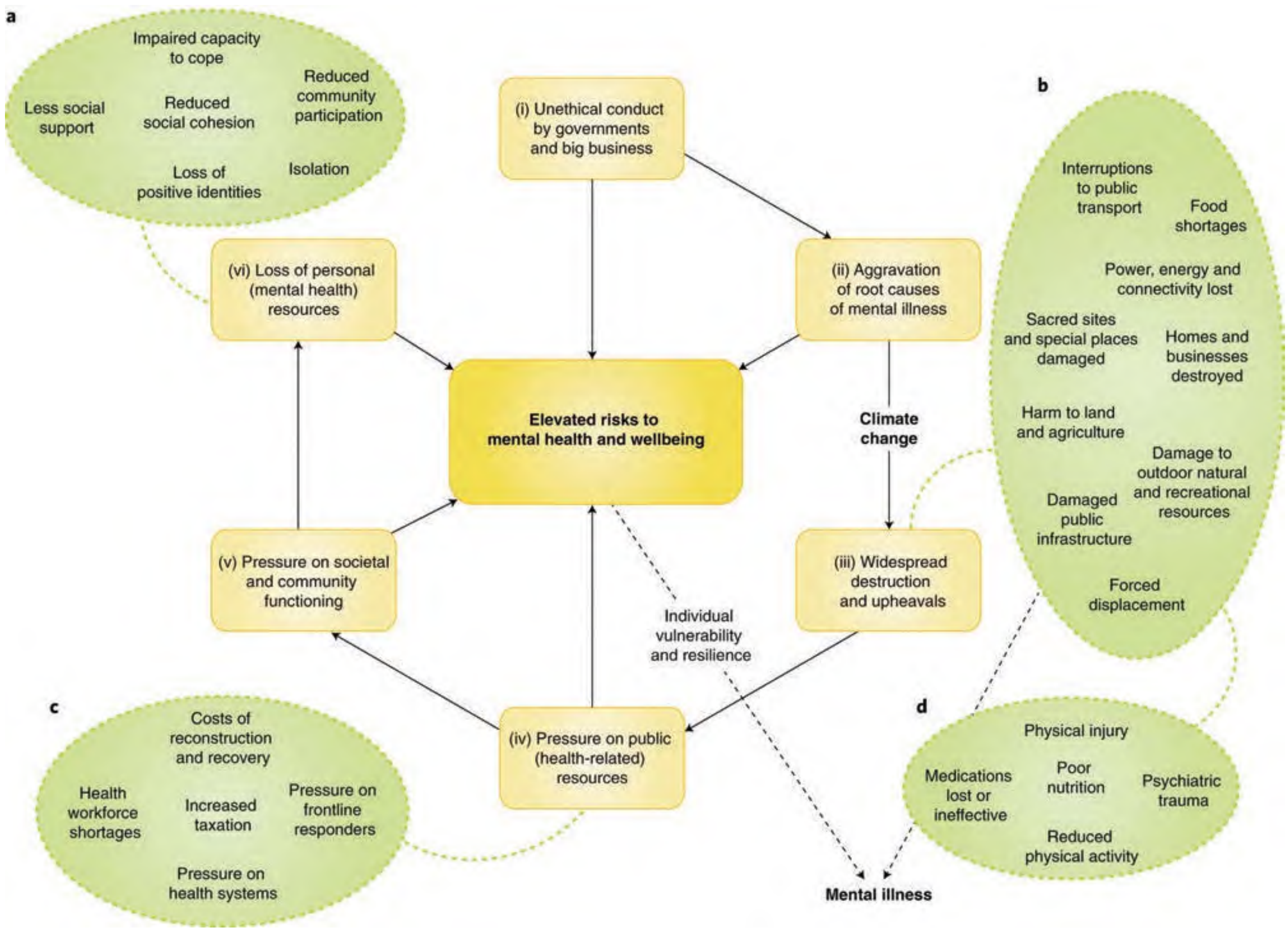


Figure 8.6 A top-level causal process diagram of harms linking climate change and mental health. Source: Berry et al. (2018).

8.2.7. Climate change, influenza and COVID-19

The link between climate and viruses such as influenza is well established. Epidemiological studies indicate that low temperature (e.g. Ianevski et al. (2019) and specific humidity (e.g. Shaman et al., 2010; Noti et al., 2013; Tamerius et al., 2013) are associated with greater influenza mortality. Barreca and Shimshack (2012) show that the humidity–influenza relation is non-linear. Similar links between UV radiation and influenza are well established, e.g. Sagripanti and Lytle (2007) find that "inactivation of viruses in the environment by solar UV radiation plays a role in the seasonal occurrence of influenza pandemics". Although research on the effects of climate on COVID-19 is at an early stage, and provides some conflicting results, some clear trends emerge on the role of local climate, especially for temperature and humidity. A systematic review of research finds a negative association between temperature and humidity and COVID-19 mortality in most studies (Romero Starke et al., 2021).

In Ireland, temperature (Volume 1) and humidity (Nolan and Flanagan, 2020) are projected to increase, which has the potential to alleviate future outbreaks of influenza and COVID-19. Conversely, surface radiation is projected to decrease slightly (Nolan and Flanagan, 2020), which has the potential to exacerbate future outbreaks. However, more research is required at a national level to quantify the impacts of climate change on influenza and COVID-19. In particular, the non-linear association of climate variables (and their inter-dependencies and opposing impacts) on COVID-19 and influenza needs to be better understood. Furthermore, potential links between low UV radiation and COVID-19 risk needs to be further researched to quantify the direct (sterilisation of COVID-19) and indirect (e.g. decreased immunity due to diminished vitamin D production (Erem and Razzaque, 2021)) mechanisms involved.

8.3. Facilitating healthy adaptations

Across multiple government plans and reports there are calls for more detailed planning and collaboration to manage the health and wellbeing impacts of climate change in Ireland. COVID-19 revealed how health systems struggle in acute scenarios and highlighted the need for joined-up, effective planning. The experience of COVID-19 has also demonstrated that during crises individual and community responses are as integral to public health as public agency response, and that an integrated approach that includes communities, care agencies and public health agencies will offer the most effective approach to managing the impacts of future climatic change.

The HSE has outlined a new Climate Change Oversight group in its climate adaptation plan (DOH, 2019) that will meet every 4–6 months. Within this plan there is an emphasis on leadership and on applying the Health in All Policies approach, with particular attention being paid to reducing health inequalities (DOH, 2019). Given the broad range of social determinants of health, this holistic and integrated approach will help ensure that adaptation planning going forward is more effective across all sections of the population. The impacts of wider societal processes, such as the housing crisis, have a very real impact on household adaptive capacity, affecting both physical and mental health. The new EU Adaptation Strategy (EC, 2021) emphasises a systemic approach to adaptation planning to consider societal adaptation in its broadest sense. One potential opportunity would be health and wellbeing county plans that consider geographical and organisational specificities (as suggested in the health sector adaptation plan).

8.3.1. Adaptation planning and collaboration – working with organisations and communities

A major barrier to effective adaptation interventions in the health sector is siloed planning and policy (Watts et al., 2021). Improved collaboration and statutory partnerships between health departments and other government departments and organisations offers opportunities to address gaps in planning for climate change. There are several examples of the Health in All Policies approach in Ireland that can help to bring co-benefits, with mitigation efforts as detailed above. Effective collaboration between departments requires agreement on what counts as desirable and effective adaptation. Indeed, this is outlined in the health sector adaptation plan, where the need for oversight and leadership is highlighted as a key action, and in the broader Health in All Policies approach. Given the need for collaboration and coordinated action, creating opportunities for interactions across departments can increase collective social learning (Pelling et al., 2008), as per the Climate Action Plan 2021, which outlines the building of collaborative relationships between key stakeholders as a priority in the design and implementation of health-related climate policies.

The Lancet Countdown on climate change and health in 2021 identified the essential role that climate services can play in improving adaptation to climate change. However, while there have been improvements in climate forecasting and the availability of climate information, there is a sustained gap in its use in climate decision making (Webber, 2019). Forecasts can aid with planning for flood, storm and heat events in the short term, while in the longer term seasonal forecasting can be used for health system planning. Alexander and Dessai (2019) suggest that climate services could consider using the idea of 'servicescapes', focusing on the experience of the user and user capacity. This is particularly relevant for the health sector, where users can include the HSE, social care stakeholders, schools, community organisations and individual citizens.

8.4. Priorities for research

8.4.1. Vulnerability and inequality

The nature of health inequalities has been signposted in the academic and policy literature. However, there are gaps in knowledge about vulnerable populations and how adaptation strategies can address health inequalities in Ireland. There is an opportunity to explore the potential role of transformative adaptation in helping to address the health and wellbeing of the Irish population.

> *"In Ireland, temperature (Volume 1) and humidity (Nolan and Flanagan, 2020) are projected to increase, which has the potential to alleviate future outbreaks of influenza and COVID-19. Conversely, surface radiation is projected to decrease slightly (Nolan and Flanagan, 2020), which has the potential to exacerbate future outbreaks. However, more research is required at a national level to quantify the impacts of climate change on influenza and COVID-19."*

8.4.2. Register of exposure and vulnerability of health infrastructure

Further research is needed to develop a register of exposure and vulnerability of health infrastructure and services in Ireland to climate change risks (also an action point in the Climate Action Plan 2021).

8.4.3. Heatwave plan

The epidemiology of heat risk in Ireland requires further research alongside the design of a new heatwave plan. Fragmented approaches to managing heat risks need to be addressed; other countries more accustomed to heat risk can provide examples of best practices.

8.4.4. One Health approach for water and health

The high levels of private ownership of water supply and wastewater systems in Ireland pose a particular threat to health during both flood and drought events. Further analysis is needed that brings a systems approach to understand the nature of these risk. A One Health approach would be relevant here in identifying the links between human, animal and environmental health.

8.4.5. Climate change and psychological health

There is a lack of understanding of the psychological consequences of climate change for the Irish population; further research is required to understand the vulnerability of psychological health across populations.

8.4.6. Understanding cross-sectoral linkages

Risk to health from climate change is a cross-sectoral issue. Further research is required to explore how collaboration across sectors, such as the One Health approach, can be developed to support positive health outcomes in climate change adaptations.

9

Business, Industry and Tourism

Key messages

1. Climate change is likely to bring risks and costs to the Irish economy amounting to billions of euros per year by 2050. In 2020, Ireland experienced the third highest climate-related economic losses per inhabitant in Europe (Eurostat, 2022). Climate change adaptation in business and industry in Ireland is limited to date, and significant efforts are required to coordinate effective adaptation efforts with actors in the private sector.

2. As a highly globalised country, Ireland is vulnerable to shocks to supply chains, but these risks are yet to be sufficiently systematically assessed. Further research is needed to identify the vulnerabilities of business and industry to supply chain risks. In addition, important local direct and indirect risks for businesses, employees and customers emanate from flooding and storms, sea level rise, coastal erosion, heat extremes, water scarcity and drought.

3. Currently, the scale of climate change risks to the banking and financial sector in Ireland has yet to be quantified. Climate risks are not well reflected in the pricing of insurance, investment and lending. As these risks become more fully integrated into financial processes, they will affect access to capital and insurance.

4. Tourism, a key sector in the Irish economy, is highly exposed and vulnerable to climate risks and extreme events. While warmer summers are often held up as an opportunity for Irish tourism through increasing visitor numbers, without careful management this could create damaging and unsustainable pressures on sensitive heritage sites and environments. Careful and integrated adaptation planning that values heritage protection and ecosystem services is needed.

9.1. Introduction

In Ireland, climate change is estimated to have cost €4,617 million between 1980 and 2019, with losses amounting to 2.3% of Irish gross national income (Deignan et al., 2022; McInerney, 2022). Climate change is likely to bring risks and costs to the Irish economy, amounting to billions of euros per year by 2050, with costs to the EU estimated to rise to approximately €250 billion a year in the same time frame (McDermott and Petrov, 2016). Globally, up to 30% of manageable assets may be at risk due to climate change (Goldstein et al., 2019) and therefore there is significant interest in ensuring a fuller engagement by the private sector in adaptation efforts. Successful societal adaptation to climate change requires a resilient, sustainable and well-adapted private sector, and the NAF (DECC, 2018) acknowledges government's responsibility to provide an enabling environment for people and businesses to adapt to climate risks. The Irish government has committed to pursuing sustainable development, with the second iteration of Ireland's Implementation Plan for the Sustainable Development Goals published in 2022 (DOT, 2022a).

A recent global stocktake of academic evidence on adaptation to climate change finds that there is limited published academic literature examining private sector response to climate change, and this may be due to the restrictions relating to proprietary information or data being published in other outlets (Berrang-Ford et al., 2021). In addition, there is a discrepancy between the risks that are reported through financial disclosures and the estimated cost that climate change is likely to have on manageable assets (Goldstein et al., 2019). Despite the fragmented nature of evidence on adaptation in the private sector, there are positive indicators that businesses and industries are starting to think more seriously about adaptation, and a consolidation of evidence will help to support these efforts.

Climate action for businesses and industry will involve addressing three broad types of risk: physical risks to operations such as storms and floods; transition risks that are experienced in moving to a lower carbon economy; and liability risks for insurance companies relating to claims for loss and damage. In this chapter, we focus on physical risks to business and industry, reviewing how the private sector in Ireland, from small and medium-sized enterprises (SMEs) through to larger multinational companies, is responding and planning for climate-related risks.

9.1.1. Adaptation in the sector to date

The private sector is key for successful adaptation to climate change in Ireland. Business continuity contributes to broader societal capacity to adapt, and the private sector can play a leadership role in innovation and implementation of climate-resilient development. However, to date, limited attention has been paid by research and business in Ireland to considering climate change adaptation (Forfás, 2010; CCAC, 2021). The Economic Recovery Plan (DOT, 2021) does acknowledge the need for resilient enterprise, but there is little explicit guidance on how to adapt to the consequences of climate change. Similarly, while the NAF sets out the importance of businesses investing in adaptation planning, including long-term considerations of asset management and supply chains, there is limited information and guidance for businesses within the 12 sectoral plans, with the agricultural adaptation plan providing the most detail on impacts and possible adaptation strategies. There is also limited examples of local authorities providing advice for businesses under the NAF, with Deignan et al. (2022) suggesting that authorities are cognisant of the importance of the private sector in adaptation and plan to engage the sector more fully in future planning phases. The NAF highlights that effective adaptation can provide opportunities through job and ecosystem enhancement and developments in innovation.

The recently developed EU Strategy on Adaptation to Climate Change outlines approaches for a climate-resilient EU by 2050 (EC, 2021). The strategy consists of four main principles focused on smarter, swifter systemic adaptation alongside an increased drive in international action on climate change. The strategy sets out that there will be support for the private sector in identifying risks and encouraging investment towards effective adaptation and climate resilience. Specifically, the strategy states that:

By offering solutions to help meet the rising awareness of climate impacts (such as the non-financial disclosure obligations, the EU taxonomy for sustainable activities and the Renewed Sustainable Finance Strategy), it will help large companies, SMEs (small and medium-sized enterprises), local administrators, social partners, and the public. It will also help correct the misperception that adaptation is solely a cost – it is an investment. (EC, 2021)

Echoing broader international trends and reflecting different levels of capacity, larger multinational companies with bases in Ireland are more advanced in adaptation action than SMEs (Deignan et al., 2022). The recent review by Deignan et al. (2022) finds that, in Ireland, adaptation at the SME scale is underexplored and businesses at this scale are less likely to have business continuity plans in place relative to larger companies – there is significant room for improvement in terms of support for capacity building and knowledge sharing with SMEs. Forfás (2010) suggests that there is potentially weak buy-in from the enterprise sector in Ireland regarding climate change adaptation, and while this report was published over a decade ago there is still a significant lag in climate adaptation investment relative to mitigation (CCAC, 2021). This slow response to the challenges of climate change reflects broader international trends, with a mismatch between the short- and medium-term planning of firms and organisations, and the longer-term planning needed to adapt to climate change (Carney, 2015).

9.1.2. Types of business adaptation

One of the few studies carried out globally to characterise the types of adaptations businesses are undertaking analysed data from an annual CDP survey (CDP is a not-for-profit charity that runs a global disclosure system for environmental reporting). Based on this survey, Goldstein et al. (2019) suggest a three-pronged typology of business adaptation: soft adaptation (planning and de-risking approaches), hard adaptation (capital investments in technology, including built infrastructure) and ecosystem-based adaptation (approaches that harness the sustainable management of ecosystems as part of adaptation action). The types of adaptations needed will differ across sectors and workplaces, with some relatively easier to implement, requiring, for example, shifts in work practices, and others requiring significantly higher levels of capital investment. It is rare for companies to report the costs of inaction of climate adaptation, which limits investors' abilities to compare strategies with alternatives and reduces investment incentives for proactive adaptation. Goldstein et al. (2019) note that the disclosures reported reveal a strong preference for incremental and reactive adaptations and they suggest that coupled biophysical and socioeconomic valuations that more accurately reflect non-linear climate change risks can help to support movement towards more transformative approaches in adaptation planning.

9.1.3. The Irish context

In 2020, Ireland experienced the third highest climate-related economic losses per inhabitant in Europe (Eurostat, 2022). As an island nation with a highly globalised economy that imports many materials and goods, Ireland is relatively exposed to movement in price points internationally – the impacts of climate change abroad will be felt in local markets in Ireland. This economic openness underpinned the relatively speedy economic recovery after the 2008 financial crash but also brings relatively high exposure to potential adverse external shocks (Conefrey et al., 2018). As the National Economic & Social Council's (NESC's) 2023 report on the Irish economy in a time of turbulence highlights, the impacts of climate change are being experienced alongside the biodiversity crisis, geopolitical shifts, rising costs of living and demographic change (NESC, 2023).

The Irish Economic Recovery Plan (DOT, 2021) puts sustainable and resilient economic recovery at the heart of planning; like the NDP (DPER, 2021), discussions of sustainability are mostly focused on decarbonisation, with limited attention to strategy or guidance for adaptation. However, the NDP review does include provisions for government departments to rate their capital expenditure across a range of indicators, including climate adaptation. At the EU scale, the new Adaptation Strategy (EC, 2021) calls for improved, standardised climate change-related risk and loss data across Member States, and the European Commission is considering financial mechanisms to encourage disclosure of climate risks (discussed in more detail below). These policy drivers across scales are encouraging business and industry to take account of current and future climate risks, with implications for the Irish private sector.

The NAF (DECC, 2018) outlines the economic rationale for adaptation, with expectations that sectors will reflect key priorities in their budgets. A recent review from the CCAC (2022) emphasises that, as well as identifying the costs of adaptation, future research is needed to calculate the costs of inaction and the damages caused by climate change that cannot be prevented.

Climate change impacts will be sector specific and will vary across firm size, which we discuss further in section 9.2. In its 2010 report, Forfás identified key exposures and vulnerabilities for Irish business as:

- sectors currently affected by weather events (e.g. food and drink, construction);
- sectors making long-term investment decisions (e.g. utilities, pharmaceuticals);
- sectors heavily reliant on transport/infrastructure in (global) supply and demand chains (e.g. ICT/pharmaceuticals);

- sectors that are global in nature and are particularly exposed to adaptation internationally (e.g. financial services);
- sectors that need a lot of high-quality water, such as pharmaceuticals, ICT (wafer manufacturing), food and drink.

9.1.4. How to cost climate change impacts?

The climate-related focus for business tends to be on resilience of existing systems rather than adaptation or more systemic transformation (Surminski, 2021). However, the ability of businesses to think in the long term and in terms of broader systems is often limited by in-house knowledge and time/resource constraints, with a focus on near-term risks – especially for SMEs (Deignan et al., 2022). A recent report by the World Business Council on sustainable development suggests that a resilient business should include safeguarding the natural environment and communities in its business planning (WBCSD, 2020), but doing so requires new ways to measure costs and success.

Commonly, climate impacts are framed in terms of financial costs, and adaptation strategies are framed in terms of cost–benefit efficiencies. Such costs can be measured by examining impacts on livelihoods, assets and profits. Analysis of adaptation in Irish coastal cities (Galway, Cork and Dublin) shows that, when planners do use a predominantly financial framing, the resulting development strategies focus on protecting growth and promoting investments, with the long-term goal of keeping cities competitive on an international stage (Jeffers, 2013). The dominance of financial analyses in adaptation planning has consequences for how such strategies deal with issues of vulnerability across the general population and draws attention to the types of mechanisms through which adaptations can complement long-term sustainable development goals. There is increasing interest in alternative pathways to sustainable prosperity, including approaches such as degrowth and doughnut economics (Figure 9.1) that prioritise wellbeing and ecological health alongside economic metrics and have been flagged in NESC's 2023 report on the Irish economy (NESC, 2023). Applying these approaches would require that adaptation efforts consider social and ecological impacts as well as economic growth if they are to be considered successful and sustainable.

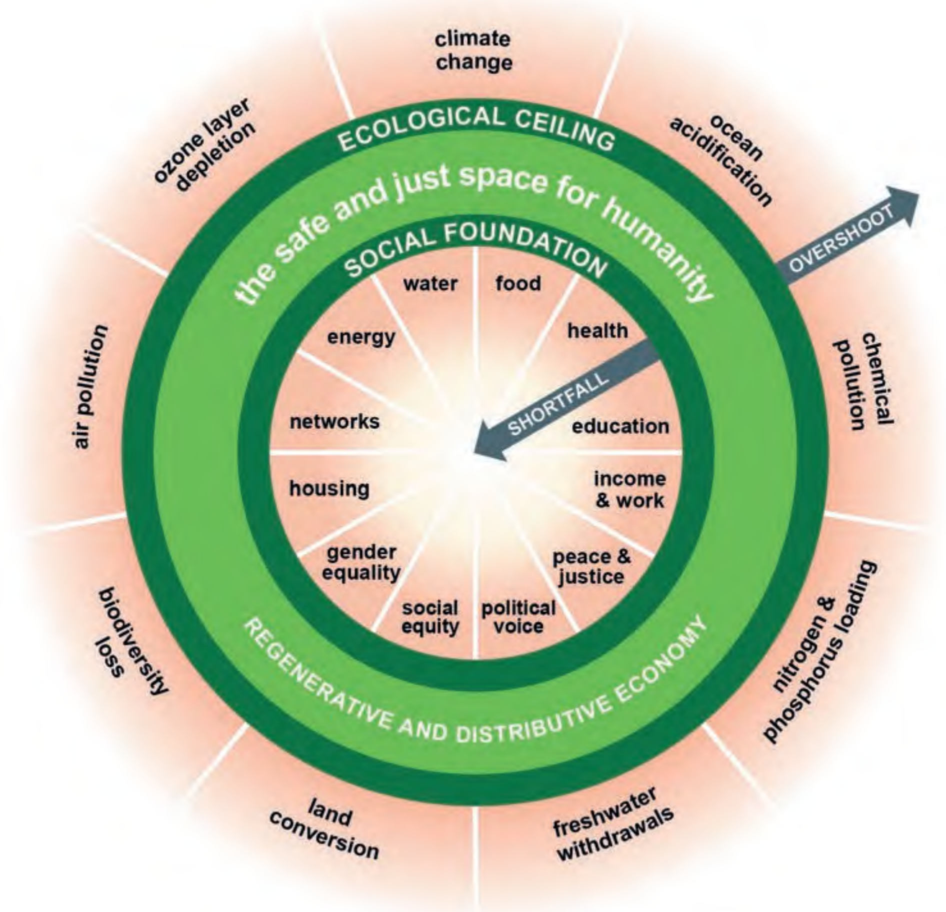


Figure 9.1 The Doughnut of social and planetary boundaries, Kate Raworth and Christian Guthier. Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

The concept of non-economic losses (losses that are not traded in markets) is gaining increasing attention in discussions and negotiations on loss and damage. Such costs include impacts on heritage, sense of place and biodiversity (Serdeczny et al., 2018). Non-economic losses are rarely referred to in economic assessments of climate impacts and as a result can be left unaddressed in risk analyses and policymaking (Serdeczny et al., 2018). The growing attention on how the non-economic costs challenge current accounting processes for climate change impacts highlights the need for a broader set of measures to evaluate adaptation strategies, including a focus on wellbeing in development planning (see Box 9.1). Going forwards, a big challenge for policymakers in Ireland will be deciding on what counts as successful adaptation, balancing the demands of different sectors and civil society (see Chapter 10). Recognising that there is a limit to financial framings for adaptation, future research is required to explore different measures of success that can be a win–win for businesses and for society.

Box 9.1 Sustainable wellbeing: policy innovation for a flourishing people and planet

For most of the 20th century, economic growth was promoted as the primary route to national progress, to improve people's lives and to deliver human wellbeing through income. It is widely acknowledged that growth in economic output and income contributed to increased material provision and related poverty reduction. However, it is also acknowledged that the increase in material consumption among the wealthy has become a 'mega-driver' of environmental degradation, and consequent climate and ecological destruction (Fleurbaey et al., 2014). Growth in economic output has also been associated with increasing inequality, and with limited addition to human wellbeing, beyond a point. As the 20th century unfolded, recognition of these challenges led to changes in public policy, to spread the economic gains and encourage environmentally and socially sustainable development. From the dawn of the 21st century, it has become generally accepted that income and economic growth are not sufficient for wellbeing, nor for sustainability (Stiglitz et al., 2009). This prompted debates on economic growth versus degrowth (Grubb et al., 2022), and decoupling wellbeing and income, for 'prosperity without growth' (Jackson, 2009). The business-as-usual path has been deemed no longer fit for purpose, requiring pursuit of innovation in public policy, a transformation that reconceptualises development (Fleurbaey et al., 2014). This shift in framing can be assisted by moving from means to ends, from the economy and income to 'sustainable wellbeing', as the flourishing of people and planet (O'Mahony, 2022).

Ireland has recently made a start in bringing a wellbeing approach into public policy, targeting indicators and evaluation (DOT, 2022b). Graduating to next steps, for real-world implementation, requires new conceptualisation of development goals and related innovation in public policy that can substantially deliver. While a nascent area for research and policy, it offers significant potential for win–win outcomes, in transformation to 'sustainable wellbeing' in a climate-resilient, low-carbon future.

9.2. Vulnerabilities, impacts and adaptation strategies

9.2.1. Flooding and storms

Flood risk is one of the most significant climate change risks for Ireland, with several Irish cities exposed to rising sea levels and increased risk of flooding (OPW, 2019; Paranunzio et al., 2022). Figure 9.2 shows OPW-projected scenarios for flooding and sea level rise by 2050 in Dublin, Cork and Limerick, with flood risk affecting sites of residential housing, services, business and industry. In 2016, Dublin generated approximately 53% of Ireland's gross domestic product and 43% of employment (OECD, 2018). Expansion of business and industry continue in these at-risk locations, as detailed in Chapter 7, with the Dublin Docklands (see Figure 9.3) designated as a strategic development zone in 2012, enabling fast tracking of planning and approval processes, with ongoing plans for the development of the area, including housing, offices and retail (Brooks et al., 2016). Development in flood-risk zones continues along coastlines globally; however, there are limited funds to protect shoreline locations. As residents and businesses continue to be attracted to coastal sites, issues of responsibility for flood protection and recovery are likely to become increasingly contentious as climate change challenges our capacity to manage the risk of flooding.

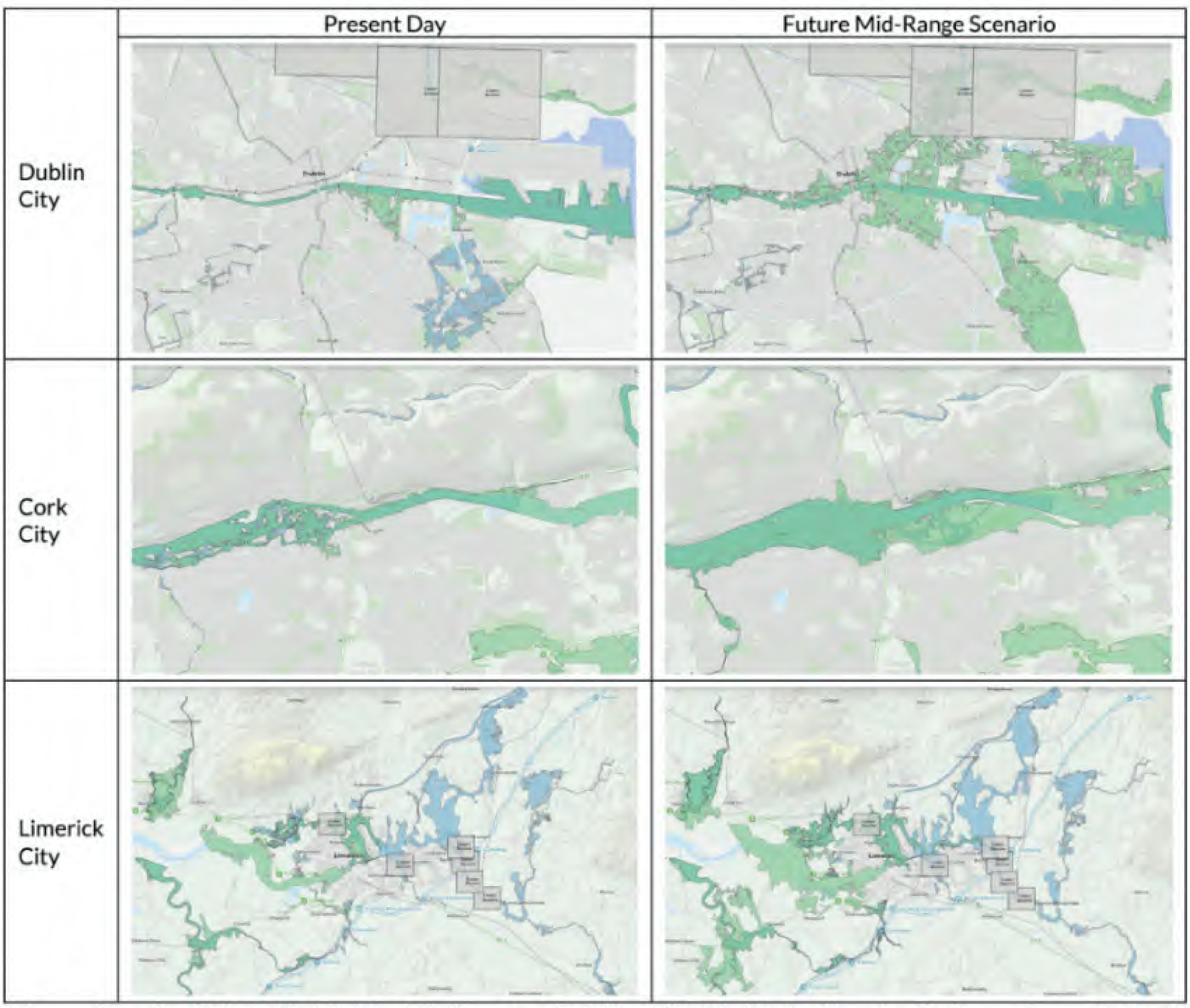


Figure 9.2 OPW's mid-range (medium probability) future scenarios showing the impacts of increased rainfall and sea level rise in Dublin, Cork and Limerick (projected for 2045–2050 in global business-as-usual emissions scenario and 2100 in global net zero emissions by 2050 scenario, includes information from Ordinance Survey Ireland). Source: Carroll (2022).

Figure 9.3 Aerial view of Dublin Port. Source: Brooks et al. (2016).

Current risks and impacts. Current and future risks to business sites in Ireland from flooding and storms are significant and include power loss and failure of ICT systems and other energy-dependent infrastructure, posing a range of risks to employees and the ongoing running of businesses. Research in the UK analysing the economic impacts of flood events that cause power outages shows a potential 300% increase in total economic losses when a loss of power is modelled alongside other flood-related damages (Koks et al., 2019). As described in Chapter 7, failure of critical infrastructure has cascading effects across sectors, and effective evaluations of flood risk to business and industry require careful consideration of the vulnerabilities of supporting infrastructures.

Significant flood events can affect working conditions for employees and their safe access to sites, potentially causing unsafe working conditions (Deignan et al., 2022). The study by Kilgarriff et al. (2019) study of flooding after Storm Desmond (2015) shows the differentiated impact of the storm on commuting times of employees in Galway (illustrated in Figure 9.4). Calculations based on the impacts of the storm show that people already facing large commutes incurred extra costs, with those living in the worst-affected areas having to spend up to 39% of earnings on travel costs for the period. People on lower incomes suffered proportionately greater losses, with rural populations particularly badly affected (Kilgarriff et al., 2019). The lack of public transport options in rural areas further reinforces the vulnerability of this population to the impacts of disrupted travel routes. Kilgarriff et al. (2019) suggest that flood risk and adaptation policies should consider that commuting costs have a regressive impact on inequality, and people who already have long commutes and a low income are most vulnerable to extreme weather disruptions.

Flooding of roads, premises and critical infrastructure disrupts the movement of customers and their access to businesses. Deignan et al. (2022) describe the costs of flooding in shopping centres and underground carparks, such as happened in Dundrum town centre in 2011 and again in 2021, resulting in business closures in Dundrum Shopping Centre. The disruption associated with storms and floods creates customer uncertainty about accessibility and opening hours, as happened during Storm Emma in 2018 over four key trading days, Thursday to Sunday. The storm also impacted supply chains, disrupting trade for up to a week, with some businesses experiencing losses of up to 30% relative to the same period in 2017 (Retail Ireland, 2018). Erosion of coastal areas in and around businesses will also impact the viability of access to business sites as well as the business sites themselves (climate change and coastal erosion is dealt with in more detail in Chapter 4).

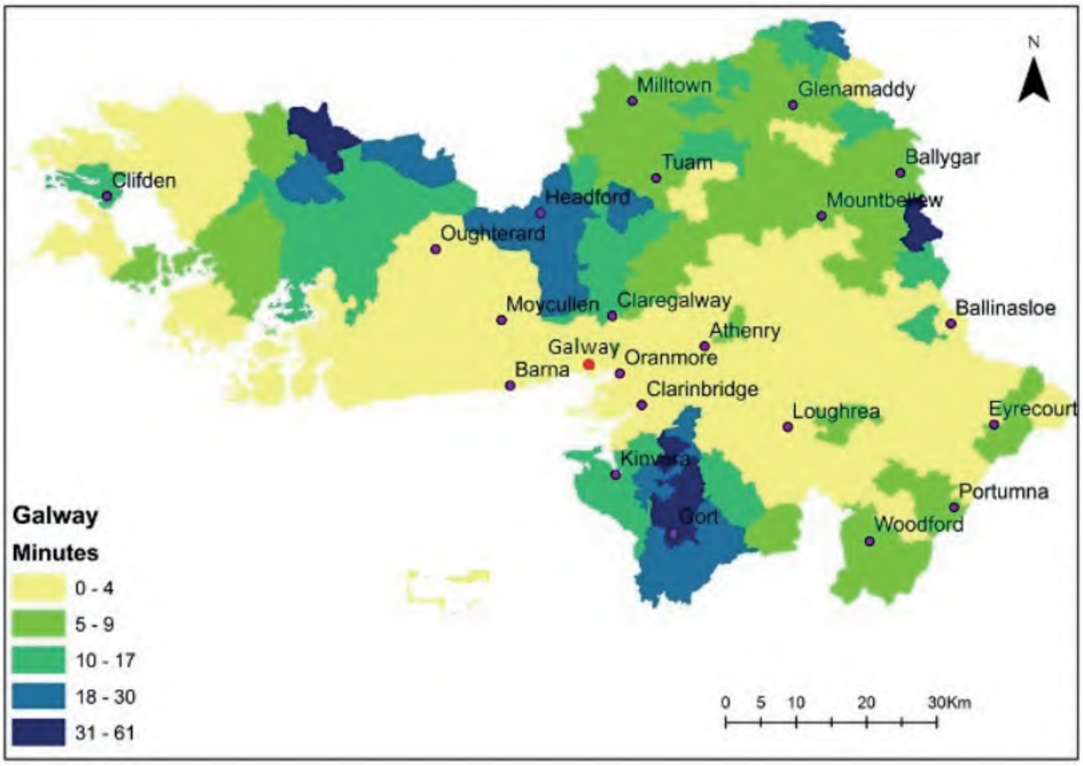


Figure 9.4 Additional time commuting due to floods. Calculated by status quo commute subtracted from commute time post Storm Desmond. Source: Kilgarriff et al. (2019).

Supply chains and the ability to deliver to sites, as well as transport of goods between locations, can be compromised by flooded access routes. Particularly vulnerable to disruptions are businesses with goods requiring refrigeration or delivery within limited time frames (Forfás, 2010). In the longer term, the increased business insecurity driven by the risk of flooding is likely to affect the costs of insurance for businesses, which will be reflected in the cost of coverage for buildings, in employer liability and indemnity insurance.

Adaptation strategies. Businesses can adapt workspaces and operations to improve resilience to flood risk (e.g. moving sensitive equipment to higher floors, moving sockets higher on walls) to reduce the risk of disruption to business activity. Investing in more significant resilience measures, such as the purchase of back-up generators, will entail additional expenditure in the short term owing to increased operational and capital spending but may be required to ensure business continuity when significant flood events occur (DHLGH, 2019). Business continuity plans will need to consider the cascading risks that occur with extreme events, balancing short-term resilience measures and larger-scale capital investment. There is significant scope to improve the availability of advice on climate resilience and business continuity measures (e.g. on the Climate Ireland website or as part of county action plans), support that will be particularly useful for SMEs, which are less likely to have in-house expertise.

Re-zoning by councils has had a major effect on flood risk in Ireland (Forfás, 2010) and there is a disincentive for local councils to change this, as the costs of floods largely fall on national government, with developers not significantly incentivised to avoid or reduce flood risk because this has not tended to affect prices of developments (Surminski, 2017). Surminski (2017) describes the need for greater sharing of data used in the insurance sector and transparency around risk levels in Ireland, aiding better coordination for insurance coverage. Information sharing has been aided significantly by the OPW's floodinfo.ie website, which outlines spatial flood risk and information on risk management plans.

9.2.2. Coastal change

The risks associated with rising sea levels are occurring alongside and in relationship with other 'coastal squeeze' processes, including increased population density, threats to water quality, threats to biodiversity and the introduction of invasive species (Brooks et al., 2016). The interplay of social and environmental processes is particularly evident in coastal areas and provides unique challenges for business and industry located along coastlines. Given that most large urban centres in Ireland are located on the coast, climate change-driven changes in coastal areas will be challenging for businesses and industries. Presently, there is no national coastal management strategy in Ireland; however, the evidence base for joined-up coastal management is improving with, for example, the National Coastal Flood Hazard Mapping project (OPW, 2021) producing maps of sea level rise across a range of future scenarios.

Jeffers (2013) shows in his work on coastal cities in Ireland (Dublin, Cork and Galway) that the prevailing framing of cities in adaptation planning is of economic entities vying in global competition for capital. This approach to valuing cities influences the type of adaptation strategies that planners engage with, placing an emphasis on technical responses and cost-effectiveness that can sometimes exclude consideration of impacts on the most vulnerable populations. The planners in this study consider adaptation as key to economic development because a city vulnerable to climate change is not likely to be competitive in attracting investment (Jeffers, 2013). There is evidence globally of communities challenging private sector and government management of risk, with examples of legal challenges over their roles in disaster events that draw attention to issues of negligence, failure to control water levels and inadequate maintenance of flood water systems (Moudrak and Feltmate, 2019). As methods of accountability and attribution for disaster events are increasingly refined, economic framings of adaptation may prove inadequate and litigation risk may start to act as a bigger driver for adaptation planning in business and industry, especially when impacts spread to broader social ecological systems.

Current risks and impacts. Businesses in coastal locations are vulnerable to the risks of flooding described in section 9.2.1, with the potential for cascading risks due to the number of critical infrastructures coalescing in coastal areas, including roads, train stations, ports, power stations and railways. A significant amount of business and commercial activities is located along Ireland's coast, with chemical and pharmaceutical plants based in coastal areas, particularly in Cork Harbour and the Shannon Estuary areas where sites are vulnerable to flood risk (Forfás, 2010). Recent analysis by Vousdoukas et al. (2018) suggests that Ireland could be one of the most heavily economically impacted countries (relative to gross domestic product) by coastal flooding in Europe under projections of Middle and Late action efforts to reduce greenhouse gas emissions (RCP4.5 and RCP8.5). The physical and regulatory risks associated with coastal flooding require particular attention given the number of businesses and industries in flood zones in coastal areas, where processes of handling, transmission and storage safety standards are potentially undermined by flood events (Forfás, 2010).

Adaptation strategies. Coastal management strategies that protect physical sites and wider supporting infrastructure are addressed in detail in Chapters 4 and 7; here we focus on risk to business. In the short term, businesses can develop enhanced continuity plans, including regular reviews and tests, with medium- and long-term business planning requiring analysis of the viability of business sites as well as supporting infrastructure with regard to projected local flood and erosion risks. In the absence of long-term planning, there is the potential that (costly) short-term risk reduction could inhibit engagement with more transformational approaches to climate risks, including relocation (Keeler et al., 2018). Businesses located in coastal zones may face the risk of becoming 'unprotected' in flood risk management terms, potentially becoming uninsurable and experiencing loss of asset value and possible business failure.

For businesses, long-term coastal management plans will provide guidance (and assurance) for investment and potentially on insurability of enterprises – especially important for loans with long repayment periods. We emphasise the need for a coordinated coastal plan consisting of several planning horizons to ensure that future development is sustainable; by involving a broad range of stakeholders this process can reduce the risk of transferring vulnerability between places and sectors.

9.2.3. Hot weather

Current risks and impacts

Hot weather poses a direct risk to employees and customers, as well as to business continuity. People working in jobs that are physically challenging or require time outside where temperature control is not possible are particularly vulnerable to the impacts of heatwaves, with high humidity and/or UV exposure potentially compounding this risk. There is currently no legal maximum working temperature in Ireland; however, the HSE provides health and safety suggestions for managing thermal comfort within workplaces. Suggested maximum temperatures vary across workplaces depending on the type of work, with lower temperatures recommended for workplaces that involve physical workloads or more vulnerable employees/customers. Older employees and new workers are particularly vulnerable to the impacts of heat stress (Heat Shield, 2022).

Research assessing the economic impact of climate change in Europe draws attention to the negative impact that extreme heat has on the safety and productivity of industrial and construction workers, illustrated in Figure 9.5 (Schleypen et al., 2019). Drawing on learnings from a UK project, it is also likely that prolonged hot weather will more significantly affect low-waged roles in industries such as agriculture or tourism, with employees already in ill-heath particularly vulnerable to the impact of hotter workplaces (Surminski et al., 2021).

Prolonged periods of hot weather will challenge industries that have temperature sensitivity along their supply chain; importantly for Ireland this includes pharmaceuticals and the food and drink industry. In 2018, the horticultural sector in Ireland had to take action to adapt to warmer temperatures, with extra irrigation and additional energy required to keep temperatures cool in glasshouses and to keep crops cool following harvest. These collective measures at various sites along the supply chain drove up production costs across the sector (Deignan et al., 2022).

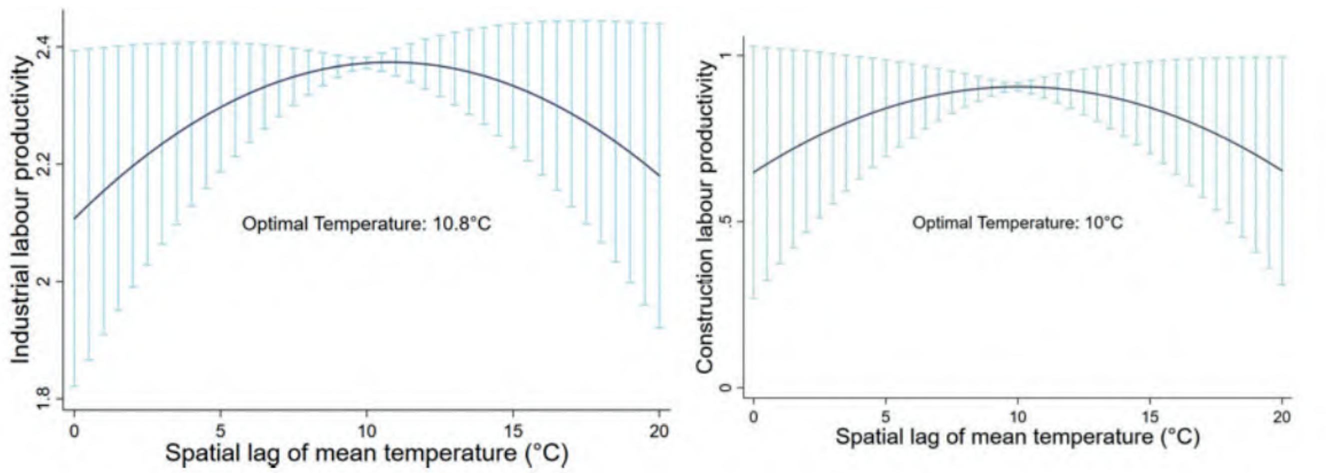


Figure 9.5 The non-linear relationship between mean temperature and productivity (dark navy line). The left panel shows the impact on the industrial sector and the right panel the impact on the construction sector.
Source: Schleypen et al., 2022.

Adaptation strategies. There are varying limits for heat in the workplace, with the European Trade Union Confederation calling for legislation to protect workers EU wide (ETUC, 2019). Provision of cooling through air conditioning and upgrading of buildings will increase capital and running costs (and emissions in the short term) but are likely to be required to climate-proof workplaces and protect employee wellbeing. A recently funded EU project called Heat Shield developed guidelines and resources for reducing the impact of heat stress for the tourism, transport, manufacturing, construction and agricultural sectors. The recommendations centre on managing the temperature of workplaces, hydration and changing work practices around the hottest parts of the day (Heat Shield, 2022). As noted in Chapter 8, the development of an occupational heat stress index could help to identify thresholds in extreme event situations that then trigger targeted management plans. Here, climate services can play a role in producing tailored heat warnings for workplaces particularly exposed to heat stress. There are clear win–win opportunities to make the built environment more resilient to climate risks, as outlined in Chapter 6. Prolonged hot periods have not traditionally been a risk to Irish businesses, and learning can be gained from reviewing guidance in other countries where heat risk management is more established in business practice.

9.2.4. Water scarcity

Current risks and impacts. Water is used throughout business operations for a range of practices, including for drinking, sanitation, cooling, dissolving chemicals and as a direct ingredient in products. Ireland's bulk water extraction per capita is the second highest in Europe, with a 49% leakage of potable water and potential reductions in water resource availability with climate change (Irish Water, 2021b). Lower river flows may lead to restrictions on water abstractions and discharges of high-temperature water (Forfás, 2010). In the Greater Dublin Area, leakage needs to be reduced and a new water supply source is required, as the Liffey is near to maximum sustainable abstraction, with available headroom regularly reduced to

2% (Byrne et al., 2019). The current vulnerability of the water supply system in Dublin was demonstrated in 2013 when production problems at the Ballymore Eustace water treatment plant (which provides 50% of supply to Dublin) resulted in water restrictions in Dublin (Byrne et al., 2019). The impacts of climate change may compound risks in an already stressed system and policies will need to be coordinated across a range of sectors, including agriculture and forestry, to ensure that water quality is satisfactory and is available to support the general population as well as business and industry. The recently passed Water Environment (Abstractions and Associated Impoundments) Bill 2022 (DHLGH, 2022c) lays out a process for assessment, management and regulation of surface water and groundwater abstractions over 25m^3 per day, aiming to improve knowledge of abstraction activities and support more rigorous regulation across sectors.

A loss of water supply can make workplaces uncomfortable and potentially unsafe if standards of hygiene cannot be maintained. Businesses obtain water through either public supply systems or direct abstraction, and policymakers and regulators play a significant role in designing laws, regulations and management practices for businesses in their access to water. Issues of water supply can develop due to drought or long-term water scarcity (insufficient and/or unreliable access to water), flooding (damage to infrastructure and water supply) and pollution (where water is unsafe for use).

Adaptation strategies. As set out in the Water Quality and Water Services Infrastructure Sectoral Adaptation Plan, water scarcity adaptation strategies include business continuity planning with actions for operational improvements, efficiency, maintenance and up-to-date asset management. Where disruption to water supplies can affect customers directly, businesses should have communication strategies in place that consider impacts on customers most vulnerable to changes in water supplies. Adaptation to this risk requires coordination between sectors, especially by stakeholders that rely heavily on water sources for everyday operations. One organisation's action can have a direct impact on another's risk, and indeed can quickly have impacts for the general population.

9.3. Tourism: a key sector

Tourism is a key sector in the Irish economy, with Ireland receiving 9.7 million visitors in 2019 (Fáilte Ireland, 2021). The sector is well placed to provide significant employment and foreign earnings, generating €9.5 billion annually and employing approximately 260,000 people, with mainland Europe the biggest market – accounting for 37.3% of overseas tourists in Ireland (McLoughlin and Hanrahan, 2019; Fáilte Ireland, 2021).

As a sector, tourism is highly exposed to climate risks, given the importance of weather and outdoor activities for businesses. Many tourist centres are located in coastal areas, sites of significant environmental change where a number of climate risks interact (including flooding, sea level rise, ocean acidification, erosion and biodiversity loss) to produce particular landscapes of vulnerability (Deignan et al., 2022). These multiple intersecting risks have been flagged in the transport sector's climate change sectoral adaptation plan (DTTAS, 2019), which highlights ocean acidification and coastal erosion as threats to Ireland's coastal tourism and natural attractions. There is a small but growing research base on the impacts and challenges of climate change for this sector in Ireland and the opportunities that may develop with a lengthening summer season. This is a sector where sustainability standards are relatively well developed, and further work is needed to inform integration of climate change adaptation into wider industry standards.

9.3.1. Risks and adaptations

The coastal nature of many tourist sites in Ireland leaves them particularly exposed and vulnerable to storms and flooding. Similar to other sectors, floods prevent access to sites and can cut off travel routes and undermine infrastructure (Forfás, 2010). Deignan et al. (2022) detail the impacts of Storm Ophelia when a red weather warning resulted in cancelled tours and the mass cancellation of hotel bookings following the experience of Storm Emma. While it is difficult to capture the impact of such events on a whole sector, the uncertainty introduced by extreme events on the ability to travel and to engage with outdoor activities shapes the sensitivity of this sector to climate change risks.

Sea level risk and coastal erosion will challenge the integrity of tourist infrastructure and amenities, including heritage sites along Ireland's coast (see Chapter 4). Many resort beaches are backed by sea walls and promenades, and the narrowing of beaches from increased erosion reduces both recreational space and the environmental quality of beach areas. Management of beach loss will involve choices over how to invest resources, for example the Galway County Council Climate Adaptation Strategy includes plans for beach management to improve the resilience of the local tourism sector (Deignan et al., 2022). Such options include enlarging existing defences, moving sea walls landwards or replenishing beach materials. Beach replenishment is relatively common in other countries, but not often pursued in Ireland, with a limited number of examples at Courtown, Rosslare and Cahore (all in Wexford) (Cooper and Boyd, 2018). Coastal infrastructure is of course exposed to the impact of storms, reducing the lifespan of some coastal assets. In County Cork, the illustrative example of the Youghal boardwalk shows the ongoing investment and resilience building that will be required in adapting Ireland's tourism sector. The Youghal boardwalk was constructed in 2012 to attract visitors to the town and beach, originally extending for 1.2km along the beach. As shown in Figure 9.6, the boardwalk was destroyed by storms in January 2014 and the town was subsequently awarded funds of €220,000 to rebuild the structure with an extended section added.

Figure 9.6 The Youghal boardwalk in County Cork destroyed in storms in 2014 (top) and rebuilt in 2019 (bottom). Credit: John Finn and Smith et al., 2022

The interacting pressures of coastal erosion and tourism activities is becoming evident in several 'honeypot' locations in Ireland. The Maharees in Kerry experiences large numbers of tourists, with accompanying issues of illegal dumping, congestion and trespassing undermining the sustainability of tourism in the area (Farrell et al., 2023a). The impacts of large numbers of tourists are accelerating the destabilisation of the fragile dune system, which is already experiencing chronic erosion from Atlantic storms (the dunes have retreated by over 40m in the last 45 years; Farrell et al., 2016). The Maharees Conservation Association (MCA), set up in 2016, has engaged in a range of actions to address this degradation, including targeted educational strategies, dune restoration and nature-based approaches. While the MCA has been held up nationally as an example of mobilising community responses to climate change, the MCA recognises that its efforts are not permanent, are constrained and require a co-designed enforceable coastal plan for the peninsula (Farrell et al., 2023a)

The possible narrowing of intertidal zones caused by coastal erosion and periods of high and low river flows is likely to have implications for trade-offs between coastal users (and between sectors), where, for example, there may be competition between leisure activities and commercial shipping activities (Forfás, 2010). Coordinated planning will be required to ensure that different users and interest groups can collectively shape coastal futures, and there are efforts under way with the establishment of the National Coastal Change Management Strategy Steering Group to facilitate integrated coastal change strategy.

Warmer summers bring both opportunities and challenges for the tourism sector in Ireland. Warmer, more reliable summer seasons may support an extension of the peak tourist season into April and October and will allow further development of tourist products, in particular the provision and variety of water-based holiday activities. The relative attractiveness of other regions (e.g. the Mediterranean) may also weaken due to weather extremes (Nicholls and Amelung, 2008; Forfás, 2010). While warmer summers may provide benefits for the tourist industry, heatwaves and prolonged hot weather will also provide a challenge for tourist infrastructure not prepared for warmer conditions. Many older hotels do not have air conditioning, and travel on public transport becomes less comfortable during hot weather periods (Deignan et al., 2022). Outdoor tourism facilities may also become less safe during periods of high temperatures due to heat risk and exposure to UV.

As an important sector for the Irish economy, further consideration of climate change impacts on tourism in Ireland is needed at both local and regional government scales (McLoughlin and Hanrahan, 2019). Tourism has been criticised for supporting low-wage economies and for being environmentally unsustainable, although there are attempts from within the industry to address these issues (see the example of the Burren Ecotourism Network[7]). For sustainable future development of the industry in the light of climate impacts, research and sharing of good practice can help to ensure that further development is aligned with broader societal goals.

9.4. Risk to finance, investment and insurance

Climate change risks for the finance sector in Ireland will be driven by interactions between policy, physical risks and real economy changes (Carroll, 2022), the potential scale of climate change risk for the banking and finance sector in Ireland is yet to be quantified. Climate risks are not well reflected in pricing for insurance, investment and lending, and fully integrating these risks into financial processes will affect access to capital and insurance (Surminski et al., 2021). Indeed, companies perceived to be taking insufficient account of climate risk may find it harder to get credit as the costs of climate change impacts become materially clearer.

The Central Bank of Ireland (CBI) regulates and monitors firm-scale risk management practices and has established a Climate Risk and Sustainable Finance Forum to facilitate sharing of information and best practice. In 2021, CBI issued a 'Dear CEO' letter on climate and environmental, social and governance issues, which was sent to all CEOs of Irish regulated entities. In it the CBI outlines expectations in five key areas:

1. **Governance.** Firms' boards will need to demonstrate clear ownership of climate risks while also promoting an internal culture that emphasises the importance of climate and other environmental, social and governance issues.
2. **Risk management framework.** Firms will need to understand the impact of climate change on their risk profiles and ensure that existing risk management frameworks are appropriately robust to identify, monitor, measure and mitigate climate risks.
3. **Scenario analysis.** Appropriate scenario analysis and stress testing will be critical to assess the impact of future climate outcomes for firms.

[7] https://burren.ie/about-burren-ecotourism/

4. **Strategy and business model risk.** Appropriate business model analysis should be undertaken to determine the impacts (and potential opportunities) of climate risks on firms' overall risk profile, business strategy and sustainability.
5. **Disclosures.** Transparent disclosures to consumers and investors will be key, with the CBI reiterating the importance of not engaging in greenwashing.

As part of the EU, Ireland is aligned with several financial regulatory bodies, including the European Securities and Markets Authority, European Insurance and Occupational Pensions Authority for the insurance sector and the European Banking Authority. There are significant efforts under way at the EU scale on climate change and finance, with the European Commission developing legislative frameworks for green bonds and disclosure regulations, and a broad body of work housed under these frameworks is developing guidance on how these obligations can be integrated into the supervision and day-to-day activities of firms. The increasing push for financial disclosure relating to climate risks means that banks in the future may have to reveal the book of lending they have, and whether the industries and businesses they lend to are sustainable. To this end, in 2015, the Financial Stability Board established the Task Force on Climate-Related Financial Disclosure to provide guidance for companies to report the financial implications of climate risks (Goldstein et al., 2019).

Recent activities such as the Single Supervisory Mechanism Climate Risk Stress Test run by the European Central Bank is drawing attention to possible changes in the ways that firms are likely to be lent to in the future. The European Commission is exploring the possibility of a green supporting factor to inform bank lending and investment. Green supporting factors would require a bank to hold less capital if its lending activities are provided to green customers (which are deemed less risky). An alternative would be the pursuit of brown penalising factors, whereby banks would have to hold more capital if they are lending to less sustainable businesses. There are debates as to whether such factors truly reflect risks, and the focus is largely on low-carbon assets, but there is scope for such an approach to include exposure and vulnerability to physical climate risks more comprehensively.

Understanding of the link between climate change risks and financial risks in Ireland (and globally) is limited but is likely to be particularly significant for an open economy such as Ireland (Carroll, 2022). Recognising these risks, work assessing how physical risks outside Ireland will affect the Irish economy is under way (Carroll, 2022). Further research is needed to identify specific risks for the finance sector from global processes of climate change (see Chapter 10).

9.5. Supply chains

Research on the impact of climate change on supply chains is relatively new (Ghadge et al., 2020), with the COVID-19 pandemic and the war in the Ukraine highlighting the vulnerability of supply chains in response to changes in demands and shocks to the system and the subsequent impact for inflation on goods in Ireland. As a country that imports many materials and goods, Ireland is highly exposed to international price movements, but we have yet to grapple within research or industry with the details of what this means for the Irish economy in a changing climate.

Supply chain risk management involves coordination and collaboration between supply chain members, with strategies required for both the short and long term that reduce disruption and promote continuity (Tang, 2006; Wieland and Wallenburg, 2013). The main elements of such strategies consist of risk identification, assessment and mitigation of sources of risk, and assessment of the likelihood and possible consequences of an event (Christopher and Lee, 2004; Ghadge et al., 2020). HSBC's 2020 report distinguishes between acute, one-off disruptions and longer-term disruptions that can drive up supply costs, reduce quality and slow down deliveries (HSBC, 2020). It also emphasises that climate-driven disruptions to supply chains are distinctive due to more frequent and longer duration disruptions that are likely to occur at multiple points along supply chains.

Exposure and vulnerability to supply chain disruption are specific to sectoral contexts, with those relying on cold supply chains particularly sensitive to climate change risks. Extreme weather events can disrupt pharmaceutical supply chains, increasing both the costs of transport and the requirements for extra storage capacity. Recently, SustainabilityWorks led a review and series of workshops on the impact of climate change on Irish industries and identified supply chain risk as a high priority across industries (Deignan et al., 2022). Businesses that rely on single transport routes or that have highly specialised supply chains may experience more severe disruption when supply chains are interrupted or constrained by severe weather events.

The most recent NDP (DPER, 2021) highlights the importance of a more circular economy in managing supply chain risk, and the Whole of Government Circular Economy Strategy (DECC, 2022b) sets out the ambition for Ireland to become an EU leader in the circular economy. The recent Circular Economy and Miscellaneous Provisions Act 2022 (ISB, 2022) brings statutory status to circular economy efforts and ringfences funding to support projects and initiatives. While these efforts are not always framed as adaptation responses to climate change, by keeping materials and products in use for longer, a more circular economy can reduce demand for particular resources, increasing the resilience of economies to climate-driven disruptions in supply chains.

Currently there is a lack of empirical analysis and evidence on the vulnerability of Ireland to supply chain issues because of climate change. Careful planning and strategy are key for adapting supply chains to climate risks. Collaborative efforts with supply chain partners, including scenario planning, can help to develop approaches to making supply chains more climate resilient, while climate services can also play a role in supporting industry readiness to respond to extreme events.

9.6. Cross-cutting issues

There have been two major reviews of how climate change is likely to impact business and industry in Ireland – Forfás' report in 2010 and a report by Sustainability Works led by Deignan et al. (2022), which focuses on five specific sectors. These reviews provide a useful overview of the exposure of sectors, but also reveal the lack of data and research on how businesses are responding to climate change. Both reports reflect the fledgling state of adaptation for Irish businesses, with a relatively recent uptick in interest across industries. Innovation will inevitably come from within business and industry, and government policy can help to support the development of climate change adaptation in Irish business and industry, especially in sectors where there is limited adaptation to date.

Like the findings of the UK's Climate Change Risk Assessment (Surminski et al., 2021), in Ireland there is a knowledge gap between information and practices mobilised in large multinationals and those engaged in by SMEs (as noted in the 2010 Forfás report and in the most recent report by SustainabilityWorks (Deignan et al., 2022)). SME adaptation decision-making processes are more likely to be similar to those of individuals, while in large multinationals adaptation decisions are more likely to be driven by corporate governance and shareholder pressures. Facilitating learning across businesses and industries can be a relatively inexpensive method of improving knowledge on adaptation opportunities, with initiatives such as the recently established Climate Risk and Sustainable Finance Forum led by the CBI helping to facilitate cross-sectoral learning.

There is potential to implement financial disclosure obligations as in the UK, where listings of climate-related risks will be required by listed companies by 2025. A focus on disclosure obligations reflects the broader international push towards disclosure regulations reflected in the establishment of the Task Force on Climate-Related Financial Disclosers and is being explored by the European Commission on the topic of green supporting factors and brown penalising factors. Such changes to the finance system is likely to produce substantial new reporting responsibilities for business and industry, and further research and support will be needed to help businesses navigate new policy and regulatory terrains.

Across sectors, the process of digitalisation will bring a range of challenges and benefits for businesses. Ireland is already in a strong position as a highly digitalised country (fifth in the EU Digital Economy and Society Index in 2022); however, the European Investment Bank describes Ireland as running at two different speeds, with large multinational companies having high levels of digitalisation, but slower levels of uptake among SMEs (EIB, 2019). Broader efforts on digitalisation in Ireland will have implications for climate action at the firm scale, improving monitoring capacity, and is also likely to be harnessed for regulatory purposes. Connected to this process, increased use of ICT will enable more immediate engagements with early warning systems, for example in partnership with climate services, with significant implications for management of national and international supply chains (Ghadge et al., 2020). As companies increasingly move towards digitalised operations, there will be scope for increased use of data to manage and monitor adaptation actions and responses. In tandem with this there are likely to be challenges in ensuring that data are handled fairly and transparently. This issue is not unique to climate change adaptation, and the EU and the Irish Government are developing and implementing strategies for considered digital development, with the launch of the Harnessing Digitial Strategy (DOT, 2022c) by the Department of the Taoiseach.

Research on coastal city planning in Ireland shows that rationales for adaptation are sometimes focused on the lens of investors, with a focus on risk reduction that puts business continuity and attractiveness to investment at the core of planning (Jeffers, 2013). The resulting adaptation strategies are then likely to focus not on the impacts of climate risks but on the perceptions of climate risks by external investors, e.g. if a city is judged to be a safe site to build offices, given estimates of flood risk (Jeffers, 2013). Engineering solutions may be prioritised over a focus on reducing the vulnerability reduction of at-risk populations. Here, planning processes and the measures of success used will play a key role in balancing the interests of business and those of the wider population.

> *In terms of adaptation, climate change will bring multiple challenges to businesses, namely the risks associated with physical hazards and the challenges of a new regulatory terrain designed to take a fuller account of the climate-related risk profiles of businesses. New guidance and skills will be needed to navigate the changing demands on industry and to ensure the long-term resilience of Ireland-based companies.*

In terms of adaptation, climate change will bring multiple challenges to businesses, namely the risks associated with physical hazards and the challenges of a new regulatory terrain designed to take a fuller account of the climate-related risk profiles of businesses. New guidance and skills will be needed to navigate the changing demands on industry and to ensure the long-term resilience of Ireland-based companies. This will require a significant effort in upskilling of employees, and a focused approach to addressing the current skills gap in adaptation expertise in Irish industry (Deignan et al., 2022).

9.7. Priorities for research

9.7.1. Adaptation supports for business and livelihoods

There is a lack of readily available and accessible support for business and industry wanting to adapt to climate change, with large multinationals that host in-house expertise the best placed to implement adaptation strategies. Further research on how to best support businesses in different sectors, building on efforts such as the Climate Ireland platform, will help to advance capacity at the firm scale. The impact of climate change on livelihoods and health will impact employees in sector-specific ways. Further evidence is needed on the direct and indirect impacts of climate events on employees, and the strategies needed to mitigate these. In particular, research and policies are required on managing heat and thermal stress in Irish workplaces.

9.7.2. Supply chains and climate impacts

As a highly globalised country, Ireland is vulnerable to supply chain impacts of climate change, and further research is needed to identify the vulnerabilities of business and industry to this type of risk and to develop management strategies for different potential futures. Analysis is needed on how different types of supply chain interruptions may have socially differentiated impacts within Irish society. Lessons from circular economy theory and practice can provide insight into a more systemic approach for supply chains.

9.7.3. Fair use of data

Aided by the broader processes of digitalisation, adaptation decision making and accounting will increasingly engage with large datasets to judge business risks and exposure. It is important that such data sharing reflects broader societal goals and does not create biased or unfair impacts for citizens and communities. Research is needed to consider how big data and artificial intelligence are likely to shape adaptation decision making, and what the consequences may be for different societal stakeholders.

9.7.4. Upskilling for the private sector

European and national efforts for greater transparency on climate action by businesses is likely to change the regulatory environment, with costs and challenges for businesses. This will require upskilling and development of new skill sets for business and industry. Analysis of trends in risk management and regulation can inform investment in training and development.

10

Moving Adaptation Forwards

Key messages

1. In Ireland, and internationally, monitoring and evaluation of adaptation are limited as the focus is primarily on progress in implementation. Greater focus needs to be placed on process and outcomes, including elements of justice and wellbeing. An all-purpose and globally acceptable set of indicators that comprehensively measures adaptation does not exist. Learning requires knowledge of how and why adaptation has or has not happened, which cannot be accomplished by quantitative metrics alone. Opportunities for institutional feedback, peer learning and knowledge sharing, with adaptation built on a culture of learning, collaboration and sharing insights, need to be further developed.

2. Successful adaptation depends on reducing vulnerability. This necessitates a better understanding of the spatial, temporal and socioeconomic nature of vulnerability. Consideration should be given to how assessments of vulnerability can inform the development of adaptation plans and the evaluation of outcomes.

3. Widening adaptation actions to include nature-based approaches opens opportunities for multiple co-benefits for people and nature. Implementation of nature-based approaches can have positive outcomes for environmental quality, biodiversity, health and wellbeing. A greater focus on non-structural measures and opportunities for better governance will help open pathways to transformation.

4. Successful adaptation requires collaborative planning efforts and co-production. Methods that facilitate adaptation across sectors need to be further developed and integrated into policy processes. The role of the private sector and individuals/communities in adaptation also needs to be further developed. Communities will need support for adaptation and need help to generate leadership in collaboration with local government.

5. As a small, open economy heavily dependent on imports and exports, Ireland is highly exposed to transboundary climate risks (i.e. the impacts of and responses to climate change experienced elsewhere in the world). Understanding transmission pathways of transboundary risks, including through trade, finance, people and psychological, geopolitical, biophysical and infrastructure pathways, is an important knowledge gap. Assigning governmental responsibilities for managing transboundary risks and facilitating input from the private sector will be crucial to building resilience to transboundary climate risks.

6. Effective climate services should be based on scientifically credible information and expertise, have appropriate engagement from and between users and providers, and have effective access mechanisms to meet user needs. Important for the development of effective climate services in Ireland is the opportunity to provide ongoing dialogue and learning about how climate research and model outputs can be best tailored to decision needs, contexts and decision-making frameworks. The National Framework for Climate Services is a beneficial mechanism to support adaptation planning and action.

7. Future projections of climate change impacts contain, sometimes large, ranges of change. It is critical that adaptation decision making recognises this. Numerous frameworks exist to support decision making under uncertainty but are under-deployed in Ireland. This is even more important where adaptation decisions concern critical infrastructure and/or where exposure and vulnerability are high. Frameworks for decision making under uncertainty and for evaluating adaptation actions are needed to support adaptation in Ireland.

8. Adaptation needs to be seen not as a cost but as a necessary investment. Adaptation is about placing Ireland in a position to prosper in the decades ahead. Resourcing of adaptation needs to move beyond the limits of traditional cost–benefit analysis. Aside from the material impacts, climate change threatens cultural heritage, sense of place, wellbeing and nature – all non-economic losses that are rarely captured in traditional economic assessments.

10.1. Introduction

Climate change is happening now, with impacts already being felt across sectors and clear indications of an adaptation deficit. This volume highlights that climate change poses risks to biodiversity, agriculture, coastal environments, urban and rural communities, water resources, business and tourism and human health and wellbeing. Furthermore, how these changing risks interact and cascade will alter future vulnerability. The extent of future impacts will depend on actions to reduce greenhouse gas emissions globally. Even under Early action scenarios adaptation is necessary. In fact, adaptation is needed now, as the impacts of climate change and existing vulnerabilities are already apparent (see Chapter 1). Adaptation can generate multiple benefits, including for biodiversity, health and wellbeing, sustainable development, better and more secure livelihoods, enhanced environmental quality and, ultimately, a more resilient Ireland. Conversely, poorly planned adaptation can result in maladaptation and negative outcomes for those affected by adaptation interventions.

Climate action to date has focused largely on mitigation, with significantly less attention being paid to adaptation. Indeed, the CCAC has highlighted the limited progress that has been made on adaptation across multiple sectors (see Chapter 1). Here, we consider how adaptation can be further enabled to support more rapid progression and sustainable outcomes. For adaptation, success is dependent on the extent to which actions reduce vulnerability and risk and achieve goals and how learning and improvement are integrated. Adaptation is continuous and iterative, and not a static one-off intervention. For adaptation to be successful, clear goals need to be established, progress monitored, outcomes tracked and lessons acted upon. Important attributes that constitute successful adaptation include the extent to which an action is considered feasible, effective and in accordance with the principles of justice (see Chapter 1). Adaptation in Ireland has to date been predominantly framed through a technical lens, with emphasis placed on quantifiable physical risks in a typically impacts-led approach. Less considered have been aspects such as feasibility at community level and analysis of the legitimacy of adaptation, its unequal outcomes or indeed how reducing existing vulnerabilities can be an important starting point for adaptation. In the following sections we highlight dimensions of adaptation that need to be considered to move research and policy forwards in pursuit of a climate-resilient Ireland.

10.2. Governance

Adaptation in Ireland has often taken a sectoral focus, with associated pros and cons. However, this sectoral approach has yet to include critical areas such as coastal environments, Ireland's islands, the built environment, finance, and tourism and sport. As highlighted in this volume, each of these areas has significant existing vulnerabilities and exposures and is likely to experience increased climate risks in the future. It is imperative that adaptation planning be extended to cover these gaps. Successful adaptation to climate change must take an integrated, systematic approach. Despite adaptation plans, and indeed this volume, adopting a sector-specific approach, successful adaptation requires consideration of cascading risks and how climate action in one sector may enhance or limit action and risk in another. Climate risks are interlinked and require a systems-based approach to be sustainably tackled. For example, drought in spring 2020, during the height of the COVID-19 pandemic, nearly necessitated the introduction of water restrictions at a time when water and handwashing was central to public health objectives. A flood event in Donegal that impacted on Letterkenny hospital saw the closure of essential hospital services. Large-scale power outages following storm events can cascade into problems across sectors if critical infrastructure is disrupted. A purely sectoral approach to adaptation can miss these cascading risks, and greater leadership is required to coordinate action across sectors, including key stakeholders and local communities in decision making (CCAC, 2022). A useful approach to consider, as undertaken in the UK Climate Change Risk Assessment, is the development of thematic approaches to adaptation planning that might consider cross-cutting themes such as natural and cultural capital, critical infrastructure, public health, transboundary climate risks, etc.

10.3. Cross-border and transboundary risks

Climate change does not respect borders. As a shared island, collaborative approaches to adaptation between north and south will be critical to building resilience and successful adaptation (Leonard et al., 2023). Key shared priorities include water and flood risk management, trade, agriculture, emergency response, public health, biodiversity and critical infrastructure. The timing is favourable for increased all-island collaboration and cooperation in adaptation with the third UK NAP due to be published in 2023 followed by the Northern Ireland Climate Adaptation Programme in 2024. In Ireland, a revised NAF is due in 2023/2024. Existing collaborative efforts such as the North South Ministerial Council and the British Irish Council, together with insights from successful all-island partnerships such as the Shared Island Dialogue on Environment and Climate, the All-Island Climate and Biodiversity Research Network, the North West Climate Action Framework and the NESC Shared Island Consultation on Climate and Biodiversity Challenges and Opportunities, offer innovative forums through which lessons can be learned and transformative collaboration might proceed. Barriers to better cross-border collaboration on adaptation, as identified by the EPA-funded Transboundary Climate Risks for the Island of Ireland (TCRII) project (Murphy et al., 2023), include sharing of data, learning and climate services, ownership of risk and competing priorities, resourcing and finance, and shared research funding opportunities.

Climate risks have traditionally been framed from a local perspective, with climate services developed to understand climate change impacts at local scales for informing adaptation planning. However, there is increased recognition that domestic risks resulting from climate change impacts in other parts of the world form an important gap in knowledge – these are termed transboundary climate risks (Figure 10.1). Exposure to transboundary climate risks depends on economic openness, export and import dependencies, and country size (Challinor et al., 2018). Ireland is thus exposed and vulnerable to climate change impacts and policy responses elsewhere, but this is poorly reflected in adaptation policy to date. Studies in the UK have concluded that transboundary impacts on trade, investment and supply chains in the food sector could be an order of magnitude greater than domestic climate change impacts (Challinor and Benton, 2021).

The EU CASCADES project on climate change and systemic risks in Europe puts forward seven key transmission pathways of transboundary climate risks of relevance for Ireland (Carter et al., 2021):

1. trade (flow of commodities on international markets);
2. finance (the movement or change in value of public and private capital);
3. people (migration, displacement and tourism);
4. psychological (impacts due to perceptions/communication of transboundary risks);
5. geopolitical (impacts on international relations, resource access and strategy);
6. biophysical (movement of species, pests or pathogens and water transfers);
7. infrastructure (transport and telecommunications links).

To advance adaptation planning for addressing transboundary risks, priorities should be the development of methodologies for the identification, monitoring and evaluation (M&E) of risks, guidance on how to prioritise risks in a rapidly changing world, collaboration at EU and international levels, assigning ownership of risks, and developing understanding of risk transmission chains and mechanisms for risk amplification (Harris et al., 2022). A sensible starting point is to understand, as part of a national risk assessment, who our key trade partners are and how international policy can support adaptation in countries of risk origin. Input from the private sector will be crucial. Several countries and large-scale projects are leading on the development of knowledge, frameworks and policies for adapting to transboundary climate risks and offer learning opportunities for how best to integrate these into Irish adaptation policy. These include the UK via the UK Climate Change Risk Assessment (Challinor and Benton, 2021) and Nordic countries (Berninger et al., 2022) via the IMPRESSIONS project (Benzie et al. (2019), the CASCADES project (Carter et al., 2021), the UNCHAIN project (Harris et al., 2022) and the Adaptation without Borders Initiative (Harris et al., 2022).

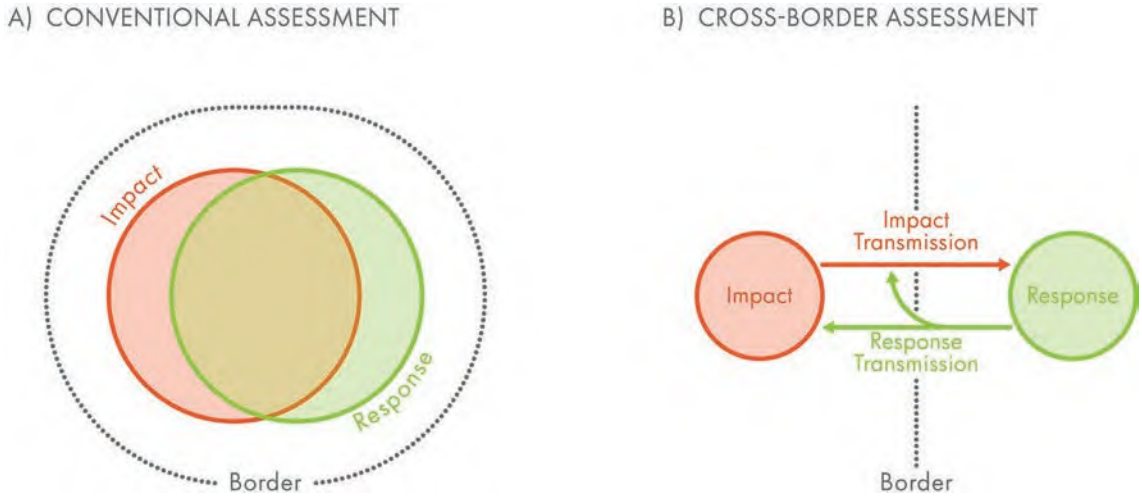


Figure 10.1 Relationship between an impact and response in (a) conventional climate change impacts, adaptation and vulnerability (IAV) assessments, where the impact and response to that impact lie within the same region; and (b) cross-border IAV assessment. Source: Carter et al. (2021). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

10.4. Improving knowledge of exposure and vulnerability

Climate risks are not determined only by changes in hazards but are strongly shaped by the exposure and vulnerability of people, ecosystems, resources, services and infrastructures, and economic, social and cultural assets. Moreover, neither the impacts of climate change nor the benefits of adaptation will be equally distributed socially or geographically. Unpacking these dimensions of risk will help to bring detail to issues of fairness and equity in adaptation planning by examining who is most at risk and who is most likely to benefit and for what reasons. Socioeconomic vulnerability and related concepts of just resilience have not been adequately addressed in national, sectoral and local adaptation policy to date and must be a key focus of future adaptation frameworks and plans (CCAC, 2022). The importance of just and fair adaptation is emphasised in the European Green Deal and revised EU Adaptation Strategy (EC, 2021). Relatedly, measuring progress towards realising a climate-resilient Ireland, as outlined in the national objective, is simply not possible without understanding the dynamics of exposure and vulnerability (see section 10.7 on M&E).

Quantitative analysis of vulnerability commonly involves identifying the key components of exposure, sensitivity and adaptive capacity, which can be then aggregated into indices (Paranunzio et al., 2020). Such vulnerability analyses have been conducted in Ireland. For example, the Urb-ADAPT project used data on housing, household composition, health and information access (alongside other indicators) to consider the distribution of vulnerability within the Dublin area to climate risks. Fitton et al. (2021) developed and mapped the Irish Social Vulnerability to Environmental Hazards Index, also using quantitative statistical data from the CSO, and identified the distribution of households with above-average social vulnerability. Such information can inform climate action, spatial planning and economic and community planning to reduce risk and support Ireland in a just transition to a sustainable and resilient future. However, guidance is needed on how to integrate such information into adaptation planning and where gaps in understanding exist.

While quantitative indicators of vulnerability have utility, there are also intangible aspects of vulnerability that require different methods of investigation (Thomas et al., 2019). The significance of cultural heritage, psychosocial needs and social ties require qualitative analysis. Looking to the future, projections of vulnerability will need to take account of a range of scenarios that reflect, for example, demographic change, climate neutrality measures and economic trends. Further research is required into how vulnerabilities are likely to evolve in Ireland under different scenarios, and what type of policy responses prove equitable and just across potential futures.

10.5. Decision-centric climate services

Climate services aim to support decision making in adapting to climate change and are targeted at timescales that range from near real time to seasonal and multi-decadal timescales (Hewitt and Stone, 2021). Effective climate services that operate at the interface between climate science and decision making need to be based on scientifically credible information and expertise, have appropriate engagement from and between users and providers, and have effective access mechanisms to meet user needs. Successful climate services are dependent on long-term, trusted relationships between scientists and decision makers and can entail high transaction costs associated with co-produced solutions (Heaphy, 2017; Jacobs and Street, 2020). At the European level, a mix of governance, implementation and innovation activities are contributing to the development of climate services. In particular, the EU Strategy on Adaptation to Climate Change places an emphasis on the EU as a global leader in the development of climate services. Research and innovation actions play a critical part in supporting the implementation activities mentioned above, for example to gain a greater understanding of how climate services can be co-created, to develop models and tools. EU leadership in this area is evident, with initiatives such as Copernicus Climate Change Service (https://climate.copernicus.eu/) underpinning the development and provision of climate services.

In Ireland, climate services are provided by several state agencies and universities, while the EPA is developing its climate service activities and has assimilated Climate Ireland, Ireland's climate information and adaptation platform, into its responsibilities. In June 2022, the Irish Government approved the establishment of the NFCS with Met Éireann as coordinating lead. The NFCS will coordinate and strengthen collaboration among climate information providers and users, enabling the co-production, delivery and use of accurate, salient, actionable and accessible climate knowledge and tools in support of climate resilience planning and decision making. Most important for the development of effective climate services is the opportunity to move beyond the provision of passive services through a one-stop shop to developing ongoing dialogue and learning about how climate research and model outputs can be best tailored to decision needs and decision making frameworks (Figure 10.2). This requires tailored levels of interaction between service providers and users, which can be context specific and require significant resource investment and commitment to co-design and co-development of climate services, with significant input from stakeholders, climate scientists and social scientists. In addition, scientists need to listen to and understand the needs of decision makers, rather than deliver products with which they happen to be familiar (Jacobs and Street, 2020). Attention needs to be given to enhanced training of users to better understand the strengths and limitations of available data, and for climate scientists and service providers to better understand decision making contexts.

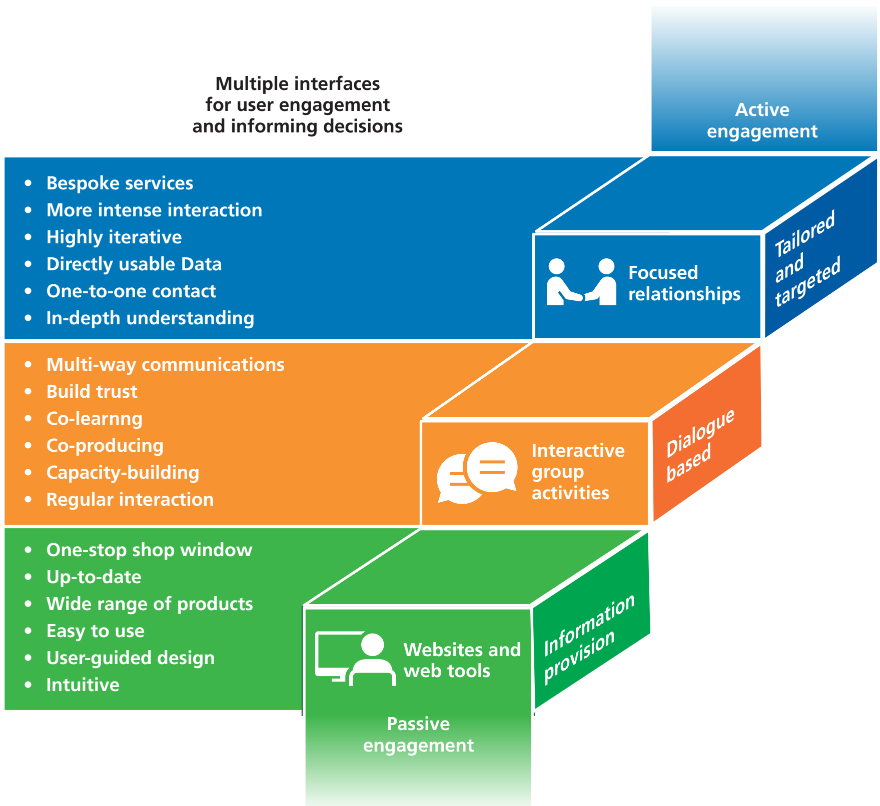


Figure 10.2 Schematic of three broad categories of engagement between users and providers of climate services. Source: Ranasinghe et al. (2021; their cross-chapter box 12.2, figure 1).

Relatedly, Ireland currently does not have an official standardised climate projection dataset. To bridge that gap, the TRANSLATE project (O'Brien and Nolan, 2023) aims to produce a standardised set of climate projections for Ireland. A key challenge in the development of the first round of adaptation plans in Ireland was a lack of consistency in the use of climate model projections in understanding future climate risks (CCAC, 2022). The TRANSLATE project has the potential to help in this regard and ensure that cross-sectoral issues and risks are better accounted for in the next iteration of adaptation plans. National climate change scenarios and structured risk assessment processes can enable closer integration of local- to national-level adaptation planning, harmonise information and methods for resilience planning, and offer greater scope for identifying priority climate threats and opportunities within and between sectors (Wilby, 2022). However, it is essential that the plausible range of change across key climate variables is sampled by the TRANSLATE project and that the projected changes are assessed relative to other internationally available climate model ensembles to ensure that key uncertainties in future climate are accounted for and quantified.

A key challenge in compiling this volume is the patchy nature of impact assessments across sectors and the diversity of climate model projections and emissions scenarios used. This makes it difficult to conduct systematic evaluations and comparisons across studies. Informing adaptation needs more than projected changes in climate variables, as will be produced from the TRANSLATE project. These projections also need to be used to assess impacts within and across sectors (e.g. droughts, floods, agriculture, biodiversity). This information also needs to be developed with decision makers in mind and capture key uncertainties and will take time to deliver. There is a need for systematic assessments of impacts to be funded and timed to inform the development of climate change adaptation plans.

While at present the emphasis within climate services in Ireland is on climate model projections and impacts at multi-decadal timescales, there is large potential to expand climate services to provide seasonal and decadal forecasting, which can add significant value for decision makers. Recent research is showing the possibilities for seasonal hydrological forecasting and decadal forecasting in Irish contexts (e.g. Donegan et al., 2021; Foran Quinn et al., 2021; Golian et al., 2022;). Robust decisions require a diversity of information. As highlighted above, adaptation decision making also needs to better understand exposure and vulnerability, and thus these aspects need to be part of effective climate services. Lastly, Ireland has a rich history of observations extending over multiple centuries, and these should be leveraged to identify past extreme events that can be used to focus discussions of vulnerability, stress test critical infrastructure and assess likely changes in future. At present, a focus on recent decades (e.g. the last 30 years) disregards many extreme events that could usefully inform adaptation decision making.

10.6. Decision making under uncertainty

Although most climate model projections show relatively robust agreement on temperature increases, less agreement is evident on how changes in important variables such as precipitation may unfold over the coming decades (see Volume 1 and Chapter 5 of this volume). For instance, the magnitude and even direction of change in summer precipitation can vary depending on which climate model is applied. In addition, climate change does not happen in a vacuum and uncertain changes in technological, socioeconomic and political situations are also expected to unfold. Adaptation takes place within this context and poses challenges for planners and decisions makers. Traditionally, adaptation decision making has followed a top-down or science-first approach, whereby projected changes in climate are used to assess local impacts and changes, which often span large ranges of change, for decision makers. These large ranges of change can stymie adaptation planning, with decision makers sometimes defaulting to calls for more research to reduce uncertainty or to the precautionary principle, which may result in excessive trade-offs or expensive adaptation (Smith et al., 2018). More recently, research has begun to focus on developing solutions to decision making under deep uncertainty. These approaches are often broadly categorised as bottom-up approaches, as they typically focus on working with decision makers and addressing existing vulnerabilities and/or starting with evaluation of the decision making context and problem, rather than starting with climate change impact projections (Wilby and Murphy, 2018; Wilby, 2022).

A core concept within these approaches is that models and data be used in an exploratory rather than predictive way to evaluate system vulnerabilities and to appraise the effectiveness and trade-offs between adaptation options, and even the sequencing of adaptation actions (Vaghefi et al., 2021). Numerous frameworks exist, including dynamic adaptive policy pathways (Haasnoot et al., 2013), adaptive policymaking (Kwakkel et al., 2010), real options analysis (Woodward et al., 2014), info-gap decision theory (Ben-Haim et al., 2006), decision scaling (Brown et al., 2012) and robust decision making (Groves and Lempert, 2007). Such approaches have value in the context of specific projects and critical infrastructure where there are potentially large investment decisions, and in contexts where vulnerability is high or where decisions contain potentially large trade-offs and/or opportunity costs. Because of unavoidable uncertainty, decision makers are advised to look for robust decisions that have satisfactory performance across a range of plausible futures, offer benefits both now and in the future, and develop plans that are flexible and can be adapted over time in response to how the world actually unfolds (Hallegatte, 2009). They also offer the utility of information beyond just climate model projections, including leveraging the information content of historical extremes and process understanding of key drivers of change in the climate system. For example, the development of storylines is an example of an approach that can leverage historical extremes, large ensembles of climate model projections and stakeholder knowledge, to develop plausible storylines as to how specific extreme events and vulnerability may unfold in future. These storylines can be used to improve risk awareness, strengthen decision making by identifying failure points, stress test adaptation decisions, incorporate compound risks and explore the boundaries of plausibility, thus avoiding false precision and surprise (Shepherd et al., 2018).

Frameworks for decision making under uncertainty contain many common elements or building blocks, exemplified in Figure 10.3. Rather than starting with future climate change impacts, they start with establishing a deep understanding of the system in question (e.g. a water supply system) and establish a strategic vision for the future that clearly defines the objectives of adaptation based on system performance. Key indicators can then be identified to monitor system performance and identify thresholds or tipping points to denote when the system is performing to acceptable levels and track adaptation outcomes. This vision and associated indicators then act as a guide to frame short-term actions and future interventions, together with monitoring the outcomes of adaptation (Ranger et al., 2010; Wilby, 2022). In step 2, a model of the system, typically one used in operational contexts, is established in which climatic and non-climatic stressors can be explored. In step 3, a stress test of the system is undertaken to identify how it performs when given plausible changes in climatic and non-climatic drivers. This stress test can draw on diverse information, including climate model projections, historical extremes, storylines of how extremes may change and socioeconomic scenarios. Critically, this information can range from quantitative scenarios to narratives of change built with stakeholders and scientists. The key outcome from this step is to identify the important drivers of change, climate and/or socioeconomic variables to which the system is most sensitive, and critical thresholds whereby the system can fail or performance becomes inadequate. Step 4 involves the development of a portfolio of adaptation options or interventions and evaluation of their performance, either individually or in combination, in reducing vulnerability. Adaptation options and their deployment can be assessed in terms of their social acceptability, economic and technical feasibility, regulatory context, timing and how they conform to the principles of robustness (e.g. avoid lock-in, demonstrate flexibility) (Wilby and Dessai, 2010). Lastly, step 5 develops an adaptation pathway that sequences the deployment of adaptation interventions, monitors system performance and adaptation outcomes, and sets conditions for re-evaluation. Such approaches are founded on navigating uncertainty by deepening understanding of system vulnerability, evaluating trade-offs, M&E, learning, viewing adaptation as dynamic and iterative, and embracing the principles of robustness. Importantly, they can also be tailored to the level of detail required based on the decision at hand.

Applications of frameworks for decision making under uncertainty are growing in academic and real-world settings, including for flood risk management in the Thames estuary (Ranger et al., 2010), flood management in the UK (Prudhomme et al., 2010), water management in the Rhine delta (Haasnoot et al., 2013), coastal community responses to sea level rise in Australia (Barnett et al., 2014) and water management in Colorado (Yates et al., 2015). In Ireland, early applications include the deployment of decision scaling to evaluate safety margins for flood defences (Broderick et al., 2019) and the development of adaptation pathways for Midleton flood relief scheme (Buckley et al., 2021) (Figure 10.4).

Figure 10.3 Typical steps involved across frameworks for adaptation decision making under uncertainty. Source: Authors' original.

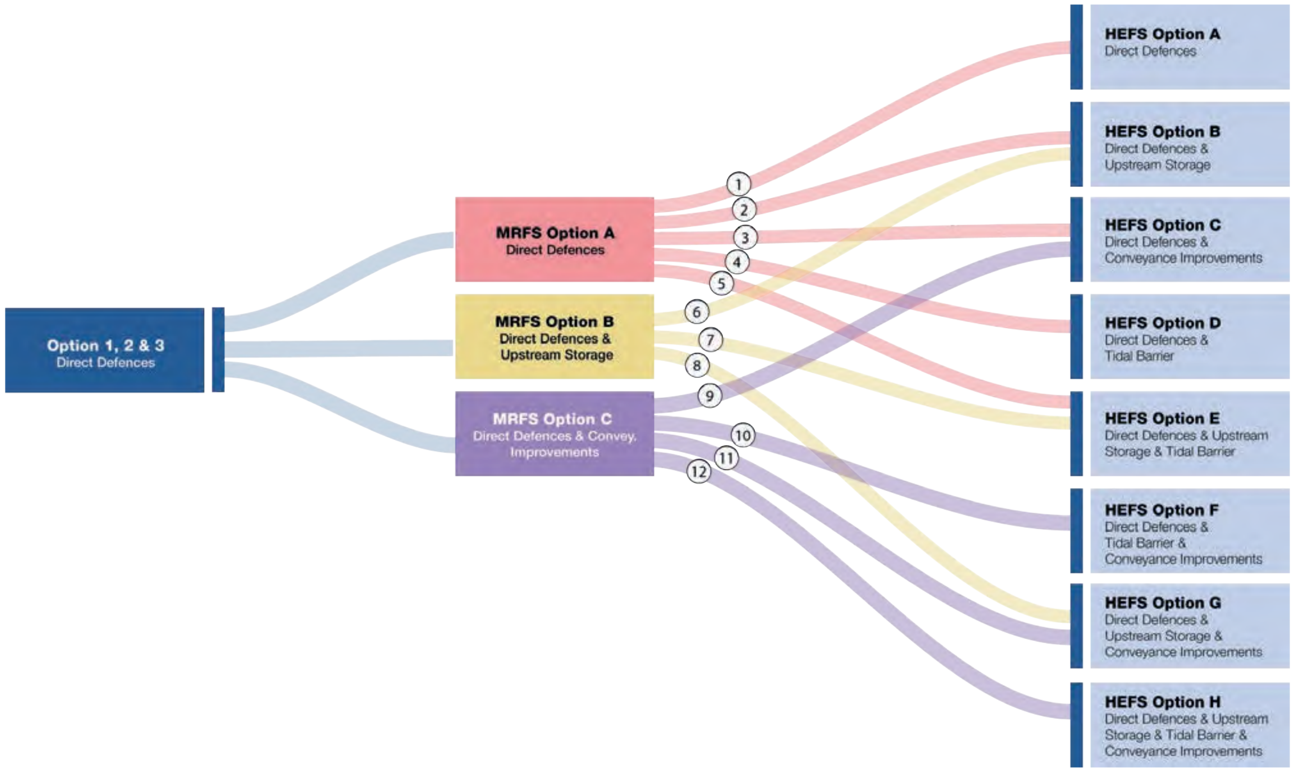


Figure 10.4 Example adaptation pathway established for the Midleton flood relief scheme depending on extent of climate change impacts experienced. Source: Buckley et al. (2021).

10.7. Monitoring and evaluation

M&E is a difficult but critical component of adaptation, being essential for understanding the progress made in reducing climate risks, assessing the success of measures in terms of outcomes, avoidance of maladaptation and learning to improve subsequent adaptation strategies and policies. The Paris Agreement encourages countries to engage in monitoring, evaluating and learning from adaptation plans, policies, programmes and actions. Distinctions between monitoring and evaluation typically view monitoring as assessing the progress of adaptation implementation, while evaluation is a more comprehensive assessment of achievements, unintended effects and lessons learned. M&E is undertaken for multiple reasons, including for understanding whether actions have had the intended impact in reducing climate risks, including vulnerability and exposure, increasing resilience or adaptative capacity, informing ongoing implementation and future plans, and providing accountability. Effective communication of M&E findings and feedback into decision-making processes is essential to achieve the purpose of M&E and facilitate learning (New et al., 2022).

Assessment of progress in implementing adaptation in Ireland for local authorities and sectors identified under the NAF is undertaken by the CCAC. An adaptation scorecard was adopted in the 2021 Annual Review of the CCAC to measure, in the form of a questionnaire, the progress of sectoral and local adaptation plans, and to monitor the implementation of the NAF itself. The adaptation scorecard considers metrics pertaining to progress in risk identification, prioritisation and adaptative capacity, resourcing and mainstreaming of adaptation and governance, coordination and cross-cutting issues. As in most countries, emphasis in Ireland is placed on monitoring implementation (number of actions identified in the adaptation plan that are commenced or completed, number of people trained, etc.), rather than assessing outcomes of adaptation interventions, to extract key lessons for learning and improving progress (New et al., 2022). To improve M&E, opportunities for learning and thereby progress and success in adaptation, additional effort needs to be made on assessing the nuances of implementation (challenges and opportunities encountered) and the outcomes of adaptation (New et al., 2022). This will require support in terms of development of frameworks, as, unlike mitigation, adaptation has no common reference metrics upon which to report outcomes. Furthermore, the way in which adaptation is framed as a technical or sociopolitical challenge can shape understanding of progress, outcomes and management (Singh et al., 2022).

As implementation of adaptation actions has grown since the development of adaptation plans, there is a pressing need to examine outcomes at different scales (local, sectoral and national) for effectiveness, adequacy and justice/equity aspects of process and outcomes, synergies and trade-offs with mitigation, and other socioeconomic and environmental goals. For success to be measured, it is crucial that all adaptation actions are associated with clear aims and objectives. In addition, success in adaptation outcomes is not a simple dichotomy between success and failure/maladaptation. Rather, outcomes of actions need to be evaluated along an adaptation–maladaptation continuum relative to established criteria (New et al., 2022) (see Figure 10.5 for an example of this continuum and outcome criteria). Presently in Ireland, M&E is entirely focused on progress in implementation, with sectors ranked from no progress to advanced progress. By contrast, recent research has shown that, despite best intentions, adaptation interventions can have significant detrimental impacts on the wellbeing of those affected (Phillips and Murphy, 2021), with the process of adaptation and means of engagement often a telling factor in determining outcomes (Clarke et al., 2018; Quinn et al., 2023).

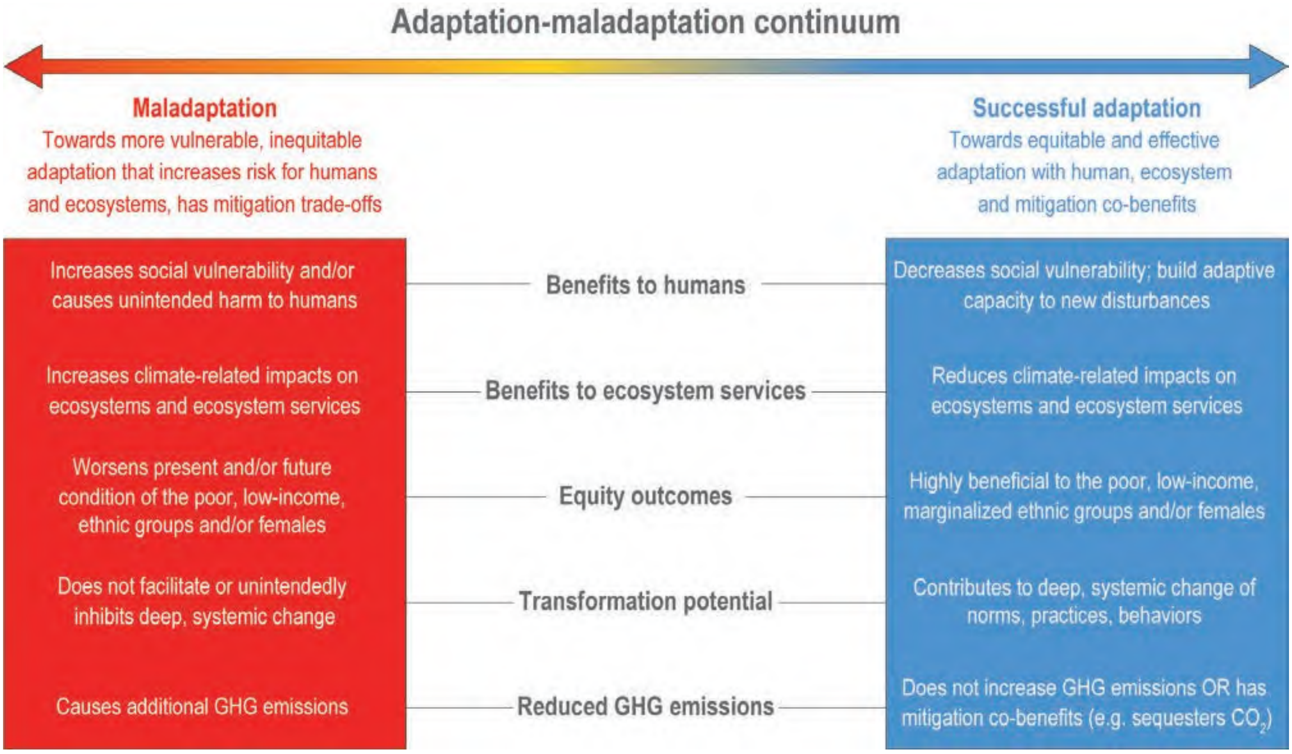
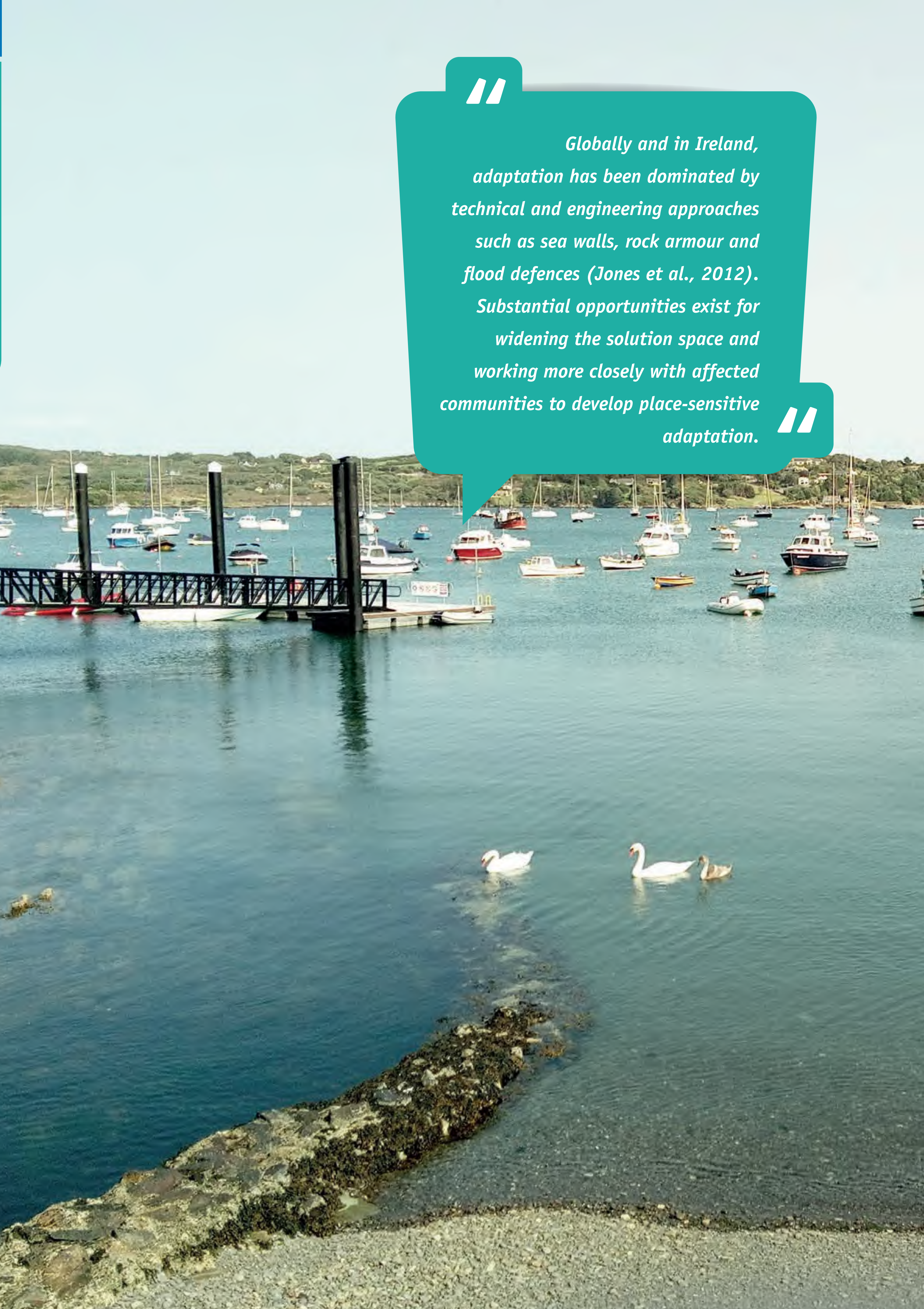


Figure 10.5 Successful adaptation and maladaptation are conceptualised as the two end points of a continuum, with adaptation options being located along the continuum based on outcome criteria (how they benefit humans and ecosystems; how they contribute to or hinder equity goals; whether they enable transformative change of climatic risks; and synergies and trade-offs with climate mitigation). Adaptation options might rate largely positive and slightly negative across outcome criteria (tending towards successful adaptation), while other adaptation options might have small positive aspects and larger negative ones across different outcome criteria (tending towards maladaptation). CO_2, carbon dioxide; GHG, greenhouse gas. Source: New et al. (2022; their figure 17.10).

A key question for M&E is what data, indicators and indices to employ to track implementation and outcomes. The CCAC has recommended that adaptation indicators must be set out in the revised NAF, with particular importance given to inclusion of indicators on socioeconomic vulnerabilities, wellbeing and social justice (DECC, 2022a). It also recommends the need for indicators describing resilience and the effectiveness of adaptation actions across key sectors, including on cross-cutting risks, synergies and co-dependencies. Critical to the deployment of indices will be clear aims and objectives of adaptation interventions, with clear prioritisation. Ongoing work in Ireland to develop indicators includes collaboration between the transport sector and the EPA in developing a draft set of indicators. Flood et al. (2021) identify a set of 127 indicators, prioritising 91 for implementation consideration. Of the latter, 15 are climatological indicators, 23 are climate change impact indicators, 32 are focused on tracking implementation and 21 are focused on outcomes.

> *"Globally and in Ireland, adaptation has been dominated by technical and engineering approaches such as sea walls, rock armour and flood defences (Jones et al., 2012). Substantial opportunities exist for widening the solution space and working more closely with affected communities to develop place-sensitive adaptation."*



However, in many cases, data may be difficult to collate at the necessary scale, and indicators will require considerable effort from numerous agencies, both in compiling and maintaining them. While climatological and impact indicators are identified through stakeholder consultation, statistical analysis of the links between identified climate variables and impacts is required. Recent work undertaken by O'Connor et al. (2023) links climatological indices of drought with impacts reported in newspaper archives for Irish catchments, identifying the drought indices and definitions most closely related to impacts in the water and agriculture sector. Notable differences between sectors were apparent, highlighting the challenge of identifying universal climatological indices for tracking impacts. Similar work is required for other types of hazards. Novel datasets such as newspaper archives offer potential, especially in the absence of formal data collection on impacts. Jobbová et al. (2023b), for example, recently developed a drought impact database for Ireland, spanning multiple centuries. Others highlight the potential for novel indicators using Google Trends, such as Wilby et al. (2023) who showcase an example for the UK water sector.

There may also be disagreement in terms of what constitutes adaptation outcomes. For instance, Flood et al. (2021) use the establishment of a national flood forecasting and monitoring service as an outcome indicator when outcomes such as reducing vulnerability and losses, the intended objectives of flood forecasting, are difficult to appraise from this metric alone. In other cases, attribution of cause and effect in terms of outcomes may be difficult. For example, assessing reductions in road flooding impacts or forest fires following implementation of adaptation plans may be very difficult where reliable historical records of impacts are not available to track outcomes, again highlighting the importance of novel datasets for establishing baselines.

In summary, an all-purpose and globally acceptable set of indicators that could comprehensively measure adaptation does not exist (New et al., 2022). Indeed, complex processes and outcomes may not be usefully measurable using quantitative metrics and there are often unrealistic expectations around what indicators can accomplish. Without careful selection and updating, indicators can also become misguided incentives that might steer adaptation away from what matters or result in emerging risks being missed (Leiter and Pringle, 2018; Hallegatte and Engle, 2019; New et al., 2022). Process-based metrics that focus on the quality of a project's design and implementation are more likely to avoid these pitfalls and should be considered a viable alternative to aggregated universal resilience indicators (Hallegatte and Engle, 2019). Learning requires knowledge of how and why change has or has not happened, which cannot be accomplished by metrics alone. Rather, indicators are best used in combination with other types of information, including scorecards, interviews and focus groups, with input from adaptation practitioners as well as those affected by adaptation. There also needs to be better opportunities for institutional feedback, peer learning and knowledge sharing, with adaptation built on a culture of learning and gathering and sharing insights (Street and Jude, 2019). The climate action regional offices have been playing an important role in this regard at local authority level, but these opportunities could be further supported as they are few and far between at the sectoral and national levels.

While the above paragraphs concern monitoring of adaptation, it is also necessary to emphasise the importance of continued monitoring of key hazards. Met Éireann and others have recently invested in data rescue and homogenisation activities that are critical for confidently monitoring and detecting emerging climate change signals. In the water sector, ongoing work funded by the EPA is updating the Irish Hydrometric Reference Network and expanding it beyond river flows to include groundwater and lakes. Such high-quality monitoring networks are essential for tracking change, attribution and adaptation, and as such it is essential that they are prioritised and that other areas that require bespoke networks for climate change monitoring are identified.

10.8. Working with nature and people

Globally and in Ireland, adaptation has been dominated by technical and engineering approaches such as sea walls, rock armour and flood defences (Jones et al., 2012). Substantial opportunities exist for widening the solution space and working more closely with affected communities to develop place-sensitive adaptation. Nature-based approaches involve working with and enhancing nature to tackle societal challenges. They incorporate a wide range of actions, ranging from protection and management of natural and semi-natural ecosystems, and integrating nature-based infrastructure in urban areas, to the integration of ecosystem-based principles into management. Crucially, nature-based approaches also enhance and deepen community participation in adaptation (Seddon et al., 2020) and broaden the goals of adaptation to include human wellbeing, socioeconomic development, biodiversity and other challenges, resulting in significant co-benefits. Moreover, nature-based approaches explicitly recognise and integrate the vulnerability of ecosystems with the vulnerability of socioeconomic systems and integrate climate change mitigation with adaptation. Seddon et al. (2020) highlight that there is growing evidence that protecting, restoring and managing natural forests and wetlands in catchments can help regulate water quality and supplies, reducing flood risk and susceptibility to soil loss through erosion and landslide risks. In Ireland, Collier and Bourke (2020) highlight the case for mainstreaming nature-based approaches in integrated catchment management, with multiple co-benefits for adaptation, while Farrell et al. (2023a) consider opportunities and lessons from such approaches in coastal domains.

Widely acknowledged challenges associated with the implementation of nature-based approaches include measuring their effectiveness at reducing risk, identifying the contexts in which they are most effective, mobilising investment, increasing capacity for implementation and overcoming governance challenges (Collier and Bourke, 2020; Seddon et al., 2020). Novel research, implementation and monitoring of nature-based approaches is ongoing in Ireland, including for flood risk management (Collier and Bourke, 2020), water quality assessment and coastal management (Farrell et al., 2023a) and in urban contexts (Clabby, 2016; Scott and Lennon, 2016; Collier et al, 2023). Such work needs to be further supported with opportunities for developing test spaces and the monitoring of outcomes critical to the mainstreaming of nature-based approaches into adaptation policy (Farrell et al., 2023a). Realising a climate-resilient Ireland will require deployment of multiple approaches to adaptation, and nature-based approaches must be an increasingly important part of the portfolio of adaptation actions put forward.

Adaptation actions that are sustainable and result in just adaptation or just resilience (including the elements of procedural and distributive justice) need to be co-created with affected communities (Grainger et al., 2021). A lack of engagement with communities in developing adaptation strategies, particularly where adaptation can alter place-based relationships, has been shown to have detrimental impacts for wellbeing, resulting in increased risks of maladaptation (Phillips and Murphy, 2021; Phillips et al., 2022; Clarke and Murphy, 2023), increasing contestation and ultimately the costs of interventions (Clarke et al., 2018). Farrell et al. (2023a) showed the multiple benefits of empowerment and the ultimate success and sustainability of adaptation when resilience building prioritised engagement and co-production with communities affected by coastal change in the Maharees. Adaptation that results from co-creation also tends to be more clearly goal oriented, respectful of different knowledge types, sensitive to values associated with place, pluralistic and inclusive and attentive to power dynamics, and provides opportunities for reflection and learning (Bolger et al., 2021). However, co-production is expensive in terms of time and resources, and often requires skill sets and capacity not always currently available. As such, moving adaptation forwards requires investment in these skills and a commitment to the co-production of adaptation measures.

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Abbreviations and symbols

ACRES	Agri-Climate Rural Environment Scheme
AEP	annual exceedance probability
AFOLU	agriculture, forestry and other land use
AR6	Sixth Assessment Report from the Intergovernmental Panel on Climate Change
BIM	Bord Iascaigh Mhara
CBD	Convention on Biological Diversity
CBI	Central Bank of Ireland
CC	Clausius–Clapeyron
CCAC	Climate Change Advisory Council
CIViC	Critical Infrastructure Vulnerability to Climate Change
CFRAM	Catchment Flood Risk Assessment and Management
CMIP	Coupled Model Intercomparison Project
CMIP6	Coupled Model Intercomparison Project Phase 6
CORDEX	Coordinated Regional Climate Downscaling Experiment
CSO	Central Statistics Office
CVI	coastal vulnerability index
DAFM	Department of Agriculture, Food and the Marine
DECC	Department of the Environment, Climate and Communications
DOC	dissolved organic carbon
ECN	electronic communications network
ESM	Earth system model
ESPREssO	Enhancing Synergies for Disaster Prevention in the European Union
GIA	glacial isostatic adjustment
GIS	geographical information system
HAB	harmful algal bloom
HDD	heating degree-day
HEFS	high-end future scenario
HSE	Health Service Executive
ICT	information and communications technology
ICZM	integrated coastal zone management
IPCC	Intergovernmental Panel on Climate Change

IUCN	International Union for Conservation of Nature
LoS	level of service
M&E	monitoring and evaluation
MCA	Maharees Conservation Association
MPA	marine protected area
MRFS	mid-range future scenario
MSF	Marine Strategy Framework
NAF	National Adaptation Framework
NAO	North Atlantic Oscillation
NBAP	National Biodiversity Action Plan
NDP	National Development Plan
NESC	National Economic and Social Council
NFCS	National Framework for Climate Services
NPWS	National Parks & Wildlife Service
OPW	Office of Public Works
PET	potential evapotranspiration
PV	photovoltaic
RCP	representative concentration pathway
SDG	Sustainable Development Goal
SLR	sea level rise
SMEs	small and medium-sized enterprises
SSP	shared socioeconomic pathway
UHI	urban heat island
WAFU	water available for use
WG	Working Group II in the Intergovernmental Panel on Climate Change
WTP	water treatment plant

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