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Well informed adaptation decision making under uncertainty

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Evidence to support the development of national and local climate resilience policy

Coastal erosion at Courtown, County Wexford. August 2015. Source: Wikimedia Commons

WORKING PAPER

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For the Climate Change Advisory Council of Ireland Adaptation Committee

Executive summary

The climate of Ireland is changing. Rising temperatures, more extreme storms, floods, droughts and higher sea levels are expected in the future. Meanwhile, plans are being made for another one million people by 2040, with associated urban renewal, new housing, transport systems, water infrastructure, rural development, and more – all whilst transitioning to a low carbon and climate resilient society.

Even with scientific advances, uncertainty will remain inherent to the adaptation decision-making process and should be considered by both knowledge providers and decision-makers. This is essential because significant investments and decisions across sectors must be resilient to uncertain climate impacts. Accordingly, this Working Paper recommends ways of handling uncertainty throughout the adaptation planning process of Ireland. Evidence is reviewed around six themes:

- ***Attitudes*** to uncertainty in climate impacts and adaptation outcomes.
- ***Conceptual approaches*** to adaptation decision making under uncertainty (including Top-down and Bottom-up perspectives).
- ***Decision-making frameworks*** and strategies for adaptation that account for uncertainty (such as adaptive management).
- ***Indicators*** as a basis for informing/assisting decision-making.
- ***Costs and benefits*** of adaptation under uncertainty.
- ***Communication*** of uncertainties in decision-making.

Attitudes to deep uncertainty include: taking a precautionary approach to climate risks (i.e., designing for the worst case); waiting and seeing; delaying in order to gather more information; reducing critical uncertainties by improving knowledge; enhancing resilience to known threats; or implementing adaptive management. The last is about maximising flexibility and phasing options in response to uncertain climate risks and evolving socio-economic priorities in an open-ended and iterative way. To date, no such adaptive management plan has been developed in Ireland.

Recommendation 1: Pilot an adaptative management framework for a sector or plan, to map options, identify trade-offs and trigger points, and develop ***adaptation pathways*** – such as for improving the resilience of water resources in the Greater Dublin Area.

There are two main conceptual approaches to adaptation planning. ‘Top-down’ perspectives cascade information about greenhouse gas emissions to climate and impact models, and eventually to adaptation responses. ‘Bottom-up’ perspectives concentrate on reducing vulnerability by limiting exposure and sensitivity, whilst enhancing capacities to adapt, to known climate hazards. Elements of both ‘Top-down’ and ‘Bottom-up’ approaches are evident in Ireland’s National Adaptation Framework (NAF). Sectoral planning is informed by fine-resolution climate change scenarios for 2041-2060. Although there is high confidence in projections of air temperature and sea level rise, model outputs have large biases and ranges of uncertainty for important variables such as winter precipitation. There is also a sense that a wider set of evidence is needed for vulnerability and sensitivity testing adaptation actions.

Recommendation 2: Develop a set of climate change ***storylines*** for Ireland – including low likelihood, high-impact scenarios (High++) – with cross-sector relevance for testing adaptation actions and communicating key risks to diverse audiences.

Early action on adaptation may be a priority where there is an identified need to: (1) address an adaptation gap with respect to present climate variability, plus building future climate resilience; (2) intervene early to embed adaptation in near-term decisions with long lifetimes, thereby reducing the risk of 'lock-in'; or (3) fast-track early adaptive management actions for decisions with long lead times or requiring transformative change. However, the urgency of action should be assessed in a systematic and consistent way.

Recommendation 3: Strengthen the criteria and processes for ***urgency scoring*** of adaptation options within and across sector plans to establish national priorities for action in Ireland.

Ireland is relatively well-endowed with long-term climate records and resources such as *The Status of Ireland's Climate* and *Climate Status Tool*. These are helpful for tracking climate drivers and impacts; monitoring progress in improving resilience and preparing for climate change; triggering actions within adaptive management plans; and communicating future climate risks and opportunities. Nonetheless, the indicators set could be expanded to improve coverage of climatic co-stressors and impacts on natural environments and agri-systems. More indicators could be provided on socio-economic vulnerabilities, such as the location, condition and performance of critical infrastructure, or for health and social care delivery. Above all, there is scope for more indicators describing resilience and effectiveness of adaptation actions for key sectors such as agriculture, natural environment, people and the built environment, and infrastructure.

Recommendation 4: Undertake a comprehensive sector and cross-sector based review of ***adaptation indicators***, including their purpose, the cost and availability of data, the length, quality and homogeneity of records, and their future sustainability.

The NAF lays out the economic basis for adaptation with cost-effectiveness amongst the criteria for prioritising adaptation options (alongside efficiency, risk and urgency, and distributional impacts). However, the *Climate Action Plan 2021* is largely silent about economic appraisal linked adaptation, beyond costing extreme weather impacts and including potential rises in future flood damages within the economic case for flood relief schemes. Internationally, it is recognized that benchmarking costs and establishing the relative economic benefits of different adaptation options are far from straightforward tasks.

Recommendation 5: Develop workflows for proportionate and transparent ***economic appraisal*** of adaptation options that can be applied to project- and sector-level actions.

Finally, it is noted that the *National Dialogue on Climate Action* is an important vehicle for improving climate literacy, understanding behaviour change, and enabling community engagement. Advances in understanding about *how* to communicate climate change issues could help accelerate the transition of society from awareness, to concern, to adaptation action.

Recommendation 6: Incorporate adaptation within existing communication Actions (mainly targeting mitigation efforts), plus make use new insights about place attachment, memorable extremes, and storylines to ***personalize climate risks and adaptation opportunities*** for diverse audiences.

Ireland's climate is changing. Mitigation and adaptation action that is planned, coordinated and prioritised is required to build the resilience of society and the economy in the face of current and projected climate change impacts.
(EPA, 2021a:449)

Introduction

The climate of Ireland is changing. Over the last 120 years, annual mean air temperatures rose by about 0.9°C. The number of warm days increased slightly in the last 60 years, whilst the decade 2006-2015 was the wettest on record. Spells of wet weather have become longer and average river flows are generally increasing but with some regional variations. Sea levels around Ireland rose by approximately 2–3 mm per year since the early 1990s, and by about 1.7 mm per year since 1938 in Dublin Bay (EPA, 2021b). These changes are broadly consistent with global trends and increasingly linked to human influence on the climate system (IPCC, 2021).

However, climate is not the only driver of environmental change in Ireland. Planning and provisions are being made for another one million people by 2040, with associated urban renewal, new housing, transport systems, water infrastructure, rural development, and more – all whilst transitioning to a low carbon and climate resilient society (DHPLG, 2018). Major expansions in renewable energy and forestry are expected to bring about significant land use changes. For instance, a commitment has been made to increase afforestation rates such that a national forestry land cover target of 18% is achieved by the second half of this century (DCCAE, 2021). Local to national environmental transitions will be further shaped by global 'megatrends' in public debt, information and communication technology, the rise of the individual, and demographic change, all of which shape patterns of natural resource consumption and create new vulnerabilities (KPMG, 2014; Wilby, 2017).

This means that preparations for climate change cannot be undertaken in isolation of other strategic investment priorities and pressures. Moreover, as Ireland progresses from adaptation planning to climate action, investments in resilience measures will need to be aligned across sectors (such as agriculture, biodiversity, and water services) and across scales (from local to national) to maximise co-benefits ('win-wins') and reconcile trade-offs (CCAC, 2019). For example, investments in upgraded flood defences to counter rising flood risk should not be at the expense of floodplain habitats and ecosystems which may likewise be stressed by changing river flow regimes (Poff et al., 2016). Synergies will also need to be maximised across the 475 actions of the Climate Action Plan 2021 wherever measures intended to reduce greenhouse gas emissions align <u>with</u> increased climate resilience (DECC, 2021).

Centrally-produced, national climate change scenarios, guidelines, and a structured, risk assessment process can enable closer integration of local to national level adaptation planning (DCCAE, 2018a;b; Warren et al., 2018). Such resources increase the likelihood that different sectors will harmonize information and methods in their resilience planning; the burden of (re)producing scenarios is also reduced for statutory bodies, sectors, and local authorities (CCAC, 2019). Moreover, there is greater scope for identifying most significant climate threats and opportunities within and between sectors /regions, then prioritizing areas for action within the National Adaptation Framework (NAF) (DCCAE, 2018a). To this end, the Climate Ireland platform provides access to ~50 essential climate variables[1] for tracking historic conditions, plus high resolution climate model projections[2] for 2041-2060. The TRANSLATE project[3] is intended to further advance coherent national, sectoral adaptation planning through provision of standardised national climate projections and information.

Consistency is also needed in the handling of uncertainty throughout the adaptation planning process for Ireland. Although attention often focuses on climate scenarios, there are, in fact, implicit and explicit uncertainties in all six steps of the workflow (Figure 1). For instance, Step 1 (Preparing the Ground) depends on the maturity of the knowledge base, as well as the representativeness and level of engagement of stakeholders and specialists – considerations that differ by sector and over time. Step 2 (Climate Impact Screening) rests on the breadth of climate scenarios used to evaluate sector vulnerabilities, and the seldom acknowledged uncertainties involved with climate impact modelling. Step 3 (Prioritisation) hinges on the specified criteria and goals for adaptation which may vary with the stakeholders consulted and with the evolving socio-economic context. Step 4 (Priority Impact Assessment) has the same uncertainties as Step 2 but at the more granular scales of detailed risk assessments. Step 5 (Develop your Plan) involves appraisal and phasing of adaptation options – factors that depend on national to local policy priorities as well as the emerging pace/ expression of regional climate changes. Step 6 (Implement, Evaluate and Review) requires indicators to monitor adaptation outcomes in ways that are meaningful to planners, set within the constraints of data quality/availability.

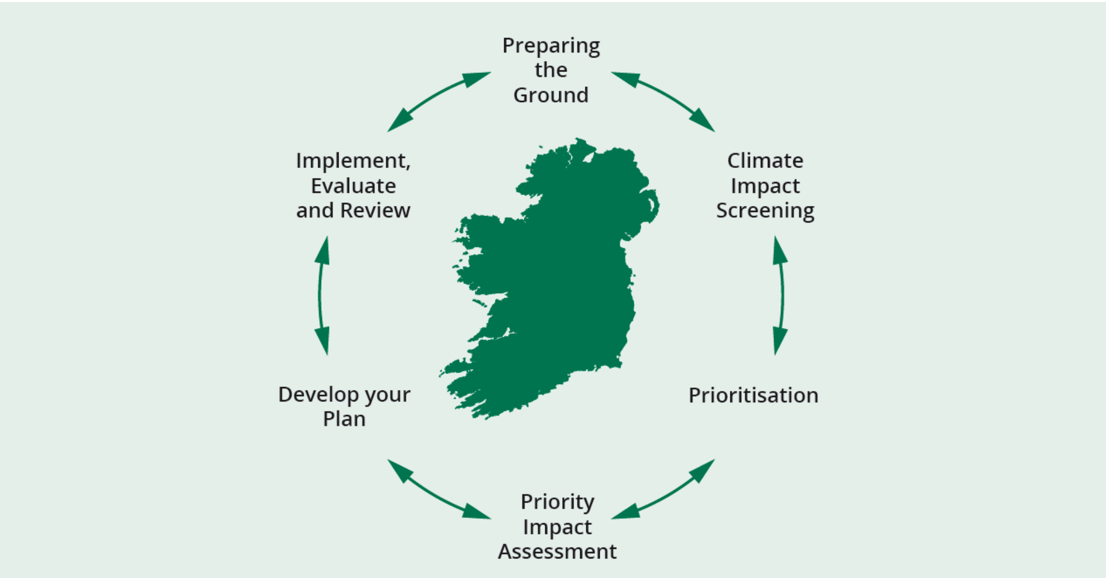


Figure 1 The adaptation planning process for Ireland. Source: DCCAE (2018b)

Accordingly, this Working Paper explores various ways of handling uncertainty throughout the adaptation planning process. The overarching goal is to inform the development of adaptation strategies and investments that deliver intended socio-economic and environmental outcomes regardless of deep uncertainty about future climate (and non-climatic) drivers in Ireland.

[1] *Ireland's Climate Status Tool* https://www.climateireland.ie/#!/tools/statusReport
[2] *Climate Data Explorer* https://www.climateireland.ie/#!/tools/climateDataExplorer
[3] https://www.met.ie/translate-project-to-standardise-future-climate-information-for-ireland

Working paper aims

Even with scientific advances and understanding, uncertainty will remain inherent to the adaptation decision-making process and should be considered by both knowledge providers and decision-makers. This is essential because significant investments and decisions across sectors must be resilient to uncertain climate impacts. The Climate Change Advisory Council (CCAC) has requested evidence on this issue to help inform deliberations and advice to Government. The Adaptation Committee have also identified this as an area requiring research. Accordingly, this Working Paper covers six related themes:

- ***Attitudes*** to uncertainty in climate impacts and adaptation outcomes.
- ***Conceptual approaches*** to adaptation decision making under uncertainty (including Top-down and Bottom-up perspectives).
- ***Decision-making frameworks*** and strategies for adaptation that account for uncertainty (such as adaptive management).
- ***Indicators*** as a basis for informing/assisting decision-making.
- ***Costs and benefits*** of adaptation under uncertainty.
- ***Communication*** of uncertainties in decision-making.

The above evidence is intended to support the development of national and local climate resilience policy in Ireland. The following sections address each theme in turn and lead to a set of high-level recommendations for consideration by the CCAC.

Attitudes to uncertainty

Uncertainty is a fact of life, but attitudes differ around how to live with it. According to DCCAE (2018a:19) *rather than a barrier to action, uncertainty may be treated as a motivation to take a **precautionary approach** to climate change*. This is warranted in high-risk situations where the consequences of failure – such as over-topping of a flood defence, causing harm to people or loss of critical services – could be catastrophic (e.g., Wilby et al., 2011). However, by planning for credible worst-case scenarios, adaptation investments may be more expensive than necessary and thereby incur opportunity costs by diverting resources from other needs.

Alternative strategies for dealing with deep uncertainty include: wait and see; delay to gather more information; reduce critical uncertainties by improving knowledge; enhance resilience to known threats; or implement adaptive management (Curry and Webster, 2011; Hallegatte, 2009; Wilby and Darch, 2021). Other practical ways of adapting under uncertainty include reversible, flexible or modular adaptation measures (e.g., easier to retrofit coastal flood defences, insurance) and reduced decision horizons (e.g., shorter rotation times for forestry, or maintenance cycles for infrastructure such as roads and drainage systems) (Hallegatte et al., 2009). These options tend to be exercised on a project- or site-basis within sectors. There are also a wide range of structured decision-making processes for appraising sets of options under uncertainty which will be discussed later (Siders and Pierce, 2021).

'Wait and see' or 'delay' are not always feasible, especially when significant vulnerabilities are already apparent and/or when adaptation measures could take decades to implement. For instance, the summer 2018 Irish drought returned attention to the high leakage rates, rapid population and economic growth, and limited headroom between water supply-demand in Dublin (Kelly-Quin et al., 2014). The high vulnerability of the livestock economy to loss of pasture was also exposed (Falzoi et al., 2018). However, major infrastructure investments may require long lead times to move from proposal to approval and financing, to detailed engineering design, then construction, and eventual operation. For example, the 170 km water transfer between the River Shannon and Greater Dublin area was proposed by Dublin City Council in 2010, approved by Cabinet in 2019, and could take another 10 years to complete – about 20 years in total (Brady and Gray, 2017).

'Reducing uncertainty' is a very appealing proposition but seldom fully achieved. After two decades of uncertainty-orientated research, the climate science community is now much better placed to *characterize* and *compare* various sources of epistemic (knowledge-based) uncertainty, but there remains considerable ambiguity about future risks and adaptation benefits (Clark et al., 2016; Hall, 2007; Smith et al., 2018). Some may contend that *policy* uncertainty has narrowed with international climate commitments reducing the chance of the 'unlikely worst case' Representative Concentration Pathway RCP8.5 (Hausfather and Peters, 2020). Hence, it may be reasonable to devote less attention to adaptations under RCP8.5 (except for safety margins in most risk-averse adaptation contexts), and more to evaluating mid-range Shared Socioeconomic Pathways such as SSP2-4.5 (modest mitigation), SSP4-6.0 (weak mitigation), and SSP3-7.0 (reversal of some current mitigation policies).

'Enhancing resilience' to known hazards is a good start. This can include 'low-regret' measures such as controlling development (and future 'lock-in' of assets) in high risk areas such as floodplains or the coastal zone; improving contingency planning, forecasting and emergency responses to climate disasters; strengthening observing and reporting systems to track evolving risks and impacts; upgrading building standards and public health services; or reducing water demand. All such measures are regarded as robust to uncertainty because they deliver benefits regardless of the future climate (Wilby and Dessai, 2010). However, residual risks left after resilience measures may remain or increase with changing frequencies of exposure and sensitivity to climate change. For example, the ability to forecast a deadly heatwave does not imply that every vulnerable person has the means to avoid harm. Other hazards may have been 'forgotten'. Until the events of summer 2018 and spring 2020, improving resilience to droughts in Ireland would have seemed a strange proposition. Yet, reconstructions confirm that, although the post 1995 period was benign, this is a drought prone island (Noone et al., 2017; Murphy et al., 2020).

'Adaptive management' is about maximising flexibility and phasing options in response to uncertain climate risks and evolving socio-economic priorities. Adaptation pathways are an emergent property of this strategy, which is both open-ended and iterative (e.g., Ranger et al., 2013; Gell et al., 2019). However, to have such agility in the face of uncertainty depends on having clear adaptation objectives, portfolios of economically, socially and environmentally feasible actions, and agreement about the conditions under which they might be triggered. As will be discussed later, adaptive management of climate risks can be undertaken at different scales spanning individual sites, river basins, regions, and even national scales.

Conceptual approaches

There are two main conceptual approaches to adaptation (Figure 2a). So-called ‘Top-down’ (sometimes called ‘scenario-led’ or ‘science-led’) perspectives begin with global socio-economic drivers of future emissions and atmospheric concentrations of greenhouse gases. These force responses in global and regional climate models which in turn provide information about changes in local weather for impacts modelling (to estimate, for example, future river flows or crop yields). Finally, having quantified climate change impacts, adaptation policies are invoked to manage risks (Wilby and Dessai, 2010). ‘Top down’ is used because information cascades from one step to the next, with uncertainty expanding at every stage (Figure 2b). Until relatively recently, this was the dominant conceptual approach to climate impacts and adaptation planning. However, it is now recognized that the uncertainty range presented to decision-makers can be so wide as to confound practical action such that the planner is typically left with only ‘low regret’ options (World Bank, 2012).

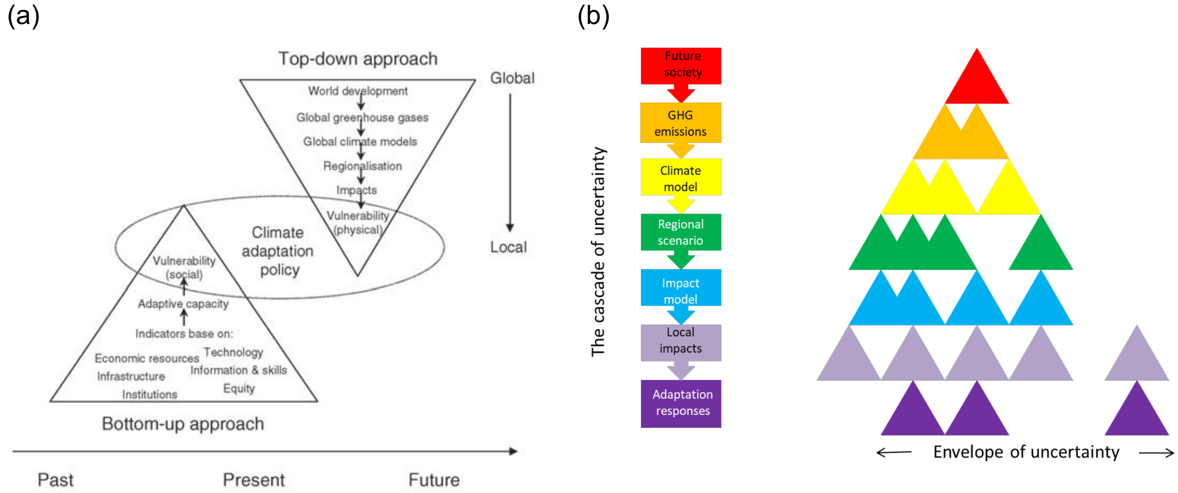


Figure 2 (a) ‘Top-down’ and ‘Bottom-up’ approaches used to inform climate adaptation policy. Source: Dessai and Hulme (2004). **(b)** A representation of the cascade of uncertainty proceeding from a ‘Top-down’ analysis of local climate impacts and adaptation responses. Missing triangles represent gaps in knowledge. Adapted from: Wilby and Dessai (2010).

‘Bottom-up’ (sometimes called ‘vulnerability-led’ or ‘policy-led’) perspectives concentrate on reducing vulnerability to climate variability (Pielke Sr et al., 2012) (Figure 2a). The term ‘Bottom up’ is used because the analysis begins with an assessment of the resources and infrastructure that enable (or impede) coping with known climate-related hazards at the scale of the receptor (which may be an individual, household, community, physical asset, river basin, etc.). Initial evaluation does not depend on climate change scenarios, but detailed data are needed to relate observed hazards to societal and/or environmental impacts (Wilby and Dessai, 2010). Indicators may show ‘hot spots’ of vulnerability or be used to track changes in climate risk exposure, sensitivity to climate hazards, and capacity to adapt (as with the ND-GAIN indices[4]). However, vulnerability assessments are less suited to guiding adaptation planning when coping thresholds change, or climate risks emerge that are outside the range of historic experience (e.g., Thompson et al., 2017).

[4] https://gain.nd.edu/our-work/country-index/

Elements of both ‘Top-down’ and ‘Bottom-up’ conceptual approaches to climate risk management are evident in the NAF and first generation adaptation plans for Ireland. Early steps in the sectoral planning process (Figure 1) are informed by fine-resolution climate change scenarios for Ireland by 2041-2060 (Nolan, 2015). Although there is high confidence in projections of air temperature and sea level rise, model outputs have large biases and ranges of uncertainty for important variables such as winter precipitation. This has ramifications for key sectors such as Water Resources and Flood Risk Management. Hence, the allowances used by the Office of Public Works (OPW) to evaluate flood risk were based on a wider set of evidence that resulted in two indicative futures (Table 1). These span the majority of flood conditions arising from the CMIP5 climate model ensemble (Broderick et al., 2019).

Table 1 Allowances in flood parameters for the Mid-Range (MRFS) and High-End (HEFS) Future Scenarios. Source: OPW (2019)

Parameter	MRFS	HEFS
Extreme Rainfall Depths	+ 20%	+ 30%
Peak Flood Flows	+ 20%	+ 30%
Mean Sea Level Rise	+ 500 mm	+ 1000 mm
Land Movement	- 0.5 mm / year[1]	- 0.5 mm / year[1]
Urbanisation	*No General Allowance – Review on Case-by-Case Basis*	*No General Allowance – Review on Case-by-Case Basis*
Forestation	- 1/6 Tp[2]	- 1/3 Tp[2] + 10% SPR[3]

Note 1: Applicable to the southern part of the country only (Dublin – Galway and south of this)

Note 2: Reduction in the time to peak (Tp) to allow for potential accelerated runoff that may arise as a result of drainage of afforested land

Note 3: Add 10% to the Standard Percentage Runoff (SPR) rate: This allows for temporary increased runoff rates that may arise following felling of forestry.

The OPW Mid-Range (MRFS) and High-End (HEFS) Future Scenarios are also noteworthy because they are not specifically time-bound – they are primarily intended for sensitivity and vulnerability testing. With these, OPW (2019:54) *assessed flood hazard and flood risk, including the production of flood maps, for the MRFS and HEFS as well as for the current conditions for 300 communities that are home to over 3 million people, and for reaches in between these communities and down to the open sea*. However, these scenarios could be elaborated and expanded into a wider set of ‘storylines’ or ‘narratives’ of the future that encompass more diverse climatic and non-climatic conditions than typically offered by regional climate projections (Shepherd et al., 2018). For example, KNMI (2015) conceived four narratives (based on visions of future temperature and storminess) that are applicable across *all key sectors* in the Netherlands (Figure 3, overleaf). Others have imagined climate narratives with associated land-cover changes for more coherent assessments of water resources (e.g., Yates et al., 2015); or combinations of events such La Niña with global warming (Sillmann et al., 2021); or barely conceivable ‘black swan’ events such as cyclones followed by deadly heat (Matthews et al., 2019). Critically, storylines are not assigned probabilities; instead, the emphasis is on *plausibility, salience, and relevance from a vulnerability perspective* (Sillmann et al., 2021:4). This aspect is revisited in the section on Communications below.

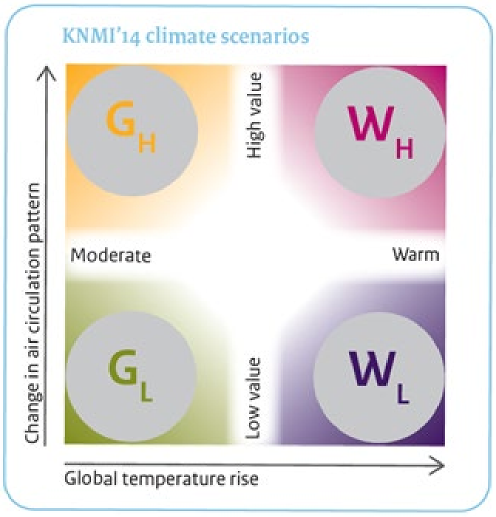


Figure 3 The KNMI scenarios. Large ensembles of climate model projections and weather variables were distilled into just four internally consistent descriptions of most relevant climate variables for evaluating potential risks and adaptation measures across key sectors. For the Netherlands, these narratives were captured by two major axes describing future changes in global temperature (with associated sea level rise) combined with future changes in atmospheric circulation (and associated changes in storminess/ rainfall). Source: KNMI (2015).

Another feature of the OPW (2019:67) plan was the broad statement of intent around *promoting sustainable communities and supporting our environment through the effective management of the potential impacts of climate change on flooding and flood risk*. This was underpinned by three objectives for (1) enhancing knowledge of potential flood risks; (2) changing flood risk management practices; and (3) aligning flood resilience actions across sectors and Government. These in turn led to lists of specific adaptation actions, with responsible agencies, and timelines for delivery. Indicators were designed to measure progress with mapping, the number of schemes assessed and under construction, and the number of properties benefitting from flood relief schemes for which adaptation options had been assessed.

A similar hybrid approach was taken by the Third UK Climate Change Risk Assessment (CCRA3) (Annex 1). This posed an over-arching question to tease out cross-sectoral priorities: *Based on the latest understanding of current and future climate risks and opportunities, as well as current and planned adaptation, what should the priorities be for the next National Adaptation Programme and adaptation programmes of the devolved administrations?* (Watkiss and Betts, 2021:2). Like OPW, the CCRA3 assessed the urgency of action but in a more systematic way. The CCRA3 identified three types of early adaptation priority to: (1) address any current adaptation gap by implementing 'no-regret' or 'low-regret' actions that reduce risks associated with current climate variability, plus building future climate resilience; (2) intervene early to embed adaptation in near-term decisions with long lifetimes, thereby reducing the risk of 'lock-in'; or (3) fast-track early adaptive management actions, especially for decisions with long lead times or requiring major future change. Based on the assessed evidence, each risk was scored (from most to least urgent) as: (i) "more action needed"; (ii) "further investigation"; (iii) "sustain current action"; or (iv) "watching brief". The CCRA3 also considered potential risks associated with low-likelihood, high-impact outcomes, including High++ scenarios and major discontinuities (Wade et al., 2015). Similarly, future sectoral adaptation plans and cross-sectoral integration in Ireland could be strengthened by more formal urgency scoring and consideration of High++ scenarios.

Decision-making frameworks

Many frameworks are available to structure decision-making under uncertainty (see reviews by: Means et al., 2010; Wilby and Murphy, 2018; Orlove et al., 2020; Siders and Pierce, 2021). Each framework has pros and cons depending on the decision context, associated resource requirements, and treatment of uncertainty (Table 2). The processes adopted thus far by the NAF for Ireland are probably best described as a mix of Risk Analysis and ‘no regrets’. The question arises as to whether other decision-making strategies could add value?

Table 2 Frameworks to support adaptation decision-making. Source: Siders & Pierce (2021)

Decision-making strategy	Description	Notes
Idealized Rational Planning	Assess current conditions and goals; Identify all options; Forecast outcomes of adopting each option; Evaluate forecasted outcomes; Select course of action with optimal outcome	Difficult to apply when future conditions or probabilities are unknown or uncertain
Risk Analysis	Risk calculated as probability of an event occurring multiplied by the probable consequences of the event; Optimal actions are those that most effectively or efficiently reduce the risk	
Cost-Benefit Analysis (CBA)	Estimate monetary costs and benefits of pursuing a course of action (translate non-monetary costs and benefits into monetary units). Optimal course is that which maximizes cost:benefit ratio. Costs and benefits include financial, environmental, and social effects. Elements that are difficult to monetize are often omitted	
Multi-Criteria Decision Analysis (MCDA)	Score alternatives on multiple criteria; Aggregate scores to find the optimal option. Numerous aggregation methods exist; popular options include: Analytical hierarchy process, Technique for order preference by similarity to an ideal solution, and Simple additive weighting. Open to incorporation of social values	Similar to CBA but more opportunity to consider ordinal or nominal criteria
Probabilistic Decisions Trees	Diagram options and outcomes; Assign probabilities to each outcome to help identify the optimal course of action	Evaluate multiple future scenarios; RDM does not assign probabilities to future scenarios but does calculate quantitative outcomes; Scenario-based planning is a general category and may include both qualitative or quantitative criteria
Robust Decision Making (RDM)	Iterative computational process; Evaluate performance of options under a range of future conditions to determine which options perform well in multiple conditions (are robust); Does not assign probabilities to future conditions	
Scenario-Based Planning	Create scenarios — quantitatively or qualitatively — to envision future conditions and outcomes of adaptation options; May involve back-casting or adaptation pathways; Several types, including: Epoch-Era Analysis, problem-focused, actor-focused, and reflexive-interventionist	
Dynamic Adaptation Policy Pathways (DAPP)	Identify potential actions and thresholds at which actions should be taken or future decisions made; Identify pathways (sequences of option decisions); Monitor conditions and when thresholds are met, trigger a new pathway	Rather than commit to a single decision, these approaches consider future decision-points and options; DAPP aligns these decisions into a pathway, while ROA uses computational techniques to assess future options
Real Options Analysis (ROA)	Treat decisions not as a single decision point but as an analysis of all options that are currently or may become available in future conditions	
‘No regrets’	Prioritize strategies that yield benefits even if climate does not change or does not change to the extent projected	
Heuristics	Establish simplified, often rule-based decision-making strategies to identify solutions based on a relatively small number of inputs (called ‘cues’). Examples include ‘Tallying’ (weigh all inputs equally to make a decision) and ‘Take-the-Best’ (compare several alternatives using one metric at a time, then take the first option that stands out based on any metric).	Heuristics rely on less information than rational decision-making approaches and are therefore quicker. They may be as or more effective in some situations

An implicit assumption of rationality lies behind most frameworks – after considering available evidence and options, decision-makers and organizations select a course of action. However, few climate risk and adaptation assessments apply formal decision-making tools (Orlove et al., 2020). This may be due to the complexity of some methods and their required computing resources. The large array of tools available may also present a dilemma (Siders and Pierce, 2021). At the highest level, it is possible to distinguish those deliberative frameworks that seek to *optimize* based on 'predict-and-act' (e.g., CBA, MCDA) from those that try to *satisfice* or minimize regret via 'assess-risk-of-policy' (e.g., RDM). Another division is between those that lead to *static* solutions (e.g., RDM, scenario-based planning) and those that yield *dynamic* adaptation pathways (e.g., DAPP, ROA). There is also a split between *structured* and *heuristic* processes, with the latter offering 'fast and frugal' routes to adaptation, such as 'pick the first' option demanded by stakeholders.

Some frameworks have hybrid features. For example 'decision-scaling' is a dynamic version of RDM with advantages of flexibility, stakeholder involvement, iteration and evaluation of trade-offs (e.g., Brown et al., 2012; Girard et al., 2015; Poff et al., 2016). The emphasis is on delivering specified project outcomes despite climate change; climate monitoring and scenarios inform rather dictate adaptation strategies; and stakeholder engagement is critical for defining adaptation objectives, actions, and performance indicators at outset. Furthermore, stress-testing of adaptation options enables exploration of measures within system models under plausible ranges of climate conditions to uncover limits and expected benefits of adaptation (Broderick et al., 2019; Culley et al., 2019; Prudhomme et al., 2010). Decision-scaling is most helpful when there are relatively few adaptation options or there are trade-offs (such as between using reservoir storage to manage drought or flood risk).

Adaptive management frameworks may be preferred where there is the possibility of reflexive learning (feedback loops), large numbers of options, or a risk of 'spill-over' (consequences) from adaptation decisions made by one actor on another (or across sectors). Moreover, adaptation pathways may be applied in uncertain and resource-constrained contexts, and where there are contested or ambiguous goals (Werners et al., 2021). Their intent is to deliver what some have called 'dynamic robustness' (Maier et al., 2016). Early applications were to flood risk management in the Thames Estuary (Ranger et al., 2013), long-term water management in the Rhine delta (Haasnoot et al., 2013), and coastal community responses to sea level rise in Australia (Barnett et al., 2014). Figure 4 shows an example for water resource management in London. These and subsequent studies demonstrate the versatility of adaptive frameworks in terms of the scale (local, city, landscape, national), purpose (project, plan, policy) and sector covered (until now, mainly coastal zone, water resources, urban infrastructure, conservation, and flood management).

As far as the author is aware, no adaptation pathways have been developed for Ireland yet. To fill this gap, the vital building blocks are (Gell et al., 2019:1296):

(1) ***Portfolios of options*** identified through inclusive and participatory stakeholder consultations. Preferred options should be 'low regret' and avoid lock-in or narrowing of future options. Intergenerational equity of options and implications for social cohesion should also be considered.

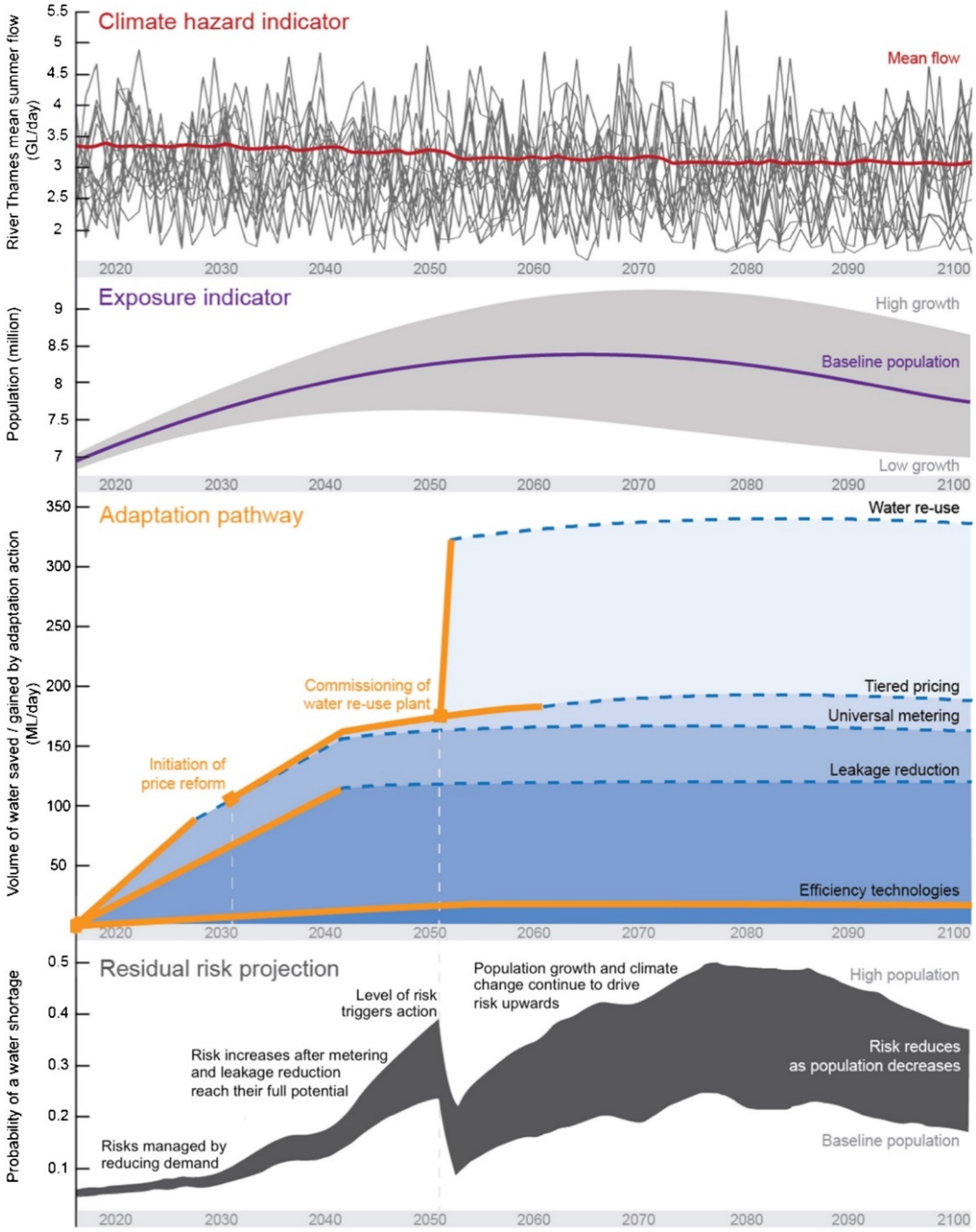


Figure 4 Adaptation pathways for water resource management in London. The portfolio of options has efficiency measures, leakage reduction, metering, pricing, and water re-use. Decision trigger points occur in years 2030 and 2050. These are based on the probability of water restrictions linked to established levels of service. Source: Kingsborough et al. (2016)

(2) ***Trigger points*** or decision criteria to specify the circumstances under which a given option might be invoked. Example triggers could be farm income, the water table depth in a wetland, local sea level, or an environmental flow requirement.

(3) ***Monitoring systems*** to track evolving socio-economic and environmental conditions with respect to the trigger points in (2). Options and trigger points should also be periodically reviewed and refreshed to reflect changing circumstances or socio-economic priorities.

(4) ***Indicators*** to evaluate the performance of options using metrics such as water security (in terms of resilience and reliability), number and duration of outages, avoided damages, economic costs, or greenhouse gas emissions.

(5) ***Governance and institutional architecture*** to provide the informal and legal jurisdictions within which (1) to (4) operate, recognizing that these structures are themselves dynamic, as they adapt to changing community and cultural priorities, new knowledge, processes for conflict resolution, and policy reform.

Climate risk and action indicators

Indicators have four main purposes, namely to (1) *track* climate drivers and impacts; (2) *monitor* progress in improving resilience and preparing for climate change; (3) *trigger* actions within adaptive management plans; and (4) *communicate* future climate risks and opportunities. Indicators may be based on historic data or model projections (including regional climate and impact model simulations). Ideally, indicators are periodically updated, freely accessible, and in the public domain.

Ireland is relatively well-endowed with long-term climate records and syntheses such as *The Status of Ireland's Climate* (EPA, 2021b). Considerable efforts are also being made to quality assure and reconstruct hydroclimatic series to place recent extreme events and trends in a long-term context (e.g., Noone et al., 2017; Murphy et al., 2013a;b; 2020; Shoari Nejad et al., 2021; Wilby et al., 2016). As mentioned before, Ireland's Climate Status Tool[1] provides observed trends for 50 variables with a brief commentary about the monitoring infrastructure. The variables show historic trends in atmospheric composition; the upper- and surface-atmosphere, surface and subsurface ocean physics; ocean biology and biogeochemistry; anthroposphere, biosphere and hydrosphere. Further information and supporting resources are also provided for each variable. This is an admirable 'one-stop-shop' – a centralised, public data resource that represents best practice[5].

Nonetheless, Ireland's indicator set could be expanded to improve coverage of climatic co-stressors and impacts on natural environments and agri-systems, such as air and water quality (including temperature), soil moisture and erosion, tree growth, habitat change and condition, non-native species and pests, disease (e.g., Johne's Disease), farm water use, field drainage, and crop yields. More indicators could be provided on socio-economic vulnerabilities, including the amount of urban greenspace, security of international supply chains, the location, condition and performance of critical infrastructure, amount of new development in the floodplain, socio-demographic trends, health and social care delivery. Other indicators could provide information that is pertinent to both climate impacts and mitigation, such as forest estate condition, pests and disease.

Above all, there is scope for more indicators describing resilience and effectiveness of adaptation actions in different contexts. For example, the UK Climate Change Committee initially had two bespoke measures of resilience: (1) the size and spatial configuration of woodland patches within the landscape; (2) reported and forecasted spend on resilience measures by water companies (ASC, 2019). Other indicators of climate-related risks and actions are given in Table 3 (and also in Arnell et al., 2021). All are potentially applicable to Ireland – even the area under vine and volume of wine produced! However, there would still be some notable gaps in sector coverage,

[5] In 2021, the UK Climate Change Committee commissioned ADAS to review and update nine of the Adaptation Committee's full indicator set. However, unlike Ireland, the UK is still without a publicly accessible, central repository of climate indicators. See: https://www.theccc.org.uk/publication/research-to-review-and-update-indicators-of-climate-related-risks-and-actions-in-england-adas/

such as for health, where admissions for heat-related conditions could be added. Likewise, more consideration could be given to metrics of cross-sectoral integration and systems-of-systems resilience (e.g., Uday and Marais, 2015).

Table 3 Novel indicators of climate-related risks and progress on adaptation. Compiled from ASC (2019), Ffoulkes et al. (2021), Wilby (2020), Wilby and Johnson (2020).

Agriculture	• Average field size (grassland and arable). • Volumes of abstraction from non-tidal water sources for agriculture. • Change in total hedgerow length. • Area under vine and volume of wine produced.
Natural Environment	• Freshwater temperature. • Condition of natural heritage areas, nature reserves, and conservation sites. • Tree losses as a result of extreme weather. • Size and spatial configuration of woodland patches within the landscape. • Proportion of water bodies meeting EU Water Framework Directive Good status.
People and the Built Environment	• Percentage and number of new properties built on land assessed as having >1% annual probability of river flooding, or >0.5% annual probability of flooding by the sea in any year. • Number of planning permissions that are granted contrary to agency advice. • Area of permeable and impermeable land within all urban areas. • Weighted average water consumption per capita.
Infrastructure	• Total number of minutes of delay per weather related incidents (rail). • Total leakage for all water companies. • Reported and forecasted spend on resilience by water companies. • Uptake of natural flood management.

Clearly, gathering and maintaining sector-specific indicators of climate-drivers, co-stressors, impacts, action, and resilience requires considerable resources as well as co-ordination across multiple agencies and private sector entities. Action 450 of *Climate Action Plan 2100* (DECC, 2021:205) is to *continue to improve Ireland's national climate monitoring capabilities through the delivery of advanced, sustainable, and long-term, climate and environmental monitoring programmes*. This will involve modernising the surface climate and weather station network, as well as expanding groundwater monitoring (Action 445) and analysis of physical risks to key sectors (Actions 437, 446, 447, 459, 473). Additional resources will be needed to obtain data and create new indicators (such as those suggested in Table 3), then use them to track adaptation at the national level (Action 436). There will also be technical considerations around data completeness, homogeneity, and freedom of access (in the case of proprietary information) (Wilby et al., 2017). Finally, whenever metrics are based on climate model output it is essential that their physical realism be evaluated, especially under non-stationary conditions when important land-surface properties and feedbacks may be parameterised (Ekström et al., 2018).

Costs and benefits of adaptation

The NAF lays out the economic basis for adaptation (DCCAE, 2018a). Cost-effectiveness is amongst the criteria for prioritising adaptation options (alongside efficiency, risk and urgency, and distributional impacts). Detailed guidance on appraisal methodologies is provided by the *Public Spending Code*. However, the *Review of Statutory Sectoral Adaptation Plan Making 2018-2019* called for greater integration of climate action in Government policy and investment decisions, plus more information about the costs of climate/weather related damages, adaptation measures, and expected benefits (CCAC, 2019). Tellingly, all costs mentioned in the *Interim Climate Actions* (DCCAE, 2021) pertained to abatement of greenhouse gas emissions; but the successor, *Climate Action Plan 2021* (DECC, 2021), does call for costing extreme weather impacts (Actions 293, 472), and inclusion of potential rises in future flood damages within the CBA of flood relief schemes (Action 441).

One of the earliest assessments of impact costs in Ireland was, in fact, for flooding. This highlighted the need to look for coping mechanisms beyond insurance – not least because indirect damages from emotional stress, health impacts, and reduced economic competitiveness of impacted communities and regions are not covered (Doran et al., 2015). The five impact severity categories used by OPW (2019) for floods were based on the number of properties affected and spatial extent, with indicative costs ranging from <€1m (low) to >€1bn (high). OPW (2019:48) further noted that *taking account of the potential increased damages due to climate change in the economic appraisal of schemes will reflect the damages avoided by providing for climate change in scheme design and will support early adaptation*. For example, the cost of flood damages to Limerick City and Environments could rise from €83 Million (present scenario) to more than €1 Billion (HEFS) for a 1 in 200 year event.

Flood relief schemes may subsequently be adapted for climate change by: (1) incorporating an additional allowance for climate change in the design up-front (the ‘assumptive approach’); (2) designing for future retrofit or upgrading of the structure at a later date (the ‘adaptive approach); (3) adopting other catchment-based measures (such as upstream storage/ flow retention); or (4) living with greater flood risk (by improving non-structural measures such as flood forecasting). Adaptation options may then be assessed using a mix of decision-tree analysis, multi-criteria analysis, and economic cost-benefit analysis.

Short-term, marginal costs of adaptation are context specific but lowest for “do nothing”, and generally less for adaptive than assumptive approaches (OPW, 2019). However, the benefit-cost ratio will reflect other factors such as the assumed future climate risk scenario, discount rate, any included co-benefits or externalities. Sensitivity testing can help to establish the significance of these uncertainties to the viability of a scheme. For instance, higher economic discount rates reduce the economic costs of future negative impacts of climate change, weakening the case for investment in adaptation now (Figure 5). In fact, a discount rate of 3% or lower is needed to yield significant benefits from a scheme over 45-50 years – the typical lifetime of major water infrastructure, but likely shorter than the detection time for local climate-related impacts with large inter-annual variability (Stakhiv, 2011).

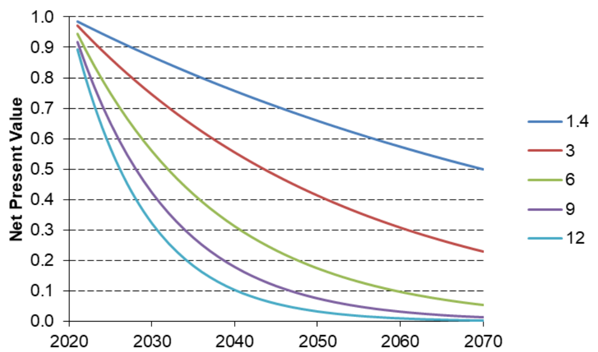


Figure 5 The effect of various discount rates on the Net Present Value of benefits from an investment made in 2021. The “social rate of discount” (3%) advocated by Stakhiv (2011) and the discount rate (1.4%) applied in the Stern (2007) Report are shown.

A case for investment could still be made where there is already an adaptation deficit to extreme events or where there are substantial co-benefits. Guidance followed by some Multilateral Development Banks (MDBs) already distinguishes between measures that (a) enhance the resilience (i.e. 'climate proof') a project (Type 1), from those that are (b) intentionally designed to provide adaptation benefits (Type 2) (Watkiss et al., 2020). In other words, Type 2 projects are predicated solely on the basis of managing climate change risks and would not otherwise occur (e.g., higher coastal flood defences to contend with sea level rise). A good test is whether the project complies with the three joint-MDB climate adaptation finance principles[6]. To qualify for adaptation finance, it is necessary to (1) set out the climate vulnerability context; (2) provide a statement of intent to address the identified risks, vulnerabilities, and impacts; (3) demonstrate a direct link between the identified risks, vulnerabilities, and impacts to the financed activities.

The distinction between Type 1 and 2 projects can also signal whether a detailed or light-touch economic appraisal is warranted (Table 4). Detailed economic analysis is required for projects with long lifetimes, a high degree of irreversibility (i.e., lock-in), where there is a need for precaution, and/or for very large investments (>$400m) (ADB, 2017; Watkiss et al., 2020). Whether detailed or light-touch, the economic analysis should be early in the project life-cycle in order to appraise a wide set of options, rather than later when design specifications may be 'baked in'. Annex 2 provides pragmatic ways of filtering options based on the urgency, uncertainty, and rationale for adaptation. Other lookup tables with benchmarking costs and indicative economic benefits (plus good practice case studies) could help to develop capacities in what is often the weakest part of an adaptation project (e.g., EC, 2017).

Table 4 Examples of project suitability for detailed versus light-touch climate risk and adaptation assessment (CRA). Source: Watkiss et al. (2020)

Type of Project	Detailed CRA	Light-touch CRA
Type 1. Climate Proofing *(climate adaptation is a secondary objective)*	New large hydro-electric power plant and reservoir *(long lifetime, high risk of lock-in, high level of precaution [safety] required, large project)*	Upgrade of existing road project or new wind power project *(shorter lifetime, low risk of lock-in, low level of precaution, small project)*
Type 2. Adaptation *(climate adaptation is the principal objective)*	New hard coastal protection to defend against sea-level rise risks *(principal objective, long lifetime)* New building codes or engineering design standards that incorporate allowances for climate change *(principal objective, risk of sector lock-in)*	Some technical assistance projects, policy reform, and resilience financing[a] *(principal objective, but short lifetime, and focus on enabling conditions for in-depth adaptation)*

[6] *Common Principles for Climate Change Adaptation Finance*
https://www.eib.org/attachments/documents/mdb_idfc_adaptation_common_principles_en.pdf

Communications

Interim Climate Actions set out various activities designed to enhance stakeholder engagement, knowledge transfer, and changes in practice, but these initiatives addressed only mitigation efforts (DCCAE, 2021). However, the National Dialogue on Climate Action (NDCA) was carried into the *Climate Action Plan 2021* and remains an important vehicle for awareness-raising, citizen and community engagement (DECC, 2021). The three key planks of the NDCA are around improving climate literacy, enabling wider participation in climate actions at all levels, and evidencing the effectiveness of communications on climate action. Specific communication measures that might encompass adaptation include: developing the evidence base on behaviour change (Action 46); wider outreach agenda for schools (Action 61); co-creation and delivery of climate services (Action 449); and publicising the benefits of investment in climate resilience for the energy sector (Action 475).

All the above will benefit from proposed research into understanding *how to* communicate climate change issues more effectively and thereby transition society from awareness, to concern, to (adaptation) action. Long-recognised challenges include remoteness (in space and time) of climate impacts and adaptation benefits, complexity, uncertainty, and a growing sense of hopelessness (Moser, 2010; 2016). Others are more concerned about the credibility, legitimacy and saliency of climate information for adaptation decision-making (Tang and Dessai, 2012). For instance, the inherent complexity of probabilistic climate projections may present a significant obstacle to non-expert audiences.

Some of these issues may be overcome with clarity of purpose and scope of the communication, appropriate framing of messages and language for the target audience, careful choice of the messengers and modes of communication, with subsequent review of communication outcomes and effectiveness (Moser, 2014). Emerging insights around place attachment and place identity could be deployed to make adaptation personally relevant and to create opportunities for public dialogue (Scannell and Gifford, 2013; Devine-Wright and Quinn, 2020). For example, dramatic changes in coastal environments are known to cause distress and affect how communities view the future (Figure 6). Some even assert that place attachment offers a better starting point for conversations about adaptation than an emphasis on climate change impacts (Amundsen, 2015). Place attachment may also shape attitudes to authority and present a barrier to disruptive, transformative adaptation such as migration or major engineering works (Clarke et al., 2016; 2018).

Figure 6 North beach at Courtown in 1967 (left) and in 2015 (right) with rock armour. Source: Phillips and Murphy (2021)

Another way of communicating climate change with at risk communities is to speak in terms of memorable seasons and extreme events. For instance, the chance of a hot summer like 1995 increased 50-fold over the period 1900-2014 (Matthews et al. 2016). The Irish heatwaves and droughts of summer 2018 and spring 2020 could be similarly characterised as changes in likelihood or linked to anomalies projected by regional climate models (Nolan, 2015). In this way, abstract and distant changes in maximum temperatures by 2041-2060 could be recast as an *x*-fold increase in the chance of a heatwave like summer 2018. Memorable extreme weather and impacts endured by different sectors and groups are thereby connected with comparable – but likely more frequent – events under climate change. Alternatively, notable droughts of the past could be imagined as unfolding in different ways (e.g., Chan et al., 2021). Where there are interacting climate hazards (such as increased storminess with sea level rise) and/or significant uncertainties in the outlook, narratives and storylines may be used (Shepherd et al., 2018). As explained before, storylines provide internally-consistent and non-probabilistic ways of communicating uncertain climate change impacts (and other drivers) in terms that are meaningful to decision-makers.

Recommendations

What knowledge is produced, how scientists, decision-makers and the public interact and how climate risk information is applied, are all shaped by the political culture of a nation and the respective roles played by science, government and non-state actors (Skelton et al., 2017:2337). This Working Paper has evaluated frameworks and information sources for adaptation decision-making under uncertainty, viewed through the lens of policy and practice in Ireland. Where relevant, experiences have been incorporated from elsewhere. The fundamental goal of adaptation planning is taken as achieving positive socio-economic and environmental outcomes regardless of deep uncertainty about future climate (and non-climatic) drivers of change.

Based on the evidence reviewed and in addition to the measures already proposed by the *Climate Action Plan 2021*, the following six high-level recommendations are made to strengthen adaptation decision-making in Ireland:

1) Pilot an adaptative management framework for a sector or plan, to map options, identify trade-offs and trigger points, and develop ***adaptation pathways*** – such as for improving the resilience of water resources in the Greater Dublin Area.

2) Develop a set of climate change ***storylines*** for Ireland – including low likelihood, high-impact scenarios (High++) – with cross-sector relevance for testing adaptation actions and communicating key risks to diverse audiences.

3) Strengthen the criteria and processes for ***urgency scoring*** of adaptation options within <u>and</u> across sector plans to establish national priorities for action in Ireland.

4) Undertake a comprehensive sector and cross-sector based review of ***adaptation indicators***, including their purpose, the cost and availability of data, the length, quality and homogeneity of records, and their future sustainability.

5) Develop workflows for proportionate and transparent ***economic appraisal*** of adaptation options that can be applied to project- and sector-level actions.

6) Incorporate adaptation within existing communication Actions (mainly targeting mitigation efforts), plus make use new insights about place attachment, memorable extremes, and storylines to ***personalize climate risks and adaptation opportunities*** for diverse audiences.

References

Adaptation Sub Committee (ASC), 2019. *Progress in Preparing for Climate Change—2019 Progress Report to Parliament*. Committee on Climate Change: London.

Amundsen, H. 2015. Place attachment as a driver of adaptation in coastal communities in Northern Norway. *Local Environment*, **20**, 257-276.

Arnell, N.W., Kay, A.L., Freeman, A., Rudd, A.C. and Lowe, J.A. 2021. Changing climate risk in the UK: a multi-sectoral analysis using policy-relevant indicators. *Climate Risk Management*, **31**, 100265.

Asian Development Bank (ADB), 2017. *Guidelines for the Economic Analysis of Projects*. Manila, Philippines.

Barnett, J., Graham, S., Mortreux, C., Fincher, R., Waters, E. and Hurlimann, A. 2014. A local coastal adaptation pathway. *Nature Climate Change*, **4**, 1103-1108.

Brady, J. and Gray, N.F. 2017. Reform of the Irish water sector: opportunities and challenges. *Proceedings of the Institution of Civil Engineers-Water Management*, **170**, 165-174.

Broderick, C., Murphy, C., Wilby, R.L., Matthews, T., Prudhomme, C. and Adamson, M. 2019. Using a scenario-neutral framework to avoid potential maladaptation to future flood risk. *Water Resources Research*, **55**, 1079-1104.

Brown, C., Ghile, Y., Laverty, M. and Li, K. 2012. Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector. *Water Resources Research*, **48**, W09537.

Chan, W.C., Shepherd, T.G., Smith, K.A., Darch, G. and Arnell, N.W. 2021. Storylines of UK drought based on the 2010–2012 event. *Hydrology and Earth System Sciences Discussions*, pp.1-34.

Clark, M.P., Wilby, R.L., Gutmann, E.D., Vano, J.A., Gangopadhyay, S., Wood, A.W., Fowler, H.J., Prudhomme, C., Arnold, J.R. and Brekke, L.D. 2016. Characterizing uncertainty of the hydrologic impacts of climate change. *Current Climate Change Reports*, **2**, 55-64.

Clarke, D., Murphy, C. and Lorenzoni, I. 2016. Barriers to transformative adaptation: Responses to flood risk in Ireland. *Journal of Extreme Events*, **3**, p.1650010.

Clarke, D., Murphy, C. and Lorenzoni, I. 2018. Place attachment, disruption and transformative adaptation. *Journal of Environmental Psychology*, **55**, 81-89.

Climate Change Advisory Council (CCAC), 2019. *Progress towards a Climate-Resilient Ireland: Review of Statutory Sectoral Adaptation Plan Making 2018-2019*.

Culley, S., Bennett, B., Westra, S. and Maier, H.R. 2019. Generating realistic perturbed hydrometeorological time series to inform scenario-neutral climate impact assessments. *Journal of Hydrology*, **576**, 111-122.

Curry, J.A. and Webster, P.J. 2011. Climate science and the uncertainty monster. *Bulletin of the American Meteorological Society*, **92**, 1667-1682.

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

Department of Communications, Climate Action and Environment (DCCAE), 2018b. *Sectoral Planning Guidelines for Climate Change Adaptation*. Dublin, Ireland. https://www.gov.ie/pdf/129614/?page=null

Department of Communications, Climate Action and Environment (DCCAE), 2021. *Interim Climate Actions*. Dublin, Ireland.

Department of the Environment, Climate and Communications (DECC), 2021. *Climate Action Plan 2021: Securing Our Future*. Dublin, Ireland.

Department of Housing, Planning and Local Government (DHPLG), 2018. *Project Ireland 2040 National Planning Framework*.

Dessai, S. and Hulme, M. 2004. Does climate adaptation policy need probabilities? *Climate Policy*, **4**, 107-128.

Devine-Wright, P. and Quinn, T. 2020. Dynamics of place attachment in a climate changed world. In: Manzo, L.C. and Devine-Wright, P. (eds). *Place Attachment*, Chapter 14, Routledge.

Doran, J., McDermott, T., Kilgarriff, P., Surminski, S. and Alaniz, M.P. 2015. *Adaptive Responses to Climate Impacts (ARC): Costing the Impacts of Climate Change on the Irish Economy and Assessing the Options for Adaptation, with a Specific Focus on the Role of Key Stakeholders*. Prepared for the Environmental Protection Agency, Johnstown Castle, Wexford.

Ekström, M., Gutmann, E.D., Wilby, R.L., Tye, M.R. and Kirono, D.G. 2018. Robustness of hydroclimate metrics for climate change impact research. *Wiley Interdisciplinary Reviews: Water*, **5(4)**, p.e1288.

Environmental Protection Agency (EPA), 2021a. *Ireland's Environment – An Integrated Assessment 2020*.

Environmental Protection Agency (EPA), 2021b. *The Status of Ireland's Climate 2020*. Environmental Protection Agency, Marine Institute and Met Éireann, Dublin.

European Commission (EC), 2017. *Economics of Climate Change Adaptation in Europe (ECONADAPT) Project: Inventory and Look-Up Tables*. Brussels: https://econadapt-library.eu/

Falzoi, S., Gleeson, E., Lambkin, K., Zimmermann, J., Marwaha, R., O'Hara, R., Green, S. and Fratianni, S. 2019. Analysis of the severe drought in Ireland in 2018. *Weather*, **74**, 368-373.

Ffoulkes, C., Hockridge, B., Illman, H., Holmes, G., Manning, F. and Wilson, L. 2021. *Research to review and update indicators of climate-related risks and actions in England*. ADAS report to the Committee on Climate Change.

Gell, P.A., Reid, M.A. and Wilby, R.L. 2019. Management pathways for the floodplain wetlands of the southern Murray–Darling Basin: Lessons from history. *River Research and Applications*, **35**, 1291-1301.

Girard, C., Pulido-Velazquez, M., Rinaudo, J.D., Pagé, C. and Caballero, Y. 2015. Integrating top–down and bottom–up approaches to design global change adaptation at the river basin scale. *Global Environmental Change*, **34**, 132-146.

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

Hall, J. 2007. Probabilistic climate scenarios may misrepresent uncertainty and lead to bad adaptation decisions. *Hydrological Processes*, 21, 1127-1129.

Hallegatte, S. 2009. Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19**, 240-247.
Hausfather, Z. and Peters, G.P. 2020. Emissions–the ‘business as usual’ story is misleading. *Nature*, **577**, 618-620.
IPCC, 2021. *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, in press.
Kelly-Quinn, M., Blacklocke, S., Bruen, M., Earle, R., O'Neill, E., O'Sullivan, J. and Purcell, P. 2014. Dublin Ireland: a city addressing challenging water supply, management, and governance issues. *Ecology and Society*, **19**(4).
Kingsborough, A., Borgomeo, E. and Hall, J.W. 2016. Adaptation pathways in practice: Mapping options and trade-offs for London’s water resources. *Sustainable Cities and Society*, **27**, 386-397.
KNMI, 2015. *KNMI’14 climate scenarios for the Netherlands; A guide for professionals in climate adaptation*. KNMI, De Bilt, The Netherlands, 34 pp.
KPMG, 2014. Future State 2030: The global megatrends shaping governments. Available from: https://assets.kpmg/content/dam/kpmg/pdf/2014/02/future-state-2030-v3.pdf (accessed 16 October 2021).
Maier, H. R., Guillaume, J. H., van Delden, H., Riddell, G. A., Haasnoot, M. and Kwakkel, J. H. 2016. An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling and Software*, **81**, 154-164.
Matthews, T., Mullan, D., Wilby, R.L., Broderick, C. and Murphy, C. 2016. Past and future climate change in the context of memorable seasonal extremes. *Climate Risk Management*, **11**, 37-52.
Matthews, T., Wilby, R.L. and Murphy, C. 2019. An emerging tropical cyclone–deadly heat compound hazard. *Nature Climate Change*, **9**, 602-606.
Means, E., Laugier, M., Daw, J., Kaatz, L., and Waage, M. 2010. *Decision support planning methods: Incorporating climate change uncertainties into water planning*. Water Utility Climate Alliance White Paper. San Francisco. https://www.wucaonline.org/assets/pdf/pubs-whitepaper-012110.pdf [Accessed 20/10/21]
Moser, S.C. 2010. Communicating climate change: history, challenges, process and future directions. *Wiley Interdisciplinary Reviews: Climate Change*, **1**, 31-53.
Moser, S.C. 2014. Communicating adaptation to climate change: the art and science of public engagement when climate change comes home. *Wiley Interdisciplinary Reviews: Climate Change*, **5**, 337-358.
Moser, S.C. 2016. Reflections on climate change communication research and practice in the second decade of the 21st century: what more is there to say?. *Wiley Interdisciplinary Reviews: Climate Change*, **7**, 345-369.
Murphy, C., Harrigan, S., Hall, J. and Wilby, R.L. 2013a. Climate-driven trends in mean and high flows from a network of reference stations in Ireland. *Hydrological Sciences Journal*, **58**, 755-772.
Murphy, C., Harrigan, S., Hall, J., Wilby, R. L. 2013b. *HydroDetect: The Identification and Assessment of Climate Change Indicators for an Irish Reference Network of River Flow Stations*. Climate Change Research Programme (CCRP) 2007-2013 Report Series No. 27. Wexford: EPA.

Murphy, C., Wilby, R.L., Matthews, T., Horvath, C., Crampsie, A., Ludlow, F., Noone, S., Brannigan, J., Hannaford, J., McLeman, R. and Jobbova, E. 2020. The forgotten drought of 1765–1768: Reconstructing and re-evaluating historical droughts in the British and Irish Isles. *International Journal of Climatology*, **40**, 5329-5351.

Nolan, P. 2015. *Ensemble of regional climate model projections for Ireland*. Environmental Protection Agency Report No. 159. Irish Centre for High-End Computing and Meteorology and Climate Centre, School of Mathematical Sciences, University College Dublin.

Noone, S., Broderick, C., Duffy, C., Matthews, T., Wilby, R.L., Murphy, C. 2017. A 250-year drought catalogue for the island of Ireland (1765-2015). *International Journal of Climatology*, **37**, 239-254.

Office of Public Works (OPW), 2019. *Flood Risk Management – Climate Change Sectoral Adaptation Plan*. Office of Public Works, Trim, County Meath, Ireland. [3575554721374f7ab6840ee11b8b066a.pdf (www.gov.ie)]

Orlove, B., Shwom, R., Markowitz, E. and Cheong, S-M. 2020. Climate decision-making. *Annual Review of Environment and Resources*, **45**, 271-303.

Phillips, C. and Murphy, C. 2021. Solastalgia, place attachment and disruption: insights from a coastal community on the front line. *Regional Environmental Change*, **21**, 1-14.

Pielke Sr, R.A., Wilby, R., Niyogi, D., Hossain, F., Dairuku, K., Adegoke, J., Kallos, G., Seastedt, T. and Suding, K. 2012. Dealing with complexity and extreme events using a bottom-up, resource-based vulnerability perspective. *Extreme Events and Natural hazards: The Complexity Perspective*, **196**, 345-359.

Poff, N.L., Brown, C.M., Grantham, T.E., Matthews, J.H., Palmer, M.A., Spence, C.M., Wilby, R.L., Haasnoot, M., Mendoza, G.F., Dominique, K.C. and Baeza, A. 2016. Sustainable water management under future uncertainty with eco-engineering decision scaling. *Nature Climate Change*, **6**, 25-34.

Prudhomme, C., Wilby, R.L., Crooks, S., Kay, A.L. and Reynard, N.S. 2010. Scenario-neutral approach to climate change impact studies: application to flood risk. *Journal of Hydrology*, **390**, 198-209.

Ranger, N., Reeder, T. and Lowe, J. 2013. Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. *EURO Journal on Decision Processes*, **1**, 233-262.

Scannell, L. and Gifford, R. 2013. Personally relevant climate change: The role of place attachment and local versus global message framing in engagement. *Environment and Behavior*, **45**, 60-85.

Shepherd, T.G., Boyd, E., Calel, R.A., Chapman, S.C., Dessai, S., Dima-West, I.M., Fowler, H.J., James, R., Maraun, D., Martius, O., Senior, C., Sobel, A.H., Stainforth, D.A., Tett, S.F.B., Trenberth, K.E., van den Hurk, B.J.J.M., Watkins, N.W., Wilby, R.L. and Zenghelis, D.A. 2018. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change*, **151**, 555-571.

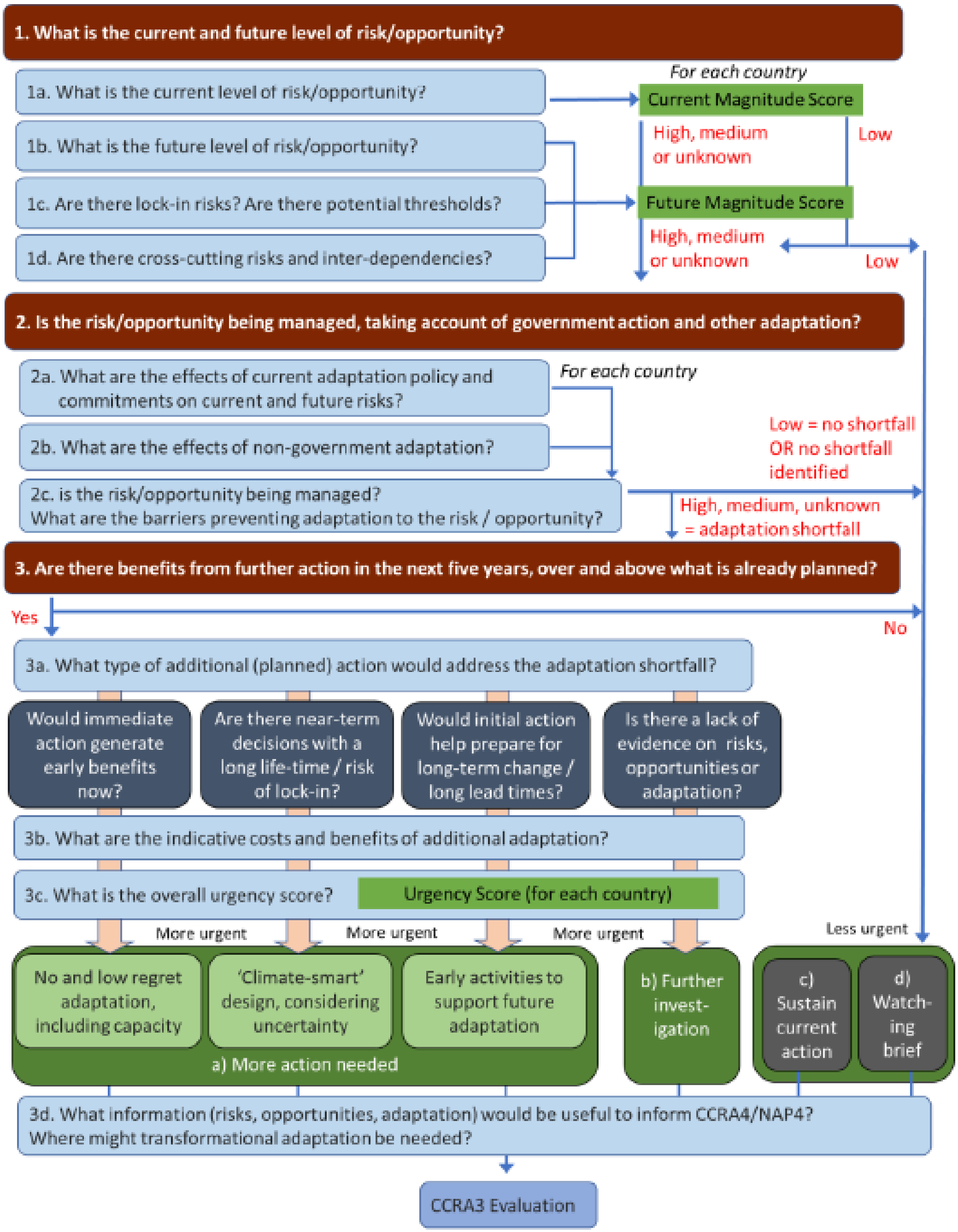
Shoari Nejad, A., Parnell, A. C., Greene, A., Thorne, P., Kelleher, B. P., Devoy, R. J. N., and McCarthy, G. 2021. A newly reconciled data set for identifying sea level rise and variability in Dublin Bay. *Ocean Science Discussion* [preprint], https://doi.org/10.5194/os-2021-92, in review.

Siders, A.R. and Pierce, A.L., 2021. Deciding how to make climate change adaptation decisions. *Current Opinion in Environmental Sustainability*, **52**, 1-8.

Sillmann, J., Shepherd, T.G., van den Hurk, B., Hazeleger, W., Martius, O., Slingo, J. and Zscheischler, J. 2021. Event-based storylines to address climate risk. *Earth's Future*, **9**(2), p.e2020EF001783.
Skelton, M., Porter, J.J., Dessai, S., Bresch, D.N. and Knutti, R. 2017. The social and scientific values that shape national climate scenarios: a comparison of the Netherlands, Switzerland and the UK. *Regional Environmental Change*, **17**, 2325-2338.
Smith, K.A., Wilby, R.L., Broderick, C., Prudhomme, C., Matthews, T., Harrigan, S. and Murphy, C. 2018. Navigating cascades of uncertainty—as easy as ABC? Not quite…. *Journal of Extreme Events*, **5**, p.1850007.
Stakhiv, E.Z. 2011. Pragmatic approaches for water management under climate change uncertainty. *Journal of the American Water Resources Association*, **47**, 1183-1196.
Stern, N. 2007. *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge.
Tang, S. and Dessai, S., 2012. Usable science? The UK climate projections 2009 and decision support for adaptation planning. *Weather, Climate, and Society*, **4**, 300-313.
Thompson, V., Dunstone, N.J., Scaife, A.A., Smith, D.M., Slingo, J.M., Brown, S. and Belcher, S.E. 2017. High risk of unprecedented UK rainfall in the current climate. Nature Communications, 8, 1-6.
Uday, P. and Marais, K. 2015. Designing resilient systems-of-systems: A survey of metrics, methods, and challenges. *Systems Engineering*, **18**, 491-510.
Wade, S., Sanderson, M., Golding, N., Lowe, J., Betts, R., Reynard, N., Kay, A., Stewart, L., Prudhomme, C., Shaffrey, L. and Lloyd-Hughes, B. 2015. *Developing H++ climate change scenarios for heat waves, droughts, floods, windstorms and cold snaps*. Committee on Climate Change, London, 145pp.
Warren, R.F., Wilby, R.L., Brown, K., Watkiss, P., Betts, R.A., Murphy, J.M. and Lowe, J.A. 2018. Advancing national climate change risk assessment to deliver national adaptation plans. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**, p.20170295.
Watkiss, P. and Betts, R.A. 2021. *Chapter 2: Method*. In: The Third UK Climate Change Risk Assessment Technical Report [Betts, R.A., Haward, A.B. and Pearson, K.V. (eds.)]. Prepared for the Climate Change Committee, London.
Watkiss, P., Wilby, R.L. and Rodgers, C.A. 2020. *Principles of climate risk management for climate proofing projects*. Working Paper No. 69. Asian Development Bank, Manila, Philippines. http://dx.doi.org/10.22617/WPS200203-2
Werners, S.E., Wise, R.M., Butler, J.R., Totin, E. and Vincent, K. 2021. Adaptation pathways: a review of approaches and a learning framework. *Environmental Science and Policy*, **116**, 266-275.
Wilby, R. L. 2017. How connected is climate change to other global challenges? *Climate Change in Practice*, Chapter 18. Cambridge University Press, Cambridge.
Wilby, R.L. 2020. Resilience viewed through the lens of climate change and water management. *Water*, **12**, 2510.
Wilby, R.L. and Darch, G. 2021. Uncertainty in hydrologic and water resources modelling. In: Mearns, L.O., Forest, C.E., Fowler, H.J. and Wilby, R.L. (Eds.) *Uncertainty in Climate Change Research: An Integrated Approach*. Springer, Switzerland.
Wilby, R.L. and Dessai, S. 2010. Robust adaptation to climate change. *Weather*, **65**, 180-185.

Wilby, R.L. and Johnson, M.F. 2020. Climate variability and implications for keeping rivers cool in England. *Climate Risk Management*, **30**, p.100259.
Wilby, R.L. and Murphy, C. 2018. Decision making by water managers despite climate uncertainty. In: Pfeffer, W.T., Smith, J.B. and Ebi, K.L. (Eds.) Oxford *Handbook of Planning for Climate Change Hazard*s. Oxford University Press, Oxford.
Wilby, R.L., Clifford, N.J., De Luca, P., Harrigan, S., Hillier, J.K., Hodgkins, R., Johnson, M.F., Matthews, T.K., Murphy, C., Noone, S.J. and Parry, S. 2017. The 'dirty dozen' of freshwater science: detecting then reconciling hydrological data biases and errors. *Wiley Interdisciplinary Reviews: Water*, **4**(3), p.e1209.
Wilby, R.L., Nicholls, R.J., Warren, R., Wheater, H.S., Clarke, D. and Dawson, R.J. 2011. Keeping nuclear and other coastal sites safe from climate change. *Proceedings of the Institution of Civil Engineers-Civil Engineering*, **164**, 129-136.
Wilby, R.L., Noone, S., Murphy, C., Matthews, T., Harrigan, S. and Broderick, C. 2016. An evaluation of persistent meteorological drought using a homogeneous Island of Ireland precipitation network. *International Journal of Climatology*, **36**, 2854-2865.
World Bank, 2012. *Adapting to Climate Change: Assessing World Bank Group Experience*. World Bank Independent Evaluation Group, Washington DC, 193pp.
Yates, D., Miller, K.A., Wilby, R.L. and Kaatz, L. 2015. Decision-centric adaptation appraisal for water management across Colorado's Continental Divide. *Climate Risk Management*, **10**, 35-50.

Annex 1 Overview of the UK CCRA3 methodology. Source: Watkiss and Betts (2021).



Annex 2 Adaptation type, timing, and economic rationale. Source: Watkiss et al. (2020)

Adaptation Type and Timing	Examples of the Adaptation Type	Economic Rationale for Choice of Adaptation
Design and engineering for decision NOW	Site or location change	Possible choice from: • **No-regret/Win-win** – economic benefits even without climate change • **Low-regret** – low-cost or cost-effective • **Shorter design lifetime** to include climate in future cycles • **Robust project** – alter now to perform well over range of future uncertainty • **Precautionary over-design** if needed (critical infrastructure)
	Design change (engineering) Includes dimensions, materials, technology, structural considerations (defenses)	
Design and engineering for climate change LATER	Flexibility built into the design	**Flexible** design to allow easier upgrade later
	Modular or iterative design to enable later change	**Iterative** design to monitor and learn – upgrade later if needed
Maintenance and operations	Change in maintenance regime or infrastructure operations (on-site, system)	Focus on: • No-regret or win-win • Low-regret
Nontechnical and nonengineering options (alternatives to design changes) Can include accessing new opportunities as well as addressing risks	Institutional and capacity-building measures	Focus on: • No-regret or win-win • Low-regret
	Includes information, research, and behavioral change Nontechnical options or measures	
	Financial- and market-based measures (including insurance)	
	Policy and legislative measures	
Option to do nothing	No adaptation (live with the risks)	If risks and benefits are low, or costs of adaptation very high
Option to reconsider the project		If risks are unacceptable and no suitable adaptation is achievable/justifiable