Report No. **140**

epa Research

Climate - Water - Sustainability

Identifying pressures • Informing policy • Developing solutions

ADAPT: Quantifying the Costs and Benefits Associated with Climate Change Risks and Adaptation

Authors: Craig Bullock, Rowan Fealy, J. Peter Clinch and Robert O'Shea

Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

www.epa.ie

ENVIRONMENTAL PROTECTION AGENCY

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

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

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

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

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

Our Responsibilities

Licensing

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

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

National Environmental Enforcement

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

Water Management

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

Monitoring, Analysing and Reporting on the Environment

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

Regulating Ireland's Greenhouse Gas Emissions

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

Environmental Research and Development

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

Strategic Environmental Assessment

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

Radiological Protection

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

Guidance, Accessible Information and Education

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

Awareness Raising and Behavioural Change

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

Management and structure of the EPA

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

- Office of Climate, Licensing and Resource Use
- Office of Environmental Enforcement
- Office of Environmental Assessment
- Office of Radiological Protection
- Office of Communications and Corporate Services

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

EPA Research Programme 2014–2020

ADAPT: Quantifying the Costs and Benefits Associated with Climate Change Risks and Adaptation

EPA Research Report 140

Prepared for the Environmental Protection Agency

by

School of Geography, Planning and Environmental Policy, University College Dublin

Authors:

Craig Bullock, Rowan Fealy, J. Peter Clinch and Robert O'Shea

ENVIRONMENTAL PROTECTION AGENCY

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

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

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme. The Research Programme is administered on behalf of the Department of the Environment, Community and Local Government by the Environmental Protection Agency which has the statutory function of co-ordinating and promoting Irish environmental research.

The authors would like to thank Dr Paul Watkiss as external advisor to the project and Dr Nicola Ranger, who provided external advice, and Margaret Desmond of the EPA for her supervision of the project. They would also like to thank the following individuals for their contribution to the project: Mark Adamson and Jim Casey (Office of Public Works), Noel Casserly, Steven Fadian and George Hussey (Department of the Environment, Community and Local Government) and Conor Murphy (National University of Ireland Maynooth).

DISCLAIMER

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

EPA Research Programme 2014–2020

Published by the Environmental Protection Agency, Ireland

PRINTED ON RECYCLED PAPER

ISBN: 978-1-84095-572-9

Price: Free

01/15/50

Details of Project Partners

Dr Craig Bullock
School of Geography, Planning and
Environmental Policy
University College Dublin
Belfield
Dublin 4
Ireland
Tel: +353 1 7162677
Email: craig.bullock@ucd.ie

Dr Rowan Fealy
Irish Climate Analysis and Research Units
Department of Geography
National University of Ireland Maynooth
Maynooth
Co. Kildare
Ireland
Tel +353 1 7084862
Email: rowan.fealy@nuim.ie

Prof. J. Peter Clinch
School of Geography, Planning and
Environmental Policy
University College Dublin
Belfield
Dublin 4
Ireland
Tel +353 1 7162771
Email: peter.clinch@ucd.ie

Mr Robert O'Shea
School of Geography, Planning and
Environmental Policy
University College Dublin
Belfield
Dublin 4
Ireland
Tel: +353 1 7162677
Email: robert.oshea@ucd.ie

Table of Contents

Executive Summary

Given the inevitability of some degree of climate change and the slow progress that is being made in reducing emissions of greenhouse gasses, the case for adaptation strategies is receiving more attention at international level and in policy and guidance documents produced by the likes of the Intergovernmental Panel on Climate Change (IPCC), the European Environment Agency and the European Commission.

This report sets out the findings of the ADAPT Project. The objectives of the project were to examine the role that economic appraisal methods, including cost–benefit analysis (CBA), can play in the choice of adaptation options, and to make recommendations on possible approaches. The specific aims of the project were to:

- Formulate methods to allow decision makers to choose between adaptation options in the face of climate and socio-economic uncertainty;
- Develop guidelines for the application of economic appraisal methods to adaptation choices;
- Test a decision support tool with a case study; and
- Recommend how economic appraisal methods can be incorporated into adaptation frameworks.

This report describes current thinking with regard to climate projections and adaptation. It finds that climate modelling has come to acknowledge the considerable uncertainty attached to future projections. In this context, conventional methods of policy or project appraisal, including CBA, will continue to have a role, but within a wider framework of adaptive risk management.

1 CBA and Climate Change

CBA is routinely used in project appraisal and is recommended by the Department of Finance for projects in excess of €20 million. However, the application of CBA to climate change is challenging. This is mainly due to the high degree of uncertainty attached to future impacts. There is much uncertainty over the direction and rate of climate change. Uncertainty is also associated with human behavioural responses, socio-economic change, economic growth, rates of technological development and agreement on the mitigation of emissions. There are various ways in which climate modelling may choose to characterise or present this uncertainty. Much climate modelling has assumed that uncertainty can be reduced. A range of emissions ‘storylines’ may be referenced, each of which rests upon certain assumptions with regard to economic development and mitigation. To simplify the message for policy makers, scenarios have often been developed with reference to preferred or median climate projections. However, a reliance on these ‘single trajectory’ models can actually obscure much of the uncertainty. Recent extreme weather events have indicated that low probability/high impact events could be an inherent feature of climate change in both the short and long terms.

The most recent IPCC Working Group 1 report[1] has attached qualitative statements of likelihood and expert confidence to climate projections. In independent models, probabilities are increasingly being allocated to impact projections. The role that both mitigation and adaptation can play in moderating climate impacts is also being acknowledged. However, significant uncertainty remains.

2 CBA and Adaptation

Adaptation was once proposed on a predict-and-provide logic in response to climate scenarios. Now a more continual process is proposed that may call upon a variety of appraisal methods at different stages. Of these, CBA has many attributes. It compares costs and

1. IPCC, 2013. *Climate Change 2013: The Physical Science Basis*. Stocker et al. (Eds) Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA.

benefits in the same units, i.e. monetary units. It examines these costs and benefits from a societal perspective to decide whether or not a project can make a positive contribution to social welfare. It allows for approaches that can convert non-market social and environmental costs and benefits into monetary units so that these are fully represented in the decision-making process. In addition, CBA can be used to examine distributional factors and take the lifespan of a project into account through the use of discounting.

The reliance on quantitative data means that values are not subjective and that the analysis can potentially be understood and replicated by others. Alternative methods, such as multi-criteria analysis, may seem more straightforward or transparent than CBA, but require clear definitions of the rationale used to apply particular weights or scores.

However, the quantitative data needed for CBA are not always available early in a process unless sufficient resources are made available for their collection as well as their proper interpretation and analysis. Furthermore, CBA can be applied where there are estimates of risk, but it is poorly equipped to account for uncertainty. Indeed, there is no single method available that excels in this area, although sensitivity analysis and computer-based simulation can be applied to particular variables.

3 Appraisal of Adaptation Options

This report describes how economic appraisal can be part of a wider framework of *adaptive risk management*. This provides a strategy whereby iterative steps allow for an understanding and interpretation of risk through learning and feedback. The report also describes the various methods that are available to appraise adaptation options in this context at successive stages as information becomes available.

There is a role for *robust adaptation* methods in this framework to identify why or where receptors are or infrastructure is most vulnerable to climate change risk. Measures are sought which strengthen resilience and adaptive capacity. Where possible, initial measures should be no regret, low cost or win–win and provide benefits even in the context of familiar adverse weather events. These could include measures such as information exchange, early warning systems and incentives to householders and the private sector to take autonomous measures to increase their own resilience.

If projections of continued climate change persist, and it there is a risk of extreme events with significant consequences, then more fundamental measures will become necessary. The framework of adaptive risk management allows the adapting organisation to continually reassess risk through stakeholder engagement, feedback loops and the collection of new information. In the initial phases, much of this information is likely to be qualitative. Methods such as cost-effectiveness analysis or multi-criteria analysis can be used to appraise adaptation options. However, as data are collected over time from the implementation of initial measures or commissioned studies, these methods can be complemented or succeeded by more quantitative approaches. Once evidence is forthcoming on the probability of climate impacts, on autonomous adaptation, distributional consequences and the value of impacts in non-market sectors, then economic appraisal becomes feasible. CBA is especially relevant where a project has social or environmental implications once the range of adaptation options has been narrowed down or if it is decided that a large project is needed.

Decision pathways are an extension to this process that proactively manage the impact of uncertainty. A distinction from the adaptive risk management framework is that a set of objectives for adaptation is identified from an early stage, along with a range of possible adaptation options. The need to implement a particular option is triggered by the realisation of predetermined climate indices. A pathways approach presumes more pre-planning than adaptive risk management, but the appraisal of options proceeds in a similar manner. The selection of some adaptation options may remove the prospect for other later options, but as far as possible the route to adaptation remains flexible and responsive to new information on risks and impacts.

4 Recommendations

This report recommends that the appraisal of adaptation options should fall within a framework of continual adaptive risk management. Adaptation options should be selected according to principles of sustainability and aim to be robust in varying circumstances. This requires that decision makers begin by assessing their receptors' levels of vulnerability and resilience and then strengthen adaptive capacity by implementing low cost, no regret or win–win measures in the first instance where possible.

A proactive approach is proposed in which adaptation objectives and climate thresholds are broadly agreed at the outset. Thereafter, adaptation proceeds using iterative steps, monitoring progress, collecting new information and reassessing strategy using progressively more quantitative methods as experience grows and data are collected. Although most adaptation options will have been identified, the actual route to adaptation is subject to specific climatic triggers being realised. There is a clear role for economic appraisal, including CBA, to determine the viability of adaptation options and to address impacts of social and economic significance once this can be supported by sufficient information. Further research will be needed to provide guidance on impact types and adaptation responses based on applications to particular sectors in the public and private domains or at national or local level.

The key recommendations are to:

- Implement an adaptive risk management framework for the progressive appraisal of adaptation options;
- Assess the vulnerability of receptors and implement robust adaptation measures to reduce this vulnerability and increase resilience;
- Select further robust adaptation measures that are resilient to changing circumstances, that begin with low cost measures that deliver win–win outputs where possible, including resilience to more familiar climate events;
- Once the essential climate risks are understood, manage uncertainty through the adoption of decision pathways in which adaptation measures and options are identified at an early stage along with the climatic indices that would trigger their implementation;
- Use progressively more sophisticated appraisal methods to determine the viability and effectiveness of these adaptation options, beginning with more qualitative or score-based approaches and culminating in more quantitative methods, such as CBA, where there are implications for social well-being; and
- Undertake involved studies within government departments or agencies to quantify impacts and to appraise adaptation options using the framework proposed.

1 Climate Change Observations and Projections

1.1 The Evidence for Climate Change

The link between human activity and climate change is now accepted as ‘extremely likely’ by the most recent Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) released on 27 September 2013 (IPCC, 2013a). A recent report by the European Environment Agency (EEA) (2012) confirms that the decade 2002–2011 was the warmest on record. Trends in precipitation have been more variable, although the IPCC (2013a) finds it ‘likely’ that the frequency and intensity of precipitation will increase as temperatures rise. Increased storms and flooding are anticipated.

Over the period 1900–2012 there has been an increase in mean annual temperatures in Ireland of approximately 0.8°C, consistent with mean global temperature increases over this period. Six of the 10 warmest years on record have occurred since 1990. More recently, for the period 1961–2010, the number of ‘warm’ days (>20°C) increased, while the number of frost days (<0°C) decreased (Dwyer, 2012). Changes in rainfall are also evident, though more difficult to detect as analysis is hampered by the significant variation that can occur in rainfall over both time and space. Annual average rainfall increased by 5% (60 mm) in the 30-year periods from 1961 to 1990 and from 1981 to 2010, with the greater increases evident in the western half of the country (Dwyer, 2012).

Sea levels are expected to rise due to a combination of ice cap melt and thermal expansion. On the basis of international projections of warming, sea levels will rise by between 0.26 m and 0.82 m for 2081–2100 relative to 1986–2005 (IPCC, 2013a). However, the rates of increase are very dependent on ice melt in polar regions and some observers predict far more substantial increases. In addition, the effect of sea level rise will be multiplied by surge events where the effect is combined with high tides, storms and fluvial flooding.

These climate trends, should they continue, will have significant impacts on both human and natural systems, especially if the rate of change exceeds the ability to adapt. To prevent dangerous anthropogenic interference with the climate system, the European Union has adopted a target to limit the rise in global mean surface temperatures to not more than 2°C above pre-industrial levels. Internationally too, policy makers have begun to accept the need to keep temperature below this threshold beyond which impacts could become cumulative. This consensus was reflected at the United Nations Framework Convention on Climate Change (UNFCCC) meeting in Cancun in 2010, where the 2°C target was endorsed.

Climate change above a 2°C increase will have a considerable impact on the world economy. The Stern Report (Stern, 2007), commissioned by the UK Government, revealed the very significant economic costs that could result and discussed the merits of a cost–benefit approach for deciding on mitigation and adaptation policy. The report clearly demonstrated that the cost of emissions reductions would be far less than the cost of the damage averted.

In part, because of the inevitability of at least some degree of climate change and because of the difficulty of achieving global consensus on measures to mitigate climate change through the control of greenhouse gases (GHGs), attention is turning to the need for adaptation. De Bruin et al. (2009) argue that optimal adaptation should commence immediately whereas mitigation can be permitted to increase over time. The IPCC Fourth Assessment Working Group II report (IPCC, 2007) discussed the potential adaptation challenges presented to ecosystems, water resources, agriculture, human health, coastal regions, industry and settlement. These issues are also examined in the European Commission (EC) White Paper *Adaptation to Climate Change*[1] *– Towards a European Framework for Action* (CEC, 2009).

1. http://europa.eu/legislation_summaries/environment/tackling_climate_change/28193_en.htm

1.2 Climate Change Impact Assessments

The theme of this report is the potential for the economic appraisal of adaptation options in the context of the significant uncertainties associated with climate change. Global climate models (GCMs) are the preferred tools to predict climate change, but ultimately represent a simplification of reality. Work to develop climate scenarios of practical value at sectoral and local levels crosses territories occupied by very different disciplines. Climate is itself a non-linear dynamic system and models based on future projections can result in a range of outcomes. Rather than being reducible through science in line with many conventional problems (Walker et al., 2013), climate uncertainties arise at each stage and have the effect of cascading through subsequent models. Even then, there remains the potential for surprises due to unanticipated factors or feedback mechanisms.

Much uncertainty arises from the effects of future human actions and technological change. As these are inherently unpredictable, individual climate models have, to date, employed various 'storylines' of future emissions based on scenarios of future economic development and mitigation policy (Hulme and Carter, 1999). National baselines have, to date, drawn on the various emissions scenarios first provided by the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart, 2000).[2] This process has resulted in a suite of climate projections, each of which is subject to considerable uncertainty, and any one of which may be selected based on whether the user opts for optimistic or pessimistic assumptions of future net emissions.

In a significant recent development reflected in the AR5 (IPCC, 2013a), the climate modelling community has moved away from 'storylines' based on assumptions about future GHG emissions. These have been replaced by Representative Concentration Pathways (RCPs), which define a specific emissions trajectory and its radiative forcing. The IPCC (2013a) takes the view that any particular RCP may never be realised and so assigns no probability to any one scenario.

The RCPs are not dependent on any particular set of socio-economic or technological developments, but will be accompanied by a new set of socio-economic projections or 'shared socio-economic pathways' (SSPs). These projections allow for a more regional exploration of climate and socio-economic uncertainties, including the role of policies for mitigation and adaptation (O'Neill et al., 2013; van Vuuren et al., 2013). An integration of RCPs and SSPs will be made in the final IPCC reporting stages to provide insight into the costs, benefits and risks of different climate futures, policies and development pathways.

Four RCPs (Box 1.1) have been independently developed by different research institutes using rather different criteria. They do not reflect the full range of potential scenarios.

Policy to date has tended to be based on single trajectory climate scenarios. These have often been selected from a range of scenarios based on a preferred GCM using best-guess, median values or ensemble means. The IPCC AR5 provides the most recent systematic analysis of the outputs from a range of GCMs. The convenience of the single trajectory model is that it does not explicitly consider uncertainty. Nevertheless, uncertainty is present. Over-reliance on a single emissions trajectory approach significantly increases the potential to over- or underestimate risk by failing to take into account the probabilities associated with various outcomes (Hulme and Carter, 1999). It also conceals the genuine uncertainties from decision makers.

At a global level, there is general agreement on GCM mean temperature projections, especially in the short to medium term, given that warming in this time frame represents a response to emissions to date (Wilby et al., 2009). However, while most models indicate that global surface temperatures will increase, they differ in the amounts. Indeed, for precipitation, models disagree on both the magnitude and direction of

2. While over 40 emissions scenarios had been developed by the IPCC SRES, there are four central 'families' (or sets) of equally probable scenarios, which span approximately 80% of the projections. The four principal emissions scenarios are A1 (rapid economic growth), A2 (more heterogeneous economic growth, human fertility patterns converging only slowly), B1 (more convergent economic growth with world population peaking mid-century) and B2 (intermediate economic growth, slowing increase in population).

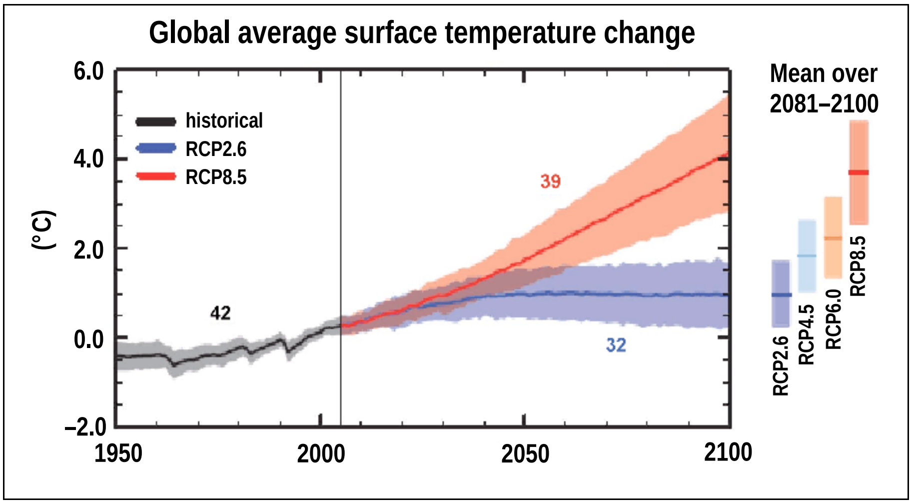


Figure 1.1. Global average surface temperature change for the Representative Concentration Pathways (RCPs) (IPCC, 2013a).

Box 1.1: Description of the Representative Concentration Pathways (RCPs) (source: van Vuuren et al., 2011)

RCP 2.6 assumes that radiative forcing will peak (3 W/m^2) mid-century and reduce to 2.6 W/m^2 by 2100. GHG emissions are reduced substantially over time. The radiative forcing is equivalent to 490 ppmv CO_2 equivalent.

RCP 4.5 assumes that radiative forcing stabilises at 4.5 W/m^2 before 2100 due to technological solutions and reduced GHG emissions. The radiative forcing is equivalent to 650 ppmv CO_2 equivalent.

RCP 6.0 assumes that radiative forcing stabilises at 6 W/m^2 after 2100 without overshoot due to technological solutions and reduced GHG emissions. The radiative forcing is equivalent to 850 ppmv CO_2 equivalent.

RCP 8.5 is characterised by increasing GHG emissions over time leading to high GHG concentration levels. The radiative forcing is equivalent to 1,370 ppmv CO_2 equivalent.

change. In spite of these limitations, there have been calls for higher resolution models that satisfy the need for practical adaptation decisions at local level. Although, at approximately 10–40 km, the resolutions of Regional Climate Models (RCMs) are considered too coarse to meet the needs of local adaptation (Sweeney et al., 2009).

An alternative route is to incorporate probability estimates and distributions (Fealy, 2010). Such estimates, which in climatology are typically based on subjective or Bayesian approaches, are beginning to be used to formulate regional scenarios. At one level, probability-based approaches provide policy makers with more realistic information, including the range within which future climate could vary. However, these approaches require that policy makers are conversant with the notion of uncertainty. Models can be falsely interpreted as presenting a preferred outcome between confidence levels when, in fact, actual climate trends could veer off in any number of directions.

1.3 Impact Assessments in Ireland

Data from GCMs have been used to project the likely nature of climate change in Ireland. Scenarios have been developed by Met Éireann (Dunne et al., 2008; Gleeson et al., 2013) and the National University of Ireland Maynooth (NUIM) (e.g. Fealy and Sweeney, 2007, 2008). Table 1.1 illustrates the seasonal and annual temperature (ΔT) and precipitation (ΔP) response for four respective GCMs for the 2080s

Table 1.1. Global (ΔTglobal) and regional (Irish grid box(es)) for summer (ΔT_{JJA}), winter (ΔT_{DJF}) and annual (ΔT_{AN}) temperature change (°C) and precipitation (ΔP) change (%) for four GCMs and respective marker emissions scenarios (data from Mitchell et al. (2002); http://www.cru.uea.ac.uk/~timm/data/index-table.html).

Model	Scenario	ΔT_{JJA}	ΔT_{DJF}	ΔT_{AN}	ΔP_{JJA}	ΔP_{DJF}	ΔP_{AN}
CGCM2	A1FI	3.3	2.7	2.8	0	18.2	7.0
CGCM2	A2	2.7	2.1	2.2	0	14.7	5.6
CGCM2	B2	2.0	1.6	1.7	0.4	7.3	6.2
CGCM2	B1	1.6	1.3	1.4	0.3	6.0	5.1
CSIRO Mk2	A1FI	2.8	2.9	2.7	–9.0	18.3	7.3
CSIRO Mk2	A2	2.7	3.1	2.7	–0.9	21.1	10.4
CSIRO Mk2	B2	2.2	2.6	2.2	–2.1	21.9	10.2
CSIRO Mk2	B1	2.1	2.2	2.0	5.3	6.1	7.8
HadCM3	A1FI	3.1	2.7	3.0	–35.2	25.0	4.2
HadCM3	A2	2.3	2.3	2.4	–27.0	20.8	3.9
HadCM3	B2	1.5	1.4	1.5	–17.4	7.3	1.1
HadCM3	B1	1.5	1.6	1.5	–21.9	14.4	2.7
PCM	A1FI	1.7	2.3	2.3	3.3	8.4	9.2
PCM	A2	1.4	1.9	1.9	2.6	6.8	7.5
PCM	B2	0.9	1.5	1.5	7.3	7.1	7.0
PCM	B1	0.7	1.2	1.2	5.9	5.7	5.7

based on the former SRES (note the significant variation in rainfall projections).

Downscaled scenarios have been developed for Ireland by Fealy and Sweeney (2007, 2008) and have recently been used as a basis for probabilistic projections by Fealy (2010, 2013). For the 2020s, these regional projections suggest that seasonal average temperatures are likely to increase by between 0.7 and 1.0°C relative to the 1961–1990 period (Fealy and Sweeney, 2008). By the 2050s, the continental effect becomes more established, with mean temperatures projected to increase by 1.4–1.8°C. This effect becomes apparent for all seasons by the 2080s, when mean temperature is projected to increase by between 2.1 and 2.7°C.

Projected changes in precipitation reveal both increased seasonality and a change in the spatial distribution for all future time periods. By the 2020s, mean ensemble changes suggest that summer precipitation is likely to decrease by approximately 3%, although a larger regional decrease of the order of 10–16% is projected to occur along the south and east coasts. Conversely, in the winter, a 3% increase in precipitation is anticipated, although this again conceals regional differences in direction from higher precipitation in the West and Midlands to lower precipitation in the South and East (Fealy and Sweeney, 2008).

Further seasonality of precipitation becomes evident during the 2050s, with an increase in the order of 12% projected to occur during the winter months and a reduction of a similar scale projected for the summer months. These seasonal and spatial changes are further extended in the 2080s by which time winter precipitation is expected to have increased by 15% nationally, with above-average increases projected for the Midlands. Nationally, summer reductions of 19%

are likely, with sizeable decreases of between 30 and 40% along the east and south coasts (Fealy, 2008). However, recent probability-based projections by Fealy (2010, 2013) report an equal likelihood of increased or decreased spring rainfall, which complicates the policy response. These seasonal and regional variations are broadly consistent with those described above by Met Éireann (Gleeson et al., 2013), with variations subject to the choice of a medium-low or a high emissions scenario.

Overall, the general presumption based on the lagged response to past emissions has been that climate change will follow a general course towards warmer, drier summers and wetter winters in north-west Europe. A divergence of scenarios post-2050 emerges, depending on the choice of emissions scenario (Hall et al., 2012). However, this confidence could be misplaced as, in addition to the general trends, extreme weather such as heavy rainfall events, storms and droughts are also expected. For example, data collected by Met Éireann indicate that the number of days of intense rainfall (>10 mm) has already increased by 7% since 1990 and by up to 20% in some areas. Although extreme events are by their nature difficult to predict, an increase in severity and shorter return periods are expected (Sweeney et al., 2009). In the short term, it is increasingly looking possible that climate change could be characterised by disturbances that vary wildly from long-term projections, noting recent alternating sequences of wet summers or harsh and mild winters. In fact, some of these disturbances appear to be related to long-term trends, such as the effect of higher polar temperatures on the Atlantic jet stream.

2 Adaptation to Climate Change

2.1 Climate Change Adaptation Policy

2.1.1 Adaptation in Europe

Adaptation acknowledges the inevitability of some degree of climate change. However, while momentum is gathering internationally on the need for mitigation, strategies that would allow society to adapt to climate change are much less well developed. To stimulate action, the EEA published the report *Vulnerability and Adaptation to Climate Change in Europe* (EEA, 2005). The report argued that there was significant scope for adaptation, but found that few European states had embarked on practical steps as of 2006. At a sectoral level, the report found that adaptation was most advanced in the area of flood management, largely because of the relevant agencies' historical experience in responding to weather events. The report identified a need for more RCMs, further research on extreme events, vulnerability indices and integrated sectoral strategies.

The EC followed up the EEA initiative in 2007 with the launch of a Green Paper *Adapting to Climate Change – Options for European Union Action* (CEC, 2007), which was followed by the White Paper 2 years later (CEC, 2009). The policy documents were the first step towards identifying the structures that will be necessary for adaptation and the priorities and balance of measures that are needed. The CEC argued that adaptation strategies, if adopted quickly enough, could be largely represented by 'soft' measures, i.e. relatively painless measures such as planning and climate proofing. By contrast, delay would inevitably require "*costly, defence and relocation measures*". The policy documents called for the development of adaptation strategies at regional and local levels, including information sharing, spatial planning, social impact assessment, risk management and sensitivity mapping.

The *EU Strategy on Adaptation to Climate Change* (CEC, 2013) was launched in 2013. It identified three key objectives, namely:

1. The promotion of adaptation by Member States;
2. The need to provide for more informed decision making; and
3. Climate proofing to ensure that essential infrastructure is not at elevated risk from storms and sea level rise.

The Strategy consists of general guidance to integrate adaptation into policy for sectors such as infrastructure, human and animal health and the coastal/marine sector.[3] Advice and information is provided on the European climate adaptation platform Climate-ADAPT (http://climate-adapt.eea.europa.eu).

3. http://ec.europa.eu/clima/policies/adaptation/what/documentation_en.htm

Box 2.1: Key adaptation terms

Vulnerability: The degree to which an individual, group or system is susceptible to, or unable to cope, with the adverse effects of climate change (Kasperson and Kasperson, 2001; IPCC, 2007). Vulnerability depends not only on a system's sensitivity, but also on its exposure and adaptive capacity (Willows and Connell, 2003).

Resilience: The amount of change a system can undergo without changing state (IPCC, 2007). The tendency to maintain integrity when subject to a disturbance (UNDP, 2005). The ability to self-organise, to buffer disturbance and the capacity for learning and adaptation.

Adaptive capacity: The set of resources available for adaptation that will enhance a system's coping capacity thereby reducing vulnerability (UNDP, 2005). Adaptation can be spontaneous or planned and can be carried out in response to, or in anticipation of, change (Willows and Connell, 2003).

2.1.2 Adaptation policy in Ireland

The National Climate Change Strategy (DEHLG, 2007) is the overarching climate policy document for Ireland. The strategy commits the Irish Government to develop a strategy on adaptation. In 2007, the Climate Change Unit within the Department of the Environment, Community and Local Government (DECLG) wrote to all government departments requesting a response to the European Union Green Paper on adaptation. Relevant steps had already been undertaken by some sectors. For example, consideration of climate change is advanced in relation to inland and coastal flooding following the 2003/2004 Flood Policy Review Group's recommendation that flood management be based on a strategic and proactive approach.

A summary of potential climate impacts has been provided by Desmond et al. (2009). This report identifies cross-cutting themes related to specific impacts and the sectoral implications for:

- Agriculture, biodiversity, forests and peatlands;
- Surface water, coastal and marine resources;
- Settlement and society, health and tourism; and
- Transport and communications, energy, industry and insurance.

A subsequent Environmental Protection Agency (EPA) report *Integrating Climate Change Adaptation into Sectoral Policies in Ireland* (Desmond and Shine, 2012) discussed the opportunities for integrating adaptation into key economic sectors and infrastructure, but acknowledged that some sectors had yet to engage with the issue. For local decision making, it recommended information management, increased awareness, co-ordination, policy integration and relevant planning instruments. McGloughlin and Sweeney (2012) highlight the benefits of information sharing between local authorities, dedicated climate change teams, the monitoring of progress with measurable targets, and reviews of adaptation initiatives in council publications and budgets.

The National Economic and Social Council (NESC, 2012) has recommended greater momentum too, calling for a move from predictive to adaptive policy analysis, including an assessment of the strengths and weaknesses of economic analysis, richer information on behavioural responses and a realistic view of targets and timetables. More recently, a National Adaptive Capacity Assessment (Desmond and Shine, 2011) has been undertaken by the EPA based on the approach developed by the World Resources Institute (WRI). This identifies adaptation as an iterative process of improved actions and capacity building that can monitor and respond to system changes. It recognised that many adaptation initiatives will need to be undertaken by local government.

The National Adaptive Capacity Assessment also recommends a vulnerability assessment, a national approach to risk assessment, a cost prioritisation of options, an inventory of adaptation actions and case studies. It proposes steps to allow for more thorough assessment, prioritisation, a sustained programme of information provision (rather than individual projects) and the integration of climate risk reduction into plans, policies and programmes.

In December 2012, the Government launched its National Climate Change Adaptation Framework (NCCAF) (DECLG, 2012). The DECLG set itself the objective of leading and co-ordinating adaptation policy and of supporting strategic decision making in line with European Union and international initiatives. The NCCAF conforms to the two-phased approach expressed in the EC White Paper of identifying vulnerability and of then developing local and sectoral adaptation plans. It provided a mandate for local authorities, state agencies and government departments to commence stakeholder consultation, with a view to publishing draft adaptation plans by mid-2014. Reference was made to ongoing research by the EPA Climate Change Research Programme (CCRP) and the Irish Climate Information Platform (ICIP) which will provide a national web portal for up-to-date information and advice similar to Climate-ADAPT.

2.2 Adaptation and the Role of Government

Government-led approaches are necessary because of the public-good nature of adaptation to climate change. Government has a vital role in promoting adaptation due to the presence of market failures that prevent adaptation occurring spontaneously. Cimato and Mullan (2010) emphasise the importance of government intervention in a variety of circumstances, including infrastructure planning, instances where adaptation is costly, where state leverage would be useful, where information and early warnings are needed, in non-market sectors such as biodiversity, and in developing cross-sectoral linkages. Government intervention can be used to counter under-adaptation where agents misunderstand the benefits. Similarly, it can counter maladaptation where agents adopt inappropriate responses that could even aggravate the challenges ahead. Fundamentally, intervention also provides a social good, given that individuals and the private sector are prone to discount investments with distant pay-offs. However, central government intervention can only extend so far. Mitigation and adaptation must be decided on by different people at different spatial levels and at different times and many decisions will need to be taken at local level with local benefits in mind (Tol, 2005; Osberghaus et al., 2010).

In practice, implementing adaptation can be difficult even for governments. Adaptation is needed over a longer time period than most government policies and, indeed, most governments. A variety of climate risks may be relevant to any one location, giving rise to a range of impacts from drought to flooding. Such impacts can be experienced in the short, medium or long term and will range across a number of different sectors. While top–down national initiatives and guidance are valuable, bottom–up disaggregated and cross-sectoral approaches are often needed on the ground. These can be difficult to co-ordinate.

Faced with these challenges, Wilby et al. (2009) describe adaptation policy as lagging 10 years behind impact assessment. Many national impact assessments have listed potential adaptation options, but few have examined how adaptation will occur in practice, particularly in the short term or at local level. As of September 2013, 16 Member States had prepared their own National Adaptation Strategies (NASs). However, the EEA (EEA, 2013) notes that rather few of these have provided active policy support for either the public or private sector.

2.2.1 Top–down approaches

The standard top–down approach begins with preferred climate choice scenarios prior to assessing impacts. This approach uses GCMs as the point of departure, often with some form of downsizing to provide local scenarios. The approach is also referred to as ‘prediction oriented’ (Dessai and van der Sluijs, 2007), ‘scenario-led’ (Wilby and Dessai, 2010), ‘science first’ or ‘predict-then-act’ (Ranger et al., 2010). These models concentrate on quantifiable effects.

At international levels, general equilibrium or Integrated Assessment Models (IAMs) have been used to indicate to government how resources should be allocated to mitigation and adaptation. These models assume that adaptation is decided by government and not undertaken spontaneously at local level. Their purpose is to present policy makers with an opportunity to see how the future could look based on a continuation of the status quo or alternative storylines of development (Parson et al., 2007).

Increasingly IAMs are being asked to address questions of uncertainty, learning and irreversibility. Uncertainty in these models takes two forms, parametric and stochastic.[4] The former refers to climate parameters such as the nature of the damage function. Stochastic uncertainty relates to processes that are unlikely to be fully resolved, including random elements of climate, but also the economic situation or social aspects. The more sophisticated models assume that new information on climate parameters will be received periodically (Ha-Duong, 1998). However, even these models become unwieldy if there are more than a few decision points, particularly where stochastic uncertainty is present.

In principle, stochasticity can be accommodated through the use of simulation, such as a Monte Carlo analysis. The disadvantage is that while this can be used to predict a range of outcomes, it does not remove the ambiguity over the most advantageous paths to mitigation or adaptation. Neither do the models allow for active, rather than passive, learning

4. Sometimes reference is made to aleatory uncertainty, i.e. inherent indeterminacy, e.g. of aspects of human behaviour, and to epistemic or systematic uncertainty that is reducible with greater knowledge.

or that there exist uncertainties other than just climate (Ingham et al., 2006). As a consequence, simulation is unrealistic when used alone.

The general expectation has been that parametric uncertainty will decline over time as models become more sophisticated. However, this does not seem to be happening. The more we learn more about the complexity of climate systems, the more possible it seems that this optimism may be misplaced. Dessai et al. (2009) point out that 20 years of climate science has not reduced the uncertainty range. Hall et al. (2012) add that greater knowledge of climate processes and feedbacks could reveal further unknown processes, with the effect that uncertainty is actually increased. In particular, there could be a distinct difference between climate change in the long term and climate change in the short term when key decisions need to be made. Recent events indicate that the short term could be characterised by variable climate, e.g. alternations between mild and cold winters, warm but wet summers, etc. In addition, a growing acceptance of the likelihood of more extreme events cautions against the use of a limited set of scenarios. The outcome in the long term may indeed fit the best existing models, but these trends could be obscured in the short term by other climate disturbances.

2.2.1.1 The inclusion of socio-economics in scenarios

The alternative approach recognises the capacity of adaptation to *influence* socio-economic storylines and emissions policy. Carter (2012) describes how climate scenarios are being developed by 23 scientific institutions to place socio-economic storylines in parallel with the climate models (see Fig. 2.1). The approach begins with the RCPs described earlier to distinguish changes in atmospheric composition from emissions scenarios and is distinct from the Impacts, Adaptation and Vulnerability (IAV) assessment introduced by the IPCC Fourth Assessment Report in that adaptation is allowed the capacity to influence the various emission storylines via the SSPs.

At heart, scenarios remain in this revised approach. They have been defined as "*descriptions of potential future conditions developed to inform decision making under uncertainty*" (Parson et al., 2007; Parson, 2008). Scenarios can be used to:

- Define a problem;
- Define objectives;
- Set out the alternatives;
- Estimate consequences; and
- Evaluate trade-offs.

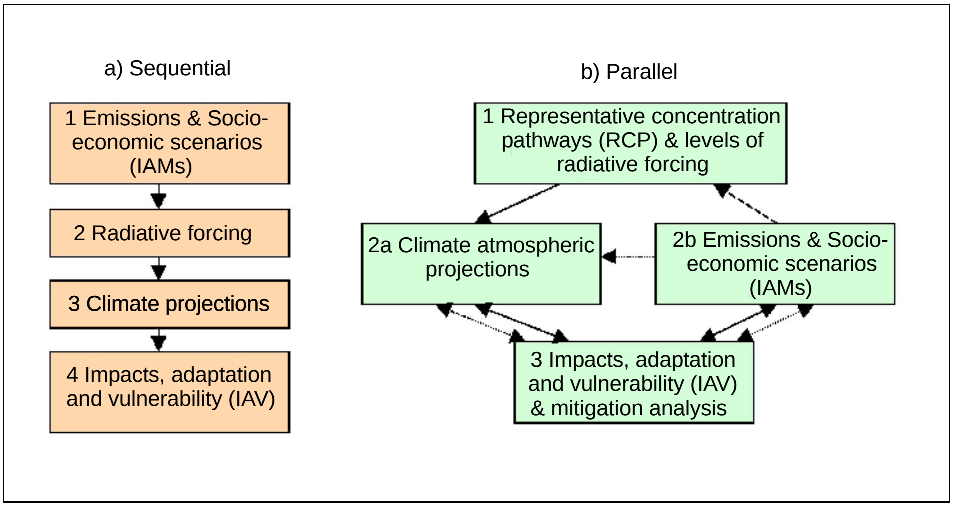


Figure 2.1. Sequential and parallel modelling approaches (after Moss et al., 2008). Boxes indicate analytical steps. Arrows indicate transfers of information (solid), selection of RCPs (dashed) and integration of information and feedbacks (dotted).

For the policy community, scenarios can also be used to identify driving forces as well as consequences. As noted earlier, the IPCC has now labelled all scenarios as 'equally sound' and has chosen not to apply probabilities to any outcome. It can be argued that the absence of probabilities dissuades decision makers from neglecting particular scenarios and allows them to confront the consequences of all possible alternative futures. On the other hand, having no probabilities means that decision makers may be tempted to apply their own (Parson et al., 2007). A scenario-based assessment must therefore find a balance between giving direction at the expense of concealing uncertainty while, at the same time, not confusing decision makers with a "*plethora of scenarios, models and techniques*" (Bradfield et al., 2006). Providing no information on risk and uncertainty can conceal the caveats and leave policy makers vulnerable to surprises.

In Britain, the 2008 Climate Change Act established a Committee on Climate Change, including an Adaptation Sub-Committee (ASC), to provide advice on a National Adaptation Programme (NAP). A Climate Change Risk Assessment (CCRA) is being undertaken to assess the risks associated with climate scenarios for the 2020s, 2050s and 2080s. Using a scoring system, it has assessed the magnitude, likelihood and urgency of 100 climate risks and has estimated a response function of the economic, environmental and social consequences. Although scenario based, the CCRA has recently adopted probabilistic projections (Murphy et al., 2009). Watkiss and Hunt (2012) regard the increasing inclusion of probabilistic methods as a positive move in that the projections are more representative of the state of knowledge as regards future impacts. They identify several key risks that adaptation must address, including factors that are dynamic or changing, such as:

- Existing vulnerability;
- Impacts due to 'slow onset' climate change;
- Changes in the frequency or severity of climate events over time; and
- Major impacts arising, for example, from the exceedance of thresholds.

However, while decision makers want quantitative information, they do not want unmanageable uncertainty (Watkiss et al., 2009). The challenge, therefore, is to provide a decision framework that can explicitly take account of uncertainty. Such a framework may need to draw on probabilistic climate scenarios, but without allowing decision makers to become over-reliant on these such that they lose awareness of the uncertainties.

2.2.2 Policy-first composite approaches and adaptive risk management

The top–down approach is the more conventional one of *science first*, in which the climate change impacts are assessed before considering what adaptation alternatives are available. An alternative is a policy-first approach (Ranger et al., 2010), which examines the upper and lower bounds of climate projections before identifying flexible adaptation strategies (Fig. 2.2).[5] This approach makes it easier for decision makers to decide what information they need from the climate scenarios rather than being led into a decision by such scenarios.

Various studies (e.g. Smit et al., 1999; Adger et al., 2005; Möhner and Klein, 2007) have emphasised the need for adaptation to be efficient and equitable, but also frequently mention the need for feasibility, political legitimacy and flexibility. They have argued that adaptation must tie in with familiar decision-making procedures and policy, but be flexible enough to respond to new information or changed conditions. This flexibility allows *adaptive capacity*, i.e. a system's ability to adjust to climate change, to build up over time in parallel with physical investments.

The move from a top–down science-first approach to a policy-first approach has been related to a shift from a problem level to a solutions level (Bourque, 2012). However, policy-first approaches are not analogous to a bottom–up approach as climate change scenarios still inform the process. Vulnerability assessments can

5. A related scenario-neutral approach has been proposed by Prudhomme et al. (2010) and Wilby and Dessai (2010). This proposes a repositioning of climate scenarios to a point further down the assessment chain following an assessment of current vulnerability or existing climate events and non-climate pressure. Reeder and Ranger (2011) also discuss a *context-first* approach that begins by identifying problems of adaptation. Each has its virtues.

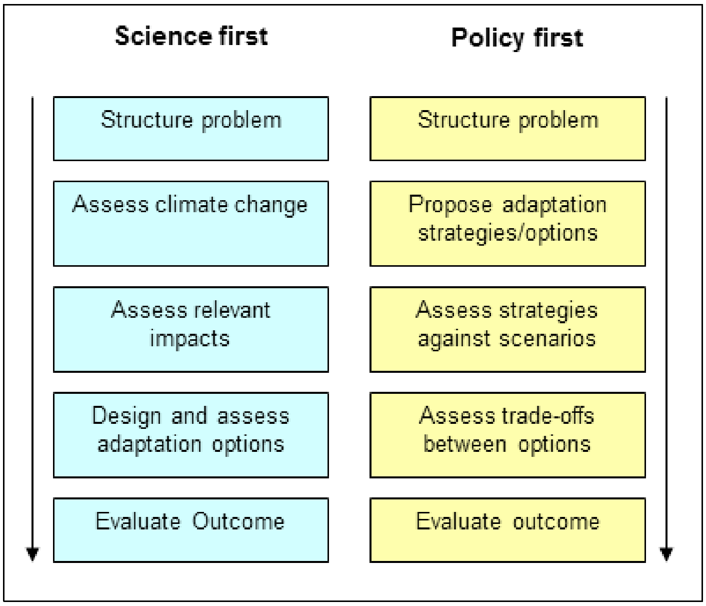


Figure 2.2. Respective stages involved in science-first and policy-first approaches to adaptation (Ranger et al. (2010) from Dessai and Hulme (2007)).

be used to identify social and economic areas that are sensitive to climate change. An assessment of the response of existing infrastructure to recent weather events can help to identify vulnerabilities (Burton et al., 2002). The process can be followed for indices of climate change based on a range of climate scenarios including extreme events (Murphy et al., 2004). Many adaptation actions can be described as being 'win-win' in this context in that they strengthen society's resilience to all types of climate and weather impacts. Efforts to reduce vulnerability in this way conform to conventional scenario planning, where a system's response to varying circumstances is examined.

Consideration of vulnerability also takes into account distributional impacts and the potential for adaptive capacity, including both *planned adaptation* taken in anticipation of change and *autonomous adaptation* by households, communities or businesses responding to change on their own initiative (Burton, 2009). These individual decision makers face varying degrees of risk, depending on their access to resources. While government must provide planned adaptation, it must also support autonomous adaptation, but do so without efficiency losses including the risk of moral hazard where agents fail to adapt in the expectation that government will provide instead.

In recent years there have been more specific adaptation assessments that have considered impact assessment within the context of decision-making processes with a view to identifying vulnerability and the potential for resilience at all levels. Examples include the Finnish adaptation strategy, FINADAPT (2005), and the Dutch Routeplanner. Increasingly, adaptation is being considered within the context of an *adaptive risk management framework*. This is a composite of impact assessment and adaptation which begins with climate change scenarios, but as part of a continuing discourse with stakeholders to prepare adaptation plans in response to incremental changes in acceptable risk (Wilby et al., 2009).

2.3 Decision-Making Strategies and Robust Adaptation

As the uncertainty associated with climate change exceeds that for many of the problems with which planners and other decision makers have habitually been familiar, there is a case for changing the decision framework itself (Hallegatte, 2008). Watkiss and Hunt (2012) make the case for a strategy of decision making under uncertainty that allows public and private organisations and households to learn as they go. This can be achieved by introducing the principles of *robust* *adaptation* into an adaptive risk management framework.

Robust decision making (RDM) emerged from assumption-based planning, which was developed in the nineties to explore the circumstances under which a plan could fail and the actions needed to prevent this (Dewar et al., 1993; Dewar, 2002). Robust decision making therefore begins by examining decisions rather than by characterising climate uncertainties (Groves and Lempert, 2007; Lempert, 2013). Lempert and Schlesinger (2000) describe this as an approach that does not ask what is likely to happen in the future, but rather "*what actions should we take now given that we cannot predict the future?*".

Formal RDM, introduced by Groves and Lempert (2007), is a modelling method that retains a role for probabilities and which formally examines the circumstances under which a plan could fail. By comparison, the informal approach requires only that a plan is selected that is relatively insensitive to uncertainty, that avoids situations under which the strategy could fail and that identifies remaining vulnerabilities (Groves and Lempert, 2007; Walker et al., 2013). This approach is informed by the following criteria (Lempert et al., 2003), i.e.:

- No regret;
- Reversible;
- Providing margins of safety, e.g. in the design of infrastructure;
- Prioritising soft strategies without high sunk costs or fixed engineering;
- Can reduce the decision time horizon of investments; and
- Reduced long-term commitments.

A robust approach is sequential beginning with the building of capacity and awareness, and followed by an identification of early adaptation activities that are win-win, low regret or low cost. The resulting robust plan (Van Drunen et al., 2009; Walker et al., 2013) is one that offers:

- Resistance, i.e. can deal with the worst possible outcomes;
- Resilience, i.e. whatever happens, can recover quickly;
- Reduced vulnerability in the face of a range of conditions (static robustness); and
- A capacity to change as circumstances change (dynamic robustness).

While commencing with flexible options, a plan is likely to concede to long-term investment over time as the climate risk grows (Watkiss and Hunt, 2012). Until this point there are opportunities to learn and take account of changing circumstances. Truly robust adaptation can respond with a wider range of options than might emerge from a narrow or 'static' range of climate futures or scenarios.

Robust strategies perform well over a range of probability-based scenarios including low-frequency/ high-impact events (Wilby and Dessai, 2010), but are likely to provide satisfactory outputs rather than optimum results (Walker et al., 2013). In practice, some options will not always be available and trade-offs will need to be made between robust approaches and alternative strategies that aim to optimise returns, albeit with a corresponding risk of maladaptation (Ranger et al., 2010). There will be occasions when incremental measures will no longer suffice and significant investments have to be taken. Implications or externalities for other sectors will also need to addressed (Hallegatte, 2008).

A role is given to robust measures within the UK Climate Impacts Programme (UKCIP), which was established in 2007 to co-ordinate climate change adaptation research. The UKCIP is a risk management framework (Willows and Connell, 2003) that alerts national and local policy makers to the risks and uncertainties that exist at every decision-making level. The framework is an iterative process by which decision makers in various sectors can accumulate relevant information and select a mix of qualitative and quantitative methods appropriate to the choice of adaptation options. These could include multi-criteria analysis (MCA), cost-effectiveness analysis or cost–

benefit analysis (CBA). A step-by-step ‘adaptation wizard’ is supplied by the programme, the object of which is to allow stakeholders to identify adaptation options and to appraise the uncertainty associated with each in relation to climate scenarios.

As it makes use of climate scenarios, the UKCIP represents a composite approach. It comprises eight stages (see Fig. 4.1), each of which allows for feedback, iteration and transparency. The scoping of vulnerability and risk is followed by a risk assessment, an identification of options, an appraisal of options and a monitoring of the outcomes. Assessment proceeds via tiers, whereby decision makers can begin with a broad assessment rather than taking climate scenarios and impacts at face value. Users are encouraged to identify the most robust options through a risk screening process focusing on the lifetime of an adaptation decision rather than responding blindly to scenarios with comprehensive programmes of adaptation. Subsequent stages assess risk in more detail through the successive use of qualitative, semi-quantitative and fully quantitative tiers, depending on the availability of information.

In all instances, uncertainty remains the key obstacle. The structured sequential process encapsulated by the UKCIP allows for varying levels of appraisal, but also possible postponement of options until better information is anticipated. A flexible approach allows for adaptive capacity to develop and responds to feedback and information over time.

3 Economic Methods and Uncertainty

3.1 Introduction

The previous chapter discussed the status of and the approaches to adaptation, introducing the use of robust decision measures within an adaptive risk management framework. The data required to support a full economic appraisal of adaptation options are rarely available at the outset of an adaptation process, particularly at local or regional scale. In addition, the considerable uncertainty associated with climate change sits uneasily with decision makers who must justify their use of scarce resources to a doubtful public.

However, while the potential for conventional CBA-style optimisation may be compromised by high levels of uncertainty, this does not exclude the case for economic appraisal. There is something of a continuous scale between strategies that aim to optimise parameters (the conventional objective of economics) and strategies that are robust (Lempert and Collins, 2007).

Economic appraisal becomes necessary for projects, especially larger investments, where the efficient use of resources needs to be demonstrated. CBA is the preferred method for large project selection in Ireland and the Public Spending Code (CEEU, 2011) recommends that it is used for capital projects in excess of €20 million. For adaptation, the need for quantitative data on impacts, including non-market costs and benefits, that adequately account for risk and uncertainty, means that detailed economic analysis rests upon the prior collection of relevant data.

CBA has some distinct merits. According to the OECD (2006), CBA:

- Forces a rational examination of benefits spatially and temporally;
- Can examine a policy as one of a series of options;
- Demonstrates where benefits are maximised by using the same units for costs and benefits;
- Can be used to show where and to whom benefits and costs accrue;
- Is explicit in addressing time with discounting methods; and
- Is democratic in that it is based on the belief that individual preferences count (thereby providing a ‘check’ on the judgements of experts or politicians).

In principle, CBA can be applied to adaptation in a conventional manner. There is a role for detailed quantitative analysis whenever significant trade-offs exist as with other types of investment. Adaptation, however, requires that much attention is given to uncertainty and that much consideration is also likely to be given to non-market environmental and social goods, distributional factors and the relative timescale of costs and benefits. The technical demands and data requirements of CBA may restrict its use to larger projects and programmes as is standard in appraisal. For adaptation, the entire decision-making process, if routed through adaptive management and risk appraisal, provides a means to collect information that is relevant to CBA.

3.1.1 Level of quantification in existing national studies

Reviews of various adaptation studies, e.g. Adger et al. (2007) and Agrawala and Fankhauser (2008), confirm that economic data are partially and unevenly distributed. At a sectoral level, most quantitative assessments have been undertaken in the fields of health, flooding and water availability. In the UK, only the Foresight Study (Evans et al., 2004) attempted to quantify some of the investment returns to adaptation. Other applications to adaptation include:

- **Coastal zone management** – e.g. Brown et al. (2011) based on the PESETA project (http://peseta.jrc.ec.europa.eu), which used the SRES A1B balanced emissions scenario. Previous estimates by Bosello et al. (2012)

estimated a benefit to cost ratio (BCR) of 6:1 for the 2050s, increasing thereafter. There are also studies by the Deltacommissie in the Netherlands (2008) and Evans et al. (2004, 2008) in the UK.

- **Flooding** – e.g. Feyen et al. (2011) estimate net benefits from maintaining a 1 in 100 year protection across Europe of €8 billion/year in the 2020s under the A1B scenario, rising to €19 billion/year by the 2050s and €50 billion/year by the 2080s. From a variety of European studies, the EEA (2013) report san average BCR of 4:1.

- **Water sector** – e.g. Bosello et al. (2009) estimate benefits of €2.7 billion/year by the 2060s. The cost-effectiveness of policy options was considered by Florke et al. (2012) (www.climwatadapt.eu).

More recent adaptation models have included economic estimates, for example studies for the UK (Metroeconomica, 2006), Australia (Garnaut, 2008), France (ONERC, 2006) and Europe. In the UK, a detailed Economics of Climate Resilience Project is being prepared for various sectors for the Department of Environment, Food and Rural Affairs (DEFRA).

Each of these studies demonstrates the high degree of detail that would be needed even at the local scale, especially where this is compounded by the presence of numerous intangible or non-market benefits and costs. Impacts on non-market ecosystem services are discussed in the EPA COCO-ADAPT study (Sweeney et al., 2013). The terms of reference for the ongoing Adaptation Economic Assessment (AEA) being undertaken for the UK NAP acknowledge that some costs and benefits cannot be monetised and that assessment should instead focus on approaches that allow for consistent comparisons between sectors and regions.

Economic efficiency is not the only criterion. An assessment of adaptation options must satisfy numerous objectives. There is, for example, a need to:

- Allow for information, knowledge and learning so as to strengthen adaptive capacity;
- Facilitate adaptation by the market, but also in non-market sectors such as biodiversity;
- Mainstream climate resilience across sectors;
- Consider inequality and distributional aspects;
- Locate ancillary benefits that accord with sustainability;
- Avoid regional or sectoral conflicts;
- Identify barriers to adaptation, and
- Overcome uncertainty.

3.2 CBA

CBA provides a means by which to evaluate the costs and benefits of adaptation programmes or projects. Adaptation involves costs and many of these are financial, including upfront investment costs. However, both costs and benefits can be social and environmental. The principal benefits accrue from *damage avoided*. The CBA compares the costs and benefits of various options with the counterfactual, i.e. the do nothing or do minimum. It converts cost and benefit flows into a common measure of value, i.e. money. As these will arise at different points in time, discounting is used to ensure that values are comparable.

CBA is founded on the principles of welfare economics and identifies how best to use scarce resources to obtain the greatest possible benefit for society, i.e. to identify the socially efficient solution. Societal net costs/benefits (welfare losses/gains) form the basis by which projects are selected and represent the sum of all individuals' costs and benefits as valued in terms of their preferences measured by willingness to pay (WTP) for a benefit or willingness to accept (WTA) compensation for a loss. A project should only proceed if at least some people gain, but nobody actually loses. For practical purposes, an improvement is sought based on the Kaldor–Hicks compensation principle whereby those who gain/benefit can compensate those who lose.[6]

To progress a project the basic rule is that discounted benefits should exceed costs, or that net present value

6. It is the strict Pareto criterion that requires that a project or policy can only proceed if at least some people gain, but nobody actually loses. A Potential Pareto improvement occurs if a project meets the Kaldor–Hicks compensation principle.

(NPV) should be positive. In principle, any project with a positive NPV can proceed but, in practice, there are limitations to this basic selection criterion, not least the resources available. Projects or options for which a CBA is to be undertaken should be narrowed down by an initial screening process. Where a fixed capital budget exists, a positive NPV may not be enough and projects may need to be ranked by their BCR. As the BCR provides no indication of the relative size of projects, the project with the best mix of a high NPV and BCR should be selected, guided by the financial constraints.

Guidelines on project appraisal, including CBA, have been produced by the Central Expenditure Evaluation Unit (CEEU, 2011) and by the Department of Finance (2005, 2006), but do not need to be reproduced here. Rather, this section focuses on aspects that are especially relevant to adaptation, namely intangible goods and benefits, distribution, the timing of benefits and costs, and uncertainty.

3.2.1 Assigning values: non-market goods or intangibles

Under perfect competition, markets exist for goods and services and price reflects society's WTP, with resources allocated to their best use value or on the basis of opportunity cost. In practice, market distortions often exist such that market prices do not always reflect a good's true value to society. To overcome this, 'shadow pricing' can be employed, whereby prices are adjusted to reflect true value. An example that is often proffered is that of the price of labour where wages are raised by obligations such as minimum wage legislation, whereas in circumstances of very high unemployment the real wage rate would fall towards a subsistence level.

There is also a need to account for the shadow price of public funds in that taxation reduces the resources available for private investment. Guidance on the allowance that should be made for this factor is provided by the CEEU (2011). Public projects can displace private investment in the same area or have a dead-weight loss of allocative efficiency. While this consideration might apply less to the physical infrastructure needed for adaptation, it reinforces the need for robust adaptation to map the bounds of private adaptive capacity and to seek out opportunities for autonomous adaptation. Once this is achieved, the public sector can address those areas of adaptation where the market or private individuals are not incentivised to undertake adaptation themselves, i.e. situations of market failure.

Aside from resources that are priced in the market place, there is a wider range of social and environmental costs and benefits that are often described as *intangibles* in that markets simply do not exist. These types of costs and benefits apply especially to climate change impacts, which can be expected to have significant impacts on such diverse areas as landscape, water quality, coastal ecosystems, social cohesion or health. In this respect, the process of undertaking a CBA is as important as the estimate of NPV as it allows the decision maker to examine the trade-offs between financial, social and environmental criteria and their impact on human well-being. A suite of non-market valuation methods is available that includes both revealed and stated preference approaches (see Box 3.1).

The CEEU (2011) favours revealed preference due to its attachment to reality. An example of revealed preference could be the use of travel cost data to demonstrate the value of a beach that would be threatened by sea level rise without adaptation to protect it. However, revealed preference data will not always be relevant to the issue in hand. While stated preference must rely on the presentation of hypothetical scenarios, it is the only method that is able to capture a sizeable portion of people's consumer surplus in terms of their total WTP. Furthermore, stated preference is best equipped to deal with future scenarios as would clearly be a feature of climate change. To anchor stated preference scenarios in current reality, it is possible to combine revealed and stated preference within a choice experiment using an appropriate scaling factor (Train, 2003), but only where there is a good correspondence between the two. For example, current revealed recreational choices could be combined with stated recreational choices in response to a climate change scenario.

There will be other intangible or non-market values (or aspects of these) that are difficult to quantify in

Box 3.1. Non-market valuation methods

There are four principal approaches to the economic valuation of environmental goods:

1. Avoided cost, replacement cost and avertive expenditure
2. Production function methods
3. Revealed preference
4. Stated preference.

1. **Avoided cost** represents the damage that would have occurred had the (adaptation) policy not been in place. Replacement cost and avertive expenditure indicate the amount that must be spent to replace or substitute for the protective benefits provided by existing infrastructure or a natural feature that prevents an impact occurring, for example through artificial protection measures such as sea walls. These approaches are often applied to the ecosystem services provided by natural defences such as dunes, salt marsh, flood plains, etc. They do not measure the full consumer surplus or total WTP, but nevertheless provide a measure of the benefit provided in avoiding costs due to such impacts as flooding or storms.

2. **Production function methods** are applied where an environmental good is an input into a wider process or final good that has a market price or can be quantified in these terms. The objective here is to identify the contribution provided by the environmental good and attribute a value accordingly. This method is again regularly applied to ecosystem services. It does not measure total WTP, but provides a measure of the benefit provided.

3. **Revealed preference** includes expenditure associated with observed behaviour, for example visits to a beach threatened by erosion or sea level rise. Travel cost can be used to indicate value and should include, where practicable, the value of travel or on-site time. Local expenditure provides an extension of this value. Careful modelling may be required to define the contribution of the non-market good and to separate this from other attributes with which there is an interaction. Once again, revealed preference does not capture the full consumer surplus.

4. **Stated preference** uses surveys to ask individuals how much they value an environmental good in terms of their WTP to protect it or to avoid damage. In principle, stated preference can capture the full consumer surplus, although in practice typically only represents part of this due to biases and deficiencies of survey methods.

    - **The contingent valuation method** (CVM) asks for WTP or WTA directly sometimes as an open question, but more typically using a discrete choice format in which respondents are asked whether they would be willing to pay €x where this amount varies for respondents. The figure is often succeeded by a follow-up €x (higher or lower) depending on the response (yes/no) to the first question. For an application of CVM in Ireland, see Clinch (forestry) (2006), Hynes and Hanley (recreation) (2006) or Bullock and Collier (peatlands) (2011).

    - **Choice experiments** obtain WTP values indirectly as the probability of choosing between two or more alternative scenarios and a baseline. A price is included as one of a number of varying attributes/attribute levels for each scenario. For applications of choice experiments in Ireland, see Hynes and Campbell (agriculture) (2011), Stithou et al. (water quality) (2011) or Bullock (housing) (2008). These methods provide an approximation of the consumer surplus value, but can be subject to errors if the implementation is inadequate or inappropriate to the type of good.

monetary terms. For example, climate change presents a risk of loss of life. Value-of-statistical-life (VOSL) estimates are available based on the marginal likelihood of death. These are not equivalent to a 'value of life', but are a revealed preference value of life expectancy based on the precautions that people take to accept risk, e.g. higher wages, insurance payments, etc. In Ireland, VOSL has been calculated at €1.32 million in relation to a road fatality (Goodbody, 2005). This can be thought of as a lower bound estimate. In other areas, as is the case for some ecosystem services, too little is known of their contribution to human well-being to arrive at a realistic monetary estimate.

Another limitation is that many of these intangibles apply to externalities. An externality exists when the consumption or production choices of one individual (or firm) impact on the utility or production function of another (prior to any compensation). Market failure occurs when price fails to take into account these impacts and thereby the full social costs and benefits. CBA should aim to account for the externalities associated with a project and particularly so in the case of adaptation. Externalities can be valued using the above market or non-market methods, but can be troublesome to identify. The range of externalities associated with some adaptation options, for example managed retreat from existing coastlines, will present a significant challenge. General equilibrium models could be more successful at capturing indirect impacts between sectors.

3.2.2 Accounting for time

As costs and benefits are likely to occur over a period of time, it is necessary to identify the time horizon and to discount future values to present values. (Box 3.2) Discounting reflects society's rate of time preference based on our general preference to realise benefits as soon as possible, for example €1 received in the future

Box 3.2. Discount rates

The question of discount rates requires some consideration as these act to reduce future costs and benefits. In the case of climate change, current policies have varying upfront costs, but potentially high, though distant, costs and benefits. Therefore, the choice of discount rate is central to decisions over mitigation or adaptation.

After Ramsey (1928), the social discount rate

$$s = \rho + \mu g$$

consists of pure time preference ρ plus the marginal utility μ of future growth in consumption g. Thus, a positive discount rate is enforced by the expectation that future generations will be richer. However, a positive discount rate could appear to be inconsistent with sustainable development and intergenerational fairness. On the other hand, a zero discount rate can be criticised as impoverishing the current generation to benefit those of the future (Olson and Bailey, 1981).

Much of the argument revolves around the use of a constant discount rate. In practice, people appear to exhibit hyperbolic discounting in which they discount the near term more than the more distant future. Weitzmann (1998) and Gollier (2002) have argued that this observation can be justified by uncertainty about the future and that this provides an argument for applying a discount rate that declines over time. In the opinion of Weitzmann, uncertainty arises in relation to future interest rates. This uncertainty should be reflected in weighted discount factors which, when averaged over a set time period, result in the certainty equivalent discount rates that are lower for longer time periods. Gollier takes a different perspective based on expectations of economic growth. He argues that the Ramsey social discount rate should include a second term to account for the 'prudence effect' of the precautionary amount people save depending on their expectations of economic growth. When there is a risk of recession, the prudence effect increases the discount rate, while rates fall where there is no risk of recession. Over time, the prudence effect tends to have a reducing effect countering the 'wealth effect' of μ. Discount rates are argued to fall in the presence of uncertainty about the future.

is perceived to be worth less than €1 received now. Inflation is dealt with separately from discounting. To remove its effect, all costs and benefits included in the CBA are expressed in constant prices according to a common base year.

The choice of a social discount rate will impact significantly on the selection of projects. Benefits and costs that occur far into the future will have a low rating, for example, with a discount rate of 4%, a cost of €1 million occurring 100 years from now would be valued at just under €20,000. This raises the troublesome moral issue of intergenerational fairness, i.e. should a project that imposes a cost of €1 million on future generations go ahead because of the low present value of the costs.

Each country typically has its own official discount rate. In Ireland it is 4%. While official discount rates do not normally decline over time, declining rates are applied in some instances. For example, the UK government provides a schedule of declining discount rates for projects with impacts over 30 years (HM Treasury, 2013). A declining discount rate is considered to better reflect actual perceptions of the distribution between near and long-term benefits. Given the difficulty of selecting an appropriate discount rate, a sensitivity analysis based on a range of discount rates is typically used.

3.2.3 Distributional considerations

Ethical issues apply to property rights relevant to WTP or WTA and to intergenerational values (discounting). Consequently, it is important to identify to whom costs and benefits accrue. The Kaldor–Hicks compensation principle provides the basis whereby those who benefit can compensate those who lose. This allows equity to be achieved through existing or alternative policies such as taxation or the social welfare system. Of course, actual outcomes may not conform to this laudable principle.

The process of identifying the range and recipients of costs and benefits in CBA, including non-market costs and benefits, means that the method must take account of distributional impacts. If, at a policy level, it is considered appropriate to highlight impacts on particular socio-economic groups, then it is possible to apply weights to different individuals. For example, a person with 50% of the average income would be allocated a weight of 1/0.5 = 2, while a person with twice the average income would have a weight of 0.5. There is no agreement on a 'correct' weighting, but consultation and stakeholder involvement can help with consensus on the treatment of distributional effects.

3.2.4 Risk and uncertainty

The matter of risk (probabilistic outcomes) and uncertainty (when probabilities are not known) is a major consideration for adaptation to climate change. The attitude of the policy maker is relevant in this respect. A risk-neutral decision maker would be indifferent between impacts whose values, after accounting for probabilities, were the same irrespective of whether the impact itself was extremely averse or not. A risk-adverse decision maker, by contrast, attaches a higher weight to adverse outcomes. In the context of uncertainty (rather than risk) an optimistic decision maker may choose an option that provides a higher pay-off from a range of outcomes under a range of scenarios. This same choice, should an alternative scenario be realised, could result in a poor outcome. A key consideration for the risk-adverse decision maker is the risk of a bad and irreversible outcome.

CBA addresses risk by calculating expected values and explores uncertainty through the use of scenario analysis or sensitivity analysis, both of which are relevant to adaptation. Scenario analysis maps the consequences of different scenarios. Having information on climate probabilities is clearly of value for the quantitative estimation of risk for CBA, but comes with the caveats discussed in Chapter 2. Sensitivity analysis involves systematically introducing changes in key assumptions or marginal changes in variables (or combinations of variables) to examine the impact on NPV. Where sufficient quantitative data are available, computerised simulation approaches, such as Monte Carlo analysis, can be used to vary numerous variables to assess the distribution of a range of possible outcomes.

In certain instances, postponement of a decision can allow for improved understanding of the likely costs and benefits, i.e. waiting allows for new information that may reduce uncertainty. This is of particular relevance where the commitment of significant resources cannot be reversed, i.e. sunk costs. It would also apply to climate indicators that are variously projected to increase or decrease, as for example with recent probabilistic precipitation projections for Ireland. Of course, a delay will not necessarily lead to better understanding and inaction could result in increased costs or lost benefits.

3.2.5 *Formal treatment of risk and uncertainty*

Risk is measurable uncertainty, i.e. uncertainty that can be defined by a probability function (Dorfman, 1972). Benefits depend on the probability of either B_1 or B_2 occurring, i.e.

$$B = p(B_1) + (1+p) \cdot (B_2)$$

The traditional economic approach to risk is to estimate expected value (EV) contingent on the choice of a strategy and its position along a probability distribution. EV is the sum of the possible outcomes weighed by their probabilities and is most relevant where the decision maker is risk neutral. Risk neutrality, though, may be difficult to maintain where the probability distributions associated with policy options are of varying dispersion. However, governments, by virtue of the variety and size of policy expenditure, can often afford to take a risk-neutral position by being able to pool risk between numerous projects.

Alternatively, where risk aversion is present and the objective is to find the socially optimal solution, expected utility (EU) is the relevant measure rather than EV. It has the same formulation except that a diminishing marginal utility of income would be expected to apply, converting a potentially linear relationship into a non-linear one, i.e. the expected utility of benefit, B, i.e. $EU(B) < U(B)$. If the utility function is known, a certainty equivalent can be used to convert the set of probable outcomes to figures known with certainty. This is equivalent to the lower income on the non-linear utility curve that provides the same utility as a higher income amount that is subject to a lottery. The difference between the two income levels is the price differential at which a person is indifferent between options. In principle, this can be added to the discount rate as a risk premium to account for uncertainty.

By comparison, probabilities do not apply with pure uncertainty. One option is that a Bayesian perspective can be taken where some level of subjective belief is applied based on available information to arrive at an estimate of probability. However, according to Morgan and Henrion (1990), it would be inappropriate to attach probability distributions to such uncertain decision variables or to value parameters where human preferences or behaviour rule out the existence of true values. In these situations, it could be argued that a better solution would be to vary coefficients parametrically or to use sensitivity analysis.

3.2.6 *Treatment of uncertainty within climate models*

Uncertainty is often present for projects relying on conventional applications of CBA, but climate change is argued to be characterised by ‘deep uncertainty’. This is not uncertainty that results from a lack of information, but rather uncertainty that cannot be reduced (Walker et al., 2013). It is uncertainty that contains significant or ‘unknowable’ unknowns (Lempert and Schlesinger, 2000; Walker et al., 2013). Dessai and Sluijs (2007) describe a ‘cascade of uncertainty’ (Fig. 3.1) which is multidimensional, i.e. parametric and stochastic. At each stage, uncertainty is multiplied by new parameters including socio-economic parameters.

The IPCC AR5 is preceded by a Guidance Note (Mastrandrea et al., 2010) on how the expert teams should treat uncertainty. It is recommended that they should communicate their degree of confidence in climate projections based on the evidence as well as on their own level of agreement. The guidance recommended that this should take the form of a qualitative expression of confidence in climate projections and a quantified measure of the likelihood of an event. In the first working group report (IPCC, 2013a), confidence was expressed qualitatively from *very low* to *very high*, while probability has been quantified via an expression of likelihood from *exceptionally unlikely* (0–1%) to *virtually certain* (99–100%). The guidance believes that risk management should involve an awareness of the range of

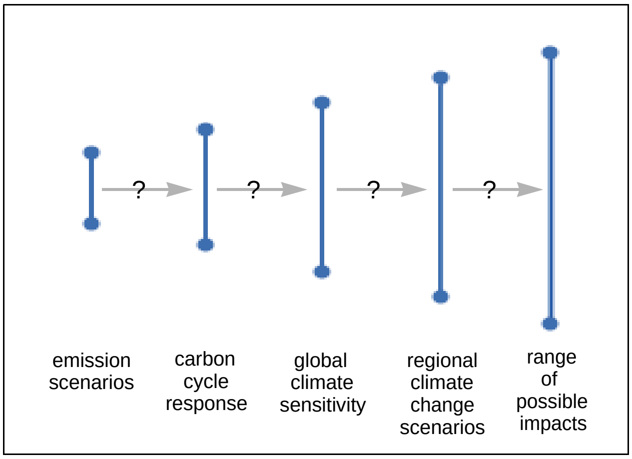


Figure 3.1. The cascade effect of uncertainty (source IPCC Third Assessment Report).

consequences, particularly for the probability tails (i.e. climate extremes). The reasoning is that even low probability impacts are significant where they are characterised by large magnitude, long persistence, broad prevalence and/or irreversibility.

The IPCC Guidance Notes (Mastrandrea et al., 2010) acknowledge that concealing uncertainty could make matters worse. Climate projections are still *projections*. Extreme events could exacerbate the risks of overlooking uncertainty. However, while there is a strong argument for not concealing uncertainty, there can be problems with how policy makers choose to characterise it, as discussed in Chapter 2. Decision makers can get locked into particular behaviour modes by institutional factors (Jackson, 2005). This is especially a factor for adaptation in that the relevant decision makers will often be at local level rather than representatives of national departments. They will consist of a variety of actors, most especially those working in planning (Ingham et al., 2006). The day-to-day priorities they face, together with the extent of their powers (for example in relation to financing), may provide them with minimal incentive to take account of long-term climate change.

3.3 Prospects for CBA

CBA is placed in the position of attempting to select an optimal policy in the face of multiple plausible alternative future climate scenarios (NESC, 2012). Probabilities are no stranger to CBA, but much of the uncertainty associated with climate change cannot be quantified. At the extremes, there is the risk that climate outcomes will be either positive or negative, making CBA impossible.

Fundamentally, the problem for CBA is in estimating the value of damage functions in the distant future. In the first instance, because climate change is long term, the choice of discount rate makes a tremendous difference to any estimation of the BCR. Secondly, uncertainty is attached to future states of the world. As well as considering the direct impact of climate change, an assessment has to project a future reference scenario based on expectations of economic growth, population growth and growth in incomes, as illustrated by Fig. 3.2. In addition, public agencies have to aim to maximise social welfare, which also requires accounting for future social and environmental costs and benefits. We have little or no idea about the future preferences by which these outcomes will be valued (Richardson, 2000). Furthermore, assuming that the ends and means are fixed from the outset means that alternative solutions are never revealed (NESC, 2012). This runs the risk that decision makers could exclude options for innovative solutions.

In the absence of a crystal ball with which to foresee future values, some insight can be provided by foresight exercises supported by widespread expert consultation. For example, studies have been undertaken at sectoral level by the UK Foresight Programme (http://www.bis.gov.uk/foresight), which also includes a report on the effect of international climate impacts on British society (GOS, 2011).

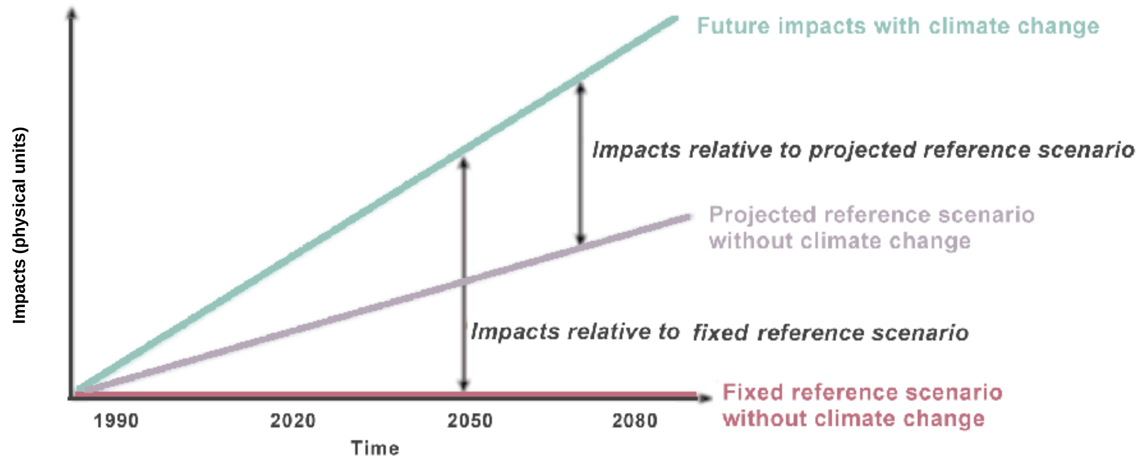


Figure 3.2. Estimating future costs and benefits.

However, uncertainty is "*inescapable, not crippling*" (Pielke, 2010). Decision makers are accustomed to dealing with uncertainty even though climate uncertainty may be of another order. An alternative approach is to frame the problem as one of decision making under uncertainty (Hallegatte, 2008; Watkiss and Hunt, 2012) and to integrate uncertainty into policy making (Schneider and Kuntz-Duriseti, 2002) so as to make it more proactive rather than reactive to events (Aal and Groven, 2013). These arguments favour an adaptive risk management framework that is robust, sequential and responsive to new information.

The prospect of learning is positively related to the scale of uncertainty and to the benefit of avoiding sunk costs today versus the future losses to climate change. Expensive upfront investment is an argument for a cautious sequential strategy of adaptation, whereas future extreme climate outcomes could be an argument for more radical action. Decision trees, to whose 'branches' probabilities can be attached, are one means of comparing alternative actions and are discussed below.

3.4 Other Methodologies

3.4.1 Introduction

"*No one method is right or wrong — their usefulness depends on the objectives of any given assessment. Different methods may be more or less appropriate according to whether they are aimed at providing headline information, scoping possible options, looking at the costs of climate proofing, or undertaking detailed economic assessment of specific plans or projects.*" (EEA, 2013, p. 119)

A CBA is an undertaking that requires identification of cost and benefit flows (including non-market costs and benefits), distributional effects and the use of discounting. The assessment should aim to ensure that the costs and benefits are as comprehensive as possible unless CBA can be complemented by other methods. This section considers approaches that can be used as alternatives to CBA to select between adaptation options or that can potentially include either economic estimates or CBA. The approaches do not need to be thought of as being mutually exclusive. Each has its own way of addressing intangibles, distributional considerations and uncertainty.

3.4.2 CEA

Cost-effectiveness analysis (CEA) is used to identify the least-cost option for achieving an agreed outcome. CEA can be employed for capital projects where data on significant costs or benefits cannot be valued (Department of Finance, 2005). It permits a trade-off between benefits and resource costs as in CBA, but the benefits or objectives are measured in relative physical units rather than in monetary terms, thereby measuring *technical efficiency* only, rather than allocative efficiency (European Union, 2008). The approach can be used to rank alternative options in order of those that deliver the most benefit for the lowest cost, i.e. are most cost-effective. It is less relevant where benefits cannot be rendered into physical units or where the decision maker must compare adaptation options across sectors. For this reason, it is a useful and familiar approach *within* some sectors, but is less commonly applied *between* sectors as it cannot compare options with different outputs. Boyd et al. (2006) provide an example of CEA for water resource adaptation in the UK.

3.4.3 MCA

Multi-criteria analysis is a commonly applied means of structuring decisions where the criteria (or attributes) include at least some variables (intangibles) that cannot be quantified or satisfactorily traded off against monetary variables. MCA allows impacts to be measured in different units, including both qualitative and quantitative data. Unlike CBA, it is not restricted to efficiency criteria (i.e. that benefits should exceed costs). Its flexibility and ability to incorporate qualitative information make it a useful method for adaptation especially at the scoping stage. MCA proceeds in four steps, namely:

1. Problem definition;
2. Selection of decision criteria;
3. Identification of stakeholder preferences; and
4. Aggregation into a total score.

Dodgson et al. (2000) argue that the method can potentially be more open than CBA and facilitate both participatory and sequential decision making. However, without a common unit of measurement, MCA is unable to definitively demonstrate whether or not a preferred option represents a net addition to well-being.

The positive feature of MCA is its ability to deal with intangibles. A performance matrix is used to weight objectives or criteria and to score actions on the basis of their expected performance or consequences (Table 3.1). Stakeholders can be called upon to help with this process. Options that are dominated on the basis of sets of criteria are removed at an early stage. For more complex decisions, sets of criteria can be clustered for comparison at various stages in a hierarchical process or value tree.

Uncertainty can be explored through sensitivity analysis. This can highlight the effect of alternative weightings and may be particularly beneficial in demonstrating the consequences of alternative options in a participatory process. Where there is much uncertainty, Dodgson et al. (2000) propose scenarios that use the same set of criteria, but which weight these by a sensitivity analysis. If uncertainty is associated with one or two criteria only, they propose penalising the criterion's score based on the degree of confidence or certainty. An alternative, noting that MCA emerged from decision theory (Golub et al., 2011), is to use decision trees to help decide which new alternative to choose at different stages in the adaptation process.

3.4.4 Decision trees and real options analysis

To combine the management of risk and accumulation of data relevant to decision making within a

Table 3.1. Simple multi-criteria analysis of two projects (EC, 2008).

	Project A			Project B		
	Score	Weight	Impact	Score	Weight	Impact
Equity	2	0.6	1.2	4	0.6	2.4
Equal opportunity	1	0.2	0.2	1	0.2	0.2
Environment	4	0.2	0.8	2	0.2	0.4
Total			**2.2**			**3.0**

Box 3.3. Multi-criteria analysis in Ireland

The Department of Finance (2005) recommends that MCA should be carried out at a minimum for projects between €5 million and €50 million but be accompanied by CEA determining the least cost. All MCAs should include financial appraisal. The main steps in the MCA process are:

1. Devise a scoring scheme for marking a project under each criterion heading;
2. Devise a weighting mechanism to reflect the relative importance of each criterion;
3. Allocate scores to each investment option for each of the criteria;
4. Document the rationale for the scoring results for each option;
5. Calculate overall results and test for robustness; and
6. Report and interpret the findings.

A framework for the appraisal of transport investment projects involves MCA supplemented by a monetised CBA where appropriate (Department of Transport, 2009). A standard or project-specific weighting or ranking is not provided. A risk assessment is recommended to evaluate risks in relation to capital expenditure and project outturns or benefits. Non-market benefits are acknowledged, but only qualitative assessments of these are generally expected. The assessment of the accessibility and social inclusion impacts should be considered through a qualitative, quantitative and scaling statement.

comprehensive time frame, it is useful to map out where future climate projections are likely to impact significantly. The decision-tree structure allows the adapting organisation to conceptualise the process of adaptation based on thresholds at which new strategies will need to be considered. These thresholds could relate to climate criteria or the dates by which particular climate impacts are anticipated. Figure 3.3 illustrates the essential tree and branch architecture of a decision-tree approach.

The figure provides an illustration of the process. This could commence with low cost, no regret or win–win measures that can be conveniently implemented without recourse to detailed quantitative data. Subsequent adaptation builds on these initial steps progressing to a selection of new options using more sophisticated assessment approaches once each threshold is reached.

Decision trees are used to map out the various alternative paths, depending on the information available at each decision point. An initial decision leads to a subsequent decision point where alternative new options present themselves, followed subsequently by a possible third, fourth or more decision points with further adaptation options. Where possible, small incremental changes are accommodated first, leaving larger possibly irreversible investment decisions until later. Flexibility and learning potential are key elements (HM Treasury and DEFRA, 2009).

Real options analysis (ROA) includes estimates of impact values and probabilities for cases where adaptation investment can be phased or adjusted over time. If sufficient quantitative information is available, NPV can be estimated for different adaptation option outcomes represented by the alternative branches of the decision tree using the assumed probabilities of each climate scenario. ROA therefore allows the adapting organisation to quantify the pay-off from these alternative options or of delaying a decision in the expectation of new information, i.e. whether it is best to invest now or to wait, or to invest in options that allow greater flexibility in the future (Mediation, 2013).

The best decision may be to do nothing but to maintain existing infrastructure if this has a higher NPV but still allows for flexibility in Stage 2. Acting prematurely could result in unnecessary cost when it might be sufficient to maintain infrastructure already in place beyond its replacement date. On the other hand, adaptation has to be adequate enough to deal with

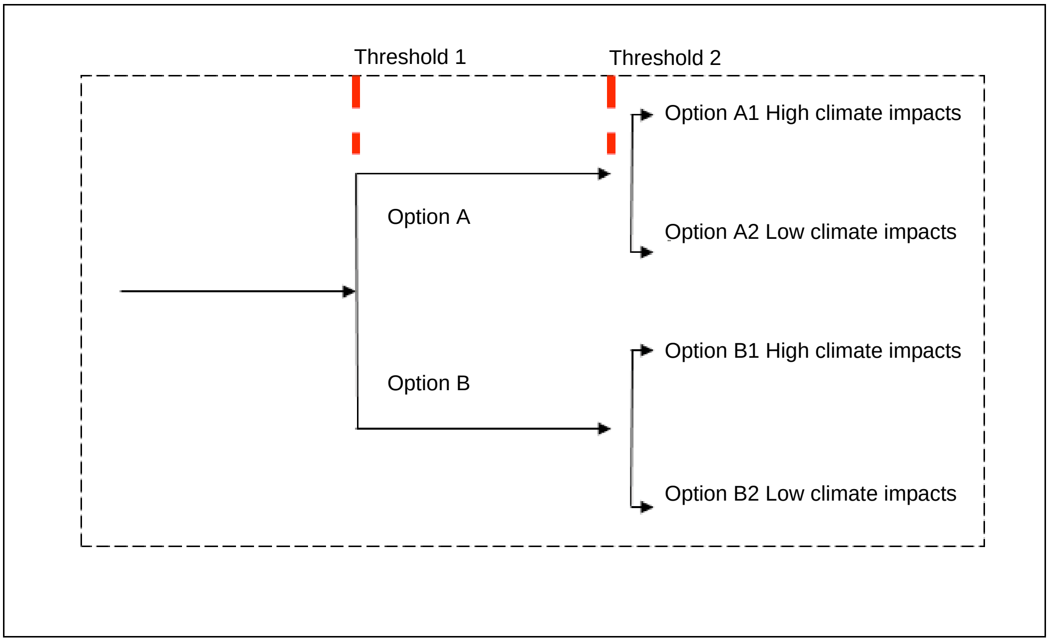


Figure 3.3. Decision tree.

more extreme events. The catastrophic failure of the New Orleans flood defences during Hurricane Katrina in 2005 is an example. The levees had permitted a perception of low risk and allowed for 'safe' development in the surrounding low-lying area. Therefore, even where probabilities have been estimated, there is a case for mapping out future impacts, the decisions required to mitigate them, and the costs that would be incurred.

More detail is provided in the Flood Management Case Study summarised in Chapter 5. The merits of using decision trees to plan future actions can be understood even without the inclusion of probabilities. The more quantitative analysis that is possible, based on what probabilities allow, means that ROA is most applicable to major investment decisions such as major flood relief schemes or coastal barrages. It can be formalised into an optimisation model using expected values. However, the caveat remains that any estimated pay-off depends on the estimated probabilities being realised.

3.4.5 PA

Portfolio analysis (PA) can be used to assess the effectiveness of a number of adaptation options that spread the effect of risk and uncertainty. Like ROA, modern portfolio theory has its origins in investment planning. Markowitz (1952) argued that it is not a financial security's own risk that should concern the investor, but its contribution to the variance of the entire portfolio. PA also conforms to the principles of RDM in that the method identifies the vulnerabilities of a range of adaptation options to changes in risk.

PA offers a route to higher returns than pure diversification by capturing all the benefits of efficient risk diversification taking into account co-variance (Rubenstein, 2002). It assembles portfolios of options and estimates their maximum return (or net return) subject to a given level of risk *or* the minimum risk for a given level of return (or net return). A mapping of a joint probability distribution is required together with estimates of mean, variance and covariance. PA works best where there is the potential for outcomes to be negatively correlated, for example where there is uncertainty over the direction of climate change impacts (as with precipitation in some Irish projections) or where adaptation options perform conversely under different climate scenarios.

As yet, there are few applications to climate change. Ando and Mallory (2012) applied PA to the optimal spatial targeting of conservation activity in a lakeland area of the US Midwest used by wintering wildfowl. They drew up an 'efficiency frontier' based on indices of conservation value and two sets of climate scenarios with respective probabilities. Using the financial portfolio software MATLAB they identified alternative locations for conservation land purchase which have near equivalent benefits, but lower risks.

Crowe and Parker (2008) used PA to examine options for adaptation in the forestry sector of Ontario. The object was to spread risk as measured by the variance of projected outcomes. They used principal component analysis to identify the main sources of variance and covariance in the growth of various tree species which they then regressed against climate scenarios. Their aim was to ensure that there would be a continued supply of timber by minimising variance and covariance, subject to incremental increases in expected returns. They found that the ideal solution is robust rather than optimal based on a mix of tree species that can exploit niches so as to minimise variance of growth while providing good overall returns. In their study, probabilities were not necessary to demonstrate the trade-offs, although they would be associated with the climate scenarios.

For the analysis of adaptation options, PA highlights the trade-off between alternative options in terms of their risk and effectiveness. It is therefore an approach that is most useful where the adapting organisation wishes to reduce its *exposure* to climate change. Effectiveness can be defined in terms of physical output, cost or economic efficiency. This results in options that are effective over a range of climate scenarios. The limitation is that quantified data on probabilities, effectiveness or co-variance, will not always be available (Mediation, 2013).

3.5 Summary

This chapter has introduced and explored the characteristics and attributes of CBA, but also of other methodologies that could be useful for making adaptation choices, either in isolation or in combination. Table 3.2 provides a summary of their virtues and limitations, each of which can be used to complement economic assessment or to inform a detailed CBA. There are methods that are useful for scoping options, for mapping the future consequences of decisions, which rely on quantitative modelling. All can be used for a robust strategy within an adaptive risk management framework. This is a process that does not evolve gradually, but rather is mapped out as a flexible, but committed, strategy from an early stage.

Table 3.2. Requirements, strengths and weaknesses of assessment tools.

Method	Useful where…	Advantages	Disadvantages
CEA	• To identify least-cost outcomes to achieve a particular outcome • Compares relative costs of one or a limited range of options with related outputs • Justifying monetary assessment	• Compares costs against effectiveness • Can demonstrate least-cost means to achieve an objective • Expresses benefits in physical rather than monetary terms and is familiar in climate policy as is often used for mitigation	• No single metric to capture benefits • Does not work well with uncertainty • Not very useful for comparing the benefits of multiple options
MCA	• Where full set of quantitative data is not available • Can be used with expert or stakeholder consultation (including participatory MCA) • Scoping • Analysis of uncertainty	• Combines both qualitative and quantitative data • Useful where monetisation is difficult • Straightforward and transparent • Useful for expert input • Useful for participatory processes with stakeholders	• No single metric on which to base trade-offs • Often needs subsequent interpretation • View of stakeholders can differ • Analysis of uncertainty often subjective
CBA	• If socially efficient solutions that take into account social, economic and financial criteria are required • To justify significant financial investment • For large or long duration (by this time many of the data relevant to the quantification of costs and benefits will have been collected)	• Compares social benefits and costs • Uses a single metric (€) • Can demonstrate and rank projects on their economic and social returns • Permits examination of trade-offs between criteria • Takes time into account	• Can be difficult to quantify many non-market elements in monetary terms • Better at addressing risks than uncertainty • Better where estimates of probability are available • Accounts for time, but issues over choice of discount rate
Informal ROA	• Applied with decision trees or pathways within iterative risk assessment • For programmes of adaptation	• Demonstrates returns from alternative pathways • Takes into account prospect of future new information	• Absence of detailed estimates of probabilities rather undermines effort put into the process (although option exists to vary risk estimates) • Can be difficult to identify decision points/thresholds
Formal ROA	• For major investment decisions • Where investment is irreversible • Where uncertainty is present but potential for new information	• Takes into account prospect of future new information • Maintains flexibility and can be combined with decision trees • Can be used to quantify alternative options when decisions taken at different points	• Requires quantitative data • Ideally requires probabilistic information • Demanding of resources and expertise. Most formal ROA requires optimisation • Can be difficult to identify decision points/thresholds
PA	• Where is a value in spreading risk	• Needs quantitative information on variance and co-variance • Potential for expert input	• Requires quantitative information • Requires information on probabilities

CEA, cost-effectiveness analysis; MCA, multi-criteria analysis, CBA, cost–benefit analysis; ROA, real options analysis; PA, portfolio analysis.

4 Including Economic Assessment in a Risk Management Framework

4.1 Choice of Economic Tools for Adaptation

Having described the principal methods available for the appraisal of adaptation options, this chapter explores which methods are most applicable to particular situations and how these might be included or combined in an adaptive risk management framework. Key elements of such a framework include:

- **A sound knowledge base –** i.e. a clear understanding of expected climate change, the exposure and sensitivity of economic sectors, areas, populations and ecosystems and of the potential impacts;
- **An assessment of adaptive capacity –** i.e. of the capacity and willingness to adapt at institutional level or by socio-economic group;
- **An assessment of vulnerability –** combining the assessment of potential impacts and adaptive capacity in order to determine vulnerability;
- **An identification of adaptation requirements and options** and their costs and benefits;
- **An action plan** – detailing the adaptation required and an associated implementation plan; and
- **A review mechanism** – to review the success or otherwise of adaptive actions.

Economic assessment has habitually included an element of risk assessment. However, this report has demonstrated that climate change in subject to considerable uncertainty – even 'deep uncertainty' – for which measures of probability cannot be calculated with high reliability. Uncertainty also arises from the sensitivity to climate change of individuals, organisations and sectors, and from the adaptive capacity of the same. This presents a considerable challenge to the conventional predict-and-provide approach to adaptation. Nonetheless, difficult decisions still need to be taken with regard to the choice of adaptation options and the respective allocation of resources. Therefore, there remains an important role for economic analysis within a wider framework of risk assessment and decision making.

4.2 Sources of Information

To determine the climate risk, the adapting organisation must first gather the key climate data that are relevant to its sector. The Irish Climate Information Platform (ICIP) (www.climateireland.ie) is currently under development. This will bring together climate data and projections, together with the tools through which organisations can raise awareness, assess their vulnerability and select the most appropriate adaptation options.

Other key data sources include various reports and data available on the EPA SAFER web-based interface (http://erc.epa.ie/safer/index.jsp) or produced under the EPA CCRP (www.epa.ie/pubs/reports/research/climate/), in particular:

- *The Status of Ireland's Climate 2012* (Dwyer, 2012);
- *A Summary of the State of Knowledge on Climate Change Impacts in Ireland* (Desmond et al., 2009); and
- *Climate Change – Refining the Impacts for Ireland* (Sweeney et al., 2009).

The CCRP database includes various reports on adaptation too, including a National Adaptive Capacity Assessment (Desmond and Shine, 2012) and COCO-ADAPT (Sweeney et al., 2013), which examined priorities for adaptation across various sectors in Ireland.

As climate projections are subject to frequent modification, the reports and data sets maintained by Met Éireann (www.met.ie/climate), ICARUS (http://icarus.nuim.ie) and University College Dublin (http://earth.ucd.ie/researchcategory/climate/) should be consulted. Additional up-to-date information on climate projections and adaptation is also available from the IPCC (www.ipcc.ch) and the EEA (www.eea.euopa.eu).

4.3 The Risk Management Approach

4.3.1 Economic and other assessment methods in a risk management framework

Adaptive risk management is an integrated and iterative strategy that embeds considerations of risk in the decision-making framework, and is subject to continuing modification as new information becomes available. This framework also supplies feedback on society's tolerance of risk and information on the costs and benefits of different courses of action (Willows and Connell, 2003).

Within this framework, a robust adaptation process provides the basis for an efficient use of resources by focusing on those areas that are considered to be most vulnerable so as to examine the limits of resilience and narrow down the range of options for adaptation. Robust adaptation can enhance adaptive capacity through the gathering and sharing of information, creation of supportive networks, and encouragement of autonomous adaptation. Other robust adaptation options include the acceptance of some impacts, the offsetting, sharing or spreading of risk associated with others, or the identification of associated new opportunities. For example, for local authorities in Ireland, McGloughlin and Sweeney (2012) highlight the benefits of building adaptive capacity through the sharing of information between authorities, the establishment of dedicated climate change teams, monitoring progress with measurable targets, and reporting of adaptation initiatives in council publications and budgets.

An adaptive risk management framework can include economic data and analysis, but a full CBA can be an involved and lengthy process. This is especially the case where non-monetary valuation is required, when there are numerous interdependencies and externalities present, or where there is a variety of receptor groups to be considered, including different socio-economic population subsets. Within a risk management framework, CBA is more likely to be applied once the adapting organisation has identified a handful of options that it would like to pursue in more detail. Applying complementary tools at an earlier stage allows qualitative data to be replaced with quantitative data, including economic data, as the strategy progresses. By this stage, adaptation investment costs will have been estimated along with at least broad estimates of impact costs, i.e. adaptation benefits. CBA can then be used to refine the evaluation of which options perform best in response to a range of scenarios and criteria.

The UKCIP (http://www.ukcip.org.uk), introduced in Chapter 2, is an example of such a strategy. It is now regarded as being amongst the best examples of a decision-making framework for risk assessment. The approach accords with the stepwise approach recommended by the EPA and the NCCAF.

As originally devised by Willows and Connell (2003), the UKCIP risk management approach consists of eight stages (see Fig. 4.1) connected by circular feedback loops that allow decisions to be reviewed and revisited in the light of new information. The process is iterative in that tiered stages permit problem identification, selection of decision-making criteria, risk assessment and appraisal options to be refined in an ongoing analysis. The use of tiers also minimises the time and resources for appraisal and implementation and allows screening, evaluation and prioritisation of options before moving to a more detailed appraisal of options.

The first stage requires the adapting organisation to identify the problem and its own objectives. The second stage converts these objectives into decision-making criteria for a more formal risk assessment. It is during the third, fourth and fifth stages that use of economic and related appraisal methods becomes most relevant. Figure 4.1 illustrates the importance of feedback loops between these stages which ensure that methods are selected that are relevant to the decision stage. These methods can be joined or replaced by new methods as more information becomes available and as the adapting organisation becomes more adept at their use.

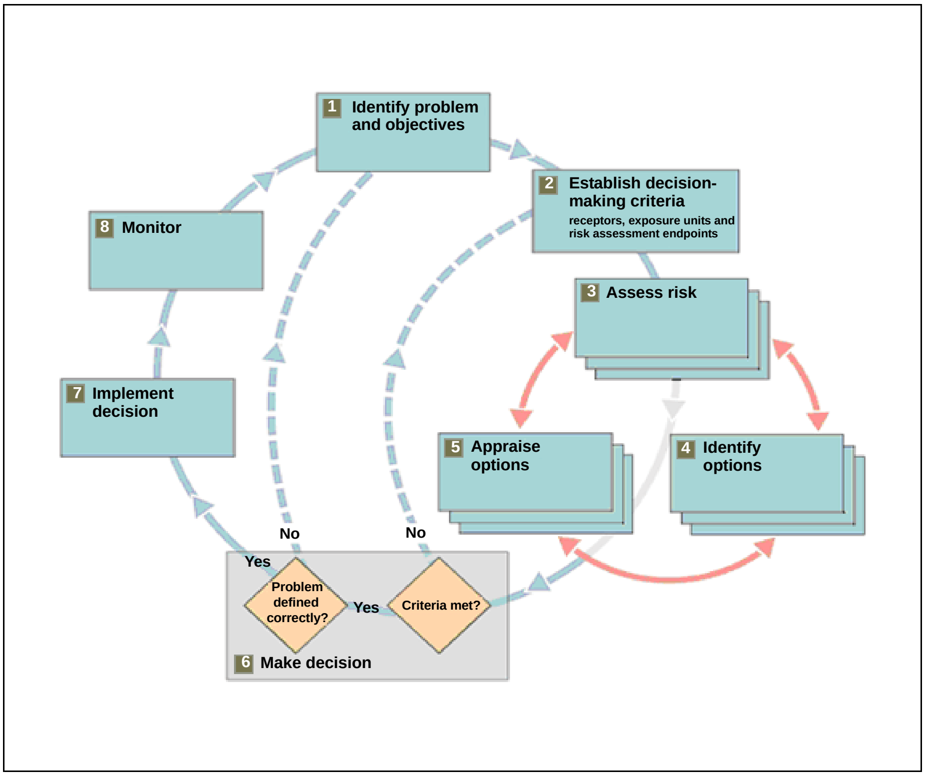


Figure 4.1. UKCIP risk management approach (Willows and Connell, 2003).

A checklist (Fig. 4.2) of climate variables against relevant impact types prepares the ground for the third stage. The checklist can be populated with data from available climate scenarios and is used to explore the range of uncertainties associated with climate events and extremes. The experience of past weather events is useful in this regard, but detail can be added as new data allow. A checklist provides the basis for an evaluation of the causal chain between climate variables, non-climate socio-economic drivers and impacts. This allows the adapting organisation to explore a variety of futures and to identify which exposure units are most vulnerable or sensitive to climate change, considering also the prospects for autonomous adaptation. It can also be used to highlight connections and interdependencies with other sectors or units.[7]

The checklist therefore provides the basis for the adapting organisation to draw up decision trees and to identify where data are available for a risk assessment, specifically:

- A characterisation of the nature of the risks and uncertainty presented by the identified impacts;

7. For example, for businesses, the UK BACLIAT has identified the six generic categories – people, premises, processes, markets, logistics and finance – for which a spreadsheet can be downloaded at http://www.ukcip.org.uk/bacliat/.

Variable	Magnitude/ Direction of projected change	Statistical basis of change (e.g. average, frequency, etc.)	Sensitivity of system change to change in variable	Nature of impact	Scale of impact	Impact on specific exposure units	Interaction with non-climate stressors	etc.
Impact types ↓								

Figure 4.2. Example checklist of climate variables (Willows and Connell, 2003, Table 7, p. 23).

- Qualitative or quantitative estimates of the scale of risk;
- An assessment of the consequences of risk or uncertainty for decision options; and
- Identification and comparison of the sources of risk and uncertainty (both climate and non-climate).

The adapting organisation must determine the relative significance of the various risks given receptors' or the organisation's own vulnerability, and assess preparedness and levels of tolerance to risk. The scale and nature of adverse impacts (or opportunities) can be identified along with any information and constraints on adaptation or thresholds (tipping points) at which impacts become more severe.[8]

The choice of specific assessment method will depend on a range of criteria, including:

- Effectiveness (i.e. will the actions meet the objectives?);
- Efficiency (will the benefits exceed the costs?);
- Equity (should not affect other vulnerable groups);
- Sustainability (of the option in itself and in meeting other sustainability objectives);
- Practicality (be undertaken within a reasonable timescale);
- Legitimacy (politically and socially acceptable); and
- Speed of implementation.

It also depends on the nature and variety of impacts and the extent to which these can potentially be quantified. This depends firstly on the data that are available and on whether risk or uncertainty is present and can be quantified or addressed. Secondly, it depends on the extent of impacts to intangible goods and the nature of these goods, primarily whether or not these can be quantified in monetary or non-monetary terms, if at all.

Where there are numerous intangible goods that cannot be quantified in monetary terms, then it may be necessary to use CEA, at least where a single or small number of adaptation options are being considered and a single objective has been defined. However, CEA is unable to address intangible goods outside of those included in the direct objectives. When there are several options to be considered in which intangibles have a significant influence, then MCA is an alternative, especially as discussed above, early in the strategy before more comprehensive data have become available.

Where good quantitative data are available and the adapting organisation is interested in reducing its exposure to climate risk, then PA is a possibility. If instead the organisation has an interest in identifying the implications and benefits beyond reducing its own exposure, then CBA begins to emerge as the appropriate option. This particularly applies in the case of central or local government investment for which economic and social well-being or distributional issues are important considerations. Information that allows for the quantification of risk, including the probability of different climate indices being realised, is ideal for a CBA. Where a good spread of quantitative data is available and where these can be fitted into a reasonably reliable time frame, then a combination of CBA, decision trees and ROA makes for a further combined approach. A simple assessment of risk is provided by multiplying the probability of an impact by its magnitude. Alternatively, where detailed estimates are not available, the probability and magnitude of impacts can be assigned values, respectively, of between (for example) 0 and 5. Stakeholder participation and experience can be used to help to quantify likelihoods and magnitudes of events. Risks can then be ranked in order of magnitude beginning with those that are high probability and a high magnitude.[9]

8. The ESPACE project provides tools for tipping point analysis and constraints mapping.

9. The ESPACE project also contains a higher-level risk screening tool to indicate where more detailed risk assessment is necessary.

However, as discussed earlier, reliance on probability-based estimates of risk is hazardous, especially in sectors vulnerable to uncertain projections or subject to extreme events. The data available to make reliable assessments may not be available for a formal ROA, but could be sufficient to permit the use of sensitivity or scenario analysis within a CBA process.

In practice, much of the data required for these more quantitative methods are unlikely to be available early in the adaptation. The exception is where a significant near-term risk has been identified or where investment is needed in major infrastructure. In these circumstances, it becomes necessary to rapidly identify the feasible options and to commence an involved process of data collection and analysis. In other circumstances, the implementation of early robust measures proceeds together with the collection and refinement of data, feedback and evaluation, as exemplified by the feedback loops contained in the adaptive risk management framework. This can permit quantified data to be incorporated into the more qualified data initially collected for the purpose of MCA.

4.4 Decision Pathways

To combine the management of risk and accumulation of data relevant to decision making within a comprehensive time frame, it is useful to map out where future climate projections are likely to impact significantly. The preliminary causal chain prepared earlier in the risk management process provides the basis for this.

Decision trees are useful for mapping out an adaptive management framework. Decision *pathways* are an extension that originate from assumption-based planning and differ from decision trees in that alternative options have been identified within a wider strategy of adaptation. Pathways are sometimes described as a *route map* in that a destination has been identified, but the steps taken to reach it remain flexible and responsive to new information and circumstances. Various pathways are assessed for their robustness based on 'what-if' scenarios of future climate change. The approach is an example of *dynamic* rather than *static* robustness (refer to Chapter 2) in that actions will have been identified to deal with the risk of failure (Walker et al., 2013). Prior 'contingency planning' provides for particular actions in the event that thresholds or 'tipping points' are realised. These tipping points will themselves have been identified earlier (for instance in Stage 3 of a UKCIP strategy). A tipping point could, for example, be an increase in temperature impacting on water supply or successive increases in sea level, e.g. 0.5 m, 1 m, 2 m, etc., for flood management.

The pathways approach permits the adapting organisation to prepare for *when* adaptation is needed and to decide *how much* is needed. Flexibility is maintained as the adapting organisation has evaluated options in response to new information or thresholds being realised. A preferred pathway connecting phased decision stages can be decided upon at the outset, but with the possibility that the route or sequencing will change as time progresses. *Decision points* occur once a switch is made between one adaptation route and another. Various decision-making tools, including economic assessment, will be relevant at successive stages. Plausible futures are identified but, unlike, ROA probabilities are not required.

Vulnerabilities and options are assessed based on climate scenarios, but an important characteristic of decision pathways is that they are scenario neutral. Objectives are set, but flexibility is maintained without the need for long-term commitments at the start of the process (Reeder and Ranger, 2011). The only requirement is that progress is monitored over time, taking account also of the latest projections for climate and permitting decision points to be brought forward where climate change is progressing faster than expected.[10] The timing of tipping points may be uncertain, but the strategy to be adopted in the event of their being exceeded (or avoided) is not. The main challenge is that extreme weather events will continue to be difficult to predict.

Figure 4.3a and b (ESPACE, 2008) shows an example of the pathways approach used in the case of the

10. According to Walker et al. (2013), actions to be taken in response to monitoring can include mitigating actions (to reduce adverse effects), hedging actions (to spread risk), seizing actions (to take advantage of new opportunities), or shaping actions (to reduce the risk of failure or increase success).

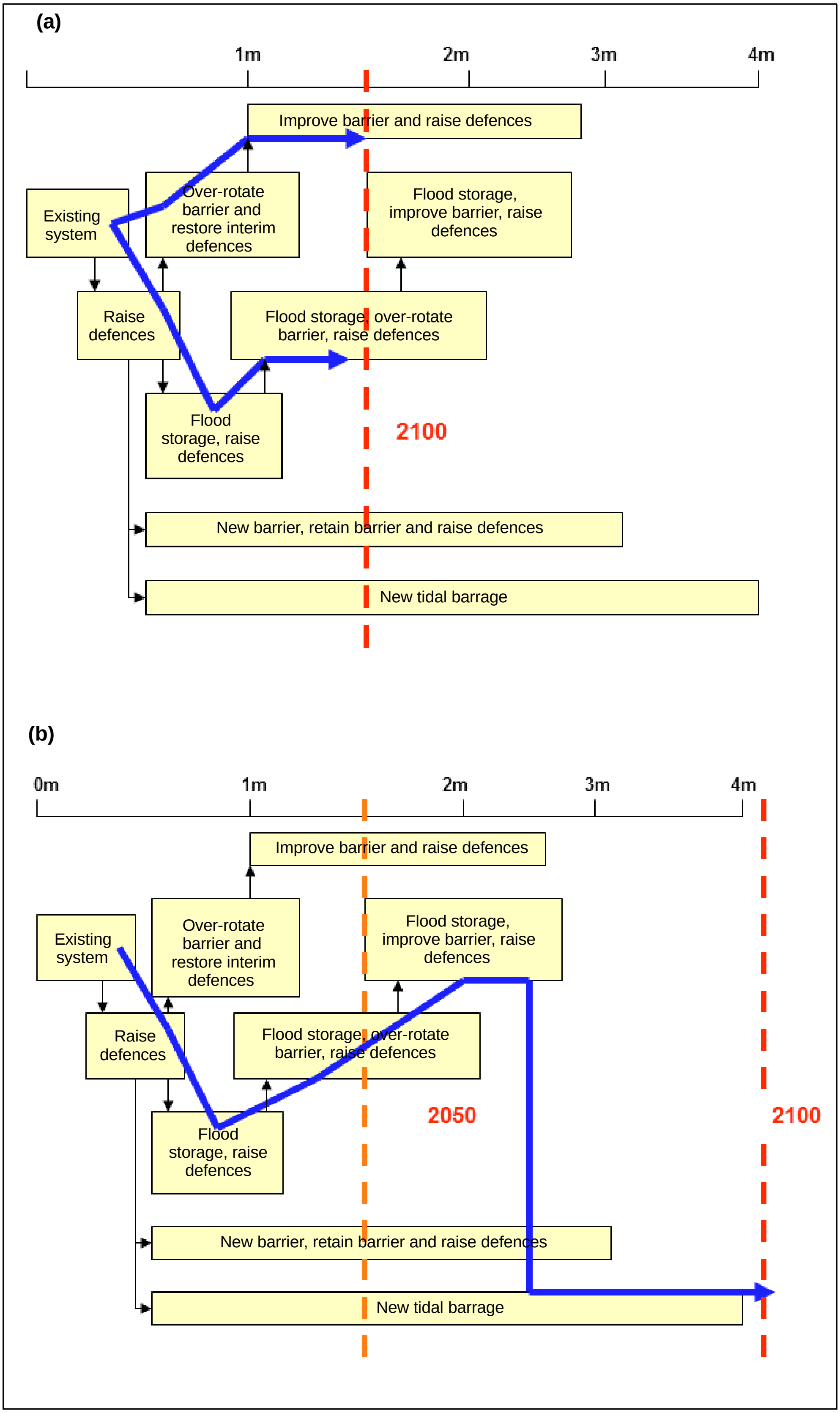


Figure 4.3. Decision pathways for a flood risk management situation (a) assuming 1.5 m rise by 2100, and (b) assuming 1.5 m rise by 2050 (Thames Estuary 2100 Project (based on Haigh and Fisher (2010), Reeder and Ranger (2011) and EEA (2013)).

options considered for the Thames Estuary 2100 Project (TE2100). Figure 4.3a shows how two options could be selected from four alternative options to manage the risk of flooding of 1.5 m by 2100 based on a Medium High Climate Change Scenario, while Fig. 4.3b shows how two alternative possible options could be selected in the event of a 1.5 m rise being realised much earlier, by 2050, based on projections from a High Climate Change Scenario. This brings forward the next more ambitious adaptation option of a tidal barrage.

A new decision is made based on the information available at each successive stage. This decision may be to continue with existing adaptation or to move onto the next suite of options. Although the preference is for inexpensive and win–win options, steps may need to be taken to implement other more ambitious adaptation options if supported by new information. For example, if the likelihood of extreme events is believed to have risen, based on new climate evidence, and if the potential cost of the impact of this extreme event is high, then it may be necessary to make a start on an appropriate adaptation option. In Fig. 4.3b, it is realised that sea levels are rising faster than anticipated and therefore decisions need to be brought forward.

4.5 Summary

This chapter has presented guidelines to demonstrate how economic assessment, including CBA, can be incorporated into an iterative adaptive risk management framework as exemplified by the UKCIP. CBA is a valuable tool in that it aims for the socially efficient solution, takes account of time and highlights trade-offs between different social groups or different environmental, social and economic resources. However, conventional CBA is ill-equipped to account for high levels of uncertainty associated with climate change. It also demands quantitative data that may be time consuming to collect or not always available. Incorporating CBA into a wider framework helps to overcome these limitations. Furthermore, the methodology can be complemented with alternative approaches such as MCA or ROA.

The adaptive risk management framework reveals how CBA can form part of a robust decision-making process as momentum develops following the early stages of win–win or low-cost options. Major projects or programmes still require economic appraisal, but the proposed framework allows for tiered levels of investigation and increasingly detailed data to be collected. It can provide for the mapping of a strategic process of iterative adaptation through the use of decision pathways in which major investments that require a CBA are flagged from an early stage.

5 Case Study of Flood Management and Adaptation

5.1 Introduction

This chapter sets out the policy background to flood management, the relationship with climate change, and methods for the assessment of adaptation options. This case study demonstrates one way in which CBA and MCA are being combined at present and introduces the use of decision trees, ROA and, potentially, decision pathways as aids and methods for the assessment of adaptation options.

5.1.1 Flood mitigation policy

5.1.1.1 Irish and European Union flood policy

After severe storm events in the eighties and early nineties, Irish policy towards flood management shifted away from land drainage and a reactive focus on localised measures. Instead, flood protection measures were directed to specific locations that were deemed to be at most risk. Further flood events led to a review of national flood policy and the subsequent report by the Flood Policy Review Group (OPW, 2003) proposed a more strategic catchment approach, with an emphasis on the management of risk and an acceptance of the inevitability of some flooding. A multi-agency strategy for the planning and management of flood mitigation was recommended, with the Office of Public Works (OPW) as lead agency.

The recommendations of the Review Group included a more proactive prioritisation of actions comprising structural measures, but also non-structural measures. Structural measures include physical engineering such as river realignment, canalisation, construction of walls/bunds and drainage. Non-structural measures range from education to improved preparedness and emergency response to flood warning systems.[11] In addition, green engineering approaches were proposed such as restoration of wetlands or natural flood plains.

Along with these national developments, the European Union Flood Directive (2007/60/EC) was transposed into Irish law in 2010. The Directive confirmed that flood policy should be guided by a risk management approach. It required Member States to take common actions, including a preliminary flood risk assessment for all major river basins followed by the completion of flood hazard and flood risk maps by 2013 and flood risk management plans by 2015. These actions are to be co-ordinated with the objectives of the Water Framework Directive (WFD).

11. In adaptation terminology, these measures could alternatively be described as grey and soft adaptation.

5.1.1.2 The CFRAM Programme

The OPW has initiated Catchment Flood Risk Assessment and Management (CFRAM) Studies to provide strategic flood risk management plans to identify the most cost-effective and sustainable measures to manage flood risk. These plans address all areas of flood risk management, including prevention, protection and preparedness. The revised strategy was broadly endorsed by a value-for-money (VFM) review (Goodbody, 2008). This recommended consideration of the likelihood of events, the sensitivity of communities to flooding and an assessment of the expected scale of impacts.

Although not designed to address climate change, the CFRAM Programme contains the elements of a robust approach to adaptive risk management. The preparation of the management plans considers the sensitivity of communities to current and potential future flooding and of measures to strengthen preparedness based on forecasts and early warning systems. Predictive flood hazard maps are prepared to underpin an integrated and proactive response to risk in relation to two potential flood scenarios. Measures are selected on the basis of an MCA in which benefits are identified and allocated a score. Adaptation is part of the design philosophy and is one of the criteria assessed in the MCA, which is undertaken in parallel with a more quantitative CBA. However, as specific measures are not assessed in detail at this stage, the CBA is in outline form.

The flood hazard maps define flood extents and depth in areas of potentially significant risk (APSRs) and for associated river catchments (fluvial APSRs). The assessment of appropriate measures is undertaken at four spatial scales. The CFRAM Studies assess a range of adaptations from engineering works to non-structural methods, including raised awareness, warnings and possible soft engineering works. In addition, the Studies identify individual risk receptors (IRRs) such as assets of economic, infrastructural or social importance. New data on flood risk assist the compilation of source-pathway-receptor models by planning authorities in line with the Planning System and Flood Risk Management Guidelines (Environ and OPW, 2009). These are intended to guide and inform future spatial planning in areas at risk of flooding and to arrive at projections of flood hazard based on probabilities, extent, depth and possible velocity, and rate of onset. Where data on climate change are not available, planning authorities are asked to take a precautionary approach by basing their assessment on the guidelines for more severe flood zoning.

The pilot CFRAM Studies included the assessment of flood hazard and risk for a Mid-Range Flood Scenario (MRFS) and a High-End Flood Scenario (HEFS), as well as for current conditions. In response to these projections, the consultants were required to propose defence options from which preferred solutions are subjected to flood simulation modelling. This approach provides the opportunity for the assessments to be linked to climate projections in the future. Flood risk is modelled for four receptor groups.

1. **Social groups**
   - Residential properties (inhabitants to be divided by the number of properties)
   - Sites or facilities relevant to vulnerable population subsets
   - Valuable social infrastructure (e.g. fire stations, etc.)
   - Social amenities
2. **Environmental risks**
   - Sites presenting pollution risk
   - Vulnerable areas identified under the WFD
   - Other vulnerable or valuable sites such as Special Areas of Conservation (SACs)
3. **Risks to cultural heritage**
4. **Economic risks**
   - Location, type and numbers of residential and non-residential property
   - The density of risk based on annual average damage per unit area
   - The location, type and vulnerability of transport infrastructure
   - The location, type and vulnerability of utility infrastructural assets

As noted above, options are subjected to MCA. Irish guidelines (Department of Finance, 2005) countenance the use of MCA for projects valued at between €5 and €30 million. MCA is used in the CFRAM Programme to assess technical, economic, social and environmental criteria of options in relation to overall objectives. Each set of criteria is weighted based on its importance or sensitivity both in terms of national significance using a global weighting (GW) of 5–30, and local significance using a local weighting (LW) of 0–5. A score (S) defines whether a measure partly, or fully, meets its minimum or aspirational target. The process results in a weighted score (WS) for each option, i.e.

$$WS = (GW \times LW) \times S.$$

The CBA is prepared for the potentially viable set of flood risk management options based on the performance criteria above. Outline costs and benefits are prepared, the latter based on annual average damage predictions for a range of flood probabilities. These are related to assumptions on the points at which flood management infrastructure would be expected to fail (analogous to RDM). Monetary costs and benefits are compared using CBA and an MCA is presented alongside the estimated BCR. Proposed actions are fitted into time phases depending on their urgency.

The assessment of management options is guided by a sensitivity-based approach that assumes an increasing level of hazard and risk from climate change. An adaptive approach is applied to the design and implementation of specific strategies. This allows for an option to be amended in a technically feasible or cost-efficient manner in the future if necessary.

Of the studies undertaken to date, the River Lee CFRAM Study is of interest in the context of climate change, given the risk faced by Cork City from a mix of fluvial flooding and storm or tidal surges. The study observes that a tidal barrage would become beneficial on cost–benefit grounds in the event of a 315 mm rise in sea level. A sea level rise of this order is predicted to occur between 2050 and 2075.

5.2 Methods for Assessing the Benefits of Flood Risk Management

An assessment of the net benefits of flood mitigation requires an analysis of the efficacy of a scheme in relation to damage costs avoided. These costs will, amongst other factors, depend on the size of the relevant population, its vulnerability to possible loss of life, the mix of residential and non-residential property, and the presence of critical infrastructure. *The Benefits of Flood and Coastal Risk Management:* A *Handbook of Assessment Techniques* (Penning-Rowsell et al., 2010), produced by the Flood Hazard Research Centre in the UK, is widely referenced, including by the CFRAM Programme, for guidance on the economic assessment of flood relief schemes. The Handbook recommends a process that commences with an assessment of risk in terms of the probability of future flood events, followed by a vulnerability assessment of the benefits of damage avoided. CBA is proposed to compare the do-something alternative with the do-nothing scenario, although the Handbook recommends that a sensitivity analysis of options is first performed. Incremental BCRs are defined for each economically viable option that meets an appropriate level of risk management.

The economic assessment is informed by economic welfare approaches, including estimates of WTP (see Section 3.2) to disaggregate benefits to different interest groups. *The Green Book: Appraisal and Evaluation in Central Government* (HM Treasury, 2013) is referenced for guidance on CBA, including for variable discount rates for projects of long duration and for weighting and scoring approaches relevant to objectives and distributional impacts. An Irish appraisal would naturally be guided by respective government publications (Department of Finance, 2005; CEEU, 2011).

The Handbook identifies a role for MCA for the comparison of options with reference to a broader set of objectives and criteria that may be available for quantification in a CBA. The inclusion of MCA is argued to complement the use of CBA and also has the value of adding transparency for the purpose of stakeholder involvement. For flood-related expenditure, the Handbook summarises the weightings that are used to indicate social classes at risk[12], the treatment of residential properties including property values, non-residential property and other types of flood damage including disruption and emergency services. Environmental valuation methods are recommended for situations where data exist, but with MCA for occasions where these are not available.

5.3 Climate Change

5.3.1 Climate change projections

Since the mid-seventies, annual rainfall amounts appear to have increased by 10%, with much of the increase occurring in the spring and late autumn (Kiely et al., 2012). Research by Murphy and Charlton (2007) based on the A2 SRES scenario (medium-high emissions) suggests that, by the 2020s, nearly all catchments will display an increase in the frequency of flood events that have hitherto tended to occur once every 2 years. In addition, simulations suggest that the magnitude of flood events is also likely to increase.

Subsequent research by Bastola et al. (2011) has examined the sensitivity of the 20% design allowances allowed for in the MRFS CFRAM Studies. The results for the Rivers Blackwater, Moy, Suck and Boyne demonstrate the relatively narrow range of the total uncertainty space that is protected by the existing design allowance. In the first instance, Bastola et al.

12. Average annual damage to unprotected properties is put at £5,393 stg. The Guidance (HM Treasury and DEFRA, 2009) recommends weighting only where social classes AB or DE are predominant. Weightings are: AB = 0.74, C1 = 1.12, C2 = 1.22, DE = 1.64.

found that the seasonality of rainfall appears to be becoming more pronounced. In particular, they found that the potentially adverse impact is greater for low-frequency, high-impact events than for high-frequency events. These events are reflected in the 'fat tail' of a damage probability distribution. The authors conclude that the very nature of extreme events means that they are near impossible to predict and that adaptation is best addressed through approaches that are robust to uncertainty.

5.3.2 Consideration of climate adaptation in flood management

The OPW guidance for the CFRAM Programme proposes an MRFS and a HEFS relating to a future 500 mm and 1,000 mm rise in sea level by 2100 and a 20% and 30% rise in rainfall depth and flood flows. The ranges are not formally associated with IPCC scenarios and have not explicitly taken into account national climate change projections. The scenarios are rather intended to provide 'representative futures' within the plausible range of climate projections so as to enable an assessment of the vulnerability of communities and to inform appropriate adaptation strategies. Nevertheless, the CFRAM procedure resembles many of the elements discussed in previous chapters, including assessment of vulnerability, robust strategies of soft and hard engineering, flexibility, quantification of non-market benefits and respective use of MCA and CBA.

These types of strategies are also proposed by the UK Adaptation Sub-Committee (ASC, 2012), which recommends a robust approach to adaptation beginning with low-regret solutions. In the first instance, it proposes the removal of barriers to adaptation and the use of various non-structural measures for flood management. The latter could encompass an adjustment of incentives (e.g. tax incentives for household protection), reductions in behavioural barriers, improved adaptive capacity and strategic land use planning (Box 5.1).

The ASC proposes a toolkit whereby the adequacy of flood management measures can be evaluated over time using various indicators, namely:

- Indicators of risk;
- Indicators of adaptation actions; and
- Indicators of climate change.

The indicators can be used to demonstrate how key criteria vary over time. Indicators of risk, for instance, involve an assessment of current and future risk and may include levels of preparedness through to indicators that demonstrate changes in vulnerability and exposure. Candidates could include the number of properties in a flood plain, the number of properties at risk of flooding (accounting for/not for defences), rates of development, the area of hard surfaced ground, vulnerable infrastructure and vulnerable populations/ subgroups at risk. Indicators of action can include the reductions in the number of properties at risk due to new defences, the effect of measures undertaken at the level of individual properties and the management of surface water (e.g. separation of run-off from sewage, sustainable urban drainage systems (SUDS), etc.).

5.4 Robust Decision-Making and Real Options Approaches

5.4.1 Optimisation

In practice, there is a wide variety of measures available for flood managers to choose from. In a report by the Flood Risk Management Research

Box 5.1. Projecting the benefits of non-structural measures

Dawson et al. (2011) lend support for the non-structural approach, finding that such measures can make a significant difference. Taking various UK foresight socio-economic scenarios for the Thames catchment, they find that measures such as spatial planning and insurance incentives related to flood risk and levels of household adaptation can make a considerable difference to the level of risk presented by selected scenarios. Their model demonstrates that much of the difference in the gross level of risk arises from the spread of new development and the value of property, factors that can be picked up by the indicators of risk advocated by the ASC.

Consortium (Gouldby et al., 2012), Michelle Woodward describes how a conventional, if formal optimisation, method can be used to trade off various options and to select the best performing options through either single or multi-objective algorithms that maximise NPV. However, optimal solutions do not usually exist where deep uncertainty is present. Woodward et al. (2011) therefore describe how the approach can be modified to select the most robust solution, i.e. robust optimisation, rather than the highest NPV. This approach is analogous to the formal RDM of Groves and Lempert (2007). They refer to Beyer and Sendhoff (2007) who demonstrate how optimisation algorithms can be modified to account for uncertainty by searching for robust solutions rather than ones that maximise economic criteria. An advantage of this approach is that elements of competing options can be allowed to remain in their native metric rather than being monetised for the purposes of an NPV estimate. For example, reduced loss of life could be compared against cost akin to CEA. The output from the multidimensional model is a series of trade-offs along a Pareto optimal frontier connecting the most robust options.

5.4.2 ROA

There are several challenges to the application of the formal optimisation approach. Firstly, it requires a high level of quantitative modelling skills, particularly in cases where many factors are involved (flood damage is rarely a consequence of rainfall alone). Secondly, there is the uncertainty attached to projections of climate change. Conventional economic methods estimate NPV over a project's lifetime and use sensitivity analysis to examine a range of outcomes. However, as Bastola et al. (2011) found, the distribution of rainfall events may be characterised by distributions with 'fat tails'. Furthermore, many flood management investments are not 'now-or-never', but rather lend themselves to phasing over time.

Given the problem of uncertainty, the HM Treasury Green Book appended Supplementary Guidance to address climate change (HM Treasury and DEFRA, 2009). This includes an illustration of ROA. ROA functions best where there are estimates of probability. However, it attaches an economic value to maintaining flexibility by preserving an option to act analogous to a call option in financial trading (Copeland and Antikarov, 2003). The method anticipates the potential for new information on future damage costs (learning) and a capacity to choose from a range of options and to modify these as time goes by (flexibility).

A simple example often used in flood management is that of providing a wider base for dykes or flood walls. This permits the flood manager the flexibility to upgrade the defences with taller walls in the future if this strategy is confirmed by new information. The Supplementary Guidance used just such an example in its decision-tree approach, which is reproduced below (Box 5.2). In this simple example, decisions are made at two points for two alternative future climate outcomes. This demonstrates how investment alternatives examined within ROA can yield quite different results and conclusions. In the example, higher values are returned from maintaining flexibility with an upgradeable wall in contrast to the net benefits of between –€40,000 and –€75,000 that would be realised in the event of a low climate impact scenario based on the erection of a standard wall. The difference in the economic estimates of alternative options provides a measure of the risk premium that can be used to justify expenditure on incentives or other incremental investments (Blyth and Watkiss, 2011). Maintaining flexibility can rarely be achieved without additional cost, but this must be weighed against the benefits (Hino and Hall, 2014).

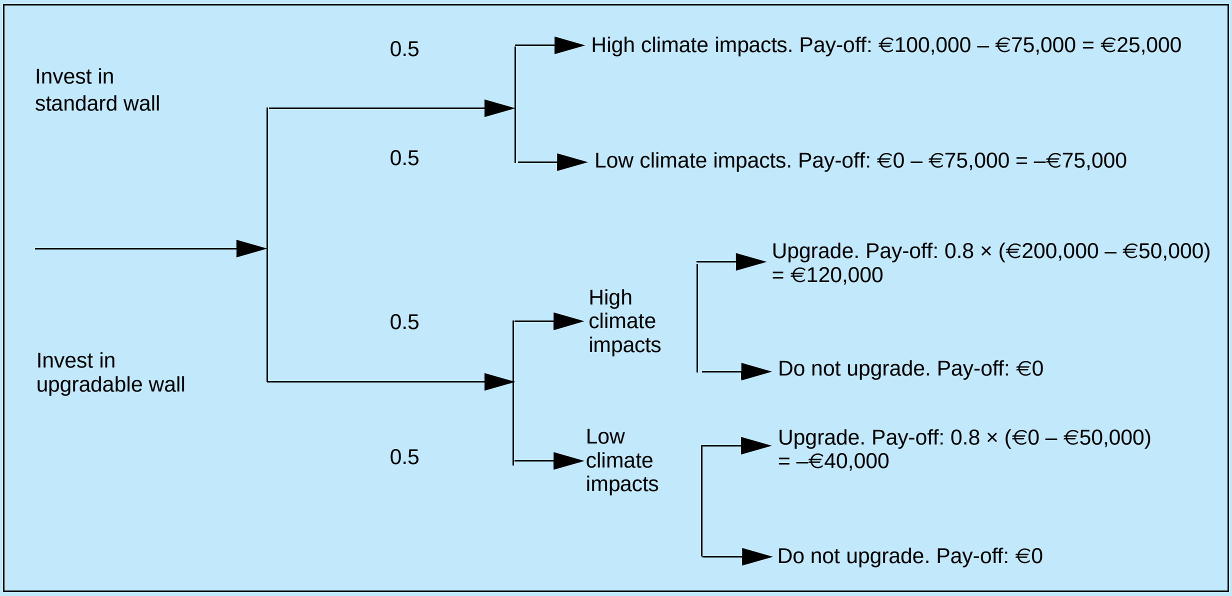
The flood mitigation decision follows successive paths selected at decision points on the basis of the threshold criteria available at that time. Woodward et al. (2011) demonstrate the value of preserving flexibility with the example of the TE2100 project. The resilience of flood defences to various flood loading levels is defined by fragility curves (failure risk) combined with estimates of the economic consequences of a breach. This provides the evidence for estimating the pay-off of different options.

5.4.3 Practical applications

There is a strong case for maintaining flexibility and allowing for new information in the future, but the practical obstacles to a formal application of ROA are many, namely:

Box 5.2. Real options example

The flood planner faces the options of whether to invest in a standard flood wall or in a wall with a wide foundation that can be upgraded in the future. At the outset, there is an equal probability of high or low climate impacts (0.5). The standard wall costs €75,000 and has potential benefits of €100,000 from damage avoided. The upgradeable wall costs €50,000 and benefits of €200,000 from damage avoided in the event of a high-impact event being realised. The calculation for the upgradeable wall includes a discount rate given that some of the investment is deferred to the future.



At the outset, the expected value of the standard wall is the average of the two possible outcomes, i.e. NPV = (0.5 × €25,000) + (0.5 × –€75,000) = –€25,000. The negative NPV suggests that the project should not proceed. The estimated value of maintaining the option to upgrade a wall in the future is €120,000 in the event of high climate impacts, assuming a discount factor of 0.8 or –€40,000 in the event of low impacts. The expected value of investing in the option to upgrade is NPV = (0.5 × €120,000) – €50,000 = €10,000. Hence, the upgradeable option is superior.

The reverse outcome could be realised with another discount rate of a different pay-off estimate, but the example shows how a decision-tree analysis can reveal alternatives.

- The IPCC has withheld from attaching probabilities to climate projections. There is a wide probability range attached to precipitation and flood events that can obscure the possibility of low-probability/high-impact events.
- Hydrological models contain their own level of uncertainty. The models examine the relationship between depth and velocity, but may break down in response to sudden rainfall events and flood velocities that determine where a breach will occur. Complex climate models must somehow be combined with the equally complex dynamic hydrological models (Murphy et al., 2011).
- The approach is best applied in circumstances where major infrastructural investments can be adopted in an incremental manner.
- Real flood management decisions at the catchment scale involve a multitude of options, structural, non-structural, small and large, not all of which can be assessed using quantitative data.

Without probabilities reliance on formal optimisation can be meaningless. However, it is possible to apply a range of probability weights so long as these are used for the purpose of a sensitivity analysis and are not taken at face value. Simulation (e.g. Monte Carlo) can be used to examine a wide range of outcomes so as to reveal the extent of risk and the performance of key flood management measures in more extreme events.

The benefit of flood protection is the reduction in risk (residual risk) of damage. In principle, it is possible to estimate economic damage functions in combination with socio-economic trends. While there is a wide range of possible scenarios, the inclusion of selected scenarios could be informative in demonstrating the consequences of low-frequency/high-impact events. The economic data could be confined to physical damage to structures, but also extended to a broad estimation of loss of life, habitats and social impacts using non-market methods. If the economic estimates of this damage are considered to be too imprecise or to require excessive primary research, MCA can initially be used in the assessment as it is for CFRAM Studies.

Hino and Hall (2014) demonstrate a variation on ROA in the field of spatial planning. They show how ROA does not have to be restricted to estimates of an optimal NPV or BCR at the outset of the process, but that decision points can be determined by the time at which a combination of climate outcomes and new information cause the BCR to exceed a particular value. With protection measures having already been identified, this threshold determines which option will be selected. They find that implementing a fixed design in Year 1 typically yields a higher BCR, but that the risk of a low BCR being realised is greater than with a flexible design. There remains scope to consider options based also on indicators or evidence of residual flexibility and robustness.

The key strength of the ROA approach is the use of a decision tree to conceptualise the investment problem and to map out alternative options (Blyth and Watkiss, 2011). However, decision trees are not unique to ROA, the limitations of which arise from the difficulty of applying probabilities where climate projections must be combined with other areas of significant uncertainty such as hydrology and socio-economic criteria. Moreover, options do not have to be found along a single branch of a decision tree, but can be connected by pathways within a wider strategy of adaptive risk management.

A pathways approach requires possible options to be identified at the outset of a process and adopted once thresholds are realised. Thresholds can potentially be supported by a parallel economic exercise that estimates costs and the benefits of damage avoided or be equally represented by the BCR exceeding a predetermined threshold. This, however, still assumes estimates of the probability of events (including non-climate events) even if the timing of those events is unknown.

A suite of measures with respective NPVs can be prepared based on a range of probabilities estimated using current information, but regularly revised. In contrast to formal ROA, the pathways approach does not have to rely on these estimates. Its key aim is to preserve flexibility through a map of future possible measures that does not direct the decision maker to follow a route towards a narrow range of options actions based on outdated projections. Rather, trigger points for the implementation of measures or the redirection of adaptation are physical climate variables such as seasonal precipitation. The approach therefore remains flexible by connecting a hierarchy of non-structural and structural adaptation options. Many of the former will represent smaller steps that will have been identified for implementation earlier. Robust decision-making rules are applied through the selection of a succession of measures beginning with those that are low regret. Autonomous adaptation can be incentivised by modest changes in policy, tax breaks or insurance that will increase the robustness and impact of adaptation.[13]

5.5 Summary

The current approach to flood management is intended to assess vulnerability, to guide adaptation and to

13. The need for public information is underpinned by the observation that adaptation is lagging at the household level. Adger et al. (2012) report a relative unwillingness by households in Galway to take autonomous measures despite residents' dissatisfaction with the authorities' response to flooding in 2009.

identify possible measures. Detailed design and adaptation would follow at a subsequent stage. The approach relies heavily on hydrological models and allowances for fixed levels of climate change. Simulation is used to indicate the circumstances under which a defence can be expected to fail. There are elements of RDM and a decision-tree approach in terms of the phasing of activity allowing for a reassessment in response to new information in 6-yearly reviews.

In terms of economic analysis, costs and benefits are estimated, but tend to have been confined mainly to property impacts rather than non-market values relating to disruption, social impacts, impacts on wildlife, etc. These additional, but very relevant, factors can be captured within a CBA or by MCA if they cannot be quantified. The CFRAM approach does not combine these methods, but rather compares the results side by side.

This chapter has illustrated how ROA can inform adaptation choices. The method can be formalised as an optimisation process requiring quantitative information, probabilities and estimates of NPV. However, this information may not be available in a situation of high uncertainty. Instead, there are benefits to identifying a variety of adaptation options at the outset that could be successively selected using a pathways approach in response to physical tipping points. Furthermore, there is scope to use economic analysis to estimate the benefits and costs associated with these options and to identify BCR coincident with physical tipping points being realised.

6 Conclusion and Recommendations

To date, much international activity has revolved around forging agreement on the science of climate change and debating the merits of strategies or targets to mitigate emissions of greenhouse gases. National governments are also drawing up strategies for adaptation, but practical measures, especially of the type that will need to be taken at local level, have been few in number. As the more extreme medium and long-term projections for climate change could involve significant economic and social costs, it is imperative that steps towards adaptation are made sooner rather than later. This is especially so given that some options will involve compromises for economic sectors, communities and the natural environment that demand co-ordinated strategies between different departments or agencies.

A constraint to the implementation of adaptation has been the considerable uncertainty presented by climate change. International institutions are struggling to repackage projections of climate in ways that communicate the potentially serious implications without discouraging policy makers from implementing appropriate measures. Specifically, this study had the objective of exploring the potential for applying economic appraisal methods, such as CBA, to inform adaptation choices. CBA is required by many governments for larger investment projects or programmes, including by the Irish Government. The report describes the characteristics and virtues of CBA and argues that it is a valid methodology for appraising adaptation options. It can also be a very suitable method for weighing up the distributional impacts of climate change and for quantifying impacts on non-market sectors. However, used in isolation, CBA is rather poorly equipped to deal with the high level of uncertainty associated with climate change.

Consequently, this study recommends that economic appraisal is undertaken within a wider framework of adaptive risk management. This approach acknowledges that adaptation must conform to the circumstances and environment in which strategic decision making occurs in practice within central government, local authorities and the private sector. Uncertainty has always been an element in such decision making and so is not unfamiliar. However, the context for adaptation is one where the benefits do not occur in the form of tangible economic gains or improvements to quality of life, but rather in terms of damage avoided. There may still be a sound case for major financial commitments where NPV is positive, but the incentive for decision makers is diminished where the outcome appears very uncertain.

The approach proposed here is one in which adaptive risk management begins, where possible, with robust adaptation measures that are with no regret, low cost or win–win, that provide ancillary benefits and that prime the adapting organisation for progressively more ambitious measures. Iterative steps are taken to build the information base, to respond to new information, to accumulate expertise, and to strengthen and incentivise adaptive capacity. In this respect, the recommended approach mirrors that of the advice provided at European Union level and reflected in other national initiatives such as the UKCIP.

The report also recommends that a framework of adaptive risk management adopts a decision-pathways approach. Although iterative in terms of stages, adaptation needs direction and broadly defined objectives from the outset. This approach avoids the prospect of adaptation occurring within a void of uncertainty, as decision makers will have prepared a range of adaptation options and be aware of the climatic indices that would trigger the implementation of any one option. Information is still collected over time and the detailed data required for economic assessment should be available prior to a decision point being reached. Only the route to adaptation is undecided at the outset as it must remain flexible to changing circumstance and new information.

In summary, this approach is characterised by:

- The progressive appraisal of adaptation options within an adaptive risk management framework;

- Superimposing decision pathways to manage uncertainty once the essential climate risks are understood. Adaption options are identified along with the climatic indices that would trigger their implementation;
- An assessment of the vulnerability and the implementation of robust adaptation measures to reduce this vulnerability and increase resilience;
- The selection of further robust adaptation measures that are resilient to changing circumstances, low cost and that deliver win–win outputs, where possible, including resilience to more familiar climate events; and
- Appraisal methods that begin with qualitative or score-based approaches and which culminate in more quantitative methods, such as CBA, where there are implications for social well-being.

The authors recommend that the practicalities of this approach and the application of economic appraisal methods be examined for various national and local organisations. Ideally, this should occur in collaboration with a state agency or major local authority that can supply access to relevant non-climate data for the purpose of benefit and cost estimation.

References

Aal, C. and Groven, K., 2013. *The Need to Move from Mastering to Coping with Climate Uncertainties*. European Climate Change Adaptation Conference: Integrating Climate into Action, Hamburg, Germany.

Adger, W.N., Arnell, N.W. and Tompkins, E.L., 2005. Successful adaptation to climate change across scales. *Global Environmental Change Part A* **15(2):** 77–86.

Adger, W.N., Agrawala, S., Mirza, M.M.Q., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B. and Takahashi, K., 2007. Assessment of adaptation practices, options, constraints and capacity. *In:* Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. (Eds) *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 717–743.

Adger, N.W., Quinn, T., Lorenzoni, I., Murphy, C. and Sweeney, J., 2012. Changing social contracts in climate-change adaptation. *Nature Climate Change* **3:** 330–333.

Agrawala, S. and Fankhauser, S., 2008. *Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments*. OECD, Paris, France.

Ando, A.W. and Mallory, M.L., 2012. Optimal portfolio design to reduce climate-related conservation uncertainty in the Prairie Pothole Region. Sustainability Science. *Proceedings of the National Academy of Sciences* **109(17):** 6484–6489.

ASC, 2012. *Climate Change – Is the UK Preparing for Flooding and Water Security?* Adaptation Sub-Committee Progress Report 2012. UK Adaptation Sub-Committee (ASC), London, UK.

Bastola, S., Murphy, C. and Sweeney, J., 2011. The sensitivity of fluvial flood risk in Irish catchments to the range of IPCC AR4 climate change scenarios. *Science of the Total Environment* **409:** 5403–5415.

Beyer, H.G and Sendhoff, B., 2007. Robust optimization – a comprehensive survey. *Computer Models in Applied Mechanics and Engineering* **196:** 3190–3218.

Blyth, W. and Watkiss, P., 2011. *Critical Review and Synthesis of Applications of Real Options Analysis*. Stockholm Environment Institute, Oxford, UK.

Bosello, F., Carraro, C. and De Cian, E., 2009. An analysis of adaptation as a response to climate change. *In:* Lomborg, B. (Ed.) *Smart Solutions to Climate Change*. Cambridge University Press, Cambridge, UK.

Bosello, F., Nicholls, R.J., Richards, J., Roson, R. and Tol, R.S.J., 2012. Economic impacts of climate change in Europe: sea level rise. *Climate Change* **112:** 63–81.

Bourque, A., 2012. *Informing and Advising on Climate Change Adaptation in Canada: A Decade of Experience.* Second Nordic International Conference on Climate Change Adaptation, Helsinki, Finland.

Boyd, R., Wade, S. and Walton, H., 2006. Climate change impacts and adaptation. *In:* Metroeconomica (Ed.) *Cross-Regional Research Programme Project E*. Final Report. DEFRA, London, UK.

Bradfield, R., Wright, G., Burt, G., Cairns, G. and Heijden, K.V.D., 2006. The origins and evolution of scenario techniques in long range business planning. *Futures* **37:** 795–812.

Brown, A., Gawith, M., Lonsdale, K. and Pringle, P., 2011. *Managing Adaptation: Linking Theory and Practice*. UKCIP, Oxford, UK.

Bullock, C., 2008. Valuing urban green space: hypothetical alternatives and the status-quo *Journal of Environmental Planning and Management* **51:** 1–35.

Bullock, C.H. and Collier, M., 2011. When the public good conflicts with an apparent preference for unsustainable behaviour. *Ecological Economics* **70:** 971–977.

Burton, I., 2009. Climate Change and the Adaptation Deficit. *In:* Schipper, E.L.F., Burton, I. (Eds) *The Earthscan Reader on Adaptation to Climate Change*. Earthscan, London, UK.

Burton, I., Huq, S., Lim, B., Pilifosova, O. and Schipper, E.L., 2002. From impacts assessment to adaptation to adaptation priorities: the shaping of adaptation policy. *Climate Policy* **2:** 145–159.

Carter, T., 2012. *Progress in the Development of New Scenarios to Support IAV Research*. Nordic Conference on Climate Adaptation, Helsinki, Finland.

CEC, 2007. *Adapting to Climate Change in Europe – Options for EU Action.* COM(2007) 354, Commission of the European Communities, Brussels, Belgium.

CEC, 2009. *Adapting to climate change: Towards a European Framework for Action.* White Paper. Commission of the European Communities, Brussels, Belgium.

CEC, 2013. *An EU Strategy on Adaptation to Climate*

Change. COM(2013) 216. Commission of the European Communities, Brussels, Belgium.

CEEU, 2011. *Guide to Economic Appraisal: Carrying Out a Cost Benefit Analysis*. The Public Spending Code. Standard Analytical Procedures. Central Expenditure Evaluation Unit, Dublin, Ireland.

Cimato, F. and Mullan, M., 2010. *Adapting to Climate Change: Analysing the Role of Government.* DEFRA Evidence and Analysis Series, Paper 1. DEFRA, London, UK.

Clinch, J.P., 2006. Cost-benefit analysis of Irish forest policy*. In:* Pearce, D. (Ed.) *Environmental Valuation in Developed Countries*. Edward Elgar, Cheltenham and Northampton, UK. pp. 15–35.

Copeland, T. and Antikarov, V., 2003. *Real Options: A Practitioner's Guide*. Cengage Learning, New York, USA.

Crowe, K.A. and Parker, W.H., 2008. Using portfolio theory to guide reforestation. *Climate Change* **89:** 355–370.

Dawson, R., Ball, T., Werritty, J., Werritty, A., Hall, J.W. and Roche, N., 2011. Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socio-economic and environmental change. *Global Environmental Change* **21:** 628–645.

De Bruin, K., Dellink, R.B. and Agrawala, S., 2009. *Economic Aspects of Adaptation to Climate Change: Integrated Assessment Modelling of Adaptation Costs and Benefits*. OECD Working Paper. OECD, Paris, France.

DECLG, 2012. *National Climate Change Adaptation Framework*. Department of Environment, Community and Local Government, Dublin, Ireland.

DEHLG, 2007. *National Climate Change Strategy 2007–2012.* Department of the Environment, Heritage and Local Government, Dublin, Ireland.

Deltacommissie, 2008. *Working together with Water: A Living Land Builds for its Future*. Deltacommissie, The Hague, The Netherlands.

Department of Finance, 2005. *Guidelines for the Appraisal and Management of Capital Expenditure Proposal in the Public Sector*. Department of Finance, Dublin, Ireland.

Department of Finance, 2006. *VFM Circular letter of 25 January 2006*. Department of Finance, Dublin, Ireland.

Department of Transport, 2009. *Guidelines on a Common Appraisal Framework for Transport Projects*. Department of Transport, Dublin, Ireland.

Desmond, M. and Shine, T., 2011. *National Adaptive Capacity Assessment*. Climate Change Research Programme. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland.

Desmond, M. and Shine, T., 2012. *Integrating Climate Change Adaptation into Sectoral Policies in Ireland*. Climate Change Research Programme. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland.

Desmond, M., O'Brien, P. and McGovern, F., 2009. *A Summary of the State of Knowledge of Climate Change Impacts for Ireland*. Climate Change Research Programme. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland.

Dessai, S. and Hulme, M., 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: A case study of water resources management in the east of England. *Global Environment Change* **17(1):** 59–72.

Dessai, S. and van der Sluijs, J., 2007. *Uncertainty and Climate Change Adaptation – a Scoping Study*. Report prepared for the Netherlands Environmental Assessment Agency Copernicus Institute, Utrecht University, The Netherlands.

Dessai, S., Hulme, M., Lempert, R. and Pielke, R., 2009. Climate prediction: a limit to adaptation. *In:* Adger, N., Lorenzoni, I. and O'Brien, K. (Eds) *Adapting to Climate Change: Thresholds, Values, Governance*. Cambridge University Press, Cambridge, UK.

Dewar, J.A., 2002. *Assumption-Based Planning: A Tool for Reducing Avoidable Surprises*. Cambridge University Press, Cambridge, UK.

Dewar, J.A., Builder, C.H., Hix, W.M. and Levin, M.H., 1993. *Assumption-Based Planning: A Planning Tool for Very Uncertain Times*. RAND Corporation, Santa Monica, CA, USA.

Dodgson, J., Spackman, M., Pearman, A., Phillips, L., 2000. *Multi-Criteria Analysis Manual*. National Economic Research Associates, London, UK.

Dorfman, R., 1972. Risk and uncertainty in cost–benefit analysis. Chapter 15. *In:* Layard, R. (Ed.) *Cost–Benefit Analysis*. Penguin Books, Harmondsworth, Middlesex, UK.

Dunne, S., Hanafin, J., Lynch, P., McGrath, R., Nishimura, E., Nolan, P., Ratnam, J. V., Semmler, T., Sweeney, C., Varghese, S and Wang, S., 2008. *In:* McGrath, R. and Lynch, P. (Eds), 2008. *Ireland in a Warmer World. Scientific Predictions of the Irish Climate in the Twenty First Century*. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland.

Dwyer, N., 2012. *The Status of Ireland's Climate*. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland. pp. 157.

EC, 2008. *Guide to Cost–Benefit Analysis of Investment Projects*. European Commission (Directorate General Regional Policy), Brussels, Belgium.

EEA, 2005. *Vulnerability and Adaptation to Climate Change in Europe*. European Environment Agency, Copenhagen, Denmark. Technical Report No. 7/2005.

EEA, 2012. *Climate Change, Impacts and Vulnerability in Europe 2012*. European Environment Agency, Copenhagen, Denmark.

EEA, 2013. *Adaptation in Europe*. European Environment Agency, Copenhagen, Denmark.

Environ and OPW, 2009. *The Planning System and Flood Risk Management Guidelines for Planning Authorities*. Department of the Environment, Heritage and Local Government and Office of Public Works, Dublin, Ireland.

ESPACE, 2008. *Climate Change Impacts and Spatial Planning Decision Support Guidance*. Environment Agency and Halcrow, UK.

European Union, 2008. *Guide to Cost Benefit Analysis of Investment Projects*. European Union, Brussels, Belgium.

Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Saul, A., Sayers, P., Thorne, C. and Watkinson, A., 2004. *Foresight: Future Flooding. Scientific Summary.* Volumes 1 & 2. Office of Science and Technology, London, UK.

Evans, E., Simm, J.D., Thorne, C., Arnell, N.W., Ashley, R., Hess, T.M., Lane, S., N, Morris, J., Nicholls, R.J., Penning-Rowsell, E., Reynard, N.S., Saul, A., Tapsell, S.M., Watkinson, A. and Wheater, H.S., 2008. *An Update of the Foresight Future Flooding 2004 Qualitative Risk Analysis*. Cabinet Office, London, UK.

Fealy, R., 2008. A Review of global climate projections and likely scenarios for Ireland*. In:* Bullock, C. (Ed.) *The Impact of Climate Change for Inland Waterways and Tourism*. Draft Report prepared for the Heritage Council by Optimize. The Heritage Council, Kilkenny, Ireland.

Fealy, R., 2010. *An Assessment of Uncertainties in Climate Modelling at the Regional Scale: The Development of Probabilistic-Based Climate Scenarios for Ireland*. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland.

Fealy, R., 2013. Deriving probabilistic based climate scenarios using pattern scaling and statistically downscaled data: a case study application from Ireland. *Progress in Physical Geography* **37(2):** 178–205.

Fealy, R. and Sweeney, J., 2007. Statistical downscaling of precipitation for a selection of sites in Ireland employing a generalised linear modelling approach. *International Journal of Climatology* **27:** 2083–2094.

Fealy, R. and Sweeney, J., 2008. Statistical downscaling of temperature, radiation and potential evapotranspiration to produce a multiple gcm ensemble mean for a selection of sites in Ireland. *Irish Geography* **41:** 28.

Feyen, L., Dankers, R., Bódis, P., Salamon, P. and Barredo, J.I., 2011. Fluvial flood risk in Europe in present and future climates. *Climate Change* **112(1):** 47–62.

Florke, M., Wimmer, F. and Laaser, C., 2012. *Final Report for the Project Climate Adaptation – modelling water scenarios and sectoral impacts*. Centre for Environmental Systems Research and European Commission Directorate General Environment. 28 October 2011. http://ec.europa.eu/environment/archives/water/adaptation/pdf/ClimWatAdapt_final_report.pdf

Garnaut, R., 2008. *The Garnaut Climate Change Review*. Cambridge University Press, Cambridge, UK.

Gleeson, E., McGrath, R. and Treanor, M., 2013. *Ireland's Climate: the Road Ahead*. Met Éireann, Dublin, Ireland.

Gollier, C., 2002. Discounting an uncertain future. *Journal of Public Economics* **85:** 149–166.

Golub, A., Daiju, N. and Schmidt, M.G.W., 2011. *Uncertainty in Integrated Assessment Models of Climate Change: Alternative Analytical Approaches*. Sustainable Development Series. FEEM, Milan, Italy.

Goodbody, 2005. *Economic Evaluation of the Government Strategy for Road Safety, 1998–2002*. Goodbody Economic Consultants, Dublin, Ireland.

Goodbody, 2008. *Value-For-Money and Policy Review of Flood Risk Management Programme*. Goodbody Economic Consultants, Dublin, Ireland.

GOS, 2011. *International Dimensions of Climate Change, Foresight*. The Government Office for Science, London, UK.

Gouldby, B., Woodward, M., Kapelan, Z., Hames, D., Filkweert, J. and Stevens, R., 2012. *Next Generation Tools to Support Robust and Sustainable Asset Management*. FRMRC (Flood Risk Management Research Consortium), Heriot–Watt University Consortium, UK.

Groves, D.G. and Lempert, R.J., 2007. A new analytic method for finding policy relevant scenarios. *Global Environmental Change* **17:** 73–85.

Ha-Duong, M., 1998. Quasi-option value and climate policy choices. *Energy Economics* **20:** 599–620.

Haigh, N. and Fisher, J., 2010. Using a “real options” approach to determine a future strategic plan for flood risk management in the Thames Estuary. *Draft UK Government Economic Service Working Paper (March 2010)*.

Hall, J., Murphy, C. and Sweeney, J., 2012. *Robust Adaptation to Climate Change in the Water Sector in Ireland*. Environmental Protection Agency, Johnstown

Castle, Wexford, Ireland.

Hallegatte, S., 2008. Strategies to adapt to an uncertain climate change. *Global Environmental Change* **19:** 240–247.

Hino, M. and Hall, J., 2014. *Real Options Analysis and Adaptation to Changing Flood Risk: Structural and Non-Structural Measures*. Environmental Change Institute, University of Oxford, Oxford, UK.

HM Treasury, 2013. *The Green Book: Appraisal and Evaluation in Central Government*. HM Treasury, London, UK.

HM Treasury and DEFRA, 2009. *Accounting for the Effects of Climate Change. Supplementary Green Book Guidance*. HM Treasury and DEFRA, London, UK.

Hulme, M. and Carter, T.R., 1999. Representing uncertainty in climate change scenarios and impact studies*. In:* Carter, T.R., Hulme, M., Viner, D. (Eds) *Representing Uncertainty in Climate Change Scenarios and Impact Studies.* Proceedings of the ECLAT-2 Helsinki Workshop, Helsinki, Finland. 14–16 April, 1999. Climatic Research Unit, Norwich, UK. p. 128.

Hynes, S. and Campbell, D., 2011. Estimating the welfare impacts of agricultural landscape change in Ireland: a choice experiment approach. *Journal of Environmental Planning and Management* **54:** 1019–1039.

Hynes, S. and Hanley, N., 2006. Preservation versus development on Irish rivers: whitewater kayaking and hydropower in Ireland. *Land Use Policy* **23:** 11.

Ingham, A., Ma, J. and Ulph, A., 2006*. Theory and Practice of Economic Analysis of Adaptation*. Technical Report 55. Tyndall Centre, Norwich, UK.

IPCC, 2007. *Impacts, Adaptation and Vulnerability – Contribution of Working Group II of the Fourth Assessment Report of the IPCC*. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

.IPCC, 2013a. Working Group 1. *Contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The Physical Science Basis*. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

IPCC, 2013b. Summary for policy makers*. In:* Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, S.K., Allen, J.B., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Jackson, T., 2005. *Motivating Sustainable Consumption: A Review of Evidence on Consumer Behaviour and Behavioural Change*. Centre for Environmental Strategy, University of Surrey, Guildford, UK.

Kasperson, J.X. and Kasperson, R.E., 2001. *SEI Risk and Vulnerability Programme Report 2001–01*. Stockholm Environmental Institute, Stockholm, Sweden.

Kiely, G., Leahy, P., Ludlow, F., Stefanini, B., Reilly, E., Monk, M. and Harris, J., 2012. *Extreme Weather, Climate and Natural Disasters in Ireland, Climate Change Research Programme 2007–2013*. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland.

Lempert, R.J., 2013. Scenarios that illuminate vulnerabilities and robust responses. *Climate Change* **177(4):** 627–646. Published online October 2012.

Lempert, R.J. and Collins, M.T., 2007. Managing the risk of uncertain threshold responses: Comparison of robust, optimum and precautionary approaches. *Risk Analysis* **23:** 1009–1026.

Lempert, R. and Schlesinger, M., 2000. Robust strategies for abating climate change. *Climatic Change* **45:** 387–401.

Lempert, R., Popper, S.W. and Bankes, S.C., 2003. *Shaping the Next One Hundred Years: New Methods for Long-Term Policy Analysis*. RAND Corporation, Santa Monica, CA, USA.

Markowitz, H.M., 1952. Portfolio selection. *Journal of Finance* **7(1):** 77–91.

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R., Plattner, G.-K., Yohe, G.W. and Zwiers, F.W., 2010. *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Jasper Ridge, CA, USA.

McGloughlin, J.S. and Sweeney, J., 2012. *Governance and Climate Change: Making the Transition to an Adapted Ireland*. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland. pp. 45.

Mediation, 2013. *Decision Support Methods for Climate Change Adaptation – Method Overview*. Seventh EU Framework Programme.

Metroeconomica, 2006. *Climate Change Impacts and Adaptation*. Cross-Regional Research Programme Project E. Final report to DEFRA, London, UK.

Mitchell, T.D., Hulme, M. and New, M., 2002. Climate data for political areas. *Area* **34:** 109–112.

Möhner, A. and Klein, R.J.T., 2007. *The Global Environment Facility: Funding for Adaptation or Adapting to Funds?* Climate and Energy Programme Working Paper, Stockholm Environmental Institute, Stockholm, Sweden.

Morgan, M.G. and Henrion, M., 1990. *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press, Cambridge, UK.

Moss, R., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J., Elgizouli, I., Emori, S., Erda, L., Hibbard, K., Jones, R., Kainuma, M., Kelleher, J., Lamarque, J.F., Manning, M., Matthews, B., Meehl, J., Meyer, L., Mitchell, J., Nakicenovic, N., O'Neill, B., Pichs, R., Riahi, K., Rose, S., Runci, P., Stouffer, R., van Vuuren, D., Weyant, J., Wilbanks, T., van Ypersele, J.P. and Zurek, M., 2008. Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies. In: *IPCC Expert Meeting Report: Towards New Scenarios.* Intergovernmental Panel on Climate Change, Geneva, Switzerland. 132 pp.

Murphy, C. and Charlton, R., 2007. Climate change and water resources in Ireland. *In:* Sweeney, J. (Ed.) *Climate Change: Refining the Impacts*. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland.

Murphy, C., Bastola, S., Hall, J., Harrigan, S., Murphy, N. and Holman, C., 2011. Against a 'wait and see' approach in adapting to climate change. *Irish Geography* **64:** 81–95.

Murphy, J.M., Sexton, D., Jenkins, G., Boorman, P., Booth, B., Brown, K., Clarke, R., Collins, M., Harris, G. and Kendon, E., 2009. *UKCP09 Climate Change Projections*. Met Office, Hadley Centre, Exeter, UK.

Nakicenovic, N. and Swart, R., 2000. *Special Report on Emissions Scenarios*. Cambridge University Press, Cambridge, UK. pp. 570.

NESC, 2012. *Towards a New National Climate Policy*. Interim Report of the NESC Secretariat. National Economic and Social Council, Dublin, Ireland.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R. and van Vuuren, D.P., 2013. A new scenario framework for climate change research: the concept of shared socio-economic pathways. Special Issue. *Climatic Change* DOI 10.1007/s10584-013-0905-2.

OECD, 2006. *Cost–Benefit Analysis and the Environment: Recent Developments*. OECD, Paris, France.

Olson, M. and Bailey, M.J., 1981. Positive time preference. *Journal of Political Economy* **89:** 1–25.

ONERC, 2006. *National Adaptation Strategy (Strategie nationale d'adaptation au changement climatique)*. National Observatory for the Effects of Global Warming (ONERC), Paris, France.

OPW, 2003. *Report of the Flood Policy Review Group*. The Office of Public Works, Dublin, Ireland.

Osberghaus, D., Dannenberg, A., Mennel, T. and Sturm, B., 2010. The role of government in adaptation to climate change. *Environment and Planning C: Government and Policy* **28(5):** 834–850.

Parson, E.A., 2008. Useful global change scenarios: current issues and challenges. *Environment Resource Letters* **3:** 1–5.

Parson, E.A., Burkett, V., Fischer-Vanden, K., Keith, D., Mearns, L.O., Pitcher, H., Rosenzweig, C. and Webster, M., 2007. *Global Climate Scenarios: their Development and Use, Synthesis and Assessment Product 2.1b*. US Climate Change Program, Washington DC, USA.

Penning-Rowsell, E., Viavattene, C., Pardoe, J., Chatterton, J., Parker, D. and Morris, J., 2010. *The Benefits of Flood and Coastal Risk Management: A Handbook of Assessment Techniques 2010*. Flood Hazard Research Centre, Middlesex University Press, London, UK.

Pielke, R.J., 2010. *The Climate Fix*. Basic Books, New York, USA.

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.

Ramsey, F.P., 1928. A mathematical theory of saving. *The Economic Journal* **38(162):** 543–559.

Ranger, N., Millner, A., Diertz, S., Fankhauser, S., Lopez, A. and Ruta, G., 2010. *Adaptation in the UK: A Decision-Making Process*. Policy Brief. Grantham Institute and Centre for Climate Change Economics and Policy, London, UK.

Reeder, T. and Ranger, N., 2011. *How do you Adapt in an Uncertain World? Lessons from the Thames Estuary 2100 Project*. World Resources Report, Washington DC, USA.

Richardson, H., 2000. The stupidity of the cost benefit standard. *The Journal of Legal Studies* **29:** 971–1003.

Rubenstein, M., 2002. Markowitz's "Portfolio Selection": A fifty year retrospective. *The Journal of Finance* **57(3):** 1041–1045.

Schneider, S.H. and Kuntz-Duriseti, K., 2002. Uncertainty and climate change policy. *In:* Schneider, S.H., Rosencranz, A. and Nilse, J.O. (Eds) *Climate Change Policy: A Survey*. Island Press, Washington DC, USA.

Smit, B., Burton, I., Klein, R.J.T. and Street, R., 1999. The science of adaptation: a framework for assessment. *Mitigation and Adaptation Strategies for Global Climate Change* **4(3–4):** 199–213.

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

Stithou, M., Hynes, S., Hanley, N. and Campbell, D., 2011. *Estimating the Value of Achieving "Good Ecological Status" under the Water Framework Directive in the Boyne River Catchment: A Mixed Multinomial Logit Approach*. SEMRU Working Paper Series No. 11. Department of Economics, National

University of Ireland, Galway, Ireland.

Sweeney, J., Albanito, F., Brereton, A., Caffarra, A., Charlton, R., Donnelly, A., Fealy, R., Fitzgerald, J., Holden, N., Jones, M. and Murphy, C., 2009. *Climate Change: Refining the Impacts for Ireland*. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland.

Sweeney, J., Bourke, D., Coll, J., Flood, S., Gormally, M., Hall, J., McGloughlin, J.S., Murphy, C., Salmon, N., Sheehy Skeffington, M. and Smyth, D., 2013. *Co-ordination, Communication and Adaptation for Climate Change in Ireland: an Integrated Approach (COCO-ADAPT)*. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland.

Tol, R.S.J., 2005. Adaptation and mitigation: trade-offs in substance and methods. *Environmental Science and Policy* **8:** 572–578.

Train, K.E., 2003. *Discrete Choice Methods with Simulation*. Cambridge, University Press, Cambridge, MA, USA.

UNDP, 2005. *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures*. United Nations Development Programme, Cambridge University Press, Cambridge, UK.

Van Drunen, M., Leusink, A. and Lasage, R., 2009. Towards a climate-proof Netherlands. *In:* Biwass, A.K., Tortajada, C., Izquierdo, R. (Eds) *Water Management in 2020 and Beyond.* Springer, Berlin and Heidelberg, Germany.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinhasuen, M., Nakicenovic, N., Smith, S.J. and Rose, S.K., 2011. The representative concentration pathways: an overview. *Climatic Change* **109(1–2):** 5–31.

van Vuuren, D.P., Kriegler, E., O'Neill, Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R. and Winkler, H., 2013. A new scenario framework for climate change research: scenario matrix architecture. *Climate Change* **122(3):** 373–386.

Walker, W.E., Haasnoot, M. and Kwakkel, J.H., 2013. Adapt or perish: A review of planning approaches for adaptation under deep uncertainty. *Sustainability* **5:** 955–979.

Watkiss, P. and Hunt, A., 2012. *Technical Paper on the UK National Adaptation Economic Assessment: Methods and Pilot Studies*. Final Report to UK DEFRA, DEFRA, UK.

Watkiss, P., Hunt, A. and Horrocks, L., 2009. *Scoping Study for a National Climate Change Risk Assessment and Cost Benefit Analysis.* Final Report. Metroeconomica, AEA Group, Paul Watkiss Associates, UK.

Weitzmann, M.L., 1998. Why the far distant future should be discounted at its lowest possible rate. *Journal of Environmental Economics and Management* **36:** 201–208.

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

Wilby, R.L., Troni, J., Biot, Y., B.C, T., Hewitson, C., Smith, D.M. and Sutton, R.T., 2009. A review of climate risk information for adaptation and development planning. *International Journal of Climatology* **29:** 1193–1215.

Willows, R. and Connell, R., 2003. *Climate Adaptation, Risk, Uncertainty and Decision Making*. UKCIP Technical Report. UKCIP, Oxford, UK.

Woodward, M., Gouldby, B., Kepelan, S.-T.K. and Townend, I., 2011. Real options in flood risk management decision making. *Journal of Flood Risk Management* **4:** 339–349.

Acronyms and Annotations

AEA	Adaptation Economic Assessment
APSR	Area of potentially significant risk
AR5	Fifth Assessment Report
ASC	Adaptation Sub-Committee
BCR	Benefit cost ratio (in Cost Benefit Analysis)
CBA	Cost–benefit analysis
CCRA	Climate Change Risk Assessment (UK)
CCRP	Climate Change Research Programme
CEA	Cost-effectiveness analysis
CFRAM	Catchment Flood Risk Assessment and Management
COCO-ADAPT	Co-ordination, Communication and Adaptation for Climate Change in Ireland: an Integrated Approach
CVM	Contingent valuation method
DECLG	Department of the Environment, Community and Local Government
DEFRA	Department of Environment, Food and Rural Affairs
EC	European Commission
EEA	European Environment Agency
EPA	Environmental Protection Agency
ESPACE	European Spatial Planning: Adapting to Climate Events
EU	Expected utility
EV	Expected value
GCM	Global Climate Model
GHG	Greenhouse gas
GW	Global weighting
HEFS	High-End Flood Scenario
IAM	Integrated Assessment Model
IAV	Impacts, Adaptation and Vulnerability (contribution of Working Group 2 to Fourth IPCC Report)
ICARUS	Irish Climate Analysis and Research Units
ICIP	Irish Climate Information Platform
IPCC	Intergovernmental Panel on Climate Change
IRR	Individual risk receptor

LW	Local weighting
MCA	Multi-criteria analysis
MRFS	Mid-Range Flood Scenario
NAP	National Adaptation Programme
NAS	National Adaptation Strategy
NCCAF	National Climate Change Adaptation Framework
NESC	National Economic and Social Council
NPV	Net present value (in CBA)
NUIM	National University of Ireland Maynooth
OPW	Office of Public Works
PA	Portfolio analysis
RCM	Regional Climate Model
RCP	Representative Concentration Pathways (the radiative forcing associated with varying concentrations of greenhouse gases.
RDM	Robust decision making
ROA	Real options analysis
S	Score
SAC	Special Area of Conservation
SRES	Special Report on Emission Scenarios (referenced in both the Third and Fourth IPCC Reports)
SSP	Shared socio-economic pathways. Projections of future social, economic and demographic change being developed in parallel with the IPCC RCPs.
SUDS	Sustainable urban drainage system
UKCIP	United Kingdom Climate Impacts Programme
UNFCCC	United Nations Framework Convention on Climate Change
VFM	Value-for-money
VOSL	Value-of-statistical-life
WFD	Water Framework Directive
WRI	World Resources Institute
WS	Weighted score
WTA	Willingness to accept
WTP	Willingness to pay

Adaptation Terms

Adaptive capacity	The set of resources available for adaptation that will enhance a system's coping capacity, thereby reducing vulnerability (UNDP, 2005). Adaptation can be spontaneous or planned and can be carried out in response to, or in anticipation of, change (Willows and Connell, 2003).
Autonomous adaptation	Adaptation by individuals or organisations themselves without necessarily government incentives or intervention.
Downscaling	The scaling down of Global Climate Models or data to regional or local resolutions.
Green adaptation	Adaptation making best use of defences provided by the natural environmental or ecosystem services.
Grey adaptation	Adaptation based on civil engineering projects.
Maladaptation	Ill-conceived adaptation. An example could be adaptation undertaken without consideration of possible adverse impacts on other sectors.
Radiative forcing	The physical heating effect of greenhouse gases in the atmosphere.
Resilience	The amount of change a system can undergo without changing state (IPCC, 2007). The tendency to maintain integrity when subjected to a disturbance (UNDP, 2005). The ability to self-organise, to buffer disturbance and the capacity for learning and adaptation.
Soft adaptation	Adaptation based on extensions of social, governance or insurance systems, etc., to provide behavioural incentives to adapt.
Storyline	A trajectory for greenhouse gas emissions based on socio-economic trends.
Vulnerability	The degree to which an individual, group or system is susceptible to, or unable to cope, with the adverse effects of climate change (Kasperson and Kasperson, 2001; IPCC, 2007). Vulnerability depends not only on a system's sensitivity, but also on its exposure and adaptive capacity (Willows and Connell, 2003).

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL

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

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

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

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

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

Ár bhFreagrachtaí

Ceadúnú

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

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

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

Bainistíocht Uisce

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

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

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

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

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

Taighde agus Forbairt Comhshaoil

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

Measúnacht Straitéiseach Timpeallachta

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

Cosaint Raideolaíoch

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

Treoir, Faisnéis Inrochtana agus Oideachas

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

Múscailt Feasachta agus Athrú Iompraíochta

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

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Measúnú Comhshaoil
- An Oifig um Cosaint Raideolaíoch
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

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

EPA Research Report 140

ADAPT: Quantifying the Costs and Benefits Associated with Climate Change Risks and Adaptation

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

Authors: Craig Bullock, Rowan Fealy, J. Peter Clinch and Robert O'Shea

The selection of/how to select measures of adaptation to climate change in the face of considerable uncertainty and the potential role of economic appraisal methods, including cost-benefit analysis.

Identifying pressures

- Given the inevitability of climate change, international attention is increasingly turning to the need to implement measures of adaptation. However, while single trajectory models of the future have often been presented, climate change is subject to considerable uncertainty. Low probability/high impact outcomes would have significant social and economic consequences. Recent weather events indicate that such extremes cannot be discounted.
- Economic appraisal methods, such as cost benefit analysis (CBA), are recommended where significant investment is needed for adaptation, including measures to address impacts that are outside the domain of normal market valuation. However, in themselves, these methods can be imprecise in instances of high uncertainty.

Informing Policy

- This report investigates the role for economic appraisal and CBA in the choice of adaptation strategies.
- It discusses how these methods can be applied in a context that allows decision makers to choose between adaptation options in the face of climate uncertainty as well as uncertain behavioural responses, socio-economic change, technological development and international agreement on the mitigation of greenhouse gases.

Developing solutions

- The report recommends the implementation of robust adaptation measures that aim to strengthen the adaptive capacity of institutions and individuals.
- It proposes the use of continual adaptive risk management involving stakeholder engagement, feedback loops, and the collection of, and response to, new information.
- Qualitative or score-based methods may be adequate for the appraisal of adaptation options early in this process, but should be succeeded by more comprehensive, quantitative methods as information accumulates.
- These methods should involve economic appraisal, including CBA, where there are significant economic, social or environmental consequences,
- Decision pathways provide a further context to pro-actively manage risk. The objectives for adaptation are agreed at an early stage along with a range of possible options. Individual options are then triggered by the realisation of pre-determined climate outcomes, although the route to adaptation remains flexible over time.

Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

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

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

www.epa.ie

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