Climate Change and Potential Economic Impacts in Ireland: The Case for Adaptation

A thesis submitted for the degree of
Doctor of Philosophy

Presented by

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ABSTRACT

This thesis explores a number of key economic impacts associated with climate change in Ireland. It begins by examining the idea of climate change as a so called "wicked problem", and in turn investigates uncertainty, the importance of ethics in economic valuation, and the complexities associated with creating economic assessments, formulating policy and carrying out appropriate action. Drawing on sustainability science the terms resilience, vulnerability and adaptive capacity are also discussed, defined and engaged with.

Key results, associated with both potential climate impact and adaptation costs, are presented from global and regional integrated assessment models and in turn vulnerable Irish sectors are uncovered. The following bottom-up approach explores key vulnerabilities in Ireland in the areas of coastal exposure, wetland vulnerability and inland flooding. Digital Terrain Modelling is used in conjunction with a range of datasets to examine vulnerabilities relating to coastal land, commercial and residential property addresses, insurance claim costs, as well as wetland and species vulnerability. It should be noted that the results presented are cognisant of the limitations of monetary evaluation alone as a measure of potential climate impacts. The bottom up approach has the added advantage of providing geographically distributed impacts in discrete sectors as apposed to the often highly aggregated regional Integrated Assessment Modelling approach.

Finally, the implications of these results for decision-making in relation to adaptation planning are discussed, along with avenues for potential future work.

ACKNOWLEDGEMENTS

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ACRONYMS

B	Billion
CFRAM	Catchment Flood Risk Assessment and Management Studies
CLC	Corine Land Class
COMEST	World Commission on the Ethics of Scientific Knowledge and Technology
CSO	Central Statistics Office
CVM	Contingent Valuation Method
DTM	Digital Terrain Model
ED	Electoral Division
EEA	European Environment Agency
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
ESA	European Space Agency
EU	European Union
EU-ETS	European Union Emissions Trading Scheme
FAA	Framework for Action on Adaptation
FEMA	Federal Emergency Management Agency
FTA	Free Trade Agreement
GCCA	Global Climate Change Alliance
GDP	Gross Domestic Product
GHG	Green House Gas
GVA	Gross Value Added
ha	Hectares
HPM	Hedonic Price Method
IUCN	International Union for the Conservation of Nature
ICZM	Integrated Coastal Zone Management
IAM	Integrated Assessment Model
IIF	Irish Insurance Federation
IPCC	Intergovernmental Panel on Climate Change
Km^2	Kilometre Squared
LIDAR	Light Detecting And Ranging
m	Metres
M	Million
MBI	Market Based Instruments
MEA	Millennium Ecosystem Assessment
MPC	Marginal Private Cost
MSC	Marginal Social Cost
NBDC	National Biodiversity Data Centre
NCPSS	National Coastal Protection Strategy Study
OECD	Organisation for Economic and Co-operation and Development
OPW	Office of Public Works
OSI	Ordnance Survey Ireland
POWCAR	Place of Work - Census of Anonymised Records
PF	Probability Function
PNS	Post-Normal Science
Ppm	Parts Per Million
SAC	Special Area of Conservation
SAFER	Services and Applications For Emergency Response
SD	Sustainable Development

SEA	Strategic Environmental Assessment
SEMRU	Socio-economic Marine Research Unit
SLR	Sea-level Rise
T	Trillion
TCM	Travel Cost Method
TEEB	The Economics of Ecosystems and Biodiversity
TEV	Total Economic Value
UK CIP	United Kingdom Climate Impacts Programme
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations International Strategy for Disaster Reduction
WRI	World Resources Institute

CHAPTER 1
INTRODUCTION

1.1 OVERVIEW OF CLIMATE CHANGE

1.1.1 Observations and projections

Global climate change engendered by past and present human activities poses a severe threat to human welfare, biodiversity and ecosystem integrity, and possibly to life itself (IPCC, 2007a). The 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change states unequivocally that anthropogenic climate change is a tangible and severe threat to life on this planet. The impacts including: long term changes in precipitation, high-tide levels, ocean salinity and acidity, wind patterns and extreme weather events, as well as droughts, heavy precipitation, heat waves and an increased intensity of tropical cyclones, confront humanity with enormous practical challenges (IPCC, 2007b).

In the second half of the twentieth century the climate system was recognised as involving five major subsystems: the atmosphere, the oceans, global snow and ice cover, and the earth's land surface with its vegetation cover (the lithosphere and biosphere). The atmosphere and the oceans are the two most critical elements in driving this complex system (Barry and Chorley, 2010). The atmosphere is a highly dynamic climate component through which all the solar energy that enters the climate system first passes. The earth's oceans function as a regulator to the more rapid atmospheric changes through their ability to store and transport large volumes of energy.

The atmosphere has a significant impact on the earth's surface temperature, although it is only 1% of the earth's radius in diameter. Without it the average surface temperature would be in the region of -18^{o}C instead of 14^{o}C, and terrestrial life as we know it would not exist. By the start of the 21st century climate scientists were beginning to amass significant evidence of the human impact in increasing global concentrations of greenhouse gases in the atmosphere. Since the industrial revolution, increasing concentrations of greenhouse gases, primarily carbon dioxide, have been observed. Carbon dioxide is one of the main by-products of fossil fuel use. Human exploitation of fossil fuels increased extensively since the beginning of the industrial revolution in the mid to late 18th century. Coal, oil and natural gas fossil fuels are formed through the anaerobic decomposition of buried dead organisms over millions of years. The fuels when burned release high levels of carbon and hydrocarbon, which when combined with oxygen produce carbon dioxide.

Pre-industrial levels of carbon dioxide are in the range of 280ppm (parts per million) in the earth's atmosphere. In fact, carbon dioxide levels have only naturally fluctuated between 180 to 280ppm over a 420,000 year period up to the middle of the 18th century. These findings were uncovered through analysis carried out on an ice core (over 3,600 metres in length) which was drilled in Vostok in the Antarctica (Petit *et al*., 1999). Current concentrations (as of August 2012) of carbon dioxide in the atmosphere are in the region of 392ppm (Tans and Keeling, 2012). Observations from the Mauna Loa observatory in Hawaii display this increase over a fifty year period (Figure 1.1). The station has continuously monitored atmospheric carbon dioxide since 1958, and therefore provides an important record of changes in observed carbon dioxide concentrations in the atmosphere. The station is also unique because of its remote location. Due to its altitude, the air around the station is quite undisturbed and, because the station is remote, the observations are less influenced by human activity in the immediate vicinity, i.e. there is minimal contamination of the data due to "noise" (Keeling *et al*., 1976).

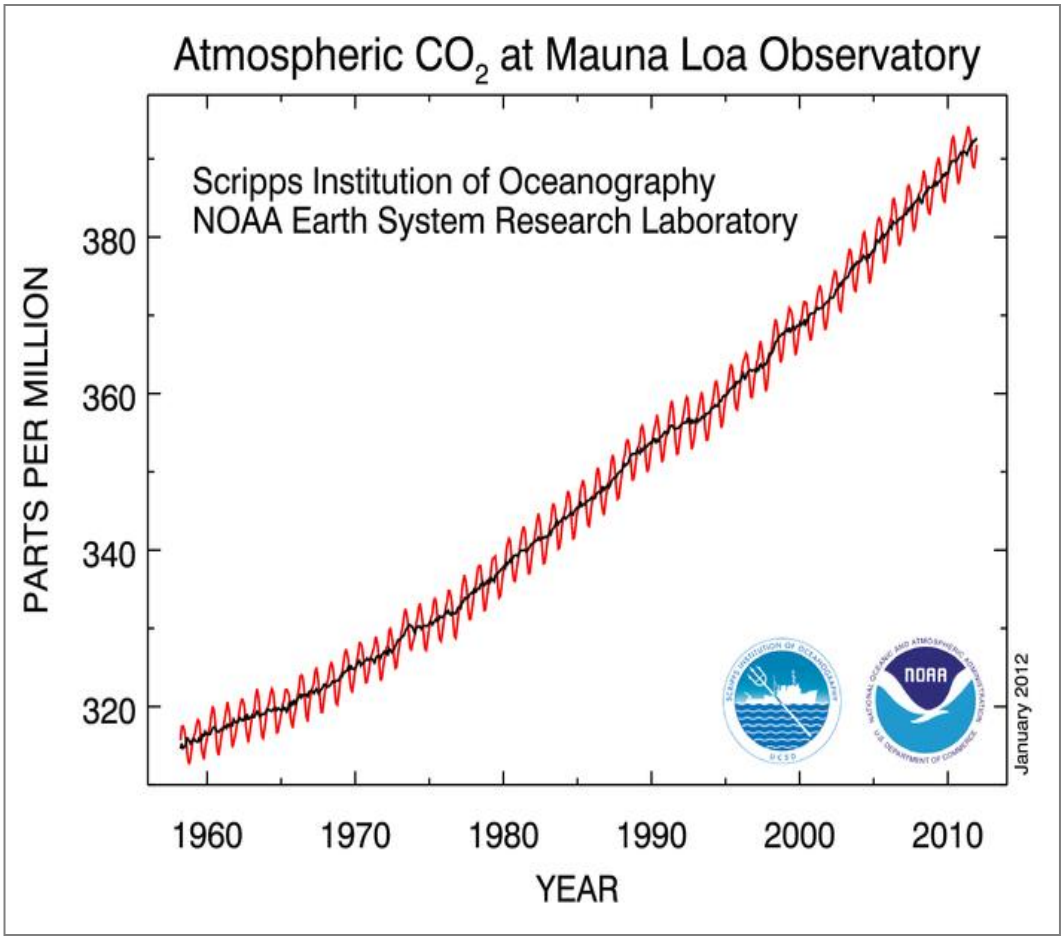


Figure 1.1: Mauna Loa carbon dioxide record indicating increases in atmospheric carbon dioxide in parts per million since 1958 (Source: Tans and Keeling, 2012).

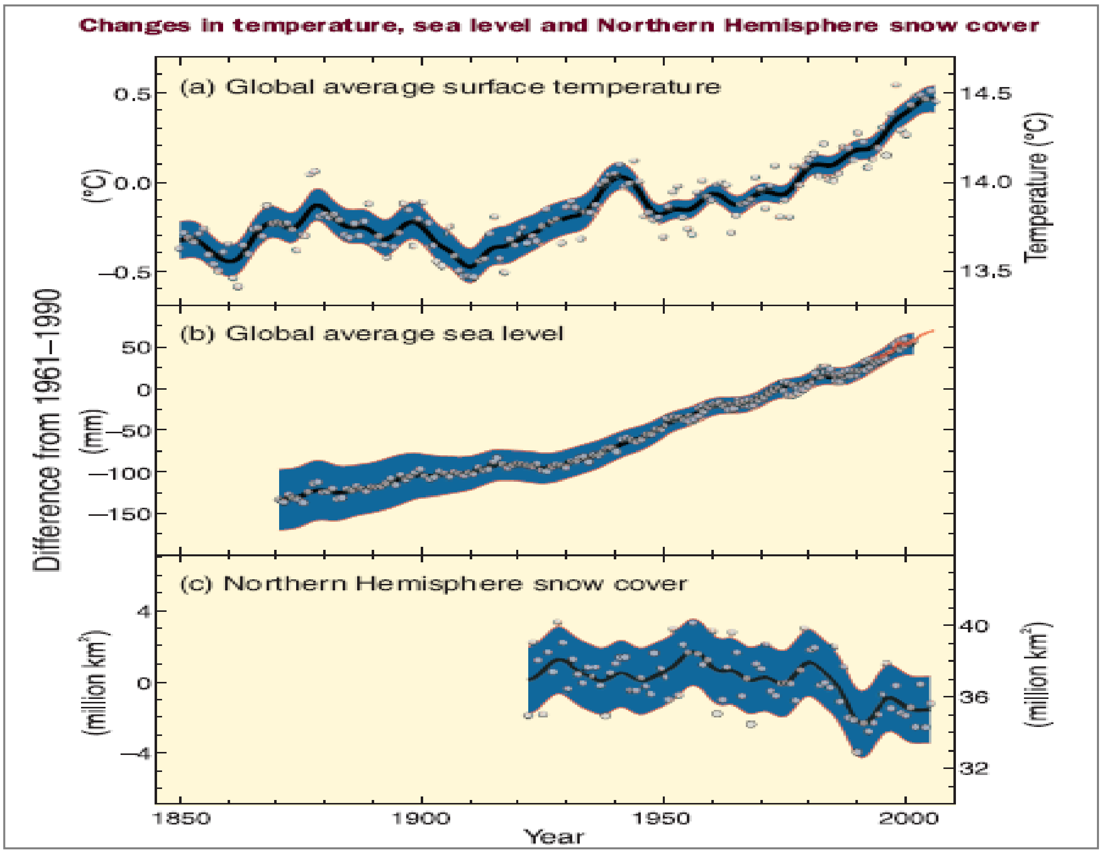


Figure 1.2: Observed changes in (a) global average surface temperature; (b) global average sea level from tide gauge (blue) and satellite (red) data; and (c) Northern Hemisphere snow cover for March-April. All differences are relative to corresponding averages for the period 1961-1990. Smoothed curves represent decadal averaged values while circles show yearly values (Source: IPCC, 2007).

The IPCC Fourth Assessment Report states with 90% confidence that human activities since 1750 have exerted a net warming effect on the climate by increasing atmospheric concentrations of greenhouse gases. The report also indicates that the average global temperature has increased by 0.74^{o}C in the last one hundred years along with an increase in SLR of approximately 0.2m (Figure 1.2). In Europe temperatures have increased by 1.4^{o}C compared with pre-industrial levels, with the last decade the warmest in one hundred and fifty years (IPCC, 2007a). Of the six Special Report on Emissions Scenarios (SRES) the A1F1 scenario of a fossil-fuel dependent, highly industrialized world is the most likely. This is also the scenario with the greatest projected global warming of between 2 and 6^{o}C (Figure 1.3).

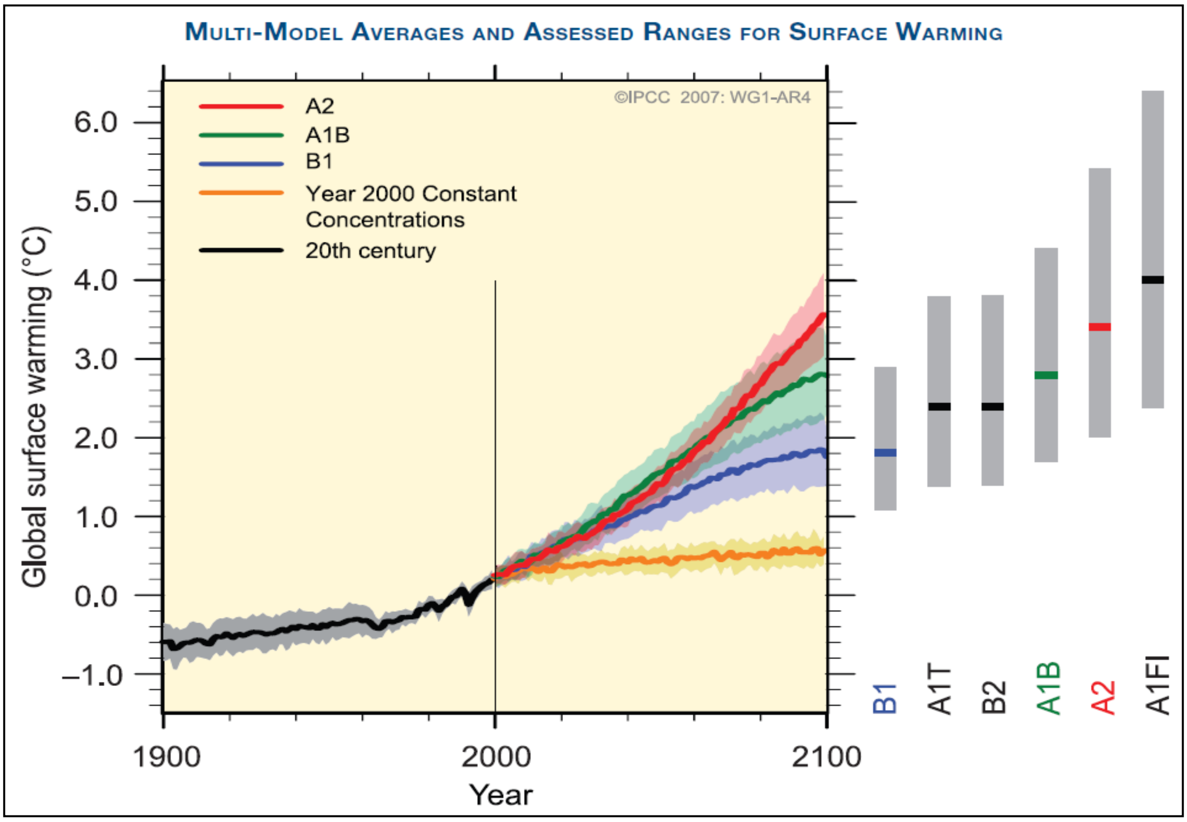


Figure 1.3: Multi-model averages and assessed ranges for surface warming. Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the **likely** range assessed for the six SRES marker scenarios (Source IPCC, 2007).

1.1.2 Impacts

Present and potential future climate change impacts are extensive and severe. Impacts relate to freshwater resources and their management, ecosystems, food production systems, coastal systems and low-lying areas, and health (Figure 1.4). In the course of the century more than one sixth of the global population will be at risk as water supplies, in the form of meltwater stored in glaciers and snow cover, are set to decline over major mountain ranges. Annual river run-off is projected to increase by 10 to 40% at higher latitudes and in some of the Earth's wet tropical areas, and to decrease by 10 to 30% over some dry regions in the mid-latitudes and in the dry tropics (IPCC, 2007b). It is likely that existing drought effected regions (such as in sub-Saharan

Africa) will increase in extent and that heavy precipitation events, with a high likelihood of increasing frequency, will amplify flood risk (IPCC, 2007b).

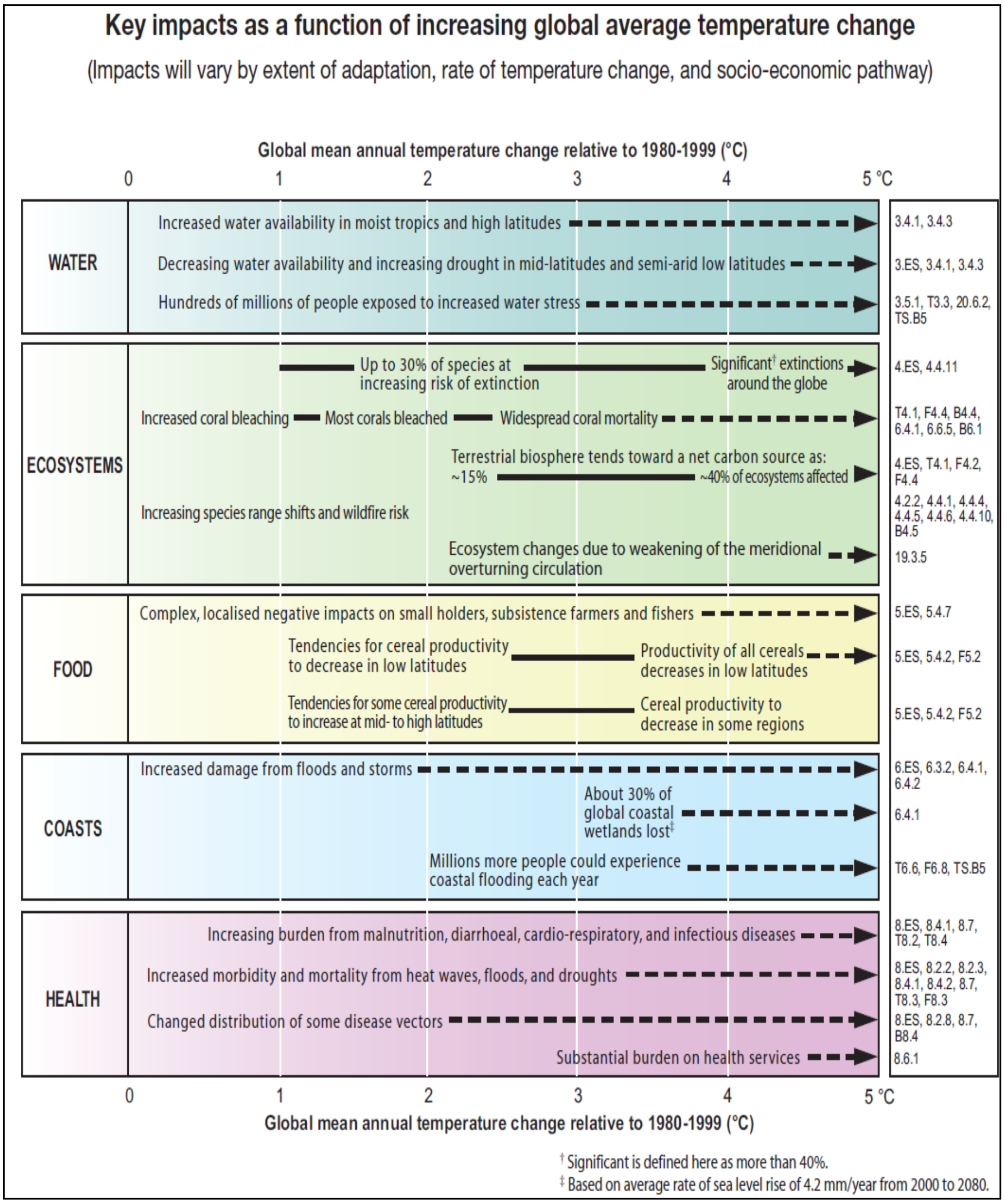


Figure 1.4: Key impacts as a function of increasing global average temperature change (Source: IPCC, 2007).

Approximately 20 to 30% of plant and animal species examined in the report are likely to face an increased risk of extinction if global average temperature increases exceed 1.5 to 2.5°C (IPCC, 2007b). If global average temperatures do increase to this extent or beyond, then major changes in ecosystem structure and function are projected with predominantly negative consequences for biodiversity and ecosystem goods and services (IPCC, 2007b). The net carbon uptake by terrestrial ecosystems is also likely to weaken, or even reverse, by mid-century. Global food production is set to increase with increases of local average temperature in the range of 1 to 3^{o}C, but is projected to decrease above this range. Increases in the frequency of flooding events, as well as droughts, are projected to affect local crop production (especially in subsistence sectors at low latitudes) negatively.

Coasts are projected to be exposed to increasing risks such as coastal erosion due to climate change and sea-level rise. Coastal wetlands including salt marshes and mangroves are projected to be negatively impacted. Millions of additional people are expected to be flooded every year due to sea-level rise by mid to late century. Those living in densely populated and low-lying areas with low adaptive capacity, where tropical storms and local coastal subsistence are already prominent, are especially at risk (IPCC, 2007b). Studies in temperate zones have shown that climate change is projected to bring some health benefits such as fewer deaths from cold exposure. Changes in the range and transmissions of malaria in Africa may also bring a mixture of positive and negative impacts (IPCC, 2007b). However, the overall health impacts due to climate change are negative. Significant increases in malnutrition levels, diarrhoea, cardio-respiratory diseases, as well as increased death, disease and injury due to heatwaves, floods, storms and droughts are all projected (IPCC, 2007b).

In order to account for, mitigate against, and help adapt to present and future potential climate change impacts, decision makers require a range of tools to assist them in understanding and quantifying climate change impacts and developing appropriate policy responses. Economic valuation and its methodologies of quantifying climate change impacts can provide such a tool.

1.2 CLIMATE CHANGE AND ECONOMICS: FOUNDATIONS

Traditional neo-classical economic approaches neglect to account for the market failure that is environmental pollution. The field of environmental economics was established to address these types of market failures or externalities.

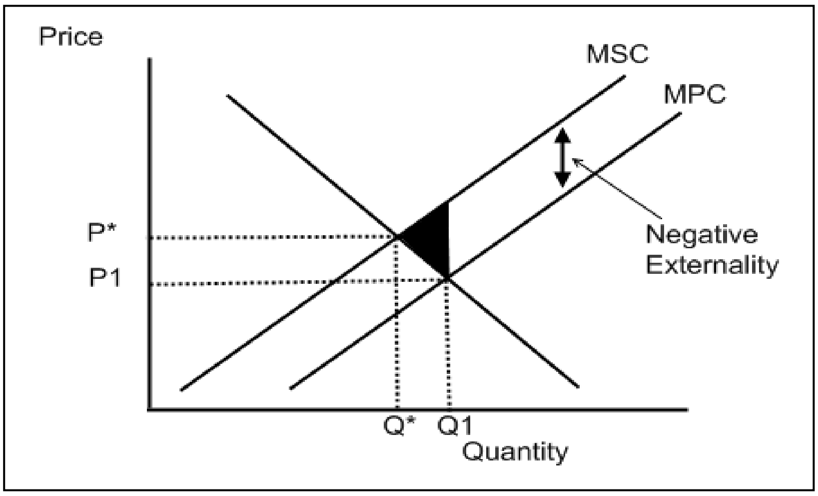


Figure 1.5: Environmental externalities of a coal power plant (Source: Tietenberg and Lewis, 2007).

Figure 1.5 displays how environmental externalities come into being. The graph displays two cost functions and their interaction with a demand function. In the case of a market failure only the marginal private cost (MPC) of a coal powered plant producing electricity is considered. The costs considered here reflect the costs of producing the electricity but do not consider the environmental costs related to the pollution created by the plant. When considering the marginal private costs alone the graph produces a certain price and quantity (P1 and Q1) for producing electricity as determined by the demand function. However, if one is also to account for the costs to society as a whole then the marginal social cost curve (MSC) is considered. This curve includes the total costs of producing electricity and hence includes the costs of pollution. When this function is employed one can see that a higher price (P*) is determined to produce a lower quantity (Q*) of electricity. This revised price and quantity take the additional cost of pollution into account. The gap between MPC and

MSC represents this negative externality or market failure and the black triangular wedge represents the cost of such an externality.

The field of environmental economics aims to internalise market externalities such as this by considering social and environmental costs relating to economic activities. Of course, determining the marginal social cost of a particular activity is not as straight forward as it might first appear. There are two requirements for decision-making when it comes to quantifying environmental damages. The first is a fundamental philosophical position and the second is the need to know the extent to which people are willing-to-pay to prevent damages or the willingness-to-accept compensation for damages suffered (Spash, 1997). The philosophical position assumed by environmental economists is that the net utility from the consequences of an action determines whether the action is right or wrong. Cost-benefit analysis and its tools, such as the contingent valuation method, assume that individuals are able and willing to consider trade-offs in relation to public goods, i.e. that individuals follow a utilitarian philosophy (Spash, 1997). The contingent valuation method involves directly asking people, in a survey, how much they would be willing to pay for specific environmental services. It is called "contingent" valuation, because people are asked to state their willingness to pay, contingent on a specific hypothetical scenario and description of the environmental service. This utilitarian standpoint is the approach from which the majority of socioeconomic impacts associated with climate change are approached in the literature.

The majority of economic assessments exploring climate change impacts are carried out on a global or regional scale, and use integrated assessment models (IAMs) to undertake their analysis. IAMs combine socioeconomic models with climate system models to estimate potential climate change impacts on human activities and ecosystems. They normally run under a range of greenhouse gas emission scenarios

(Parson and Fischer-Vanden, 1997). The majority of IAMs present their model output in terms of potential GDP impact costs and take a top-down approach in their assessment.

Bottom-up assessments model economic impacts relating to climate change vulnerabilities in individual sectors, and tend to be of particular value at the national or sub-national level (Ciscar *et al*., 2011). Sectors focused on in these analyses normally include coastal systems, human health, agriculture, tourism, biodiversity and inland flooding. Under bottom-up assessments impacts are often accounted for in monetary and physical terms (Ciscar *et al*., 2011).

1.3 GENERAL AIMS OF THESIS

The primary aim of the thesis is to quantify the economic costs of climate change in Ireland in a number of vulnerable sectors. The thesis will also aim to explore the notions of ethics, equity, vulnerability, resilience and sustainability with reference to the economic valuations of climate impacts. The thesis will present a number of significant issues relating to the economic impacts of climate change in Ireland. Case studies are presented on three specific areas; potential sea-level rise (SLR) related impacts, biodiversity impacts along the Irish coast, and inland flooding impacts for selected river catchments. When exploring these sectors a GIS modelling approach was used so that vulnerabilities could be linked with specific locations rather than aggregated to a national level. The strength of this methodology is that decision-makers can begin to prioritise locations where climate vulnerabilities are likely to be more acute, and hence formulate more useful adaption strategies. The work will aim to complement traditional monetary valuations with non-monetary indicators relating to vulnerable properties, land and biodiversity. The outputs of the modelling aim to inform policy dialogues and provide an economic argument for putting climate adaptation measures in place in Ireland. In addition, the outputs are intended to specify locations and sectors where adaptation actions should be prioritised.

1.4 STRUCTURE OF THESIS

The thesis consists of 9 interrelated chapters (Figure 1.6). Chapters 1 and 2 provide an introduction and general literature review. Chapters 4 to 8 consists of three coupled thematic areas focusing on economics impacts associated with coastal vulnerability, economic costs relating to wetland vulnerability, and economic costs associated with inland flooding respectively. Chapter 9 offers conclusions and recommendations relating to the entire thesis.

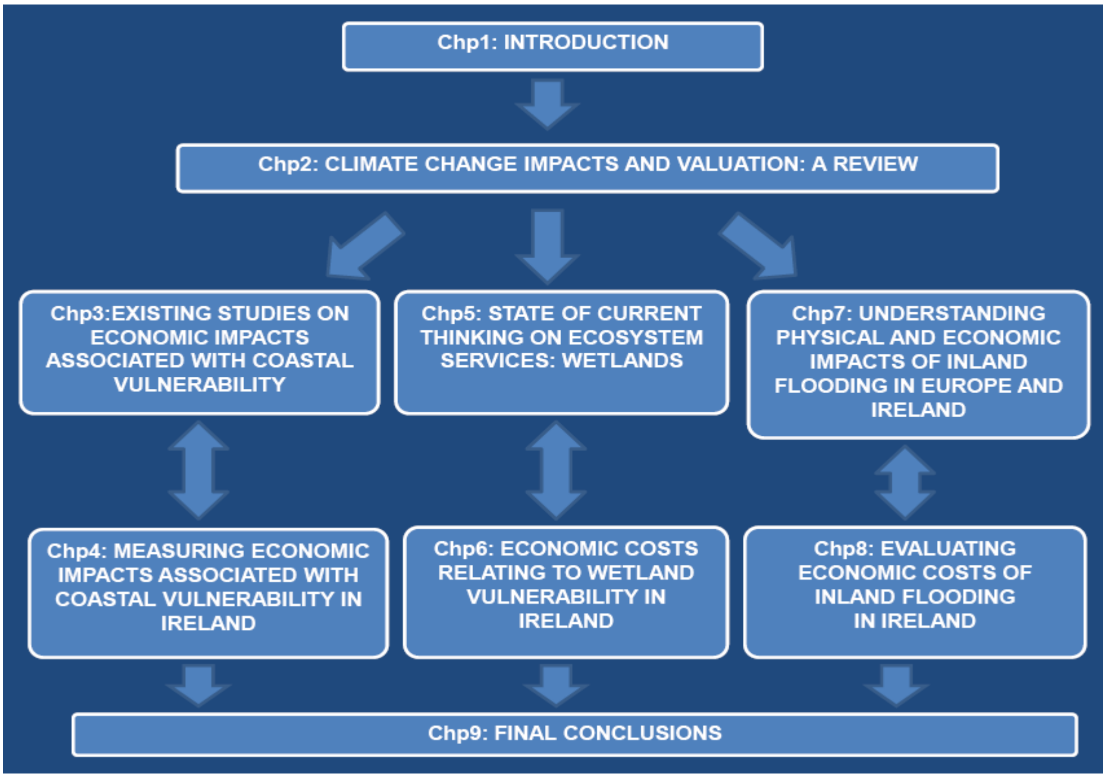


Figure 1.6: Map of thesis structure.

An overview of each chapter is provided below:

Chapter 1: Introduction gives an overview of the science of climate change and potential physical impacts, as well as discussing the foundations of climate change economics. The general aims of the thesis are also presented.

Chapter 2: Climate change impacts and valuation: A review outlines the climate change challenge by exploring complexities and methodologies associated with valuing the environment. It presents an overview of global and European economic impact and adaptation costs associated with climate change. It also analyses the role of adaptation together with the concepts of sustainable development, vulnerability and resilience to provide an appropriate approach to policy actions.

Chapter 3: Existing studies on economic impacts associated with coastal vulnerability highlights physical and socioeconomic impacts linked with climate related coastal vulnerabilities in a global and Irish context. This chapter's function is to frame the analysis carried out in Chapter 4.

Chapter 4: Measuring economic impacts associated with coastal vulnerability in Ireland uses digital terrain models to explore the potential economic impacts of sea-level rise and storm surges on the Irish coast. Six sea-level rise scenarios ranging from 0.5m to 6m are explored to determine potential impacts on coastal land and properties. The concept of the Coastal Vulnerability Index (CVI) as a decision-making tool is also evaluated.

Chapter 5: State of current thinking on ecosystem services: Wetlands discusses ecosystem services valuations, maps global, European and Irish wetlands and explores wetland services, valuation methodologies and vulnerabilities. In relation to Irish wetlands a special focus is placed on salt marshes, coastal lagoons, dunes and machairs. The work presented here is intended to provide context to the modelling work carried out in Chapter 6.

Chapter 6: Economic costs relating to wetland vulnerability in Ireland examines potential impacts of SLR on Irish wetlands. Digital terrain modelling is used to explore three SLR scenarios ranging from 0.5m to 2m. CORINE land cover data provides an indication of potential wetland loss in each of the three Irish wetland subgroups. In addition, IUCN Red List species lists along with the Irish National

Biodiversity Data Centre's species mapping tool were used to map out vulnerable species present in the two case study sites of Wexford and Dublin.

Chapter 7: Understanding physical and economic impacts of inland flooding in Europe and Ireland explores the physical processes of flooding and its link with climate change in Europe and Ireland. Irish rivers are specifically examined in relation to the economic impact of historical Irish flood events. Irish flood policies and management schemes are also investigated. This chapter provides context to the modelling work carried out in the following chapter.

Chapter 8: Evaluating economic costs of inland flooding in Ireland presents the results of vulnerability studies in four Irish river catchments. The modelling employs a hydrologically adjusted digital terrain model and explores three flood level scenarios ranging from 1m to 3m. Point data for commercial and residential addresses is used to determine potentially exposed properties. In addition, historical flood records, collated by the Office of Public Works, are displayed for the four case study catchments. Inland flooding costs in Ireland up to mid-century are also projected.

Chapter 9: Conclusions summarises the key findings of the thesis and highlights potential areas of future study.

CHAPTER 2
CLIMATE CHANGE IMPACTS AND VALUATION: A REVIEW

2.1 INTRODUCTION

Climate change is conceptually framed as a so called "wicked problem". Urban planners coined the phrase through their observations that many social planning problems could not be successfully treated with traditional linear and analytical approaches (Rittel and Weber, 1973). They classified these "wicked problems" as being difficult to clearly define, lacking in stability, and having no clear solution. Possible solutions involved a change in societal behaviour. Responsibility for such problems also does not sit within one particular organisation (Rittel and Webber, 1973). Climate change is difficult to define as the nature and extent of the problem differs, depending on which stakeholder group is involved, due to multiple perspectives on the issue (Hulme, 2011). Thinking on climate change is in flux, as the evidence relating to its understanding is evolving at the same time as policy makers are trying to address it (Australian Government, 2007). As there is no clear definition of the climate change problem it is difficult to define a clear solution. Hence, it is more appropriate to think of climate change as a problem that has to be managed rather than solved. In addition, due to the social and technical complexity of climate change, any efforts at managing the problem will involve not only engaging with stakeholders from across society (including private business, individuals, government departments and non-governmental organisations) but also from across levels from international to local. It is difficult to separate "wicked problems" from notions of equity, values, ethics and social justice (Ludwig, 2001). Therefore, ultimately, climate change management will involve significant challenges to, as well as changes in, human behaviour across societies at every level.

The following chapter outlines the climate change challenge by exploring complexities and methodologies associated with valuing the environment. It presents an overview of global and European economic impact and adaptation costs associated with climate change. It also analyses the role of adaptation together with the concepts of sustainable development, vulnerability and resilience to provide an appropriate approach to policy actions.

2.2 VALUING THE ENVIRONMENT

2.2.1 Ethics, justice and economic paradigms

In general terms, ethics is understood as knowledge of the fundamental values of human existence. Values are general attributions on the importance of objects (material or ideal, physical or spiritual) according to certain criteria. There are different kinds of values that can be broadly broken down into instrumental and intrinsic in nature. Instrumental values are important for their usefulness in gaining other values, whereas intrinsic values refer to objects that hold value in and of themselves. As such, instrumental value can never be a quality of the object itself but rather a judgement upon the object which remains inherent in the subject (Simmel, 1990). Ethical values form the basis of decision-making and action in accordance with an idea accepted in a given moral system. They are expressed in the notions of good and evil, right and wrong, just and unjust, what deserves respect or not. Ethical values are prescriptive; they articulate an imperative or must that cannot be escaped by anyone who subscribes to them (Comest, 2010).

Justice, as distinct from ethics, is concerned with what is legally right and wrong and can take several forms in the discourse of climate change. It can be distributive, compensatory or procedural. Distributive justice discusses what is unfair and unjust in the distribution of negative (or positive) effects of climate change. Compensatory justice sets out how to determine historical and current responsibility. Procedural justice explores who should participate in which processes of decision making about measures to prevent, mitigate or adapt to climate change (Comest, 2010). Climate justice plays a critical role in the entire climate change debate at a political environmental level. The principle of common but differentiated responsibilities forms the current cornerstone of the climate justice debate at the UNFCCC level (Paavola and Adger, 2002). Its application is of fundamental importance in determining both a fair way to decide which agents pay the financial burden of preventing or adapting to future climate change, and deciding who takes the lead in climate mitigation and adaptation activities (Page, 2008). Through exploring the various forms of climate justice, one can begin to understand the complexity of equitable burden sharing across countries and generations. It is argued that only by critically reviewing the rival approaches to burden sharing of "contribution to the problem", "ability to pay" and "beneficiary pays" that a satisfactory blend of theoretical coherence and practical application can be achieved (Page, 2008).

The philosophical position assumed by environmental economists is that the net utility from the consequences of an action determines whether the action is right or wrong. Cost-benefit analysis and its tools, such as the contingent valuation method, assume that individuals are willing and able to consider trade-offs in relation to public goods, i.e. that individuals follow a utilitarian philosophy (Spash, 1997). It assumes that a monetary value can be ascribed to public as well as private goods. This tendency towards the single metric of monetary valuation and the reluctance of the mainstream to consider other numéraires finds its roots in the epistemology of the Enlightenment or Age of Reason. Enlightenment thinking originates in 17th and 18th century European thinkers such as Voltaire, Rousseau, Kant and Hegel, with the foundations built upon the theories of Descartes (Van Asselt and Rotmans, 2002). Systematic investigation employing mathematical and quantitative methods was considered to lead to certain knowledge about reality. This Enlightenment thinking grew into what is generally referred to as positivism; a paradigm that defines science as the search for and prediction of empirical regularities that can be made universal. In strict positivist epistemology uncertainty is considered as something unscientific (Van Asselt and Rotmans, 2002).

It is important to note from the outset that monetary elements of the cost of climate change can only provide an incomplete picture of the damages that climate change may cause. It is even likely that aggregating all costs and expressing them in monetary terms could obscure rather than enlighten the decision making process (Azar and Schneider, 2003). Monetary price must be seen as a measure of one aspect of value reflecting one particular sort of interest expressed mainly through traditional commercial markets (Funtowicz and Ravetz, 1994).

The question of substitutability is one that burns at the very core of the debate on economic valuation, ethics and climate change. The implicit utilitarian viewpoint of environmental economics, and in particular cost-benefit analysis, precludes the preservationist perspective which focuses on non-human intrinsic values associated with environmental systems (Spash, 1997). Most environmental policy is couched in terms of calculating the usefulness to humans of preserving specific environmental goods and services provided by environmental systems. This contrasts with the foundations of ecological economics (see Figure 2.1). Ecological economics is holistic in its approach and much less anthropocentric than environmental economics. It also tends towards rights-based thinking. Figure 2.2 displays the fundamental differences between ecological economics and traditional neo-classical economics approaches, in terms of their view of the environment, economy and humanity. Neo-classical economics tends to view the environment and humanity as embedded within the economy. Ecological economics takes a more holistic approach and considers the economy as a part of humanity living within its environment. Making decisions on a utilitarian basis is considered the most sensible approach by the majority of economists (Spash, 1997).

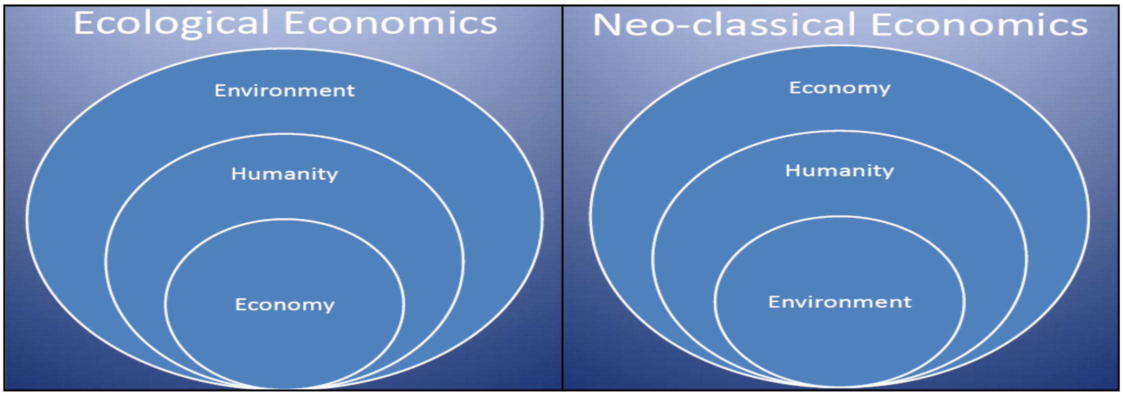


Figure 2.1: Foundations of Ecological Economics and Environmental Economics.

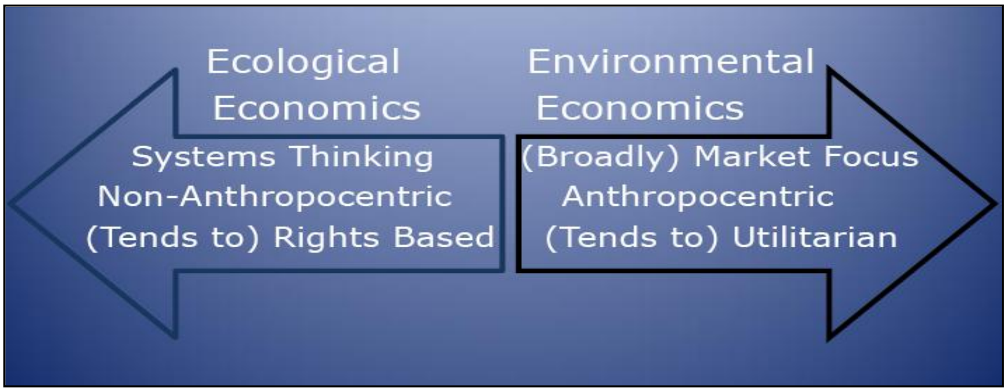


Figure 2.2: The positions of Neoclassical Economics and Ecological Economics in relation to environment, humanity and economy.

However this approach is rejected by those who hold a principles-based or rights-based deontological[1] approach to life. In the case of deontology, decisions are made on the basis of whether the act itself is right or wrong regardless of the consequences, e.g. thou shall not kill. This contrasts with teleology which is the branch of knowledge dealing with ends or purposes (telos meaning end). Teleology, when considered in modern economic thought normally takes a narrow anthropocentric utilitarian position (Spash, 1997). The fundamental flaw of taking this viewpoint is that it is humanity that is dependent on the environmental systems provided by our planet and not vice versa. The

[1] Etymological origins of deontology lie with the ancient Greeks. Dei holds the meaning “it is binding” or “it behoves” and ontology is the study of being.

asymmetric nature of this relationship is not captured within existing climate policy. Climate policy often looks at "comparable" risks of natural and economic instability even though these risks are not comparable at all (Van den Bergh, 2004: 390). Even with a moderately varying global climate and tough climate policies in place, the resulting economic impacts cannot be predicted exactly but can be guided or controlled within certain boundaries. However, economic impacts cannot be estimated or controlled under more extreme changes in the global environment that may include erratic irreversible and discontinuous changes in environmental variables (Van den Bergh, 2004).

2.2.2 Post-normal approaches

In the effort to capture climate change impacts, how can one go about including what cannot be counted easily in GDP terms in a practical manner? One possible method is that of Post-Normal Science (PNS). This approach focuses on problem solving in a different fashion to more traditional scientific practice. It attempts to capture the neglected aspects of uncertainty, value loading, and the plurality of legitimate responses (Funtowicz & Ravetz, 2003).

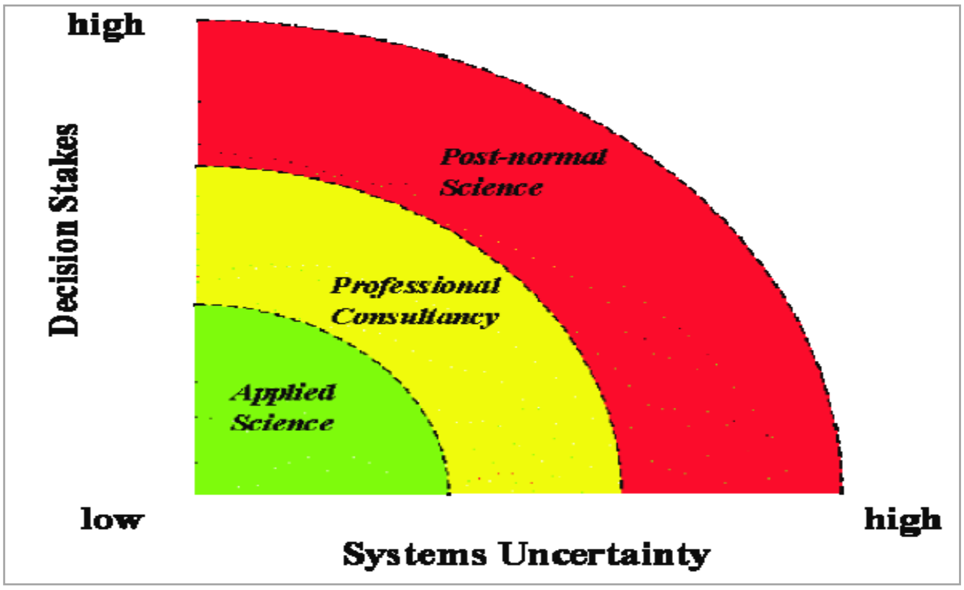


Figure 2.3: Decision stakes, systems uncertainty and Post-Normal Science.

Figure 2.3 above outlines the PNS approach relative to more traditional problem-solving strategies. Systems uncertainty is on the x axis and decision stakes are on the y axis. The expertise of applied science is fully effective when both system uncertainty and decision stakes are low. When both are of a medium level then the application of routine techniques is not enough; skill, judgment, and often courage are required (Funtowicz & Ravetz, 2003). This demands professional consultancy where the creative element can be thought of as an exercise in design rather than the discovery of facts. When both risk and uncertainty are very high then one leaves the realm of traditional expertise and traditional problem solving methodologies. Another way to conceptualise this is to explore the idea of confidence intervals in applied science. In statistics Type I and Type II errors correspond to errors relating to the excess of sensitivity and an excess of selectivity respectively. These statistical tests are useful when examining a well defined applied science problem where the conditions of relatively low decision stakes and uncertainty hold. However, statistical theory tends to undervalue what is known as Type III (or Type 0) error that examines if the modelling effort itself is fit for purpose, i.e., does the exercise sufficiently capture reality. Modelling exercises are especially vulnerable to this type of error, as the shortcomings between a manageable model and available data on the one hand, and the real policy circumstances, often cannot be reconciled (Funtowicz & Ravetz, 2003).

It is argued that the approach employed by normal science to manage complex social and biophysical systems as if they were simple scientific exercises has created our present situation – as referred to by Funtowicz & Ravetz – as the "fusion of intellectual triumph and socio-ecological peril". In the arena of climate change often difficult policy decisions need to be made where scientific inputs are uncertain. When shaping research conclusions or policy recommendations, the need for the hard or concrete science that is necessary to arrive at rational policy decisions may effectively conceal "value-loadings" (Funtowicz & Ravetz, 2003: 2). With increased complexity and plurality one can see that the quest for "truth" as the goal of science is problematic.

The PNS approach would argue that quality is of greater importance than "truth". The post-normal method argues against the use of one single valuation when appraising policy options. It argues that value is never a "quality" of the object(s), but a judgement upon them which remains inherent in the subject. This fundamental conceptualisation of value is explored in Simmel's writings on the philosophy of money (Simmel, 1990). He clarifies the difference between value as a real psychological occurrence that can be considered a part of the natural world and our human conceptualisation of value as a quality that is independent of this world. This conceptual notion of value is synonymous with instrumental valuation, and is understood by Simmel as the world viewed from a particular viewpoint.

Furthermore, it is argued that one must question whose special interests are served when only one value or numéraire is presented. For this reason, other metrics or numéraires are needed when assessing the impacts of climate change. Five potential numéraires include 1) market impacts, 2) human lives lost, 3) biodiversity loss, 4) income distributional impacts and 5) quality of life impacts that might include loss of heritage sites, forced migration and health impacts (Azar & Schneider, 2003).

PNS and ecological economics are not currently within the mainstream policy discourse on climate change. Rhetorical approaches (after Aristotle) are important in allowing a range of ethical viewpoints and valuation methodologies to have a greater voice.

2.2.3 Rhetoric and politics

The word rhetoric has two definitions; the first Platonic and the other Aristotelian. The first defined as mere flattery and cosmetics (made popular in the 19th century when sincerity was elevated to the chief virtue); with the other all "the available means of [uncoerced] persuasion” as Aristotle phrased it, or as the whole art of argument and the study of debates (McCloskey, 1994, xiii).

The broader definition of rhetoric is interesting in the context of economic argument and persuasion. One must always be cognisant of the rhetoric employed by economists, especially when it claims to be constructed from cold, clear “facts”. For example, one must always ask whose special interests are served when only one numéraire is presented. Realising that the current mainstream approach in exploring climate change and economics is that of environmental economics, one must try to understand what is not being discussed, considered and explored, and why this might be the case. Economics’ particular alignment within social science is cause for much of its singular focus on the mathematically quantifiable and especially monetary quantification. It is argued that positivism commands intellectual narrowness. It can be accused of narrowing the grounds on which scholars can converse down to the observable, to the numerical, to the non-tacit (McCloskey, 1994). This can be very dangerous in practice, especially when exploring something such as the potential far-reaching economic impacts resulting from climate change. The dangers resulting from mathematically complex quantifications of economic impacts resulting from potential climate change scenarios is their perceived presentation as an objective truth. A tonic to the quest for clear fact and objective truth in the science of economics must be the realisation that truth seeking is a hopeless epistemic project. On the other hand, trying to live a life of virtue within the framework of a rule is a possible moral ambition (Harré, 1983). In practice the scientific conversation is a complex rhetorical matter, a practice, not a theory. Rhetoric flourishes where disagreement flourishes, which is why rhetoric had a special connection with free and open societies. Barriers to inclusive discussion and open rhetorical discussion include the varying interests of actors, implicit ethical practice and market influence. Possible forums for discussion include the government, the business community, the media and popular discourse and non-governmental organisations and academics (Figure 2.3).

Figure 2.4: Global forums.

The practice of rhetoric blends into that of politics, and the politics of climate change specifically is a sphere of political engagement that has been discussed at length in the literature (Dessler, 2012; Hulme, 2011; Patterson, 1996). Climate change politics has developed in tandem with the development of climate science and a number of other global environmental issues. Ozone layer depletion along with the acid rain phenomenon were two issues that received significant political interest though the 1970s and 1980s (Dessler, 2012). At the time, those opposed to actions to prevent both impacts took up a similar strategy to the tobacco industry's efforts in protecting its business interests; they cast doubts on the science. This divergence between the public policy and scientific arenas is one reason why there is significant disagreement over climate science in the public policy sphere, even though there is a general consensus among the climate science community (Dessler, 2012). Hence it is clear that free and open debate is critical if a balanced climate change narrative is to be relayed to decision-makers in the public sphere. The framing of the climate change narrative is discussed at length in Hulme's work. The way climate change is viewed plays an important role in how it is engaged with politically, and in turn how it is governed (Hulme, 2011). In accordance with its definition as a "wicked problem" it can be viewed through a wide range of perspectives including security, economics, social justice and environment.

Ethical approaches or ideologies are critical in further framing the issue. The approach of market environmentalism, or neoclassical environmental economics, raises a set of particular criticisms categorised under the term 'carbon colonialism' (Hulme, 2011). The criticism is that market environmentalism seeks to achieve "economically efficient" solutions to climate change impacts through mitigation and adaptation efforts that pay little or no regard to geography and, it can be argued; often pay little attention to temporal issues. As a consequence issues of justice, equity and ethics are often neglected.

It is interesting to try and place this market environmentalism within the current global systems that govern climate change mitigation and adaptation efforts. The role of traditional state sovereignty and the international community in relation to climate change governance have been explored at length in the literature. It is worth expanding on some of these theoretical constructs in the context of this preceding discussion on rhetoric. The traditional neorealist theory stresses the difficulties in achieving international cooperation. It also emphasises the unity and dominance of state actors (Patterson, 1996). In contrast to this construct Hass (1989; 1990) and others see the notion of "epistemic communities" as a much more useful approach that is also grounded in present day political interactions. An epistemic community is defined as:

"a network of individuals or groups with an authoritative claim to policy relevant knowledge within their domain of expertise … They adhere to the following: (1) shared consummatory values and principled beliefs; (2) shared causal beliefs or professional

judgement; (3) common notions of validity based on intersubjective internally defined criteria for validating knowledge; and (4) a common policy project."

(Adler, 1992: 101n1)

It is thought that the knowledge that they generate and have control over gains political importance when the consensus among this epistemic community is sufficient enough to be convincing to the external political community (Patterson, 1996). However, the clear distinction between the epistemic community and the political community simplifies the reality of the system somewhat. As Haas states; "epistemic agreement [is] possible only in those areas removed from the political whirl" (Haas, 1992: 5). In practice all agents have implicit political ties of some kind and this weakens the epistemic community construct somewhat.

These political ties often come down to geographical identities associated with North-South relations. During the 18th and 19th centuries inequalities in terms of wealth, education, and health care were much greater within countries than between countries. However, increasingly from the later 19th century that relationship has been reversed (Brown, 1992). The theory of historical materialism explores these inequalities in some depth (Froebel *et al*., 1980; Augelli and Murphy, 1988). The differing political identities of North versus South are critically linked with the notions of climate justice and ethics (Page, 2008). This is highlighted in the proceedings of current international climate negotiations with representatives from the North and South arguing over issues that reflect the structural inequality in the world political economy that clearly question notions of justice and ethical viewpoint (Hulme, 2011).

The following Section (2.2.4) presents an argument based on the Aristotelian notion of rhetoric within the sphere of academic debate surrounding the Stern Review on the costs of climate change. It provides an interesting cross-section of viewpoints relating to different economic thinkers and displays a wide range of perspectives and approaches to economic valuation and climate change. It highlights the importance of open and frank debate and discussion, as well as the difficulty of formulating universally accepted valuation methodologies.

2.2.4 Stern and post-Stern

The publication of the Stern Review in October 2006 marked the beginning of an intense period of global interest and attention in climate change. The review, published on behalf of the British government by a team of economists lead by Sir Nicholas Stern, created significant attention across all public forums: the government, the business sector, academics and NGOs as well as the media and the general public discourse. This period, before the property-fuelled global financial crash in September 2008 and the ensuing global economic downturn, marked a sustained level of attention on climate change issues. The Review painted a clear picture of the dangers and costs of climate change to the world economy. It stated that the scientific evidence is overwhelming that climate change presents very serious global economic risks. In turn, it advocated a global response of strong, early action on climate change in order to outweigh future potential costs (Stern, 2006). The academic critique on the Review is varied but a number of specific issues and themes repeatedly appear. The arguments presented can be broadly categorised into four main themes: those that find fault with the discount rate applied in the report, those who disagree with the scale of the climate change impacts presented in the report that drive the economic modelling, those that find the modelling and results are inadequate and biased, and those that find the methodology in general inappropriate. These critiques provide a useful case study in identifying ideas and arguments within the spectrum ranging from environmental to ecological economic thought. The following account outlines the critiques of seven leading economists in relation to the Review.

Kenneth Arrow, an environmental economist, comments on the way in which the Review treats discounting but agrees with its fundamental conclusions (Arrow, 2007). He agrees that society is much better off to act now to reduce carbon dioxide emissions substantially rather than suffer the potential risks associated with climate change impacts. Arrow argues that this conclusion holds even if one heavily discounts the future. Arrow also points out two critical elements of the cost-benefit analysis approach[2]. Firstly, the need to allow for uncertainty is stressed along with the assumption that individuals prefer to avoid risk. The possible outcomes of global warming in the absence of mitigation are very uncertain, although assumed to be negative. It follows that the uncertain losses should be evaluated as a single loss greater than the expected loss. The other critical aspect is how future outcomes are treated relative to current outcomes. This leads on to a discussion on discounting and discount rates. The consumption discount rate (used in cost-benefit analysis) evaluates how future losses of consumption should be discounted to present values using the following formula:

$$\delta = \rho + g\eta$$

δ is the consumption discount rate,
ρ is the social rate of time preference,
g is the projected growth rate of average consumption and
η is the elasticity of the social weight attributed to a change in consumption.

The final parameter (η) accounts for the possibility that, as consumption grows, the marginal unit of consumption may be considered as having less social value. This component of the consumption rate of discount is relatively uncontroversial. However, there is significant argument surrounding the appropriate value of ρ, the social rate of

[2] Cost-benefit analysis (CBA) is the principle economic approach for deciding whether actions to mitigate against climate change are warranted. In CBA, benefits and costs are expressed in money terms, and are adjusted to account for the time value of money. Using the CBA method all flow of costs and benefits which tend to occur at different points in time are expressed on a common basis in terms of their "present value."

time preference. This parameter allows for discounting the future simply because it is the future, even if future generations' incomes are no higher than ours. The Stern Review generated a significant level of criticism by adopting a value of zero for the social rate of time preference. Arrow defends this decision because of the severity of potential losses from climate change impacts. He argues that even with higher discounting in place the cost-benefit analysis results indicate that mitigation action should be taken now.

Richard Tol and Gary Yohe, both environmental economists, argue that the Stern Review estimates economic impacts related to climate change well outside the range of the literature of estimates on climate change (Tol and Yohe, 2006). They also argue that the role of adaptation in avoiding many of these impacts is not seriously considered. In addition, Tol and Yohe criticise the modelling used in the report. They argue that the results are not robust as the report only uses one model (the PAGE2002 Integrated Assessment Model). It is also pointed out that the model incorrectly assumes that vulnerability to climate change is independent of development. They also criticise the report for not providing enough information on how the results it presents were calculated and call attention to the fact that the consumption discount rate is lower than the official recommendations by HM Treasury. They conclude by stating that the report is alarmist and incompetent.

Martin Weitzman, an environmental economist, also criticises the Review's low discount rate (Weitzman, 2007). He believes that the Review deserves a measure of discredit for not fully disclosing that the policy recommendations suggested depend upon extreme assumptions and unconventional discount rates that most mainstream economists would consider too low. He also believes that mitigation of climate change should be seen as comparable to buying an insurance policy to offset a ruinous catastrophe that is difficult to compensate by ordinary savings. He criticises the Review for not formally confronting this issue of what to do about catastrophe insurance against the possibility of high-impact, low probability disasters. However, Weitzman concludes by praising the Review for effectively raising the level of public discourse on economic impacts of climate change. He is also in favour of the global carbon tax recommended in the Review as a policy tool, and for popularising to a wider audience, outside of economists, the cost-benefit analysis methodology. In addition, he believes that the Review deserves some praise for highlighting the difficulty of making decisions to anticipate events whose scale and probability cannot be known precisely.

A number of ecological economists have also voiced their criticism at the report but on different grounds. Eric Neumayer highlights the fundamental flaw of traditional cost-benefit analysis carried out in the Review, as it does not account for the often non-substitutable nature of natural capital loss (Neumayer, 2007). He finds the discount rate selected in the Review as ethically defendable but argues that the discourse needs to move beyond the discounting debate. He also makes the point that the cost-benefit analysis tool is misleading in offering up quantitative results for future potential climate change impacts. He argues that many of the effects of climate change cannot be adequately valued in a monetary fashion. In addition he points out that discount rates are informed by normative value judgements and are hence heavily influenced by ethical choices. He believes that the non-substitutability argument is much closer to the real concerns of people and that cost-benefit analysis is strangely out of touch with reality.

Simon Dietz *et al.* echo the comments of Weitzman in arguing for a more comprehensive analysis of low-probability/high-damage scenarios (Dietz *et al.*, 2007). They also call for caution in over relying on cost-benefit analyses and argue for an approach built on broader foundations. They argue that cost-benefit analysis makes a particular value judgement and that rights-based approaches are not considered in the analysis. Economic modelling is considered useful in estimating an order-of-magnitude quantification of the economic consequences of unabated climate change. Dietz *et al.* thus consider Integrated Assessment Modelling as providing a useful input into the broader discourse on intergenerational equity, wealth distribution and the management of risk and uncertainty.

Clive Spash also argues against the sole use of cost-benefit analysis as an appropriate tool for generating policy recommendations (Spash, 2007). He points out that the authors of the Stern Review maintain allegiance to an economic orthodoxy that follows a belief that current economic growth can be sustained and answer all our problems. He believes this allegiance diverts attention away from alternative approaches, including ethical discussions on climate change and its impacts on future generations. It also diverts attention away from consideration of the impacts of the current economic growth model on our environmental systems. He concludes that the argument furnished by Stern limits the climate change issue to examining impacts on future consumption growth. In this way its results are oversimplified and based on narrow ethical positions.

These six different critical analyses on the Stern Review highlight the wide ranging display of arguments and critiques that vary from technical issues relating to discount rates and economic modelling approaches to critiques of the cost-benefit methodology itself. These critiques thus display the implicit importance of ethics in the entire exercise of estimating economic impacts relating to potential future climate change impacts.

The next Section (2.2.5) draws upon the debate and critique around Stern, as well as the preceding discussion on valuation, by suggesting that a clear understanding and appreciation of sustainability, vulnerability, and resilience are needed to frame our economic evaluations, as well as our actions, in relation to climate change.

2.2.5 Sustainable development, vulnerability and resilience

The term Sustainable development (SD) was coined with the publication of the 1987 Report of the Brundtland Commission; Our Common Future (United Nations, 1987). The Report grounds the principles of SD and framed its definition, which is still in use today: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987, 24). The Report is wide-ranging in scope and thematically explores common concerns relating to conceptualising SD, environmental degradation, the role of the international economy in the context of our environment, and human development. Common challenges are outlined, which include issues relating to population and human resources, food security, species and ecosystems, energy needs, industrial processes and the challenge of developing sustainable cities. The report closes by focussing on common endeavours such as managing the global commons, peace and security in relation to development and the environment, as well as proposals for institutional and legal change.

Use of the term SD became widespread and pervasive a number of years after the publication of the Report and indeed became the developmental paradigm of the 1990s (Lélé, 1991; Aguirre, 2002). However, with time, its exact meaning and application became increasingly unclear and fuzzy. On the one hand, it can be argued that the value of the phrase rests on the fact that it is so broad. This vagueness allowed people with greatly varying positions on environmental development to enter more readily into dialogue and debate and search for common positions (Lélé, 1991). However, on the other hand, this vagueness also gave rise to real concerns that SD may be misinterpreted or distorted with many becoming disillusioned with the term (Fergus and Rowney, 2005). During the early 90's the scientific community also became increasingly estranged from the SD agenda as they felt that societal and political processes were overly dominant in shaping the debate on SD (Kates *et al*., 2001). A new field of sustainability science began to emerge with the goal of understanding the fundamental character of interactions between nature and society. Table 2.1 below proposes a set of core questions of sustainability science. All of these questions are of relevance to the area of climate change science with one in particular of significant relevance to the economic valuation of present and potential climate change impacts: "What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?

Table 2.1: Core questions for sustainability science (source: Kates *et al*., 2001).

CORE QUESTIONS OF SUSTAINABILITY SCIENCE
How can the dynamic interactions between nature and society – including lags and inertia – be better incorporated into emerging models and conceptualisations that integrate the Earth system, human development, and sustainability?
How are long-term trends in environment and development, including consumption and population, reshaping nature-society interactions in ways relevant to sustainability?
What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?
Can scientifically meaningful "limits" or "boundaries" be defined that would provide effective warning of conditions beyond which the nature-society systems incur a significantly increased risk of serious degradation?
What systems of incentive structures – including markets, rules, norm, and scientific information – can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?
How can today's operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?
How can today's relatively independent activities of research planning, monitoring, assessment and decision support be better integrated into systems for adaptive management and societal learning?

Economic impacts relating to climate change are unevenly distributed globally (Stern, 2006). This question focuses on determining which places, are particularly vulnerable or indeed resilient, which ecosystems are particularly vulnerable or resilient and which human livelihoods are particularly vulnerable or resilient. Note that it is the entire nature-society *system* (my italics) that is examined in this instance. System thinking finds its origins in the field of system dynamics, which was founded in 1956 by

Jay Forrester (Forrester, 1961). Traditional forms of analysis focus on breaking a problem into its constituent parts. System thinking, in contrast, explores how the object that is being studied interacts with the other constituents of the greater system (Aronson, 1998). Vulnerability, in the context of climate change, relates to the extent to which "… geophysical, biological and socio-economic systems are susceptible to, and unable to cope with adverse impacts of climate change" (IPCC, 2007b: 73). The term vulnerability can thus refer to the vulnerable system itself (e.g., low lying coastlines), the impact to this system (e.g. coastal flooding or increased prevalence of disease), or the mechanism causing these impacts (e.g. disintegration of the West Antarctic ice sheet) (IPCC, 2007b).

O'Brien *et al*. explore two competing interpretations of vulnerability in the climate change literature (O'Brien *et al*., 2004). The first interpretation views vulnerability as a residual of climate change impacts minus adaptation actions, and is known as the "end point" approach. In this case vulnerability is determined at the end of a process that moves from emission trend projections, to impact studies, to identification of adaptive capacity and adaptation options. The second interpretation takes vulnerability as a general characteristic generated by multiple factors and processes or as a "starting point". In this interpretation vulnerability represents a present inability to cope with external pressures or changes. The first interpretation considers that adaptation and adaptive capacity determine vulnerability, whereas the second interpretation posits that vulnerability determines adaptive capacity. The manner in which vulnerability is defined becomes very important when it comes to policy formulation and decision making. If one holds an "end point" definition of vulnerability then it can be addressed by limiting impacts, through mitigation activities, or by increasing adaptations that reduce climate sensitivity, such as introducing drought-tolerant seed varieties or changing infrastructure (O'Brien *et al*., 2004). From a "starting point" perspective vulnerability is addressed by enhancing the ability to cope with current climate vulnerability as well as long term climate uncertainty. There is a focus on improving coping capacity and decreasing vulnerability not only to climate change but to other multiple stressors. Table 2.2 below draws up a useful comparison between the two terms under a number of headings.

Table 2.2: Two interpretations of vulnerability in climate change research (Adapted from Füssel, 2007).

	"End point" interpretation	**"Starting point" interpretation**
Root problem	Climate change	Social vulnerability
Policy context	Climate change mitigation, compensation, technical adaptation	Social adaptation, sustainable development
Illustrative policy question	What are the benefits of climate change mitigation?	How can vulnerability of societies to climatic hazards be reduced?
Illustrative research question	What are the expected net impacts of climate change in different regions?	Why are some groups more affected by climatic hazards than others?
Vulnerability and adaptive capacity	Adaptive capacity determines vulnerability	Vulnerability determines adaptive capacity
Reference for adaptive capacity	Adaptation to future climate change	Adaptation to current climate variability
Starting point of analysis	Scenarios of future climate hazards	Current vulnerability to climatic stimuli
Analytical function	Descriptive, positivist	Explanatory, normative
Main discipline	Natural sciences	Social sciences
Meaning of "vulnerability"	Expected net damage for a given level of global climate change	Susceptibility to climate change and variability as determined by socioeconomic factors
Vulnerability approach	Integrated, risk-hazard	Political economy

Resilience is defined in the United Nations International Strategy for Disaster Reduction (UNISDR) as:

"*The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions*". (UNISDR, 2009, 24)

There is a significant volume of literature discussing the issues of both vulnerability and resilience (Adger, 2006; Gallopín, 2006; Vogel *et al*., 2007; Turner, 2010). In the field of sustainability science the terms are highly interrelated and often overlapping.

Vulnerability research generally focuses on threats to some element of society due to a particular hazard or a range of hazards (Adger, 2003). Resilience on the other hand is grounded in the ecological sciences and is occupied with addressing persistence and change in ecosystems (Carpenter *et al*., 2001). It gradually has found a place in the study of nature-society systems and entered into social sciences terminology. Both these concepts are attractive for geographers with vulnerability focusing on inherent risks that are experienced by people living in particular areas, with resilience referring to the ability of ecosystems and people in adapting to both opportunities and risks (Adger and Brown, 2009). Vulnerability has a strong foundation in risks and hazards research, and places a strong focal point on economic and social conditions as causes of social vulnerability. Resilience, is focused on understanding complex system studies with an emphasis on adaptive capacity (Adger and Brown, 2009; Nelson *et al*., 2007). Essentially resilience examines a system's ability to retain its system function and character. Vulnerabilities are normally defined in terms of perturbations or changes outside of the control of human communities, and are usually portrayed as something negative or to be avoided (Adger and Brown, 2009). Seen from this perspective vulnerability can be seen as the opposite to resilience. However, referring back to sustainability science, and specifically to the core question that frames this thesis, both concepts are gradually converging towards a common agenda that recognises the place-specific nature of resilience communities along with the necessity to determine those who benefit and that that lose out as a result of interventions and adaptation actions that seek to promote resilience and the capacity to adapt (Adger and Brown, 2009).

This Section reiterated the importance of viewpoints and approaches when it comes to the measurement and valuation of climate change; SD and resilience can be thought of taking a systems thinking approach that one could align more easily with the foundations of ecological economics than with those of environmental economics. “End point” or “starting point” definitions of vulnerability can also shape policy approaches and actions in relation to climate change. The following section (2.3) presents an overview of global and European economic impact and adaptation costs associated with climate change. These economic values provide decision-makers with a useful indication of the potential magnitude of climate change impacts and adaption costs expressed in monetary terms.

2.3 ECONOMIC IMPACT AND ADAPTATION COSTS

As aforementioned, the economic impacts of climate change were brought fully to the attention of the public consciousness in late 2006 with the publication of the Stern Review (Stern, 2006). The main recommendations of the report suggest that the expected benefits of tackling climate change far outweigh the expected costs, and that early action is preferable to reduce and avoid the worst of the impacts. The key messages from the economic modelling carried out in the report forecast that an increase of global average temperatures of 2-3°C could lead to an equivalent loss of up to 3% in global GDP with poorer countries suffering the highest costs. With global average temperature increases of 5-6°C, resulting from an estimate of temperature increases following abrupt and large scale climate change, the losses in global GDP are estimated to be in the region of 5-10%, with poor countries suffering costs in excess of 10%. However, the risks considered in the assessment cover a very broad range and involve the possibility of much higher losses (Stern, 2006). Adaptation costs are also discussed in the report with a focus on the additional costs of new climate resilient infrastructure and buildings. These costs are estimated to range from €11-111 billion each year in OECD countries (0.05-0.5% of GDP), dependent on the warming scenario (Stern, 2006).

Adaptation in developed countries is considered to be still at an early stage, even though there are well developed market structures and the capacity to adapt is relatively high. The Stern Review believes that market forces are unlikely to deliver the full necessary response needed to deal with climate risks and subsequently governments provide a role through providing clear policy frameworks to guide effective adaptation by individuals and organisations in the medium to long term (Stern, 2006). The Green Climate Fund, operationalised in the 2011 UN climate negotiations in Durban, is currently the primary supranational non-market revenue source intended for developing countries (and especially those particularly vulnerable to climate change) to adapt to climate change impacts. Current fast-start finance to be made available to developing countries is in the order of €22B from 2010-2012 including Irish pledges of €100M. Medium-term financing is currently set to €100B a year by 2020 (WRI, 2011; UNFCCC, 2010; UNFCCC, 2008). However, there was little discussion at the 2011 Conference of the Parties in Durban on how this €100B medium-term financing would be raised (Economist, 2011).

The Stern Review was a welcome addition to the literature as it has raised the profile of potential economic impacts relating to climate change. While it received significant criticism from various standpoints (Yohe & Tol, 2008; Neumayer, 2007; Dietz *et al*., 2007; Sterner & Persson, 2008) the majority of commentators found that the central messages of the report were sound.

Modeling global costs associated with climate change is a very complex task which presents many challenges including capturing the uncertain changes that occur over long periods in economies and societies at large, and taking account of high impact low probability risks. Stern uses an Integrated Assessment Model (IAM) which combines the scientific and economic aspects of climate change to provide policy options. The PAGE2002 model (Policy Analysis of the Greenhouse Effect 2002) used in the report takes account of risks and uncertainty by allowing outcomes to vary probabilistically across many model runs, with the probabilities calibrated to the latest scientific evidence on particular risks (Hope, 2006). Other Integrated Assessment Models include RICE/DICE (Nordhaus, 1992; Nordhaus & Zang, 1996), MERGE (Manne *et al*., 1995), and FUND (Tol, 1997). RICE and FUND simulate regionally specific impacts in a number of sectors (either in the aggregate or sector-specific). PAGE, DICE and MERGE simulate aggregate global market and non-market damages, as well as damage due to rapid or catastrophic climate change. Only the PAGE model is probabilistic in nature and can explicitly simulate adaptation (Warren *et al*., 2006).

Table 2.3 below displays some of the modelled economic damage costs referring to possible future climate change scenarios. The timeframes, assumptions, regions and economic sectors examined differ between models leading to estimated damage costs ranging from 0.2% of European GDP up to 2.49% of global GDP. These losses are considerably lower than the 5-10% losses estimated by Stern. However, Stern explored 5-6°C temperature increases, using the PAGE2002 model, and uses a much lower discount rate than the models explored above. The subject of discounting is an important one, and should be carefully approached when issues of substitutability and intergenerational equity are considered in relation to economic climate change impacts. As discussed in Section 2.2.4, discounting considers the issue of temporal aggregation of costs while equity weighting explores spatial aggregation of costs. Discounting is based on the principle that costs and benefits in the future count for less in the present because they affect a larger expected income. A "discount rate" is used to convert economic costs to "present values" (European Environmental Agency, 2007)[3]. The issue of discounting is particularly important when looking at the economic analysis of climate change as long time frames are often considered. Discount rates therefore decide in which time period it is economically cheaper to implement adaptation or mitigation.

Table 2.3: GDP percentage loss damage costs referring to modelled future climate change scenarios.

Model	Damage Cost	Time Frame	Countries Included	Sectors	Comments on methods/ sources
DICE & RICE (1999)	1.5% of GDP	2100	Global	*Agriculture, Other vulnerable market, Coastal, Health, Non-market time use, Catastrophic, Settlements*	Impact of 2.5°C warming above 1900 on different sectors shown in output weighted global GDP % loss
MERGE (2004)	0.5% of GDP	Up to 2200	Developing Countries	*Market Sectors only*	Impact of 2.5°C warming above 1900 shown in GDP % loss
	2.49% of GDP	Up to 2200	Developed Countries	*Market and non-market sectors*	
FUND (2006)	1.2% of GDP	2095	Global	*Agriculture, Forestry, Water Resources, Energy Consumption, Sea level rise, Ecosystems, Human health*	Impact of 2.5°C warming above 1990 shown in GDP % loss
GEM-E3 (2005)	0.2% of GDP	2080's	European region	*Agriculture, river flooding, coastal impacts, tourism*	Impact of 2.5°C warming above 1900 shown in GDP % loss

The World Bank provides global economic costs relating to climate impacts in its 2009 report that sets its focus on the developing world. The report points out that global mean temperature increases in the magnitude of 4°C will significantly increase the likelihood of irreversible and potentially catastrophic impacts including extinctions for half of our species worldwide, inundation of up to 30% of coastal wetlands and significant increases in malnutrition, diarrheal and cardio-respiratory diseases (World

[3] A high discount rate leads to lower economic costs as large future negative effects are reduced through discounting. A low discount leads to higher economic costs as large future negative effects are reduced to a much lesser extent through discounting.

Bank, 2009). The outputs of this work forecast that the cost, between 2010 and 2050, of adapting to 2°C warmer world by 2050 is in the range of €56B to €74B a year. It is also noted that this sum is of the same order of magnitude as the foreign aid that developed countries currently give developing countries each year (World Bank, 2009). Please see Table 2.4 below for a summary of a range of adaptation costs from various studies.

The OECD has also published a number of reports exploring the economic aspects of adapting to climate change. Their 2008 report points out that while there is a significant body of literature accumulated on assessing adaptation costs at a sectoral level it is unevenly spread across sectors (see Table 2.5). For example, economic impacts relating to climate change on agriculture and coastal zones are well developed at a global level (OECD 2008). However, information on adaptation costs is quite limited for other sectors including tourism, public health, water resources, energy and infrastructure. The majority of information available for these sectors is also tied to the local context and this makes generalisations in the broader global context difficult (OECD, 2008).

Table 2.4: Adaptation costs from a number of key economic assessments (Adapted from OECD, 2008).

Review	Adaptation Cost	Time Frame	Countries Included	Sectors	Comments on methods/ sources
World Bank (2006)	€7 - 30 billion/yr	Present	Developing Countries	*unspecified*	Based on OECD & World Bank (WB) analysis of official flows exposed to climate risk. Costs of "Climate Proofing" are assumed.
Stern Review (2006)	€3 - 27 billion/yr	Present	Developing Countries	*unspecified*	Update, with slight modifications of WB Study.
	€11 - 111 billion/yr	Not Specified	Developed Countries		
Oxfam (2007)	*At least* €37 billion/yr	Present	Developing Countries	*unspecified*	WB study + extrapolation of cost estimates from NGO & National adaptation programmes of action (NAPAs) projects.
UNDP (2007)	€64 - 81 billion/yr	2015	Developing Countries	*unspecified*	WB study + costing of targets for adapting poverty reduction programmes & strengthening disaster response systems.
UNFCCC (2007)	€21 - 50 billion/yr	2030	Developing Countries	Agriculture; water supply; human health; coastal zones; infrastructure	In-depth costing of specific adaptations in water, health & coastal zones. Less detailed costing for agriculture, infrastructure & ecosystems. Infrastructure more abstract. Infrastructure adaptation costs overlap with costing in coastal zones & water resources.
UNFCCC (2007)	€36 - 127 billion/yr	2030	Global		
World Bank (2010)	€56 - 74 billion/yr	2010-2050	Global	Agriculture; water supply; health; coastal zones; Infrastructure; forestry; fisheries & extreme weather events.	This study estimates the costs for major economic sectors under two alternative future climate scenarios – one wetter and one drier. The study mostly estimated costs for 'hard' options involving engineering.

Table 2.5: Adaptation cost coverage (Source: OECD, 2008).

Sector	Coverage	Cost Estimates	Benefit Estimates
Coastal Zones	Comprehensive – most coastlines	√	√
Agriculture	Comprehensive – most crops & growing regions	-	√
Water	Isolated Case studies	√	√
Energy	Primarily N. America	√	√
Infrastructure	Cross-cutting issue; Isolated studies	√	-
Tourism	Very limited – winter tourism	√	-
Health	Very limited	√	-

Table 2.6: ClimateCost headline results (Source: European Commission, 2011).

Model	Damage Cost	Time Frame	Sector	Comments on methods/ sources
DIVA	€156 billion/ yr	2100	*Coastal zones and sea-level rise*	Impact of 1m SLR using high emission scenario RCP8.5[4]. Undiscounted values.
LISFLOOD	€50 billion/ yr	2080s	*River floods*	Marginal effect of climate change impacts using A1B1 scenario at current, undiscounted values.
VOLY and VSL[5] analysis	€1.3 billion/ yr (VOLY) €146 billion/ yr (VSL)	2080s	*Health*	Impacts under an A1B1 scenario, without adaptation, and accounting for autonomous acclimatization.
POLES	€95 billion/ yr	2100	*Energy*	Additional energy costs under an A1B scenario.

The European Commission's CLIMATE COST project provides sectoral bottom-up analysis exploring European climate impacts relating to sectors including

[4] This scenario reaches a global warming of about 3.5°C by 2071-2100 relative to the 1961-1990 baseline.
[5] VOLY stands for Value of a Life Year Lost and VSL stands for Value of a Statistical Life.

coastal vulnerabilities, inland flooding, health, and energy (Table 2.6) (European Commission, 2011).

The European Commission's Joint Research Centre's report exploring climate change impacts in Europe highlights a number of impact categories as areas of concern for Ireland (Ciscar *et al*., 2011). The report focuses on 5 impact categories including agriculture, inland flooding, coastal systems, tourism and human health. In Ireland (often included with the British Isles in the study) the impact categories under greatest threat from climate change are forecast to include coastal systems and inland river flooding. These areas also mirror those considered of greatest exposure under the United Kingdom Climate Impacts Programme (Jenkins *et al*., 2009) various regional impact studies coordinated under the aegis of ClimateUK (ClimateUK). Climate impacts on agriculture in Ireland calculated using the GTAP general equilibrium model (Hertel, 1997) are estimated to be marginally positive in terms of GDP; ranging from close to negligible for a 2.5°C scenario[6] to approximately 0.05% under a 4.1°C scenario[7] equating to an €80M boost in Irish GDP (European Commission, 2009a). Climate change impacts on tourism revenues in Ireland are also positive when modelled with a European tourism demand equation in conjunction with climate models. Under the 2.5°C scenario above tourism receipts are set to increase in the region of €680 M in the 2080's and by up to €4.5B under a 5.4°C scenario[8] (European Commission, 2009a).

This section presented an overview of global and European economic impacts associated with future potential climate change. It highlighted the rational of implementing strong adaption actions in the face of uncertain but potentially large climate impact costs. Coastal and inland flooding were also recognised as sectors of particular vulnerability in the Irish context. The following section (2.4) discusses how

[6] B2 HadAM3h scenario referring to the 2080s climate, compared to the 1961-1990 period
[7] B2 ECHAM4 scenario referring to the 2020's climate
[8] A2 ECHAM4 scenario exploring change in tourism receipt in the 2080's

the outputs of economic modelling, presented above, can best be used to inform climate policy.

2.4 CLIMATE CHANGE ECONOMICS AND POLICY

2.4.1 Climate policy informed by economics

Environmental economics, and its primary cost-benefit analytical approach, is clearly positioned in the current climate change policy arena as the dominant school of economic theory. As this review has discussed, its analysis is framed by a series of choices in relation to implicit ethical decisions on perceptions of value, risk, uncertainty and the environment. It is imperative that the inherent values, assumptions and methodologies that inform this economic approach are communicated in a transparent manner.

Over and above the universal complexities of modelling uncertain future events associated with climate change economics, Frank Ackerman, an environmental economist, suggests that there are four fundamental requirements necessary when looking to create an adequate economic framework for climate policy that challenge orthodox styles of economic analysis:

- Discounting and ethical judgments relating to the importance of current versus future generations;
- Incorporating multidimensional, often unmonetisable impacts, that create methodological difficulties for the cost-benefit analysis approach;
- Recognition of the problems of catastrophic risks and irreducible uncertainty, which leads to a precautionary approach to policy;
- An understanding of institutional barriers in relation to the nature of implementation costs associated with climate policy.

(Ackerman *et al*., 2009)

Discounting was discussed in Section 2.2.4 in relation to the Stern Review as well as in Section 2.3. The discussion here will briefly present some additional thinking relating to discount rates and climate change economic analysis. Howarth in agreement with Weitzman (2007) argues that the idea of using discount rates associated with typical capital investments (in the region of 5%) is flawed, as investments to mitigate against climate change can be understood to be closer to insurance-type investments in their characteristics rather than typical capital investments (Howarth, 2003). Howarth understands climate mitigation efforts as social insurance against disaster rather than ordinary profit seeking investments. If they are considered as such then a risk free rate of return is closer to 1% or less in real terms. A further argument suggests that impacts that cannot be readily expressed in monetary terms be excluded from any exercise in discounting (Scrieciu *et al.*, 2011). This includes impacts relating to the loss of human lives and the loss of particular species. Declining discount rates, which are based on research into individuals' time preferences, are also starting to appear in climate policy analyses (Lowe, 2008).

Ackerman's second fundamental requirement, that discusses the challenges of incorporating the multidimensional, often unmonetisable climate impacts into economic analyses of climate change economics, is discussed at length in Section 2.2 of this chapter. His third fundamental requirement, on recognising catastrophic risks and irreducible uncertainty when looking at climate policy, is discussed under Stern and post-Stern (Section 2.2.4) and under decision-making on adaptation (Section 2.4.2). His final fundamental requirement on understanding institutional barriers is also touched on in Section 2.4.2.

The following section bolsters the economic argument presented by the Stern Review, as well as modelling by the World Bank and others, that early action on adaption makes sound economic sense as it is the less costly alternative to potential climate impact costs. The strength of this argument is further underpinned by the drafting of the European white paper on adaptation.

2.4.2 Adding weight to the economic argument for adaptation

In 2010 global CO_2 emissions reached a record high of 30.6Gt in spite of the global recession. Economic modelling carried out by the OECD predicts that with current climate policies in place GHG emissions will increase by another 50% by 2050. This is primarily in response to a 70% growth of CO_2 emissions from energy use as a result of an 80% increase in global energy demand (OECD, 2011). A significant rise in demand for cars in developing countries is expected to lead to a doubling of transport emissions in the period. The world is locking itself into high-carbon systems to a greater degree with each passing year (OECD, 2011). This can be clearly seen in the power sector, where 80% of the projected emissions in 2020 are inevitable, as they are produced by existing plants or plants being built today. The OECD predicts that atmospheric concentrations of GHGs will reach almost 685ppm of CO_2 equivalents by 2050 without significantly more ambitious policies in place. This level of GHG concentration far exceeds the 450ppm concentration level required to have at least a 50% chance of stabilising the climate at a 2°C global average temperature increase.

Under current projections global average temperatures could be in the region of 3 to 6°C higher than pre-industrial levels by the end of the century (OECD, 2011). It is also important to take account of the fact that it will take time for the Earth’s atmosphere to process and recover from GHGs already emitted. It is thought that the world may be faced with climate change impacts for the next 50 years even if GHG atmospheric concentrations are reduced to within so called safe levels (Wigley, 2005; Meehl *et al*., 2005).

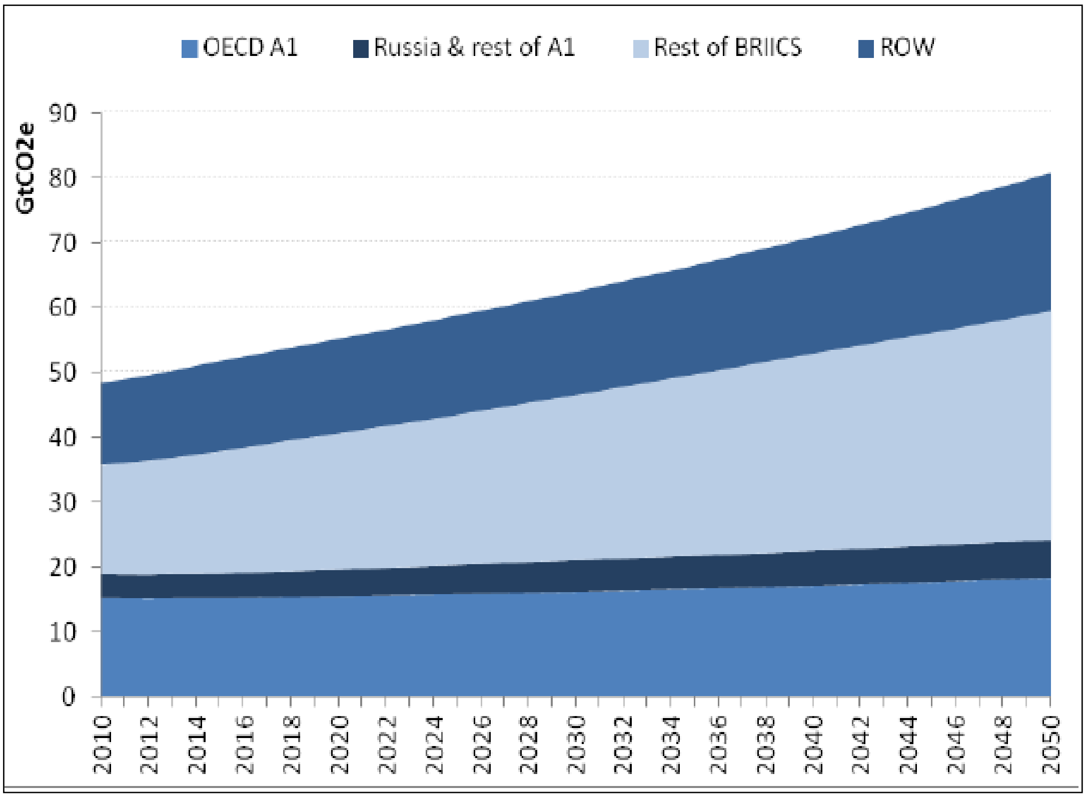


Figure 2.5: GHG emissions by region (in GtCO2e): Baseline scenario (Source: OECD Environmental Outlook Baseline; ENV-Linkages model). Note: OECD A1 countries include most OECD member countries and some countries from central and eastern Europe and the Commonwealth of Independent States that are undergoing the process of transition to a market economy, BRIICS refer to Brazil, Russia, India, Indonesia, China and South Africa, ROW refers to Rest of World.

These projections add weight to the importance of adaptation measures in coping with future potential climate change impacts. It must be noted that, to date, global climate policy has been framed in terms of climate change mitigation. European climate policy also leads with mitigation efforts, which include the EU ETS[9] along with an ambitious Climate and Energy Package (with mitigation targets of 20% reductions in GHG emissions, from 2005 levels, in non-ETS sectors by 2020). However, the 2009 white paper on adaptation outlines some important policy measures acknowledging the importance of adaptation. An adaptation strategy is viewed as a means of enhancing the EU's resilience to climate change impacts. An increase in energy efficiency, the uptake

[9] The European Union's Emissions Trading Scheme, launched in 2005, functions on a "cap and trade" principle. This means there is a "cap", or limit, on the total amount of certain greenhouse gases that can be emitted by the factories, power plants and other installations in the system (excluding aviation). Within this cap, companies receive emission allowances which they can sell to or buy from one another as needed. The limit on the total number of allowances available ensures that they have a value.

of green products and infrastructural modernisation are viewed as cornerstones in developing a competitive low-carbon economy (European Commission, 2009c). The EU maps out its adaptation strategy in an Adaptation Framework nested within the EU sustainable development objectives. The Adaptation Framework is set out in two phases. The objective of phase one, from 2009-2012, is to prepare and set out the comprehensive EU adaptation strategy to be implemented during phase two which commences in 2013 (European Commission, 2009c). The European Adaptation Strategy presents an ambitious EU level framework that links climate change adaption with the concepts of sustainable development and resilience.

The value and importance of adaptation to future climate change impacts has been demonstrated and quantified. The next Section (2.4.3) explores the important issue of how sensible and cost effective decisions should be reached in relation to potential adaptation options.

2.4.3 Decision making on adaptation

The practical application of adaptation measures is a complex matter that can create significant difficulties for decision makers as elaborated on throughout this chapter. All the relevant risks and uncertainties that accompany potential climate change impacts must be carefully considered. Decisions must be framed under a top-down or bottom-up approach and often mainstreamed through a whole range of policies and actions in the public and private sector to be effective. It is common practice to narrowly define adaptation as a range of technological or technical options to respond to specific risks (Nelson et al., 2007). However, it is important to examine adaptation in a holistic manner. As outlined under the United Kingdom Climate Impacts Programme (UK CIP), there are some general principles of 'good' adaptation, that if followed reduce the risk of inappropriate adaptation measures (UK CIP, 2005) (Table 2.7). These principles can facilitate intelligent decision making through generating efficiencies and taking account of uncertainty.

Table 2.7: Principles of ‘good’ adaptation (Source: UKCIP, 2005; Adger *et al*., 2005; HM Treasury, 2009).

Principles of ‘Good’ Adaptation
Work in partnership by engaging and informing the community to ensure they are well informed
Understand risks and thresholds including associated uncertainties
Frame and Communicate SMART (specific, measurable, achievable, results-orientated and time-bound) **objectives/outcomes** before starting out
Manage climate and non-climate risks using a balanced approach by assessing and implementing your approach to adaptation in the context of overall sustainability and development objectives that include managing climate and non-climate risks
Focus on actions to manage priority climate risks by identifying key climate risks and opportunities and focusing on actions to manage these.
Address risks associated with today’s climate variability and extremes as a starting point towards taking anticipatory actions to address risks and opportunities associated with longer-term climate change
Use adaptive management to cope with uncertainty through recognising the value of a phased approach
Recognise the value of no/low regrets and win-win adaptation options in terms of cost-effectiveness and multiple benefits.
Avoid actions that foreclose or limit future adaptations or restrict adaptive actions of others
Review the continued effectiveness, efficiency, equity and legitimacy of adaptation decisions by adopting a continuous improvement approach that also includes monitoring and re-evaluations of risks

The UK CIP report focuses on adaptation from the perspective of organisations, but nevertheless provides a useful framework for exploring adaptation and the decision making process in general terms (Brown *et al*., 2011). The systematic risk-based adaptation assessment they espouse is divided into the three functional components of planning, process and outcomes. This assessment methodology is displayed as a self-explanatory eight step iterative process in Figure 2.5 below.

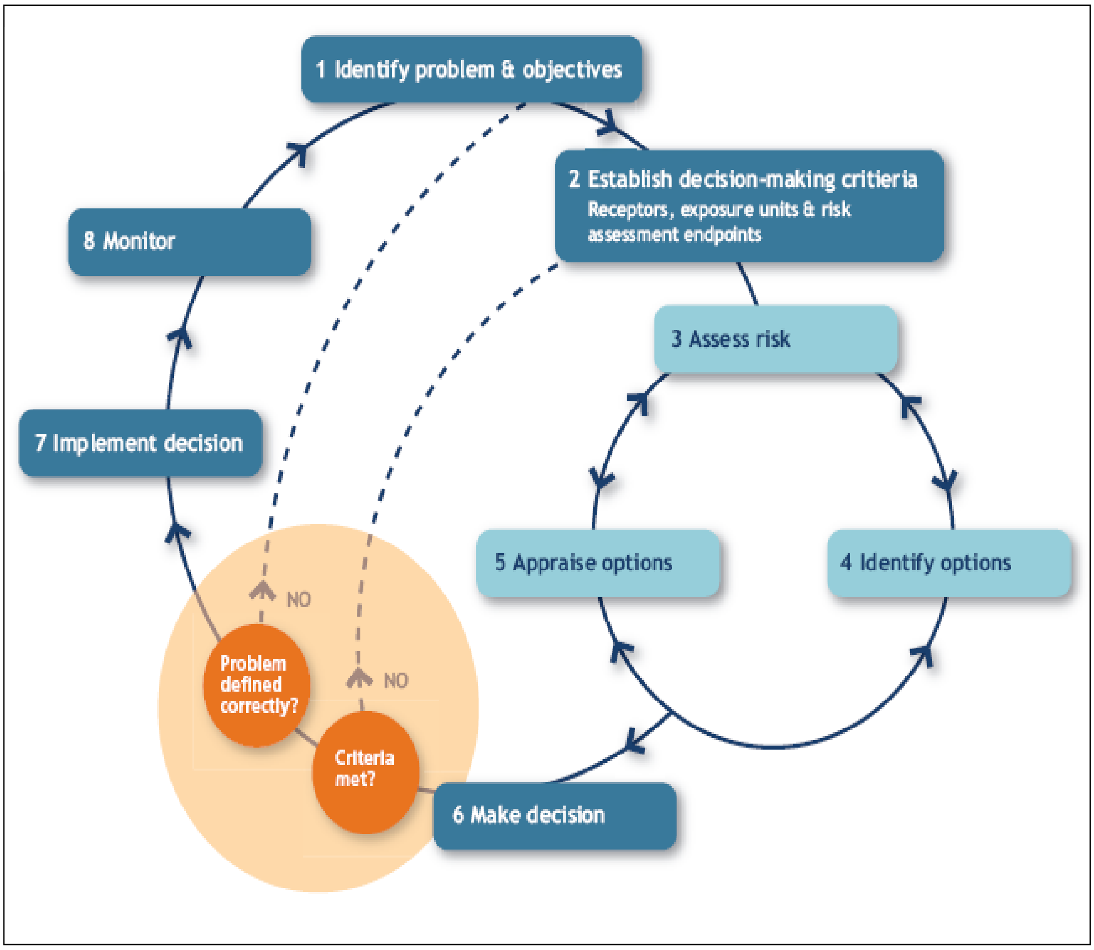


Figure 2.6: Risk, uncertainty and decision-making framework (Source: Willows and Connell, 2003).

2.5 CONCLUSIONS

The complexity and "wickedness" of climate change as an environmental and societal problem is pervasive and multilayered. A comprehensive study integrating all the relevant issues is beyond the scope of this thesis. However, the preceding review highlights these issues to uncover possible avenues in relation to economic assessment, policy formulation and adaptive management in an Irish context.

CHAPTER 3
EXISTING STUDIES ON ECONOMIC IMPACTS ASSOCIATED WITH COASTAL VULNERABLITY

3.1 INTRODUCTION

Coastal vulnerability, relating to climate change impacts such as SLR, storm surges and coastal erosion, provides a perfect example of the complexities associated with climate change management, as the issue explores uncertain physical and socioeconomic impacts that require multi-level societal engagement to manage. At a global level potential physical and socioeconomic impacts are of considerable magnitude. In Ireland, while the projected impacts are less considerable, there are a number of particularly vulnerable coastal locations. This chapter highlights and explores global physical and socioeconomic impacts relating to future potential climate change, physical impacts associated with Irish coastlines, socioeconomic impacts associated with SLR storm surges and coastal erosion in Ireland, as well as the role of coastal zone management and coastal protection options.

3.2 COASTAL VULNERABILITIES IN A GLOBAL CONTEXT

3.2.1 Sea-level Rise

When examining climate change impacts at a global scale Sea-level Rise (SLR) emerges as an issue of significant concern. It currently contributes (and has the potential to increasingly contribute) to infrastructural damages resulting from coastal flooding, losses of coastal wetlands and mangroves, along with the impacts of coastal erosion and deposition (IPCC, 2007b). Global sea level rose at an average rate of 1.8 mm per year over 1961 to 2003 and at an average rate of 3.1 mm per year from 1993 to 2003 (IPCC, 2007a). It is unclear whether the faster rate for 1993 to 2003 reflects decadal variation or an increase in the long term trend. 57% of the sea level rise since 1993 is attributed to thermal expansion of the oceans, 28% to decreases in glaciers and ice caps, with polar ice sheet loss contributing the remainder (IPCC, 2007a). The IPCC AR4 reports that due to the limited understanding of some of the important effects driving SLR a best estimate, or future upper bound, for sea level rise cannot be provided. Rahmstorf, in his SLR modelling work, also concedes that the scientific community does not yet hold a full physical understanding of sea level rise. Moreover, he argues that the uncertainty in future sea level rise is probably larger than estimated previously. His projections suggest that a rise of over 1 metre by 2100 for strong warming scenarios cannot be ruled out as long as the linear relation of the rate of sea level rise and temperature, found valid in the 20th century, remains valid in the 21st century (Rahmstorf, 2007). See Table 3.1 below for summary figures of the range of plausible SLR scenarios by the end of the 21st century.

Table 3.1: Recent global sea-level rise projections (Source: Nicholls *et al*., 2011).

Sea level rise (m/century)	**Methodological Approach**	**Source**
0.5 to 1.4	Semi-empirical projection[2]	Rahmstorf, 2007
0.8 to 2.4[1]	Palaeo-climate analogue	Rohling *et al*., 2008
0.55 to 1.2	Synthesis[2]	Vellinga *et al*., 2008
0.8 to 2	Physical constraint analysis[2]	Pfeffer *et al*., 2008
0.56 to 0.92[1]	Palaeo-climate analogue	Kopp *et al*., 2009
0.75 to 1.86	Semi-empirical projection[2]	Vermeer and Rahmstorf, 2009
0.91 to 2.15	Semi-empirical projection[2]	Grinsted *et al*., 2009

[1] A higher rate is possible for shorter periods
[2] For the 21st century

Work by Overpeck *et al*. exploring potential SLR from melting polar ice sheets suggests that polar warming may reach levels similar to those of 130,000 to 127,000 years ago by 2100 (Overpeck *et al*., 2006). This could result in SLR between 4-6 metres above present levels within the next millennium.

3.2.2 Socioeconomic impacts

There is a broad literature exploring the economic impacts of sea level rise from a global, regional and national level (Anthoff *et al*., 2009; Fankhauser, 1995; Nicholls & Tol, 2006; Nicholls *et al*., 1999, Nicholls *et al*., 2011; 2007; Dasgupta *et al*., 2007, 2009; Titus *et al*., 1991; Darwin & Tol, 2001; Turner *et al*., 1995; Hallegatte *et al*., 2008; Yohe & Schlesinger, 1998; Vafeidis *et al*., 2008; Richards and Nicholls, 2009).

Anthoff *et al*., using the FUND economic model under a range of socio-economic scenarios, examine SLR impacts of up to 2 metres over the 21st century. Importantly their work employs equity weighting to allow for damages to be modified reflecting the wealth of those impacted by SLR. Their headline results assert that vulnerable coastal zone protection is more rational than is currently widely assumed, and holds even with a large rise in sea level. This is underpinned by the fact that due to projected global economic growth, the benefits of protection increase significantly with time. Their equity-weighted results clearly communicate the importance of not only looking at the magnitude of damage but also who will be affected. The results predict potentially significant welfare losses to poor societies experiencing even small damages (Anthoff *et al*., 2009). When it comes to the distribution of costs it is shown that a few regions experience the majority of economic impacts including East Asia and Middle East/North Africa (Dasgupta *et al*., 2007). Substantial costs are anticipated from wetland loss. As these are protected ecosystems under both the EU Habitats Directive (European Commission 1992) and the 1971 intergovernmental Ramsar Convention (Ramsar, 2011) this is considered an issue of significant importance.

In a study using global SLR estimates of 38 cm from 1990 to the 2080s it is predicted that the southern Mediterranean (Turkey to Algeria), West Africa (Morocco to Namibia), East Africa (South Africa to Sudan), South Asia (Pakistan to Burma, including Sri Lanka) and South-East Asia (Thailand to Vietnam, including Indonesia and the Philippines) are the most vulnerable in absolute terms for coastal flooding (Nicholls *et al*., 1999). The largest relative increases in flood impacts are projected to occur in the Caribbean, Indian Ocean Islands and the Pacific Ocean small Islands. The largest losses of coastal wetlands are expected around the Atlantic coast of Central and North America, the small Caribbean islands, and especially the Mediterranean and Baltic (Nicholls *et al*., 1999).

With much of the world not considering SLR when looking to issues of coastal management effective adaptation is not automatic (Nicholls & Tol, 2006). This results in reactive adaptation responses to events as they occur rather than proactive adaptation that responds to modelled future events. It is clear to assume that if the reactive approach remains predominant then it is expected that a much higher incidence of coastal impacts and disasters will occur than if a proactive approach is employed (Nicholls & Tol, 2006). See Table 3.2 for an overview of natural system effects from sea level rise and possible adaptation responses.

A number of studies explore SLR impacts in conjunction with storm surges on coastal cities at a global level (Dasgupta *et al*., 2009; Hallegatte *et al*., 2008; Nicholls *et al*., 2007). Results indicate that there is a significant concentration of highly vulnerable large cities in regions with some of the lower global income distributions (Dasgupta *et al*., 2009)[10]. GDP losses (above the current 1 in 100 year reference standard) totalled at €63 billion in East Asia & the Pacific region, €9 billion for the Middle East and North

[10] A homogenous future increase in extreme water levels during storms of 10% and a sea-level rise of 1 metre were used to derive the results. The paper employed the methodology set out by Nicholls (2008) for exploring a 1 in 100 year combined storm surge and sea-level rise impact.

Africa, €6.2 billion in South Asia, €11 billion in Latin America and the Caribbean and €1.3 billion in Sub-Saharan Africa (Dasgupta *et al*., 2009).

Table 3.2: The main natural system effects of relative sea-level rise, including examples of possible adaptation responses (Source: Nicholls & Tol, 2006).

Physical impacts		Examples of adaptation responses P=protection; A=accommodation; R= retreat
Inundation, flood and storm damage	a. Surge (sea) b. Backwater effect (river)	Dikes/surge barriers (P) Building coded/floodwise buildings (A) Land use planning/hazard delineation (A/R)
Wetland loss (and change)		Land use planning (A/R) Managed realignment/forbid hard defences (R) Nourishment/sediment management (P)
Erosion (direct and indirect change)		Coast defences (P) Nourishment (P) Building setbacks (R)
Saltwater intrusion	a. Surface waters b. Groundwater	Saltwater intrusion parries (P) Change water abstraction (A) Freshwater injection (P) Change water abstraction (A)
Rising water tables and impeded drainage		Upgrade drainage systems (P) Polders (P) Change land use (A) Land use planning/hazard delineation (A/R)

It is estimated that about 40 million people worldwide[11] are exposed to a 1 in 100 year coastal flood event (Nicholls *et al*., 2007). By the end of the century this figure could increase up to 187 million exposed people or 2.4% of global population (Nicholls *et al*., 2011). This increase takes the combined effects of climate change (SLR and increased storminess), population growth, subsidence and urbanisation into consideration (Nicholls *et al*., 2011). Total assets exposed by the 2070s could reach a total of around €25,900 billion; more than ten times the current level of exposure (Nicholls *et al*., 2007). However, the key distinction between exposure and impact should be noted. Two cities with equal exposure may experience very different impacts depending on protection measures in each; developed economy cities normally have higher levels of protection than those in the developing world. While population growth

[11] The study focuses on 136 port cities around the world that have more than one million inhabitants in 2005.

and increased urbanisation are the most significant factors in driving the overall increase in exposure, climate change and subsidence can significantly intensify the effect depending on location (Nicholls *et al*., 2007).

The Dynamic and Interactive Vulnerability Assessment (DIVA) Tool was produced by the EU-funded DINAS-COAST Project (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise) (Vafeidis *et al*., 2008). DIVA models interactions between a series of biophysical and socio-economic modules to assess impacts of SLR, with outputs presented at global, regional and national scale. The 2011 European ClimateCost report uses the DIVA model to estimate, under a medium to high emission trajectory (resulting in a SLR of 37cm), with no adaptation in place, that 55,000 people could be flooded per year in the EU by the 2050s and potentially over 250,000 people could be flood each year by the 2080s (European Commission, 2012). The economic impact associated with this scenario is €11B per year for the 2050s, increasing to €25B per year by the 2080s at current prices with no discounting. These damage costs do not account for ecosystem losses. Economic costs are provisionally modelled to increase to €156B a year (undiscounted) by the 2080s with a SLR scenario of 1m.

3.3 COASTAL VULNERABILITIES IN AN IRISH CONTEXT

3.3.1 Physical Impacts in Ireland

The Irish coastline is 4,577km in length, more than 50% of the population lives within 15km of the coast, and most of the population is concentrated in the major coastal cities of Dublin, Cork, Limerick and Galway. However, historically Ireland had a low density of coastal habitation. It was only from the late 1980’s that rapid economic growth spurred on significant urbanisation with Irish coastlines experiencing the second highest rate of urbanisation in the EU (O’Connor *et al*., 2009). Coastal exposure is the cumulative result of a number of significant factors including: climate induced SLR, tidal variation, wave climate, currents, and non-periodic water movement such as storm surges. In Ireland, post-glacial isostatic rebound (resulting in SLR of a lesser magnitude in the northern half of Ireland compared to the south) and coastal geomorphological composition are additional factors to consider. (Carter *et al*., 1989).

There is a strong topographical variation between the coasts of the Atlantic Ocean and the Irish Sea. The Atlantic coastline is characterised by a high relief of rocky cliffs ranging up to 500m in height interspersed with bays and inlets (European Commission, 2009b). This rock-dominated coastline characterises the south-western, western and northern coastal regions of Ireland (Devoy, 2008). By contrast, the Irish Sea coast is mainly low lying with non-consolidated sediment and glacial tills. Approximately 20% of Ireland's entire coast is at risk of erosion (European Commission, 2009b) with sea level rise already having a significant impact on the soft boulder clay coasts of the east in the form of erosion. Currently coastal defences protect only approximately 4% of the Irish coastline (Devoy, 2008). Counties Dublin, Down, Louth, Wexford and Wicklow are where retreat is occurring fastest, with erosion rates exceeding 3 metres per year in extreme cases. However, the west and south are also affected with low-lying bays and estuaries, such as Cork Harbour, Clew Bay, Tralee Bay, and especially the Shannon Estuary, displaying increased vulnerability to sea level rise (Devoy, 2008; Sweeney *et al*., 2008).

The wave climate[12] is dominated by the Atlantic Ocean input via St. George's Channel and to a limited extent via the North Channel. Atlantic depressions generate significant local westerly storm waves as well as the significant Atlantic swell input into the Irish Sea (Orford, 1989). Tidal variation in the Irish Sea is mainly the result of a

[12] A wave climate is composed of four items; characteristic wave height and characteristic wave period distributions, direction of wave approach and duration of wave conditions.

Kelvin type wave[13] being reflected and resonated within the relatively shallow and narrow Irish Sea (Orford, 1989). The principal periodic lunar influence controlling tidal motion is known as M_2 (Proudman and Doodson, 1924). The tidal cycle determined by M_2 is known as the semi-diurnal cycle[14] with S_2 representing the spring-neap cycle[15]. At spring positions the solar and lunar forces are in phase. Water elevations due to M_2 are approximately twice the elevation of S_2. Spring tides occur every fourteen days around the time of the new and full moons as at this time the gravitational pull of the sun and moon are aligned. Typically three or four particularly high spring tides occur each year (Farrell, 2007). Maximum tidal range on the east coast is associated with the shelf areas underlining the amplification potential of shallow water. There is a spring elevation gradient on the Irish coast from approximately 0.6 metres at Arklow to 4.5 metres in Dundalk Bay (Robinson, 1979).

Sea surges can be defined as the difference between predicted and observed still water levels usually measured at high tide. Irish Sea surges are associated with the movement of major Atlantic depressions over the Irish Sea basin (Orford, 1989). The extreme 50 year surge heights are approximately 1-2 metres on the west coast of the United Kingdom and 1-1.5 metres on the Irish coast (Orford, 1989; Lennon 1963a; 1963b). Sea surge events will increase on Irish coastal areas over the next decades with ocean modelling results indicating an increase in both the frequency and height of extreme storm surges (in excess of 1 metre) (Orford, 1989). As a result of tropical sea surface temperatures there is a strong probability that tropical cyclones will become more intense (Arndt *et al*., 2010). The tails of these storms can rejuvenate while they cross the Atlantic, as they pass over the warmer surface temperatures in the Gulf Stream, and lead to significant increase in wave heights on Irish waters. The most

[13] Generated by the harmonic component of the Atlantic Ocean tidal system
[14] The most common tidal cycle of two high waters and two low waters each day
[15] The tide's range is at its maximum in the case of a spring tide and at its minimum in the case of a neap tide.

extreme surges will occur over winter periods and on the west coast. The height of extreme waves (e.g. the 10-year return values) also show up to a 10% increase on the northwest coast.

Spring tides and storm surges primarily cause flooding of low lying areas by flowing onto them. In addition, storm driven waves have the ability to seriously damage coastal defences, to erode beaches and dunes, run up sea walls and embankments and flood hinterland areas through overtopping (Farrell, 2007). When climate change impacts such as SLR, predicted increased storminess and wave height, as well as increased surge frequency and height are considered, the overall frequency and magnitude of coastal flooding is set to increase significantly. Modelled data suggests that one-in-100-year coastal flood events are likely to become one-in-10-year events (McGrath and Lynch 2008, Sweeney *et al*., 2008). The two probability plots below (Figure 3.1 and Figure 3.2) outline this phenomenon using analysed hindcast data from Dublin Bay generated as part of the National Coastal Protection Strategy Study (Farrell, 2007). Figure 3.1 models the exceedance probability of a water level of 5.62m to be 1% or a return period of 100 years. Figure 3.2 demonstrates the effect of a SLR of 0.4m. By raising the water level line on this plot by 0.4m it can be seen that a 100 year return period flood water level is now 6.02m. However, of more significance is that a flood level of 5.62m now has a return period of 3.3 years in comparison to a pre-rise value of 100 years. This indicates that a modest SLR 0.4m could lead to an increase in the incidence of coastal flooding by a factor of 30. Farrell's analysis presented here assumes that underlying surge mechanisms are superimposed unchanged on the higher base level. However, when additional climate change impacts such as predicted increased storminess and wave height, as well as increased surge frequency and height are considered the probability of flood events is increased further. This effect will move the blue dashed line in Figure 3.2 further to the left resulting in further reduced return periods.

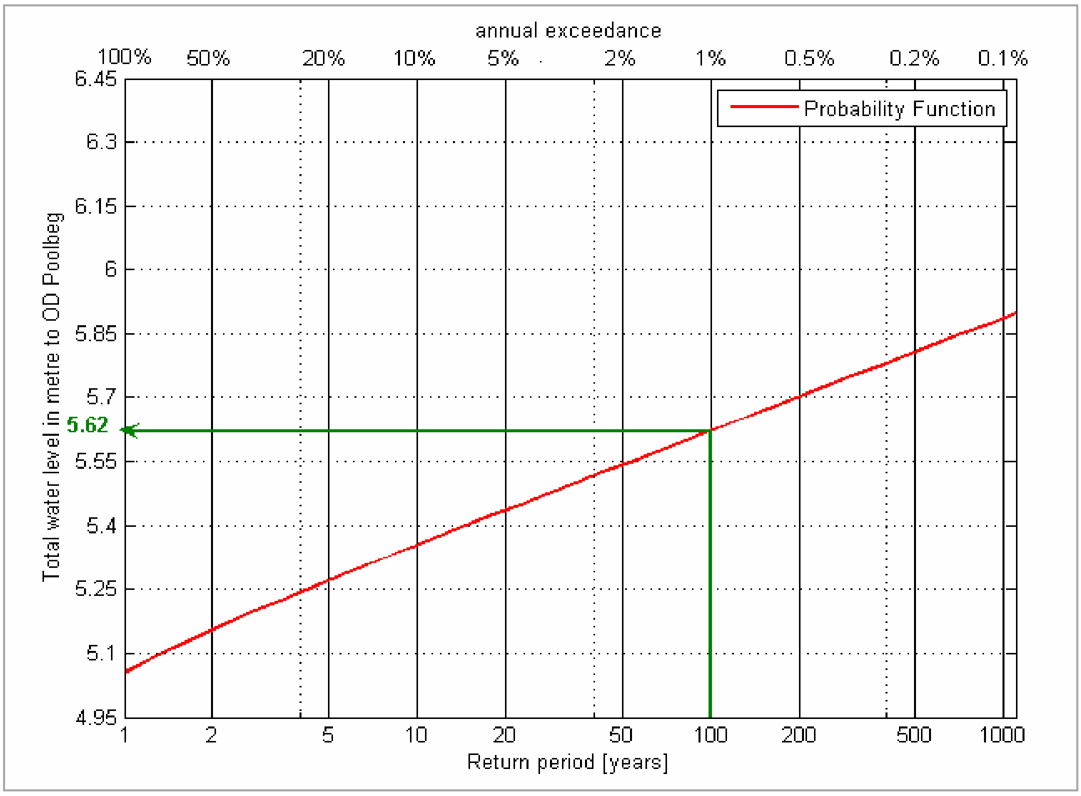


Figure 3.1: Flood level probability plot for Dublin Bay (Source: Farrell, 2007).

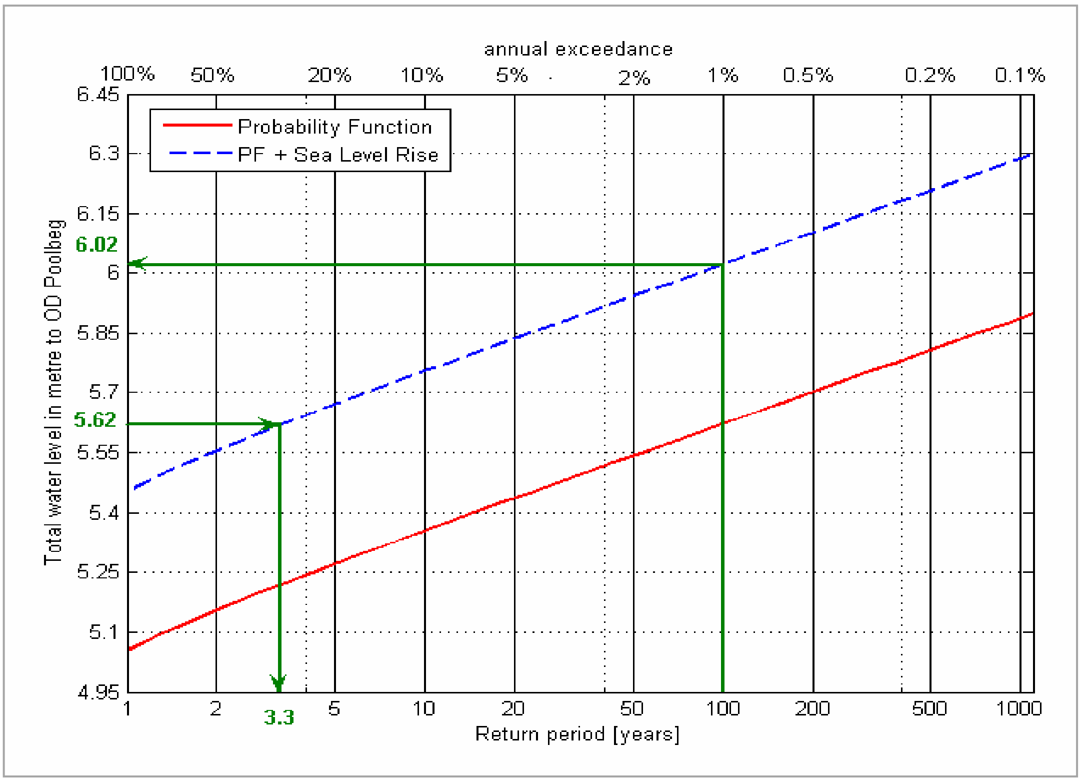


Figure 3.2: Flood level probability plot for Dublin Bay with SLR of 0.4m (Source: Farrell, 2007).

The increase in potential future coastal exposure in Ireland should be linked with potential socioeconomic impacts where possible. The following Section (3.3.2) explores some potential socioeconomic impacts of climate change on Irish coasts.

3.3.2 Socioeconomic impacts in Ireland

Several economic assessments have been carried out on both Ireland's ocean and coastal economy (Shields *et al*., 2005; SEMRU, 2009; Morrissey *et al*., 2011). The ocean economy can be defined as including any economic activity which directly or indirectly uses the sea as an input. The coastal economy represents economic activity that takes place within the coastal region which is not part of the ocean economy; this might include agriculture or major infrastructure (SEMRU, 2009). The Irish ocean economy was worth €1.44B in terms of direct economic value in 2007, and accounted for approximately 1% of Irish GPD (Morrissey *et al*., 2011). Ireland's most important ocean economy sectors comprise of water-based tourism and leisure (€453M), shipping and maratime transport (€329M), and seafood (including processing) (€220M) in 2007 Gross Value Added (GVA)[16] terms. The Irish marine sector employed approximately 17,000 individuals in 2007. Although these are the latest available figures it must be noted that they refer to the Cetlic Tiger period in Ireland and would be considerably reduced in the Irish economy of 2012. It is estimated that the ocean economy represented 2.3% of the total value of the coastal county economy and approximately 8% of the coastal shoreline district economy in 2007 (Morrissey *et al*., 2011). The Irish population density, at a shoreline district level (Figure 3.3) is 73 inhabitants per km^2. The estimated value of the shoreline electoral district economy was €44.3B as of 2007. It is also interesting to note that while coastal counties cover 69% of land area, they accounted for 85% of economic activity in the state in 2007 (Morrissey *et al*., 2011).

[16] Gross Value Added (GVA) refers to a sectors turnover (output) minus intermediate consumption (the inputs into the process of production). It is measured at basic prices, excluding taxes less subsidies on products. GVA is the contributions of individual sectors or industries to Gross Domestic Product.

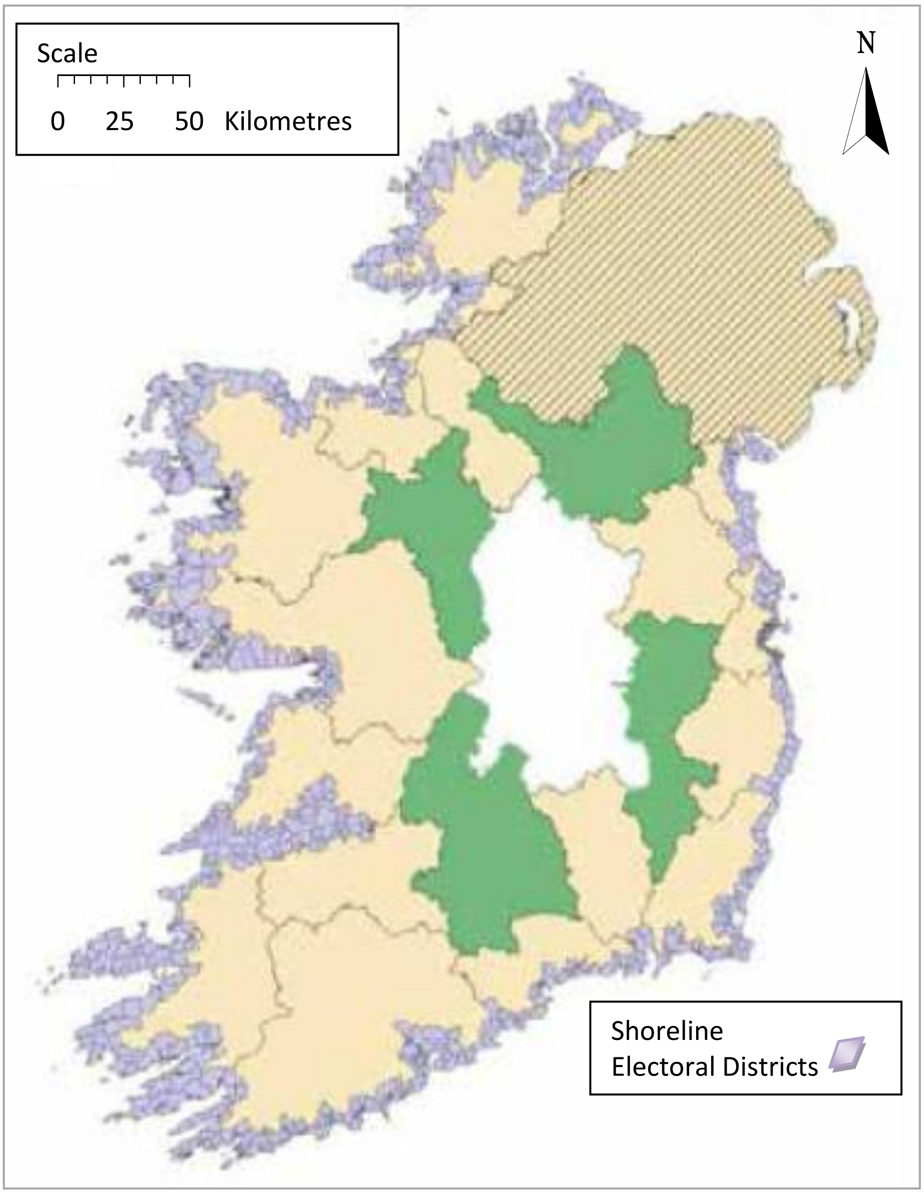


Figure 3.3: Ireland's coastal economic regions. The top (purple) coastal spatial scale on the map is the shoreline electoral districts. Beneath this are the (cream layer) coastal counties and beneath this is the Eurostat defined EU coastal regions (NUTS3) for Ireland (the green layer which extends underneath the other layers all the way to the coast). (Morrissey *et al*., 2011).

Shoreline electoral districts are the most relevant economic regions when exploring the economic impacts of climate change, and specifically SLR on the Irish coast, as they are of immediate proximity to the sea and ocean, and as such, are often highly susceptible to coastal impacts. The economic value of both Ireland's ocean and coastal economy has been highlighted. However, there are currently very few estimates of potential economic impacts associated with SLR and other climate driven factors on Irish coastal economies.

Work carried out by Richards and Nicholls using the DIVA model has estimated a number of economic costs relating to potential SLR scenarios in Ireland (Richards and Nicholls, 2009). Table 3.3 below presents DIVA model outputs driven by the ECHAM4 global climate model under the A2 SRES scenario. Three SLR scenarios are explored as projected for the end of the century; a low SLR scenario of 29.2cm, a medium SLR scenario of 43.8cm, and a high scenario of 58.5cm. The Table presents damage costs and wetland losses with and without adaptation in place. The results suggest that under the high SLR scenario of 58.5cm damage costs would amount to €224M if no adaptive management practices are put in place. Under the same scenario with adaptation in place these projected damage costs decrease to just under €22M a year with adaptation costs in the region of €70M. This analysis suggests that adaptation leads to a significantly lower economic impact of approximately €132M in comparison to no action and thus makes a strong case for adaptation.

Table 3.3: Irish DIVA output for ECHAM4 A2 scenario (Source: Richards and Nicholls, 2009).

Scenario	Adaptation Costs (M€/yr)	Residual Damage Costs (M€/yr)	Sea Flood Costs (M€/yr)	Net Loss of Wetland Area (ha)	Sea Dike Costs (M€/yr)
Baseline (1995)	0	18.6	18.6	0	0
L SLR 2020s no adaptation	0	25.1	25.1	1,600	0
2080s	0	127.6	127.6	6,570	0
M SLR 2020s no adaptation	0	65.4	65.3	1,600	0
2080s	0	170.3	170.2	8,210	0
H SLR 2020s no adaptation	0	70.9	70.9	2,000	0
2080s	0	224	220.7	9,360	0
L SLR 2020s with adaptation	19.8	20.3	20.3	1,600	16.7
2080s	39.2	13.8	13.8	6,570	35.6
M SLR 2020s with adaptation	29.5	21.7	21.7	1,600	24.6
2080s	54.7	17.6	17.6	8,210	49.9
H SLR 2020s with adaptation	41	24	24	2,000	34.1
2080s	69.5	21.8	21.8	9,360	62.5

Devoy has also carried out some work in this area with an evaluation of potential impacts under a 1m SLR scenario at the end of the century (2100) under economic conditions in 2008 (Devoy, 2008). His results, framed as an overview of vulnerabilities, indicate that under 250,000 people would be affected by coastal impacts. This figure represented 4.6% of the Irish population when calculated and was deemed to be of medium vulnerability class (in the region of 1-10%). Note that the vulnerability classes were determined from IPCC methodologies (Watson *et al.*, 1995). Under 100,000 people were determined to be at risk from SLR induced flooding. This was categorised as a low vulnerability class, with less than 10 per 1,000 people impacted. Capital losses of €135M were calculated relating to agricultural land potentially inundated under the 1m SLR scenario. This was calculated to be 0.2% of 2008 Irish GDP and deemed as a low vulnerability class. Dry land loss was estimated to be less than 230km^2, and at under 3% of total land mass, was categorised as a low vulnerability class. However, wetland loss, at approximately 800km^2, and over 30% of total Irish wetland area was determined to be of a high vulnerability class. These figures are indicative of potential climate change induced coastal impacts in Ireland.

Devoy explored some of the potential impacts but did not explicitly look at capital losses related to property or infrastructure in close proximity to the coast. Table 3.4 and Figure 3.4 provide details of important infrastructure in close proximity to the Irish coast. Key infrastructure with coastal proximity includes wastewater facilities, power stations, ports and rail lines. Particular attention should be paid to wastewater facilities and rail lines along the low lying vulnerable east coast. Figure 3.5 displays a waste water treatment facility in Shankill, Dublin and a section of rail near Killiney, Dublin.

Table 3.4: Infrastructure with coastal proximity in Ireland

Infrastructure with Coastal Proximity in Ireland	
Infrastructure	**Location**
Wastewater Facilities	
Dundalk	The Point, Louth, Leinster
Ringsend	Ringsend, Dublin, Leinster
Shanganagh	Shankill, Dublin, Leinster
Wexford	Strandford, Wexford, Leinster
Galway	Mutton Island, Galway, Connaught
Sligo	Finisklin, Sligo, Connaught
Power Stations	
North Wall	North Wall, Dublin Port, Dublin, Leinster
Poolbeg	Ringsend, Dublin, Leinster
Aghada	Whitegate, Cork Harbour, Cork, Munster
Marina	Centre Park Road, Cork City, Munster
Tarbert	Tarbert Island, Kerry, Munster
Moneypoint	Kilrush, Clare, Munster
Rail	
East Coast Rail Line	Sections of the line from Wicklow to Meath, Leinster
Ports	
Dundalk	Dundalk, Louth, Leinster
Drogheda	Drogheda, Louth, Leinster
Dublin	Dublin, Leinster
Dun Laoghaire	Dun Laoghaire, Dublin, Leinster
Rosslare Europort	Rosslare, Wexford, Leinster
Waterford	Waterford, Munster
Cork	Cork, Munster
Cobh	Cork, Munster
Bantry Bay	Cork, Munster
Foynes	Foynes, Limerick, Munster
Galway	Galway, Connaught
Sligo	Sligo, Connaught
Killybegs	Killybegs, Donegal, Ulster

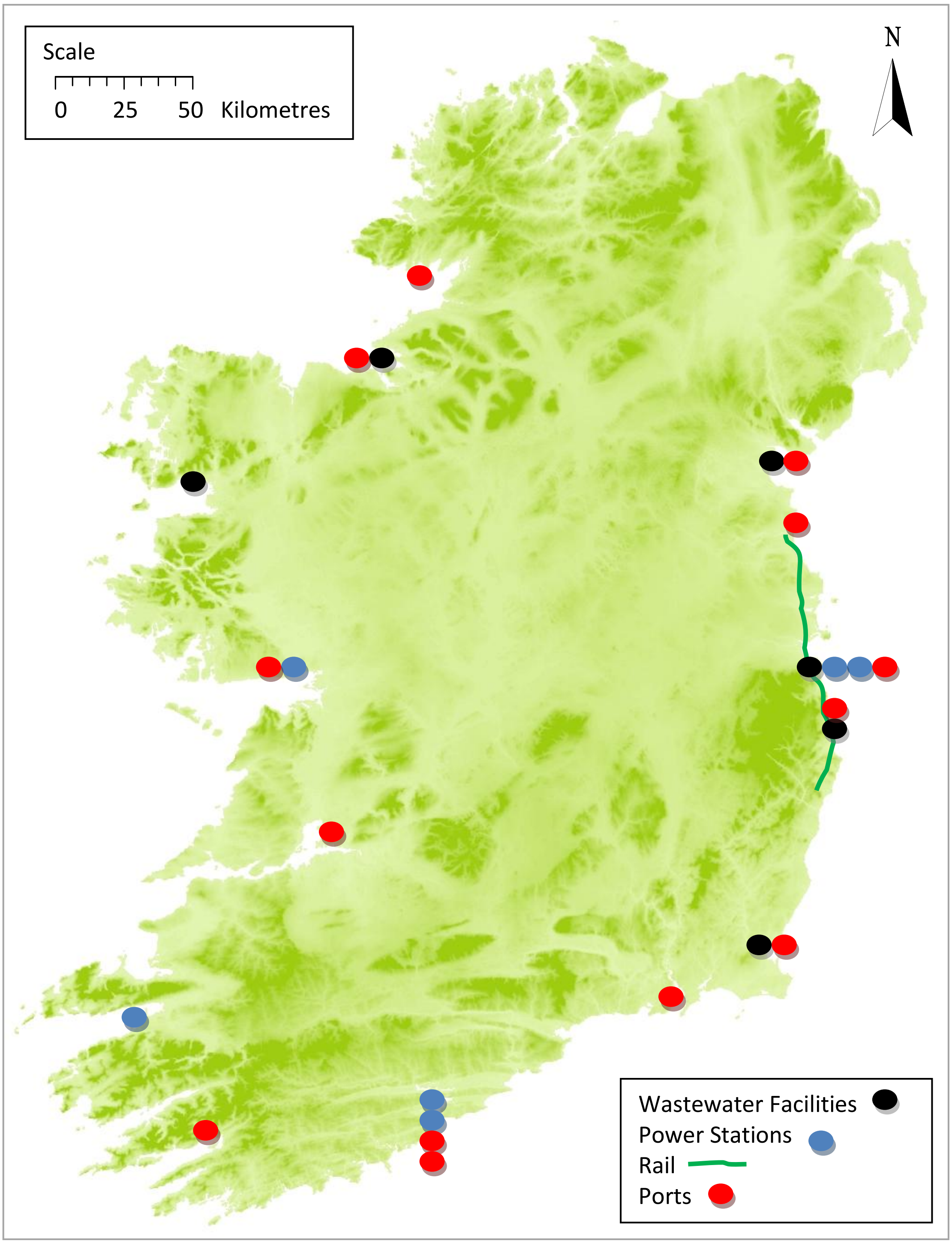


Figure 3.4: Map of Ireland displaying location of wastewater facilities, power stations and rail lines with coastal proximity along with sea ports.

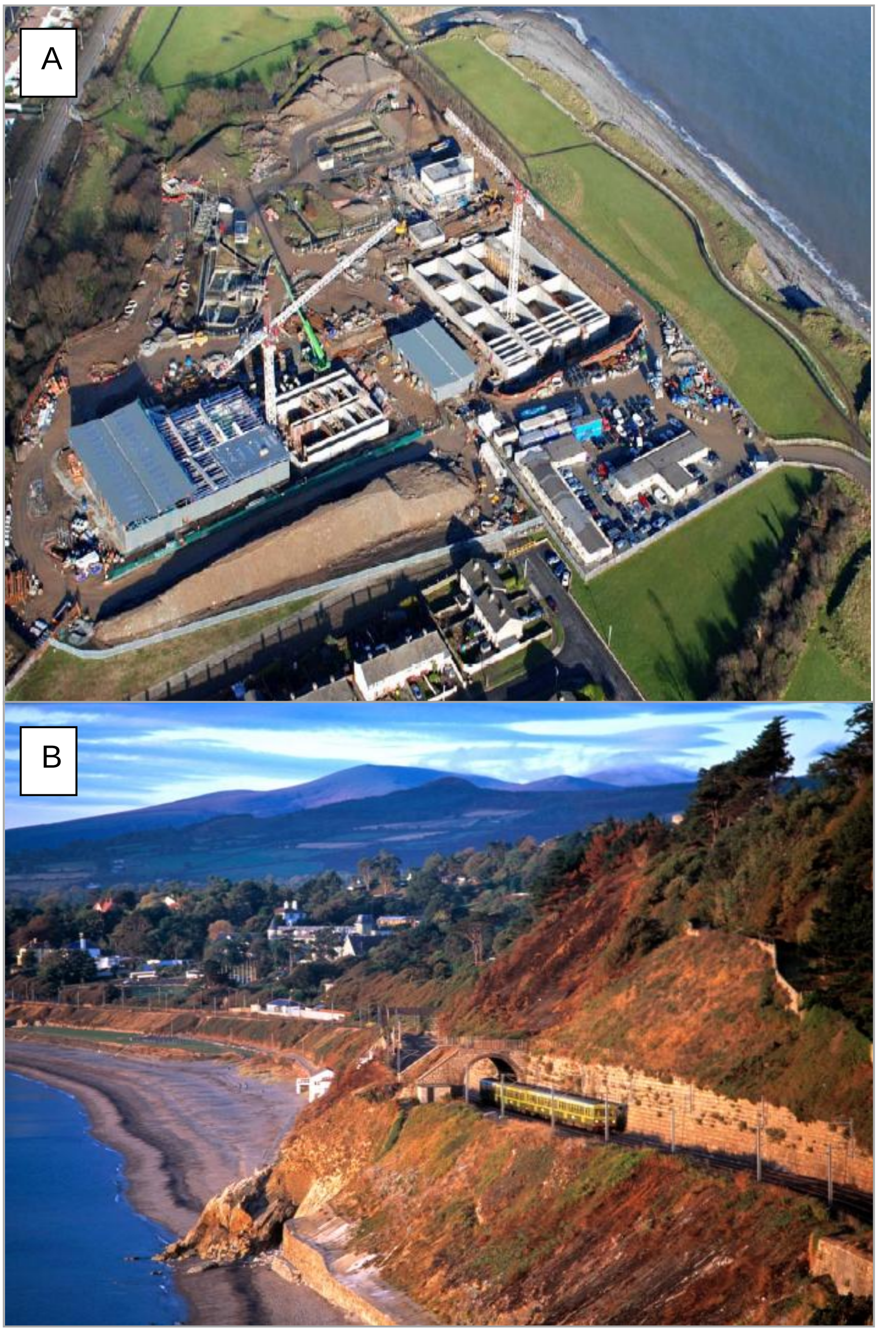


Figure 3.5: (A) Waste water facility in Shankill, Dublin, and (B) section of coastal rail line near Killiney, Dublin.

The potential physical and economic impacts on Irish coasts as a result of future climate change are uncertain yet potentially significant. There are vulnerabilities in relation to the coastal economy including its land and infrastructure. In order to protect and manage these valuable assets a strategic management approach is needed. In the following Section (3.3.3) Coastal Zone Management is introduced as a potentially useful management approach to protect coastal assets and reduce economic impacts.

3.3.3 Coastal Zone Management

Coastal flood risks and coastal erosion can be managed in a number of ways as illustrated in Table 3.2. Coastal defences such as seawalls, beach nourishment programmes or rock revetments can be constructed; the coast can be re-aligned and defended from a more landward location; or the threats can be accommodated, for example, by allowing flooding to occur but flood proofing buildings (Farrell, 2007). Another method for managing coastal flood risks is through the development of surge forecasting for disseminating coastal flood warnings. Currently Ireland does not have such a coastal flood warning system in place, although such a system is currently under development.

A series of destructive storms took place in the late 1980's in Ireland, which caused severe economic damage along the coast and accelerated erosion rates (ECOPRO, 1996). These impacts highlighted the importance of managing coastal erosion in Ireland and resulted in the formation of the National Coastal Erosion Committee with the support of the Institution of Engineers of Ireland. In turn, their 1992 report endorsed the creation of a coastal management policy rather than a free standing coastal erosion policy (National Coastal Erosion Committee, 1992). The ensuing National Coastal Protection Strategy Study (NCPSS) was commissioned by the Department of Marine and Natural Resources as part of their remit to ensure coastal protection. The study commenced in 2003 with phase one comprising of an overview of coastal protection in Ireland. Subsequently a series of nine work packages including coastal flood forecasting, erosion mapping and hazard mapping were drawn up. In 2009 responsibility for coastal flooding and coastal protection was transferred across to the Office of Public Works (OPW) and they subsequently took over the management of the project (OPW, 2009). Project partners include RPS environmental consultants and Compass Informatics; a remote sensing and mapping consultancy.

Integrated Coastal Zone Management (ICZM) is a process that can aid the decision-making process in terms of coastal defence strategies. The NCPSS will provide significant tools to aid its development, although ICZM involves more than the creation of decision making tools alone. The ICZM process provides a methodology for ensuring sustainable development through a participatory process involving all the relevant stakeholders (Falaleeva *et al*., 2011; Lane 2006). ICZM has been embraced by a wide range of international agencies including the World Bank, the United Nations Environment Programme (UNEP) and the International Union for the Conservation of Nature (IUCN) along with many national governments (Ibrahim and Shaw, 2012). The ICZM approach is a continuous, dynamic and iterative process that depends upon building a cohesive network comprising of committed stakeholders. There is a strong link between climate change adaptation measures and the implementation of ICZM as both look to the integration of sectoral, administrative and geographical governance (Few *et al*., 2004). Both approaches also call for subsidiarity[17] and participatory decision making (Van Aalst *et al*., 2008; Christopolos *et al*., 2009). Coastal management in Ireland is currently characterised by a sectoral approach with no integrated national policy framework in place (Cummins, 2004; Falaleeva *et al*., 2011). This lack of a strategic national policy leads to coastal protection practice rather than policy, with local level interventions often taking place as problems arise (O'Connor, 2009). The resulting coastal management environment can thus be characterised by both strengths and weaknesses. Strengths include strong local involvement in identifying problems along with flexibility in decision-making to suit specific needs. Local actors recognise erosion quickly and through political engagement they can often ensure a prompt response by local authorities. In the absence of a strategic framework there is no set prioritisation of schemes and this allows local authorities to undertake actions that fit

[17] Subsidiarity is decision making principle that states that central authority should have a subsidiary function and perform only those tasks which cannot be performed effectively at a more immediate or local level.

best with their capacity and resources (O'Connor, 2009). However, the relative strengths of coastal protection led by practice can often be counterbalanced by weaknesses associated with a lack of policy framework. Without strategic coastal management practices in place coastal defence is normally considered the only option to erosion problems. Other options such as retreat or managed realignment are unfavourable with local authorities as they have local community needs in mind, and often are not working within the framework of proactive environmental management (O'Connor, 2009). This lack of strategic focus means that local and often short term concerns dominate over the national interest. The outcome is often that properties are likely to be defended even when it goes against the greater good (Cooper and McKenna, 2007). Counter intuitively, it is interesting to note that there may be opposition to local coastal defences on the grounds that they may be deemed unsightly or extreme, as was the case in Clontarf, Dublin in 2011 (Irish Times, 2011). Local residents staged protests against the construction of a 3km coastal defence wall considering it a threat to tourism, security, business and sea views. Many commentators also expressed the view that Dublin City Council did not hold adequate consultations with local residents and considered the process to be undemocratic. This case study again demonstrates the importance of implementing ICZM with its strong commitment to participatory decision making and stakeholder engagement.

ICZM can provide the strategic management necessary to protect Irish coastlines. The following Section (3.3.4) explores the strengths and weakness of the specific coastal protection measures needed when engaging with the ICZM approach.

3.3.4 Overview of coastal protection techniques

Coastal protection techniques fall into the three main categories of environmental planning and development control techniques, low cost coastal management and protection techniques, and high cost coastal protection techniques (Table 3.5).

Table 3.5: Coastal protection techniques (Source: ECOPRO, 1996).

Coastal Protection Techniques	
Environmental planning and development control	Land-use restrictions Managed retreat Do nothing
Low cost coastal management and protection techniques	Seaweed planting Beach ridge restructuring Wave barrier fencing Dune recontouring Sand stabilisation Sand trap fencing Artificial dune ridge building Marram grass planting Dune fertilisation Grass seeding Walkways
High cost coastal management and protection techniques	Offshore Breakwaters Moored Breakwaters Sand By-passing Groynes Submerged groynes Beach nourishment Artificial headlands Beach drainage Mudflat restoration Silt redistribution Reventments Cliff stabilisation

The majority of the low cost techniques can be classified as soft engineering. They work with natural processes through absorbing wave and tidal energy or by using it for positive effects and aim to have minimal environmental impacts (ECOPRO, 1996). In contrast, hard engineering techniques set out to rigidly fix the position of the coastline through resisting both wave and tidal energy. Due to their expense, and often serious impacts on the local environment, they should only be considered where soft engineering techniques are deemed inappropriate. Environmental planning and development control techniques place their focus on long-term planning and strategy development for the coastal zone. Their techniques are the least expensive to initiate and maintain but are often only appropriate for areas of low development. They are particularly suitable for areas that suffer erosion from extreme storms but are expected to recover naturally (ECOPRO, 1996). Low cost techniques are useful when dealing with storm damage and can help build and strengthen coastal resilience or reduce the impacts of wave and tidal energy. High cost techniques attempt to fix the position of the coastline. They are typically required where land loss is not a viable option due to economic, social or environmental factors. However, they can cause a number of significant problems such as beach lowering, the interruption of natural processes leading to erosion elsewhere, and the creation of hard points on the coast that can become isolated from the surrounding coastline and are increasingly difficult to protect. They can also promote the future development along the coast that will increase the demand for future protection measures.

3.4 CONCLUSIONS

The magnitude of potential impacts associated with coastal vulnerability at a global level is well documented. The predicted physical and socioeconomic impacts will cost trillions of Euros in direct and indirect damage. Despite the recorded economic value generated in Irish coastal economies, studies of Irish coastal vulnerability are highly limited to date. This research gap is addressed through the modelling work presented in the following chapter which analyses economic costs associated with potential SLR and storm surge impacts, under a number of scenarios, on Irish coastal land as well as on commercial and residential properties. The results of this vulnerability analysis can act as a valuable input into Irish flood risk management strategies such as ICZM.

CHAPTER 4
MEASURING ECONOMIC IMPACTS OF COASTAL FLOOD RISK IN IRELAND

4.1 INTRODUCTION

The analysis presented in the following chapter provides a useful national estimate of the economic costs associated with coastal flooding in Ireland, a case study exploration of economic coastal flood impacts in Leinster using high resolution LIDAR data, and an examination of Coastal Vulnerability Indexes (CVIs) as applied to Irish coastlines. The analysis includes vulnerabilities relating to coastal land, as well as commercial and residential properties.

4.2 NATIONAL COASTAL ECONOMIC RISK STUDY

4.2.1 Methodology and datasets

Sea-level rise flood risk modelling was carried out for the Irish coast using a medium resolution Digital Terrain Model (DTM)[18]. The modelling is based on the manipulation of the digital terrain model (DTM) of the Irish Republic by creating a number of SLR scenarios grounded in the literature. The modelling uses six projected scenarios from 0.5 metres to 6 metres (0.5 metres, 1 metre, 2 metres, 3 metres, 4 metres and 6 metres) drawn from the envelope of possible SLR and storm surge scenarios (Rahmstorf, 2007; Overpeck *et al*., 2006; Hoozemans *et al*., 1993; Nicholls *et al*., 2011; Orford, 1989). It must be made clear at the outset of this analysis that the majority of

[18] Irish 20 metre medium scale resolution digital terrain model produced by the Irish Environmental Protection Agency with Irish Grid projection referenced in metres to Ordinance Datum Malin (OD Malin).

projected SLR estimates by the end of the century are in the region of 0.5m-2m (Nicholls *et al*., 2011). Modelled scenarios above this range are useful in carrying out sensitivity analysis, as well as capturing the temporary, but damaging, potential flood events when SLR is combined with both a storm surge and a spring tide. It must also be noted that although the resolution of the DTM used in this analysis is not sufficient for modelling sea level change in a detailed manner at a local level, as there are significant errors in the vertical projections of the model (Coveney *et al*., 2010; Gornitz *et al*., 2002), a number of studies have been carried out using such medium resolution DTMs for national or regional assessments (Li *et al.,* 2009; European Environment Agency, 2006; Dobosiewicz, 2001). The modelled output also does not account for existing Irish coastal defences. However, this qualification is not especially limiting as currently less than 4% of Ireland's coast is protected by built shore structures (Devoy, 2008). This study is thus framed as a national economic cost estimate exploring some of the potential impacts of sea-level and storm surges on the Irish coastline. The analysis is intended to inform policy dialogues as well as help indicate priority measures for coastal adaption measures.

Initially, the area of potential vulnerability to SLR was calculated from the DTM projections and any areas from the modelling that were not part of the coastline or that were part of existing river networks were manually discounted from the calculations. The An Post GeoDirectory was then used to examine potentially vulnerable addresses. The Directory is a collaboration between the Irish Post Office Service and Ordnance Survey Ireland that provides close to two million accurate geographic addresses up to July 2009 (Fahey and Finch, 2009). A geographic address is a combination of Eastings and Northings which accurately position a building on the surface of the earth. Building on the initial modelling of vulnerable land, the An Post GeoDirectory was then used in conjunction with the projected sea level scenarios to estimate the number of addresses that would be potentially impacted under a SLR/storm surge event. Address points were first screened to remove vacant and derelict addresses before being considered in the analysis. Addresses were classified as residential, commercial and joint use premises. Using the information on vulnerable addresses determined from the modelling results, and in conjunction with flood claim costs, a generalised damage cost estimate of SLR and storm surge events was calculated.

Figures released by the Irish Insurance Federation (IIF) in 2010 uncovered the insurance costs relating to flood damages from the 2009 substantial November flood events (Table 4.1). Additional figures relating to the October 2011 flood events were released in January 2012 (Table 4.1). The 2009 and 2011 flood events are the two most costly flood events as recorded by the IIF. The majority of the 2009 November flood costs were realised in Munster, the West and the Midlands. The three counties worst hit were Cork, Galway and Clare. The majority of the October 2011 flooding took place on the East coast, with most of the flooding occurring in Dublin. Using the figures from both events as a guideline, a rough average estimate of costs per claim was calculated for residental and commercial properties. The average insurance claim per residential household - averaged between both flood events - was approximated at €16,500. The average claim for residences in both flood events was almost equal, with the Munster floods averaging at €16,591 per claim, and the Leinster floods averaging €16,421 per claim. The average insurance claim per commercial property - averaged between both flood events - was approximately €75,000. The average claim for commercial properties in both flood events varied significantly, with the Munster floods averaging at €103,114 per claim, and the Leinster floods averaging €47,162 per claim. Joint use properties were estimated through an average of residential and commercial claims at approximately €46,000.

It is important to note both the limitations and strengths of insurance claim data in estimating flood damage costs (Walton *et al*., 2004). The use of these data can often save valuable time and money due to ease of accessibility. The alternative method of household level surveys can be expensive and time consuming to coordinate and run. However, survey data can often supply a greater level of detail and coverage in comparison to insurance claim information. Insurance claim data may also hide the incidence of underinsured households and thus underestimate the true economic cost of a flood event (Walton *et al*., 2004). One must also note that the the IIF figures used here relate to river flooding rather than coastal flooding. Salt water causes greater damage to properties in comparsion to river water, as it corrodes material to a greater degree than fresh water. However, river water may also be as damaging if it contains raw sewage or debris (Smith and Ward, 1998).

Table 4.1: Cost of November 2009 and October 2011 flooding by claim type (Adapted from IIF[19], 2010; 2012).

Claim Type Nov 2009	**No of Claims**	**Cost of Claims**
Household	4,629	€76.8M
Commercial property	1,541	€158.9M
Motor	2,344	€8.2M
Total	**8,514**	**€243.9M**

Claim Type Oct 2011	**No of Claims**	**Cost of Claims**
Household	3,532	€58M
Commercial property	1,251	€59M
Motor	1,920	€10M
Total	**6,703**	**€127M**

In addition, using the 2006 Central Statistics Office POWCAR dataset[20] the economic sectors potentially impacted in each county from potential SLR or storm surge events were determined. The 2006 Corine Land Class (CLC) map was also used to disaggregate potentially vulnerable land into four land classes; urban fabric, agriculture, industrial or commercial and forest. CORINE is an acronym for Coordination of Information on the Environment. CORINE was established in 1985 by the European Community with the brief of creating pan-European databases on land

[19] The Irish Insurance Federation (IFF) is the representative body for insurance companies in Ireland
[20] The 2006 Census, Place of Work - Census of Anonymised Records (POWCAR) compiled by the Central Statistics Office, Ireland

cover, habitats, soil maps and acid rain (EPA/EEA, 2010). The CORINE Land Cover (CLC) map documents the environmental landscape of Europe based on the interpretation of satellite images. It includes 44 standard land cover classes and provides digital maps of land cover for much of Europe (European Environment Agency, 2010).

4.2.2 National flood risk study results and analysis

Figure 4.1 below presents the land vulnerability output of SLR modelling carried out for this study on the Irish coast.

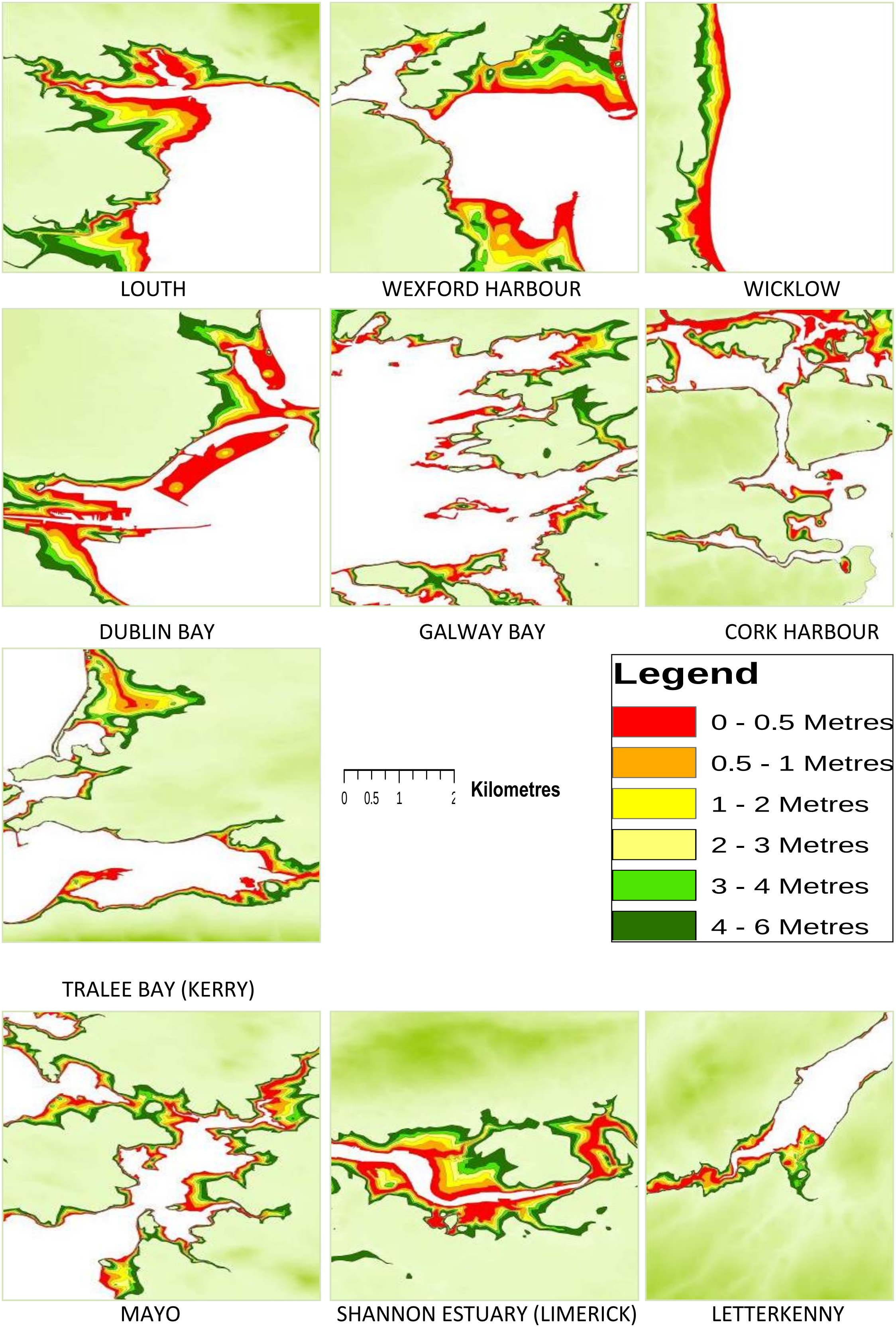
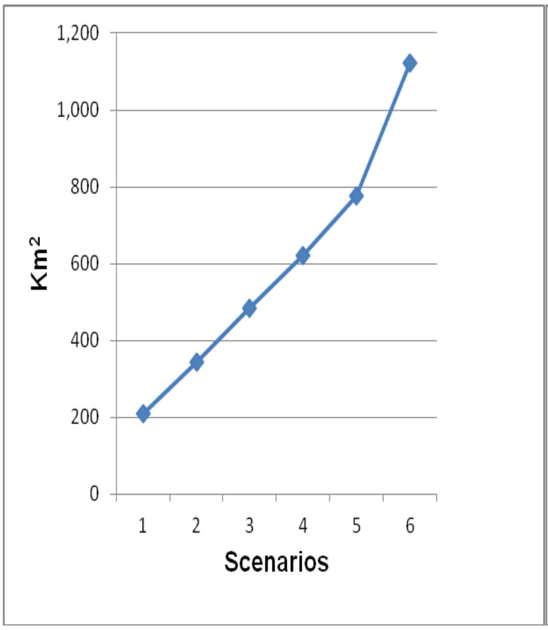


Figure 4.1: Sea-level rise scenarios on the Irish coast employing a digital terrain model.

Figure 4.2 below displays the total area vulnerable in the 15 coastal counties in to SLR/storm surges under the six scenarios. This ranges from 200km^2 to close to 1,200km^2 under the 6 metre scenario. Figures 4.3 and 4.4 below display the vulnerable land in the counties of Leinster and Munster.



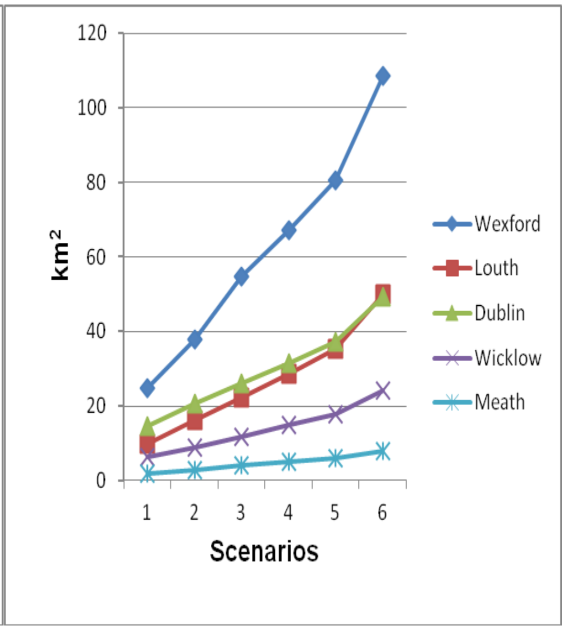
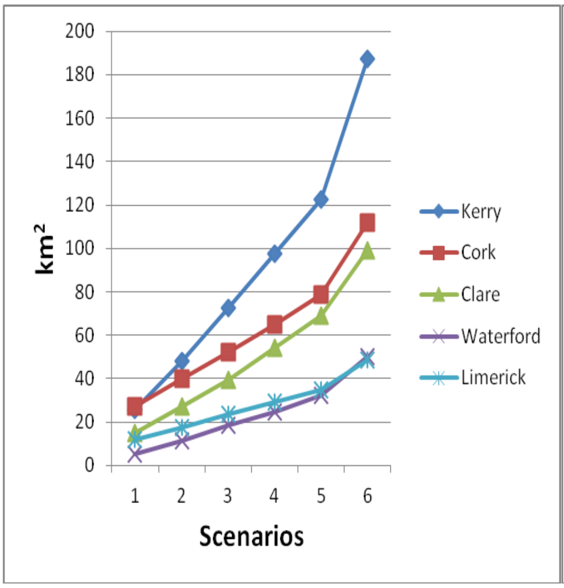


Figure 4.2: Country total vulnerable areas. Figure 4.3: Vulnerable area of counties in Leinster.



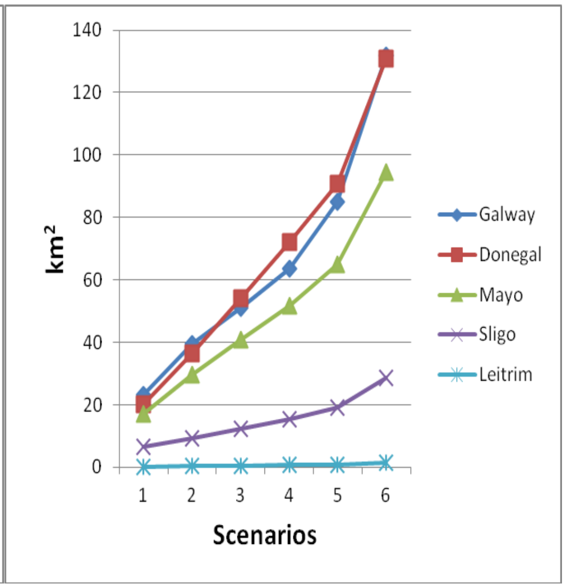


Figure 4.4: Vulnerable area of counties in Munster.

Figure 4.5: Vulnerable land in Connaught along with Donegal.

Wexford, Dublin and Louth face the greatest potential losses in Leinster with Kerry, Cork and Clare facing the greatest losses in Munster. Figure 4.5 displays vulnerable land for Connaught along with County Donegal. Here one can see that Donegal, Galway and Mayo are the most vulnerable. Table 4.2 displays the vulnerable percentage of land in each coastal county. Louth, Dublin and Wexford are the counties facing the greatest percentage losses ranging from over 1% in the first scenario to over 6% in the 6m scenario.

Table 4.2. Vulnerable percentage of land in each county under the six scenarios

	Sea Level Rise Scenarios					
	0.5m	1m	2m	3m	4m	6m
Provinces/Counties						
Leinster		Vulnerable Percentage of Land per County				
Louth	1.2	2	2.7	3.5	4.3	6.1
Meath	0.1	0.1	0.2	0.2	0.3	0.3
Dublin	1.6	2.2	2.8	3.4	4	5.4
Wicklow	0.3	0.4	0.6	0.7	0.9	1.2
Wexford	1.1	1.6	2.3	2.8	3.4	4.6
Munster						
Waterford	0.3	0.6	1	1.3	1.7	2.7
Cork	0.4	0.5	0.7	0.9	1.1	1.5
Kerry	0.5	1	1.5	2.1	2.6	4
Limerick	0.4	0.6	0.9	1.1	1.3	1.8
Clare	0.5	0.8	1.2	1.7	2.1	3.1
Connaught						
Galway	0.4	0.6	0.8	1	1.4	2.2
Mayo	0.3	0.5	0.7	0.9	1.2	1.7
Sligo	0.4	0.5	0.7	0.8	1.1	1.6
Leitrim	0	0	0	0	0.1	0.1
Ulster						
Donegal	0.4	0.8	1.1	1.5	1.9	2.7

Figure 4.6 displays the number of addresses and their composition in each coastal county. Figure 4.7 presents a representation of the Dublin Bay area displaying commercial addresses overlaid on the six sea-level rise scenarios, with Figure 4.8 displaying the residential addresses. Figure 4.9 displays all vulnerable addresses in all coastal counties. Dublin, Cork and Galway have the most vulnerable addresses ranging from 500 addresses in Galway, 5,000 in Dublin and over 6,000 in Cork under the first scenario. Using the information on vulnerable addresses determined from the modelling results and in conjunction with flood claim costs a generalised damage cost estimate of SLR and storm surge events was calculated.

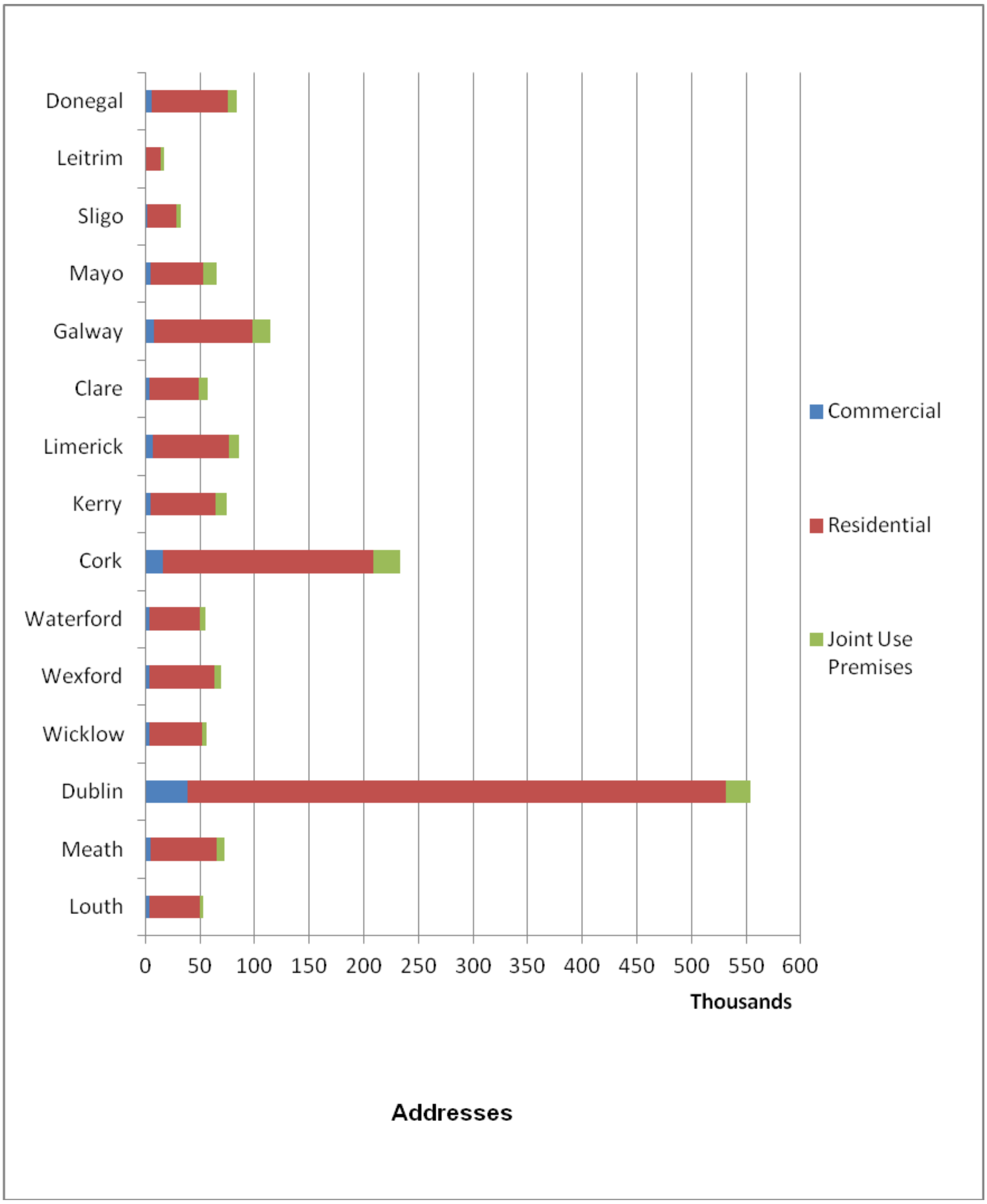


Figure 4.6: Total addresses in each coastal county.

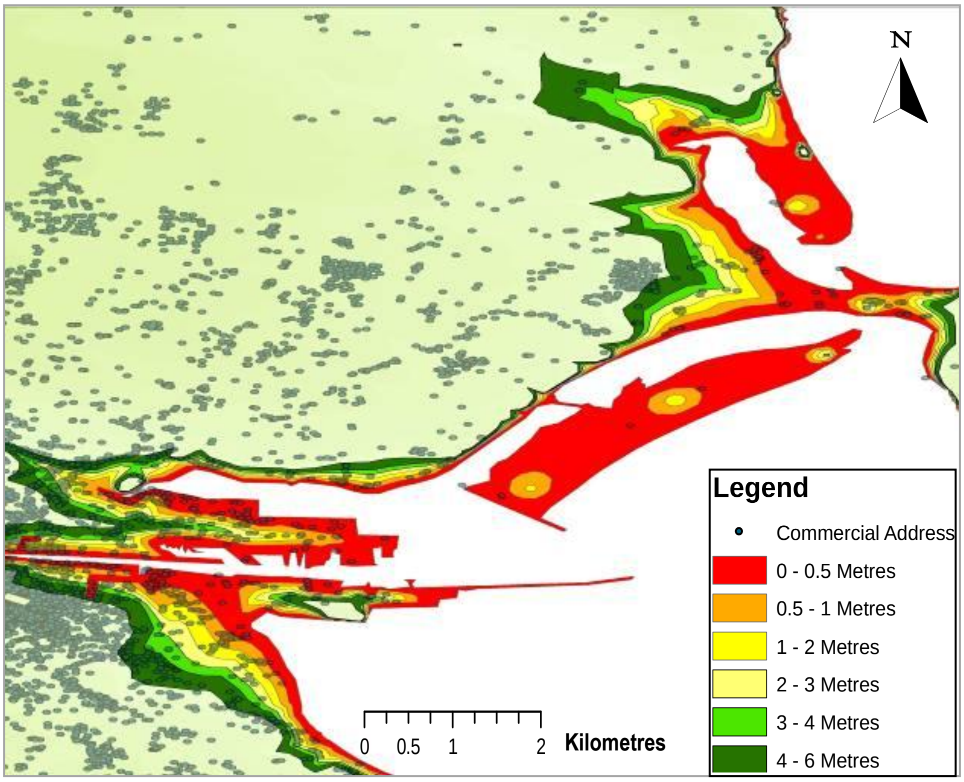


Figure 4.7: Commercial addresses displayed over SLR scenarios in Dublin Bay area.

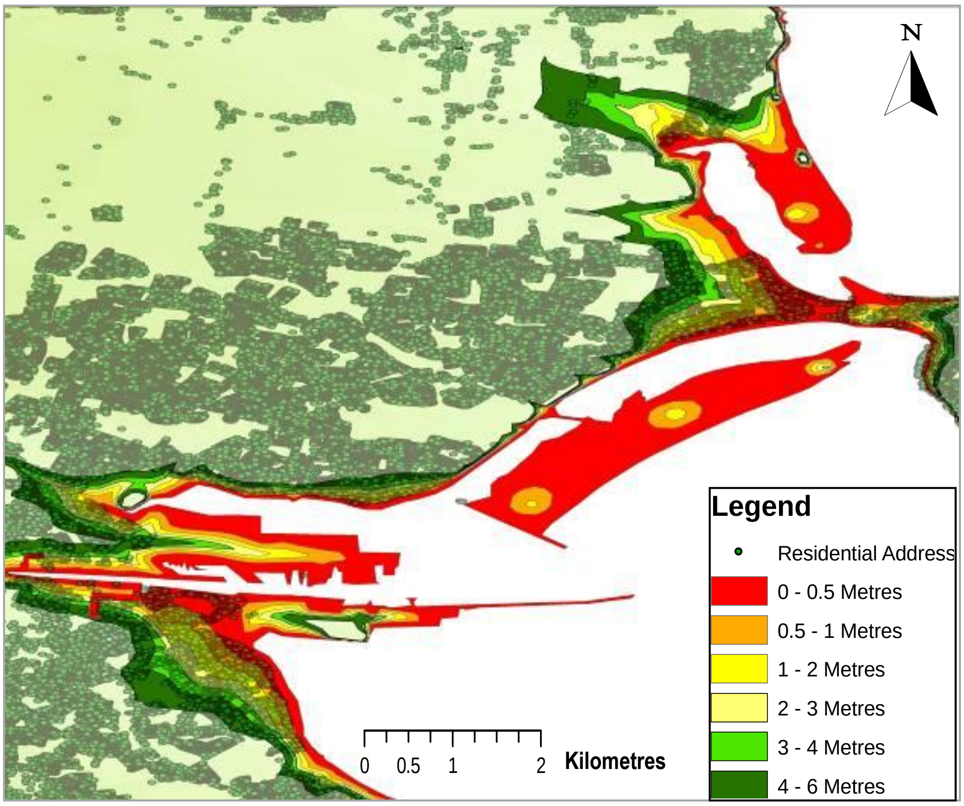


Figure 4.8: Residential addresses displayed over SLR scenarios in Dublin Bay area.

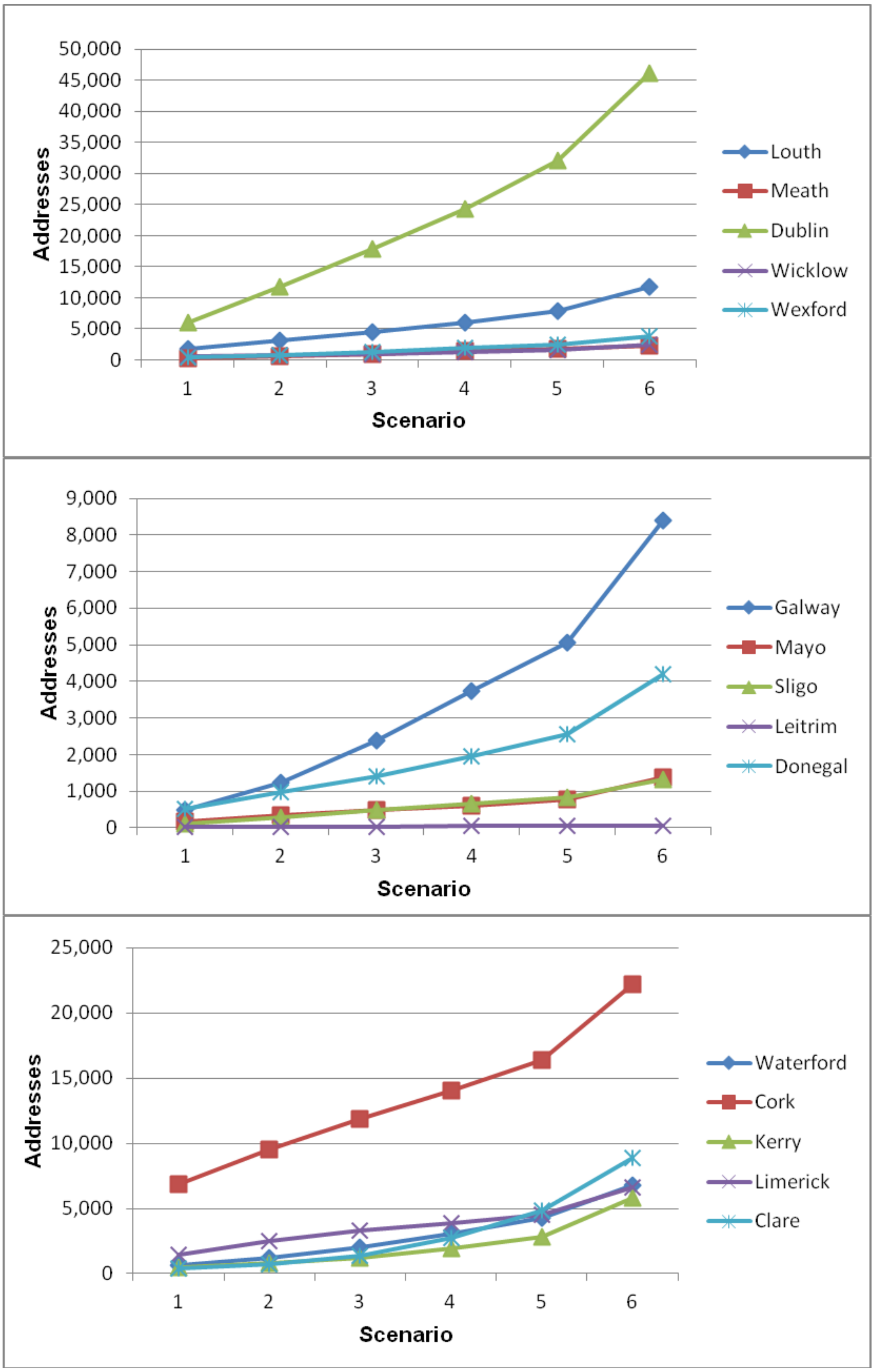


Figure 4.9: All coastal county vulnerable addresses.

Table 4.3 presents the potential claim cost for all claims under each of the scenarios. However, it must be noted that the nature and timeframe of any SLR or storm surge event will reflect on the typical insurance claim costs. These costs should therefore be considered as the potential costs that would occur if any one of these scenarios transpired in the medium term without significant adaptation measures put in place. Under the first 0.5m scenario one can see that Cork and Dublin would be impacted to the greatest extent with projected costs of €267M and €151M respectively.

Table 4.3: Potential insurance claims for all coastal counties under six scenarios.

	Sea Level Rise Scenarios					
	0.5m	1m	2m	3m	4m	6m
Provinces/Counties						
Leinster		€ M for All Claims				
Louth	43	80	111	153	197	294
Meath	5	12	22	30	37	46
Dublin	151	303	458	607	806	1,194
Wicklow	16	22	28	39	50	77
Wexford	11	21	36	54	72	114
Munster						
Waterford	13	23	38	61	78	121
Cork	267	361	439	510	582	737
Kerry	11	19	31	46	68	148
Limerick	50	75	97	112	130	184
Clare	10	19	34	65	119	226
Connaught						
Galway	12	33	58	89	125	234
Mayo	5	10	13	16	21	37
Sligo	4	11	18	24	29	47
Leitrim	0	0	1	1	1	1
Ulster						
Donegal	18	35	48	66	82	132
Total	**617**	**1,025**	**1,431**	**1,872**	**2,399**	**3,592**

Table 4.4: Number one ranked economic sector in each coastal ED by county from 2006 POWCAR.

Number one Ranked Economic Sector in Each Coastal ED by County		
Provinces/Counties	Economic Sectors	Jobs
Leinster		
Louth	Retail Trade	2,214
Meath	Food Products Beverages	431
Dublin	Real Estate, Renting and Business Activities	22,472
Wicklow	Health and Social Work	2,117
Wexford	Retail Trade	2,093
Munster		
Kilkenny	Wood and Wood Products	135
Waterford	Health and Social Work	2,413
Cork	Chemicals and chemical products	3,847
Kerry	Health and Social work	2,174
Limerick	Electrical and Optical Equipment	5,813
Clare	Hotels and restaurants	671
Connaught		
Galway	Hotels and Restaurants	3,396
Mayo	Hotels and Restaurants	1,146
Sligo	Health and Social Work	3,588
Leitrim	Agriculture and Forestry	8
Ulster		
Donegal	Hotels and Restaurants	2,246

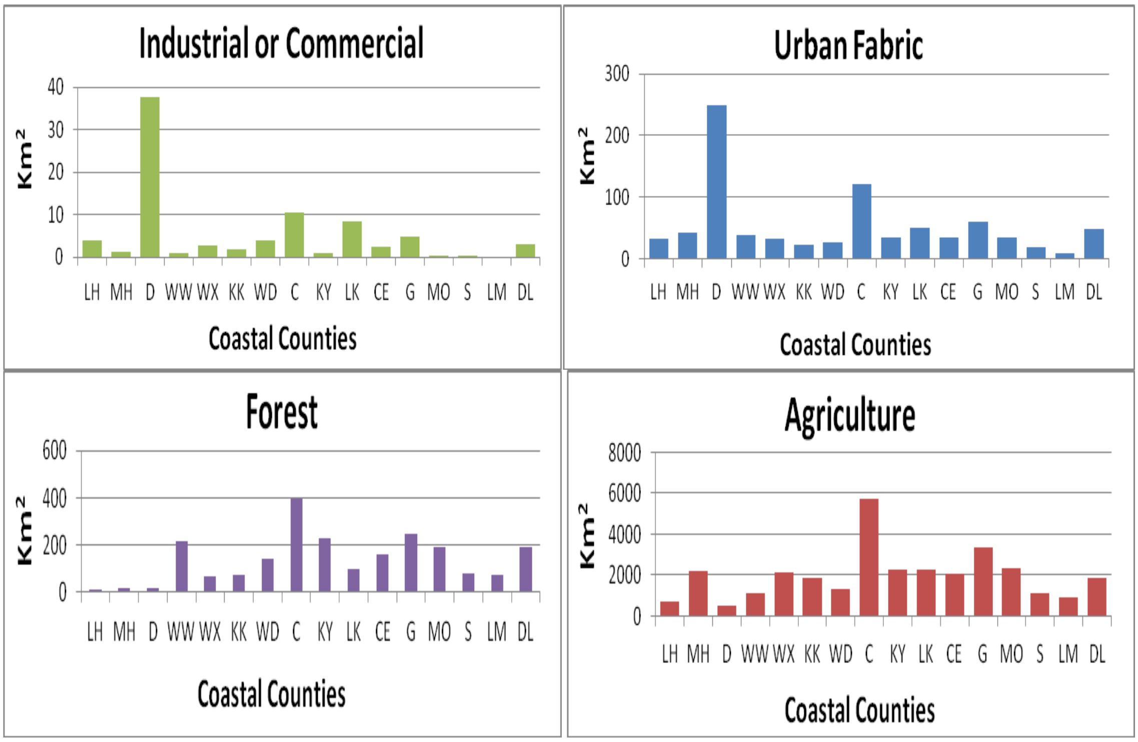


Figure 4.10: Land areas in each coastal county for agriculture, urban fabric, forest and industrial or commercial land calculated from CORINE.

Using the 2006 Central Statistics Office POWCAR dataset[21] the economic sectors potentially impacted in each county from potential SLR or storm surge events were determined. The economic sector that provided the greatest level of employment in each

[21] The 2006 Census, Place of Work - Census of Anonymised Records (POWCAR) compiled by the Central Statistics Office, Ireland

of the coastal electoral divisions[22] was determined and results are presented in Table 4.4. Urban fabric is made up of both continuous and discontinuous urban areas. Agriculture is composed of non-irrigated arable land, pastures, complex cultivation as well as land principally occupied by agriculture with areas of natural vegetation.

Industrial or commercial land is not disaggregated any further. Forest is broken down into broad leaved forest, coniferous forest and mixed forest. Figure 4.10 presents the areas taken up by these four land classes for each of the coastal counties in the Irish Republic. Figure 4.11 below displays the vulnerable area of land for each of the four mapped land classes with a log scale (log_{10}). Agriculture potentially faces the greatest vulnerabilities in terms of km^2 land area ranging from approximately $120km^2$ under scenario 1 up to $796km^2$ under scenario 6.

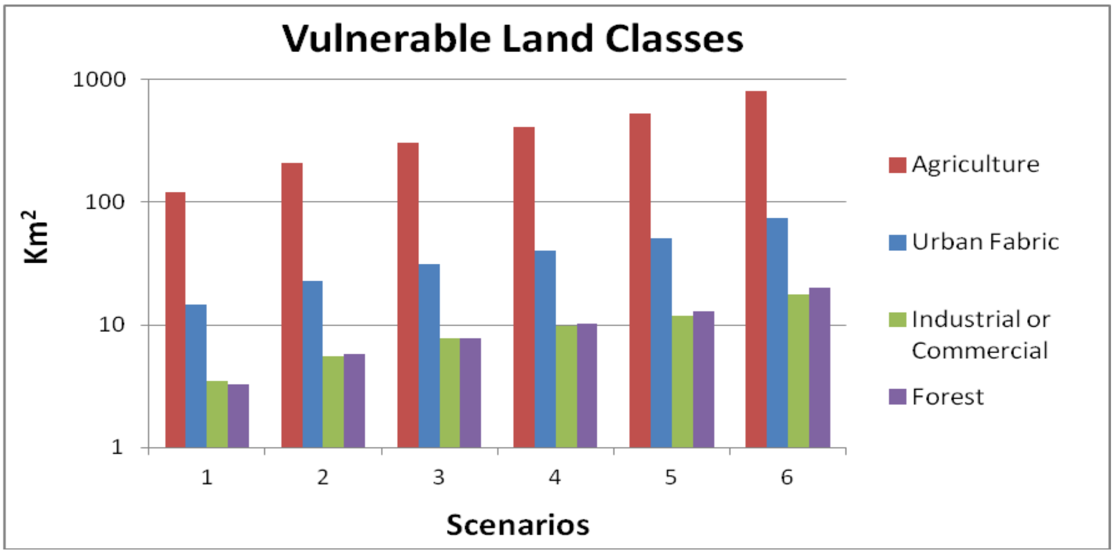


Figure 4.11: km^2 area of vulnerable land under six SLR scenarios for agriculture, urban fabric, industrial or commercial and forest.

Urban fabric is next in terms of vulnerable land. Potential impacts here range from $15km^2$ under the first scenario up to $75km^2$ under the sixth. Industrial and commercial along with forestry face the lowest potential km^2 land area impacts ranging from over $3km^2$ for both under scenario 1 and up to 18 km^2 for industrial and or commercial and $20km^2$ for forest under scenario six. This work demonstrates that the phenomena of

[22] Electoral divisions (formally known as District Electoral Division pre 1994) are low-level territorial divisions in Ireland. There are 3,440 Electoral Divisions in the Irish Republic.

SLR and storm surges are tangible drivers of coastal vulnerabilities in the form of potential land loss and capital loss in the Irish Republic. The headline results indicate that approximately 350km^2 of land is vulnerable under a 1 metre SLR jumping to 600km^2 at 3 metres. Potential economic costs relating to property insurance claims are in the region of €1B under a 1 metre scenario increasing to close to €1.9B with a 3 metre scenario.

4.3 LEINSTER LIDAR DATA CASE STUDY RESULTS AND ANALYSIS

A case study of the province of Leinster was carried out using a higher resolution DTM[23]. The DTM has a spatial resolution of 2m and was generated predominantly by interpolation from ground LIDAR. The acronym LIDAR stands for Light Detecting And Ranging. LIDAR is an optical remote sensing technology that can map out objects and terrain by illuminating the target with light and often using laser pulses to do so. Leinster was chosen as the case study site as a complete LIDAR data set was made available by the OPW for this particular region. The following case study employs the same methodology that was used for the national level sea-level rise vulnerability modelling but uses this higher resolution DTM.

Table 4.5: Vulnerable area in Leinster in km^2.

	Sea Level Rise Scenarios					
	0.5m	1m	2m	3m	4m	6m
Provinces/Counties						
Leinster	**Area vulnerable in km^2**					
Louth	0.8	1.7	5.1	18.4	32.1	53.2
Meath	0.2	0.8	1.3	2.4	4.6	6.7
Dublin	0.5	1.7	7.1	16.1	29.6	47.8
Wicklow	0.2	2.1	9.6	14.0	18.0	24.2
Wexford	30.7	39.3	52.9	66.2	77.6	101.3

[23] This DTM data was provided for the Leinster region by the Office of Public Works in Ireland.

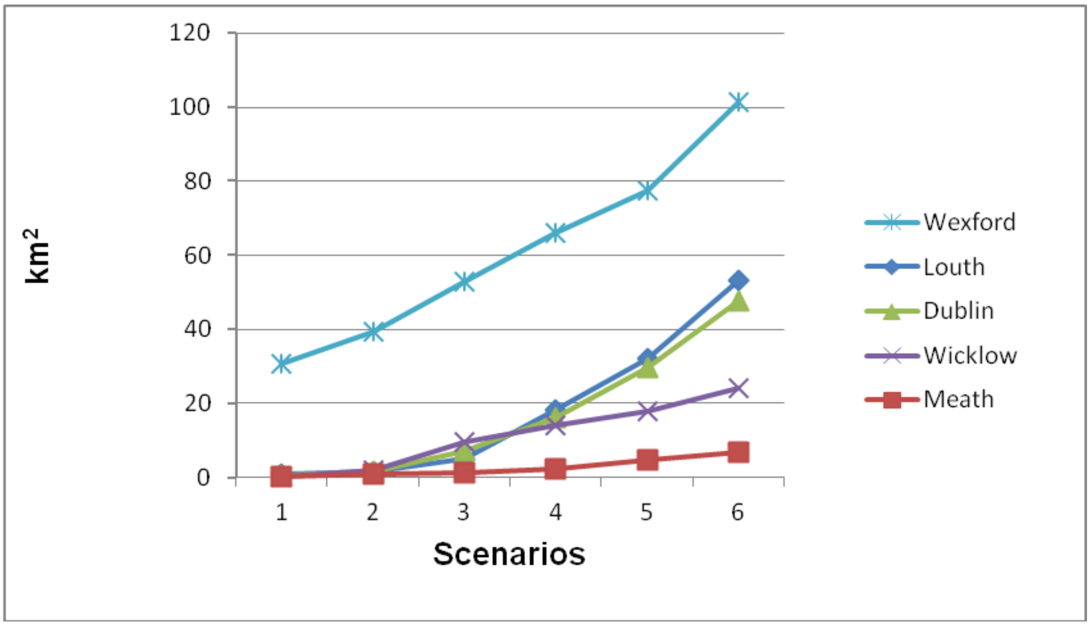


Figure 4.12: Vulnerable area in LIDAR case study counties under the six scenarios.

Table 4.5 along with Figure 4.12 highlight the vulnerable area in km^2 for the Leinster case study area. Under a 2 metre SLR scenario one can see that county Wexford displays the greatest absolute land area vulnerability at close to $53km^2$. Wicklow comes in at close to $10km^2$ with Dublin's potential vulnerable land coming in at just over $7km^2$ under a 2 metre SLR scenario. Figures 4.13-4.15 present the mapping outputs for this LIDAR case study for counties Wexford, Dublin and Louth. The use of a higher resolution LIDAR dataset is clear from these map outputs as they display much greater detail compared with the EPA 20m DTM outputs presented in Figure 4.1.

Through using this higher resolution dataset one can see that potential impacts under the first 3 scenarios are of a significantly lesser magnitude compared to the EPA 20m DTM modelling outputs. This observation is also displayed in the following tables and graphs. Figure 4.16 and Table 4.6 present the vulnerable percentage of land in Leinster under the six modelled scenarios. One can note that from the 0.5m to the 2m scenario the percentage vulnerabilities are all under 1% with the exception of county Wexford. Wexford displays vulnerabilities ranging 1 to 2% under these first three scenarios. Wexford's relatively high modelled vulnerability under these scenarios is due to its coastal profile; its low lying natural harbour and wetlands (slobs or mud flats) (Figure 4.13). One can also notice a significant jump in percentage vulnerability in Dublin and Louth between the 2m and 3m scenarios.

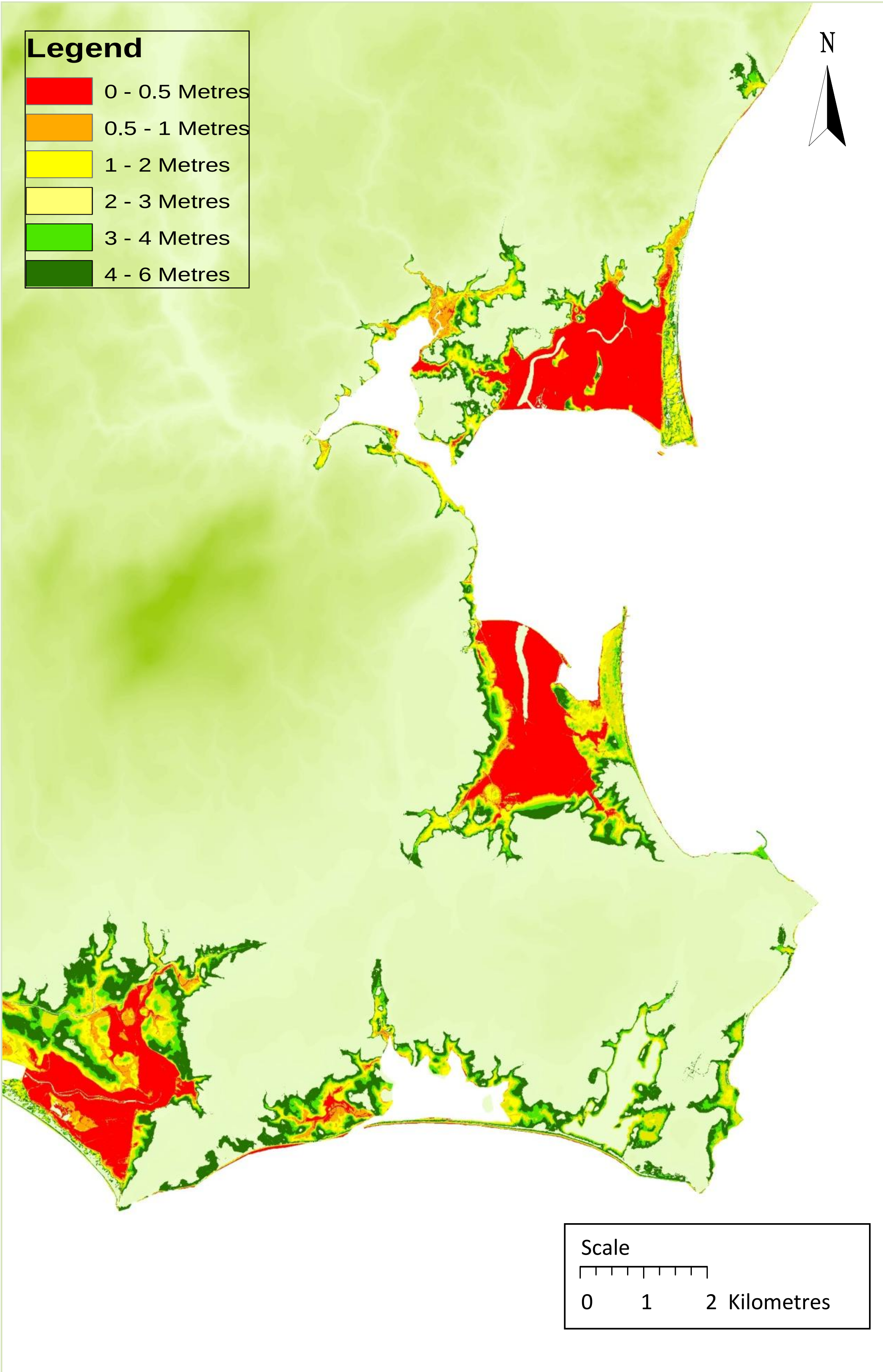


Figure 4.13: Vulnerable land in Wexford under the six modelled scenarios.

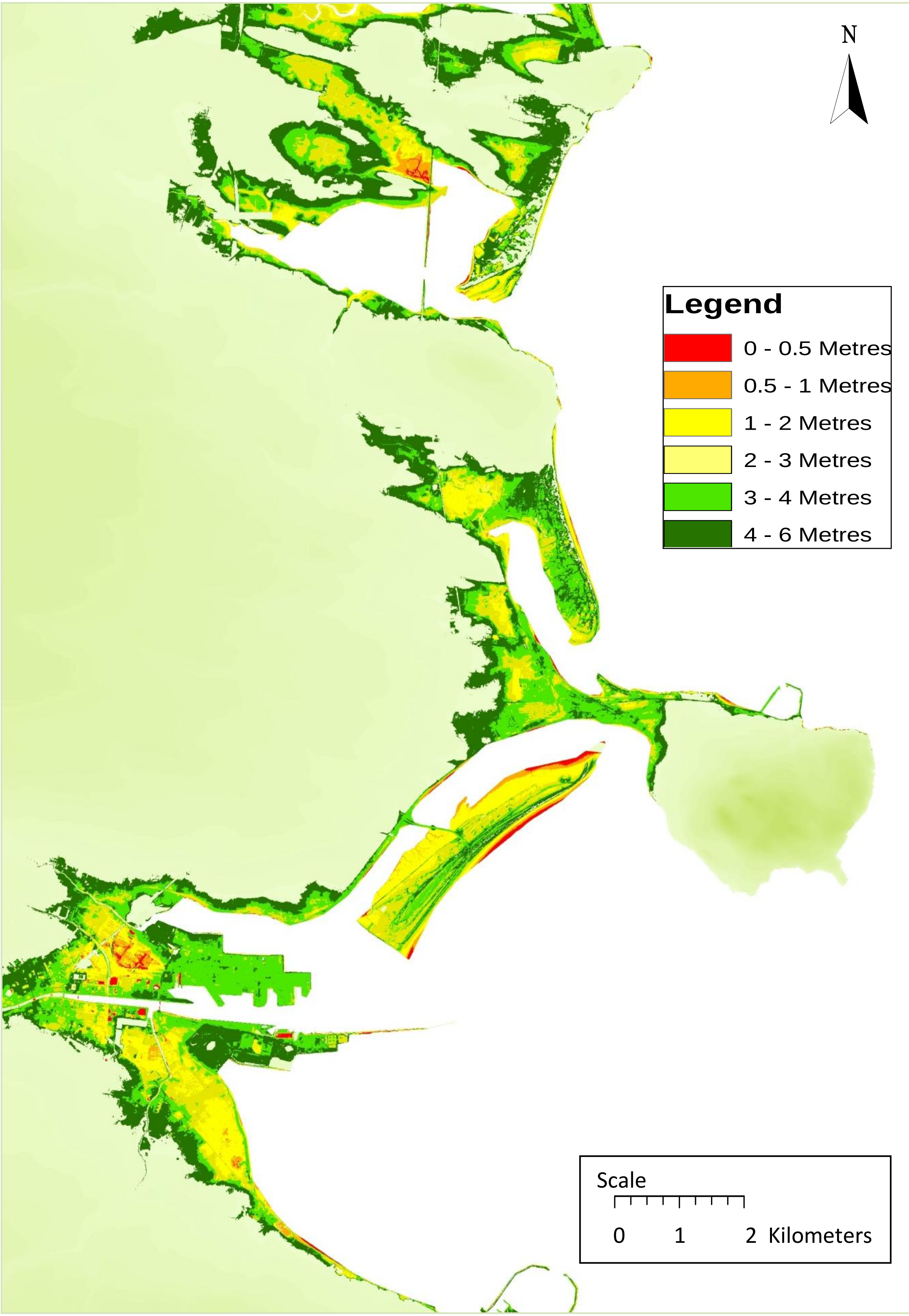


Figure 4.14. Vulnerable land in The Greater Dublin Area under the six modelled scenarios.

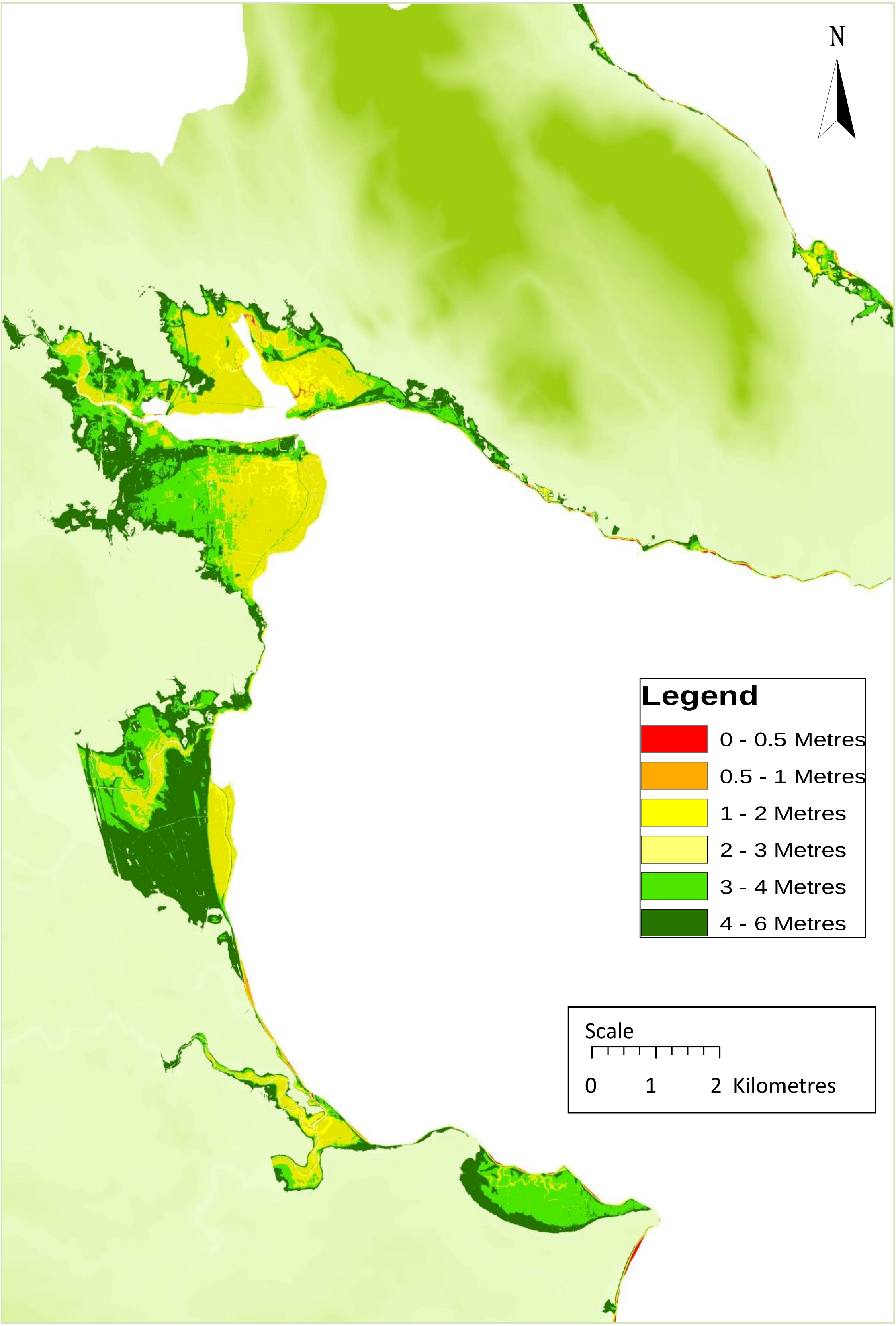


Figure 4.15: Vulnerable land in Louth under the six scenarios.

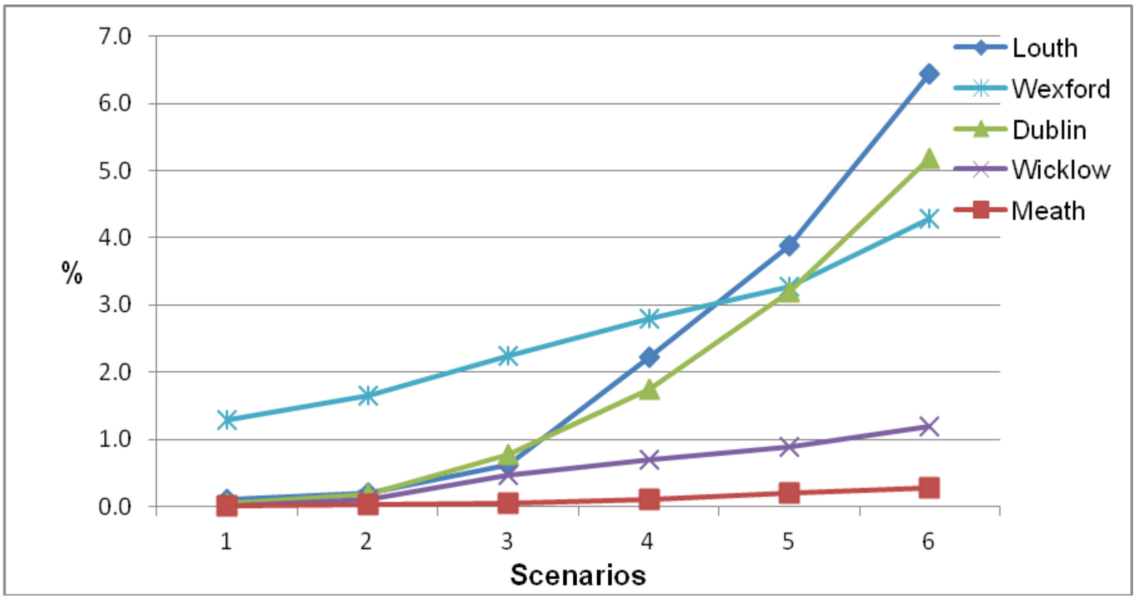


Figure 4.16: Vulnerable percentage of land in Leinster under the six modelled scenarios.

Table 4.6: Vulnerable percentage of land in Leinster under the six modelled scenarios.

		Sea Level Rise Scenarios				
	0.5m	1m	2m	3m	4m	6m
Provinces/Counties						
Leinster	**Vulnerable Percentage of Land per County**					
Louth	0.1	0.2	0.6	2.2	3.9	6.4
Meath	0.0	0.0	0.1	0.1	0.2	0.3
Dublin	0.1	0.2	0.8	1.7	3.2	5.2
Wicklow	0.0	0.1	0.5	0.7	0.9	1.2
Wexford	1.3	1.7	2.2	2.8	3.3	4.3

Vulnerable addresses were determined using the same methodology and GeoDirectory dataset that was used in the national study. The vulnerable addresses are presented here under the subgroups commercial addresses, residential addresses and joint use premises. Figure 4.17 along with Table 4.7 present vulnerable commercial addresses in each of the LIDAR case study counties. The modelled results indicate that Dublin and Wexford are vulnerable under the first three scenarios. Under the 2m scenario 516 commercial Dublin addresses are vulnerable along with 169 Wexford addresses. The modelling estimates that the other coastal counties experience minimal vulnerabilities in the commercial building stock up to the 2m scenario. However, under the 2m scenario Wicklow has 69 potentially vulnerable commercial addresses and Louth has 11. Significant potential vulnerabilities are modelled in the 3m, 4m and 6m scenarios in four out of the five coastal counties. Dublin proves to be particularly vulnerable under these modelled scenarios with 1,444 potential vulnerable buildings under a 3m scenario increasing to 3,517 under a 4m scenario and finally reaching 6,260 addresses under a six metre scenario.

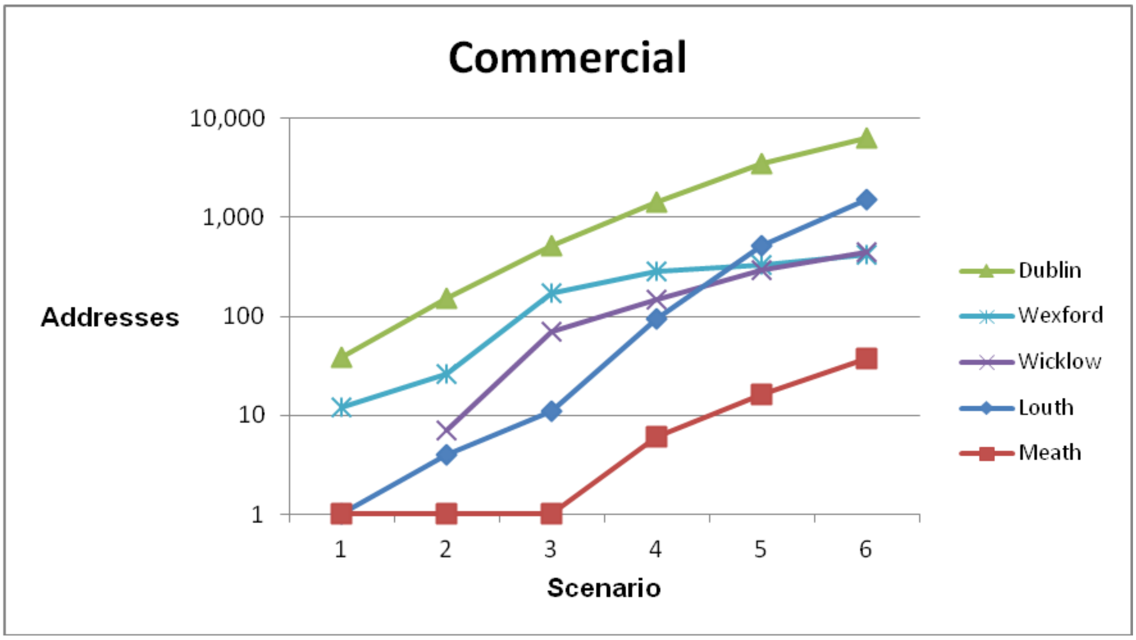


Figure 4.17: Vulnerable commercial addresses under each of the six scenarios.

Table 4.7. Vulnerable commercial addresses under each of the six modelled scenarios.

	Sea Level Rise Scenarios					
	0.5m	1m	2m	3m	4m	6m
Provinces/Counties						
Leinster	**Vulnerable Commercial Addresses**					
Louth	1	4	11	95	516	1,495
Meath	1	1	1	6	16	37
Dublin	38	150	516	1,444	3,517	6,260
Wicklow	0	7	69	147	294	441
Wexford	12	26	169	286	333	422
Total	**52**	**188**	**766**	**1,978**	**4,676**	**8,655**

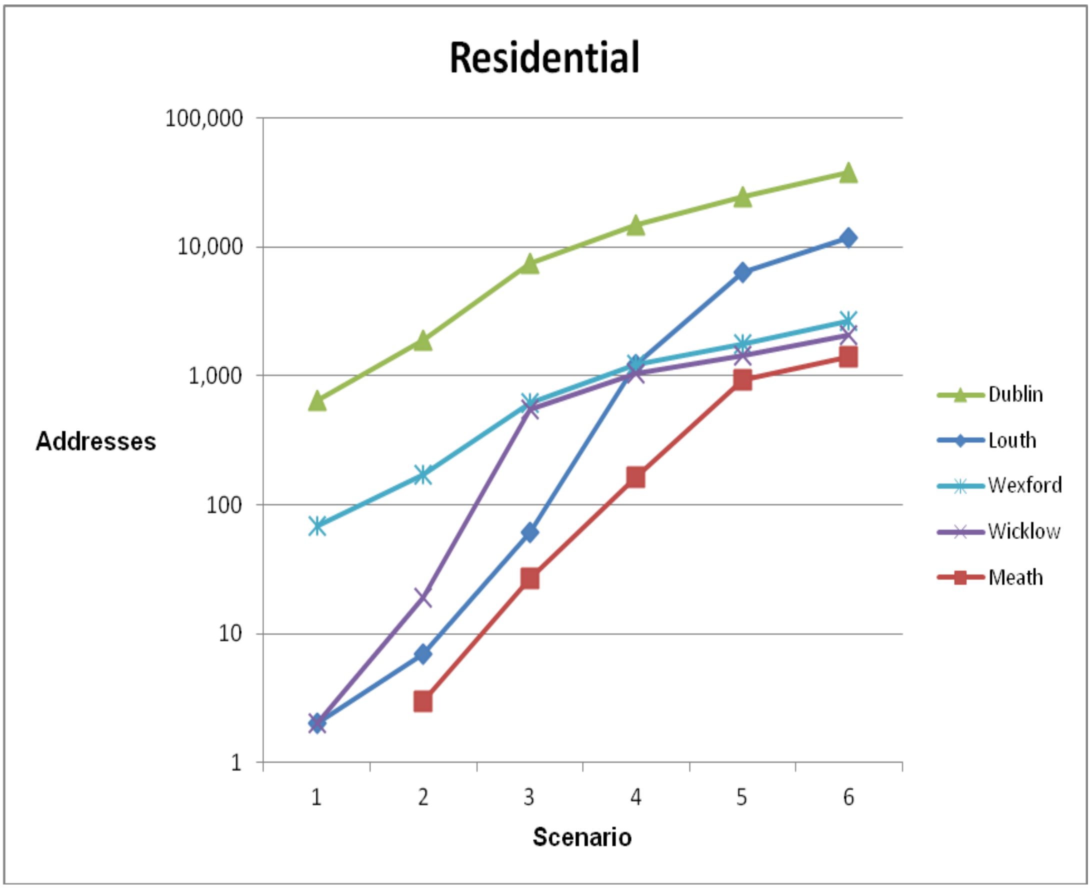


Figure 4.18. Vulnerable residential addresses under each of the six scenarios.

Table 4.8. Vulnerable residential addresses under each of the six scenarios.

	Sea Level Rise Scenarios					
	0.5m	1m	2m	3m	4m	6m
Provinces/Counties						
Leinster	**Vulnerable Residential Addresses**					
Louth	2	7	61	1,218	6,342	11,757
Meath	0	3	27	164	930	1,399
Dublin	641	1,901	7,472	14,705	24,823	37,900
Wicklow	2	19	555	1039	1,449	2,088
Wexford	68	173	621	1,228	1,781	2,646
Total	**713**	**2103**	**8,736**	**18,354**	**35,325**	**55,790**

Figure 4.18 and Table 4.8 display vulnerable residential addresses in the LIDAR case study area under the six SLR scenarios. Dublin is clearly the most impacted when it comes to the potential vulnerability of residential addresses. The modelling results

suggest a figure of 641 vulnerable addresses under a 0.5m scenario could potentially build to 37,900 addresses under a 6m scenario. Outside of Dublin, counties Wicklow and Wexford potentially face the greatest vulnerability under the first three scenarios with 555 and 621 vulnerable residential addresses respectively under the 2m scenario. All counties display vulnerability under the second three SLR scenarios of 3m, 4m and 6m. Louth presents the greatest number of potentially vulnerable addresses at 11,757 (outside of Dublin) under the 6m scenario followed by Wexford (2,646), Wicklow (2,088) and Meath (1,399).

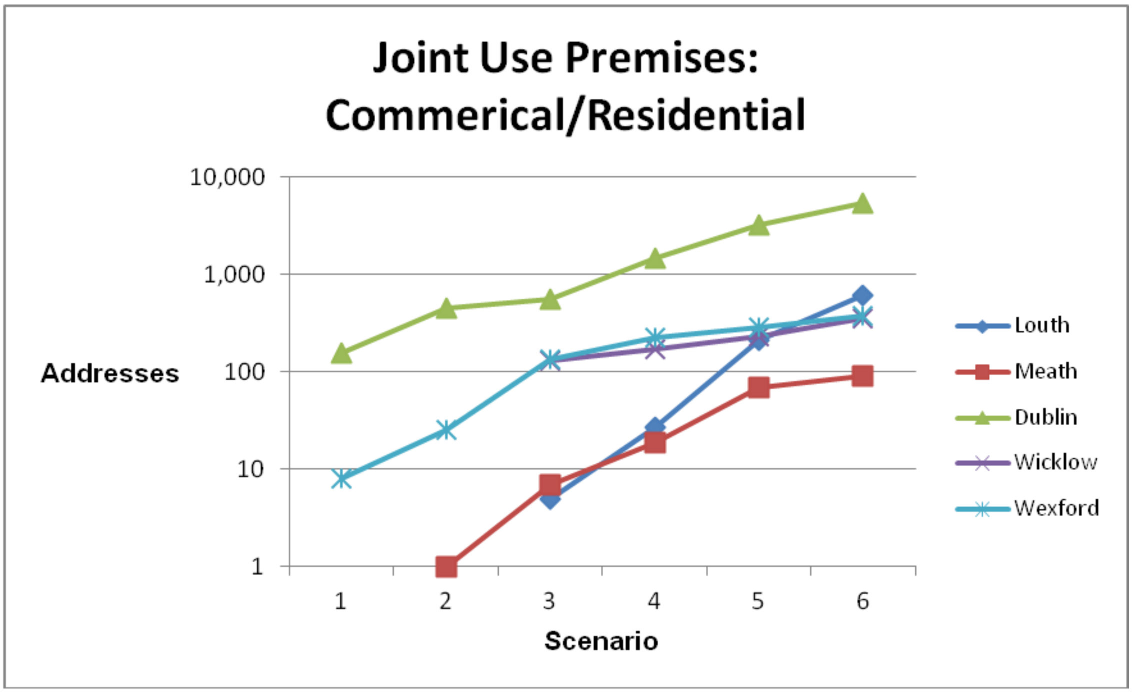


Figure 4.19. Vulnerable Joint use addresses under each of the six scenarios.

Table 4.9. Vulnerable Joint use addresses under each of the six scenarios.

	Sea Level Rise Scenarios					
	0.5m	1m	2m	3m	4m	6m
Provinces/Counties						
Leinster	**Vulnerable Joint Use Addresses**					
Louth	0	0	5	27	209	615
Meath	0	1	7	19	68	89
Dublin	158	446	555	1,453	3,198	5,336
Wicklow	0	0	129	168	233	349
Wexford	8	25	135	225	285	370
Total	**166**	**472**	**831**	**1,892**	**3,993**	**6,759**

Figure 4.19 and Table 4.9 present the modelled outputs for joint use addresses in the LIDAR case study area under the six SLR scenarios. Once more Dublin displays the greatest vulnerabilities with 158 modelled vulnerable joint use addresses under the first 0.5m scenario increasing up to 5,336 addresses under the final 6m scenario. Vulnerabilities in other counties are minimal until the 2m SLR is modelled. At this point Wexford and Wicklow show vulnerabilities of 135 and 129 addresses respectively. These modelled vulnerabilities build to 370 addresses (for Wexford) and 349 addresses (for Wicklow) under the 6m final scenario. Louth also displays vulnerabilities of 209 addresses under the 4m scenario and 615 addresses under the 6m scenario.

Table 4.10 and Figure 4.20 detail the potential insurance claims for the LIDAR case study sites under the six modelled scenarios. It can be observed that claims figures increase significantly as the SLR scenarios increase in height. Commercial claims increase by a factor of 3.6 between the 0.5m and 1m scenario. They quadruple from a 1m SLR scenario to a 2m SLR scenario. They increase by a factor of 2.5 between 2m and 3m SLR scenarios and more than double from the 3m SLR scenario to the 4m scenario. Residential claims increase by just under a factor of three between the 0.5m and 1m scenario. They also quadruple in value from the 1m to the 2m SLR scenario. They more than double between the 2m and 3m scenarios and they almost double between the 3m and 4m scenarios. Joint use claims almost triple between the 0.5m and 1m scenario. They increase by a factor of 1.76 between the 1m and 2m scenario. They more than double between the 2m and 3m scenario and between 3m and 4m scenarios.

Table 4.10. Potential insurance claims for LIDAR case study under the six scenarios.

	Sea Level Rise Scenarios					
	0.5m	1m	2m	3m	4m	6m
Provinces/ Counties						
COMMERCIAL						
Leinster	Euro (Thousands) for Commercial Claims					
Louth	75	300	825	7,125	38,700	112,125
Meath	75	75	75	450	1,200	2,775
Dublin	2,850	11,250	38,700	108,300	263,775	469,500
Wicklow	0	525	5,175	11,025	22,050	33,075
Wexford	900	1,950	12,675	21,450	24,975	31,650
Total	**3,900**	**14,100**	**57,450**	**148,350**	**350,700**	**649,125**
RESIDENTIAL						
Leinster	Euro (Thousands) for Residential Claims					
Louth	33	116	1,007	20,097	104,643	193,991
Meath	0	50	446	2,706	15,345	23,084
Dublin	10,577	31,367	123,288	242,633	409,580	625,350
Wicklow	33	314	9,158	17,144	23,909	34,452
Wexford	1,122	2,855	10,247	20,262	29,387	43,659
Total	**11,765**	**34,700**	**144,144**	**302,841**	**582,863**	**920,535**
JOINT USE						
Leinster	Euro (Thousands) for Joint Use Claims					
Louth	0	0	230	1,242	9,614	28,290
Meath	0	46	322	874	3,128	4,094
Dublin	7,268	20,516	25,530	66,838	147,108	245,456
Wicklow	0	0	5,934	7,728	10,718	16,054
Wexford	368	1,150	6,210	10,350	13,110	17,020
Total	**7,636**	**21,712**	**38,226**	**87,032**	**183,678**	**310,914**
GrandTotal	**23,301**	**70,512**	**239,820**	**538,223**	**1,117,241**	**1,880,574**

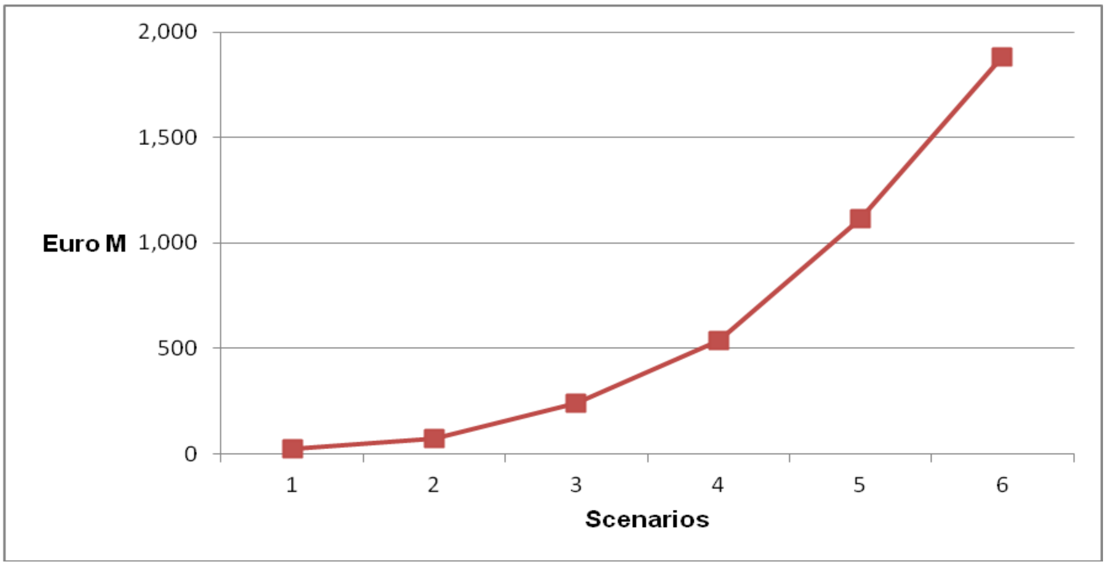


Figure 4.20: Total potential insurance claims for LIDAR case study under the six scenarios.

The outputs of this LIDAR case study demonstrate a marked revision in the modelled impacts under the six SLR scenarios compared with the national modelled outputs. The national study results for Leinster indicate potential insurance claims in the region of €226M for all 0.5m scenario claims compared to €23M for the same scenario using the higher resolution LIDAR data. However this gap between the modelled outputs lessens as the SLR scenarios increase in magnitude. The potential insurance claims are in the region of €1.7B for all 6m scenario Leinster claims for the national modelled outputs compared to just under €1.9B for the same scenario using the higher resolution LIDAR data. Table 4.11 below outlines the variations in the outputs.

Table 4.11 Variations between claims values for LIDAR and national DTM datasets.

	Sea Level Rise Scenarios					
	0.5m	1m	2m	3m	4m	6m
DATASET	**€ M for All Claims in Leinster**					
National DTM	226	438	655	883	1,162	1,725
LIDAR	23	71	240	538	1,117	1,881
Difference	203	367	415	345	45	(156)

The next section (4.4) explores the Coastal Vulnerability Index as an additional tool for assessing Irish coastal vulnerability. This index valuation provides another valuation methodology to complement the modelling effort of the preceding sections.

4.4 TOWARDS A COASTAL VULNERABILITY INDEX

Coastal Vulnerability Indexes (CVIs) are a commonly used tool to assess coastal exposure to SLR and coastal erosion. A CVI provides policy makers and coastal managers with a method for ranking the potential vulnerability of a particular coastline and identifying the regions where risks, as well as economic losses, may be especially high (Gornitz *et al*., 1991). Normally five or six key variables, that represent particular coastal vulnerabilities, are selected. Variables include mean tidal range, shoreline erosion or accretion rates, and coastal protection structures present. Once the variables are selected quantification is normally based on collation of semi-quantitative scores ranking on a scale from 1 to 5 (Gornitz, 1990; Hammer-Klose and Thieler, 2001). A ranking of 1 indicates a low contribution to coastal vulnerability of a specific key variable for the particular area, with a ranking of 5 indicating a high contribution. Finally, the key variables are integrated into a single index through various formulas such as the product mean or sum of squares of the terms (Gornitz *et al*., 1997). Table 4.12 below lists key physical and human-related variables along with their ranking criteria and scores. Although Irish data does exist for a number of key variables listed in Table 4.12, only some are publically available at a sufficient level of detail to carry out a full CVI. Table 4.13 presents a partial CVI for Irish Coastal counties in Leinster dependent on available data.

Table 4.12: Key physical and human related variables along with their ranking and scores (Gornitz, 1990)

	Very Low	Low	Moderate	High	Very high
Variable	1	2	3	4	5
Physical Parameters					
Mean wave height (m)	0-2.9	3.0-4.9	5.0-5.9	6.0-6.9	≥7.0
Mean tidal range (m)	≤0.99 Microtidal	1.0-1.9 Microtidal	2.0-4.0 Mesotidal	4.1-6.0 Mesotidal	≥6.1 Macrotidal
Shoreline erosion/accretion (m/yr)	≥+2.1 Accretion	1.0-2.0 Stable	-1.0-+1.0 Erosion	-1.1- -2.0 Erosion	≤-2.1 Erosion
Geomorphology	Rocky cliff coasts, fiords	Medium cliffs, indented coasts	Low cliffs, glacial drift, alluvial plains	Cobble beaches, estuary, lagoon	Barrier beach, sand beach, salt marsh, mudflats, deltas
Human Parameters					
Land use pattern	Protected area	Unclaimed	Settlement	Industrial	Agricultural
Coastal protection structures	>50%	30-50%	20-30%	5-20%	<5%
Engineered frontage	<5%	5-20%	20-30%	30-50%	>50%

Mean wave height for the entire country falls under very low in the vulnerability ranking scale of 0 to 2.9m (Figure 4.21). Irish mean wave heights range from 0.25m found mostly on the east coast along with some sheltered bays in the west, to 2.5m on a number of peninsulas on the west coast. The mean tidal range in Ireland ranges from micro right through to macro tidal (Figure 4.22). Macro tidal is defined as over 4m by Devoy (2008) and as over 6.1m by Gornitz *et al*., (1997) (Table 4.12). Coastal erosion is prevalent in a number of Irish coastal counties with Wexford, Wicklow and Donegal hit the hardest (Figure 4.23). Data on coastal geomorphology in Ireland is readily available

(Carter, 1988). As discussed in Chapter 3, the east coast is predominantly low lying consisting of non-consolidated sediment and glacial tills. The west coast is defined by rocky cliffs, at times up to 500m in height, interspersed with bays. Land use patterns are also documented though the CORINE data set. However, a detailed inventory of coastal protection structures is not publically available. Nevertheless, it is reported that national levels of coastal protection are under 4% (Devoy, 2008). Similarly detailed data on engineered coastal frontage is not readily available.

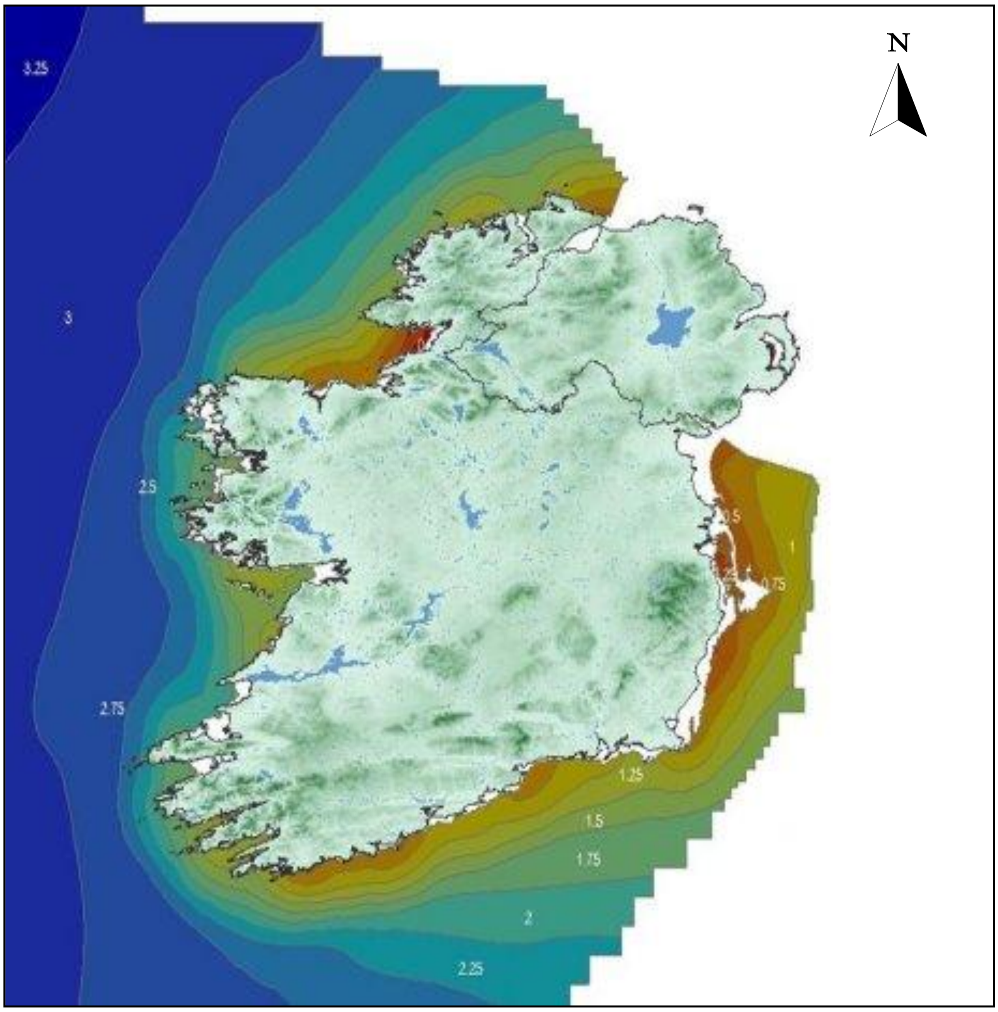


Figure 4.21: Annual average wave height (Source: Marine Institute, 2005).

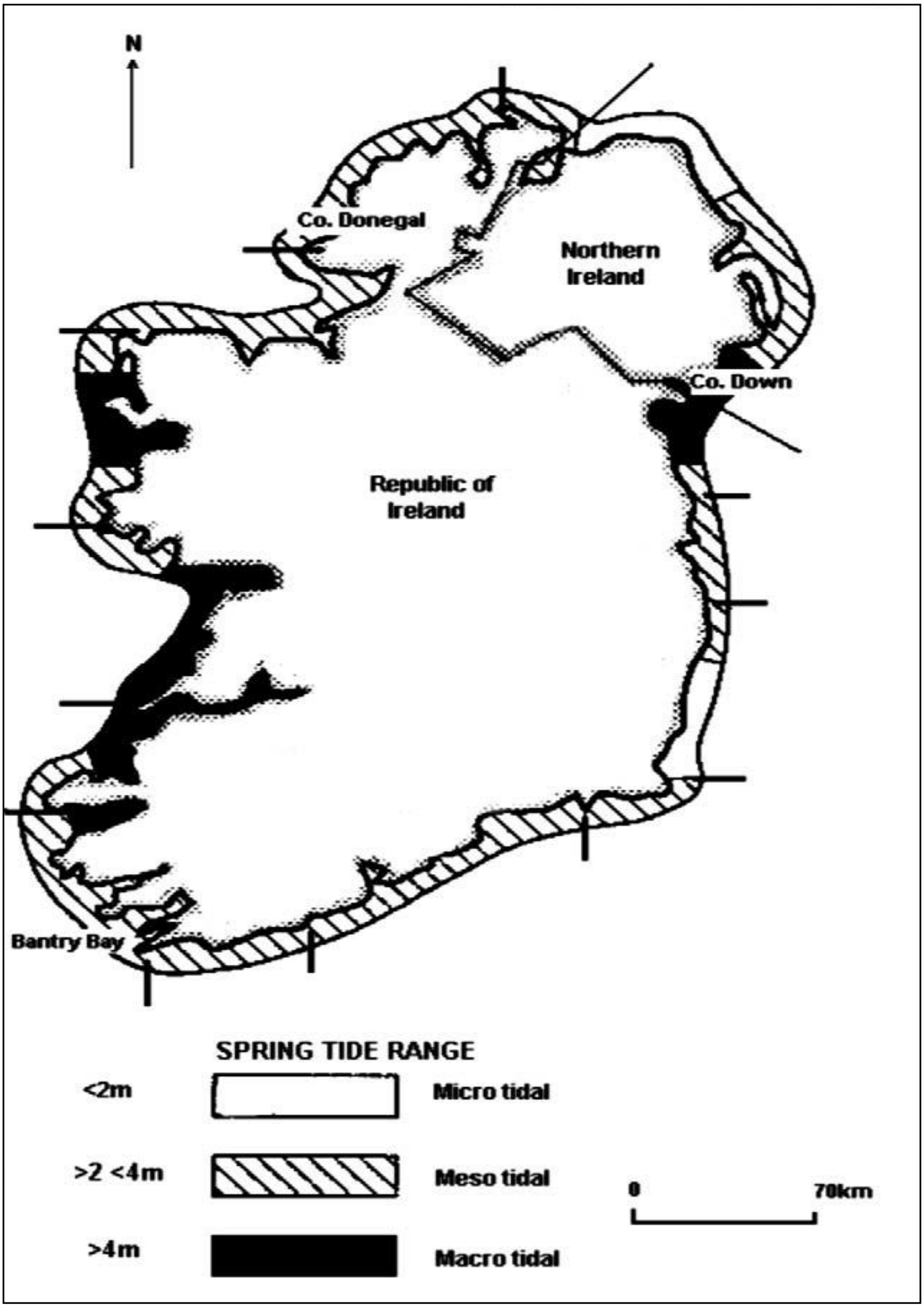


Figure 4.22: Variation in tidal regimes as measured by spring tidal range (Source: Devoy, 2008).

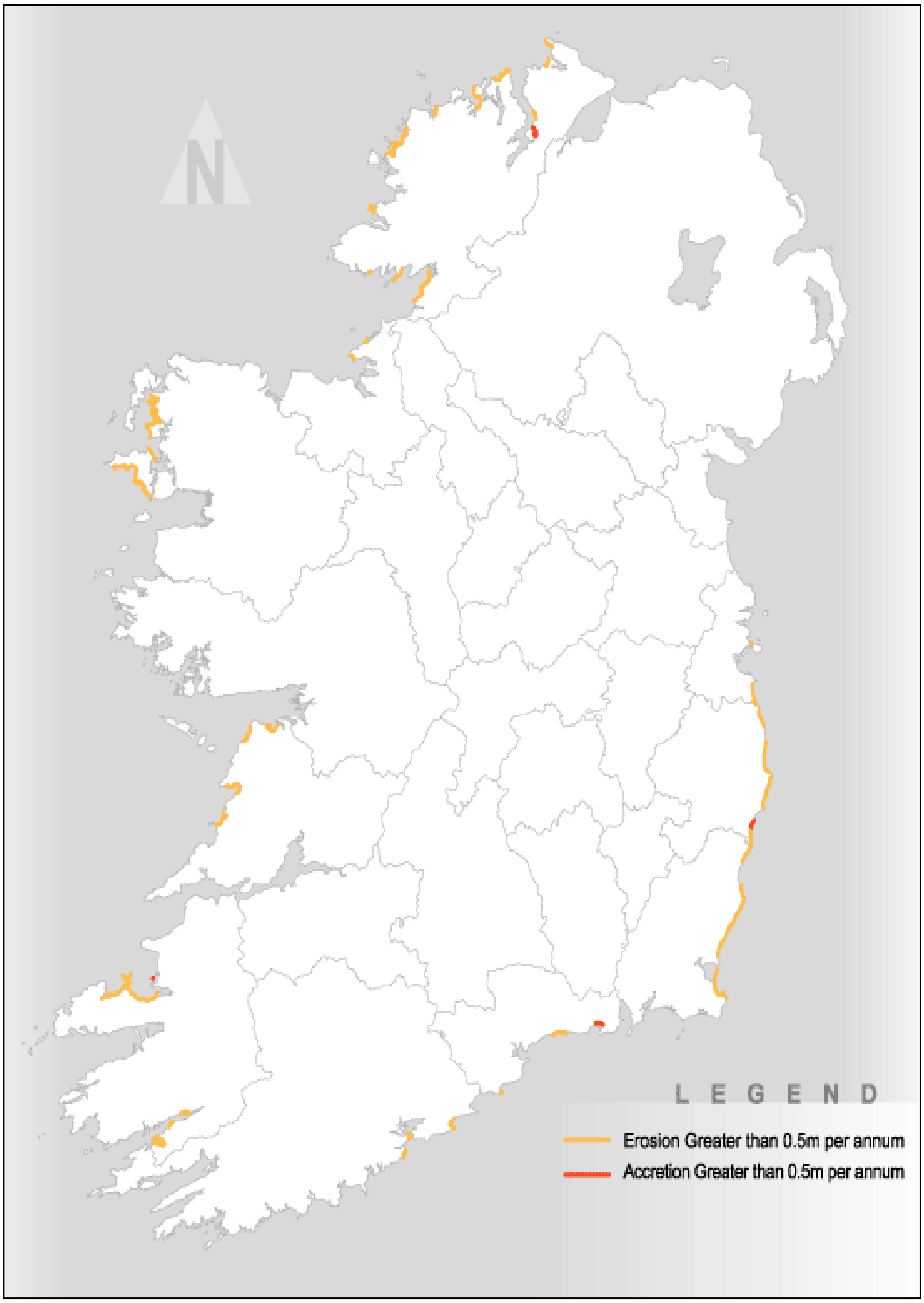


Figure 4.23: Coastal erosion and deposition (Source: Department of Environment and Local Government, 2001).

Table 4.13: Partial CVI for coastal counties in Leinster.

	Louth	Meath	Dublin	Wicklow	Wexford
Variable	**Ranking**				
Physical Parameters					
Mean wave height (m)	1	1	1	1	1
Mean tidal range (m)	4	3-4	3-4	1-2	3-4
Shoreline erosion/accretion (m/yr)	1	1	2-3	3-4	4-5
Geomorphology	4-5	4-5	4-5	4-5	5
Human Parameters					
Land use pattern	3-5*	3-5*	3-5*	3-5*	3-5*
Coastal protection structures	Unknown	Unknown	Unknown	Unknown	Unknown
Engineered frontage	Unknown	Unknown	Unknown	Unknown	Unknown
Product mean	14.4	12.6	31.5	18.9	63
Average sum of squares	10.9	10.1	11.2	10.35	14.9

* All five counties present a mix of coastal settlement, industy and agriculture.

Table 4.13 presents a partial CVI for the coastal counties in Leinster. It presents a reasonable assessment of coastal vulnerability, except for missing detailed data on coastal protection structures and engineered frontage. In this incomplete CVI Wexford and Dublin are calculated to be the most vulnerable, and primarily differentiated from the other counties through factors relating to tidal range and shoreline erosion.

4.5 CONCLUSIONS

The coastal economic impact modelling carried out above underlines the case for adaptive management of the Irish coastline. The national estimate of the economic costs associated with coastal flooding provides a useful estimate that uncovers significant potential land loss and property flood claim costs relating to SLR and storm surge predictions. The results also indicate the important role of uncertainty in this analysis. This is demonstrated when the medium resolution DTM results are compared to the higher resolution LIDAR outputs. The quality of data resolution is thus a significant factor in relation to reducing both uncertainty and error in the analysis. The methodology used to carry out the analysis also creates uncertainty in the results. The chosen methodology is useful for providing an indication of potentially vulnerable coastal areas, but could be developed further by integrating a greater number of physical parameters into the analysis. For example, factors relating to coastal geomorphology or coastal protection structures could be integrated into the methodology applied in this study.

As discussed above, the LIDAR case study of Leinster reveals substantially less potential impacts in comparison to the national level modelling. However, the national results are still useful in pointing out order of magnitude impacts and highlighting counties that face particular coastal economic vulnerabilities. While the LIDAR Leinster case study reveals significantly reduced potential economic impacts, especially under more modest SLR scenarios, it does suggest that impacts increase significantly in magnitude from the 0.5m scenario to the 1m scenario and in turn from the 1m scenario to the 2m scenario. These results underpin the argument for strategic adaptive coastal management.

The CVI analysis carried out above complements the DTM vulnerability mapping exercise by considering factors such as tidal range and coastal erosion. The two approaches of CVI analysis and DTM vulnerability modelling can also be catagorised as taking a “starting point” interpretation and “end point” position respectively, in relation to conceptualisations of vulnerability; CVI focuses on current vulnerabilities and DTM risk mapping is focused on potential climate impacts. Taken together they can offer policy makers and planners a more robust analysis of coastal flood risk and provide useful inputs into ICZM processes.

The analysis is this chapter addressed post-normal approaches through providing values that relate to potential land losses, vulnerable properties, and economic costs associated with insurance claims. Presenting potential impacts in addition to monetary costs allows decision-makers to gain a fuller appreciation of the range of potential impacts, and puts them in the position to make more fully informed choices. In addition, the spatial distribution of potential impacts, as provided in the analysis, empowers decision-makers to take site specific factors into account in their policy decisions.

CHAPTER 5
STATE OF CURRENT THINKING ON ECOSYSTEM SERVICES: WETLANDS

5.1 INTRODUCTION

Ecosystems are of critical importance to the healthy functioning of life on our planet. This chapter explores the concept of ecosystem services to humanity along with their valuation. It places special focus on coastal wetlands in Ireland, as they fall within the realm of coastal systems that make up one of the five noted impact categories in Ireland – along with agriculture, inland flooding, tourism and human health – that are under greatest threat in relation to climate change (European Commission, 2009a; Jenkins *et al*., 2009). The focus is narrowed further to the wetland subgroups of salt marshes, dunes and machairs and coastal lagoons, as they are especially sensitive and unique coastal wetland habitats in Ireland. This chapter provides useful context to the economic appraisal of Irish wetlands' vulnerability to climate change presented in Chapter 6.

5.2 ECOSYSTEM SERVICES VALUATION

Ecosystems are dynamic and complex communities of plants, animals and micro-organisms and their non-living environments, which include air, soil, water and sunlight. An ecosystem acts as a functioning unit (Campbell and Reece, 2002). Deserts, wetlands, rain forests, urban parks and cultivated farmlands are examples of ecosystems. They can exist completely without the influence of humans or be modified by human activity. Ecosystem services, also known as environmental services or ecological services, are the “benefits” that people obtain from ecosystems (Tietenberg and Lewis, 2007).

The total value of the world’s ecosystem services was conservatively valued in 1997 to be in the range of €12-40 trillion (10^{12}) per year with an average of €24 trillion per year[24] (Costanza *et al.*, 1997). Most of this value is not captured directly within existing markets and this is considered a minimum estimate because of the level of uncertainties involved (Pimm, 1997). Of the €24 trillion just over €13 trillion is attributed to soil formation services. Recreation comes in second at €2 trillion. Nutrient cycling along with water regulation and supply are both valued at €1.7 trillion. Climate regulation (temperature and precipitation), natural habitat and flood and storm protection come in at €1.3 trillion, €1 trillion and €0.8 trillion respectively. Global gross national product was valued at €13 trillion at the time.

There are four broad categories of ecosystem services:

- **Provisioning Services** are the goods or products obtained from ecosystems such as food, fresh water, timber, and fibre.
- **Regulation Services** are the benefits obtained from an ecosystems control of natural processes such as climate, disease, erosion, water flows, and pollination, as well as protection from natural hazards.
- **Cultural Services** are the nonmaterial benefits obtained from ecosystems such as recreation, spiritual values, and aesthetic enjoyment.
- **Supporting Services** are the natural processes such as nutrient cycling and primary production that maintain the other services.

(Millennium Ecosystem Assessment, 2005)

The Economics of Ecosystems and Biodiversity (TEEB) Report (European Communities, 2008) provides some sobering figures on the potential losses to biodiversity if “business as usual” practices remain in place. By 2050 it is projected that

[24] This value was estimated for 17 ecosystem services for 16 biomes, based on published studies as well as a number of original calculations.

11% of “natural areas” in existence in 2000 could be lost, primarily as a result of conversion to agriculture, the expansion of infrastructure and climate change. Almost 40% of land currently being cultivated under low-impact forms of agriculture could be converted to intensive agriculture, leading to significant biodiversity losses. 60% of coral reefs could be lost, by 2030, through pollution, coral bleaching due to climate change, overfishing and disease (European Communities, 2008). The economic argument for maintaining intact ecosystems is persuasive. Balmford *et al*., (2002) calculated the marginal value of goods and services delivered by a biome when relatively intact and when converted to typical forms of human use. The resulting cost benefit ratio of an effective global program for the conservation of remaining unspoilt ecosystems was determined to be at least 100:1.

The estimated total marginal value of ecosystem services in Ireland is €2.6 billion per annum. This total captures the value of ecosystem services in Ireland in terms of their contribution to productive output and human “utility”. (Bullock *et al*., 2008). The figure does not include a number of significant services such as waste assimilation by aquatic biodiversity. This total figure is broken down into a number of different environmental sectors including agriculture, forestry, fisheries, water, human welfare and policy costs. Table 5.1 provides an overview of these sectoral groupings.

Forfás released a report in 2008 that valued ecosystem goods and services at €2.8 billion at a national level (Forfás, 2008). The report notes that this estimate does not include the market for environmental goods and services in building and construction materials. This figure can be broken down further into four sectors. Water/Wastewater treatment is valued at €1 billion, waste management comes to €550 million, renewable energies are €700 million and environmental services and other clean technology comes to €560 million.

Table 5.1: The value of ecosystem services at a sectoral level (Adapted from Bullock, 2008).

Sector	Details	Value
Agriculture	Soil Biota	€1 billion per year
	Pollination	€220 - €500 million per year
	Natural pest control	€20 million per year
	Landscape and wildlife habitats relating to sustainable farming	€150 million per year
Forestry	Ecosystem services including recreation and habitats for wildlife	€55 - €80 million per year
Fisheries	Quayside value of the fish catch	€180 million per year
	Aquaculture and seaweed industry	€50 million per year
Water	Value to biodiversity	€385 million per year
Human Welfare	Utility value (excluding health)	€330 million per year
Total		**2.6 billion approx**

5.3 WETLANDS IN A GLOBAL CONTEXT

5.3.1 Wetland mapping and overview

Wetlands provide an array of important services to human society and are highly ecologically sensitive systems. Wetlands are defined as: "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt including areas of marine water, the depth of which at low tide does not exceed 6m" (Ramsar, 2011: 7).

The 1999 Global Review of Wetland Resources and Priorities for Wetland Inventory estimates that the global extent of wetlands is in excess of 1,280M ha (of 14.8B ha of total land on earth) (Finlayson, 1999). This figure, calculated from multiple information sources, includes inland and coastal wetlands, nearshore marine areas (to a depth of six metres below low tide), as well as human-made wetlands, such as reservoirs and paddy fields (Millennium Ecosystem Assessment, 2005). Peatlands occur in over 173 countries worldwide and it is estimated that their total area is approximately 400 million hectares. The majority of peatlands occur in Russia (30%) and Canada (37%). There are a number of global inventories of rivers including major river systems, their drainage area, length and flow volume. However, there is significant variability between estimates due to the method and definitions used. Globally, there are approximately 1,200 major estuaries with a total area of approximately 50 million hectares. Rice fields have been estimated to make up an area of 130 million hectares with the vast majority, 90%, cultivated in Asia. There are an estimated 5-15 million lakes on earth although information on them is highly variable and dispersed (Finlayson, 1999). Mapping of coastal wetlands such as mangrove forests, estuaries, coral reefs, and seagrass beds is quite extensive. Mangrove forests, found in both tropical and sub-tropical areas, cover a global area of 16-18 million hectares and the majority are found in Asia. Reefs occur as barrier reefs, atolls, fringing reefs, or patch reefs. Combinations of these types exist on the majority of the islands in the Pacific, Indian Ocean and Caribbean Sea.

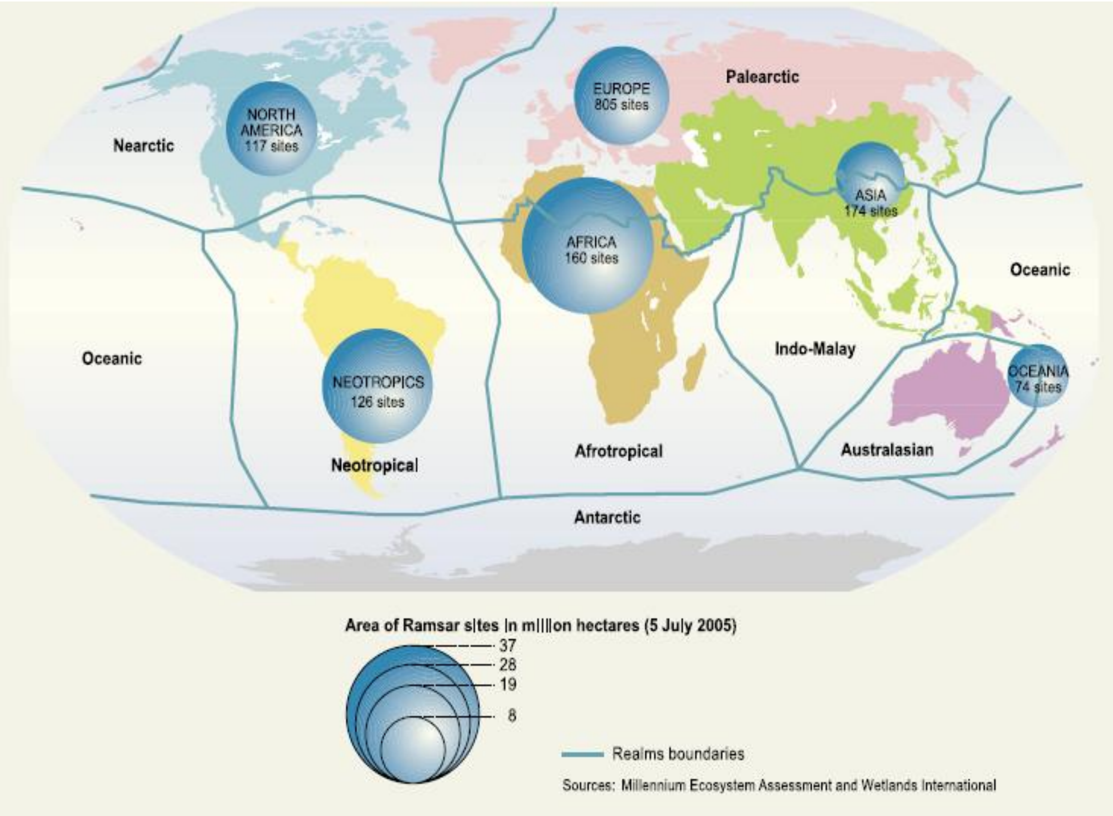


Figure 5.1: Global distribution of Ramsar sites as of July 2005 (Source: MEA, 2005)

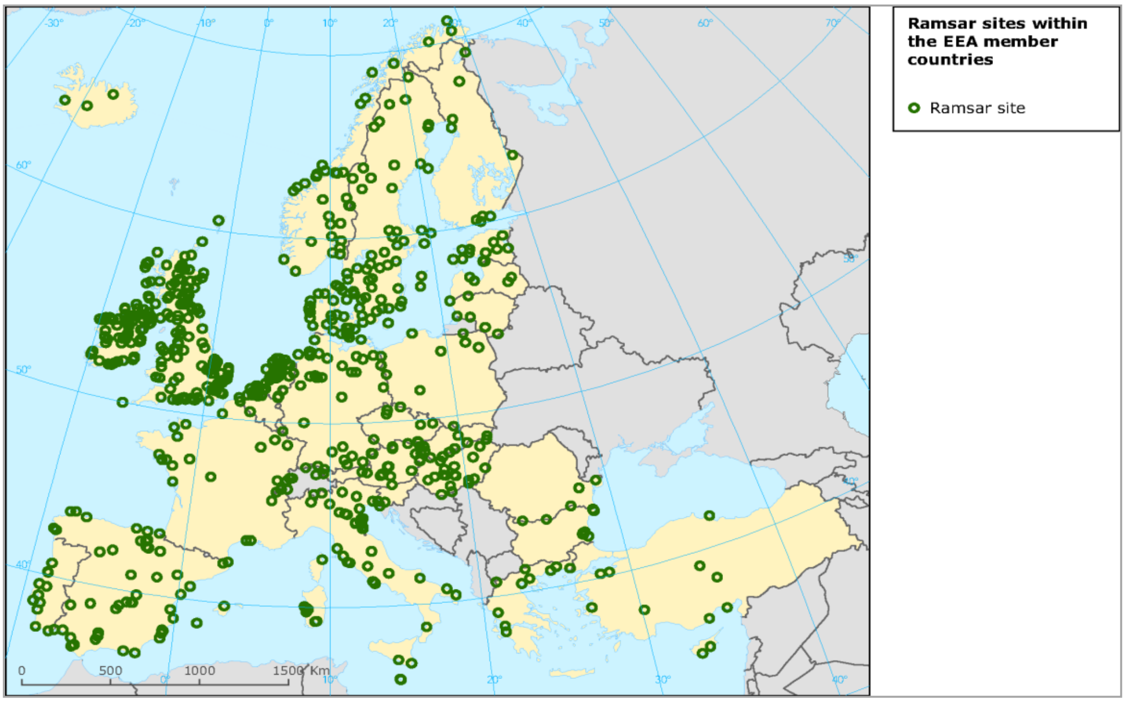


Figure 5.2: Ramsar sites within the EEA member countries (Source: EEA, 2004).

Wetlands are the only single group of ecosystems to have their own international convention. In 1975 the 'Convention on Wetlands of International Importance Especially as Waterfowl Habitat' (better known as the Ramsar Convention) came into force. As of December 2010 there are 160 contracting parties building from 38 signatories in 1985. Currently 1,906 wetland sites are listed under the Ramsar Convention, covering over 180M ha (Figure 5.1) with 798 Ramsar sites occurring in Europe (Ramsar, 2011) (Figure 5.2).

5.3.2 Wetland services

Wetlands provide an important subset of global ecosystem services (see Table 5.2 below). They supply a broad array of provisioning services, regulation services, cultural services and supporting services. Provisioning services include food sources provided by wetland flora and fauna such as fish (including shellfish), certain mammals, plants including rice, seaweed, as well as a range of leafy vegetables and nuts. Other food sources include reptiles, amphibians, insects and other arthropods, snails etc., (Jones, 2010). Fish and rice are by far the two most important wetland food sources. Wetlands also play a pivotal role in climate change mitigation and adaptation through the regulation services they offer. Peatlands, mangroves and salt marshes provide a significant function in climate change mitigation through their functioning as store or sinks of carbon. It is important to note that healthy wetlands lock up significantly more carbon compared to wetlands that have been drained or over harvested. Adaptive capacity can be greatly enhanced through healthy coastal wetlands. Coastal wetlands such as tidal flats, salt marshes and mangroves absorb a significant volume of the energy created from storm and tidal surges. The roots of wetland plants also act to stabilise shorelines and reduce erosion. In the pre-industrial era rising sea levels would result in coastal wetlands gradually moving inland. However, in recent times due to the significant coastal development of agriculture, cities, towns and industry, there is often nowhere for coastal wetlands to go. Thus, wetlands are squeezed into an ever narrowing fringe between developed coastal land and the sea (Doody, 2004; Nicholls and Mimura, 1998). The maintenance of wetland networks and corridors is vital in facilitating wetland-dependent flora and fauna in migrating to new areas in response to climate change stressors.

Cultural services provided by wetlands are numerous and range from religious significance and cultural heritage to wetland-based recreation and tourism. Religious practice has been linked to wetland sites for many thousands of years in some cases. Wetlands are of religious significance to people of many different faiths due primarily to their combination of outstanding natural beauty and their ability to supply the water vital for agriculture. Cultural heritage can often be captured through their ability to preserve remains of human civilisation. The study of pollen grains and other plant remains from wetlands can also provide a historical picture of vegetation and climates from thousands of years ago (Zedler and Kercher, 2005; O’Sullivan, 2007).

Supporting services provided by wetlands include sediment retention and nutrient storage, processing and recycling. Wetlands capture and store sediments and nutrients carried in rainwater runoff, streams and rivers. This wetland function generates continuous natural fertility for floodplains and deltas that provides communities with a means to grow crops. Wetlands also help to improve water quality by dissolving nitrates and phosphates from fertilisers and sewage effluent. These pollutants are taken up by wetland plants and stored in leaves, stems and roots (Zedler and Kercher, 2005).

Table 5.2: Ecosystem services provided or derived from wetlands (Source: MEA, 2005).

Ecosystem Services Provided Or Derived From Wetlands	
Services	**Examples**
PROVISIONING SERVICES	
Food	Production of fish, wild game, fruits and grains
Fresh Water	Storage and retention of water for domestic, industrial, and agricultural use
Fibre and Fuel	Production of logs, fuelwood, peat, and fodder
Biochemicals	Extraction of medicines and other materials from biota
Genetic Materials	Genes for resistance to plant pathogens, ornamental species, etc.
REGULATING SERVICES	
Climate Regulation	Source of and sink for greenhouse gases, influences local and regional temperature, precipitation and other climatic processes
Water Regulation (Hydrological Flows)	Groundwater recharge and discharge retention
Waste Purification and Waste Treatment	Retention, recovery, and removal of excess nutrients and other pollutants
Erosion Regulation	Retention of soils and sediments
Natural Hazard Regulation	Flood control and storm protection
Pollination	Habitat for pollinators
CULTURAL SERVICES	
Spiritual and Inspirational	Source of inspiration; many religions attach spiritual and religious values to aspects of wetland ecosystems
Recreational	Opportunities for recreational activities
Aesthetic	Source of beauty or aesthetic value in aspects of wetland ecosystems
Educational	Opportunities for formal and informal education and training
SUPPORTING SERVICES	
Soil Formation	Sediment retention and accumulation of organic matter
Nutrient Cycling	Storage, recycling, processing, and acquisition of nutrients

5.3.3 Valuation methodologies

Wetlands provide vital ecosystem services and provide an important contribution to human health and well-being. They are also incredibly vulnerable to the risks of degradation and drainage and development. Determining the Total Economic Value (TEV) relating to wetlands is a complex task as displayed in Figure 5.3. In order to calculate TEV one needs to employ a range of valuation methodologies within an integrated framework that considers the integration between both natural and social sciences (Turner *et al*., 2001). The figure below displays the relationship between wetland ecology and economic valuation. Wetland characteristics, structures and processes can be seen to link in with their uses in providing a range of goods, products and services. TEV relating to wetlands can then be determined from this range of goods, products and services through calculating direct use value, indirect use value and non-use values. Table 5.3 provides details on each of the valuation methodologies that can be used to determine TEV. The table also clarifies whether direct use, indirect use or non-use values are captured within the respective valuation methodologies. Direct use values are based on the actual use of a wetland good or service, such as fishing or bird watching. Indirect use values can take the form of a wetland input that helps to produce a product that people in turn use directly; wetland plants and small invertebrates may provide a food source (or indirect use value) to fish that are used directly by humans. Finally, non-use values relate to the value people ascribe to a particular wetland to maintain its existence. For example, an individual may be willing to pay to protect a salt marsh or coastal lagoon even if they never expect to visit the site (Barbier, 1993; Turner, 1991). Using a value transfer approach, i.e. an approach that uses existing economic valuation studies to generate per hectare values, a total economic value of €2.6B per year was estimated for 63M ha of wetland (Schuyt and Brander, 2004). The study calculated that wetlands in Asia have the highest economic value at €1.4B per year. This figure increases to €53B per year when the Ramsar estimated global area for wetlands, which stands at 1.28B ha, is used.

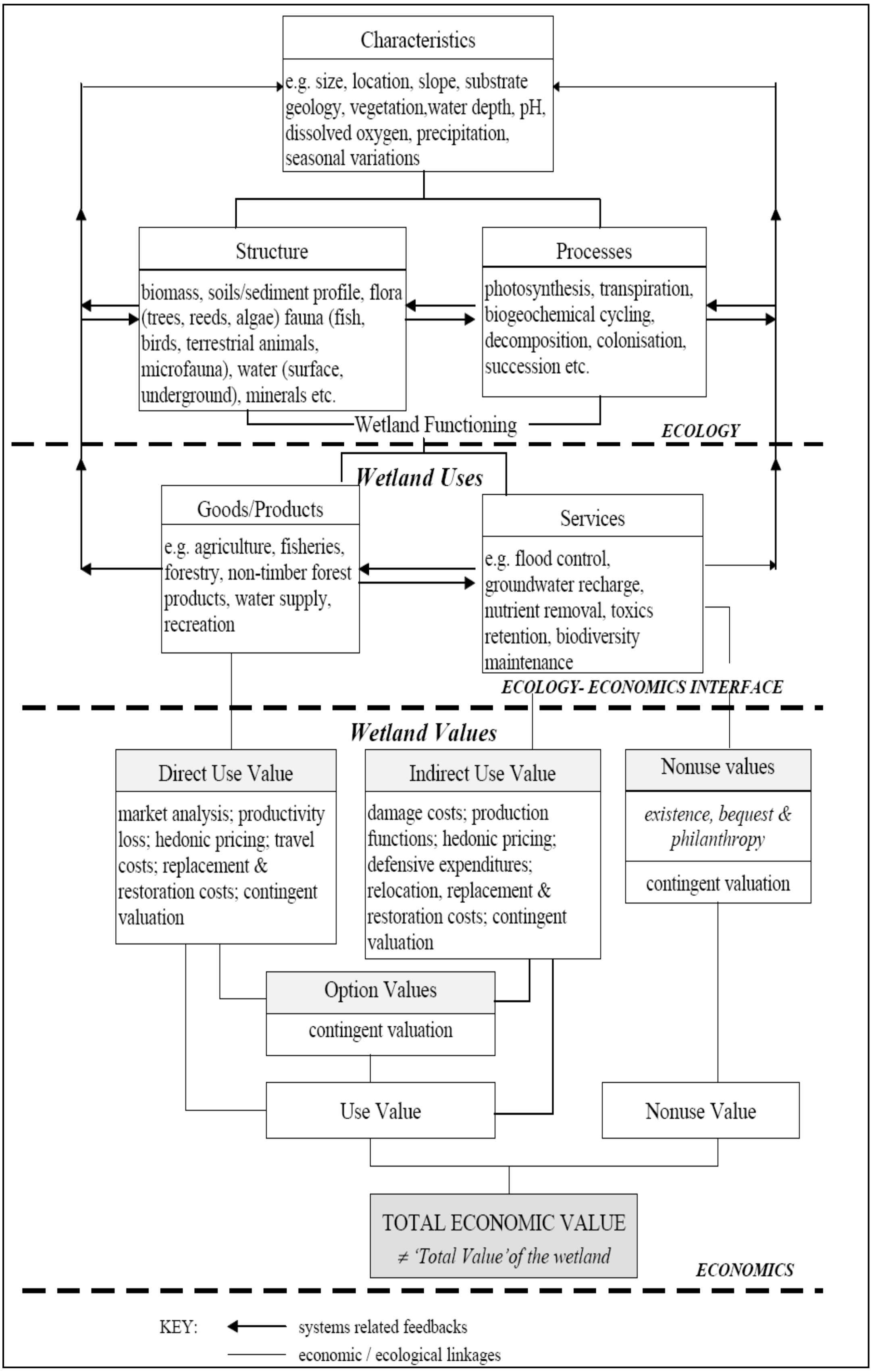


Figure 5.3: Wetland functions, uses and values (Source: Turner *et al.*, 2001).

Table 5.3: Valuation methodologies relating to wetland functions (Source: Turner *et al*., 1997).

Valuation Methodologies Relating To Wetland Functions				
Valuation Method	**Description**	**Direct Use Values**	**Indirect Use Values**	**Non-Use Values**
Market Analysis	*Where market prices of outputs (and inputs) are available. Marginal productivity net of human effort/cost. Could approximate with market price of close substitute. Requires shadow pricing.*	√	√	
Productivity Losses	*Change in net return from marketed goods: a form of (dose-response) market analysis.*	√	√	
Production Functions	*Wetlands treated as one input into the production of other goods: based on ecological linkages and market analysis.*		√	
Public Pricing	*Public investment, for instance via land purchase or monetary incentives, as a surrogate for market transactions.*	√	√	√
Hedonic Price Method (HPM)	*Derive an implicit price for an environmental good from analysis of goods for which markets exist and which incorporate particular environmental characteristics.*	√	√	
Travel Cost Method (TCM)	*Costs incurred in reaching a recreation site as a proxy for the value of recreation. Expenses differ between sites (or for the same site over time) with different environmental attributes.*	√	√	
Contingent Valuation Method (CVM)	*Construction of a hypothetical market by direct surveying of a sample of individuals and aggregation to encompass the relevant population. Problems of potential biases.*	√	√	√
Damage Costs Avoided	*The costs that would be incurred if the wetland function were not present; e.g. flood prevention.*		√	
Defensive Expenditures	*Costs incurred in mitigating the effects of reduced environmental quality. Represents a minimum value for the environmental function.*		√	
Relocation Costs	*Expenditures involved in relocation of affected agents or facilities: a particular form of defensive expenditure.*		√	
Replacement/ Substitute Costs	*Potential expenditures incurred in replacing the function that is lost; for instance by the use of substitute facilities or 'shadow projects'.*	√	√	√
Restoration Costs	*Costs of returning the degraded wetland to its original state. A total value approach; important ecological and cultural dimensions*	√	√	√

5.3.4 Wetland vulnerabilities

The primary drivers for global wetland loss and degradation relate to infrastructural development (including dams, dikes and levees), pollution, land conversion, water withdrawals, overharvesting and the introduction of invasive alien species (Gitay *et al*., 2011; Millennium Ecosystem Assessment, 2005). Global climate change and nutrient loading are projected to be of increasing importance in the next 50 years. The construction of dams and other infrastructure along with the withdrawal of water for use in agriculture, industry, and households has changed sediment and nutrient flow, altered habitats, and disrupted the migration routes of aquatic biota such as salmon (Zedler and Kercher, 2005; Millennium Ecosystem Assessment, 2005). Development-related conversion of coastal ecosystems is the greatest direct threat to coastal wetlands, which in turn leads to significant losses of habitats and services. The primary indirect drivers of wetland loss or degradation have been human population growth in coastal areas along with growing economic activity (Nicholls *et al*., 1999). Human population pressures lead to the conversion of coastal wetlands as a result of urban and suburban expansion.

More than 50% of wetlands in parts of North America, Europe, Australia and New Zealand were converted during the 20^{th} century (Millennium Ecosystem Assessment, 2005). Loss and degradation associated with inland wetlands have been reported in many parts of the world. However, there are few reliable quantitative estimates of the actual extent of this loss. It is well established that coastal ecosystems are experiencing degradation and loss globally. 35% of mangrove forests have disappeared in the twenty-year period between 1980 and 2000 (Valiela *et al*., 2001). 20% of coral reefs have been lost and an additional 20% have been degraded in the last several decades of the 20^{th} century (Bellwood *et al*., 2004). Destructive fishing practices and siltation are two of the major culprits of this degradation. Research over the past 40 years has established excessive nutrient loading as one of the most important direct drivers of ecosystem change in inland and coastal wetlands (Millennium Ecosystem Assessment, 2005).

Climate change is expected to be an additional driver of wetland loss and degradation. Coastal wetlands will undergo additional stresses and loss as a result of projected sea-level rise, increased storm and tidal surges, changes in storm intensity and frequency, and the resulting changes in river flow regimes and sediment transport. By the 2080s SLR could cause up to 22% of coastal wetlands to be lost. When combined with additional losses as a result of human action, up to 70% of the world's coastal wetlands could be lost by the 2080s (Nicholls *et al*., 1999).

5.4 WETLANDS AND CLIMATE CHANGE IN AN IRISH CONTEXT

5.4.1 Irish wetland profile

Ireland has a high volume of wetlands per hectare of surface area (Table 5.3). There are a number of contributing factors that have created such an abundance of wetlands on this island. Firstly, on average more water falls as precipitation than is lost through evapotranspiration, which is a precondition in the formation of wetlands where water levels are maintained at or just below the soil surface (Otte, 2003). Secondly, Ireland's geomorphology is favourable for wetland formation. Ireland is exceptional compared to many other islands as the central parts of the country are, on average, at a lower elevation than peripheral areas. This 'saucer shape' causes many streams and rivers to initially flow inland rather than straight out to sea. This in turn leads to an abundance of wetlands, such as bogs, fens and callows, in the central parts of Ireland. Thirdly, after the last glacial period, some 12,000 years ago, extensive deposits of glacial drift occurred, especially in the northern half of the island. This led to the creation of many poorly drained pockets of land which resulted in the formation of wetland areas (Murray, 1996; Mitchell & Ryan, 1997). Finally, due to a number of prominent bays and estuaries including Cork Harbour, Clew Bay, the Wexford Slobs and Galway Bay along with Ireland's extensive coastline, particularly the undulating western coast, there are a significant number of salt marshes, mud flats and coastal lagoons (Curtis, 2003; Otte, 2003).

Wetlands cover over 1.1M ha of the surface area of the Irish Republic out of the total land area of 7.1M ha (Table 5.4). Together they make up over 16% of the Irish land area. Of this 1.1M ha close to 94% of it is made up of peat bogs; both raised and blanket bogs (Table 5.5.).

Table 5.4: Land surface areas in Ireland (Source: EPA/EEA, 2010).

Surface Areas In Ireland		
Type	**Area (ha)**	**Percentage**
Artificial fabric	162,314.62	02.28
Agricultural areas	4,729,064.43	66.40
Wetlands	1,169,225.00	16.40
Forest and semi-natural areas	899,972.50	12.64
Water bodies	161,689.90	02.27
Total	7,122,267.00	100.00

Table 5.5: Wetland areas in Ireland (Source: EPA/EEA, 2010)

Wetland Areas In Ireland		
Type	**Area (ha)**	**Percentage**
Inland marshes	16,389.21	1.40
Peat bogs	1,094,436.00	93.60
Salt marshes	4,839.38	0.41
Intertidal flats	53,560.85	4.58
Total	1,169,225.44	100.00

The remaining 6% consists of the general categories of intertidal flats (4.58%), inland marshes (1.4%) and salt marshes (0.41%). Figure 5.4 displays the distribution of Irish wetlands under these four subgroups. In fact, Ireland has many other wetland subgroups including marshes, bogs, fens, turloughs, swamps, salt marshes, machair, estuaries, lagoons and wet woodland carr (Table 5.6).

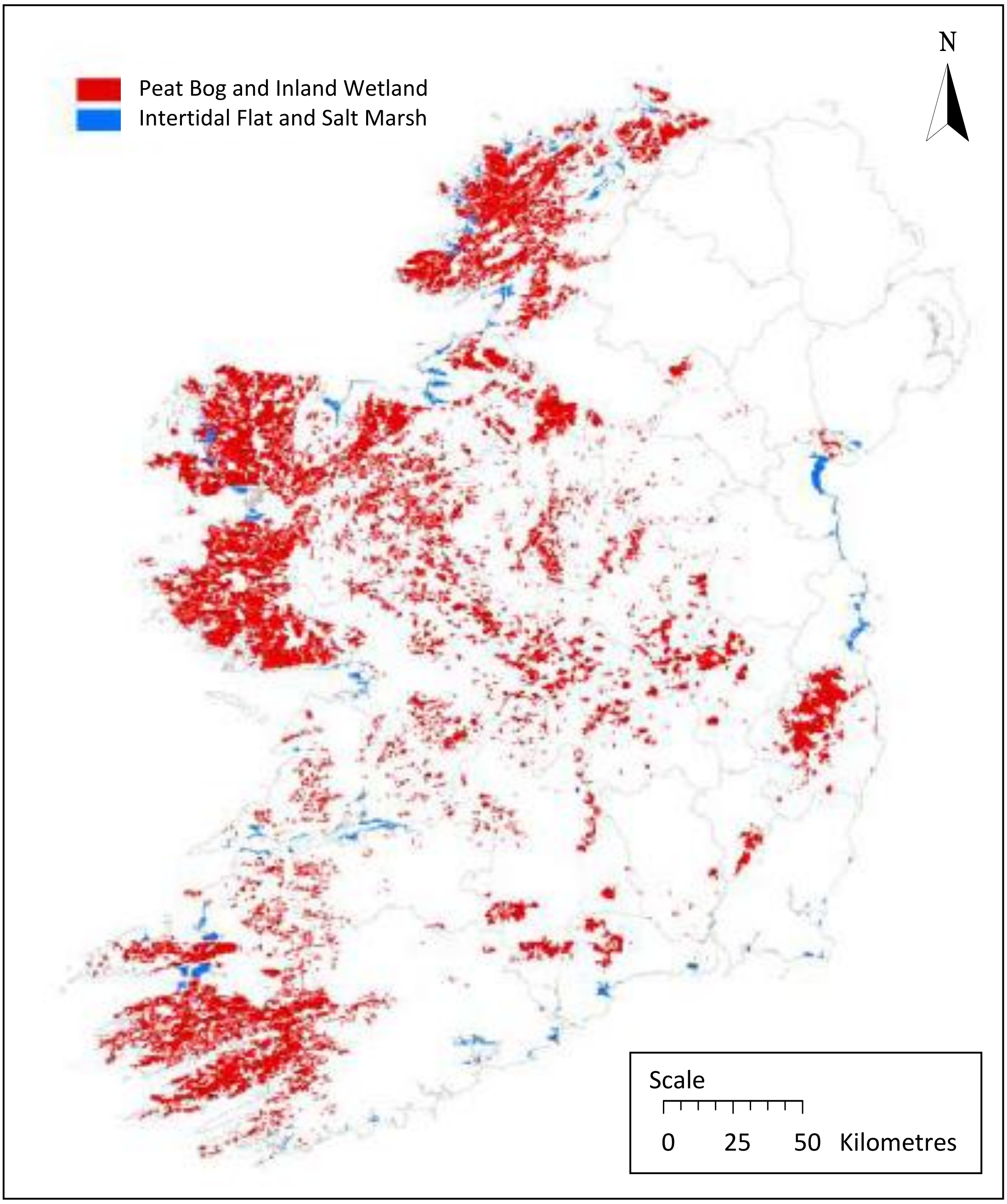


Figure 5.4: Irish wetlands (Source: CORINE, 2010).

Table 5.6: Irish wetland subgroups.

Irish Wetland Subgroups
Machairs are flat or gently sloping sand plains that develop on calcareous sand, with a mixture of sand dune, grassland and wetland species
Marsh is comprised of water-logged mineral soil in which water levels seldom rise above the surface at any time of the year.
Bog is permanently wet peat, resulting from a high water table and/or high rainfall in acid conditions. Bog vegetation is dominated by bog mosses.
Fens are permanently wet peat that lacks extreme acidity due to the presence of alkaline groundwater.
Turloughs are wet meadows that flood seasonally due to a high water table and contain a high diversity of flora. Turloughs are common in the west of Ireland.
Lagoons are bodies of standing brackish water, partially or wholly separated from the sea by banks of sand, shingle or rock or by land barriers of peat or rock.
Salt marshes are divided into upper and lower salt marsh types. They consist of stands of vegetation that occur in marine and brackish water conditions.
Estuaries are areas where rivers meet the sea. Sediment carried down rivers interacts with the saltwater and falls out of suspension forming mudflats.
Wet woodland (Carr) can be broken down into four main types in Ireland; bog woodland, wet oak penduncculate, riparian woodland and wet willow-alder-ash.
Dunes comprise mostly of glacial sediment deposited from the sea and shaped by winds and tidal forces.
Intertidal flats or mud flats are non-vegetated, soft sediment habitats that normally occur in low energy marine environments such as estuaries.

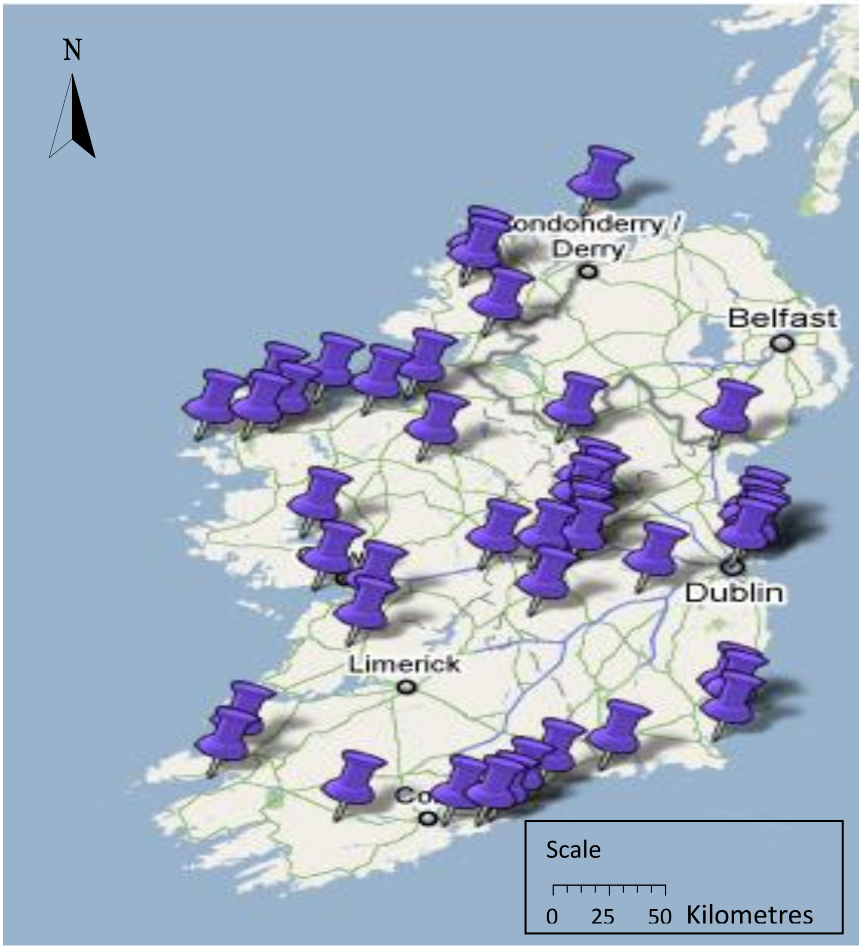


Figure 5.5: Ramsar sites in Ireland (Ramsar website).

Ireland is a signatory to the Ramsar Convention and there are currently 45 Ramsar sites in the country covering 66,994ha of land (Figure 5.5). There are seven coastal Ramsar sites in Ireland. They are located at Rogerstown Estuary (north County Dublin, Leinster), Castlemaine Harbour (County Kerry, Munster), Baldoyle Estuary (north County Dublin, Leinster), Tralee Bay (County Kerry, Munster), North Bull Island (County Dublin, Leinster), Raven Nature Reserve (County Wexford, Leinster), Wexford Wildfowl Reserve (County Wexford, Leinster).

Plants provide most of the structure of wetlands through providing shade, shelter, nutrients and organic matter. They can be submerged, floating or a hybrid between the two. Wetland plants have a common feature to help cope with the paucity of oxygen in their water dominated environment; the majority have a network of cells separated by air spaces. See Table 5.7 below for a list of Irish wetland flora.

Table 5.7: A selection of Irish wetland flora (various sources).

Wetland Flora		
Water Lilly	Sea Milkwart	Sand Couch
Yellow Flag Iris	Sea Beet	Lyme-grass
Reedmace	Sea Pea	Sea Rocket
Ladies Smock	Oysterplant	Saltwort
Ragged Robin	Baltic Stonewart	Sea Sandwort
Sea Mayweed	Foxtail Stonewart	Sand Sedge
Curled Dock	Bearded Stonewart	Ragwort
Perennial Glasswort	Borrer's Saltmarsh Grass	Round-leaved Wintergreen
Cottonweed	Bird's Foot	Spring Vetch
Lesser Centaury	Golden Dock	Sea Spurge
Helleborine	Marram	Sea Holly
Cat's Ear	Red Fescue	Creeping Bent
Spotted Orchid	Pyramid Orchid	Cord-grass
Thrift	Ribwort/Sea Plantain	Marsh/Sea Arrowgrass
Sea Aster	Sea-purslane	Lax-flowered Sea Lavender
Rushes	Common Scurvygrass	Lesser Hawkbit
Parsley Water-dropwort	Daisy	Lady's Bedstraw
White Clover		

Table 5.8: A selection of wetland fauna present in Irish wetlands (after Pender, 2010).

Wetland Fauna				
Birds	**Invertebrates**	**Butterflies and Moths**	**Mammals**	**Amphibians**
Mallard Duck	Small Bluetail Dragonfly	Orange-tip Butterfly	Otter	Smooth Newt
Tufted Duck	Damselflies	Marsh Fritillary	Bats	Common Frog
Mute Swans	Whirligig Beetle	Green-veined White	Brown Rat	Natterjack Toad
Moorhen	Ladybird	Small Elephant Hawk-moth	American Mink	
Coot	Crayfish	China-mark Moths		
Grey Heron	Flea Beetle	Eyed Hawk-moth		
Little Egret	Caddis Fly	Gatekeeper Butterfly		
Curlew	Leeches	Dark Green Fritillary Butterfly		
Snipe	Water Cricket	Grayling Butterfly		
Lapwing	Water Measurer	Wall Butterfly		
Brent Goose	May Fly	Small Heath Butterfly		
Sand Martin	Water Boatmen			
Swallow	Back Swimmers			
Dipper	Red-legged Moss Beetle			
Grey Wagtail	Breeched Water Beetle			
Kingfisher	Spattered Diver Water Beetle			
Bewick's Swan	Marine Moss Beetle			
Red-necked Pharlarope	Orangeman Water Beetle			

Table 5.8 above lists birds, invertebrates, butterflies and moths, mammals and amphibians found in Irish wetlands. The most common species of bird to be found in Irish wetlands are ducks including mallards, the tufted duck along with swans. Invertebrates (animals without a backbone) play a crucial role in wetlands by breaking down organic matter, pollinating plants and providing a food source to other fauna. There are 37 species of butterfly in Ireland, with 23 species found commonly in wetland habitats. Amphibians rely on wetlands as their key habitat and are therefore particularly vulnerable to the impacts of wetland loss and degradation.

5.4.2 Salt marshes

Salt marshes are wetlands which are fully or partially inundated twice a day by the sea. The extent of this inundation is a function of the stage in the tidal cycle and the location of any specific area of the marsh in relation to the reach of a particular tide (Curtis, 2003). The variation in tidal reach determines plant and animal distribution on any given salt marsh as the inundation period is greatest lower down the marsh, while the higher areas experience less inundation (Curtis, 2003). The aforementioned heavily indented Atlantic coastline has a broad topography that allows for considerable salt marsh development to take place. Of Ireland's (including Northern Ireland's) 250 salt marsh sites some 36% of them occur along the west coast (Figure 5.6) (Curtis and Sheehy Skeffington, 1998). Salt marshes in Ireland fall into one of five possible types; those that occur at estuaries, those found in sheltered bays, those found alongside dune systems, those occurring along the edge of lagoons and those which overlie peat substrates. There are over 16 families, with 64 individual species, of vascular plants found in Irish salt marshes (Tutin *et al*., 1993). The arguments for the conservation of salt marshes are numerous. They offer a valuable range of ecosystem services as unique sites for scientific research, as a genetic resource, as important feeding grounds for birds and a range of other fauna and flora, in their modest use for sewage treatment, through their importance as a grazing resource and in their role in coastal defence.

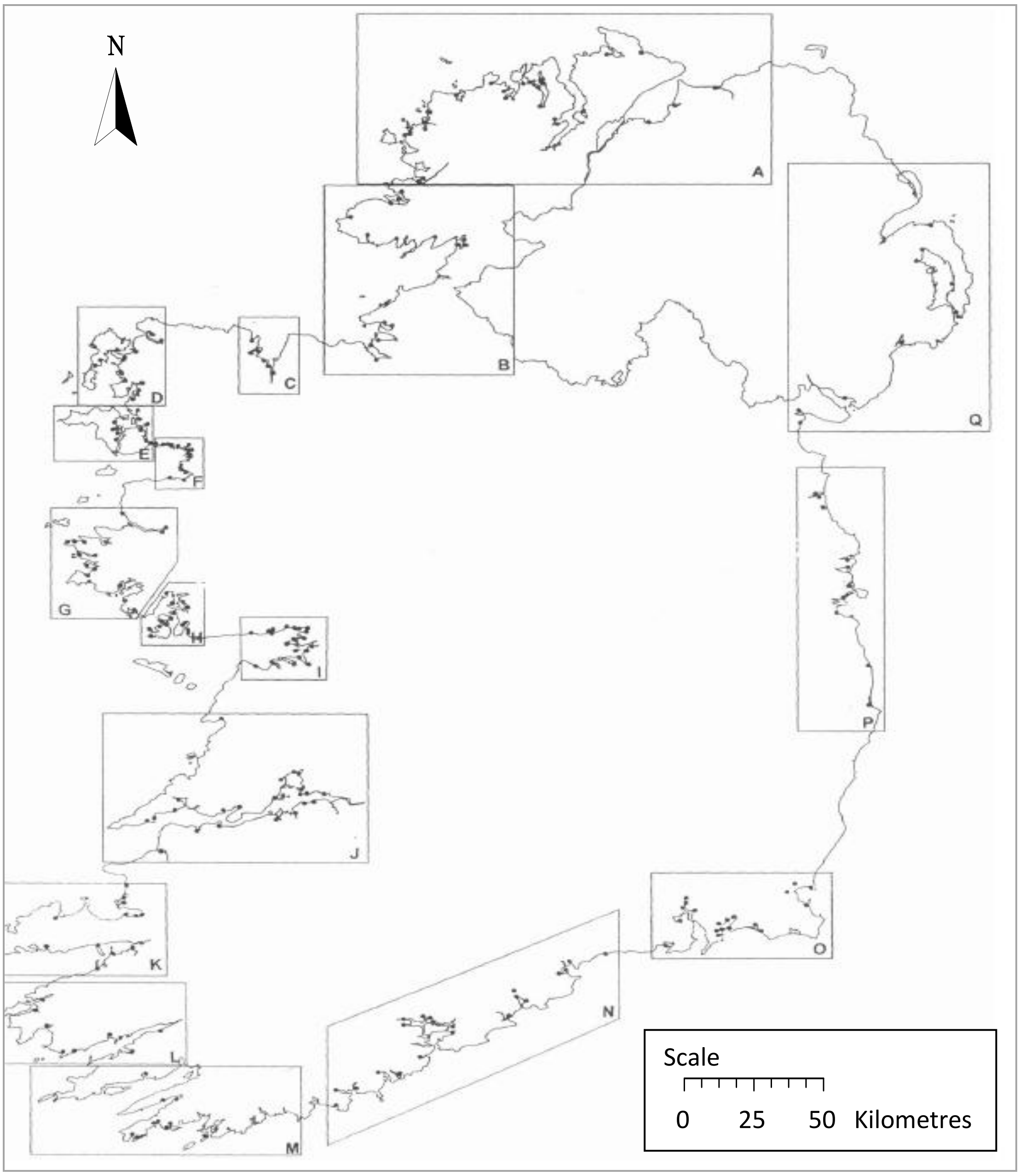


Figure 5.6: Salt marsh sites in Ireland (Source: Curtis, 1998).

5.4.3 Coastal lagoons

Coastal lagoons (in the European context) are saline coastal lakes or enclosed bays. They experience a restricted tidal range and contain brackish water along with the associated brackish flora and fauna. Surveying has revealed that there are approximately 103 sites along the Irish coastline that have lagoonal biota making up 2,500ha of land (Healy, 2003). Three quarters of Irish lagoons are less than 50ha in area and only seven exceed 100ha. Figure 5.7 maps out 60 known Irish coastal lagoon sites. The four broad lagoon types are sedimentary, rock, saline lake, and artificial. The barriers that go to create sedimentary lagoons are derived primarily from offshore deposits and dunes of wind-blown sand. These sedimentary barriers are often dynamic formations that are constantly changing and are subject to storm damage (Healy, 2003). The offshore deposits are made up from course material that has its origin in glacial deposits from the seabed that have been washed ashore since the last ice age. The supply of this glacial material has been diminishing on Irish coasts with the result that barriers are no longer building but are transgressive as they move slowly landwards (Carter, 1992). This shortage of deposits is leading to many of the coastal erosion problems affecting many parts of our coastline (Carter and Johnston, 1982). This type of lagoon is also particularly vulnerable to human activity as the barrier material is often removed for commercial use. Rock forms make up the natural barriers of rock lagoons such as karst lagoons found in Clare and Galway. Rocky seashores create another type of rock barrier and are most likely to occur on wave-beaten coasts. Saline lake lagoons are naturally occurring brackish lakes which are separated from the sea by a strip of land made up of peat or earth. They receive sea water through their natural outlets. Artificial lagoons are created where man-made barriers such as sea walls, railway lines or roads are constructed. Most artificial lagoons have an outlet in the form of a bridged or culverted channel. There are 8 families and over 30 plant species to be found in Irish coastal lagoons. Coastal lagoons are often neglected habitats in Ireland. Research into the ecological range of brackish species found in them is still far from complete. They offer significant opportunities for scientific research, environmental education as well as aiding in coastal defence.

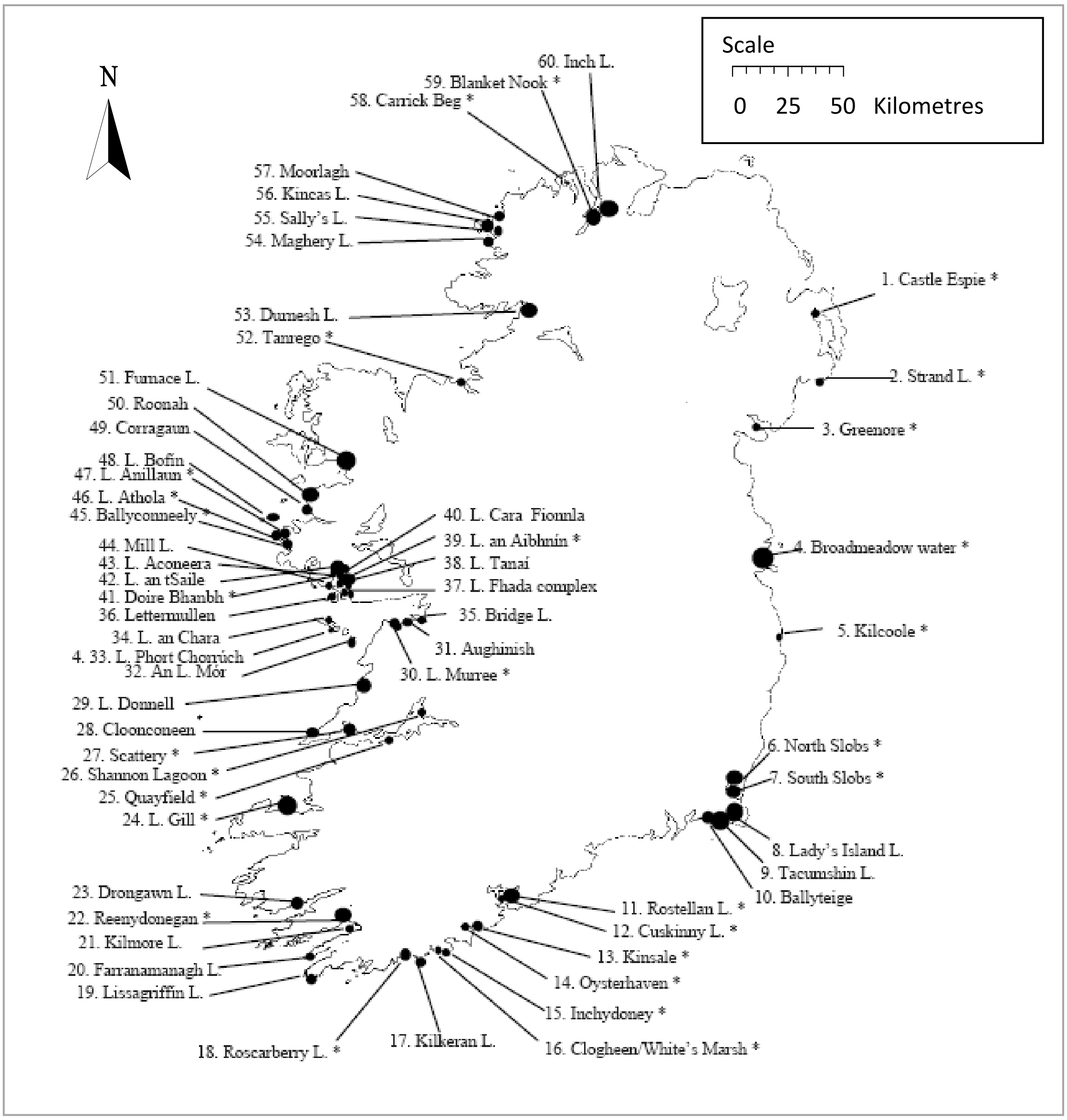


Figure 5.7: Coastal lagoon sites in Ireland (Source: Oliver, 2005).

5.4.4 Dunes and machairs

Sand dunes cover approximately 14,300ha of land in Ireland (Doody, 2008) and comprise of around 45 distinct sites (Table 5.9. and Figure 5.8.) (Curtis, 1991). Irish dunes comprise mostly of glacial sediment deposited from the sea and shaped by winds and tidal forces over the last 5,000 years. Dunes can form in close to the shore as sand splits or sand bars or in hindshore systems such as machairs (Crawford *et al*., 1998). Machairs are areas of level, stable coastal dune grassland over calcareous[25] soils

[25] Soils mostly or partly composed of calcium carbonate

(Bassett and Curtis, 1985). They are found on the north and west coasts of Ireland. Machairs are highly specialised habitats that are globally confined to the coasts of Ireland and Scotland (Gaynor, 2006) They are often grazed by cattle and sheep and provide important habitats for several endangered species including the corncrake and red-necked phalarope. These unique coastal wetlands are designated as priority habitats under the EU Habitats Directive (European Council, 1992). Both dunes and machairs provide habitats for over 50 species of flora as well as birds and other fauna. Sand dune and machair systems are degraded and lost due to coastal erosion and are under risk from potential future sea-level rise. They also face significant threats arising from development into golf courses, holiday homes, caravan parks and sand quarries.

Table 5.9: Irish sand dune and machair sites (Source: Doody, 2008).

Irish Sand Dune and Machair Sites			
Site Name	**Area (ha)**	**Site Name**	**Area (ha)**
01. Doagh Isle Machair	440	24. Inishkea North Machair	150
02. Lough Nagreany Dunes	130	25. Dooaghtry Machair	500
03. Melmore Machair	200	26. Mannin Bay Machair	500
04. Tranarossan Machair	200	27. Aillebrack Machair	300
05. Rosapenna Dunes	300	28. Dog’s Bay Machair	150
06. Rinclevan Dunes	400	29. Mweenish Island Machair	150
07. Dooey Dunes	150	30. Eararna Dunes	300
08. Lunniagh Machair	135	31. Inishmaan Machair	300
09. Derrybeg Machair	140	32. Ballyheige Dunes	250
10. Carnboy Machair	100	33. Castlegregory Dunes	350
11. Kincaslough Machair	100	34. Inch Dunes	1,250
12. Cruit Lower Machair	280	35. Lough Yganavan	180
13. Lettermacaward Machair	150	36. Rossbehy Dunes	500
14. Sheskinmore Dunes	600	37. Castle Freke Dunes	200
15.Mullanasole Dunes	350	38. Tramore Dunes	300
16. Finner Dunes	350	39. Ballyteige Burrow Dunes	440
17. Bunduff Machair	150	40. Mizen Head Dunes	150
18. Streedagh Point Dunes	160	41. North Bull Dunes	650
19. Inishcrone Dunes	100	42. Malahide Island Dunes	150
20. Bartragh Isd. Dunes	400	43. Batray Dunes	150
21. Garter Hill Machair	320	44. Murlough Dunes	-
22. Termoncarragh Lough	150	45. Magilligan Dunes	1,200
23. Cross Lough Machair	280		

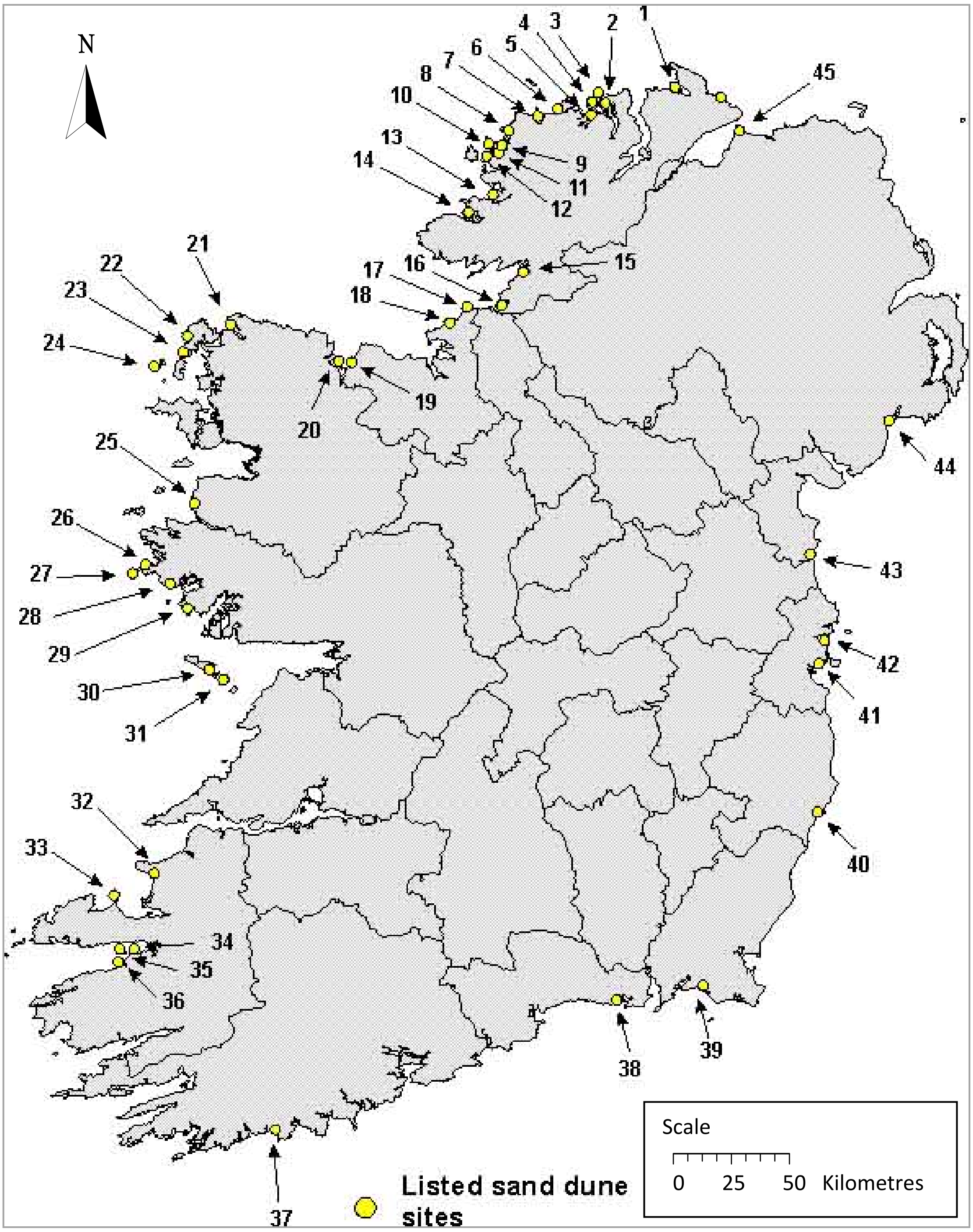


Figure 5.8: Sand dune (including machair) sites in Ireland (Source: Doody, 2008).

5.5 CONCLUSIONS

The critical economic importance of ecosystems, along with the subgroup of coastal wetlands is evident. They provide a wide range of goods and services including erosion regulation, nutrient cycling, and recreation. They are also home to many unique species of flora and fauna. This chapter presents a range of economic valuation methodologies for capturing the economic value of wetlands. Despite the complexity and clear limitations of economic valuation, it can arguably provide policy makers with a metric to asses the "value" of specific wetland sites, and hence incentivise their protection.

Coastal wetlands face severe threats due to development, pollution, the introduction of invasive species, and coastal erosion, along with climate change impacts. This chapter presents the most complete documented geographical distributions of a number of highly valuable and unique Irish coastal wetlands, including salt marshes, coastal lagoons, dunes and machairs. It also catalogues the large number of flora and fauna that are often unique to these habitats. The following chapter analyses the economic costs which may accrue should these ecosystems prove vulnerable to climate change induced SLR.

CHAPTER 6
ECONOMIC COSTS RELATING TO WETLAND VULNERABILITY IN IRELAND

6.1 INTRODUCTION

The assessment of coastal economic impacts associated with wetlands can be approached from either an "end point" or "starting point" interpretation of vulnerability. Under current climate conditions Irish coastal wetlands can be considered at risk due to environmental factors such as coastal erosion, as well as human-related factors such as coastal development and sediment removal; factors considered under a "starting point" interpretation. These valuable ecosystems are also at risk from projected future climate impacts such as SLR; looking at an "end point" interpretation. The modelling analysis carried out in this section focuses on the "end point" concept of vulnerability by exploring SLR scenarios associated with climate impacts, and examining associated potential vulnerable species in addition to wetland loss and estimated economic value.

6.2 METHODOLOGY AND DATASETS

The CORINE dataset is used to provide a record of wetlands in Ireland. Sea-level rise vulnerability modelling was again carried out for the Irish coast using a medium resolution Digital Terrain Model (DTM)[26] and three SLR scenarios of 0.5m, 1m and 2m. A meta-analysis study of wetland valuations was used to determine the TEV relating to one hectare of wetland by Brander *et al.* (2006). A range of valuation methodologies including direct use, indirect use and non-use values were used, as discussed in section 5.3.3 above. Values were found to vary considerably between

[26] Irish 20 metre medium scale resolution digital terrain model produced by the Irish Environmental Protection Agency.

studies highlighting both the complexity of the task and the problematic nature of attributing an economic value to an ecosystem that provides a myriad of goods and services and is not highly substitutable in nature. A direct value transfer method was used to capture order of magnitude costs (Brander *et al*., 2006). The direct value transfer method involves transferring the values determined from primary wetland valuation studies to the wetland site in question. This method holds the advantage of avoiding the time consuming and expensive primary valuation studies but due to its generalised nature, the valuations are subject to error. Average wetland values are highest in Europe, followed by North America, Australasia, Africa, Asia, and South America (Figure 6.1). Values also vary depending on wetland type; unvegetated sediment has the highest average value of just over €6,700ha^{-1} yr^{-1} and mangroves the lowest at €300ha^{-1} yr^{-1}. Studies also showed that the contingent valuation method (CVM) produced the highest estimates of wetland value followed by replacement cost method and hedonic pricing, with the lowest valuations coming from opportunity cost and production function methods (Brander *et al*., 2006).

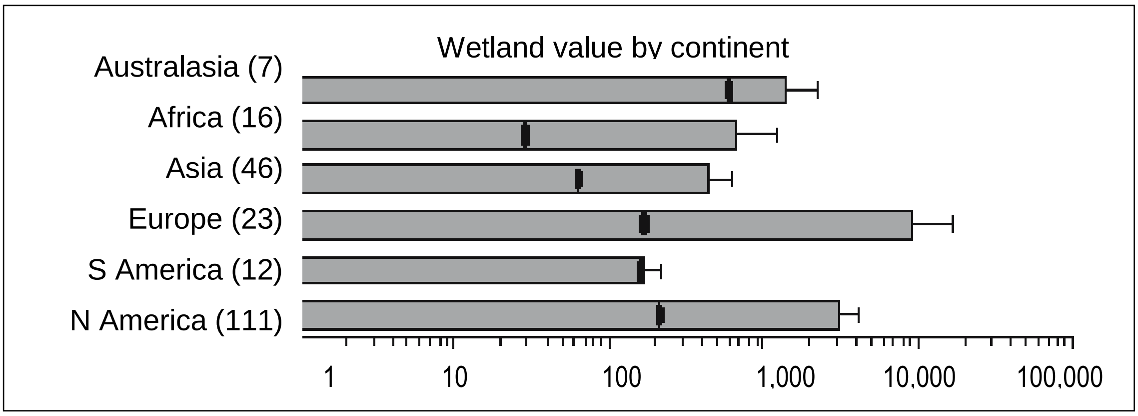


Figure 6.1: Wetland value by continent (1995 US$ ha^{-1} yr^{-1}). The number of observations is in parenthesis. The bars represent the means, the error bars represent the standard error of the mean, and the black dots represent the medians (Source: Brander *et al*., 2006).

6.3 RESULTS AND ANALYSIS

The following case study analyses the potential economic impact of three sea-level rise scenarios (0.5m, 1m and 2m) on three Irish coastal wetland systems. Beaches, dunes and sand wetlands (including machair) are analysed along with coastal lagoons and salt marshes using the CORINE 2006 dataset. It must be noted that the distribution of these wetland sub-groups as provided by the CORINE 2006 dataset is not as comprehensive as the distribution maps presented in the previous chapter, and this is reflected in the analysis that follows. Figures 6.2-6.7 show the distribution of each of the wetland subgroups, with Tables 6.1-6.4 displaying the vulnerable percentage loss and land area of each under the three scenarios.

Table 6.1: Vulnerable beaches, dunes and sand (including machair) under three SLR scenarios.

Beaches, Dunes and Sand (Including Machair)						
Scenario	0.5m	1m	2m	0.5m	1m	2m
County	**% potential loss in each County**			**Potentially impacted Area (ha)**		
Cork	15	21	25	12	17	20
Clare	10	14	18	11	16	20
Dublin	84	93	94	124	138	139
Waterford	35	37	38	62	65	67
Wicklow	9	13	19	18	26	38
Galway	14	20	27	80	115	155
Sligo	5	8	11	41	65	90
Wexford	32	40	47	337	422	495
Kerry	7	11	15	95	149	203
Mayo	7	11	14	172	270	343
Donegal	5	7	10	197	275	393
Total				**1,149**	**1,558**	**1,963**

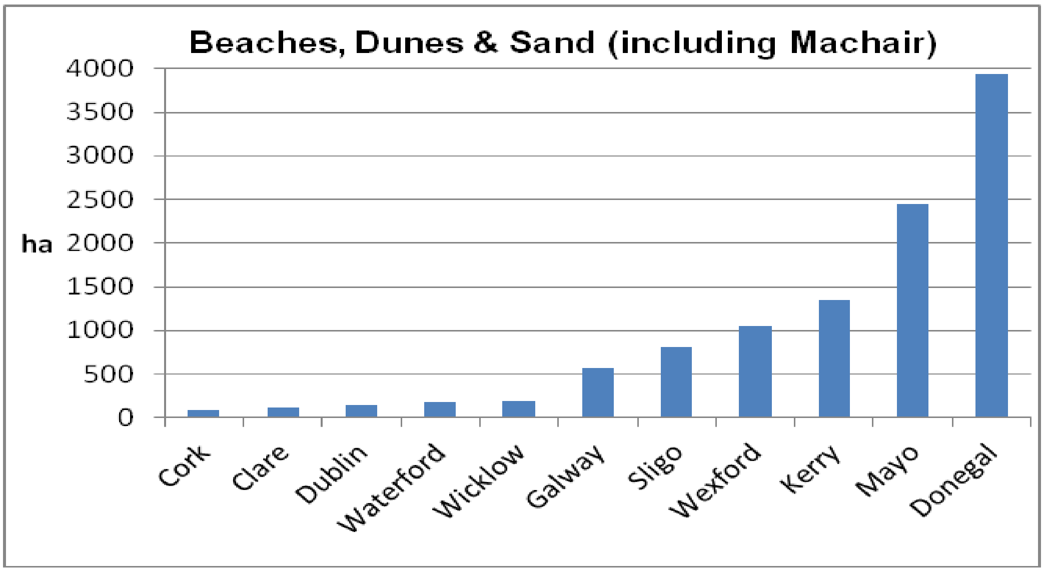


Figure 6.2: Area of beaches, dunes and sand including machair in Irish coastal counties.

Figure 6.3: Distribution of beaches, dunes and sand (including machairs).

Figures 6.2 and 6.3 show the national distribution of beaches, dunes and sand (including machairs) using the 2006 CORINE dataset. It should be noted that while this dataset accounts for the majority of the wetland areas for subgroups covered in this analysis it does not provide as complete an inventory as that provided in Chapter 5. The majority of beaches, dunes and sand (including machairs) can be found on the west coast with the exception of those in county Wexford. The SLR modelling shows that the most vulnerable of these coastal wetlands can be found in Dublin, Waterford and Wexford (Table 6.1). Dublin is at greatest risk in losing its Bull Island wetland (150ha). Increased SLR can lead to significant possible losses of over 80% for a 0.5 m rise and up to 90% for a 2 m rise. However, due to the much greater area of Wexford's coastal beaches, dunes and sand, about 1,000ha, its possible losses at approximately 40% for a 1m SLR will lead to the greatest loss of this wetland type in the country, with no additional coastal protection measures put in place.

Figure 6.4: Distribution of coastal lagoons.

Table 6.2: Vulnerable coastal lagoons under three SLR scenarios.

Coastal Lagoons						
Scenario	0.5m	1m	2m	0.5m	1m	2m
County	**% potential loss in each County**			**Potentially impacted area (ha)**		
Wicklow	90	92	94	38	39	39
Cork	20	22	22	23	25	25
Kerry	7	9	9	9	11	11
Galway	17	20	22	42	50	55
Wexford	95	95	95	278	278	278
Total				**390**	**403**	**408**

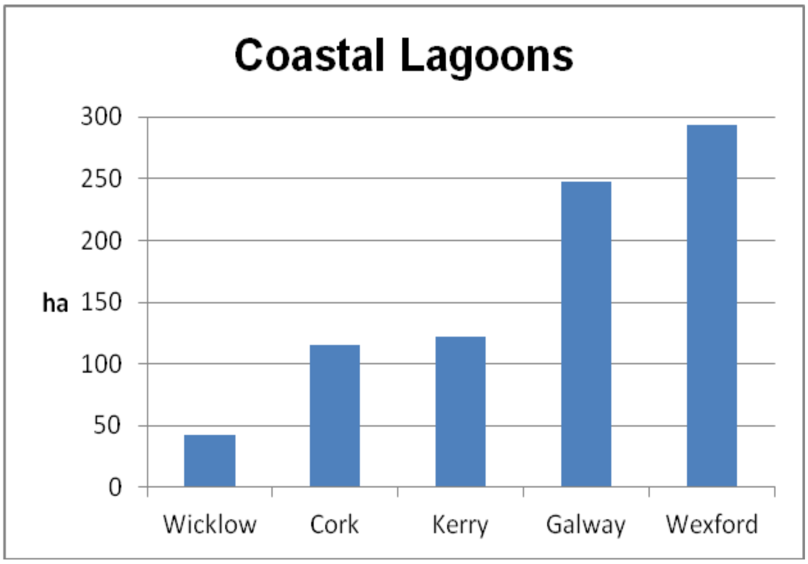


Figure 6.5: Area of coastal lagoons in Irish coastal counties.

Figures 6.4 and 6.5 show the distribution of coastal lagoons on Irish coasts. Coastal lagoons are relatively rare in Ireland and are only recorded in five coastal counties. The coastal lagoons of Wicklow (42ha) and Wexford (293ha) are at the greatest risk from SLR with possible losses of over 90% for a 1m SLR scenario (Table 6.2).

Figure 6.6: Distribution of salt marshes.

Table 6.3: Vulnerable salt marshes under three SLR scenarios.

Salt Marshes						
Scenario	0.5m	1m	2m	0.5m	1m	2m
County	**% potential loss in each county**			**Potentially impacted Area (ha)**		
Kilkenny	22	34	44	6	9	11
Waterford	35	54	68	29	45	57
Sligo	21	31	40	23	33	43
Wicklow	38	60	83	68	108	149
Limerick	26	27	28	51	53	55
Donegal	25	37	44	56	82	98
Galway	27	34	39	75	95	109
Dublin	45	52	57	149	173	189
Cork	31	40	49	131	168	206
Louth	28	29	29	133	138	138
Wexford	12	15	19	62	78	98
Kerry	23	32	40	175	244	305
Clare	24	31	36	313	404	469
Total				**1,271**	**1,630**	**1,927**

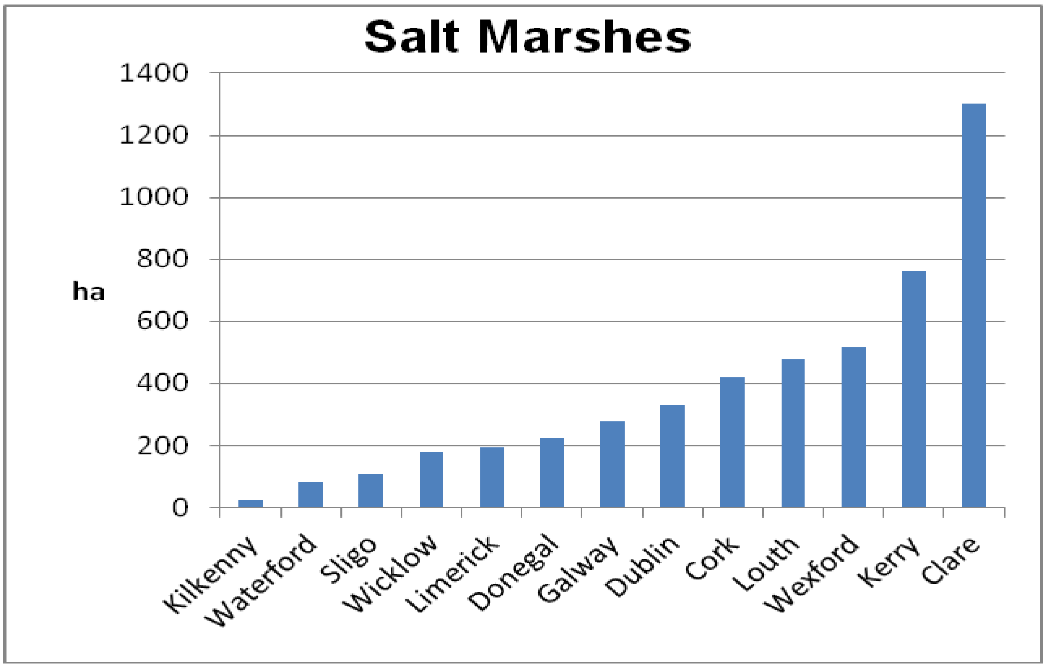


Figure 6.7: Area of salt marshes in Irish coastal counties.

Figures 6.6 and 6.7 detail Irish salt marsh distribution. They can be found in thirteen counties and are most abundant on the west coast especially in counties Kerry and Clare. The greatest potential percentage losses of salt marshes occur in Wicklow (60% for a 1m scenario) and Waterford (54% for a 1m scenario) where salt marshes make up 180ha and 84ha respectively. It is probable that the greatest area lost will occur in Clare and Kerry at over 30% with a 1 m SLR occurring on salt marsh areas of 1,303ha and 760ha respectively.

Table 6.4: Irish wetlands; displaying total area of each wetland, vulnerable % of total land for each wetland under the 3 scenarios along with Euro value per hectare per year.

Wetland Feature	**Total area (ha)**	**Vulnerable % of total**	**€ Thousands Value ha^{-1} yr^{-1}**
Beaches, Dunes and Sand	10,890		
0.5m SLR scenario		10	7,296
1m SLR scenario		14	10,215
2m SLR scenario		17	12,404
Salt marshes	4,907		
0.5m SLR scenario		26	8,548
1m SLR scenario		33	10,849
2m SLR scenario		39	12,822
Coastal lagoons	820		
0.5m SLR scenario		47	2,582
1m SLR scenario		49	2,692
2m SLR scenario		50	2,747

Table 6.4 above provides a breakdown of the total area (in hectares) occupied by the three modelled wetland habitats. These wetlands are located in the Irish Republic as classified by the CORINE 2006 dataset. The vulnerable area of each wetland type, under the three modelled scenarios, is expressed as a percentage. Also a gross economic estimate of the vulnerable area of each wetland type is determined using the average European wetland value per hectare of US$9,000 (approx €6,700) as calculated by Brander *et al*. (2006). Total percentage losses of the modelled wetlands under the 1m scenario range from 14 to 49%. The assumption is made, in the modelling results, that once a particular wetland is submerged as a result of increasing sea levels it will not be replaced. This is consistent with the occurrence of coastal squeeze, whereby wetlands are regularly squeezed between a narrow fringe between the sea and developed coastal land (Doody, 2004).

The following Section (6.4) presents some wetland vulnerability modelling outputs from a coastal impact tool to compare to the modelled results presented above. These outputs complement the CORINE/DTM analysis.

6.4 DIVA WETLAND MODELLING

The Dynamic and Interactive Vulnerability Assessment (DIVA) Tool was produced by the EU-funded DINAS-COAST Project (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise) (Vafeidis *et al*., 2008). DIVA models interactions between a series of biophysical and socio-economic modules to assess impacts of SLR, with outputs presented at global, regional and national scale. The model captures the coastline using linear representation. This segmentation model is designed to define homogenous units of coastlines for vulnerability at a broad scale of analysis. The socio-economic data used for the analysis includes datasets on global population, as well as per capita GDP figures. The strengths of this modelling approach are in its interdisciplinary nature and consistency. However, the model is best suited to global or regional assessment, as the limited resolution and spatial incompleteness of the data sets used make it less accurate in capturing potential coastal vulnerability at the national or local scale. Table 6.5 below presents DIVA model outputs driven by the ECHAM4 global climate model under the A2 SRES scenario. Three SLR scenarios are explored as projected for the end of the century; a low SLR scenario of 29.2cm, a medium SLR scenario of 43.8cm, and a high scenario of 58.5cm. The modelled results project wetland losses of over 9,000ha under the highest SLR scenario. In comparison, the first SLR scenario of 0.5m in the wetland vulnerability modelling in section 6.3 above projects total wetland losses of 2,810ha for the wetland subgroups of beaches, dunes and sand (including machairs), coastal lagoons, and salt marshes. Additional coastal wetlands not modelled in this chapter's analysis include intertidal flats with an area of over 53,000ha. These wetlands proved difficult to model with existing datasets. The DIVA modelled outputs (which include these intertidal flat areas) would suggest that economic losses relating to Irish wetland loss under a 0.58m SLR scenario could be in the region of €62.7M per year, using the average European wetland value per ha as determined by Brander (2006). This compares with €18.8M per year for the three modelled wetland subgroups under a 0.5m scenario of the analysis carried out in this chapter.

Table 6.5: Irish DIVA output for ECHAM4 A2 scenario (Source: Richards and Nicholls, 2009).

Scenario	Total Adaptation Costs (M€/yr)	Total Residual Damage Costs (M€/yr)	Sea Flood Costs (M€/yr)	Net Loss of Wetland Area (ha)	Sea Dike Costs (M€/yr)
Baseline (1995)	0	18.6	18.6	**0**	0
L SLR 2020s no adaptation	0	25.1	25.1	**1,600**	0
2080s	0	127.6	127.6	**6,570**	0
M SLR 2020s no adaptation	0	65.4	65.3	**1,600**	0
2080s	0	170.3	170.2	**8,210**	0
H SLR 2020s no adaptation	0	70.9	70.9	**2,000**	0
2080s	0	224	220.7	**9,360**	0
L SLR 2020s with adaptation	19.8	20.3	20.3	**1,600**	16.7
2080s	39.2	13.8	13.8	**6,570**	35.6
M SLR 2020s with adaptation	29.5	21.7	21.7	**1,600**	24.6
2080s	54.7	17.6	17.6	**8,210**	49.9
H SLR 2020s with adaptation	41	24	24	**2,000**	34.1
2080s	69.5	21.8	21.8	**9,360**	62.5

Section (6.5) below complements the wetland vulnerability analysis carried out in the previous sections by cataloguing Irish wetland flora and fauna known to be present in the modelled wetland subgroups. County Wexford and County Dublin provide case study sites for the exercise. These counties were selected as they displayed significant wetland vulnerability under the modelled SLR scenarios carried out above.

6.5 VULNERABLE SPECIES CASE STUDIES

6.5.1 Wexford

This case study exploring at risk species surveyed in the wetlands of County Wexford is intended to complement the vulnerability modelling carried out on the three coastal wetland sub-groups of sand dune systems, lagoons and salt marshes. Through the use of several International Union for the Conservation of Nature (IUCN) endorsed Red List of Threatened Species reports, in conjunction with species distribution maps available from the National Biodiversity Data Centre (NBDC) in Ireland a list of Red List flora and fauna was compiled for coastal wetland sites in County Wexford (NBDC, 2011). The IUCN Red List of Threatened Species provides taxonomic, conservation status and distribution information on flora and fauna that have been evaluated globally using the IUCN Red List categories and criteria (IUCN, 2011). It determines the relative risk of extinction and highlights those plants and animals that are under the greatest threat of extinction (Figure 6.8). When mapping the distribution of the three coastal wetland subgroups one can note the significant overlap and close proximity of the sites to each other (Figure 6.9). Figure 6.10 provides place names for the areas where these sites are found to provide a reference for the species distributions provided in Table 6.6.

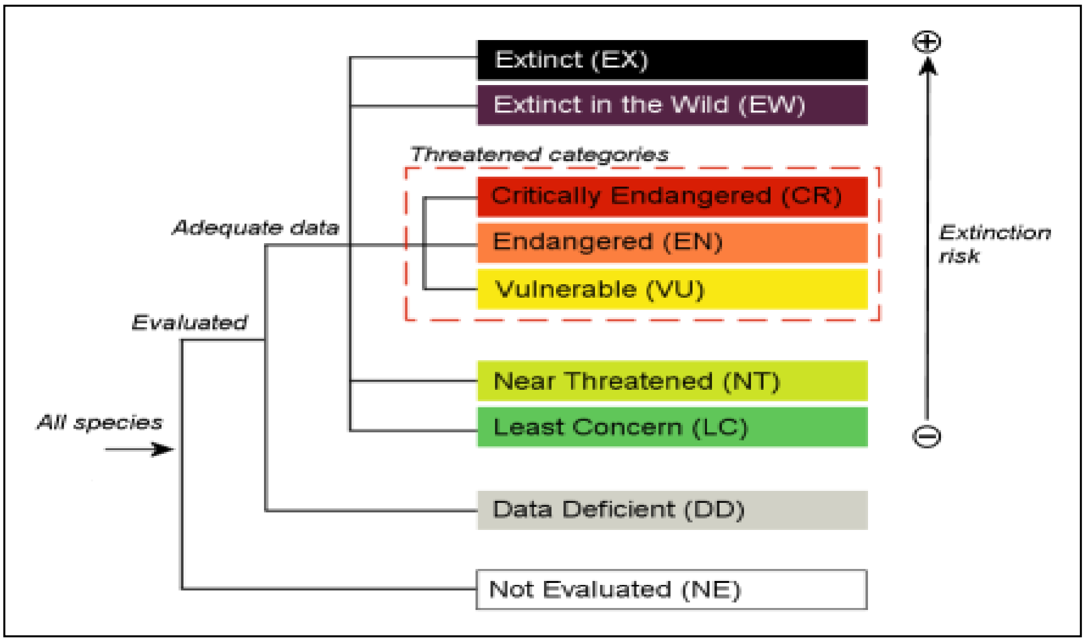


Figure 6.8: IUCN Red List System (Source: IUCN, 2011).

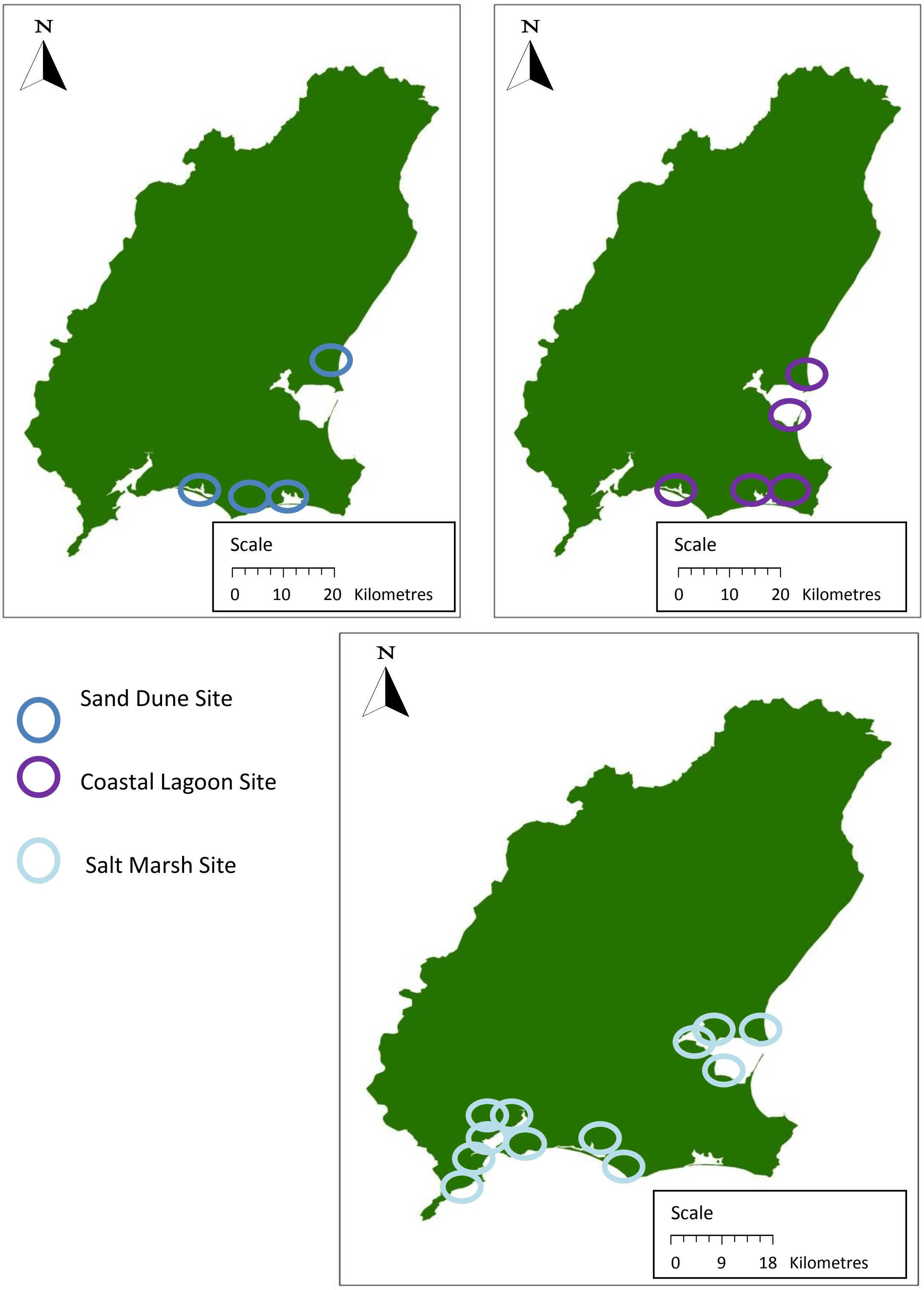


Figure 6.9: Distribution of sand dune, coastal lagoon and salt marsh sites in County Wexford compiled from various sources.

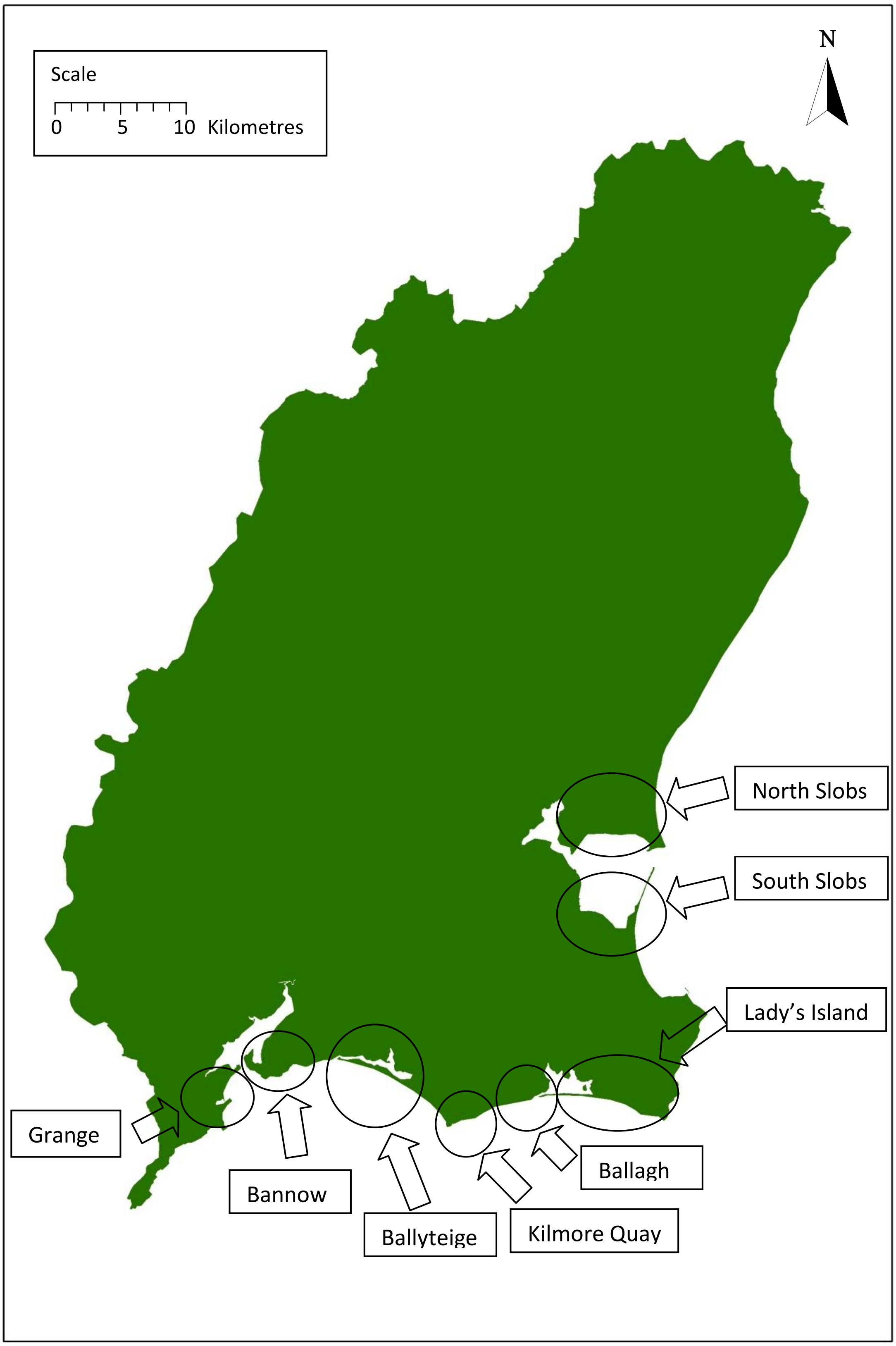


Figure 6.10: County Wexford with species location sites marked.

Table 6.6: Wetland Red List species in County Wexford.

Wetland Red List Species in County Wexford		
Species	**IUCN Status**	**Location**
Flora		
Perennial Glasswort	Endangered	Ballytiege, Bannow , Grange
Borrer's Saltmarsh Grass	Vulnerable	North Slobs, South Slobs, Ballyteige
Cottonweed	Critically Endangered	Lady's Island
Bird's-foot	Vulnerable	North Slobs, South Slobs
Round-leaved Wintergreen	Endangered	North Slobs
Golden Dock	Vulnerable	Lady's Island, Ballagh
Lesser Centaury	Endangered	Lady's Island, Ballyteige, Ballagh
Green-flowered Helleborine	Endangered	North Slobs
Fauna		
Red-necked Phalarope (Bird)	Vulnerable	Lady's Island
Bewick's Swan	Vulnerable	Lady's Island, South Slobs, Ballyteige
Spattered Diver Water Beetle	Endangered	North Slobs, South Slobs, Ballytiege, Kilmore Quay
Gatekeeper Butterfly	Near Threatened	South Slob, Kilmore Quay, Ballyteige
Grayling Butterfly	Near Threatened	North Slobs, South Slobs, Lady's Island, Ballyteige
Dark Green Fritillary Butterfly	Vulnerable	South Slobs, Lady's Island, Ballyteige, Kilmore Quay
Breeched Water Beetle	Critically Endangered	North Slobs
Red-legged Moss Beetle	Endangered	South Slobs
Small Bluetail Dragonfly	Vulnerable	South Slobs, Lady's Island

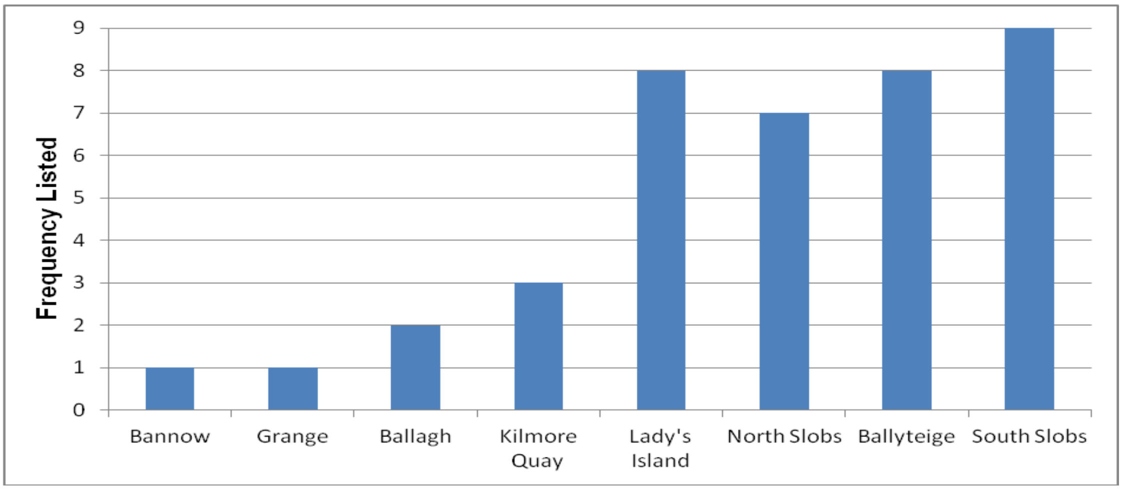


Figure 6.11: Frequency distribution of species present in selected Wexford sites.

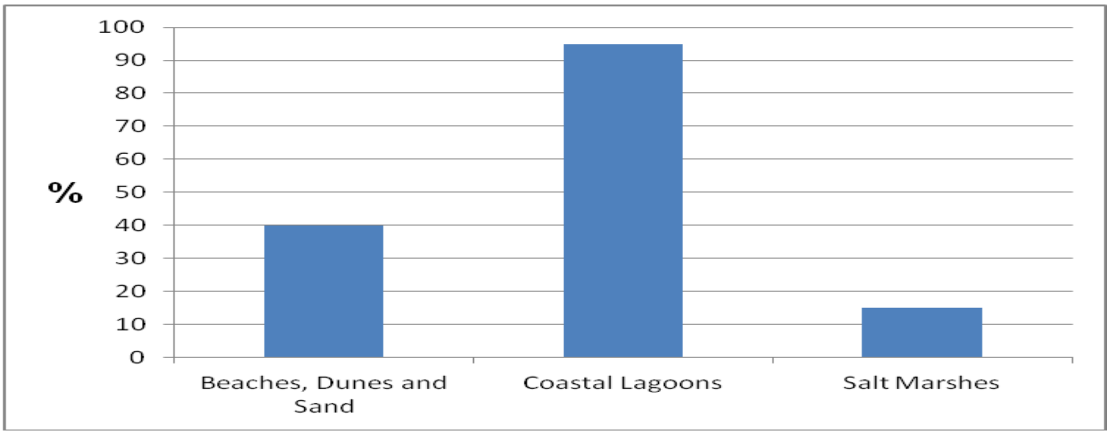
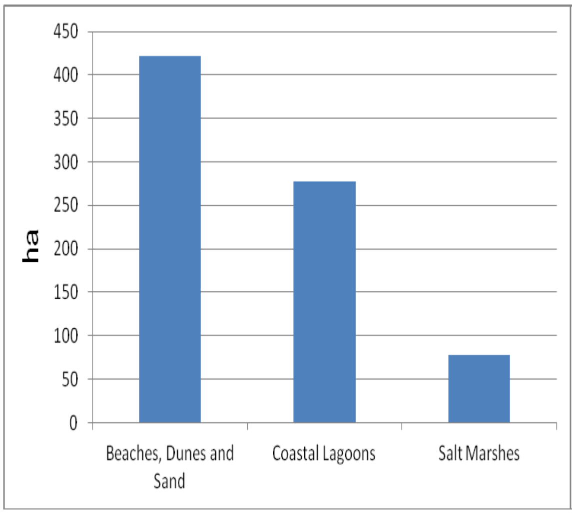


Figure 6.12: Vulnerable percentage of each wetland subgroup under a 1m SLR in Wexford.



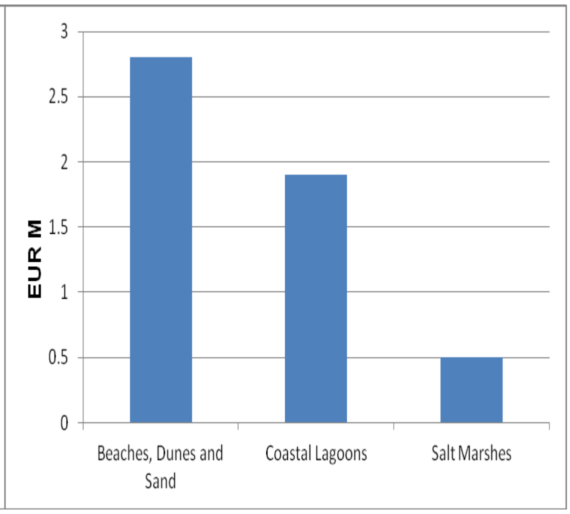


Figure 6.13: Vulnerable hectares for each wetland subgroup under 1m SLR scenario in Wexford.

Figure 6.14: € value of vulnerable wetland groups under 1m SLR scenario in Wexford.

There are eight Red List species of flora and eight species of fauna located in the coastal wetlands of County Wexford (Table 6.6). Red List flora includes vascular plants such as perennial and annual grasses, herbs and flowering plants. The fauna includes birds, water beetles and butterflies. The IUCN indicators range from Near Threatened to Critically Endangered with six species on the Endangered list and two Critically Endangered. The wetland sites with the greatest number of Red List species present are Ballyteige, Lady's Island and the South Slobs (Figure 6.11). These sites contain coastal lagoons, dunes and salt marshes (Figures 6.9-6.10). Coastal lagoons show the greatest vulnerability in terms of potential percentage loss under the 1 m modelled SLR scenario at over 90% (Figure 6.12). This equates to a potential area of approximately 275ha (Figure 6.13) with an estimated Euro value of over €1.8M (Figure 6.14). Although the potential impact of a 1 m SLR scenario on beaches, dunes and sand is significantly smaller in percentage terms, at 40%, the potential vulnerable land area is much greater at approximately 420ha.

6.5.2 Dublin

This case study exploring the Red List species located in the County Dublin's coastal wetlands follows the same methodology as that of the Wexford case study. It is again intended to complement the vulnerability modelling carried out at a national level on the three coastal wetland sub-groups of sand dune systems, lagoons and salt marshes. However, in the case of Dublin although all three wetland subgroups are represented, as displayed in Figure 6.15, only beaches, dunes and sand along with salt marshes are represented in the 2006 CORINE Land Cover map. Figure 6.16 displays County Dublin with the four species location sites marked that correspond with the locations of the coastal wetland subgroups located in County Dublin.

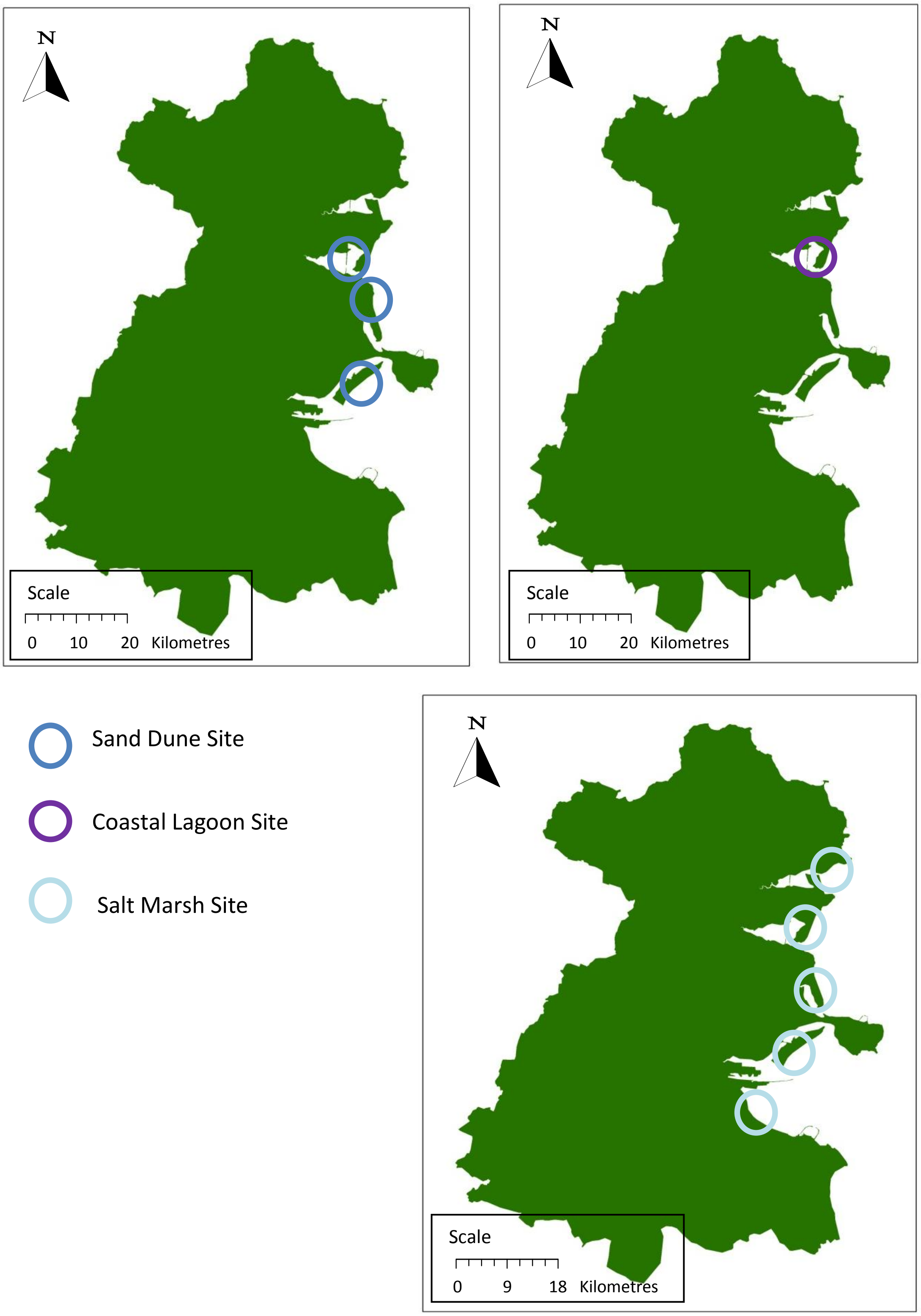


Figure 6.15: Distribution of sand dune, coastal lagoon and salt marsh sites in County Dublin from various sources.

Figure 6.16: County Dublin with species location sites marked.

Table 6.7: Wetland Red List species in County Dublin.

Wetland Red List Species in County Dublin		
Species	**IUCN Status**	**Location**
Flora		
Spring Vetch	Vulnerable	Bull Island, Malahide Estuary
Bird’s-foot	Vulnerable	Bull Island
Lesser Centaury	Endangered	Bull Island
Fauna		
The Wall Butterfly	Endangered	Bull Island, Malahide Estuary, Portmarnock Strand
Small Heath Butterfly	Near Threatened	Bull Island, Malahide Estuary, Portmarnock Strand, Booterstown Marsh
Small Blue Butterfly	Endangered	Bull Island, Malahide Estuary, Portmarnock Strand, Booterstown Marsh
Dark Green Fritillary Butterfly	Vulnerable	Bull Island, Malahide Estuary, Portmarnock Strand, Booterstown Marsh
Spattered Diver Water Beetle	Endangered	Bull Island, Portmarnock Strand
Orangeman Water Beetle	Vulnerable	Bull Island, Portmarnock Strand
Marine Moss Beetle	Near Threatened	Bull Island, Portmarnock Strand
Gatekeeper Butterfly	Near Threatened	Bull Island, Malahide Estuary
Grayling Butterfly	Near Threatened	Bull Island, Malahide Estuary, Portmarnock Strand, Booterstown Marsh

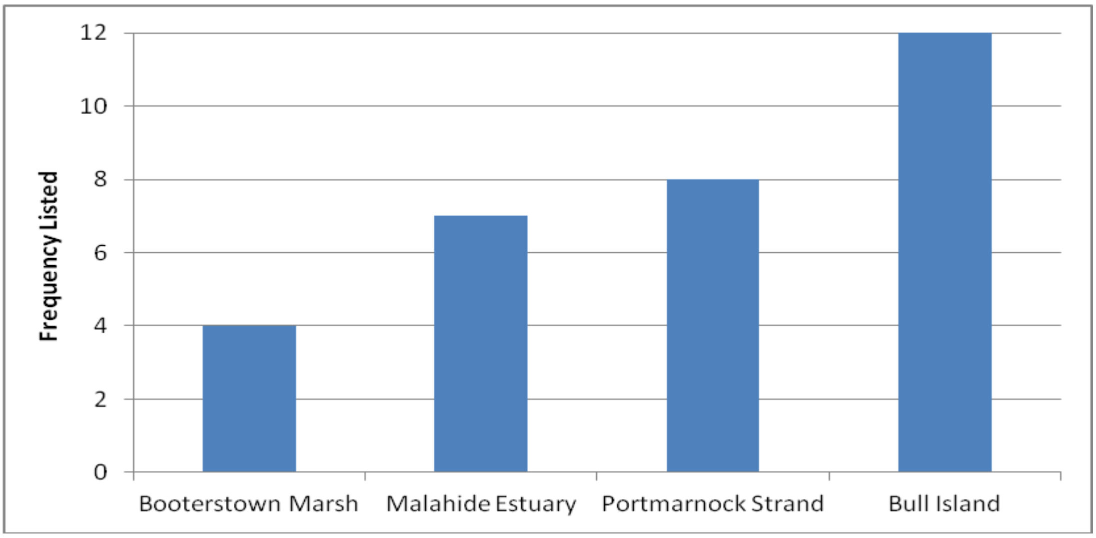


Figure 6.17: Frequency distribution of Red List species present in selected Dublin sites.

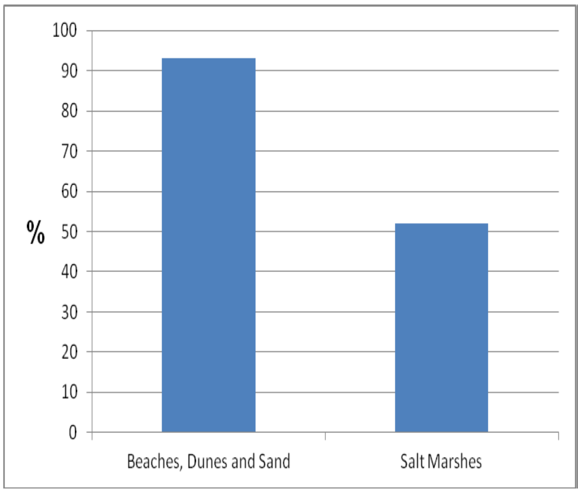


Figure 6.18: Vulnerable percentage of each wetland subgroup under 1m SLR scenario in Dublin.

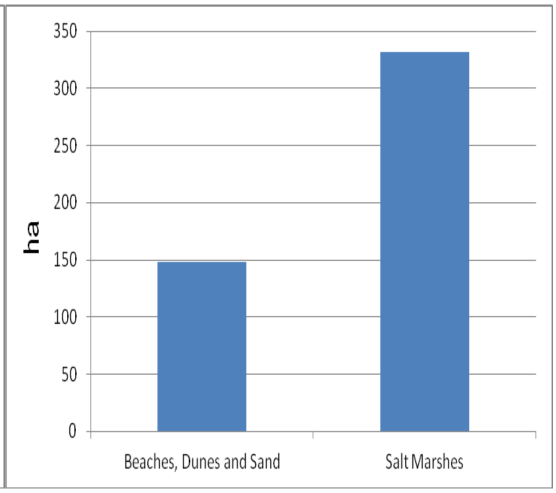


Figure 6.19: Vulnerable hectares for each wetland subgroup under 1m SLR in Dublin.

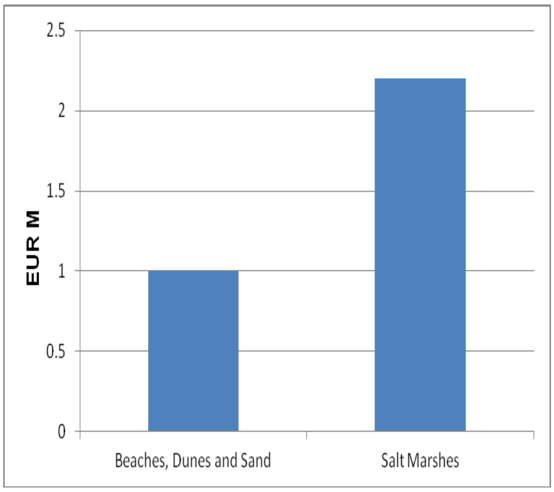


Figure 6.20: Euro value of vulnerable wetland subgroups under 1m SLR scenario in Dublin.

There are three Red List flora species and nine Red List species of fauna located in County Dublin's coastal wetlands (Table 6.7). The Red List flora includes annual and perennial species. The fauna includes butterflies and water beetles. The IUCN statuses range from Near Threatened to Endangered. Four species can be found on the endangered list. Wetland sites with the greatest number of Red List species present are Bull Island and Portmarnock Strand (Figure 6.17). Both these sites contain beaches, dunes and sand as well as salt marsh wetland subgroups (Figure 6.15). Beaches, dunes and sand show the greatest vulnerability in terms of potential percentage loss under the 1 m modelled SLR scenario at over 90% (Figure 6.18). This is calculated as a potential area of approximately 150ha (Figure 6.19) with an estimated value of €1M (Figure 6.20). Although the potential impact of a 1m SLR scenario on salt marshes is significantly smaller in percentage terms, at just over 50%, the potential vulnerable land area is much greater at approximately 320ha.

6.6 CONCLUSIONS

The modelling work carried out in this chapter highlights both the vulnerability and the value of Irish coastal wetland habitats. The chosen contingent valuation methodology, employing a direct benefit value transfer approach, is useful in attributing a TEV to the chosen wetland habitats. Although monetary valuation provides a highly subjective value (Simmel, 1990), the strength of the contingent valuation approach is that this methodology (as outlined in Section 6.2 and Section 5.3.3) captures the full range of services associated with a particular ecosystem. As this valuation approach covers direct, indirect and non-use values it can be considered one of the most robust economic valuation methodologies currently available. One must note that the methodology engages with individuals to ascertain a range of values that they would attribute to a particular environmental amenity or ecosystem. Thus any values calculated must reflect the embedded values and norms of each particular society or community that it is engaged with. It must also be noted that the framing of the questions, along with their compilation into a final TEV, also reflects the subjectivity of the researcher involved in the process.

Coastal erosion and SLR pose increasing threats to coastal wetland habitats. The national study modelling outputs provide analysis on the vulnerable percentage, area, and economic value of the three wetland subgroups. The DIVA model results complement these wetland vulnerability outputs. A comparison between the two highlights that the DIVA modelling projects much greater wetland losses than compared to the original modelling work carried out. One major reason for the difference between the two is that the DIVA model includes 54,000ha of intertidal flats, which were not captured in the modelling work carried out in this study.

The two case studies of County Wexford and County Dublin add to the national study by exploring Red List species present in the wetland coastal habitats examined. This approach of presenting monetary impacts, physical impacts and natural impacts together provides breadth in the analysis and aspires to present a post-normal science methodology rather than a strictly utilitarian economic approach. This approach is beneficial as it lists specific species that may display increased vulnerability, or indeed risk of extinction, under future SLR scenarios. While the explicit economic value of these species is difficult to calculate, the intrinsic existence value associated with their existence is clear. This type of modelling approach can thus provide conservationists and decision-makers with an augmented IUCN Red List that accounts for potential increased species vulnerability, as a result of potential climate change impacts.

The aforementioned (in Chapter 4) discussion on uncertainty in relation to data quality is also valid for the modelling results presented in this chapter. Ideally the medium resolution DTM dataset would be replaced by higher resolution LIDAR data.

The available OPW LIDAR dataset was not suitable for this vulnerability analysis, as it does not capture a number of the wetland subgroups studied. In particular, the OPW LIDAR data does not map County Wexford's coastal lagoons and only partially contains Dublin's salt marshes, as displayed in Figures 4.13 and 4.14 respectively. Notwithstanding these omissions, a comparison between the available OPW LIDAR and DTM datasets carried out for the case study sites suggests that wetland vulnerability is broadly similar for sand dune and machairs in the Wexford site. However, sand dune and machair vulnerability is considerably smaller in Dublin under the LIDAR analysis. The sand dune and machair vulnerability of 90% under the 1m scenario using the DTM data falls sharply to 15% with the LIDAR dataset.

CHAPTER 7
UNDERSTANDING ECONOMIC IMPACTS OF INLAND FLOODING IN EUROPE AND IRELAND

7.1 INTRODUCTION

Inland flooding can result in serve physical damages and economic losses. These flood impacts are driven by both environmental and socioeconomic factors. Environmental factors include precipitation events and changes in climate resulting in altered precipitation patterns. Socioeconomic factors include extensive development and urbanisation in proximity to rivers, river channelisation, and failures relating to dams or other river management infrastructure. The following chapter analyses the drivers of flooding in Europe and Ireland, along with the resulting physical and economic impacts, and thus highlights the importance of proactive Irish flood management policies in limiting flood related economic costs.

7.2 PHYSICAL PROCESSES OF FLOODING

Flooding in river valleys predominantly occurs on floodplains or wetlands when flow exceeds the capacity of the stream channels and overspills the natural banks or artificial embankments (Smith and Ward, 1998). There are a number of primary causes of inland flooding that are both climatological and non-climatological in origin. Climatological causes include precipitation events, snowmelt, icemelt and a combination of these factors. Partly climatological causes include coastal storm surges and estuarine interactions between streamflow and tidal conditions. Non-climatological causes are events such as earthquakes, landslides and the failure of dams and other control works (Ward, 1978). Conditions that intensify flooding are related to the characteristics of river basins, channels and networks. The stability or variability of a river basin, channel or network can influence flood-intensifying conditions considerably. For example, changes in river basin area, slope or altitude due to natural or human induced land use change or soil erosion can reduce or increase basin storage capacity (Ward, 1978). Similarly, changes in river network length, channel slope or river regulation works can potentially intensify flood conditions.

Flood damage is a function of depth, velocity and water quality. Water quality refers to the make-up of particular flood waters. Water may be carrying solids in suspension, such as sewage, mudflows or other debris. Flood water may also be freshwater, seawater or a mixture of the two. Other factors, such as seasonality and frequency, as well as the shape of the flood are also important in relation to potential flood damage (Smith and Ward, 1998). Flood frequency is a statistical measure of the probability of a flood of a given magnitude occurring and is often referred to as the return period or recurrence interval of a flood. For example, a small magnitude flood event may have an annual return period. However, a large magnitude event may have a return period of one hundred years. The shape of a flood refers to the peak flood discharge and water level as well as the total volume of flood water and time taken to reach peak conditions.

7.3 ECONOMIC COSTS LINKED WITH INLAND FLOODING AND CLIMATE CHANGE IN EUROPE

Europe has suffered over 175 major flooding events between 1998 and 2010 (European Environment Agency, 2010). These events include the high impact floods along the Danube and Elbe rivers in the summer of 2002, severe UK flooding in 2007 as well as the 2010 floods in Poland and central Europe (Figure 7.1). Since 1998, floods in

Europe have caused some 900 deaths, at least €34B in insured economic losses and the displacement of over half a million people (European Commission, 2007, European Environment Agency, 2010).

Climate change is projected to intensify the hydrological cycle significantly. Rising global average temperatures increase evaporation, which in turn adds to the atmospheric moisture content, and leads to enhanced precipitation rates across weather systems that range from tropical cyclones to individual clouds (Trenberth, 1999). An observed increased frequency of heavy rainfall events increases runoff and the occurrence of flooding events in large parts of Europe (European Environment Agency, 2008). In the 2080s additional economic damages related to inland flooding in the range of €7.7 to €15B are expected in the EU as a result of climate change (European Commission, 2009a). However, significant uncertainties are associated with modelled estimates of changes in flood frequency and magnitude. This uncertainty is reflected in the fact that although there has been a considerable rise in the number of reported major flood events and associated economic impacts, with twice as many flow maxima occurring in Europe between 1981 and 2000 than between 1961 and 1980, a significant climate-related trend in extreme high river flows was often not detected (Becker and Grunewald, 2003; Macklin and Rumsby, 2007). However, recent literature has shown that a climate change signal can be detected in some of Europe's near natural river catchments (Stahl *et al*., 2010). Stahl *et al*. analysed 441 small catchments in 15 European countries and used a 1962-2004 period for the majority of catchments, with longer periods for a few stations (1932, 1942 and 1952). The results confirmed patterns of regional change in streamflow trends that would be expected from future climatic changes, as projected by climate models; positive trends were found in the winter months in most catchments and a marked shift towards negative trends was observed in April, with a gradual spread across Europe reaching a maximum extent in August.

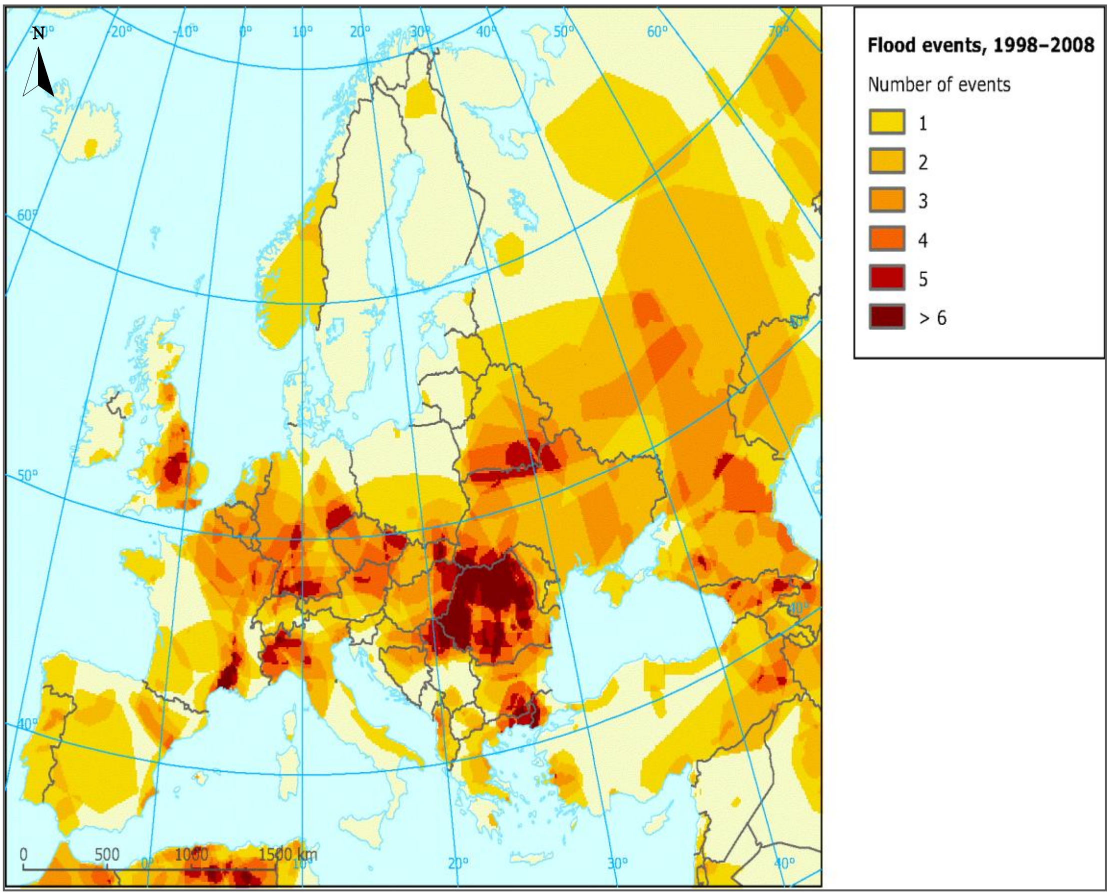


Figure 7.1: Occurrence of flood events in Europe 1998-2008 (Source: European Environment Agency, 2010).

Despite the uncertainties associated with linking the extreme flood events in Europe directly with climate change, it is argued that the frequency and intensity of these events may provide an indication of the projected increase of floods in much of Europe (Figure 7.2) (Lehner *et al*., 2006; Dankers and Feyen, 2008b). It is projected that many of these floods will take the form of flash and urban floods triggered by local intense precipitation events (Christensen and Christensen, 2003; Kundzewicz *et al*., 2006). Flood hazard incidences are also likely to increase during winters that are projected to be wetter and warmer, and with less frequent snow (Palmer and Raisanen, 2002).

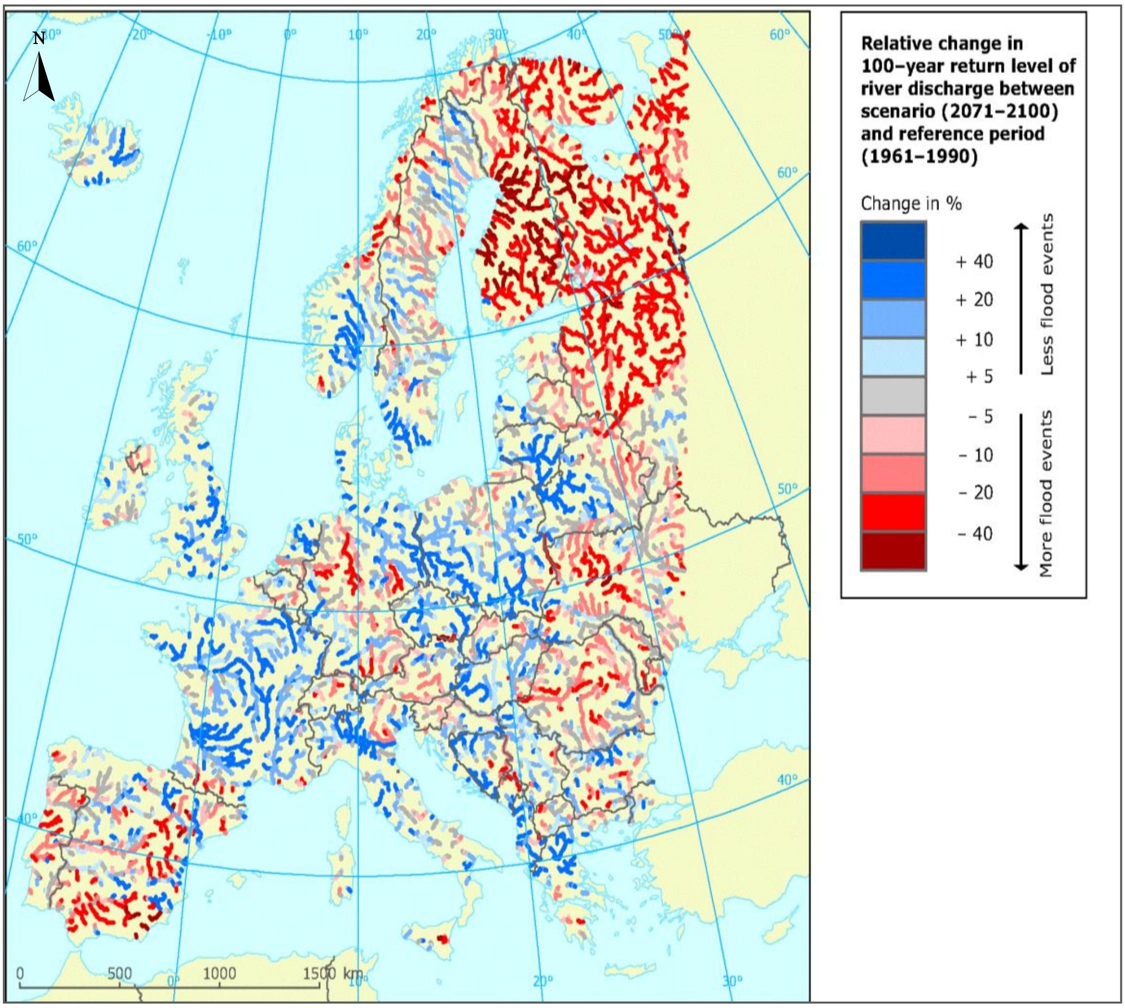


Figure 7.2: Projected change in 100-year return level of river discharge between 2071-2100 and the reference period 1961-1990. (Source: European Environment Agency, 2010).

The 2011 ClimateCost report uses the LISFLOOD model to examine the economic impacts of inland flooding in Europe associated with future climate scenarios (European Commission, 2011). The LISFLOOD model is a GIS-based hydrological rainfall-runoff-routing model that is designed to be used in large transnational catchments for a range of applications including flood forecasting, land-use change and climate change analysis (Van der Knijff *et al*., 2010). The headline results for the study reported 300,000 people to be affected every year in the EU27 by the 2050s under a medium to high emission scenario, without adaptation. This figure is estimated to increase to 360,000 people by the 2080s. It must be noted that these figures include the combined effects of socioeconomic change as well as climate change. Economic impacts under the same scenarios are estimated to be €46B per year by the 2050s and €98B per year by the 2080s using undiscounted current values for the EU 27 (European Commission, 2011). Again, one must note that these values reflect changes in population and economic growth as well as changes in climate. The economic costs associated with the marginal effect of climate change are estimated at €19B per year by the 2050s and €50B a year by the 2080s for the EU27. The economic analysis indicates that Belgium, Italy, Ireland, the Netherlands and the UK are expected to show high climate-related costs at a country level (European Commission, 2011). The study also estimates (in undiscounted current prices) the cost of maintaining 1 in 100-year levels of flood protection across Europe at €7.9B per year by the 2080s under the aforementioned scenarios with associated benefits of €50B per year by the 2080s.

7.4 ECONOMIC COSTS LINKED WITH INLAND FLOODING AND CLIMATE CHANGE IN IRELAND: A REVIEW

7.4.1 Irish river catchments and flooding

The area of land drained by each single river and its tributaries is known as a drainage basin or catchment. This area provides water and sediment to the river channel and is bounded by a drainage divide or catchment boundary (Charlton, 2007). Ireland has 20 major river catchments all over 500km^2 in area (Table 7.1, Figure 7.3).

Table 7.1: Major Irish river catchments.

Major Irish River Catchments			
Catchment Name	**Area (km^2)**	**Catchment Name**	**Area (km^2)**
Avoca	650	Kinvarra	520
Bandon	610	Lagan	560
Bann	5,810	Laune	830
Barrow	3,070	Lee	1,250
Blackwater	3,330	Liffey	1,370
Boyne	2,700	Moy	2,090
Corrib	3,140	Nore	2,530
Erne	4,370	Shannon	15,700
Feale	1,160	Slaney	1,760
Foyle	2,920	Suir	3,610

Irish river catchments are characterised by a widespread system of bogs, lakes and topographical depressions that provide storage to flood flows (Ahilan *et al.*, 2011). The mild gradient of many Irish river channels provides additional attenuation in natural floodplains. A feature related to these mild topographic gradients is the high level of arterial drainage; the widening and deepening channels throughout river basins (Reed and Martin, 2005). Extensive human intervention through reservoir development, peat extraction and forestry is another dominant feature. The Irish midlands contain many of these areas of lakes and wetlands with shallow gradients along much of their length and poor carrying capacities. Seasonal flooding is a common occurrence in the winter months in Ireland when many soils are at or near saturation (Charlton *et al.*, 2006).

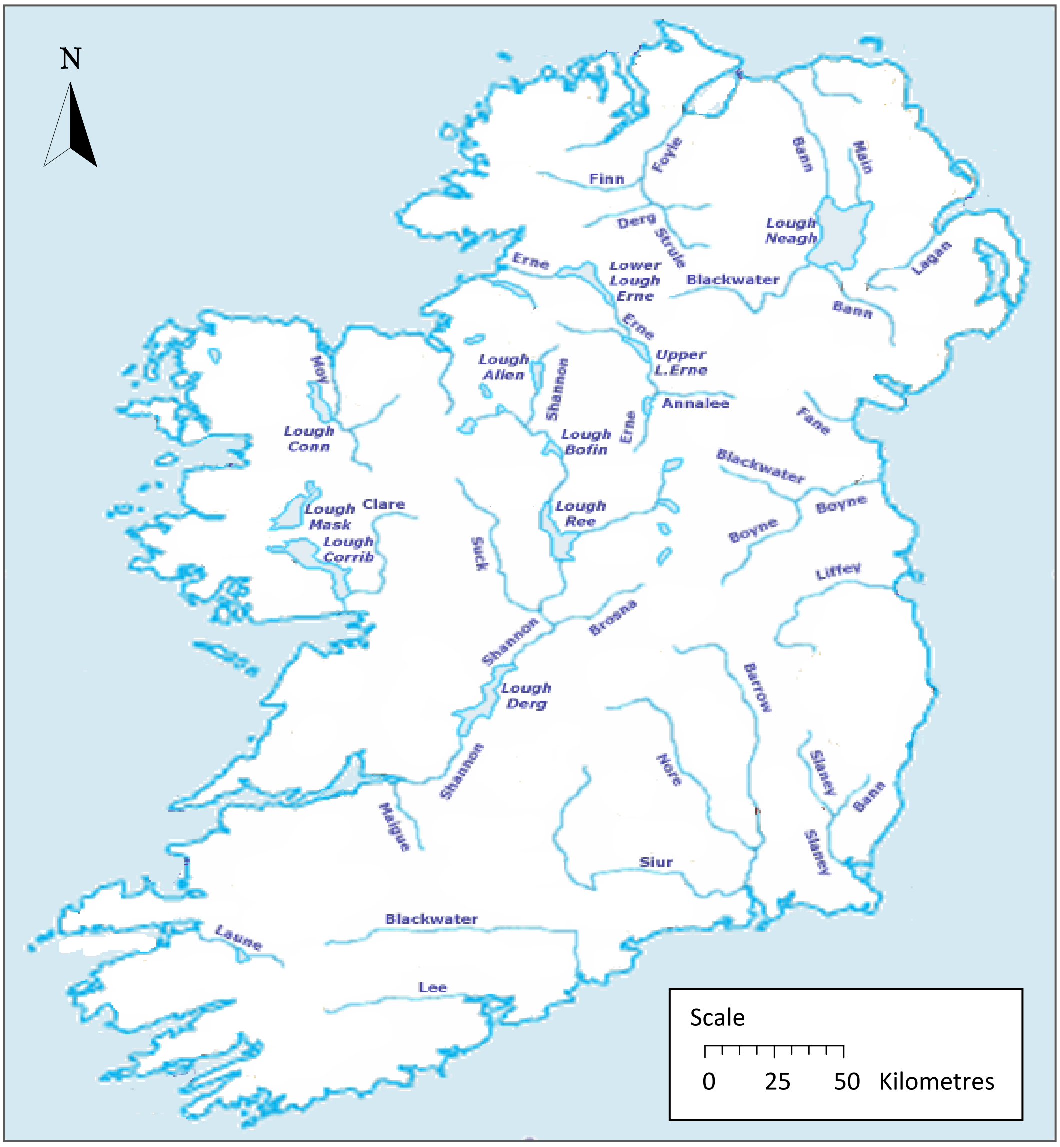


Figure 7.3: Major rivers of Ireland.

Areas where human intervention is likely to have a significant influence on flood risk are likely to include smaller catchments where extensive development (or urbanisation) has taken place (Reed and Martin, 2005). Land use changes on slopes with relatively steep gradients are likely to lead to significant increases in flood risk. It follows that flood risk problems are linked with some of Ireland's steeper rivers, especially those draining upland areas close to major urban centres. Highly permeable (karst) catchments are common, with the majority occurring in the West of Ireland (Reed and Martin, 2005; Ahilan *et al*., 2011). Over half of Ireland's river catchments flow over carboniferous limestone and lowland karsts occupy approximately 75% of this area (Figure 7.4) (Coxon, 1987; Williams, 1970). These catchments offer up unique complexities due to their high permeability and complex hydrology. They are also often located in areas historically prone to flooding such as the Shannon river basin.

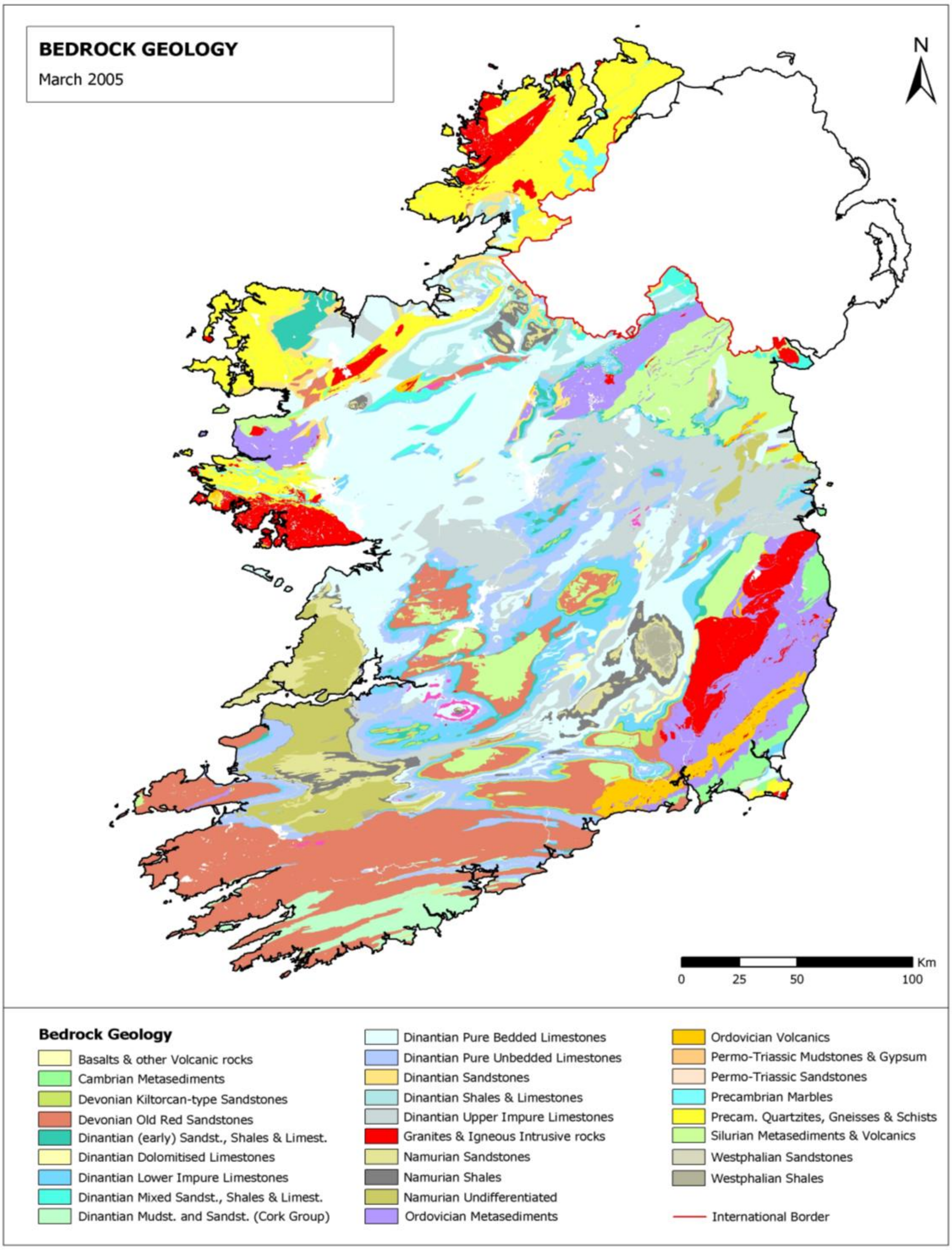


Figure 7.4: Bedrock geology of Ireland. (Source: Water Framework Directive Ireland, 2005).

The Shannon rises in County Cavan and is the longest river in Ireland at over 360km in length, with a catchment area of 15,700km^2. It is often subject to severe flooding with events recorded over the last 150 years (OPW, 2010a).

7.4.2 Climate change and Irish inland flooding

Changes in the Irish flood regime can be characterised in two ways; firstly, through simulated changes in flood magnitude under a number of return periods, under a given emission scenario[27] (Murphy and Charlton, 2008). The second method explores flood regime changes through assessing the changes in the frequency of floods of a given magnitude for each future time period (Murphy and Charlton, 2008). Figures 7.5, 7.6 and Table 7.2 present the simulated changes in flood magnitude under the A2 and B2 emission scenario respectively for the Barrow and the Moy catchments. Four flood events (or return periods) of 2, 10, 25 and 50 years were examined in this study. These

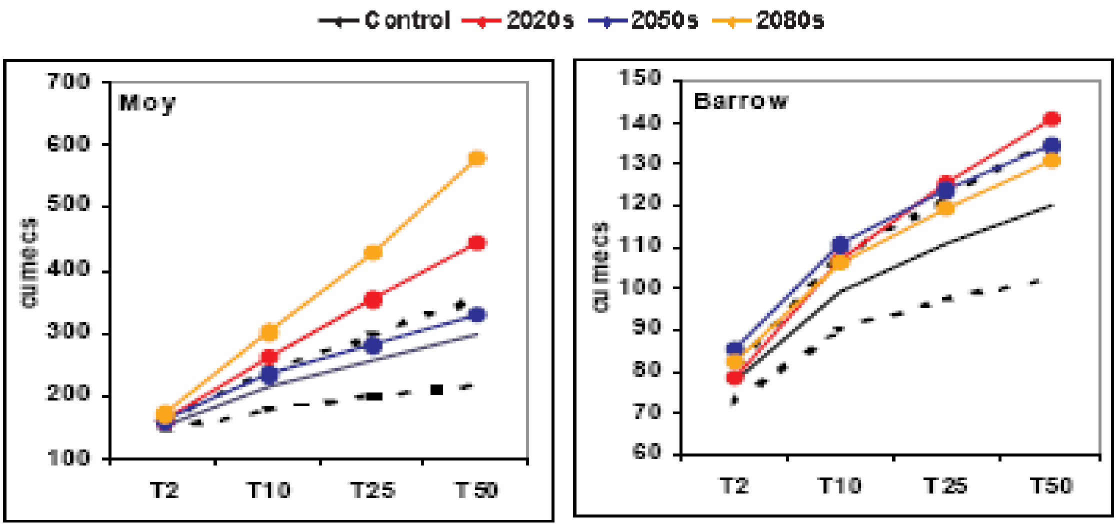


Figure 7.5: Simulated changes in flood magnitude (cubic metres per second) in the Barrow and Moy catchments under the A2 emissions scenario (Source Murphy and Charlton, 2008).

four flood events are then simulated for three future potential time periods (the 2020s, 2050s and 2080s) along with a control period. Figure 7.5 presents flood magnitude changes in the Barrow and Moy catchments under the A2 emissions scenario.

In the Barrow catchment all three future periods are closely aligned. The modelling results show increases in magnitude over the control period but a slight

[27] Murphy and Charlton use the IPCC A2 and B2 SRES emission scenarios. The A2 emissions scenario considers a world of independently operating, self reliant, nations. There is continuously increasing population and regionally orientated economic development. The B2 scenario considers a world of intermediate economic development, with emphasis on local rather than global solutions to economic, social and environmental stability. The A2 is a significantly warmer scenario compared to the B2 scenario.

decrease in magnitude over the three time periods from the 2020s to the 2080s. The Moy catchment displays a marked increase over all three future periods. The greatest increases are associated with the 50-year return period with a doubling in magnitude under the control period. Under the B2 scenario (Figure 7.6) the greatest changes in the magnitude of flow over the four flood events are associated with the 2020s time period. Again, in the barrow catchment all three time periods are closely matched and significantly greater than the control. In the Moy all three time period are also significantly greater than the control, with the 2020s and the 2050s showing the greatest increases.

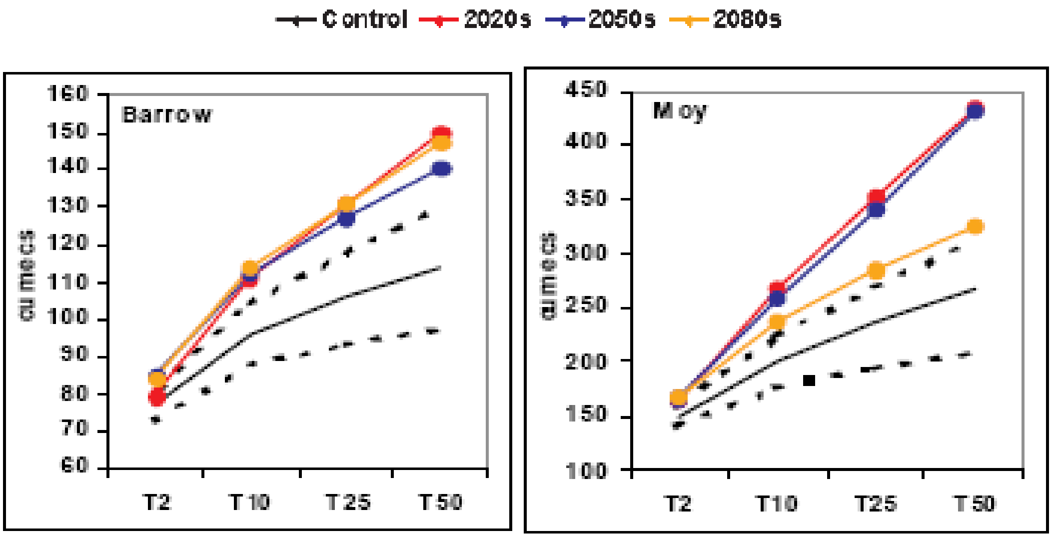


Figure 7.6: Simulated changes in flood magnitude (cubic metres per second) in the Barrow and Moy catchment under the B2 emissions scenario (Source Murphy and Charlton, 2008).

As the relationships between return period and flood magnitude is not expected to be linear, it is important to examine how the frequency of fixed magnitude events may change in the future (Murphy and Charlton, 2008). Table 7.2 below presents the results of HadCM3 modelling of changes in magnitude as well as flood frequency for the A2 and B2 scenarios for the Barrow and Moy catchments. The modelling results estimate that the frequency of all four flood events (with return periods of 2, 10, 25 and 50 years) increases in the three future time periods of the 2020s, 2050s and 2080s. The 10 year flood event in the 2050s is modelled to occur every 4.8 years when considering the warmer A2 scenario for the Barrow and every 4.4 for the Moy. 25 year events for the 2050s modelling are estimated to occur every 10.1 years for the Barrow and 8.5 years for the Moy. The 50-year event as estimated for the 2050s is modelled to occur every 18.3 years for the Barrow and every 13.9 years for the Moy. The frequencies are estimated to increase further when modelled out to the 2080s. These results show that both flood magnitude and flood frequency is set to increase significantly in these two catchments between the present day and the end of the century.

Table 7.2: Percentage change in the magnitude of flow associated with floods of a given return period under the A2 and B2 emissions scenarios for the Barrow and Moy catchment along with changes in the frequency of floods of a given magnitude for each future time period under A2 and B2 emissions scenarios based on Hadley Centre climate model (HadCM3) (Source: Murphy and Charlton, 2008).

			% Magnitude Change		Flood Frequency Change	
			Barrow	**Moy**	**Barrow**	**Moy**
T2	**A2**	**2020s**	1	6	1.8	1.6
		2050s	11	7	1.6	1.5
		2080s	7	13	1.3	1.3
	B2	**2020s**	3	9	1.8	1.4
		2050s	10	11	1.6	1.4
		2080s	9	12	1.5	1.4
T10	**A2**	**2020s**	8	24	4.8	4.2
		2050s	11	8	4.8	4.4
		2080s	7	39	3.4	2.2
	B2	**2020s**	15	29	3.7	2.2
		2050s	16	28	4	4.6
		2080s	18	17	2.9	3.9
T25	**A2**	**2020s**	13	39	8.3	7.7
		2050s	12	9	10.1	8.5
		2080s	8	64	6.7	3.1
	B2	**2020s**	23	44	5.5	3
		2050s	20	46	7.7	10.3
		2080s	24	20	4.6	8.2
T50	**A2**	**2020s**	18	54	12.6	12.3
		2050s	12	11	18.3	13.9
		2080s	9	92	11.5	4
	B2	**2020s**	31	57	7.4	3.9
		2050s	23	65	13.2	19.6
		2080s	29	23	6.8	15

It is likely that, as a result of climate change, Irish river stream flow across the majority of catchments will increase by approximately 20% in winter and spring by mid to late century (Murphy and Charlton, 2008). This change in stream flow is driven by projected increases in winter rainfall in the region of 10% by the 2050s and a reduction in summer rainfall by 12-17% (Figure 7.7). The largest percentage winter increases are expected in the midlands. By mid-century southern and eastern coasts could have 20 to 28% less rain in summer (Fealy and Sweeney, 2008). In turn, flood events are predicted to become more frequent, with current 50-year events moving closer to a 10-year return period towards the end of the century (Murphy and Charlton, 2008). Additional economic damages for this period in Ireland and the UK are expected to be in the region of over €700M to nearly €5B (European Commission, 2009a).

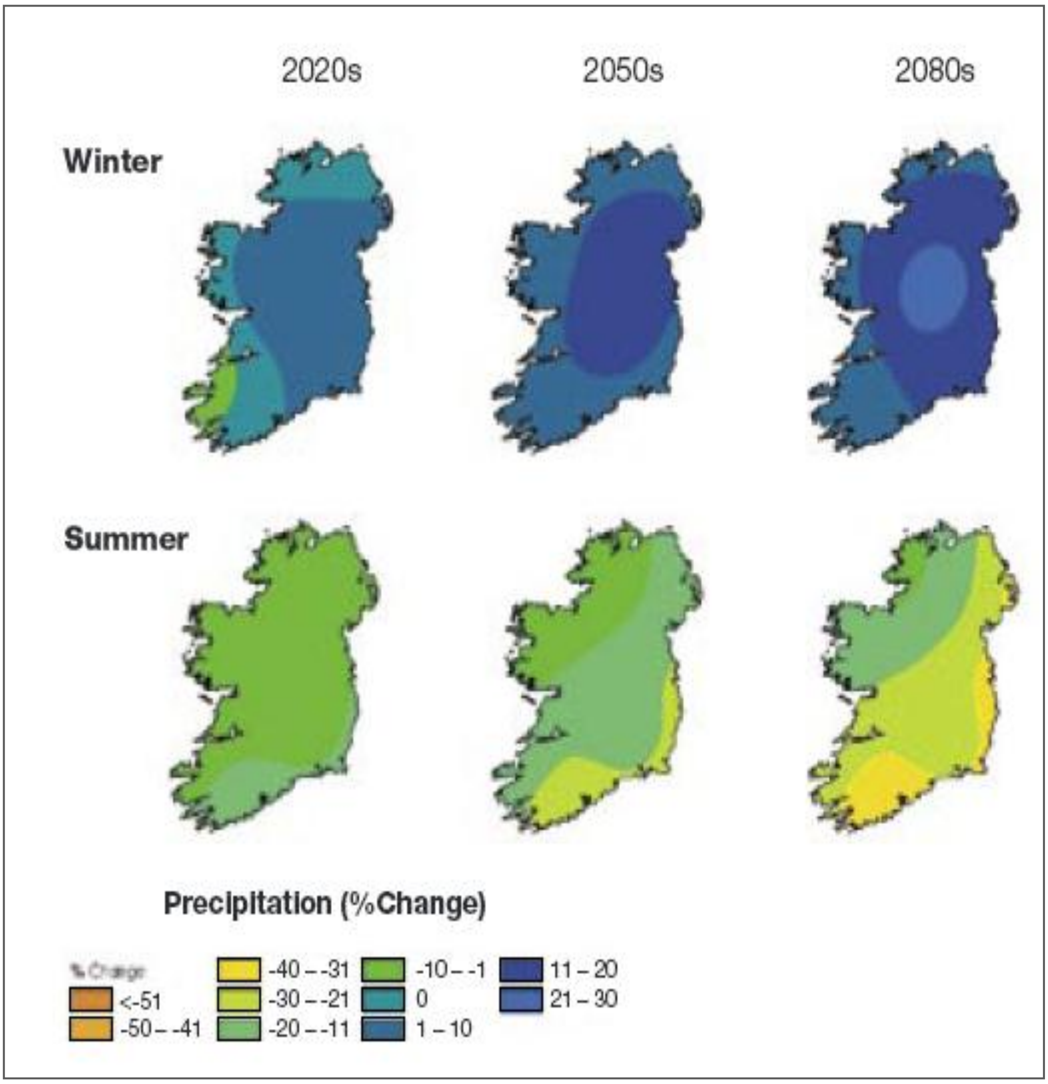


Figure 7.7: Changes in rainfall based on an ensemble of several global climate models (GCMs) and emissions scenarios, down-scaled for Ireland 2020s-2080s. (Source: Fealy and Sweeney, 2008).

7.4.3 Irish historical flood records and economic costs

Table 7.3 below lists the major flood events in Ireland in the last half-century along with the areas affected. On the basis of historical information collected by the OPW there are in excess of 300 areas in Ireland known to be at risk, or subject to, periodic flooding (OPW, 2004). Historical records of flood events are available from the OPW's flood maps website (OPW, 2011). Although inland flood defences exist in Ireland in many cases they have not been centrally recorded or indeed recognised as defences until they fail or are interfered with (OPW, 2004). These defences vary from natural features to man-made defences and can range from ditches or embankments to small stone walls to sluices and barriers. The OPW's Flood Hazard Mapping website provides map outputs on historical flood events recorded in Ireland (Figure 7.8) (OPW, 2011).

Table 7.3: Major flood events in Ireland over last half-century (Source: OPW, 2010a).

Major Flood Events in Ireland Since 1946	
DATE	**EVENT**
1946	Kilkenny flooding (Nore and Suir)
1954	Widespread flooding in the Midlands including The Shannon, Barrow, Nore and Suir
1968	Tidal flooding affecting the South West
1986	"Hurricane Charlie" cause severe flooding and damage in parts of Dublin and other towns surrounding the Wicklow Mountains
1993-94	Severe and prolonged flooding in the karst areas of South Galway
1997	Major flooding in Clonmel (Suir catchment)
1999-2000	Some of the worst flooding on record along the Shannon
2000	Severe flooding throughout the country
2002	Tidal flooding of Dublin and other towns along the East coast
2004	Major floods in the South-East
2007	Floods in the Dublin area
2008	Flash floods throughout the country with Carlow town experiencing some of the worst flooding
2009	Severe nationwide flooding especially in Cork city and Galway
2010	Flooding events in Cork
2011	Flooding primarily on the East coast with Dublin city experiencing greatest impacts

The website's primary target groups are the general public, planning authorities, developers and engineers. In addition to the map outputs the site also provides supporting data such as photographs, press articles and reports relating to the individual flood events. A limited number of flood events are additionally marked with flood extent. This can be observed in the centre of Figure 7.6 where a previous flood extent in marked with blue hatching. More detailed flood extent maps are proved as outputs of a number of Catchment Flood Risk Assessment and Management Studies (CFRAM) carried out by the OPW.

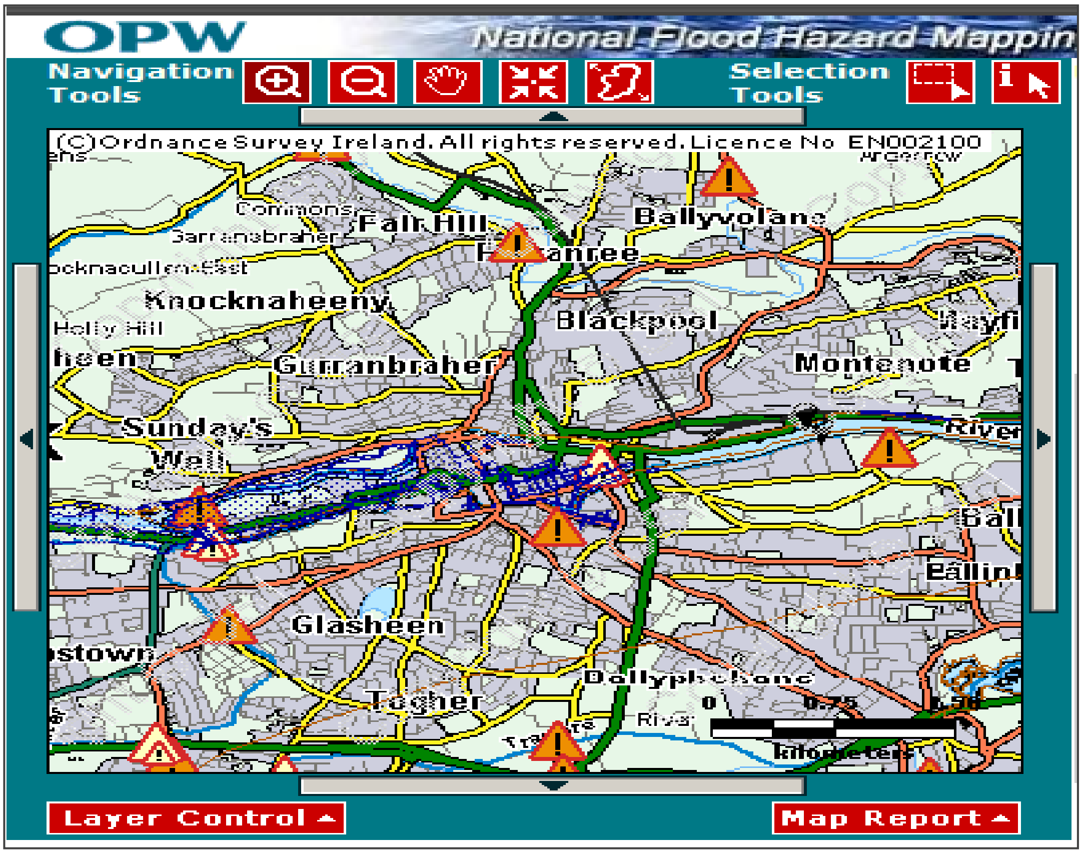


Figure 7.8: OPW flood hazard map with hazard triangles showing historical incidences of flooding in Cork City (OPW, 2011).

The outputs of the studies include flood maps displaying water extent, depth, velocity as well as hazards for a limited number of case study catchments. Unfortunately these maps are unavailable for replication here due to copyright restrictions. However, Figure 7.9 is an example of an extent map similar to those produced in the OPW studies. This map was produced by French consultancy group Sertit under the European SAFER initiative. It maps out the flood extent of the November 2009 flood event in the Shannon basin. The Services and Applications For Emergency Response (SAFER) initiative was established under the European Communities Seventh Framework Programme to reinforce European capacity to respond to emergency situations such as fires, floods, earthquakes, volcanic eruptions and landslides (SAFER, 2008). The legend magnified in Figure 7.10 indicates both the crisis time water extent (light blue) and the urban and housing areas close to the flooded area (grey).

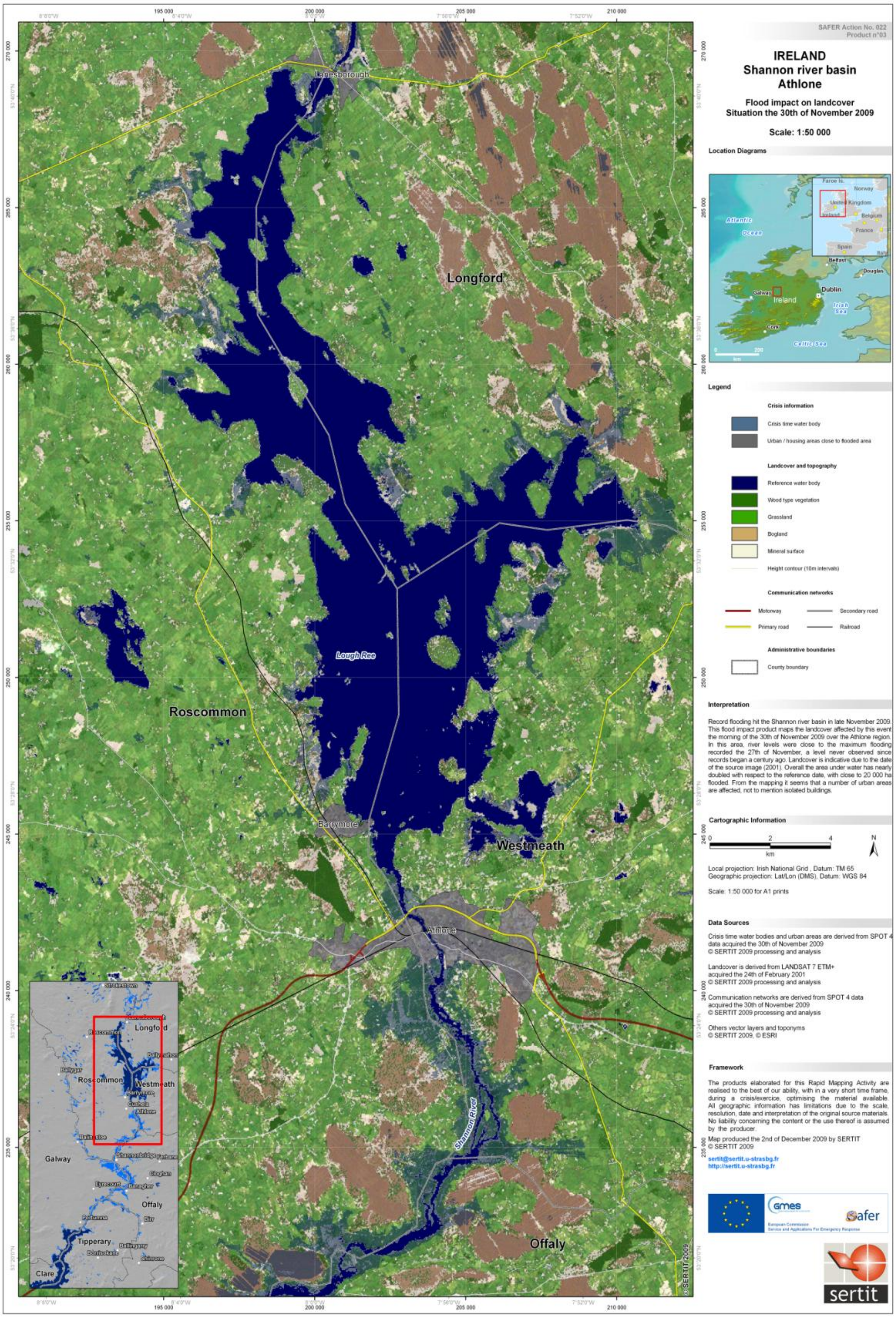


Figure 7.9: Flood extent on November 2009 in the Shannon river basin (Source: SAFER 2009).

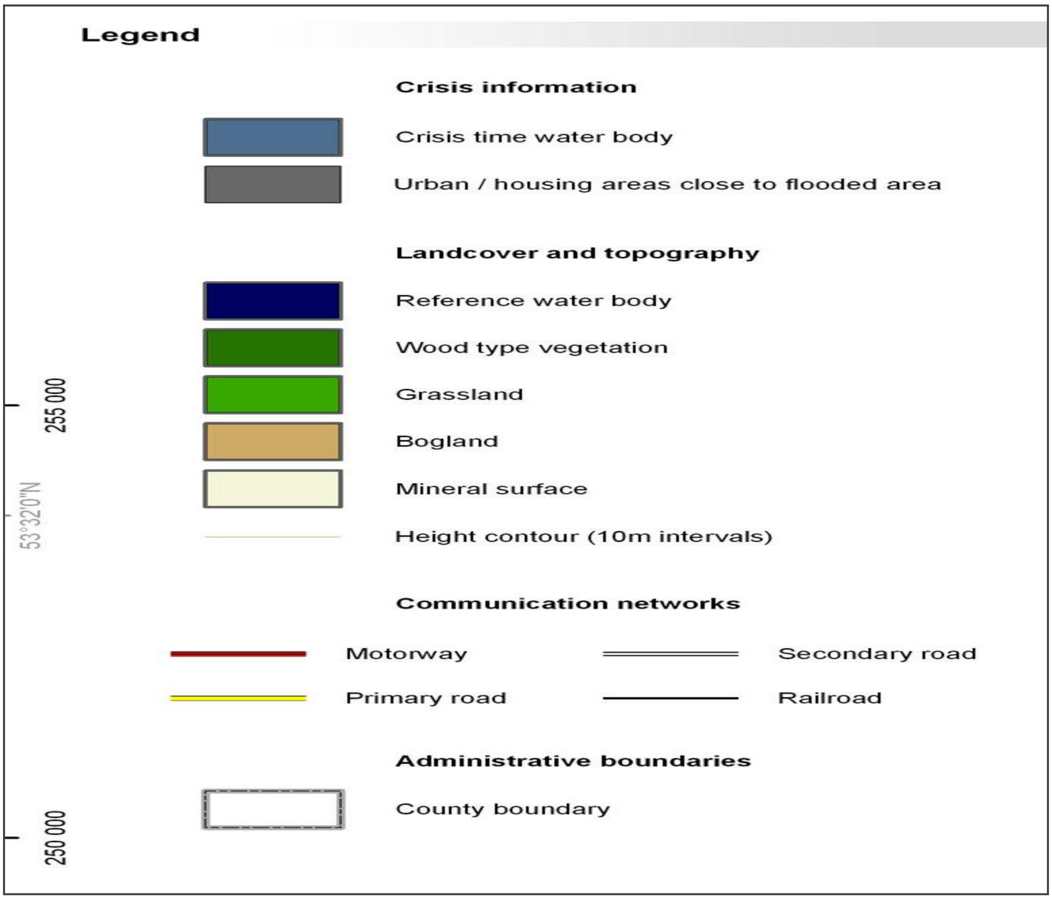


Figure 7.10: Magnified legend from Figure 7.9.

The 2003 report of The Flood Policy Review Group (OPW, 2004) was the product of a review into national flood policy carried out in response to serious flooding in the October and November 2002 floods and a general lack of clarity surrounding the State's response to flooding. It provided an overview of the economic costs associated with flooding in an Irish context and argues the case for an integrated river basin based approach for managing future flood risk. The report considers a number of economic costs relating to flood impacts. It discusses impacts on properties and land as well as impacts on public utilities, and the costs associated with loss of business due to the flooding of commercial establishments (Table 7.4).

Table 7.4: Flood impacts (Source: OPW, 2003).

Flood Impacts	
Property damage	Trauma and stress (at time of flooding)
Contents damage	Immediate risks to life and health of residents
Clean-up costs	Disruption in services
Evacuation costs	Long-term health effects
Costs of restoring public services	Trauma and stress due to fear of future floods
Costs of providing emergency public services	Damage to heritage or cultural sites
Disruption of commercial activity	Loss of amenities
Loss of property values	Environmental damage

The OPW estimates the annual average damages for studies as of 2003 lie in the range of approximately €250,000 to €2.6M, with a mean value of €1.1M. The locations subject to flood relief studies in the Report are expected to be those with the highest levels of risk. It is therefore assumed in the Report that €250,000 would be a reasonable national value. The report assumes that there are in excess of 300 locations and through a simple calculation estimates annual average flood damages of €75M.

Insurance figures released by the Irish Insurance Federation (IIF) in February 2010 report €244M of costs associated with claims relating to the November 2009 flooding, with 2012 figures reporting claims for the October 2011 flood of €127M (IIF, 2010; 2012). It is interesting to note that these figures are significantly greater than the OPW's estimated annual flood damages of €75M. The county worst hit by the November 2009 flooding events was Cork, with claims of €141M. Cork makes up over half the total value of claims as the flooding impacted upon the city centre and resulted in a large number of flooded properties. Galway's insurance claims relating to the flooding came to €23M. The flooding in Galway mostly relates to smaller towns and villages and a vast rural area hence the property damages and resulting claims costs are considerably lower than in Cork. The next most impacted county in terms of claims costs is Clare €16M. This figure relates to towns like Ennis as well as villages and rural areas. The remaining €64M worth of claims is distributed over the rest of the country and covers at least 12 counties. The October 2011 flood, amounting to €127M in flood claim costs, is the second most expensive flood event, after the November 2009 floods. The floods occurred on the east cost and mostly in Dublin city and county and consisted of 6,703 customer claims, with €58M in household claims (3,523 claims), €58M in commercial property claims (1,251 claims), and €10M in motor claims (1,920 claims) (IIF, 2012). Table 7.5 lists insurance claim costs issued by the IIF since November 2000.

Table 7.5: Insurance claim costs relating to flood events in Ireland since 2000(Source:IIF).

Insurance claim costs relating to flood events in Ireland since 2000	
DATE	**COST €M**
October 2011	127
November 2009	244
August 2008	96
October 2004	38
November 2002	50
February 2002	37
November 2000	51

This section analysed the historical records of Irish inland flooding events, as well as the economic costs linked with inland flooding. It is likely that future climate change-related increases in both river flood frequency and magnitude will increase these economic costs significantly. The level of present and potential future economic impacts linked with Irish flood events highlights the importance of developing and implementing flood management schemes in Ireland, with the aim of limiting these economic costs. The following Section (7.5) explores the role of Irish flood policy in relation to flood risk management and the reduction of economic costs relating to flooding.

7.5 IRISH FLOOD POLICY

Flooding and flood impacts have been a major consideration for those governing Ireland since the mid-19th century. Four drainage acts were passed since 1842 in the run up to the development of the 1945 Arterial Drainage Act (OPW, 2011). This piece of legislation empowered the OPW to undertake catchment-wide arterial drainage schemes in order to reduce flooding and was the primary piece of flood management legislation for a fifty year period. The emphasis of the 1945 Act was on the improvement of agricultural land. However, after the severe flooding of a number of towns in the mid to late 80s and early 90s the act was amended in 1995. The new amendment shifted the focus of flood management towards the protection of urban areas subject to flooding. This amendment in turn led to the undertaking of localised flood relief schemes designed to reduce flood risk and increase protection in individual urban areas.

In 2002-2004 a review of Irish existing flood policy took place (OPW, 2004). This review was initiated by the Minister of State with responsibility for the OPW following a series of major floods in 2000 and 2002. The Report of the Flood Policy Review Group recommended the OPW as the lead agency for flood risk management in Ireland and set out a number of recommendations suggesting new work and approaches that should be taken to identify and manage flood risk. In 2004, following government approval, the OPW along with the partner organisations of the Department of the Environment, Heritage and Local Government, the Department of Agriculture, Food and Rural Development and the Local Authorities began developing and implementing a range of work programmes relating to flood risk management. The lead recommendation of the Flood Policy Report was the creation of a National Flood Hazard Mapping Programme. It was intended that the results be published on the internet, and that all information be made available as inputs into future planning and development. Catchment Flood Risk Assessment and Management Studies Plans

(CFRAMS) form the core of these work programmes, with a CFRAM to be carried out for each river catchment in the country. The output of these studies includes a strategic Flood Risk Management Plan (FRMP) along with a Strategic Environmental Assessment (SEA) that sets out measures and policies in order to manage flood risk in a sustainable and cost effective manner. CFRAMS are currently being carried out on the River Lee, the River Dodder, the River Suir, and the Fingal-East Meath area (OPW, 2010a).

In March 2010 the Minister of State with responsibility for the OPW announced the transposition of the EU Floods Directive into Irish law (OPW, 2010c). The Directive sets out a best-practice framework for flood risk management and assessment in Europe that requires that member states prepare national flood maps by 2013 and flood risk management plans by 2015 for areas where flood risk is significant. A budget of €45.8M was allocated to the OPW for its Flood Risk Management Allocation for 2011 (OPW, 2010b).

7.6 CONCLUSION

This chapter has reviewed physical and economic impacts relating to present inland flooding in Europe and Ireland. It has also analysed the potential impacts of future climate change on river flow and flooding. Finally, it has demonstrated the importance of developing a proactive river flood management programme in Ireland in order to limit the economic costs of inland flooding. It is important to stress that flood management programmes are important even in the absence of a clear climate signals in river flow rates under the “starting point” interpretation of vulnerability. The following chapter considers “end point” vulnerability by exploring potential climate related vulnerabilities through carrying out an economic analysis of flood impacts on Irish river catchments.

CHAPTER 8
EVALUATING ECONOMIC COSTS OF INLAND FLOODING IN IRELAND

8.1 INTRODUCTION

Documented historical economic costs of flooding in Ireland, as well as potential future costs, are significant. This chapter once again takes an “end point” interpretation of vulnerability to determine potential climate change related economic costs associated with inland flood impacts. The study evaluates the economic impacts on residential and commercial properties using DTM modelling on four Irish river catchments. This original modelling work is then corroborated by mapped incidents of historical flood events as provided by the OPW. Future inland flooding costs under climate change are also projected using OPW data and historical insurance claim costs, along with inputs from the climate change hydrology literature. Finally, these estimates are again corroborated by extrapolating future inland flooding costs for Ireland from the modelling outputs obtained from the four Irish catchments.

8.2 INLAND FLOODING CASE STUDIES

Detailed economic costs relating to inland flooding in Ireland are currently not available in the existing literature. In lieu of such data this study makes use of Irish Insurance Federation (IIF) claims data from the November 2009 and October 2011 major flood events, as described in Chapter 4 (IIF, 2010; 2011). Using the figures from both events as a guidline an average estimate of costs per claim was calculated for residental and commercial properties. The average insurance claim per residential household was approximated at €16,500. The average insurance claim per commercial property is approximately €75,000. The commerical claim value is much greater than the residential claim due to additional commercial losses relating to stock and equipment.

The case study below presents indicative modelling results for four Irish river catchments. See Figure 8.1 for details on Irish catchment size and locations. Hydrologically adjusted DTMs[28] of the case study catchments were used to determine the major river networks in each catchment. A hydrologically adjusted DTM is an adjusted elevation raster in which any depressions in the source DTM have been eliminated (filled), but which allows for internal drainage since some landscapes contain natural depressions. The river network in each of the case study catchments was determined by modelling river flow, accumulation and direction from the hydrologically adjusted DTMs. A series of elevation buffers (1 metre, 2 metre and 3 metre) were then fitted to each river network to estimate a range of flood scenarios. A 1m scenario over the catchment is estimated for a 1 in 25 year return period flood event. The 2m scenario is the 1 in 50 year flood estimate and the 3m scenario is equivalent to a 1 in 100 year event. It should be noted that the return periods linked with the elevation buffers are approximate, as a uniform river elevation over a catchment does not exactly replicate an actual flood event. However, these elevation simulations do result in modelled impacts that are comparable with the particular return periods.

Point addresses were compiled from the 2009 An Post Geo-Database after first being screened for vacant and derelict addresses. These addresses were then overlaid on the catchments to create an indicative assessment of potentially exposed residential and commercial properties in each catchment under the three elevation scenarios.

[28] 20 metre resolution Digital Terrain Model from the Irish Environmental Protection Agency.

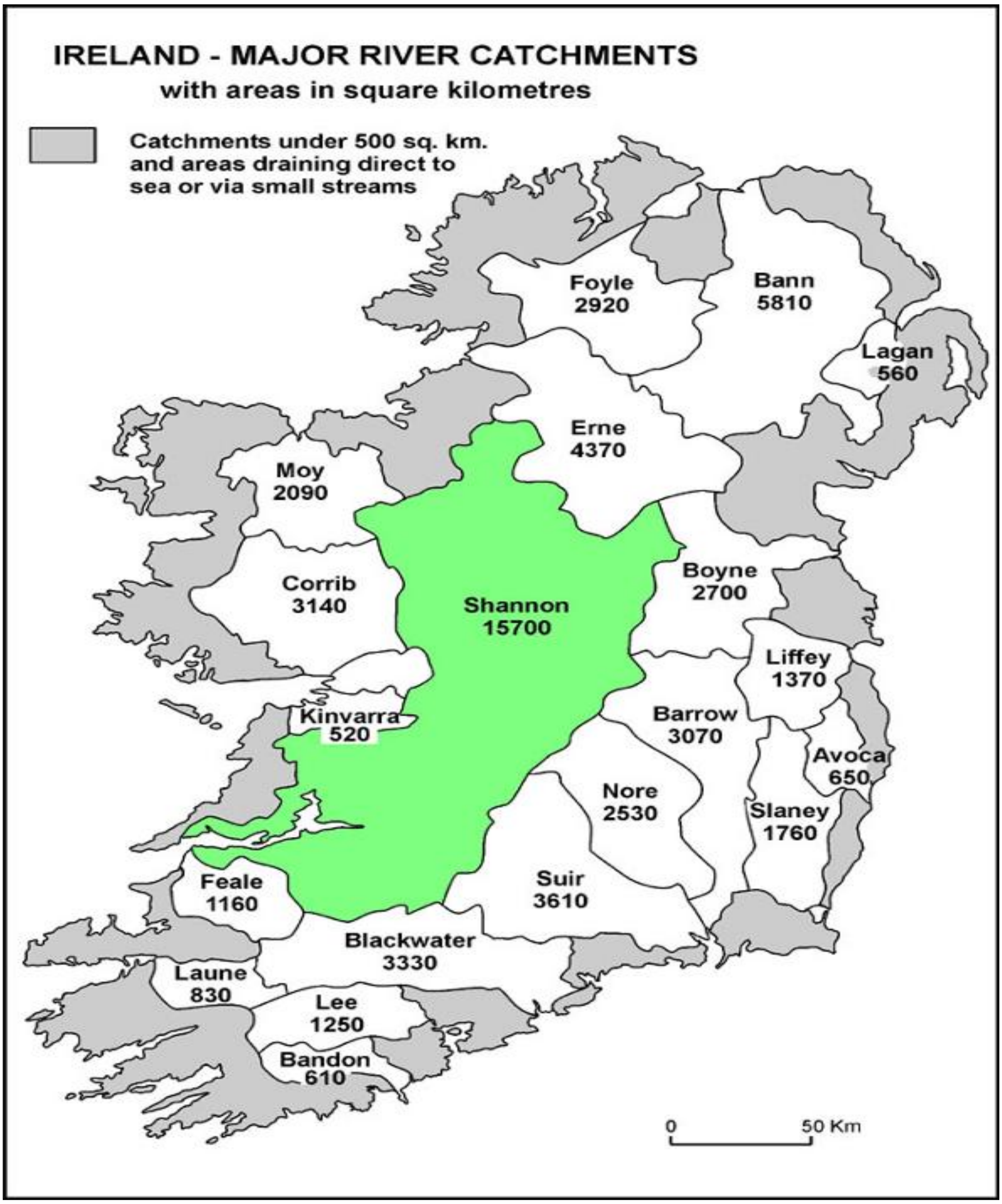


Figure 8.1: Major Irish river catchments (Ask about Ireland, 2012).

The Barrow, the Nore, the Upper Shannon and the Moy catchments were the four case study catchments chosen for this study. The Barrow is Ireland’s second longest river and rises in the Slieve Bloom Mountains in County Laois. As a legacy of past planning policies, there are significant developed areas in close proximity to, or indeed on, some of the river’s existing floodplain. This has subsequently led to significant changes in river morphology and hydrology, which have resulted in increased river flooding. In addition, climate change impacts are projected to increase flood frequency and magnitude significantly by mid to late century (Murphy and Charlton, 2008). The river Barrow is designated as a Special Area of Conservation (SAC). The Nore rises in North Tipperary and is approximately 140km in length. One of the two types of the endangered pearl mussel species can only be found in this river catchment, and sections of the river are designated as an SAC. The Shannon rises in County Cavan and is the longest in Ireland at over 360km in length. It is often subject to severe flooding with events recorded over the last 150 years. The Moy rises in the Ox Mountains in County Sligo. The Moy is one of the most prolific salmon rivers in Europe and is particularly vulnerable to future flood risks (Murphy and Charlton, 2008).

Figures 8.2–8.9 below present the modelled results for each of the four catchments. These figures highlight the potentially exposed commercial and residential addresses under a one metre elevation buffer.

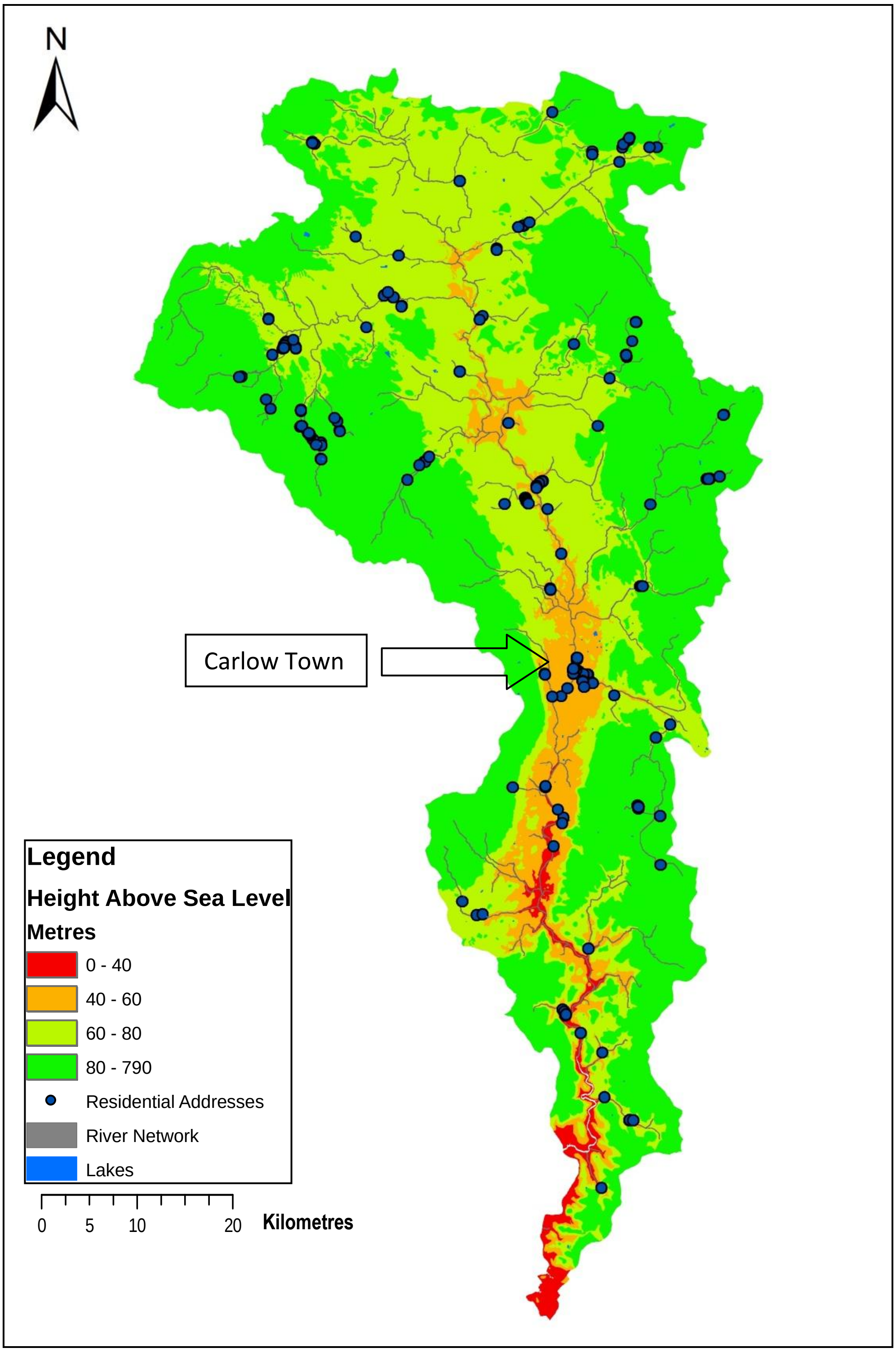


Figure 8.2: Potentially exposed residential addresses in the Barrow catchment under a 1m elevation buffer.

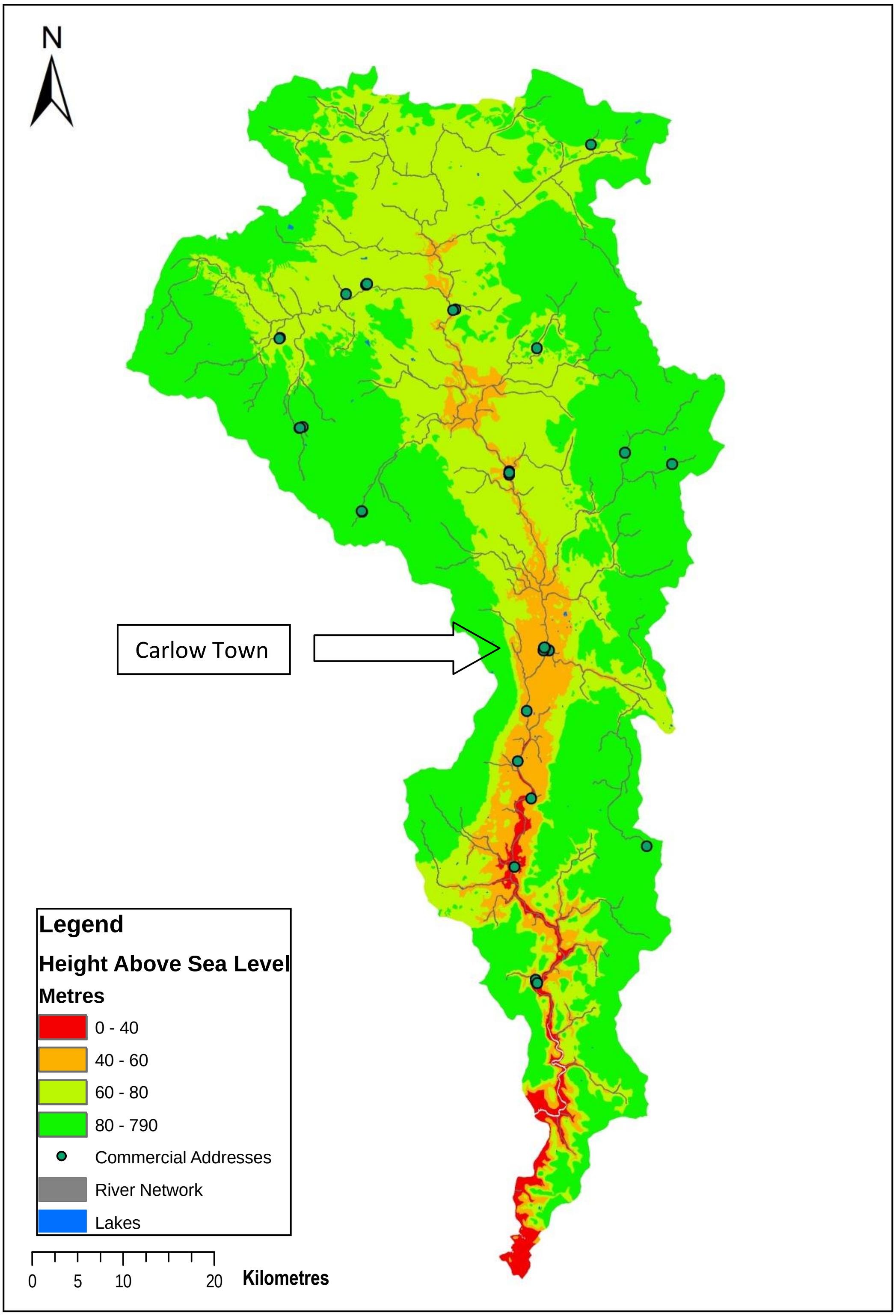


Figure 8.3: Potentially exposed commercial addresses in the Barrow catchment under a 1m elevation buffer.

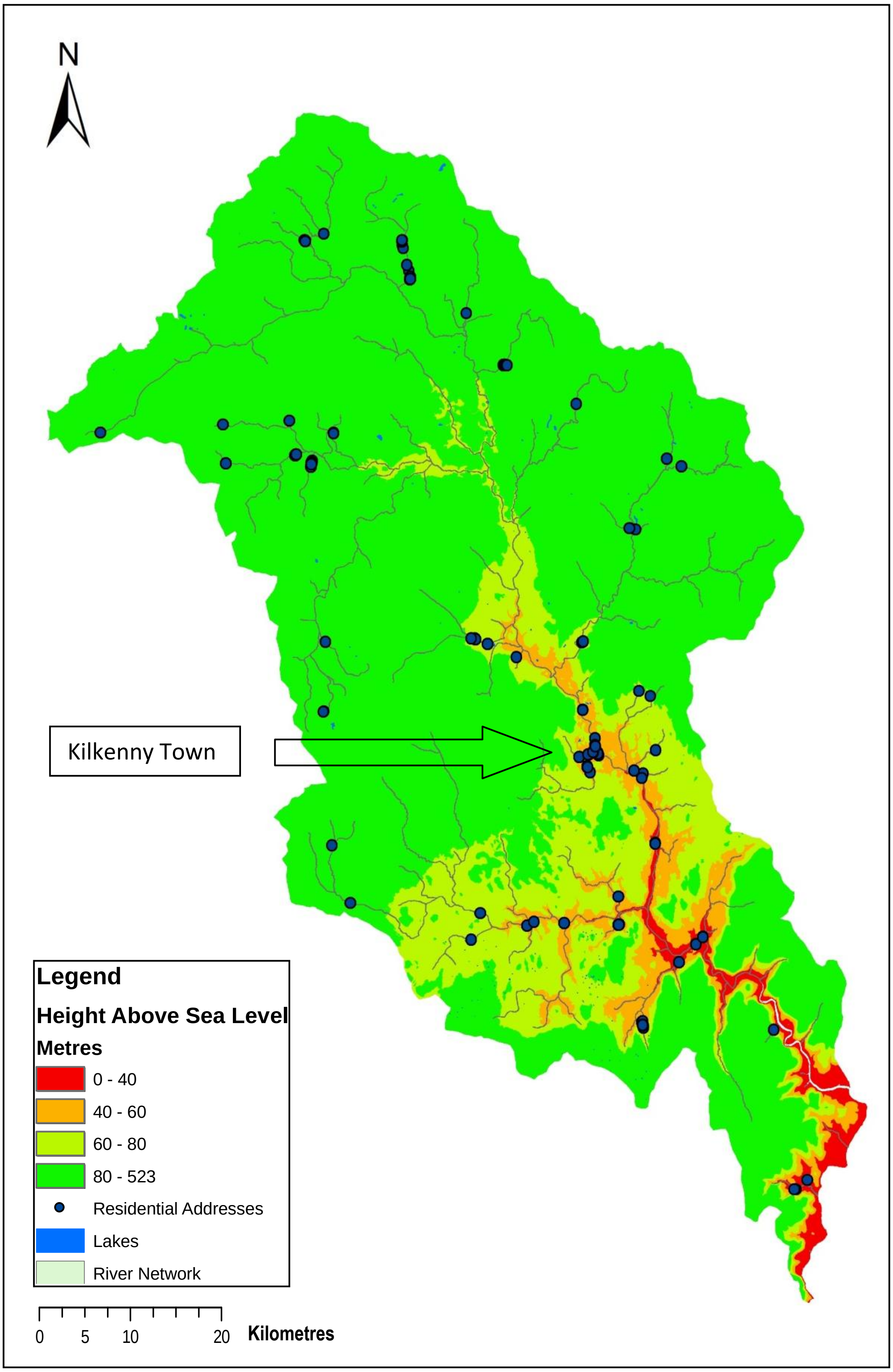


Figure 8.4: Potentially exposed residential addresses in the Nore catchment under a 1m elevation buffer.

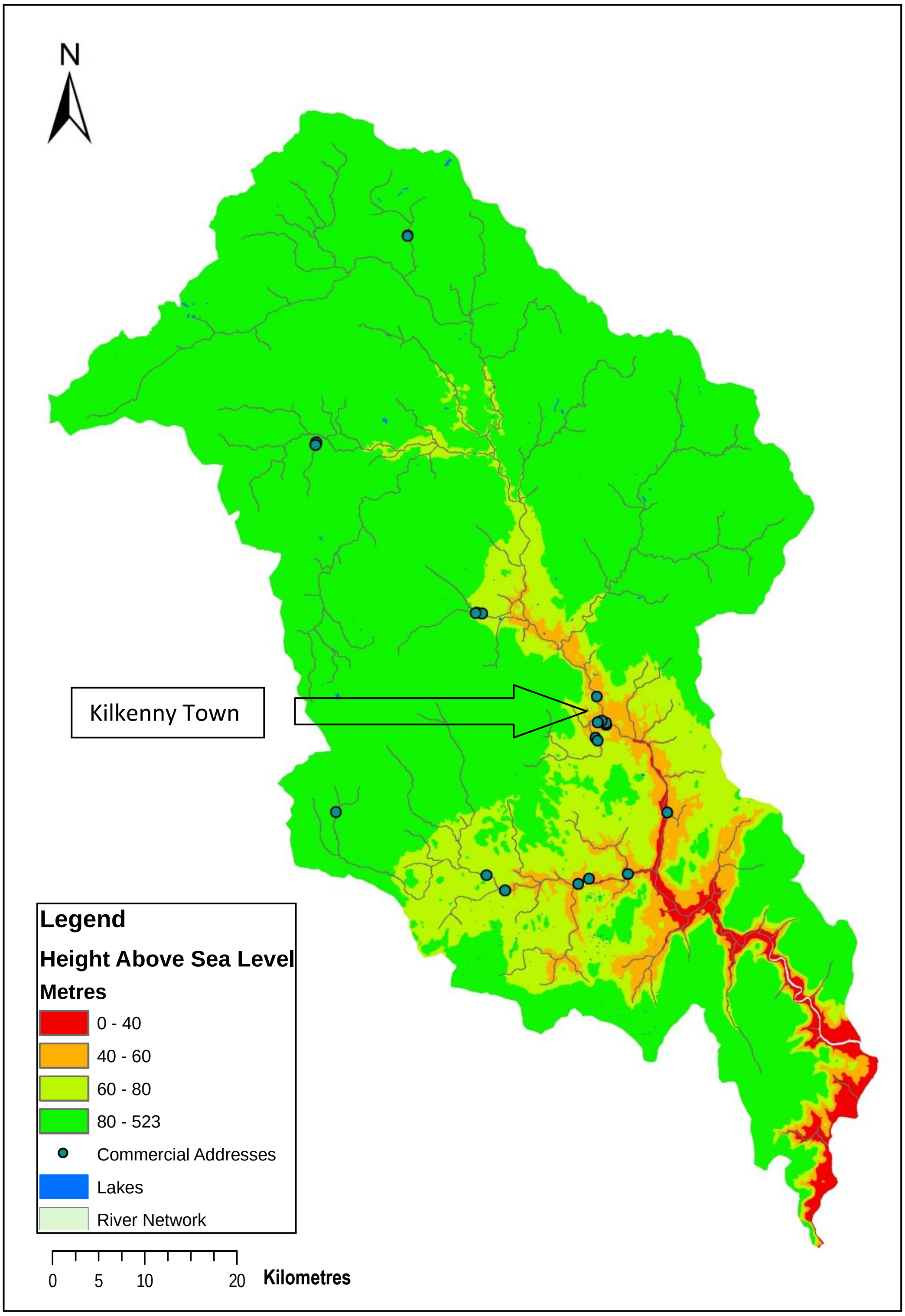


Figure 8.5: Potentially exposed commercial addresses in the Nore catchment under a 1m elevation buffer.

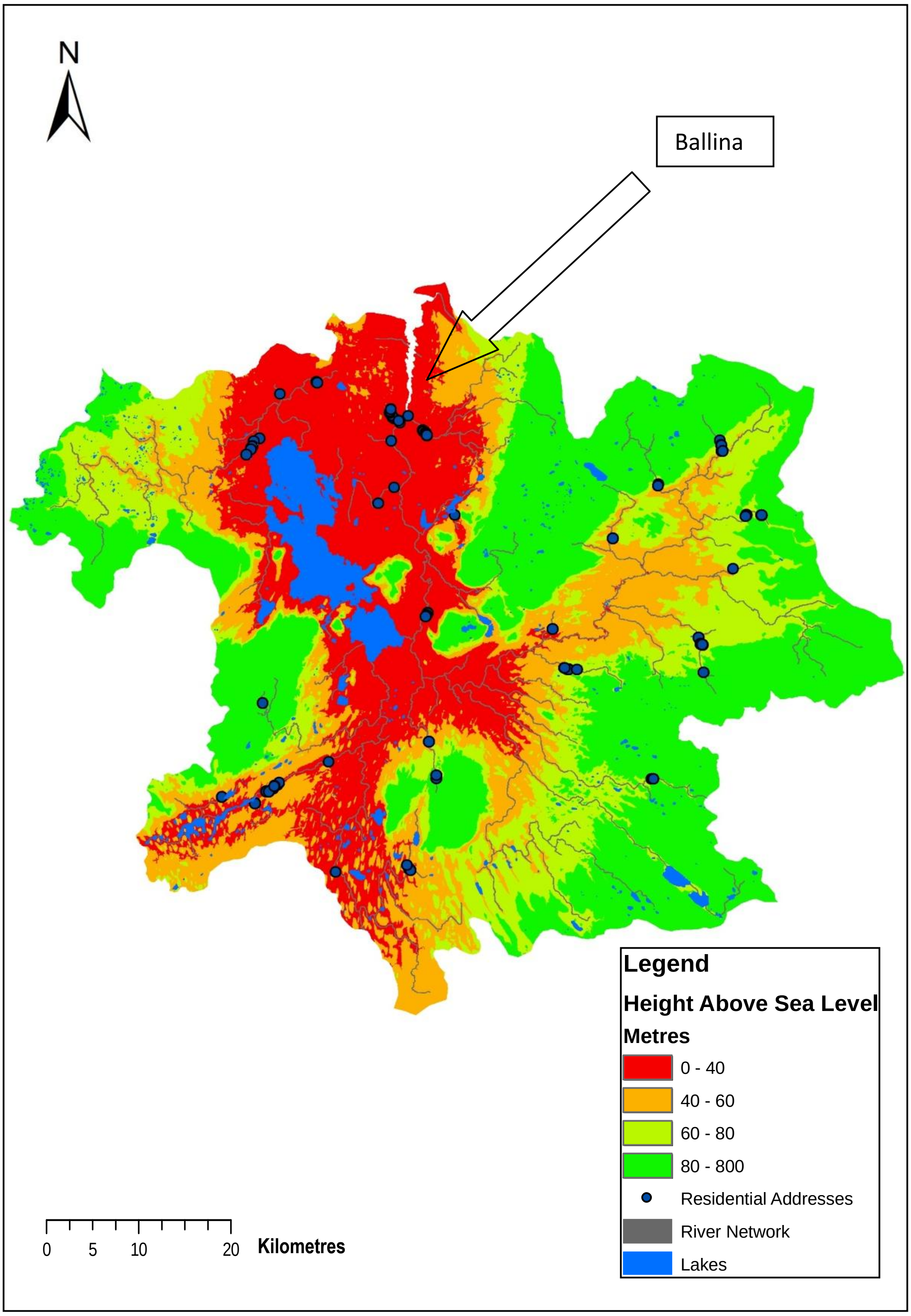


Figure 8.6: Potentially exposed residential addresses in the Moy catchment under a 1m elevation buffer.

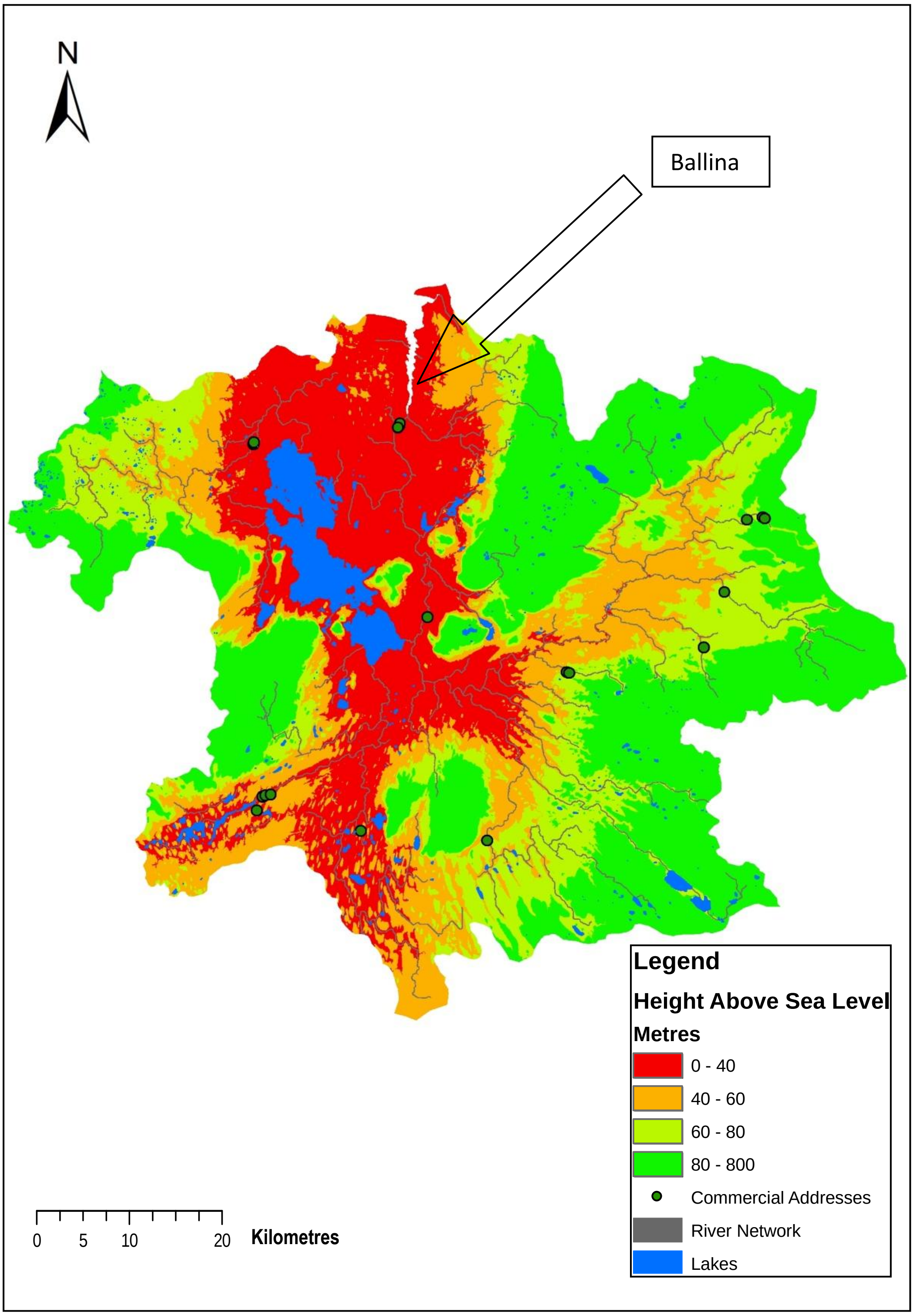


Figure 8.7: Potentially exposed commercial addresses in the Moy catchment under a 1m elevation buffer.

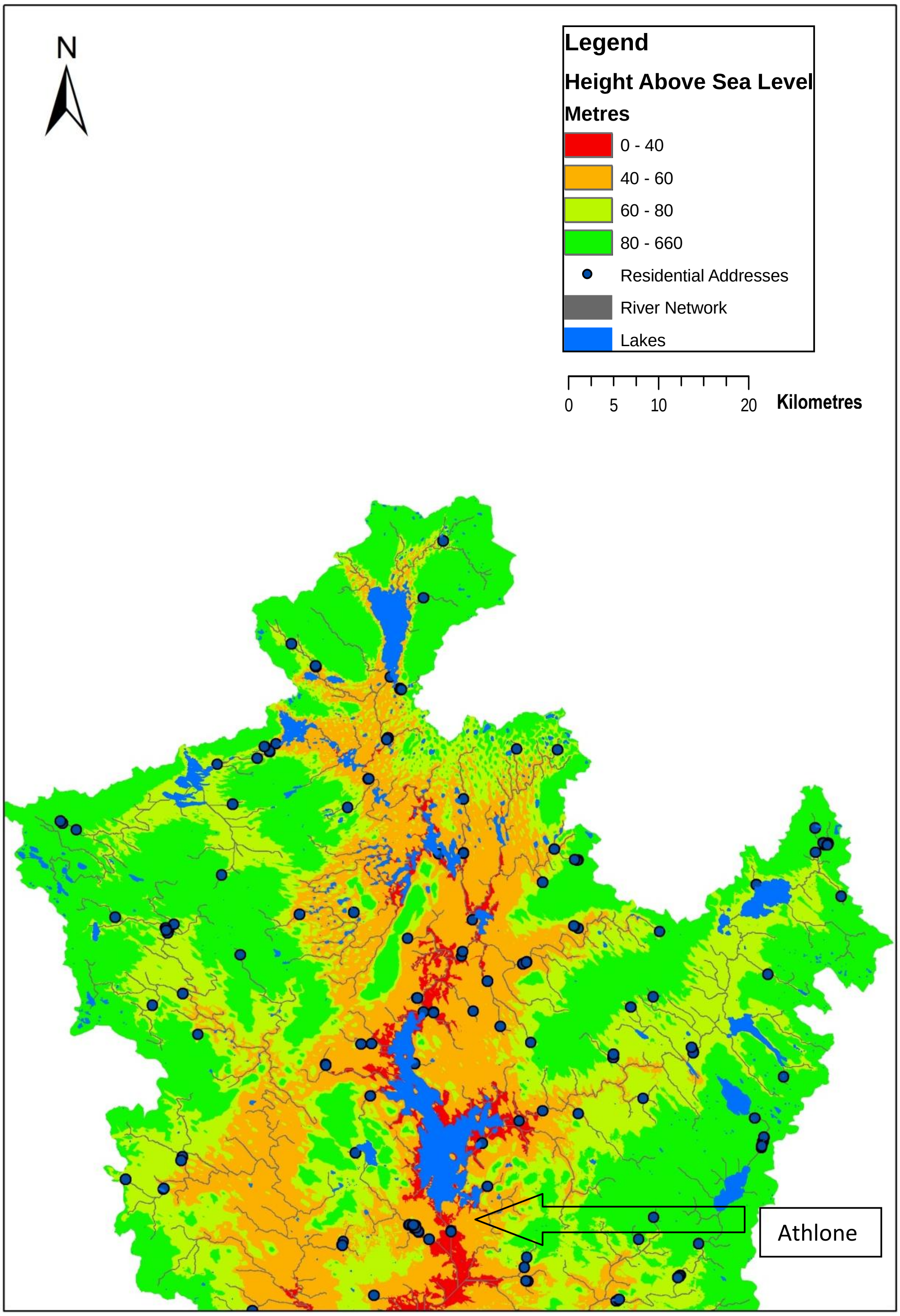


Figure 8.8: Potentially exposed residential addresses in the Upper Shannon catchment under a 1m elevation buffer.

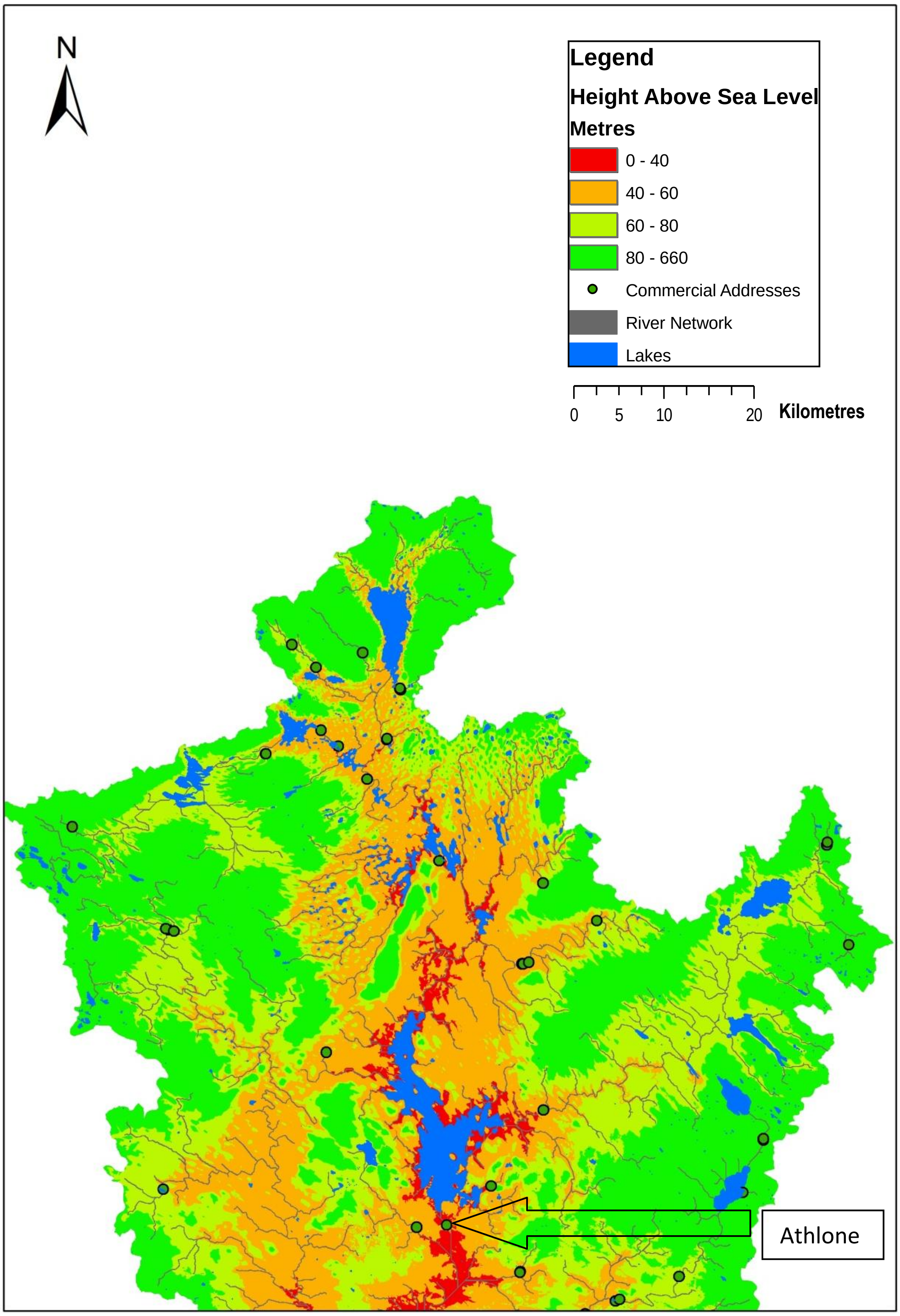


Figure 8.9: Potentially exposed commercial addresses in the Shannon Upper catchment under a 1m elevation buffer.

Figures 8.2–8.9 present the modelled outputs that were used to generate the data for exposed addresses in Tables 8.1, 8.2 and Figure 8.10. A key urban area is indicated for each case study catchment. The highlighted towns include Carlow (for the Barrow), Kilkenny (for the Nore), Ballina (for the Moy) and Athlone (for the Shannon Upper). The modelled catchment maps show the highest level of potentially exposed addresses for both Carlow (130 addresses) (Figure 8.2 and Figure 8.3) and Kilkenny towns (90 addresses) (Figure 8.4 and Figure 8.5). Ballina is next in terms of potential address exposure (50 addresses) (Figure 8.6 and Figure 8.7). The modelling results indicate the lowest levels of exposure for Athlone out of the four towns indentified in the case study catchments (25 addresses) (Figure 8.8 and Figure 8.9).

Table 8.1: Potential exposed commercial and residential addresses in four catchments under three buffer scenarios.

Catchment	**Buffer**			**Buffer**		
	1m	2m	3m	1m	2m	3m
	Commercial Addresses			**Residential Addresses**		
Barrow	62	66	78	571	618	697
Upr.Shannon	79	88	103	403	457	559
Nore	59	64	73	193	210	229
Moy	48	52	57	229	262	299

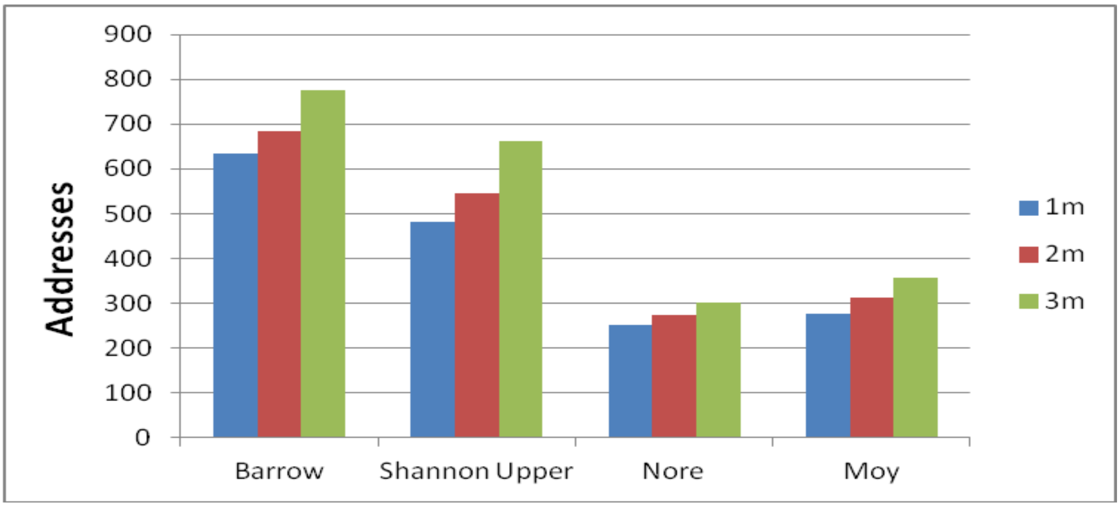


Figure 8.10: Potentially exposed addresses under 1m, 2m and 3m buffer scenarios in the four case study catchments.

Table 8.2: Potential insurance claim costs for commercial and residential addresses in four catchments under three buffer scenarios.

Catchment	**Buffer**			**Buffer**		
	1m	2m	3m	1m	2m	3m
	Commercial Addresses			**Residential Addresses**		
	€ M			€ M		
Barrow	4.65	4.95	5.85	9.42	10.20	11.50
Shannon Upper	5.93	6.60	7.73	6.65	7.54	9.22
Nore	4.43	4.80	5.48	6.65	3.47	3.78
Moy	3.60	3.90	4.28	3.78	4.32	4.93

The modelled results (Table 8.1, Figure 8.10 and Table 8.2) signify that the Barrow catchment has the greatest number of exposed residential addresses under a one metre buffer at approximately 571, and that the Shannon Upper catchment has the greatest number of exposed commercial addresses at approximately 79 with losses in the region of €9.4M and over €5.9M respectively. Total potential insurance claim costs for both commercial and residential addresses over the four case study catchments comes to €44.8M under the 1m scenario with 1,644 addresses potentially impacted. Under all three buffer scenarios the Barrow catchment (which is the second largest case study catchment at approximately 3,070km^2) has the highest level of potentially exposed addresses at over 630 addresses under the 1m scenarios, over 680 addresses under the 2m scenario and over 770 addresses under the 3m scenario.

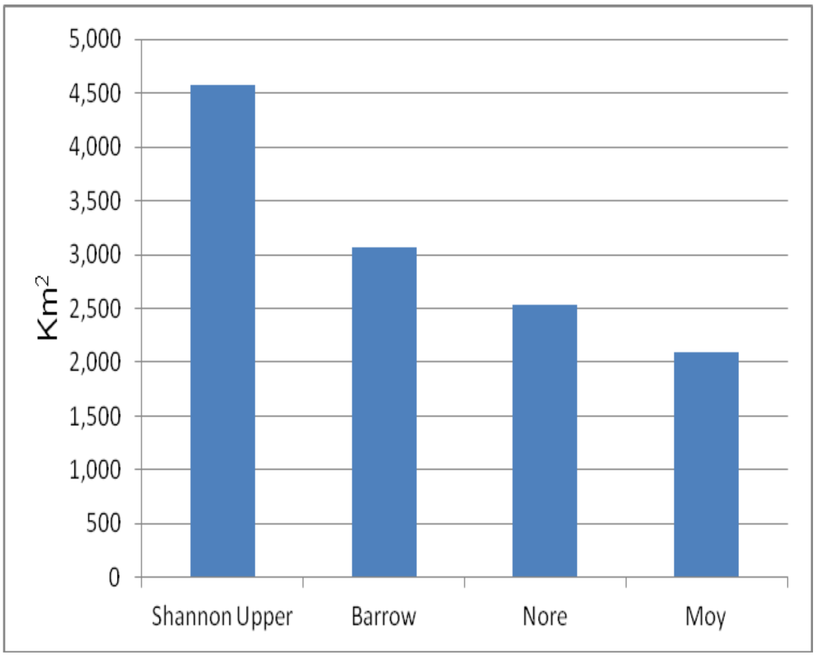


Figure 8.11: Case study catchment areas in km^2.

8.3 OPW HISTORICAL FLOOD RECORDS

The OPW have compiled a range of flood hazard maps in line with the 2004 Flood Policy Review Group’s recommendations to complete a National Flood Hazard Mapping Programme (OPW, 2004). Currently the most complete publically available flood hazard maps are national level historic flood maps (OPW, 2011). Historic flood mapping is the mapping of observed flood events as recorded by survey, photography, video, press, reports or memory. These maps are useful for providing supplementary information to predictive flood mapping. However, they are dependent on the availability of information relating to historic floods as well as the quality of that information. The OPW's historic flood maps were compiled from the records of over fifty different stakeholder organisations in the Republic including government departments, local authorities, national organisations, insurance companies and members of the public. The flood events include flooding caused by fluvial, tidal and coastal factors only. Floods relating to other causes, such as burst pipes or blocked sewers are not included in the analysis. Information sources included engineers' reports, letters, photographs, articles, eye-witness accounts and documents. This information was in turn catalogued, reviewed, classified and collated into the National Flood Data Archive (OPW, 2011). While this data set is incredibly valuable in its scope and detail, it is important to clarify the possible limitations of the historic flood mapping methodology with respect to completeness, reliability and accuracy. The OPW presents the data with the caveat that the finished archive is not a comprehensive catalogue of all past fluvial and tidal flood events in the country. They report that the material presented is limited to the available records of the source bodies and is provided at their discretion. They also note that newspaper articles often only report a limited number of the most severe known flood events in the past 120 years. It is also important to appreciate that the level of flood reporting may vary from county to county, as the propensity to report a given flood event, as well as reporting methodologies can differ between stakeholder organisations.

Figures 8.12 to 8.15 present point data provided by the OPW indicating the location of historical flood events - as found in the National Flood Data Archive - in the four case study catchments of the Barrow, the Nore, the Moy and the Shannon Upper respectively. These map outputs provide a useful overview of the catchment specific locations where historical flood events took place. This information is potentially useful both as a basis for policy dialogues and as a tool for priority setting in relation to adaptation options. The maps are also useful for corroborating the outputs of the economic impact flood risk mapping exercise carried out in Section 8.2. It should be clarified that that the OPW historical flood maps document flood events may or may not be directly linked with residential or commercial properties. These maps are useful as tools for checking to see if the spatial pattern of properties inundated under the flood modelling is displayed in the OPW historical flood events (Table 8.3).

Table 8.3: Spatial overlap between modelled exposed addresses and historical OPW flood events under two buffer scenarios.

Buffer	50m		500m	
Catchment	**Number of cases and percentage**			
Scenario				
Barrow	Com	Res	Com	Res
1m	**15**/ 62 (24%)	**40**/571 (7%)	**55**/ 62 (89%)	**308**/571(54%)
2m	**15**/66 (23%)	**34**/618 (6%)	**55**/66 (83%)	**324**/ 618 (52%)
3m	**15** /78 (19%)	**36**/697 (5%)	**61**/78 (78%)	**370**/687 (53%)
Nore				
1m	**11**/59 (19%)	**12**/193 (6%)	**48**/59 (81%)	**90**/193 (47%)
2m	**12**/64 (19%)	**12**/210 (6%)	**52**/64 (81%)	**99**/210 (47%)
3m	**14**/73 (19%)	**12**/229 (5%)	**61**/73 (84%)	**110**/229 (48%)
Moy				
1m	**3**/48 (6%)	**2**/229 (1%)	**27**/48 (56%)	**83**/229 (36%)
2m	**3**/52 (6%)	**2**/262 (1%)	**29**/52 (56%)	**100**/262 (38%)
3m	**3**/57 (5%)	**2**/299 (1%)	**31**/57 (54%)	**116**/299 (39%)
Upper Shannon				
1m	**4**/79 (5%)	**11**/403 (3%)	**43**/79 (54%)	**153**/403 (38%)
2m	**6/**88 (7%)	**13**/457 (3%)	**47**/88 (53%)	**179/**457 (39%)
3m	**6**/103 (6%)	**13**/559 (2%)	**55**/103 (53%)	**241**/559 (43%)

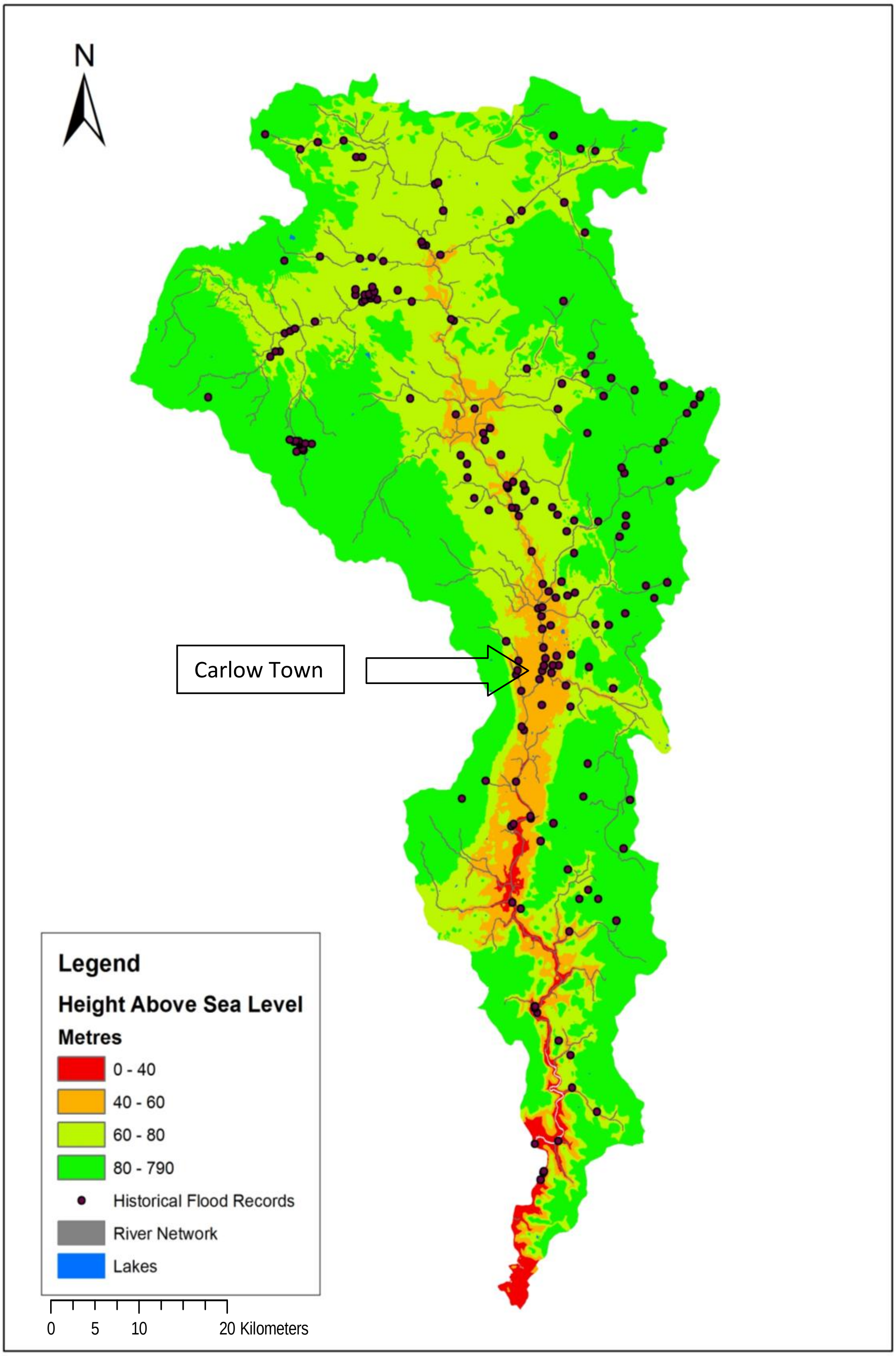


Figure 8.12: OPW historical flood records displayed in the Barrow catchment.

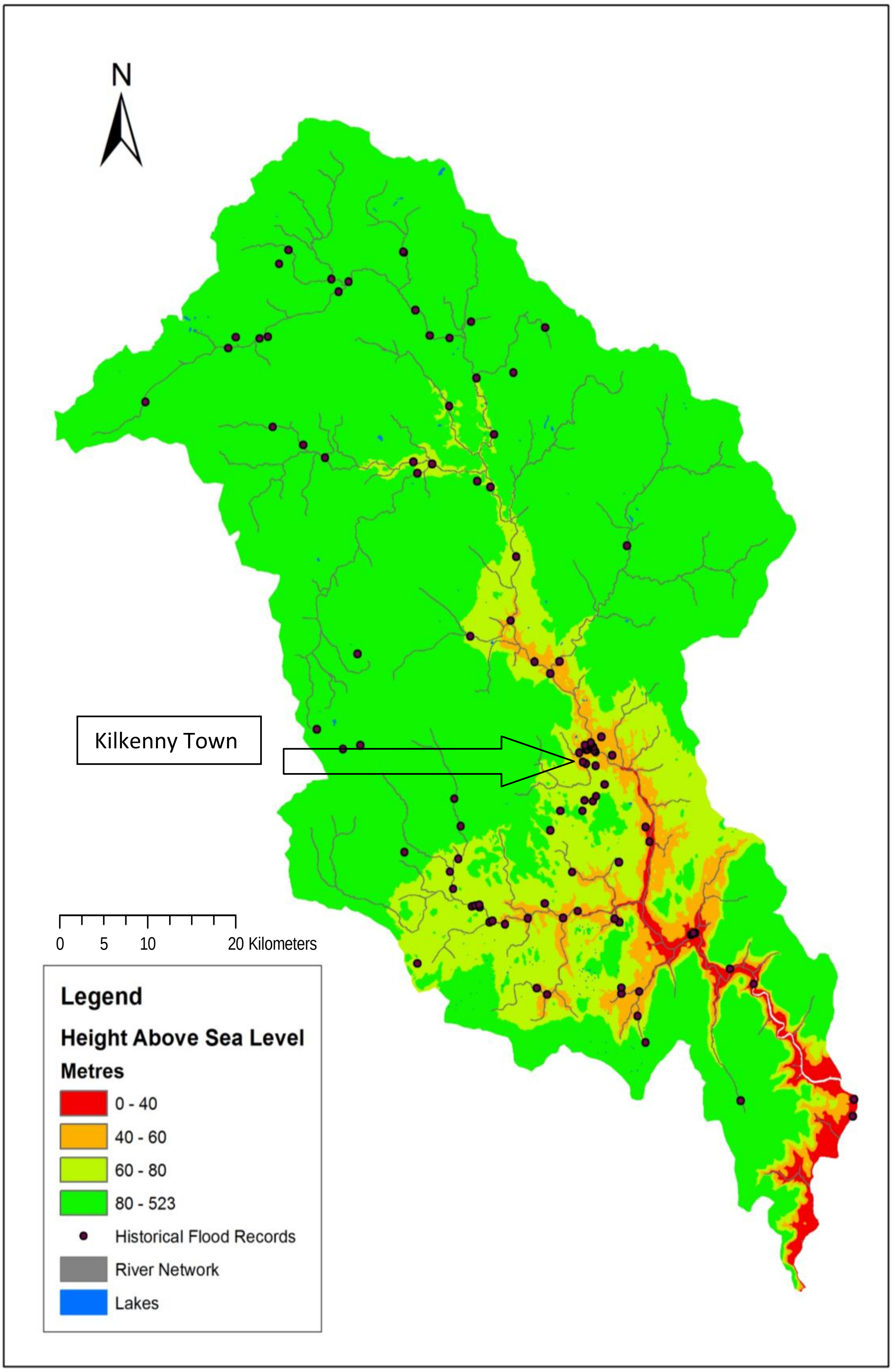


Figure 8.13: OPW historical flood records displayed in the Nore catchment.

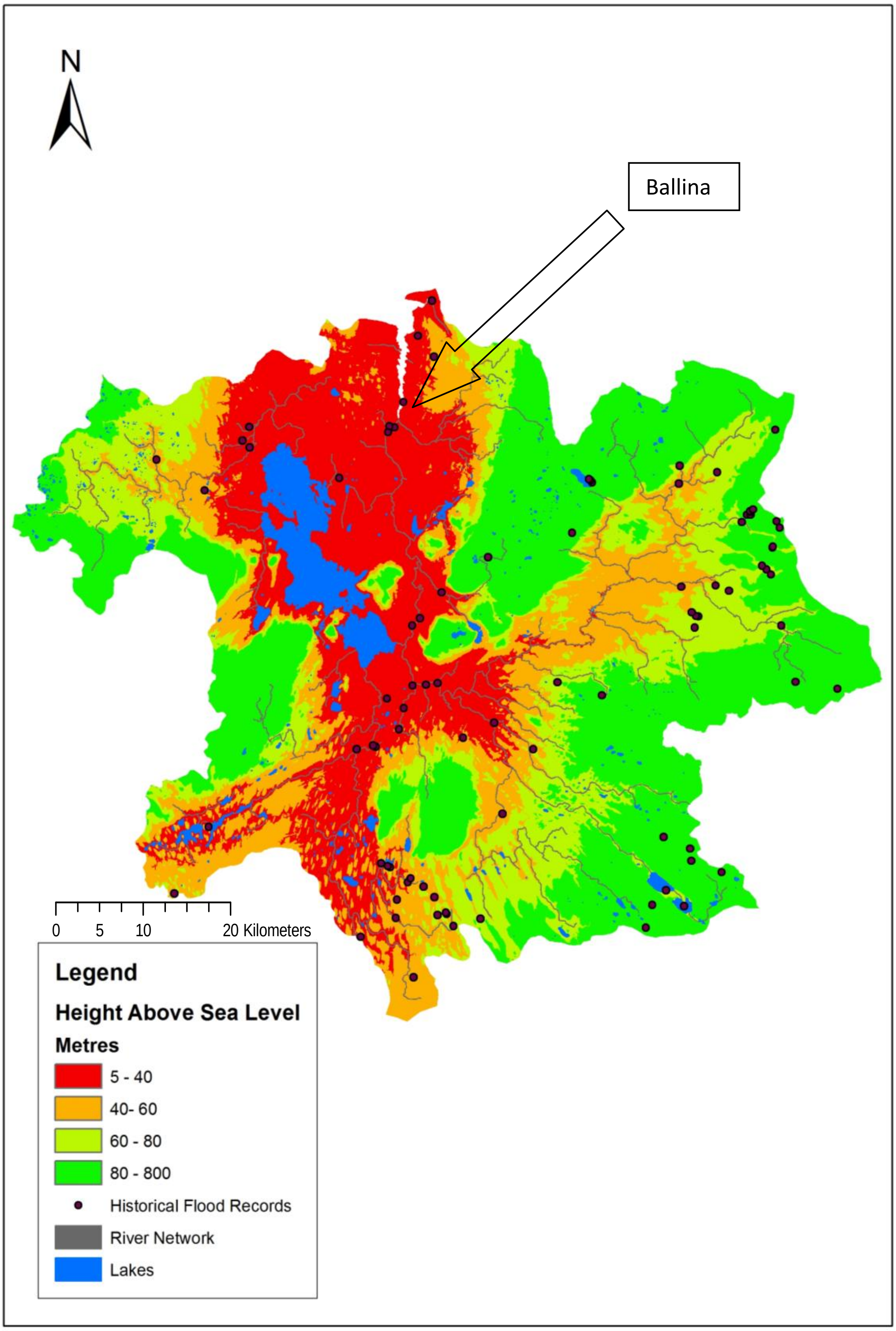


Figure 8.14: OPW historical flood records displayed in the Moy catchment.

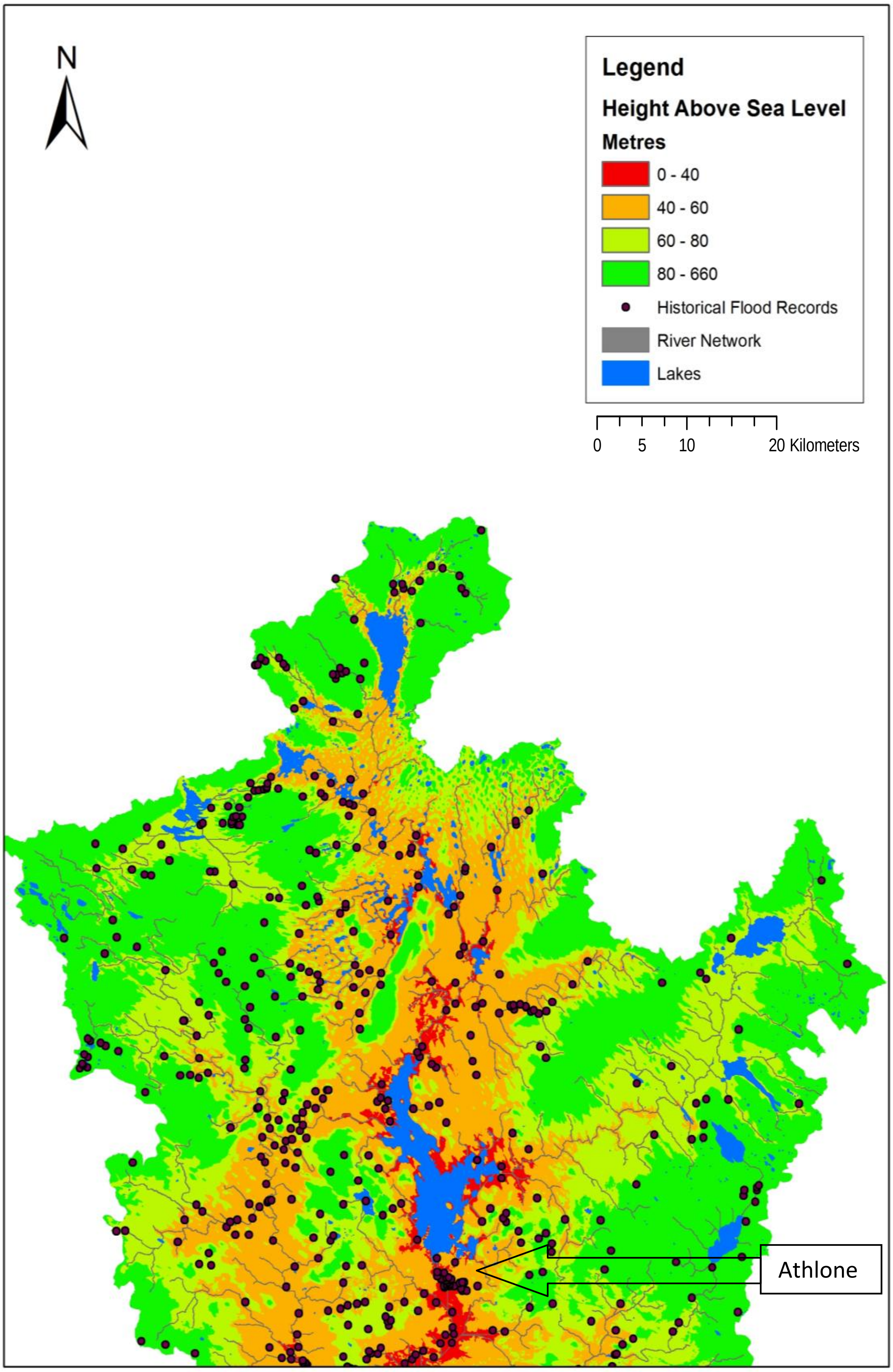


Figure 8.15: OPW historical flood records displayed in the Upper Shannon Catchment.

Table 8.3 presents the results of a spatial mapping exercise carried out in GIS to determine the spatial overlap between the modelled potentially exposed commercial and residential addresses, and the OPW recorded historical flood events. The analysis was carried out by applying two buffers (of 50m and 500m) around the modelled properties to determine the extent of spatial overlap between the two datasets. The results presented in Table 8.3 report that under the 50m buffer spatial overlap is quite low; it ranges from 24% overlap for commercial addresses in the Barrow catchments, under the 1m river elevation scenario to just 1% in the Moy catchment for residential addresses, under all scenarios. The spatial overlaps recorded under the second buffer of 500m are much higher. The greatest overlap is reported in relation to modelled commercial properties with a reported overlap of 89% in the Barrow catchment, under the 1m elevation scenario. The lowest overlap is reported at 36% in the Moy catchment, under the 1m elevation scenario. The results display that the best fit between OPW records and modelled exposed addresses is found with commercial properties in the Barrow and Nore catchments under the 500m buffer. The poorest match is found with respect to residential addresses under the 50m scenario.

These results suggest that the OPW historical records closely corroborate the modelled results with respect to potential exposed commercial properties when a buffer of 500m is used in the Barrow and Nore catchments. Using the same buffer, the spatial overlap is found to be considerably weaker for commercial properties in the Moy and Upper Shannon, as well as for residential properties in all four catchments.

8.4 INLAND FLOODING PROJECTED COSTS

This section presents some cost estimates relating to flooding by looking back at historical flooding costs, considering modelled future climate and accounting for future flood defences.

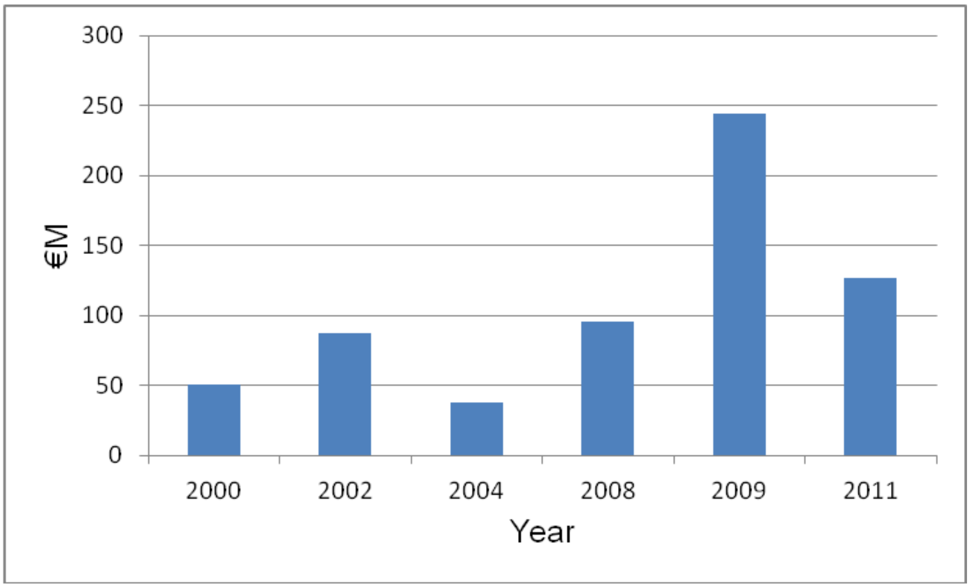


Figure 8.16: Historical flood insurance claims costs in Ireland (Source: IIF).

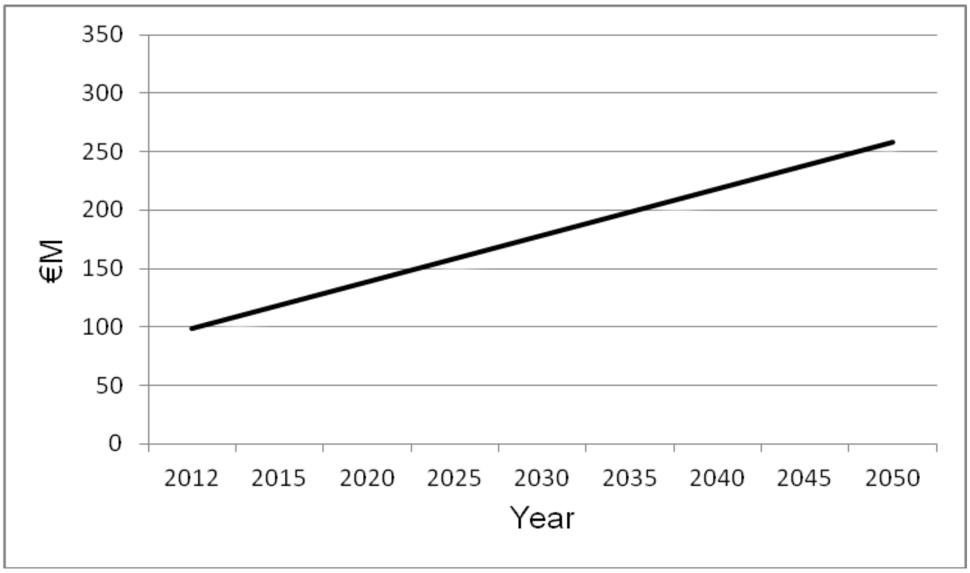


Figure 8.17: Estimated annual projected inland flood insurance costs up to 2050.

Figure 8.16 graphs Irish historical inland flooding costs for the period from 2000 to 2011. The exceptionally damaging November flooding event of 2009 is considered to be a 1 in 100 year flood event (McGrath *et al*., 2010). Figure 8.17 presents an estimation of flood insurance claims costs projected up to 2050. The projections are based on IIF flood claim insurance data in combination with the climate change hydrology modelling of future potential flood return periods. An estimated claim cost figure of €100M for 2012 is calculated from taking an average of insurance costs from the six recorded events in Figure 8.16.

Hydrological analysis on Irish river catchments projects that a 1 in 10 year flood event will move towards a 1 in 4 year event by the 2050s (Murphy and Charlton, 2008). By the 2050s a 1 in 25 year event will move towards a 10 year return period and a 1 in 50 year event will move towards a 1 in 15 year flood event (Murphy and Charlton, 2008). It is therefore not unreasonable to estimate that a 1 in 100 year event may move to a 1 in 50 year event or perhaps reach an even higher frequency. Taking these projected changes in Irish flood frequency into account the cost curve in Figure 8.17 was determined with flood insurance claim costs reaching €150M per annum by 2025 and in the region of €250M per annum by 2050. Figure 8.18 below estimates the impact of increased flood defences on Irish insurance claim costs. It is very difficult to estimate the impact of future flood defences on flood insurance claims until the defences are tested by a significant flood event. However, the assumption is made that river flood defence projects carried out by the OPW, up to 2050, will decrease Irish flooding costs by mid-century. Figure 8.18 models a 25% reduction in flood insurance costs as a result of OPW flood defence works and Figure 8.19 models a 50% reduction. It should be noted that even with a 50% reduction in flood related insurance claim costs by mid-century there is still a net increase in these projected costs moving from approximately €100M per year within the next five years to just under €150M per year by mid-century under the modelled scenario.

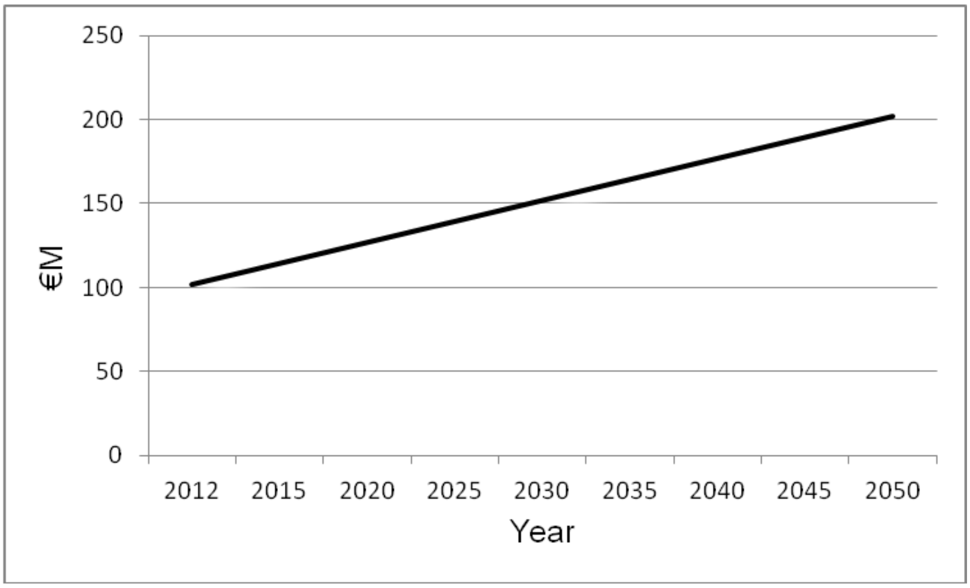


Figure 8.18: Estimated annual projected inland flood insurance costs up to 2050 accounting for a 25% decrease in flood costs towards mid-century as a result of OPW defences.

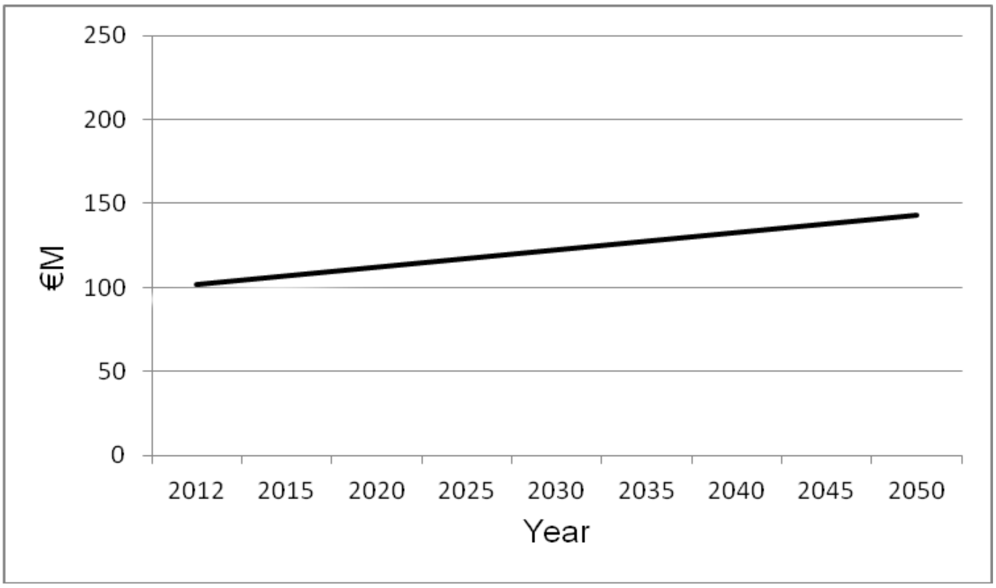


Figure 8.19: Estimated annual projected inland flood insurance costs up to 2050 accounting for a 50% decrease in flood costs towards mid-century as a result of OPW defences.

The inland flooding modelling results generated for the four case study catchments show property vulnerabilities associated with 3 buffer scenarios. Using these figures as a reference an estimated insurance cost under the 2m scenario, or an approximate 1 in 50 year return period, was estimated for all the major catchments in the country based on catchment size. There are significant limitations relating to this approach as characteristics and infrastructure will differ between each catchment. However, this exercise is framed as a macro-analysis in generating inland flooding costs associated with future climate scenarios. Table 8.4 below details the size of the twenty largest river catchments in the island of Ireland. Using the vulnerable addresses data from Table 8.1 one can calculate a multiplier for the average number of properties per km^2 for both commercial and residential addresses. These figures were calculated by dividing the area of each of the case study catchments by the number of properties vulnerable under each of the scenarios. Average number of properties per km^2 values were then calculated as inputs for the estimation of economic costs for all major Irish river catchments (Table 8.5). Table 8.5 displays the outputs of this modelling exercise.

The analysis estimates that approximately 1,300 commercial addresses and 6,500 residential addresses could be vulnerable under a two metre elevation scenario. These property vulnerabilities equate to economic costs in the region of €200M when residential and commercial claims are combined. When figures from the Northern Irish catchments of the Foyle, the Bann and the Lagan are omitted the number of national vulnerable addresses is reduced to just over 1,100 commercial properties and just over 5,500 residential properties. The national insurance claims costs come to €83M for commercial and €92M for residential which totals to €175M in claims costs for the Republic of Ireland.

Table 8.4: Major Irish river catchments.

Major Irish River Catchments			
Catchment Name	**Area (km^2)**	**Catchment Name**	**Area (km^2)**
Avoca	650	Lagan	560
Bandon	610	Laune	830
Bann	5,810	Lee	1,250
Barrow	3,070	Liffey	1,370
Blackwater	3,330	Moy	2,090
Boyne	2,700	Nore	2,530
Corrib	3,140	Shannon	15,700
Erne	4,370	Upper Shannon	4,580
Feale	1,160	Lower Shannon	11,120
Foyle	2,920	Slaney	1,760
Kinvarra	520	Suir	3,610

Table 8.5: Vulnerable addresses per km^2 in four case study catchments

Catchment	Buffer			Buffer		
	1 m	2 m	3 m	1m	2m	3m
	Commercial Addresses per km^2			**Residential Addresses per km^2**		
Barrow	0.020	0.021	0.025	0.186	0.201	0.227
Shannon Upr.	0.017	0.019	0.022	0.088	0.100	0.122
Nore	0.023	0.025	0.029	0.076	0.083	0.091
Moy	0.023	0.025	0.027	0.110	0.057	0.065
Average	**0.021**	**0.023**	**0.026**	**0.115**	**0.110**	**0.126**

Table 8.6: Estimated vulnerable residential and commercial addresses under 2m buffer for major Irish catchments and €M claims extrapolated from catchment vulnerability analysis.

Catchment	Commercial Addresses	Residential Addresses
Avoca	15	72
Bandon	14	67
Bann	134	639
Barrow	66	618
Blackwater	77	366
Boyne	62	297
Corrib	72	345
Erne	101	481
Feale	27	128
Foyle	67	321
Kinvarra	12	57
Lagan	13	62
Laune	19	91
Lee	29	138
Liffey	32	151
Moy	52	262
Nore	64	210
Upper Shannon	88	457
Shannon Lower	256	1223
Slaney	40	194
Suir	83	397
Total Addresses	**1323**	**6576**
Total €M Claims Cost	99.2	108.6

8.5 CONCLUSIONS

The modelling presented in this chapter examines the vulnerability of commercial and residential properties to inland flooding. The work is presented as an analysis of potential economic costs associated with future flood events accounting for climate change impacts. National future potential flood costs associated with climate change were extrapolated from the modelling results generated from the four catchment case studies. This exercise in projecting flood costs estimates future insurance claim costs of €175M for a 2m 1 in 50 year return period. This figure provides some indication of “end point” vulnerabilities. The chapter also briefly discusses how future flood defences may reduce flood related costs but points out the uncertainty in determining the potential magnitude of these reductions.

The strength of the methodology employed in this chapter is its ability to generate an order of magnitude economic cost associated with future potential flood impacts. This estimate can provide decision makers with an indication of potential vulnerabilities associated with specific catchments. However, it should be noted that the complexities of hydrological modelling, the role of flood defences, and uncertainties in the extent of future river flows make any projected estimates of flood vulnerability highly uncertain. For this reason river flood management programmes should consider both “end point” and “starting point” vulnerability when attempting to manage river catchments, i.e., management programmes should consider flood impact vulnerability as a residual of climate change impacts minus adaptation actions, as well as considering vulnerability as a present inability to cope with external pressures or changes often thought of as social vulnerability.

CHAPTER 9
FINAL CONCLUSIONS

9.1 SUSTAINABLE ADAPTATION

The work presented in this thesis has made a contribution in addressing one of the core questions of sustainability science that applies to climate change impacts: "What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?" The question is far reaching, and demands an understanding and appreciation of a wide range of complex systems, and their interactions, to adequately answer.

One attempt to answer this question has been through economic analysis. The vast majority of economic assessments of potential climate change impacts are framed at a global or regional level. Global GDP costs relating to climate change impacts have been estimated to range from in the region of 1% to 10% of global GDP per annum or approximately €480B to €4.8T per year (based on global GDP at current prices). The figures vary greatly as each analysis uses different economic models that consider different sectors and impacts and use different discount rates. Global adaptation costs are in the region of €40B to €130B every year. Despite the significant range of figures presented it is clear that they make a strong case for adaptation. The Stern Review estimates adaptation costs in the region of 0.05 to 0.5% of GDP. If one was to assess Irish potential future climate impacts to be 1% of GDP and adaptation costs to be 0.5% by the end of the century our impact costs of €1.6B are significantly higher than our adaptation costs of €800M based on undiscounted current GDP value.

The monetary values provided in these analyses provide broad policy incentives to act and adapt to climate change. However, they often do not offer help in deciding when to adapt, to what extent to adapt and where exactly adaptive measures should be prioritised. This is the point where the concepts of vulnerability, sustainability and resilience enter the discussion in order to help answer the questions of when to adapt and to what extent. When decision makers want to deliver sustainable and appropriate adaptive actions they need to adhere to the principles of good adaption as outlined in Chapter 2 of this document. In summary, they need to recognise the value of no or low regret and win-win adaptation options and avoid actions that foreclose or limit future adaptations. It is also wise to work in close partnership with the local communities involved and address risks associated with present climate variability and extremes. The third question, of where adaptive measures should be prioritised, provides the springboard from which the original analysis in this thesis takes off.

The original modelling work carried out on the key areas of SLR impacts, wetland vulnerabilities and inland flooding places a strong emphasis on determining which locations in Ireland are especially vulnerable, so that decision makers can prioritise where adaption actions are most urgently needed. Establishing the location of vulnerable areas was facilitated through a methodology that harnessed DTM and LIDAR data in conjunction with a range of spatial datasets. The importance of Post-Normal Science and ecological economics was also taken on board by presenting impacts relating to a range of factors, such as land, property and species, alongside traditional monetary impacts.

9.2 TOWARDS A NATIONAL ECONOMIC IMPACTS ASSESSMENT

The work carried out in the thesis focused on the three areas of SLR, wetlands and inland flooding as they are deemed to be of critical importance when exploring potential climate change impacts in Ireland (European Commission, 2009a; Jenkins *et al*., 2009). By taking an "end point" interpretation of vulnerability, potential climate impacts in each of these Irish sectors have been identified.

The national coastal economic risk study determined that close to 35,000 vulnerable properties, 34,500ha of inundated coastal land and approximately €1B of insurance claims are associated with a 1m SLR scenario by the end of the century. The framework Coastal Vulnerability Index highlighted counties Wexford and Dublin as the most vulnerable in relation to coastal risk in Leinster. These potential impacts identified in relation to SLR underline the need to employ a strategic approach, such as Integrated Coastal Zone Management (ICZM), when determining cost effective methods for protecting Irish coastal assets. The outputs from the economic coastal risk study and framework CVI can also be used by decision makers to determine the most appropriate form of coastal defense strategy for a specific coastal location, as determined by its density of habitation and potential propensity for inundation.

Under a 1m SLR scenario approximately 3,600ha of coastal wetlands could be inundated with an economic value of €24M. In addition, further analysis determined that wetland sites in urban County Dublin and rural County Wexford contain at least 11 species listed as "endangered" on the IUCN Red List of endangered species. These modelled results further strengthen the need for ICZM but also highlight the importance of adhering to existing protective legislation for wetlands as well as further strengthening of wetland conservation in Ireland. The monetary impacts in the form of ecosystem services lost are further bolstered by the potential irreplaceable loss of rare Irish wetland habitats as well as a number of IUCN Red List species.

Under a 2m flood event - estimated to approximately correspond to a 1 in 50 year event - insurance claims linked to inland flooding could be in the region of €175M and up to 6,600 properties could be impacted. These indicative figures show that future modeled Irish inland flooding costs are significant. It must also be noted that these economic figures only capture the impacts of flood events from a monetary perspective. There are significant non-monetary impacts such as personal trauma and stress, as well as potential health impacts. The magnitude of these economic and non-monetary costs present a strong case for the implementation of flood management schemes, such as the Irish Catchment Flood Risk Assessment and Management Studies (CFRAMS).

In monetary terms the potential impacts over the three sectors totals to €1.2B. This figure is relatively close in magnitude to the (€1.5B) 1% of Irish GDP at current value that might be considered a conservative figure for climate change related impacts in Ireland by the close of the century. It is important to note that climate impacts relating to tourism, agriculture and health would need to be considered to get a more complete picture of the climate change related costs. Economic modeling suggests that the net impact of climate change on agriculture and tourism may be positive in Ireland (European Commission, 2009a). However, impacts such as a potential increase in the volume and incidence of agricultural pests and diseases may offset potential climate related increases in yield (Rosenzweig *et al.*, 2001). The net impact of climate change on health is also difficult to clearly determine as reduced winter mortalities may be offset by an increased incidence of vector borne diseases (Cullen, 2007).

The modeling outputs presented in this thesis offers assessments on climate-related risks. These outputs are indicative of the magnitude of possible impacts associated with climate change. They are limited in their scope and their ability to capture the full complexities associated with the physical impacts of climate change, as well as the full impact of the economic impacts associated with these environmental stresses. There are also issues in relation to the quality and completeness of the data sets used in the analysis, as discussed in the previous chapters. However, the strength of the work presented is that it provides a set of results that can be used to argue the case for adaption in Ireland, and it can point out priority locations and sectors where adaptation efforts should be focused.

9.3 POLICY RELEVANCE

The outputs of this thesis aim to inform policy makers on the location and extent of future potential climate impacts in Ireland. They are also intended to act as a basis for policy dialogue and to help to prioritise the location of adaptation measures. Specifically, they will provide valuable input into the development of the Irish Government's forthcoming National Adaptation Strategy and the formulation of the upcoming Irish Climate Change Bill. By outlining the case for climate adaptation they can provide an important incentive to draft robust policy measures and legal instruments. The thesis outputs will also feed into the European clearing house on adaptation impacts, which is currently in development under the remit of the European Adaptation Strategy white paper (European Commission, 2009c). This clearing house is a mechanism designed to gather climate change impact data from across the European Union on a voluntary basis, so as to inform European climate adaptation policy.

9.4 GOING FORWARD

As climate change impacts upon inter-related and multi-dimensional aspects of the environment, our societies and our economies, it is clear that any meaningful climate policy response will require interdisciplinary analysis (Scrieciu *et al*., 2011). The two separate, but often overlapping and blurred, questions of what we should do about climate change and what we can do about climate change need to be unpacked and examined (Broome, 2008). What we should do about climate change is an ethical question that raises the issues of conflicting world views. On the other hand, economic analysis can help determine what we can do about climate change (Broome, 2008). However, Broome argues that one should not attempt to decouple economics from ethics, and in fact that further developments in climate economics need to be cognisant of underpinning values and explicitly state their implications for policy and society.

The important issue here is to firstly open up the discourse to examine the implicit ethical choices embedded in the 'what we can do discussion' about climate change and not gloss over or understate the importance of the 'what we should do' about climate change conversation. It is argued that climate economics research needs to break away from its own current disciplinary limitations and develop stronger links with other relevant disciplines (Scrieciu *et al*., 2011). However, it must also be argued that before economics searches outside of its own discipline to develop linkages, it ought to look hard within its own field. Ecological economics is worth examining as an alternative or auxiliary approach to valuing climate change impacts. That said, disciplines such as geography, sociology, psychology, politics, and of course further connections with climate science can add considerable depth and robustness to climate change economics as it currently stands. For example, the impacts of a coastal flooding event (that has transpired or is modelled) cannot be adequately captured without sufficient data on the topography of the coastline and coastal area, an understanding of the population volume and infrastructure, an understanding of the governance structures in place in the impacted area, as well as an understanding of the societal impacts connected with the trauma and anxiety associated with potential property damage, loss of livelihood, or loss of life.

One could argue that a more radical approach is needed to account for market externalities such as climate impacts at large and more specifically to reduce impacts on biodiversity and ecosystems. In 2011, Bolivia pioneered a new set of laws that grants nature equal rights to humans (Guardian, 2011). The so called Law of Mother Earth is set to grant 11 specific rights to the natural world including the right to life, diversity of life, water and clean air. The full bill is expected to be considered by the Bolivian legislative assembly by mid-2012. This radical set of laws could engender a change in mindset that repositions the importance of nature and ecosystems within Bolivian society. At a global level this type of legislation could severely challenge current mainstream economic practices that position the environment and humanity within the economy, rather than positioning the economy within humanity that is subject to the carrying capacity of the environment.

Climate change is a wicked problem that is not something we can solve easily but something that we need to manage. The original modelling work carried out in this thesis provides an analysis of climate impacts that are principally intended to facilitate climate change management in an Irish context. However, the thesis has also explored the importance of ethics when it comes to economic evaluations relating to climate change. It has been demonstrated how interpretations that follow anthropocentric viewpoints can evaluate the potential economic impacts of future climate change very differently to those that hold a more non-anthropocentric position. This thesis thus supports the view that our capacity to manage climate change will depend crucially on our ability to change our relationship with the environment and our planet, and thus to significantly challenge our behaviour. The geographically sensitive economic analysis demonstrated in this thesis is potentially a powerful tool that could play a significant role in enabling this change, i.e., the thesis outputs could function as a catalyst for engendering a fresh approach to climate adaption policy that captures place specificity more completely than current methods employed in the climate adaption policy arena.

BIBLIOGRAPHY

Ackerman, F., De Canio, S.J., Howarth, R.B. and Sheeran, K.A.2009. Limitations of integrated assessment models of climate change. *Climatic Change*, 95, 297-315.

Adger, W.N. 2006. Vulnerability. *Global Environmental Change*, 16, 268-281.

Adger, W.N. 2003. Social capital, collective action, and adaptation to climate change. *Economic Geography*, 79(4), 387-404.

Adger, W. N., Arnell, N. W. and Tompkins, E. L. 2005. Successful adaptation to climate change across scales. *Global Environmental Change-Human and Policy Dimensions*, 15, 77–86.

Adger, W.N., and Brown, K. Vulnerability and resilience to environmental change: ecological and social perspectives. In: *A Companion to Environmental Geography*. 2009. Castree, N., Demeritt, D., Liverman, D. and Rhoads, B. Eds. Blackwell Publishing: Sussex.

Adler, E. 1992. The emergence of cooperation: national epistemic communities and the international evolution of the idea of nuclear arms control. *International Organisation*, 46, 1, 101-146.

Aguirre, B.E. 2003. Sustainable development as collective surge. *Social Science Quarterly*, 83 (1), 101-118.

Ahilan, S., O'Sullivan, J.J. and Bruen, M. 2011. Influences of flood frequency distributions in Irish river catchments. *Hydrology and Earth System Sciences Discussions*, 8, 3305-3351.

Anthoff, D., Nicholls, R.J. and Tol, R.S.J. 2009. The Economic Impact of Substantial Sea Level Rise. Working Paper FNU-175, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Arndt, D. S., M. O. Baringer. and M. R. Johnson, Eds., 2010. State of the Climate in 2009. *Bulletin of the American Meteorological Society*, 91 (7), 1-224.

Aronson, D. 1998 Overview of systems thinking. Available from: http://www.thinking.net/Systems_Thinking/systems_thinking.html (Accessed in December 2011).

Arrow, K.J. 2007 Global climate change: A challenge to policy. *Economists Voice*, The Berkley electronic press.

Ask about Ireland. 2012. Website. Available from: http://www.askaboutireland.ie (Accessed in January, 2012).

Augelli, E. and Murphy, C.N. 1988. *American's question for supremacy and the third world*, Pinter: London.

Australian Government. 2007. Tackling wicked problems: A public policy perspective.

Commonwealth of Australia: Sydney.

Azar, C. and Schneider, S. H. 2003. Are the economic costs of (non-)stabilizing the atmosphere prohibitive? A response to Gerlagh and Papyrakis. *Ecological Economics*, 46, 329-332.

Balmford, A., Bruner, A., Cooper, P., Costanza, R., Farber, S., Green, R. E., Jenkins, M., Jefferiss, P., Jessamy, V., Madden, J., Munro, K., Myers, N., Naeem, S., Paavola, J., Rayment, M., Rosendo, S., Roughgarden, J., Trumper, K. and

Turner, R.K. 2002. Economic reasons for conserving wild nature. *Science*, 297(5583), 950-953.

Barbier, E.B. 1993. Sustainable use of wetlands valuing tropical wetland benefits: economic methodologies and applications. *The Geographical Journal*, 159(1), 22-32.

Barry, R. and Chorley, R. 2010. *Atmosphere, Weather and Climate*. Routledge: London and New York.

Bassett, J.A. and Curtis, T.G.F., 1985. The nature and occurrence of sand dune machair in Ireland. *Proceedings of the Royal Irish Academy*, 85(1), 1-20.

Becker, A., Grunewald, U. 2003. Flood risk in central Europe. *Science*, 300 (5622), 1099.

Bellwood, D.R., Hughes, T.P., Folke, C. and Nyström, M. 2004. Confronting the coral reef crisis. *Nature*, 429, 827-833.

Brander, L.M., Florax, R.J.G.M. and Vermaat, J.E. 2006. The empirics of wetland valuation: A comprehensive summary and a meta-analysis of the literature. *Environmental and Resource Economics*, 33, 223-250.

Broome, J. 2008. The ethics of climate change. *Scientific American*, May 2008 edition, 97-102.

Brown, A., Gawith, M., Lonsdale, K. and Pringle, P. 2011. Managing adaptation: linking theory and practice. UK Climate Impacts Programme, Oxford, UK.

Bullock, C., Kretsch, C. and Candon, E. 2008. The Economic and Social Aspect of Biodiversity: Benefits and Costs of Biodiversity in Ireland. Department of Environment Heritage and Local Government: Dublin.

Campbell, N. A. and Reece, J. B. 2002. *Biology*. Pearson Education: San Francisco.

Carpenter, S., Walker, B., Anderies, J.M. and Abel, N. 2001. From metaphor to measurement: Resilience of what to what. *Ecosystems*, 4, 765-781.

Carter, R.W.G., Devoy, R.J.N. and Shaw, J. 1989. Late Holocene sea levels in Ireland. *Journal of Quaternary Science*, 4, 7-24.

Carter, R.W.G. and Johnston, T.W. 1982. Ireland – the shrinking island? *Technology Ireland*, 14, 22-28.

Carter, R.W.G. 1988. *Coastal Environments*. Academic Press: London, 617p.

Carter, R.W.G. 1992. Sea level changes. In: Williams, B.E. (Ed.) Climate change: Studies on the implications for Ireland. Department of the Environment: Dublin. pp: 125-171.

Charlton, R., Fealy, R., Moore, S., Sweeney, S. and Murphy, C. 2006. Assessing the impact of climate change on water supply and flood hazard in Ireland using statistical downscaling and hydrological modelling techniques, *Climatic Change,* 74(4), 475-491.

Charlton, R. 2007. *Fundamentals of Fluvial Geomorphology*, London, Routledge.

Christensen, J.H. and Christensen, O.B. 2003. Severe summertime flooding in Europe. *Nature*, 421:805.

Christopolos, I., Anderson, S., Arnold, M., Galaz, V., Hedger, M. and Klein, R.J.T, 2009. The human dimension of climate adaptation: the importance of local and institutional issues. Ministry for Foreign Affairs: Stockholm.

Ciscar, J.C., Iglesias, A., Feyen, L., László, S., Van Regemorter, D., Amelung, B., Nicholls, R.J., Watkiss, P., Christensen, O.B., Dankers, R., Garrote, L., Goodess, C.M., Hunt, A., Moreno, A., Richards, J. and Soria, A. 2011. Physical and economic consequences of climate change in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, 108(7), 2678-2683.

ClimateUK. 2010 Website. Available from: http://www.climateuk.net/ (Accessed in January 2010).

COMEST 2010. The ethical implications of global climate change. UNESCO: Paris.

Cooper, J.A.G. and McKenna, J. 2007. Social justice and coastal defence: the long and short- term perspectives. *Geoforum*, 38, 294-306.

Costanza, R *et al*., 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387, 253-260.

Coveney, S., Fotheringham, S., S, Charlton, M. and Mccarthy, T. 2010. Dual-scale validation of a medium-resolution coastal DEM with Terrestrial LiDAR DSM and GPS, *Computers and Geosciences*, 36, 489–499.

Coxon, C.E. 1987. The spatial distribution of turloughs. *Irish Geography,* 20, 11-23.

Crawford, I., Bleasdale, A. and Conaghan, J. 1998. *Biomar survey of Irish machair sites, 1996*. Vol.1, Site information. Irish Wildlife Manuals, No.2. Dúchas, The Heritage Service, Dublin.

Cullen, E. 2007. Climate change and health in Ireland. PhD thesis: National University of Ireland, Maynooth.

Curtis, T.G.F. 2003. Salt marshes. In: Otte, M.L. (ed.) *Wetlands of Ireland: Distribution, ecology, uses and economic value.* University College Dublin Press: Dublin. Chapter 3.

Curtis, T.G.F., 1991. A site inventory of the sandy coasts of Ireland. *In:* Quigley, M.B. (ed.), *A Guide to the Sand Dunes of Ireland.* Dublin, Ireland: European Union for Dune Conservation and Coastal Management, pp. 6–17.

Curtis, T.G.F. and Sheehy Skeffington, M.J. 1998. The salt marshes of Ireland: An inventory and account of their geographical variation. *Biology and Environment: Proceedings of the Royal Irish Academy*, 98B (2), 87-104.

Dankers, R. and Feyen, L. 2008. Climate change impact on flood hazard in Europe: an assessment based on high resolution climate simulations. *Journal of Geophysical Research*, 113 doi:10.1029/2007JD009719.

Darwin, R.F. and Tol, R.S.J. 2001. Estimates of the Economic Effects of Sea Level Rise. *Environmental and Resource Economics,* 19, 113–129.

Dasgupta, S., La Plante, B., Meisner, C., Wheeler, D. and Yan, J. 2007. The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis. World Bank Policy Research Working Paper 4136.

Dasgupta, S., La Plante, B., Murray, S. and Wheeler, D. 2009. Sea-Level Rise and Storm Surges: A Comparative Analysis of Impacts in Developing Countries. World Bank Development Research Group, Research Working Paper 4901.

Department of Environment and Local Government. 2001. Coastal Zone Management. Available from: http://www.irishspatialstrategy.ie/docs/report24.pdf (Accessed in January 2012).

Dessler, A.E. 2012. *Introduction to modern climate change*. Cambridge University Press: Cambridge

Devoy, R., 2008. Coastal Vulnerability and the Implications of Sea-Level Rise for Ireland. *Journal of Coastal Research*, 24(2), 325-341.

Dietz, S., Hope, C. and Patmore, N. 2007. Some economics of 'dangerous' climate change: Reflections on the Stern Review. *Global Environmental Change-Human and Policy Dimensions*, 17**,** 311-325.

Dobosiewicz, J. 2001. Applications of Digital Elevation Models and Geographic Information Systems To Coastal Flood Studies along the Shoreline of Raritan Bay, New Jersey. *Environmental Geosciences*, 8(1), 11-20.

Doody, J.P. (ed). 2008. *Sand Dune Inventory of Europe, 2nd Edition*. National Coastal Consultants and EUCC - The Coastal Union, in association with the IGU Coastal Commission.
Doody, J.P. 2004. Coastal squeeze: A historical perspective. *Journal of coastal Conservation*, 10, 129-138.

ECOPRO. 1996. Environmentally Friendly Coastal Protection: Code of practice. Government of Ireland Stationary Office: Dublin.

Environmental Protection Agency/ European Environment Agency. 2010. CORINE land cover Ireland: Land cover update for 2006. Environmental Protection Agency: Wexford, Ireland.

European Commission. 2011. The impacts and economic costs of climate change in Europe and the costs and Benefits of Adaptation. Summary of results from the EC RDT ClimateCost Project.

European Commission. 2009a. Climate Change Impacts in Europe: Final report of the PESETA research project. Juan-Carlos Ciscar (ed). Joint Research Centre, Luxembourg.

European Commission. 2009b. Marine affairs and climate change: Irish overview. Available from: http://ec.europa.eu/maritimeaffairs/climate_change/ireland_en.pdf (Accessed in November 2010).

European Commission. 2009c. Adapting to climate change: Towards a European framework for action (White Paper). Available from: http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2009:0147:FIN:EN:PDF (Accessed in November 2010).

European Commission. 2007. A new EU Floods directive. Available from: http://ec.europa.eu/environment/water/flood_risk/index.htm (Accessed in March 2009).

European Commission. 1992. Council Directive 92/43/EEC on the Conservation of natural habitats and of wild fauna and flora. Available from: http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1992L0043:20070101:EN:PDF (Accessed in June 2009).

European Communities. 2008. The Economics of Ecosystems and Biodiversity: Interim Report. European Communities. Cambridge: UK.

European Council. 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Brussels: Belgium.

European Environment Agency. 2010. Occurrence of floods in Europe 1998-2009. Available from: http://www.eea.europa.eu/data-and-maps/figures/occurrence-of-flood-events-in-europe-1998 (Accessed on Jan 2010).

European Environment Agency. 2008. Impacts of Europe's changing climate – 2008 indicator-based assessment. European Environment Agency: Copenhagen. Report 4/2008.

European Environment Agency. 2007. Climate change: the cost of inaction and the cost of adaptation. Technical report number 17, Copenhagen.

European Environment Agency. 2006. The changing faces of Europe's coastal areas. European Environment Agency Report 6/2006. Luxembourg.

European Environment Agency. 2004. Map of distribution of Ramsar sites within the EEA member countries. Available from: http://www.eea.europa.eu/data-and-maps/figures/ds_resolveuid/635CE967-6865-4335-8023-FDB3FE37EEB3 (Accessed in December 2011).

Fahey, D. and Finch, F. 2009. GeoDirectory Technical Guide. OSI/An Post: Dublin.

Falaleeva, M., O'Mahony, C., Gray, S., Desmond, M., Gault, J. and Cummins, V. 2011. Towards climate adaptation and coastal governance in Ireland: Integrated architecture for effective management? *Marine Policy*, 35, 784-793.

Fankhauser, S. 1995, Protection versus retreat: the economic costs of sea-level rise. *Environment and Planning*, 27(2), 299-319.

Farrell, G.J. 2007. Climate change: Impacts on coastal areas. From Ireland at Risk. The Irish Academy of Engineering: Dublin.

Fealy, R. and Sweeney, J. 2008. Climate Scenarios for Ireland. In Sweeney, J. (ed) Climate Change: Refining the Impacts, Environmental Protection Agency, Ireland, Government Publications.

Fergus, A.H.T. and Rowney, J.I.A. 2005. Sustainable development: Lost meaning and opportunity? *Journal of Business Ethics*, 60, 17-27.

Few, R., Brown, K. and Tompkins, E. 2004. Scaling adaptation: climate change response and coastal management in the UK. Working Paper 60. Norwich: Tyndall Centre for Climate Change Research.

Finlayson, C.M. and Spiers, A.G. (eds.) 1999. Global review of wetland resources and priorities for wetland inventory. Supervising Scientist Report 144. Wetlands International Publication 53, Supervising Scientist: Canberra.

Forrester, J. W. 1961. *Industrial Dynamics*. Pegasus Communications: Waltham, MA.

Forfás. 2008. Environmental goods and services sector on the island of Ireland: Enterprise opportunities and policy implications. Intertrade Ireland & Forfás.

Froebel, F., Heinrichs, J. and Kreye, O. 1980. *The new international division of labour,* Cambridge University Press: Cambridge.

Funtowicz, S. O. and Ravetz, J. R. 2003. Post-Normal Science. Internet Encyclopedia of

Ecological Economics. Available From: http://www.ecoeco.org/pdf/postnormalscience.pdf (Accessed in March 2011).

Funtowicz, S. O. and Ravetz, J. R. 1994. The worth of a songbird-ecological economics as a post-normal science. *Ecological Economics,* 10**,** 197-207.

Füssel, H.-M. 2007. Vulnerability: A generally applicable conceptual framework for climate change research. *Global Environmental Change,* 17, 155-167.

Gallopín, G.C. 2006. Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change*, 16, 293-303.

Gaynor, K. 2006. The vegetation of Irish machair. *Biology and Environment: Proceedings of the Royal Irish Academy*, 106B, 311-321.

Gerlagh, R. and Papyrakis, E. 2003. Are the economic costs of (non-)stabilising the atmosphere prohibitive? A comment. *Ecological Economics,* 46**,** 325-327.

Gitay, H., Finlayson, C.M. and Davidson, N.C. 2011. A Framework for assessing the vulnerability of wetlands to climate change. Ramsar Technical Report No. 5/CBD Technical Series No. 57. Ramsar Convention Secretariat, Gland, Switzerland.

Gornitz, V.M., 1990. Vulnerability of the East Coast, USA to future sea level rise. *Journal of Coastal Research*, Special Issue No. 9, 201-237.

Gornitz, V.M., Beaty, T. W. and Daniels, R.C. 1997. A coastal hazards data base for the U.S. West coast. ORNL/CDIAC-81 NDP-043 C. Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.

Gornitz, V., Couch, S. and Harting, E.K., 2002. Impacts of sea level rise in the New York City metropolitan area. *Global and Planetary Changes*, 32, 61-88.

Gornitz, V.M., White, T.W. and Cushman R.M. 1991. Vulnerability of the U.S. to future sea-level rise. In Proceedings of Seventh Symposium on Coastal and Ocean Management. Long Beach, CA (USA), 1991, pp. 2354-2368.

Grinsted, A., Moore, J. C. and Jevrejeva, S. 2009. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics*, 34, 461-472.

Hallegatte, S. 2008. Assessing Climate Change Impacts, Sea Level Rise and Storm Surge Risk in Port Cities: A Case Study on Copenhagen, *OECD Environment Working Papers*, No. 3, OECD publishing.

Hammer-Klose, E.S. and Thieler, E.R., 2001. Coastal vulnerability to sea-level rise, a preliminary database for the U.S. Atlantic, Pacific, and Gulf of Mexico coasts. U.S. Geological Survey, Digital Data Series DDS-68, 1 CD. Available from: http://pubs.usgs.gov/dds/dds68/ (Accessed in September 2011).

Harré, R. 1983. *Great scientific experiments*. Oxford University Press: Oxford.

Hart, B., Bailey, P., Edwards, R., Hortle, K., James, K., McMahon, A., Meredith, C. and Swadling, K. 1990. Effects of salinity on river, stream and wetland ecosystems in Victoria, Australia. *Water Research*, 24 (9), 1103-1117.

Haas, P. M. 1989. Do regimes matter? Epistemic communities and Mediterranean pollution control. *International Organisation*, 43, 3, 377-403.

Hass, P.M. 1990. Obtaining international environmental protection through epistemic consensus. *Millennium*, 19, 3, 347-364.

Hass, P.M. 1992. Introduction: epistemic communities and international policy coordination. *International Organisation*, 46, 1, 1-36.

Healy, B. 2003. Coastal Lagoons. In: *Wetlands of Ireland.* R. Otte (ed). University College Dublin Press: Dublin. Chapter 4.

HM-Treasury. 2009. Accounting for the effects of climate change: Supplementary Green Book Guidance. Available from: http://www.hmtreasury.gov.uk/data_greenbook_supguidance.htm#%20Adaptation_to_Climate_Change (Accessed in June 2010).

Hoozemans, F.M.J., Marchand, M. and Pennekamp, H.A. 1993. A Global Vulnerability Assessment: Vulnerability Assessment for Population, Coastal Wetlands and Rice Production on a Global Scale. Second edition, Delft Hydraulics, Delft, Netherlands, 180p.

Hope, C. 2006. The Marginal Impact of CO2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC’s Five Reasons for Concern. *Integrated Assessment*, 6(1), 19–56.

Howarth, R.B. 2003. Discounting and uncertainty in climate change policy analysis. *Land Economics*, 79(3), 369-381.

Hulme, M. 2011. *Why we disagree about climate change: Understanding controversy, inaction and opportunity*. Cambridge University Press: Cambridge.

Ibrahim, H.S. and Shaw, D. 2012. Assessing progress towards integrated coastal zone management: some lessons from Egypt, *Ocean and Coastal Management*, 58, 26-35.

IPCC, 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2007b. Climate Change 2007: Impacts, Adaptation and Vulnerability. Summary for Policymakers. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Summary approved at the 8th Session of Working Group II of the IPCC, Brussels, April 2007.

Irish Insurance Federation (IIF). 2012. Insurance bill for October floods reaches €127 million. (Press release) Available from: http://www.iif.ie/ (Accessed in January 2012).

Irish Insurance Federation (IIF). 2010. Bill for November floods estimated at €244 million. (Press release) Available from: http://www.iif.ie/MediaPublications/PressRelease/tabid/119/language/en-GB/Default.aspx (Accessed in January 2010).

IUCN. 2011. The IUCN Red List of Threatened Species. Website. Available from: http://www.iucnredlist.org/ (Accessed in November 2011).

Jenkins, G.J., Murphy, J.M., Sexton, D.M.H., Lowe, J.A., Jones, P. and Kilsby, C.G. 2009. UK Climate Projections: Briefing report. Met Office Hadley Centre, Exeter: UK.

Jones, T. 2010. Wetland ecosystem services: wetland products. Ramsar Convention Secretariat, Gland, Switzerland.

Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., McCarthy, J.J., Schellnhiber, H.J., Bolin, B., Dickson, N.M., Faucheux, S., Gallopin, G.C., Grübler, A., Huntley, B., Jäger, J., Jodha, N.S., Kasperson, R.E., Mabogunje, A., Matson, P., Mooney, H., Moore, B., O'Riordan, T. and Svedin, U. 2001. Sustainability Science.
Science, 292 (5517), 641-642.

Keeling, C. D., Bacastow, R. B., Bainbridge, A. E., Ekdahl, C. A., Guenther, P. R., Waterman, L. S. and Chin, J. F. S. 1976. Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii, *Tellus*, 28(6), 538-551.

Kopp, R., Simons, F., Mitrovica, J., Maloof, A. and Oppenheimer, M. 2009. Probabilistic assessment of sea level during the last interglacial stage. *Nature,* 462, 863-867.

Kundzewicz, Z.W., Radziejewski, M. and Pińskwar, I. 2006. Precipitation extremes in the changing climate of Europe. *Climatic Research*, 31, 51-58.

Lane, M. B. 2006. Towards integrated coastal management in Solomon Islands: Identifying strategic issues for governance reform. *Ocean & Coastal Management*, 49**,** 421-441.

Lélé, S.M. 1991. Sustainable Development: A Critical Review. *World Development*, 19(6), 607-621.

Lennon, G.W. 1963a. The identification of weather conditions associated with the generation of major storm surges along the west coast of the British Isles, *Quarterly Journal of the Royal Meteorological Society*, 89, 381-394.

Lennon, G.W. 1963b. A frequency investigation of abnormally high tidal levels at certain west coast ports, *Proceedings of the Institute of Civil Engineers*, 25, 451-484.

Lehner, B., Döll, P., Alcamo, J., Henrichs, H. and Kaspar, F. (2006) Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated assessment. *Climatic Change*, 75, 273-299.

Li, X., Rowley, R.J., Kostelnick, J.C., Braaten, D., Meisel, J. and Hulbutta, K. 2009. GIS analysis of global impacts from sea level rise. *Photogrammetric Engineering & Remote Sensing*, 75(7), 807-818.

Lowe, J. 2008. Intergenerational wealth transfers and social discounting: Supplementary green book guidance. HM Treasury: London.

Ludwig, D. 2001. The era of management is over. *Ecosystems*, 4, 758-764.

Macklin, M.G. and Rumsby, B.T. 2007. Changing climate and extreme floods in the British Uplands. *Transactions of the Institute of British Geographers*, 32(2), 168-186.

Manne, A., Mendelsohn, R. and Richels, R. 1995. MERGE: A model for evaluating regional and global effects of GHG reduction policies. *Energy Policy*, 23(1), 17-34.

Marine Institute. 2005. Accessible wave energy resource atlas. Available from: http://www.marine.ie/NR/rdonlyres/90ECB08B-A746-4247-A277-7F9231BF2ED2/0/waveatlas.pdf (Accessed in January 2012).

Mc Closkey, D. 1994. *Knowledge and persuasion in economics*. Cambridge University Press: Cambridge.

Mc Grath, R., Fealy, R. and Sheridan, T. 2010. Recent Irish weather extremes and climate change. Royal Irish Academy: Dublin.

Mc Grath, R. and Lynch, P. (Eds.) 2008. Ireland in a warmer world: Scientific predictions of the Irish climate in the twenty-first century. C4I Project, Met Éireann.

Meehl, G.A., Washington, W.M., Collins, W.D., Arblaster, J.M., Hu, A., Buja, L.E., Strand, W.G. and Teng, H. 2005. How much more global warming and sea level rise? *Science*, 307 (5716), 1769-1772.

Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-being: Synthesis. World Resources Institute, Island Press, Washington, DC.

Mitchell, G.F. and Ryan, M. 1997. *Reading the Irish landscape*. Town House: Dublin.

Morrissey, K., Hynes, S., Cuddy, M. and O'Donoghue, C. 2011. Ireland's ocean economy. Socio-Economic Marine Research Unit (SEMRU) Report Series No. 1.

Murphy, C. and Charlton, R. 2008. Climate Change and Water Resources in Ireland. In Sweeney, J. (ed) Climate Change: Refining the Impacts, Environmental Protection Agency, Ireland, Government Publications.

Murphy, C. & Fealy, R. 2010. Climate change impacts for Ireland part 2: changes in key climatic variables. *Geographical Viewpoint*, 38, 29-43.

Murray, D.A. 1996. Freshwater resources, systems and habitats in Ireland. In: Reynolds, J.D. (Ed.) *Conservation of aquatic systems*. Royal Irish Academy: Dublin, pp. 3-19.

National Biodiversity Data Centre (NBDC) 2011. Website Available from: http://www.biodiversityireland.ie/ (Accessed in Dec 2011).

National Coastal Erosion Committee (NCEC). 1992. Coastal Management - A case for action. County & City Engineers Association. EOLAS: Dublin.

Nelson, D., Adger, W.N. and Brown, K. 2007. Adaptation to environmental change: contributions of a resilience framework. *Annual Review of Environment and Resources*, 32, 395-419.

Neumayer, E. 2007. A missed opportunity: The Stern Review on climate change fails to tackle the issue of non-substitutable loss of natural capital. *Global Environmental Change-Human and Policy Dimensions*, 17**,** 297-301.

Nicholls, R. J., Hanson, S., Herweijer, C., Patmore, Hallegatte, S., Corfee-Morlot, J., Château, J. and Muir-Wood, R. 2007. Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates, *OECD Environment Working Papers*, No. 1, OECD Publishing.

Nicholls, R.J., Hoozemans, F.M.J., Marchand, M. 1999. Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. *Global Environmental Change*, 9, 69-87.

Nicholls, R.J. and Mimura, N. 1998. Regional issues raised by sea-level rise and their policy implications. *Climate Research*, 11, 5-18.

Nicholls, R.J., Marinova, N., Lowe, J.A., Brown, S., Vellinga, P., De Gusmao, D., Hinkel, J. and Tol R.S.J. 2011. Sea-level rise and its possible impacts given a beyond 4º C world in the twenty-first century. *Royal Society of London Philosophical Transactions*, Series A, 369, 161-181.

Nicholls, R.J., and Tol, R.J.S. 2006. Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. *Phil. Trans. R. Soc. A*, 364, 1073-1095.

Nordhaus, W.D. 1992. The 'DICE' Model: Background and Structure of a Dynamic

Integrated Climate-Economy Model of the Economics of Global Warming, Cowles Foundation Discussion Papers 1009, Cowles Foundation, Yale University.

Nordhaus, W. D. and Yang, Z. L. 1996. A regional dynamic general-equilibrium model of alternative climate-change strategies. *American Economic Review,* 86**,** 741-765.

O'Brien, K., Eriksen, S., Schjolden, A. and Nygaard, L. 2004. What's in a word? Conflicting interpretations of vulnerability in climate change research. Centre for International Climate and Environmental Research, Working paper 2004, 4.

O'Connor, M.C., Lymbery, G., Cooper, J.A.G., Gault. J., McKenna. J. 2009. Practice versus policy-led coastal defence management. *Marine Policy,* 33, 923-929.

Organisation for Economic Co-operation and Development (OECD). 2011. The OECD environmental outlook to 2050 (Draft). OECD: Paris.

Organisation for Economic Co-operation and Development (OECD). 2008. Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments. OECD: Paris.

Oliver, G.A. 2005. Seasonal changes and biological classification of Irish coastal lagoons. PhD Thesis, Department of Zoology, University College Dublin.

Office of Public Works (OPW). 2011. Flood hazard mapping. Available from: http://www.floodmaps.ie/ (Accessed in November 2011).

Office of Public Works (OPW). 2010a. Overview of flood risk in Ireland. Available from: http://www.opw.ie/en/FloodRiskManagement/BackgroundPolicy/FloodRiskinIreland/OverviewofFloodRiskinIreland/#d.en.1380 (Accessed in Feb 2011).

Office of Public Works (OPW). 2010b.Catchment Flood Risk Assessment and Management Studies (CFRAM Studies). Available from: http://www.opw.ie/en/FloodRiskManagement/BackgroundPolicy/ManagingFloodRisk/FloodRiskManagementPlanning/ (Accessed in March 2010).

Office of Public Works (OPW). 2010c. Mansergh Announces Transposition into Law of the EU "Floods" Directive. Available from: http://www.opw.ie/en/LatestNews/Title,12942,en.html (Accessed in April 2010).

Office of Public Works (OPW). 2009. Minister of State Dr. Martin Mansergh, T.D. announces details of Coastal Erosion Funding. Available from: http://www.opw.ie/LatestNews/Title,12148,en.html (Accessed in June 2010).

Office of Public Works (OPW). 2004. Report of the flood policy review group. Stationary Office: Dublin.

Orford, J., 1989. A Review of Tides, Currents and Waves in the Irish Sea. In: The Irish

Sea: A Resource at Risk (ed.) John Sweeney. Special publication no. 3 of the Geographical Society of Ireland.

O'Sullivan, A. 2007. Exploring past people's interactions with wetland environments in Ireland. *Proceedings of the Royal Irish Academy*, 107, 147-203.

Otte, M.L. (ed.) 2003. *Wetlands of Ireland: Distribution, ecology, uses and economic value*. University College Dublin Press: Dublin.

Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B. and Kiehl, J.T. 2006. Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise, *Science*, 311, 1747-1750.

Paavola, J. and Adger, W.N. 2002. Justice and adaptation to climate change. Tyndall Centre for Climate Change Research, working paper 23.

Page, E. 2008. Distributing the burdens of climate change. *Environmental Politics*, 17 (4), 556-575.

Palmer, T.N. and Räisänen, J. 2002. Quantifying the risk of extreme seasonal precipitation events in a changing climate. *Nature*, 415, 512-514**.**

Parson, E.A. and Fischer-Vanden, K. 1997. Integrated Assessment models of global climate change. *Annual Review of Energy and the Environment*, 22, 589-628.

Patterson, M. 1996. *Global warming and global politics*. Routledge: London.

Pender, J. 2010. Our wetlands heritage. Irish Wildlife Trust: Dublin.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E. and Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, 399(6735), 429-436**.**

Pfeffer, W., Harper, J. and O'Neel, S. 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science*, 321 (5894), 1340-1343.

Pimm, S. L. 1997. The value of everything. *Nature*, 387, 231-232.

Proudman, J. and Doodson, A.T. 1924. The tides of the Irish Sea, *Merseyside, rit. Assoc. Adv. Sci*., Liverpool University Press, 1-8.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science*, 315, 368-370.

Ramsar, 2011. The Ramsar convention manual: a guide to the convention on wetlands, 5^{th} edition. Ramsar convention secretariat, Gland: Switzerland.

Ramsar website. Available from: http://www.ramsar.org/cda/en/ramsar-ramsar-movie/main/ramsar/1%5E24724_4000_0__ (Accessed in July 2010).

Reed, D. and Martin, J. 2005. Flood studies update: A new look at flood estimation for Ireland. National Hydrology Seminar, 26-33.

Richards, J.A. and Nicholls, R.J. 2009. Impacts of climate change in coastal systems in Europe. PESETA-coastal systems study. European Communities: Spain.

Rittel, H.W.J. and Webber, M.M. 1973.Dilemmas in a General Theory of Planning. *Policy Sciences*, 4 (2), 155-169.

Robinson, I.S. 1979. The tidal dynamics of the Irish and Celtic seas. *Geophys. J. Roy.astr. Soc*, 56,159-197.

Rohling, E., Grant, K., Hemleben, C., Siddall, M., Hoogakker, B., Bolshaw, M. and Kucera, M. 2008. High rates of sea-level rise during the last interglacial period. *Nature Geoscience*, 1, 38-42.

Rosenzwieg, C., Iglesias, A., Yang, X.B., Epstein, P.R. and Chivian, E. 2001. Climate change and extreme weather events: Implications for food production, plant diseases, and pests. *Global Change and Human Health*, 2 (2), 90-104.

SAFER. 2009. Flooding in Ireland 2009. Available from: http: //safer.emergencyresponse.eu/site/FO/scripts/myFO_contenu.php?noeu_id=89&lang=EN (Accessed in February 2010).

SAFER. 2008. Introduction to SAFER. Available from: http://safer.emergencyresponse.eu/site/FO/scripts/myFO_contenu.php?arbo=1&noeu_id=31&page_id=9&lang=EN (Accessed in April 2011).

Stahl, K., Hisdal, H, Hannaford, J., Tallaksen, L., Van Lanen, H., Sauquet, E., Demuth, S., Fendekova, M. and Jordar, J. 2010. Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences*, 14, 2367-2382.

Schuyt, K., and Brander, L. 2004. The Economic Values of the World's Wetlands. World Wildlife Fund, Gland/Amsterdam.

Scrieciu, S.S., Barker, T., Ackerman, F. 2011. Pushing the boundaries of climate economics: critical issues to consider in climate policy analysis. *Ecological Economics* (In Press).

SEMRU. 2009. Proceedings of the 1st Annual Beaufort Marine Socio-Economic Workshop. SEMRU, National University of Ireland, Galway in association with the Marine Institute, Ireland.

Shields, Y., O'Connor, J. and O'Leary, J. 2005. Ireland's ocean economy and resources. Marine Institute: Galway.

Simmel, G. 1990. *The Philosophy of Money*. (ed.) David Frisby. Routledge: London.

Smith, K. and Ward, R. 1998. *Floods: Physical processes and human impact*. Wiley:

Chichester.

Spash, C.L. 2007. The economics of climate change impacts à la Stern: Novel and nuanced or rhetorically restricted? *Ecological Economics*, 63, 706-713.

Spash, C. L. 1997. Ethics and environmental attitudes with implications for economic valuation. *Journal of Environmental Management*, 50**,** 403-416.

Stern, N. 2006, *Review on the Economics of Climate Change*, H.M. Treasury, UK.

Sterner, T. and Persson, U. M. 2008. An even Sterner Review: introducing relative prices into the discounting debate. *Review of Environmental Economics and Policy*, 2**,** 61-76.

Sweeney, J., Albanito, F., Brereton, A., Caffarra, A., Charlton, R., Donnelly, A., Fealy, R., Fitzgerald, J., Holden, N., Jones, M., Murphy, C. 2008. Climate change: Refining the impacts for Ireland. Published as part of the Science, Technology, Research and Innovation for the Environment (STRIVE) Programme 2007–2013 by the Environmental Protection Agency.

Tans, P. and Keeling, R. 2012. Scripps Institution of Oceanography. Available from: http://www.esrl.noaa.gov/gmd/ccgg/trends/ (Accessed in July 2012).

The Economist, 2011. A Deal in Durban. Available from: http://www.economist.com /blogs/newsbook/2011/12/climate-change-0 (Accessed in December 2011).

The Guardian, 2011. Bolivia enshrines natural world's rights with equal status for Mother Earth. Available from: http://www.guardian.co.uk/environment/2011/apr /10/bolivia-enshrines-natural-worlds-rights (Accessed in May 2011).

The Irish Times, 2011. Flood defence plan protest held. Available from: http://www.irishtimes.com/newspaper/breaking/2011/1016/breaking18.html (Accessed in January 2012).

Tietenberg, T. and Lewis, L. 2007. Environmental and Natural Resource Economics (5th Edition), Pearson Publishing, London.

Titus, J.G., Park, R.A., Leatherman, S.P., Weggel, J.R., Greene, M.S., Mausel, P.W., Brown, S., Gaunt, G., Trehan, M. and Yohe, G. 1991. Greenhouse Effect and Sea Level Rise: The Cost of Holding Back the Sea. *Coastal Management*, 19, 171-204.

Tol, R. S. J. 1997. On the Optimal Control of Carbon Dioxide Emissions: An Application of *FUND, Environmental Modeling and Assessment*, 2, 151–163.

Tol, R.S.J. and Yohe, G. 2006. A review of the Stern review. *World Economics*, 7 (4), 233-250.

Trenberth, K.E. 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change*, 42, 327-339.

Turner, B.L. 2010. Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science. *Global Environmental Change*, 20, 570-576.

Turner, R.K., Bateman, I.J., Adger, W.N., 2001. Ecological economics and coastal zone ecosystems' values: an overview. In: Turner, R.K., Bateman, I.J., Adger, W.N. (Eds.), *Economics of Coastal and Water Resources: Valuing Environmental Functions*. Kluwer Academic Publishers: Dordrecht/Boston/London.

Turner, R.K., Van den Bergh, J.C.J.M., Barendregt, A. and Maltby, E. 1997. Ecological-economic analysis of wetlands: Science and social science integration. Global Wetlands Economics Network (GWEN) Working Paper.

Turner, R.K. 1991. Economics and wetland management. *Ambio*, 20(2), 59-63.

Turner, R.K., Adger, N. and Doktor, P. 1995. Assessing the economic costs of sea level rise, *Environment and Planning*, 27(11), 1777-1796.

Tutin, T.G., Burges, N.A., Chater, A.O., Edmondson, J.R., Heywood, V.H., Moore, D.M., Valentine, D.H., Walters, S.M. and Webb, D.A. 1993. *Flora Europaea*, Volume One. Cambridge University Press: Cambridge.

UKCIP. 2005. Principles of good adaptation. UKCIP, Guidance Note. Available from: http://www.ukcip.org.uk/essentials/adaptation/good-adaptation/ (Accessed in Feb 2010).

United Nations. 1987. Report of the world commission on environment and development: Our common future. Available from: http://www.un-documents.net/wced-ocf.htm (Accessed in October 2009).

United Nations Framework Convention on Climate Change (UNFCCC). 2010. Press Release: UN Climate Change Conference in Cancún delivers balanced package of decisions, restores faith in multilateral process. Available from: http://unfccc.int/files/press/news_room/press_releases_and_advisories/application/pdf/pr_20101211_cop16_closing.pdf (Accessed in January 2010).

United Nations Framework Convention on Climate Change (UNFCCC) 2008. Investment and financial flows to address climate change: An update. Technical paper.

United Nations International Strategy for Disaster Reduction (UNISDR) 2009. UNISDR terminology on disaster risk reduction. United Nations: Geneva.

Vafeidis, A.T, Nicholls, R.J., McFadden, L., Tol, R.S.J., Hinkel, J., Spencer, T., Grashoff, P.S., Boot, G. and Klein, R.J.T. 2008. A new global coastal database for impact and vulnerability analysis to sea-level rise. *Journal of Coastal Research*, 24(4), 917-924.

Valiela, I., Bowen, J.L. and York, J.K. 2001. Mangrove forests: one of the world's threatened major tropical environments. *BioScience*, 51(10), 807-815.

Van Aalst, M.K., Cannon, T. and Burton, I. 2008. Community Level Adaptation to Climate Change: The Potential Role of Participatory Community Risk Assessment, *Global Environmental Change*, 18, 165-79.

Van Asselt, M.B.A. and Rotmans, J. 2002. Uncertainty in Integrated Assessment Modelling: From Positivism to Pluralism. *Climatic Change,* 54, 75-105.

Van den Bergh, J.C.J.M. 2004. Optimal climate policy is a utopia: from quantitative to qualitative cost-benefit analysis. *Ecological Economics*, 48, 385-393.

Van der Knijff, J.M., Younis, J. and De Roo, A.P.J. 2010. LISFLOOD: a GIS-based distributed model for river-basin scale water balance and flood simulation. *International Journal of Geographical Information Science*, 24(2), 189-212.

Vellinga, P., Katsman, C.A., Sterl, A. and Beersma, J.J. (eds.) 2008. Exploring high end climate change scenarios for flood protection of the Netherlands: An international scientific assessment for the Dutch Delta Committee.

Vermeer, M. and Rahmstorf, S. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Science of the United States of America*, 106, 21527–21532.

Vogel, C., Moser, S.C., Kasperson. R.E, Dabelko. G.D. 2007. Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. *Global Environmental* Change, 17, 349-364.

Walton, M., Kelman, I., Johnston, D. and Leonard, G. 2004. Economic impacts on New Zealand of climate change extreme events: Focus on freshwater floods. New Zealand Ministry of the Environment: Wellington.

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

Ward, R.C. 1978. *Floods: A geographical perspective*. MacMillan: London. 244p.

Warren, R., Hope, C., Mastrandrea, M., Tol, R.S.J., Adger, W.N. and Lorenzoni, I. 2006. Spotlighting the impacts functions in integrated assessments. Research Report Prepared for the Stern Review on the Economics of Climate Change. In *Tyndall Centre Working Paper 91*.

Water Framework Directive website. 2005. Available from: www.wfdireland.ie (Accessed in November, 2011).

Watson, R.T., Zinyowera, M.C. and Moss, R.H. 1995. Impacts Adaptations and Mitigation of Climate Change: Scientific Technical Analysis. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press, 899p.

Weitzman, M.L. 2007. A review of the Stern Review on the economics of climate change. *Journal of Economic Literature*, 45, 703-724.

Wigley, T.M.L. 2005. The climate change commitment. *Science*, 307 (5716), 1766-1769.

Williams, P. W. 1970. Limestone morphology in Ireland, in *Irish Geographical Studies*, Glasscock, R. and Stephens, N. (eds.) Queen's University, Belfast, 105-124.

Willows, R. I. & Connell, R. K. 2003. Climate adaptation: risk, uncertainty and decision-making. UKCIP technical report. UKCIP, Oxford.

World Bank. 2009. (Draft) The Costs to Developing Countries of Adapting to Climate Change: New Methods and Estimates. Washington DC: World Bank. World Resources Institute, 2011. Summary of developed country fast start climate finance packages. Available from: http://pdf.wri.org/climate_finance_pledges_2011-11-18.pdf (Accessed in Dec 2011).

World Resources Institute 2011. Summary of Developed Country Fast-Start Climate Finance Pledges. Available from: http://pdf.wri.org/climate_finance_pledges_2011-11-18.pdf (Accessed in Jan 2012).

Yohe, G.W. and Schlesinger, M.E. 1998. Sea-level change: the expected economic cost of protection or abandonment in the United States, *Climatic Change*, 38 (4), 447-472.

Yohe, G. W. and Tol, R. S. J. 2008. The Stern Review and the economics of climate change: an editorial essay. *Climatic Change*, 89**,** 231-240.

Zedler, J.B. and Kercher, S. 2005. Wetland resources: Status, trends, ecosystem services, and restorability. *Annual Review of Environmental Resources*, 30, 39-74.