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A Cultural Heritage Management Methodology for Assessing the Vulnerabilities of Archaeological Sites to Predicted Climate Change Focuing on Ireland's Two World Heritage Sites

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A Cultural Heritage Management Methodology for Assessing the Vulnerabilities of Archaeological Sites to Predicted Climate Change, focusing on Ireland's two World Heritage sites

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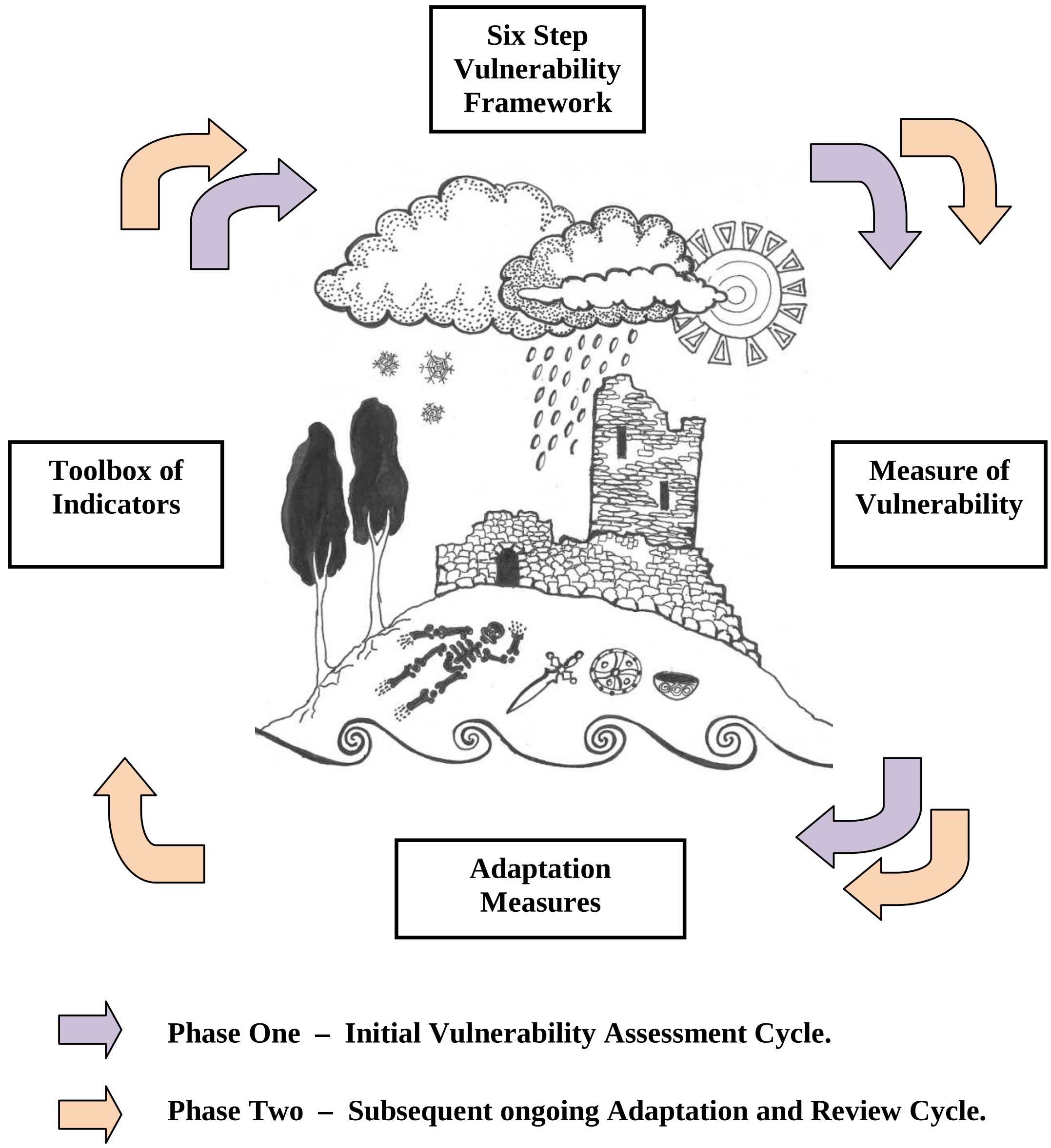
ABSTRACT

The affect climate change will have on cultural heritage preservation poses a global challenge and is being addressed by international organisations such as UNESCO and ICOMOS. The aim of this doctoral research is to assist heritage managers in understanding the implications of climate change for the sites in their care. It addresses the question of how to approach the assessment and measurement of climate change impacts on cultural heritage.

The potential future effects of climate change on cultural heritage in temperate climates are discussed and current international practice in the management of climate change impacts on cultural heritage is investigated. The results reveal several issues currently of concern amongst practitioners; namely 'what' to monitor, 'how' to monitor and how to interpret results when dealing with the highly complex and long-term issue of climate change impacts. A Vulnerability Framework for site based evaluations is defined and adapted specifically for cultural heritage. This six step method relies on expert judgement and stakeholder involvement; it is a place based approach studying the coupled 'human-environment system'. The Framework is illustrated through the assessment of the vulnerability of Ireland's World Heritage Sites, Skellig Michael and Brú na Bóinne, to the impacts of projected climate change up to 2100. The results suggest that the projected alterations in rainfall will be the most problematic climate change factor for both sites. Climate change indicators developed as part of the Vulnerability Framework are proposed as a solution to the problem of long-term monitoring. The development of a general Toolbox of Indicators is accompanied by the design and pilot trial of a Legacy Indicator Tool (LegIT). This tool, for tracking the surface weathering of stone and related materials, can be tailored to the needs of individual heritage

sites and is currently being piloted at five monuments in Ireland, including the two case studies.



Cultural Heritage Management Model developed for the assessment of, and adaptation to, climate change impacts

In this research transferable methodologies for the site level assessment and measurement of climate change vulnerabilities are developed and applied in practice. The Vulnerability

Framework, Impacts Matrix, Toolbox of Indicators and Legacy Indicator Tool (LegIT) are original and transferable outputs. They will aid decision makers with planning and prioritisation for the case study sites and provide a management model that has the potential to facilitate assessments at other sites in Ireland and internationally.

DECLARATION

I certify that this thesis which I now submit for examination for the award of PhD, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for another award in any other third level institution. The work reported on in this thesis conforms to the principles and requirements of the DIT's guidelines for ethics in research.

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Signature ___________________________________ Date _______________

Caithleen (Cathy) Daly

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GLOSSARY OF TERMS

CfC	Climate for Culture (EU FP7 project)
CZAS	Coastal Zone Assessment Survey
DAHG	Department of Arts, Heritage and the Gaeltacht
DIT	Dublin Institute of Technology
DoEHLG	Department of Environment, Heritage and Local Government
EU	European Union
GCM	Global Climate Model
GHG	Greenhouse Gases
GIS	Geographic Information Systems
IPCC	Intergovernmental Panel on Climate Change
ICOMOS	International Council on Monuments and Sites
ICCROM	International Centre for the Study of the Preservation and Restoration of Cultural Property
OPW	Office of Public Works
OUV	Outstanding Universal Value
PI	Principal Investigator
RCM	Regional Climate Model
RCZAS	Rapid Coastal Zone Assessment Survey
SCCC	Sub Committee on Climate Change (ICOMOS Ireland)
SLR	Sea Level Rise
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNFCC	United Nations Framework Convention on Climate Change
WHS	World Heritage Site
WMF	World Monuments Fund

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CHAPTER 1.

INTRODUCTION

We will respond to the threat of climate change, knowing that the failure to do so would betray our children and future generations (Obama, 2013).

1.1. BACKGROUND TO RESEARCH

That we are living in a period of accelerating climatic change is now, according to international scientific research gathered by the IPCC, an unequivocal fact (Pachauri and Reisinger, 2007). While the exact cause and appropriate response continue to be debated (Schneider et al., 2010, Leiserowitz A. et al., 2012), there also remains a great deal of uncertainty as to what the future climate will be like. The climate model projections for Ireland suggest that by 2099 winters will be warmer and wetter, summers will be warmer and drier, and there will be an increase in storms and heavy rainfall events (section 3.2.6).

The impact of climate change on natural heritage conservation is well publicised but there is a growing awareness that global climate change may also threaten cultural heritage conservation. In 2005 the World Heritage Committee, which oversees the UNESCO World Heritage list for sites of outstanding natural and cultural value, received a petition to place four natural heritage sites on the List in Danger due to climate change threats (Dannenmaier, 2010, Climate Justice Programme, 2006).[1] The Committee turned down the proposal but its resultant decision (05/29.COM/7B.a) made several recommendations that raised the issue of

[1] The sites involved were Sagarmatha National Park (Nepal), Huascaran National Park (Peru), the Great Barrier Reef (Australia) and the Belize Barrier Reef Reserve System (Belize). In 2005 a fifth petition, for the addition of Waterton-Glacier International Peace Park, Canada-USA, to the List in Danger, was submitted.

climate change as a major concern for both natural and cultural heritage sites (UNESCO, 2005).

The issue of climate change threats to cultural heritage has been recognised by international organisations such as the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) and the International Council on Monuments and Sites (ICOMOS), and at national level by agencies such as English Heritage and the Norwegian Directorate for Cultural Heritage (English Heritage, 2008a, Haugen and Mattson, 2011, Bumbaru et al., 2006, ICCROM, 2007). In 2008 the World Monuments Fund (WMF) published its Watch List of sites in danger and for the first time included monuments for which global climate change was the main perceived threat (Murdock, 2007, Clark, 2007).[2] There has also been activity at governance level with the European Union sponsored research projects Noah's Ark and Climate for Culture (CfC) investigating climate change threats for Europe (Sabbioni et al., 2010, Climate for Culture, 2013).

In 2008 the author completed a Master’s thesis on the vulnerability to climate change of the Megalithic complex of Brú na Bóinne in counties Meath and Louth. This research was undertaken as part of a Masters in World Heritage at Brandenburg University Cottbus Germany (Daly, 2008). By coincidence, during the same period, the Irish Government’s Department of Environment Heritage and Local Government[3] (DoEHLG) requested ICOMOS Ireland to make recommendations for monitoring the impacts of climate change on built cultural heritage. In 2008 a sub-committee on climate change (SCCC) was convened

[2] The sites were Scott’s Hut, Antarctica, Herschel Island, Canada, Chinguetti Mosque, Mauritania, Sonargaon-Panam City, Bangladesh, Leh Old Town, Ladakh, India and New Orleans Louisiana.
[3] The Heritage portfolio has since moved to the Department of Arts Heritage and the Gaeltacht.

for this purpose. Subsequent to volunteering for the SCCC the author was given the task of researching potential impacts and monitoring requirements for the two selected sites of Brú na Bóinne and Clonmacnoise, an Early Christian monastic site in Co. Offaly. The subsequent ICOMOS report (Daly et al., 2010) expanded on the Masters research in its application of an eight step vulnerability method to both sites as outlined by Schröter and recommended by UNESCO (Colette, 2007). In September 2009 the author received a scholarship from Dublin Institute of Technology (DIT) to pursue doctoral research on the topic and in 2011 a grant from the DoEHLG enabled the manufacture and implementation of the Legacy Indicator Tool (LegIT) designed during the research.

Thus, while this research builds upon previous work by the author it is also a response to a growing interest in the issue at national level in Ireland. The thesis will consider climate change impacts from a site management perspective, focussing on Ireland's two World Heritage properties: Brú na Bóinne and Skellig Michael, an Early Christian ascetic monastery in County Kerry.

1.2. RESEARCH QUESTION & AIMS

The RESEARCH QUESTION addressed in this thesis is:

<u>How can cultural heritage managers gain an understanding of the impacts of climate change on sites in their care?</u>

The interlinked RESEARCH AIMS that flow from this question are:

1. **To determine what method or methods are most appropriate for assessing potential vulnerabilities to climate change at site level.**
2. **To determine which monitoring solutions are capable of measuring the impacts of climate change on heritage values.**

	6 STEP VULNERABILITY ASSESSMENT FRAMEWORK
1	Define the heritage values to be assessed
2	Understand exposure, sensitivity and adaptive capacity of these values over time
3	Identify likely hazards for each value under future climate using the Matrix of Impacts
4	Develop indicators for the elements of vulnerability
5	Assess vulnerability by entering values for exposure, sensitivity and adaptive capacity into the Causal Model (table 6.2)
6	Use Stakeholder Review to refine and communicate results

Table 1.1 Six step vulnerability framework, developed in this research, for assessing potential climate change impacts at heritage sites.

In order to address the research aims the following STRATEGIC OBJECTIVES for the thesis were identified.

1. To ascertain which are likely to be the most pertinent effects of future climate change on cultural heritage in Ireland (including built heritage, cultural landscapes and archaeology).
2. To identify suitable methodologies for the assessment of potential climate change impacts on cultural heritage sites.

3. To exchange knowledge with national and international counterparts in the field in order to synthesise existing knowledge and identify current international practice.
4. To develop a robust, transferable vulnerability assessment methodology that can facilitate analysis of potential climate change impacts at other heritage sites (table 1.1).
5. To identify a toolbox that will inform and initiate the monitoring of climate change impacts at the case study heritage sites of Brú na Bóinne and Skellig Michael.

1.3. JUSTIFICATION OF RESEARCH

This research concerns two topics of global relevance:

1. The protection of material cultural heritage - specifically World Heritage which is of Outstanding Universal Value as defined by UNESCO and agreed upon by the 190 State Parties to the World Heritage Convention.[4]
2. The impacts of climate change - a global problem of concern and the focus of international co-operative agreements such as the 1992 United Nations Framework Convention on Climate Change (UNFCC).[5]

There is a growing recognition that the global threat of climate change requires a comprehensive response in order to ensure protection for cultural heritage (Haugen and Mattsson, 2011, Berenfeld, 2008, Christoff, 2008, McIntyre-Tamwoy, 2008). In a survey of States Parties to the World Heritage Convention, 46% of the sites reported as affected by climate change were cultural (Colette, 2007). Twenty years after the Rio Declaration and six

[4] For a list of the State Parties see http://whc.unesco.org/en/statesparties/ [retrieved 28.5.2013]
[5] For more detail on this convention see http://unfccc.int/2860.php [retrieved 2.6.2013]

years since UNESCO conducted that survey however, the issues surrounding climate change have yet to be addressed effectively and are becoming increasingly urgent. This research aims to contribute to two areas where gaps have been identified within the literature:

1. There is a lack of case study or site based assessments of climate change impacts on cultural heritage (see section 3.4).
2. Archaeological heritage and cultural landscapes have been under-researched in terms of impacts analysis, the focus to date having been on coastal and built heritage (section 3.5).

In 2007 the UNESCO General Assembly adopted a 'Policy document on the impacts of Climate Change'. Under the section *'Research Needs, Key Challenges'* the document states:

> *There is presently a lack of data that is specifically relevant to understanding climate change impacts on World Heritage properties, particularly cultural properties....Addressing these gaps in knowledge, information and capacity, and performing vulnerability assessments will assist in determining priorities for management action* (UNESCO, 2007).

The thesis will address these *key challenges* by developing and applying transferable, low cost methodologies for site level vulnerability assessment and impact monitoring (objectives 2, 4 and 5). The six step Vulnerability Framework, Impacts Matrix, Toolbox of Indicators and Legacy Indicator Tool (LegIT) developed in this work are original and transferable results of the research. It is hoped that they will aid decision makers with planning and prioritisation for the case study sites and also facilitate assessments of other sites in Ireland and internationally. Initiated by ICOMOS Ireland and partly funded by the Department of

Arts Heritage and the Gaeltacht (formerly DoEHLG), this research thesis therefore makes a real and practical contribution to the field of cultural heritage management.

1.4. METHODOLOGY

Managing cultural heritage entails balancing diverse needs and perceptions of value in the present with the duty to preserve resources for future generations. The methodological approach utilised in this thesis reflects that challenge and is informed by a pragmatic constructionist viewpoint (section 2.2). The research philosophy acknowledges that meaning and value are social constructs framed in reference to a material reality (Crotty, 1998). For this reason a multi-method approach was chosen. This allowed a balance to be created between theoretical and practical analyses through a deductive-inductive research cycle (Carlile and Christensen, 2005). While the research methodology used is predominantly qualitative, whenever possible, this is underpinned by quantitative data.

The main research strategy is to assess the vulnerability of Brú na Bóinne and Skellig Michael (figure 1.2) to the effects of predicted climate change (section 2.3). This 'case study' approach is defined as:

> *...a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence* (Robson, 2011: 178).

By allowing the triangulation of multiple sources of data, the case studies enable the testing and refinement of theoretical concepts, in line with the pragmatic nature of the thesis (Saunders et al., 2009).

1.4.1. Techniques and procedures

Data collection and analysis techniques for achieving the strategic research objectives will be detailed in the following chapter and include:

- Literature review (objective 1 and 2).
- Review and synthesis of current research and practice from questionnaires completed by international experts (objective 2 and 3).
- In-depth examination (field visits and interviews) of four international 'exemplar' projects (objective 3).
- Investigation and development of theoretical Vulnerability Framework for assessing the impacts of climate change on cultural heritage sites (objective 5).
- Case study application of the Vulnerability Framework to Irish World Heritage sites including field visits, desk based study and stakeholder interviews (objective 5).
- Development of a Toolbox of Indicators for use in conjunction with the Vulnerability Framework (objective 4).
- Design and production of a new indicator tool, the LegIT (objective 4). This tool was field tested at the case study sites and subsequently installed at a further three National Monuments (figure 1.1).
- Validation of results via expert feedback (objective 5).

Figure 1.1 W. Foley, OPW, assisting with LegIT; one of three installed at Knowth, February 2013

1.5. THESIS OUTLINE

Figure 1.3 presents a visual outline of the thesis structure. There are eleven chapters in all, including the Introduction (1) and Conclusion (11). Chapter two details the methodological approach and research undertaken and chapter three outlines the current state of knowledge on the topic, based on a literature review. The current state of practice is described in chapters four and five which present the results of interviews and field visits. In chapter four the results of an expert questionnaire are reported and in chapter five selected exemplar projects are analysed. The results from these primary and secondary background investigations lead to the two separate but complementary management strategies that are explored in the remaining sections. Thus, chapters six to eight deal with vulnerability assessment and chapter nine and ten investigate the potential of indicators. In chapter six a Framework for assessing the vulnerability of a site to climate change impacts is developed from existing theoretical approaches and in chapters seven and eight it is applied to the World Heritage case studies. Chapter nine discusses the theory and application of indicators within the Vulnerability Framework. In chapter ten the *LegIT*, a Legacy Indicator Tool designed and installed as part of this research, is described. Finally the concluding chapter eleven presents the conclusions, implications, and recommendations derived.

Brú na Bóinne ▲

Skellig Michael ▲

Figure 1.2. Location of Brú na Bóinne and Skellig Michael World Heritage case studies

THESIS STRUCTURE

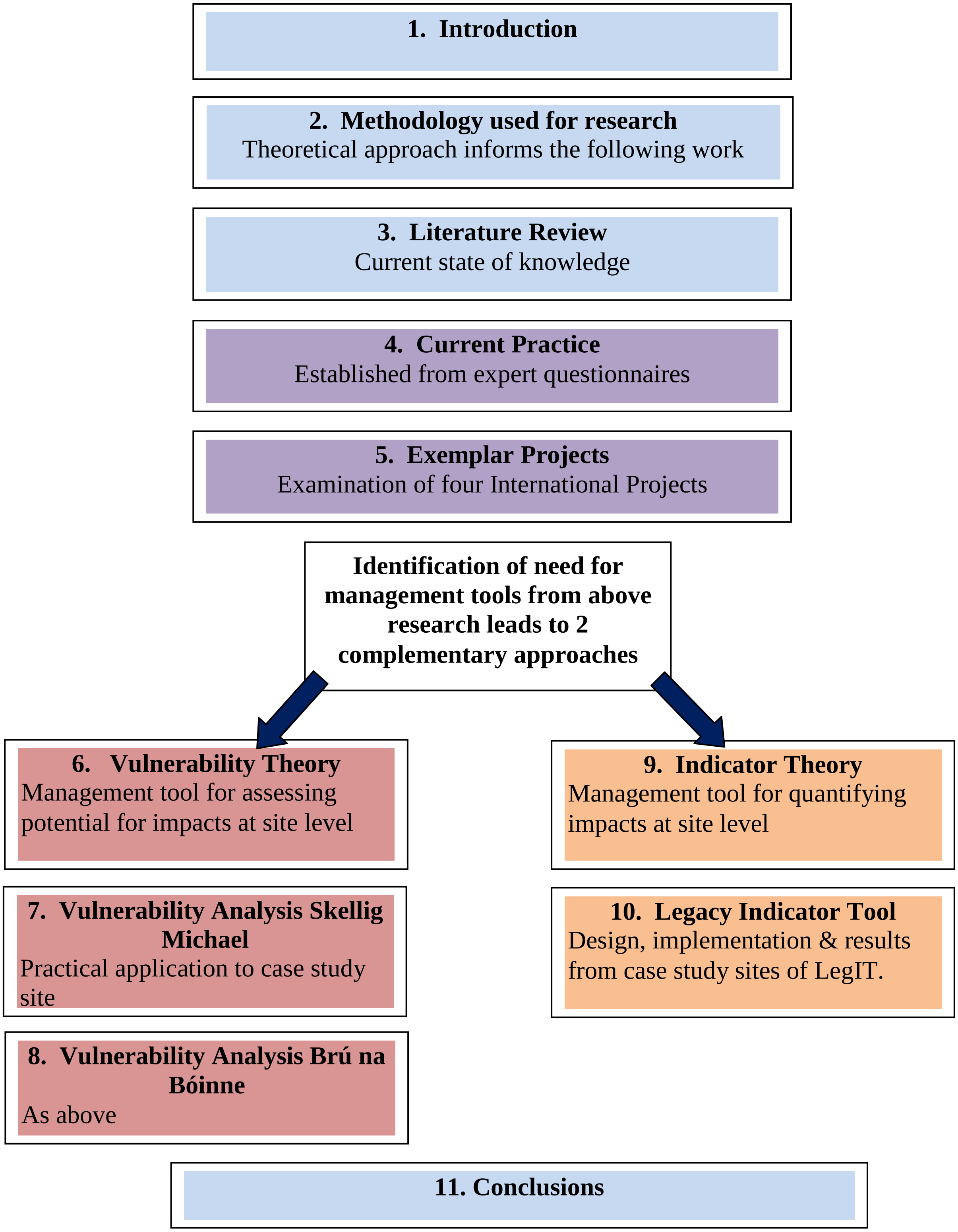

Figure 1.3 Visual outline of thesis structure

1.6. DEFINITION OF KEY TERMS

In this section the key terms used within the thesis are clarified:

Adaptation: The adjustment in natural or human systems, in response to actual or expected climatic stimuli or their effects, that moderates harm or exploits beneficial opportunities (Pachauri and Reisinger, 2007).

Archaeology: Material heritage for which archaeological methods provide the primary source of information - includes abandoned structures, subterranean and underwater evidence of human activities (ICOMOS, 1990).

Built heritage: The ICCROM definition of built heritage states built heritage takes many forms including: monuments; buildings; archaeological and other sites; urban areas; cultural landscapes…It may further be broken down into such categories as: religious or other spiritual buildings or places; vernacular architecture; historic towns, cities, or settlements; parks and gardens; cultural routes (ICCROM, 2010).

Context is central to the value of built (or any) heritage thus the definition continues: The built heritage cannot stand alone. Built heritage almost always has heritage objects associated with it, as well as intangible heritage in the form of knowhow, rituals, performances, and specific uses. Conservation and management must always take into account the entire heritage in question. The built heritage also does not stand alone from the community that lives around it and cares for it. It is an integral part of that community and must be seen as a contributor to life of the community and its social and economic well being (ICCROM, 2010).

Brú na Bóinne: The Irish name used for the case study World Heritage property 'Archaeological Ensemble of the Bend in the Boyne' (translates as 'mansion' or 'house' of the Boyne).

Climate change: A change in the average climate or its variability from one averaging period to the next i.e. 30 years (Parry and Carter, 1998).

Conservation: The processes of looking after a place so as to retain its cultural significance. It includes maintenance and may according to circumstance include preservation, restoration, reconstruction and adaptation and will be commonly a combination of more than one of those (ICOMOS, 1999).

Cultural heritage (tangible): The entire corpus of material signs handed on by the past to each culture…cultural heritage gives each particular place its recognizable features and is the storehouse of human experience – it includes built heritage, archaeology, cultural landscapes and moveable heritage (UNESCO, 1989).

Cultural landscapes: The “combined works of nature and of man” - illustrative of the evolution of human society and settlement over time, under the influence of the physical constraints and/or opportunities presented by their natural environment and of successive social, economic and cultural forces, both external and internal (UNESCO World Heritage Centre, n.d.).

Equifinality: Having the same result from different events or processes (Merriam-Webster Dictionaries, 2013).

Natural heritage: Inherited habitats, species, ecosystems, geology and landforms, including those in and under water, to which people attach value (English Heritage, 2008b).

Mitigation: The process of attempting to reduce emissions or to increase sinks of greenhouse gases in order to slow climate change (Pachauri and Reisinger, 2007).

Preservation: Maintaining the fabric of a place in its existing state and retarding deterioration (ICOMOS, 1999).

Vulnerability: The extent to which climate change may damage or harm a system dependant not only on a system's sensitivity and exposure but also on its ability to adapt to new climatic conditions (Moss et al., 2001). For further discussion on definitions of vulnerability and its elements see section 6.7.

1.7. DELIMITATION OF SCOPE

This thesis aims to address the question: *How can cultural heritage managers gain an understanding of the impacts of climate change on sites in their care?* In considering this query it was necessary to make certain choices about the scope and nature of the research.

1.7.1. Climate change

While there is a general consensus that global climate change is underway, the degree to which this is attributable to human actions versus natural factors continues to be debated to some extent.[6] This research will not enter into the climate debate however, instead it accepts the broad international consensus that climate change is now a reality (Pachauri and Reisinger, 2007). Starting with the precept that, regardless of the underlying causes, climate

[6] For examples of the climate change sceptics' arguments see Christopher Booker, 2009 or AlJazeera English, 2013.

change is underway, the focus of this research will be upon the implications of this for cultural heritage management.

1.7.2. Which heritage? Case study selection

The focus of the research is geographically limited to Ireland. As the research grew out of an ICOMOS Ireland project and is based in DIT this was a natural boundary condition. The case studies are Skellig Michael and Brú na Bóinne, Ireland's only World Heritage sites (WHS), chosen on both strategic and academic grounds:

1. They have a wealth of documentation and research that does not exist for the majority of heritage properties.
2. They have heritage values which have been clearly defined. As a prerequisite for nomination UNESCO requires WHS to have what it terms Outstanding Universal Values (OUV) (section 3.1.3). The evaluation conducted within this research project also considers national and local heritage values where they have been identified e.g. the lighthouse structures on Skellig Michael (chapter 7).
3. They combine the features of upstanding archaeological monuments, buried archaeological remains and cultural landscape common to many national monuments in Ireland.
4. They provide an interesting contrast in terms of management issues, geographical locations (figure 1.2) and climate exposure.
5. The iconic status of World Heritage sites has added value when it comes to awareness and engagement with the issue of climate change (Daly, 2010, Matsuura, 2006).

6. Their use locates this research within a wider international context by responding to the World Heritage Committee request for vulnerability studies on case study World Heritage sites (UNESCO, 2007).

1.7.3. Focusing the research on assessment processes

The thesis presents a Framework for conducting a vulnerability assessment and a Toolbox of Indicators, including the Legacy Indicator Tool (LegIT), for tracking impacts of concern. The aim is to provide decision makers with tools that can aid them in making informed choices about climate change adaptation and/or mitigation strategies. Those response strategies do not form part of this thesis. Rather, the aim is to map the first step in the management process - understanding the problem - in the most thorough manner possible.

1.7.4. Considering sustainable alternatives to conventional monitoring

The ICOMOS SCCC report includes a series of monitoring recommendations for tracking climate change impacts. There are issues in terms of the sustainability of some monitors however and the decision was taken to make a fresh contribution by looking for techniques not currently in use in the cultural heritage field but which may offer long-term solutions. For this reason it was decided that the potential of indicators should be focussed on in relation to creating a toolbox. Indicators aid in assessing vulnerability, can work in tandem with existing monitoring solutions, and offer a system for comparing climate change impacts between sites over a range of variables. Critically, for measuring climate change impacts, they can be sustainable over long time periods.

1.7.5. The time horizon

As the time horizon for assessing climate change is 30–100 years, verification of the accuracy of the vulnerability assessment based on observed impacts will not be part of the thesis. Similarly the LegIT is not expected to yield conclusive data until at least 2041. The aim is therefore to undertake a pilot study and to build sufficient flexibility into the resulting Vulnerability Framework and LegIT protocols to ensure that they can be refined and adjusted as necesary over the coming decades.

1.8. SUMMARY

In this chapter, the concepts and ideas that will underpin the rest of the thesis have been briefly outlined. General background on the topic of cultural heritage and climate change and the specific circumstances leading up to this particular research with ICOMOS Ireland have placed the thesis in context. The research question being addressed is: *How can cultural heritage managers gain an understanding of the impacts of climate change on sites in their care?* This question will be at the core of the research undertaken, as described in the aims and objectives section. The visual outline of the thesis structure presented here (figure 1.3) illustrates how the underlying research question has shaped the work, producing two complementary strands of investigation: vulnerability theory and application (chapters 6–8), and indicator theory and application (chapters 9–10).

The definitions of important terms and the conditions that create a boundary for the thesis have been established. The choice of the research area can be justified on the grounds of usefulness and originality. This originality will be demonstrated further within the body of the thesis and in the concluding section, with reference to primary research undertaken. Having established the context and laid the foundations for the thesis, we can now proceed to a more detailed description of the research carried out. In the next chapter the methodological issues and actions undertaken will be detailed.

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CHAPTER 2.

RESEARCH METHODOLOGY

2.1. INTRODUCTION

In this chapter the methodology chosen to address the research problem defined in chapter one is described. The philosophy underlying the research approach is outlined and the strategy, methods and activities chosen are described. Activities undertaken in respect of primary data gathering through interviews are given particular attention in order to render the process as transparent as possible. The specific theoretical and methodological issues regarding the vulnerability assessment, Indicator Toolbox and the Legacy Indicator Tool (LegIT) will be dealt with in subsequent chapters.

2.2. RESEARCH PARADIGM

The identification of the researcher's position within a philosophy, paradigm or *set of beliefs* (Creswell, 2007) is necessary for a few reasons. First it enables the reader to understand the epistemological stance of the researcher, giving context to the research product. By clearly outlining their philosophical approach the researcher clarifies possible bias, and this transparency is an important element in establishing credibility and trustworthiness (Robson, 2011). Examining the theoretical path and the processes of the research also creates a rigorous procedure that will improve the usefulness of the final outcome for the end user, allowing them to clearly identify which aspects are relevant to their circumstances (Carlile and Christensen, 2005). Second, from the researcher's perspective, it is important to be conscious of assumptions held regarding the production of knowledge as these will inevitably shape the research outcome. It is also useful to understand where the research fits within the broad family of theoretical approaches to aid in both the choice and justification of methods and analysis techniques (Crotty, 1998). The way in which the various layers of the research methodology relate to each other can be represented visually using Saunders' concept of a 'research onion' (figure 2.1) (Saunders et al., 2009).

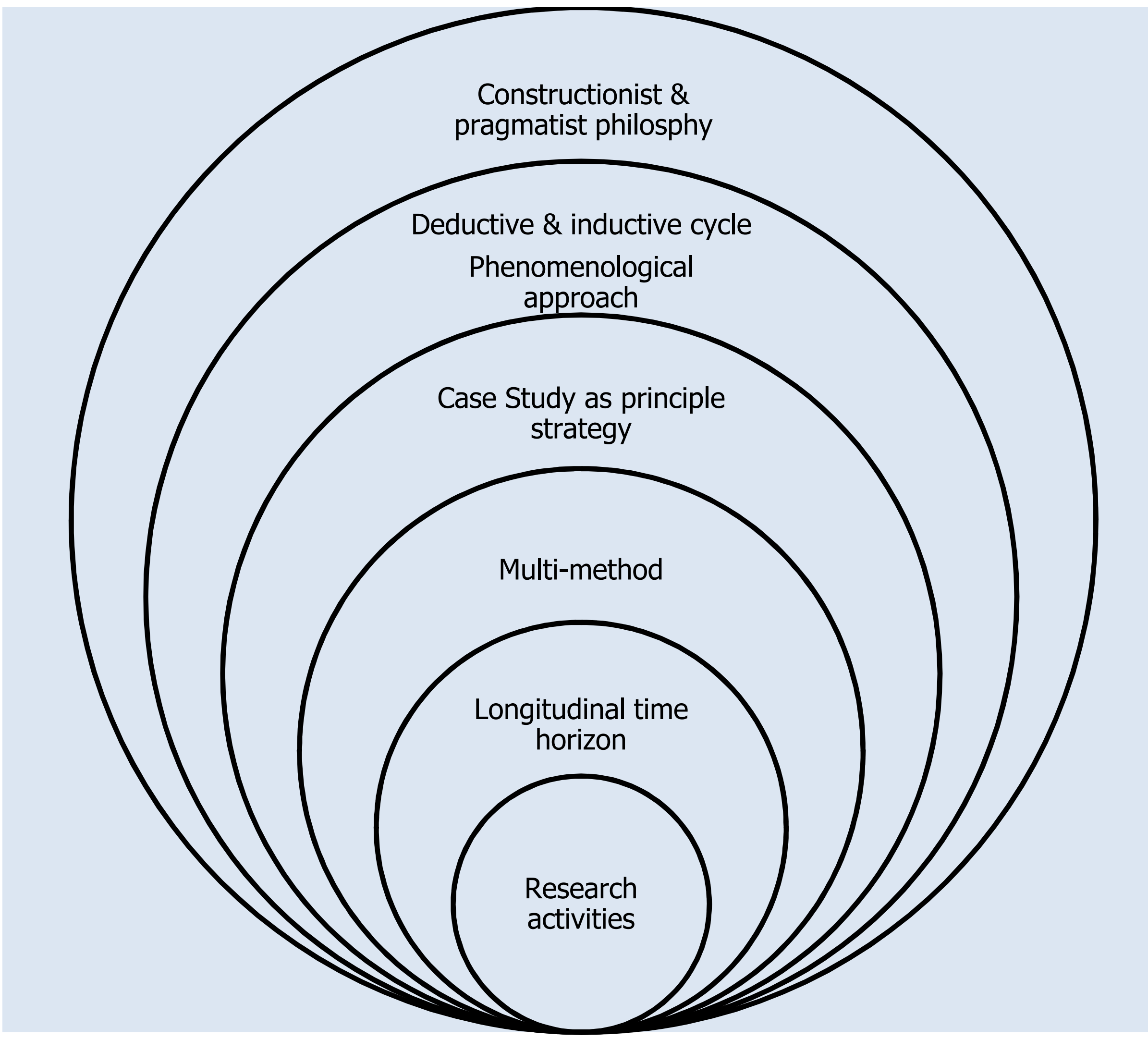

Figure 2.1. Diagram representing the nested layers of the research methodology, adapted from Saunders' research 'onion' (Saunders et al., 2009).

2.2.1. Constructionist philosophy

This paradigm, also termed interpretivist, proposes that there is no objective meaning, rather it is constructed as human beings interact with objects (Crotty, 1998). According to this view culture is the outcome of these interactions; it is an inherited social construct, a way of making sense of the world that shapes how we see and feel things (Bryman, 2008). This version of 'culture' enables us to function as human beings but may be limiting if we accept the 'constructed view' as an independent truth. The production of heritage is part of what constructionists term sedimentation: layers of social interpretation laid down over time that fix meaning in one accepted dimension (Crotty, 1998). In constructionism the key to making meaning or knowledge is to interact with the object. The product of this interaction is neither purely subjective (socially determined) nor purely objective (an absolute reality separate from human consciousness).

2.2.2. Constructionist approach to conducting research

Phenomenology offers a theoretical route to creating a methodology within the constructionist tradition, by encouraging us to engage directly with phenomena in our environment (Crotty, 1998, Saunders et al., 2009). While acknowledging we already operate under certain constructed meanings, it encourages us to let this direct experience speak to us first hand (Crotty, 1998). This theoretical focus matches with the intention of the current enquiry: to engage with both the physical heritage objects and their socially constructed 'meaning' (i.e. the cultural values). The case study sites are the subject of layers of sedimented meaning laid down over centuries, the World Heritage values being one of the most recent strata. To conduct this study, the physical objects themselves are placed at the heart of the assessment of preservation and loss. Thus when we speak about values we recognise that these are socially constructed and consider them in terms of the objects from which they have been constructed and not as independent truths. Conversely, although there is an emphasis on the physical preservation of the objects, a constructionist perspective acknowledges that they have no inherent value. Their status as 'heritage' is attributed through socially constructed concepts of significance. The aim of the constructionist approach is therefore to balance the interplay between subjective interpretation of value and the objective physicality of the sites.

The process of creating meaning is one of excluding meaning, circumscribing and limiting interpretation. Again this can be overcome by returning to the object/phenomena itself. The strand of phenomenology described by Crotty is quite radical in its desire to break free from what it sees as the restraints and fetters of dominant culture (Crotty, 1998). As a methodology it challenges the researcher to approach the work with fresh eyes and to question accepted norms and assumptions. It is therefore appropriate to take this approach when considering the issue of climate change which may challenge assumptions that underlie current heritage preservation and management systems (section 3.8).

2.2.3. The phenomenological researcher

The phenomenological researcher has to be embedded in the conventions of constructed meanings in order to have access to them and to understand the world in the same way. A prerequisite for assessing values at World Heritage sites is that the individual be conversant with the constructed meanings and values of those places. Judgement cannot be made without this knowledge. At the same time, the critical phenomenological perspective is to be suspicious of the restrictions and limitations of these constructed meanings (Crotty, 1998). By constantly returning to the phenomena themselves the possibility of different and new interpretations is retained. The primary researcher's background is relevant to the value judgments being made (Saunders et al., 2009) and clarification of his/her background therefore aids transparent research. Some detail in terms of the researcher's relationship with the topic has been given (section 1.1) and in this section the author's professional background is summarised:

- Studied archaeology, archaeological conservation and World Heritage management at graduate and post-graduate level.
- Worked in the field as an archaeological objects conservator, both on archaeological excavations and in museums.
- Studied and worked in several countries including Ireland, Scotland, England, Wales, Germany, Australia, the United States of America, Ukraine and Uzbekistan.
- Member of ICOMOS, IIC and the Irish National Blue Shield Committee. Member of the ICOMOS Ireland Sub-Committee on Climate Change and a member of the Climate for Culture PhD research group.

Thus, although embedded in the values and norms of the cultural heritage profession the author also has experienced different international perspectives on the construction and preservation of cultural values.

2.2.4. Pragmatism

The pragmatist tradition originally emerged in the 1930s in the United States amongst critical constructionist thinkers (William James, John Dewey and Charles Sanders Pierce) (Crotty, 1998). Many subsequent practitioners abandoned the critical element however, and detractors of this worldview accuse it of laziness and acquiescence. The strands of pragmatism that have developed since, critical and uncritical, have at their basis the same idea that whatever works best is the 'truth' (Crotty, 1998). Meaning lies in practical application and in terms of design, the research question itself should determine the methodological approach adopted (Robson, 2011, Saunders et al., 2009). This flexibility allows researchers to employ mixed methods and maintain openness in terms of the way the research project develops. The pragmatist approach is very suitable for the current project where a practical outcome is desired i.e. the formulation of a management tool to assess and measure climate change impacts.

In summary, the constructionist philosophy that informs the research is that meaning and value are socially constructed but have reference to an objective reality. The choice of strategy and methods flows from this, but is also influenced by a pragmatic flexibility.

2.3. RESEARCH STRATEGY

The division between quantitative and qualitative research has blurred in recent years and is challenged by mixed method researchers who see the techniques as compatible (Carlile and Christensen, 2005, Creswell, 2007, Trochim, 2006, Bryman, 2008). Carlile argues that researchers should consider all data as subjective to some degree, and takes a pragmatist view that the value of data lies in its usefulness rather than its objectivity (Carlile and Christensen, 2005). A mixed methods approach was taken in this thesis; while the emphasis was on qualitative research this was backed up with quantitative analysis where suitable. The evaluation of the Vulnerability Framework, the development of the Toolbox of Indicators and the LegIT led to a multi strategy design where both the processes and the outcomes were of interest (Robson, 2011). The historic and present-day conditions of the case-study sites were analysed in terms of the far-future threat of climate change in the coming century. This longitudinal time horizon is also called the 'diary' perspective (Saunders et al., 2009).

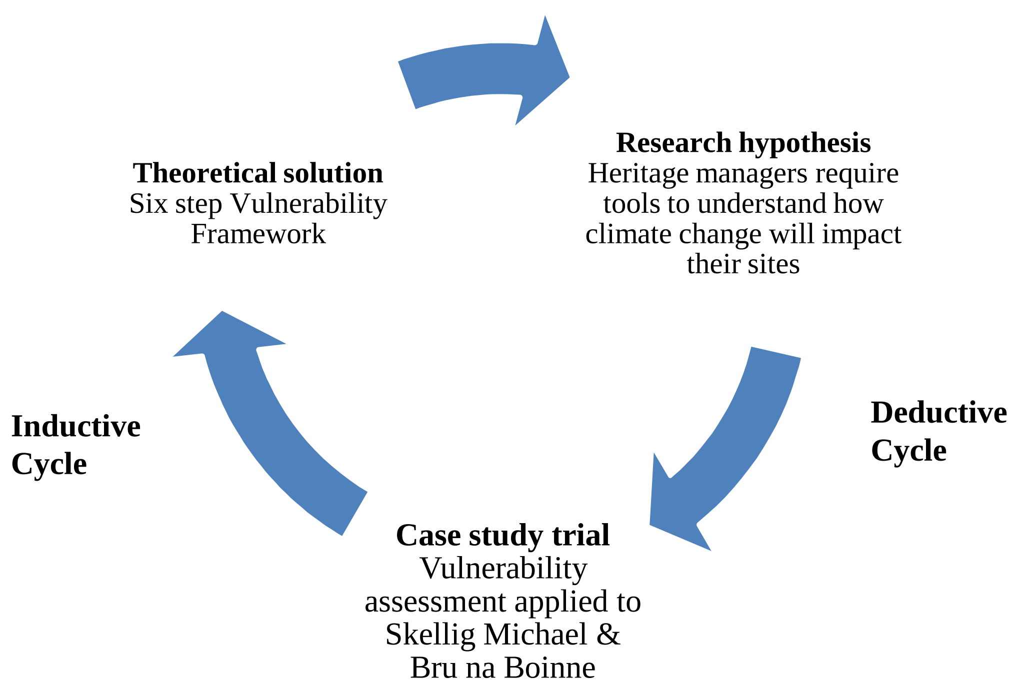

Figure 2.2. The inductive/deductive research cycle within this thesis

A combination inductive-deductive approach was taken to addressing the research question. This approach follows a cycle from theory to reality and back again, creating a robust model

(Carlile and Christensen, 2005). The deductive research phase starts from a general theory and tests this on specific data while the inductive phase moves from the specific case outward to create generalisable theory. Thus, the hypothesis that climate change would impact on archaeological sites was examined at two case studies and the outcome was the development of a transferable Vulnerability Framework (figure 2.2). The deductive cycle was repeated with the application of the Toolbox of Indicators, including the LegIT, to the case study sites. The future use of resultant measured data to refine and improve knowledge regarding adaptation measures will continue this cycle through the inductive phase.

2.3.1. Case study strategy

The main research strategy utilised is based around the assessment of the vulnerability of two case study sites to the effects of predicted climate change (chapters 7 and 8). The chosen sites are Ireland's World Heritage properties, Brú na Bóinne and Skellig Michael. Yin's definition of case study research involves three elements (Yin, 2003: 13):

1. Experience based research;
2. Examination of a phenomenon within its real life context;
3. Use of multiple sources of data.

Bryman echoes the focus on delimitation by stressing that the research must be place based or idiographic, i.e. concerned with the unique features of the case (Bryman, 2008).

The case study strategy is suited to research in the pragmatic, constructionist tradition as it involves collecting multiple strands of information out of which meaning can be constructed. Cosley and Lury suggest a mixture of qualitative methods while Bryman argues that case studies should be prepared to utilise quantitative methods as well (Cosley and Lury, 1987, Bryman, 2008). Unlike experimental research, case studies focus on a specific issue or issues in context, allowing no control over the variables involved (Robson, 2011). Generalising from the individual case study to develop mechanisms or theory for other similar cases therefore requires a degree of abstraction (Robson, 2011). The research strategy adopted in this thesis is to use heritage sites to develop and test management tools. The two case studies served to inform the development of the final Vulnerability Framework, illustrating its practical application in a real life context. This is described as analytical generalisation in the literature and involves a reasoned judgement, based on evidence (Kvale, 1996).

In summary, a multi-method approach using both qualitative and quantitative data was taken for the thesis research. Starting with climate change impacts theory, the *deductive approach* was to interrogate this via a detailed site based case study. From the case study findings an *inductive cycle* was taken, theorising on a suitable management approach for the assessment of climate change at heritage sites.

2.4. VALIDITY and RELIABILITY

The terms validity and reliability may be used interchangeably and refer to an expectation of objectivity within research (Bryman, 2008). Some qualitative researchers refer instead to trustworthiness, credibility, transferability, and dependability (Creswell, 2007). Whatever the terminology, at the most basic level all research must demonstrate its ‘truthfulness’ to the reader. Ensuring this in qualitative research can be difficult. The case study, for example, is determined by its context so is not repeatable. Meanings attributed are individual as outlined in the constructionist philosophy and bias is thus an issue. If we cannot speak of 'truth' as an independent measurable entity how can we ensure the research is valid? Kvale suggests the pragmatic approach to proving the quality of knowledge through application and effectiveness as a suitable solution to this issue (Kvale, 1996).

The fact that this thesis research was undertaken by one individual makes it especially vulnerable to the charges of bias and deficiencies. Bias can be addressed by the clarification of the researcher's personal background (section 2.2.3). Issues with single researcher projects also include limitations in the amount of data one person can ably deal with and the risk of inflexibility in terms of considering new or challenging information (Robson, 2011). As a doctoral thesis this work is part of an established academic tradition of single researcher projects to which value is attributed.

The accuracy and trustworthiness of the final research output was ensured by:

1. Triangulation: Using multiple sources of data, methods or theories to improve the credibility of results (Robson, 2011, Creswell, 2007, Saunders et al., 2009). Use of corroborating evidence from different sources creates an internal validity by providing cross-checking of the results (Bryman, 2008). Issues of incompatibilities between different sources or problems weighting their contributions, were considered where they occurred and went toward demonstrating the completeness of the research (Carlile and Christensen, 2005).

2. Consensual Validation (member checking): Agreement from respondents/‘competent others’ that descriptions, assessments and conclusions were correct, established credibility for the data (Creswell, 2007, Robson, 2011).
3. Transparent Procedures: Reliability of the data can also be demonstrated in the transparency of the data collection process and in the inclusion of information on bias or weaknesses (Rubin and Rubin, 1995, Kvale, 1996). Thus the data collected was as complete and accurate as possible and the research actions and the development of theories were outlined step by step in this and subsequent chapters.
4. Communicative Validation (peer review): Validation of the research was also provided through communicative validation (Kvale, 1996). Several publications and presentations of the work were made, including a peer reviewed journal article and a peer reviewed conference paper (Daly, 2011a, Daly, 2011b). Inclusion of the researcher within the Climate for Culture project also indicates peer validation (see http://www.climateforculture.eu/index.php?inhalt=team.phdstudents).

2.5. METHODOLOGY FOR ESTABLISHING CURRENT PRACTICE

The term ‘current practice’ is used here rather than ‘best practice’ as the latter suggests a level of standardisation and evaluation that does not yet exist in the field. Management literature offers alternatives to ‘best’ where this is problematic, referring instead to ‘good practice’ or ‘smart practice’. The concept of ‘smart practice’ is a good fit with the pragmatic approach underlying this research. Smart activities, as described by Bardach, are those that involve inter-agency collaboration and creative, flexible management solutions (Subirats and

Gallego, 2001). It was decided in the first place to establish 'current practice' with the aim of informing the development of smart practice management tools in this thesis.

A two-stage research method was designed to answer the question *what is current practice for the assessment and monitoring of climate change vulnerabilities*?

1. International Practice Questionnaires: Fact finding questionnaires (Appendix 1) conducted with experts in the field of cultural heritage and climate change to establish current international practice (chapter 4).
2. Exemplar Project Interviews: In depth interviews with managers involved in developing projects related to monitoring the impacts of climate change on cultural heritage (chapter 5). Questionnaire responses were used to identify exemplar projects for this phase.

2.5.1. International practice questionnaires

Design of questionnaire

This fact finding exercise utilised topic-focussed questions in a semi-structured questionnaire format (Rubin and Rubin, 1995). The reliability and validity of the questionnaire was established by undertaking a rigorous design and testing procedure (Foddy, 2001). As most of the interviews would be by phone, the length and type of questions were designed accordingly. Feedback from initial pretesting and subsequent pilot interviews was used to revise the questions.[1] This included highlighting some words, simplifying the information asked for and changing the phrasing where confusion occurred over the exact meaning. It is

[1] Pretesting and pilot interviews were conducted with; Penny Johnston, archaeologist; Dr Tracy Pickerill, academic; Ann Cuffe Fitzgerald, Conservation architect; Fay Daly, family of author.

recommended that telephone questionnaires should be kept short, with simple questions and responses for ease of communication (Frazer and Lawley, 2000). As the questionnaire was intended for international use, with many respondents being non-native English speakers, the use of plain language was of increased importance. The questions were also checked to ensure that they would yield relevant answers in a useable format (table 2.1).

Table 2.1. Question checking as outlined by Frazer (Frazer and Lawley, 2000)

Desired information regarding current practice	**Relevant Question**	**Level of data**	**Proposed analysis technique**
Is there a current practice in regard to assessing vulnerability to climate change impacts?	1 & 2	Nominal	Quantitative
What methodologies are used to assess vulnerability?	1 & 2	Descriptive	Thematic
What is the experience of climate change impacts?	3	Nominal & descriptive	Quantitative & thematic
Is there a recognised need to monitor climate change impacts?	4	Interval (numerical)	Quantitative
Is there monitoring for climate change impacts, if so what is it/will it be?	5, 6, 7 & 9	Nominal & descriptive	Quantitative & thematic
Is the long-term sustainability of monitoring being addressed?	8	Nominal & descriptive	Quantitative & thematic

Nominal data refers to the closed answer responses, in most cases the answers are yes, no and unsure. There is one numerical response scale used in the questionnaire (Q. 4) and this has been noted as interval i.e. the distance between the points on the scale are measurable and the numerical values have meaning (Frazer and Lawley, 2000).

Questionnaire administration

The advantage of telephone interviews over postal questionnaires is that there is a high response rate once agreement has been given. They are also inexpensive and time saving, especially when dealing with international experts. The target population was defined as professionals working on the topic of climate change and cultural heritage. The final list of respondents can be seen in Appendix 4. The sample frame used initially was the academic literature published on the subject of climate change and cultural heritage. This judgmental sampling technique relies on the personal assessment of the researcher in selecting the appropriate sample elements. It is most useful when statistical inferences to the broader population are not required (Malhotra, 2004). This technique was combined with an element of "snowball sampling" as the research progressed and the respondents suggested relevant contacts. Although the research to date is dominated by respondents from Europe, representation from the other continents was actively sought, with mixed success, to obtain a wider spread of experience. It was also important that the leading research projects such as Noah's Ark and Climate for Culture (CfC) and organizations such as English Heritage and ICOMOS were included along with academics and practitioners (see list of contributors Appendix 4).

The selected respondents were contacted individually, usually via Email, and the nature of the research, the purpose, nature and length of the questionnaire were explained. The reason why that individual was included in the sample was also explained. For those that agreed to be interviewed a convenient date, time and preferred method of contact was arranged. The respondents by telephone found it helpful to have an advance copy of the questions to which they could refer during the interview and this was made standard procedure for all phone interviews. Oppenheim suggests that interviewees should not see the questions before hand as this stifles spontaneous discussion (Oppenheim, 1992). Gillham (2005) makes the point however, that with phone interviews it is an advantage for both parties to have something visual to refer to helping the flow, and creating a sense of progress. In practice this was found to be the case.

Questionnaire analysis

The analysis of the questionnaires was twofold.

1. The closed answers were categorised to provide an overview of the meaning of the results. Quantification allowed comparison between different responses (Kvale, 1996).
2. Descriptive comments provided were subjected to a thematic study i.e. patterns within the respondents answers were identified, reported and analysed (Braun and Clarke, 2006).

Determination of themes can utilise prevalence in terms of frequency, space devoted to a subject or relevance to the research question (Braun and Clarke, 2006). In the questionnaire analysis an inductive approach was taken to identifying the themes i.e. the identification was data-driven. There was no pre-existing coding frame and the patterns identified shifted as the data-set expanded, introducing new themes or refining existing ones. In order to validate the selection, the number of times each theme occurred was noted. The themes were identified at the semantic level, from what was explicitly said by each respondent. Interpretation of the significance of the themes is based on this semantic understanding. Following the constructionist viewpoint, the thematic analysis did not simply inspect individual experience but also the context that framed and formed these experiences, in this case mostly socio-economic conditions (Braun and Clarke, 2006).

The practical procedure for analyzing the data was based on Gillham (2005). The interviews were kept to a maximum of 30 minutes in length and digitally recorded (subject to permission). The closed answers were recorded on the questionnaire form by hand during the interview and written notes on major points were also made. Following the interview, the recording was listened to and compared to the hard copy, in some cases further notes were added by hand. The recording and the hard copy were then used together to fill in the spreadsheet content analysis under both quantitative and thematic categories. In the case of the self-administered questionnaires the analysis was done using the hard copy only. The telephone interviews were not transcribed in their entirety, annotating the questionnaires by hand from the recorded interviews was found to be sufficient for the thematic analysis. In addition, as some of the respondents had opted for self-administration, transcripts of verbal responses could not be said to represent a complete data-set.

Limitations

The final sample size of thirty respondents can be justified as the target population is small. Approximately fifty individuals were contacted initially which represents a response rate of 60 per cent. The appropriate number of respondents suggested by Oppenheim is the one arrived at when no new ideas are emerging, in general 30–40 is a common quantity

(Oppenheim, 1992). As a piece of exploratory qualitative research the small sample size is considered acceptable (Malhotra, 2004).

Where respondents opted for self-administration, the data returned was less comprehensive than from phone administration (table 2.2). Despite the limitations of this option, it was valuable in soliciting responses from those who found the concept of a phone interview uncomfortable or simply inconvenient.

Table 2.2. Advantages and disadvantages of different techniques (Malhotra, 2004, Robson, 2011, Gillham, 2005)

Interview Type	Advantages	Disadvantages
Self-administered questionnaire	Increased number of samples. Quicker to analyse. Eliminates researcher influence on answers.	Possibility for misinterpretation of questions. No ability to prompt for further information.
Telephone interview/ questionnaire	Low cost way of speaking to international experts therefore increases number of respondents possible. Less time consuming for researcher. Can reduce bias (i.e. influence of researcher on answers, facial expression)	Lacks intimacy of face to face and therefore some information will be lost. Necessitates keeping questions simple and interview short which loses some potential data. Can be harder for non-English speaking respondents to follow than face to face communication.
Face to face interview	Maximises information i.e. context, body language, personal dynamic. Provides opportunity to create conversational flow.	Expensive and time consuming for researcher to conduct. Analysis and transcription afterwards also more time consuming.

Focus Group Interview	Efficient way of gathering data from multiple sources. In built checks and balances as individuals correct each other. Consensus opinions and key issues can become clear.	Confidentiality, personal conflicts and politics may prevent or colour contributions. Managing the process so that everyone contributes equally can be challenging for the researcher.

2.5.2. Exemplar project interviews

The main aim of these interviews was to establish what could be learned from the experience of others who were implementing site based assessments and/or monitoring in relation to climate change impacts on cultural heritage.

Design

The respondents for the exemplar project interviews were identified by "snowball sampling" and selected based on the following selection criteria:

1. Their project concerned vulnerability assessment and/or monitoring for impacts related to climate change.
2. Their project involved a site specific approach to cultural heritage.

In this case, an exploratory interview was undertaken in order to achieve a detailed understanding of these 'exemplar' projects. Oppenheim states that the in-depth interview is about gathering ideas not facts, and should maintain spontaneity in its lack of structure and set questions (Oppenheim, 1992). This interviewing style does not facilitate direct comparisons between interviews or the gathering of data relating to any particular hypothesis. The interviews were conducted face to face and combined with a visit to the project site. This maximised the information gathering exercise and allowed frank discussions and the exchange of practical details that may not have been possible over the phone.

Administration

As with the questionnaire procedure, respondents were initially contacted by Email to solicit their participation. The nature of the research, format of the proposed visit/interview and the reasons they had been selected were explained. In the case of the respondents that had already taken part in the questionnaire the reasons their further participation was sought were also explained. Interviews were recorded (subject to permission).

Analysis

The interviews were transcribed in full and subjected to a form of narrative analysis where the data was assessed under common headings that essentially created a 'storyline' for each project (Kvale, 1996). The purpose of undertaking the interviews was to establish the methodological and practical approaches used in these exemplar projects and how successful or otherwise they were. Therefore the headings under which the data was analysed were: background, methodology, implementation, barriers to success, and transferability.

Limitations

The number of exemplar projects was limited by the practical fact that very little research was found that fit the selection criteria (see above). In addition to the four chosen (section

5.1), one additional project at the National Museum of Greenland (section 4.7) was contacted but was too early in the development phase to be included (Knudsen[2], pers. comm.). The resources necessary to conduct international case studies were also considerable and the potential benefits to the thesis of extending the number beyond four were not warranted. Limiting the projects in number allowed for more observations and greater contextual detail (Kvale, 1996).

2.6. VULNERABILITY METHODOLOGY

The interviews detailed above aimed to establish practical methods being used to assess and monitor climate change impacts on cultural heritage. The development of a vulnerability assessment method goes towards addressing an identified gap within the current practice. The potential impacts of climate change on the case study sites of Brú na Bóinne and Skellig Michael were assessed using a Vulnerability Framework developed in this thesis (chapter 6). The method adapts previous work by Schröter, Woodside, and the author, to the current purpose (Woodside, 2006, Schröter et al., 2005, Daly, 2008). The provision of downscaled future climate data by the Climate for Culture project provided the opportunity to utilise state of the art modelling to heritage sites in Ireland for the first time. Further discussion on the methodological issues and final Vulnerability Framework will be provided in chapter six.

The development of indicators is part of the vulnerability methodology but has wider implications for tracking climate change impacts. A detailed review of indicator theory and sources for the indicators utilised in the case study assessments are provided in chapter nine.

[2] Pauline Kleinschmidt Knudsen, National Museum of Greenland, paaliit@natmus.gl, 24.1.2012.

The need for site specific indicators lead to the development of a Legacy Indicator Tool (LegIT), the methods and activities relating to this are detailed in chapter ten.

2.6.1. Stakeholder interviews

Design

For the vulnerability assessment of Skellig Michael and Brú na Bóinne interviews were conducted with specialists, guides, management and local stakeholders. The aim was to build as complete a picture of the sites and their vulnerabilities as possible. Initially semi-structured interviews were conducted but as the process evolved it was decided that a structured approach would yield more information (Appendix 2). This was because many respondents had little familiarity with the subject of climate change. A University College London study illustrated the use of structured stakeholder consultation; it outlined climate change scenarios and impacts before asking for opinions on risk (Cassar, 2005). For this thesis a brief general description of predicted climate change was outlined using bullet points (see Appendix 2, Q.3. stakeholder consultation documentation). The Impacts Matrix (table 3.1) developed from the literature review was also adapted and used as a menu for the respondents.

Administration

Most interviews were carried out in person or by phone; in a few instances respondents preferred to self-administer and this was accommodated. The face to face and phone interviews were recorded (subject to permission). Some of the semi-structured stakeholder interviews for Brú na Bóinne conducted in 2008 for a Masters in World Heritage thesis

(Daly, 2008) were included in the analysis. This occurred with five individuals (see list of contributors Appendix 4) all of whom were contacted in writing to obtain permission for this use of their data. They were also asked if they had further involvement with the topic in the intervening period, and if they had any comments in relation to the structured set of questions. Two of the five respondents volunteered to be interviewed again using the structured interview format.

Analysis

All of the recorded interviews were transcribed in full. Given the diversity of stakeholder backgrounds, the interview material varied greatly and general thematic analysis was not practical. The recordings, transcripts and written submissions were used to fill in a spreadsheet divided according to question and respondent. Once assembled in this format the data could be extracted and organised under headings that correspond to the elements of vulnerability: exposure, sensitivity and adaptive capacity. Further categorisation was then carried out as the Vulnerability Framework was implemented, with the information being used to evaluate potential effects of different climate impacts on identified values. Thus, the spreadsheet was used as a reference data-bank for completing the Vulnerability Framework.

Limitations

Given the complexities of climate change and the holistic nature of the vulnerability approach, ensuring relevance of the questions to every stakeholder was problematic. Foddy discusses applicability when designing interview questions, i.e. respondents should not be asked for information which they don't have or should be provided with a suitable filter such as ‘undecided’ or ‘don’t know’ (Foddy, 2001). While many of the stakeholders interviewed were expert in their field they generally did not have the knowledge to comment on all aspects. For this reason respondents were verbally asked to give their opinion only where they felt comfortable at the start of the interview. In the phrasing of the closed questions (1 & 2) the option *unsure* was included. In questions four and five the phrase *based on your knowledge* was included to the same end.

2.6.2. Stakeholder review

The purpose of stakeholder review was to inform those expert stakeholders who contributed to the vulnerability analysis of the results and to obtain their feedback. In this case, the review was carried out by contacting the individuals by post with hard copies of the assessment, followed up by Email and phone reminders. Each stakeholder was sent the following documents, for either Skellig Michael or Brú na Bóinne, by post (see Appendix 2):

- Draft copy of the vulnerability analysis chapter with personal communications attributed to the relevant individual highlighted in red.
- Feedback form asking for comments, corrections and approval of both the results and personally attributed information.
- Summary table of the vulnerability assessment results.
- Cover letter.
- Stamped self addressed envelope.

Comments on the accuracy of the results were invited as well as on any omissions or factual errors within the text. The comments from the returned forms were used to correct factual errors and refine the findings. The general consensus on the appropriateness and usefulness of the findings provided validation of both the method and the result.

Limitations

The limitations of the individual researcher were most apparent in the design of the stakeholder feedback method. Focus group was the method initially considered for obtaining respondents comments, and a seminar followed by discussion session for all stakeholders was devised. Attendance at a seminar or workshop requires time away from work however, involves travel costs and personal inconvenience. As the respondents were distributed around Ireland (see list in Appendix 4) bringing them together would have been logistically difficult necessitating substantial amounts of travel for many individuals. For a researcher operating under the auspices of an institution these obstacles may be surmountable. For example inter-departmental meetings could be arranged, travel expenses paid and time away from work officially sanctioned. In the case of an independent researcher however, the focus group scenario was found to be unfeasible. For this reason one-to-one review was finally selected as the method for obtaining feedback. Although contacting each contributor individually to obtain their comments and approval was time consuming, nevertheless it was effective in obtaining an 80% response rate and was therefore an appropriate solution for this thesis.

2.7. ETHICAL ISSUES

This research has been undertaken in an ethical and transparent manner. The researcher engaged from the start of the project with the self-declaration procedures of the Dublin

Institute of Technology (DIT) Research Ethics Committee. The DIT *Research Ethics Assessment of Risks Form* indicated that the impact on respondents participating in the research was the main ethical issue involved in the proposed methodology. Ethical procedures for interviewing subjects were subsequently submitted and approved by the DIT Ethics Committee. As stated by Rubin, *research ethics are about how to acquire and disseminate trustworthy information in ways that cause no harm to those being studied* (Rubin and Rubin, 1995: 93). The ethics forms relating to the thesis research can be found in Appendix 3.

Ethical interview procedure

Once respondents had agreed to participate they were sent a one page introduction that explained the research being undertaken and outlined how the data would be treated (Rubin and Rubin, 1995). This document included an undertaking that no attributions to individuals would be made without prior consent and that they would be given the opportunity to correct any text attributed to them, in line with good ethics practice (Oppenheim, 1992). The form also asked for permission to record the interview for note taking purposes. This request was repeated at the beginning of each interview to ensure that respondents were happy being recorded. The document explained that the recorded interviews would be encrypted and stored on a password protected computer for the period of the project and deleted afterwards. The respondents were asked to sign and return the form to indicate that that they understood and agreed with the procedure. The return rate for the form was low and several reminders had to be sent before all respondents had indicated their consent. When data provided by any respondent was personally attributed within the thesis the individual in question was provided with a draft copy to approve or amend.

2.8. CONCLUSIONS

This chapter has established the research philosophy, constructionism and pragmatism, underlying the thesis. These paradigms have informed the choice of an inductive-deductive research approach using the selected case studies to build theory from experience. The use of mixed methods was justified by the case study strategy and as also a means of creating internal validity. The validation of the research was also assured by transparent, ethical procedures. The detail provided in this chapter regarding interview design, procedures and analysis contribute to ensuring its legitimacy. In the following chapter the secondary research conducted to establish the current state of knowledge in the field of climate change and cultural heritage will be explored through a literature review.

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CHAPTER 3.

LITERATURE REVIEW

3.0. INTRODUCTION

Concepts that inform research, from the parent disciplines of cultural heritage management and climate change science, are outlined in this chapter. The existing themes relating to the immediate topic of cultural heritage and climate change impacts, including where overlaps occur with related disciplines, are detailed in figure 3.1. Key concepts or identified gaps that led to the definition of the research hypothesis for this thesis are numbered and **emboldened** throughout the chapter.

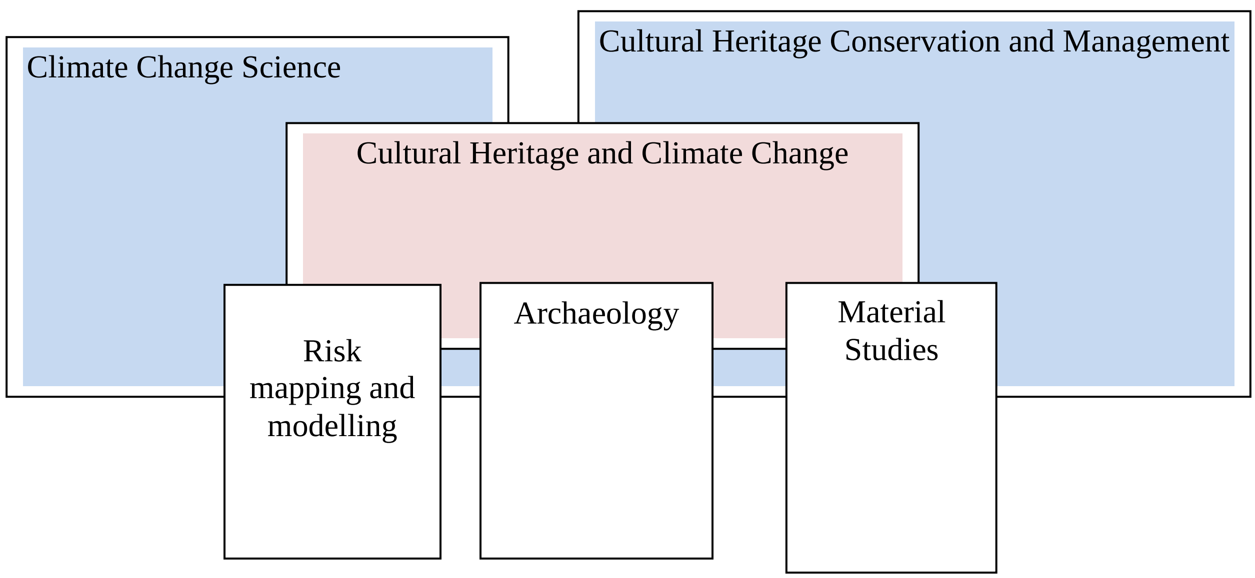

Figure 3.1. Conceptual outline for body of knowledge: Blue = parent disciplines; Pink = immediate discipline; White = intersecting disciplines

3.1. CULTURAL HERITAGE CONSERVATION and MANAGEMENT

3.1.1. Defining cultural heritage

Taking a semiotic perspective from the discipline of Cultural Studies, culture can be defined as a *stratified hierarchy of meaningful structures* (Geertz, 1975: 7). Three levels of culture were identified by Williams, the *lived* or contemporary, the *period* or historic, and the *selective combination* of those two to create a third level (Williams, 1961: 49). The Council of Europe's definition of cultural heritage reflects a constructionist viewpoint, considering culture as the product of a selection process. The importance of place and the interaction between man and the natural environment is also established:

> *Cultural heritage is a group of resources inherited from the past which people identify, independently of ownership, as a reflection and expression of their constantly evolving values, beliefs, knowledge and traditions. It includes all aspects of the environment resulting from the interaction between people and places through time* (Council of Europe, 2005: 2.a.).

Cultural heritage assets are the selected elements of our collective past to which we attribute a value and attempt to pass onward to successive generations. Heritage as a construct is thus an attempt to 'fix' certain cultural traditions or places in the face of change. This is paradoxical because it is only in the face of their potential loss that these cultural items become valued. Thus it is the process of change and decay that actually creates heritage value. Heritage is best *conceptualized as something that is always in the process of* *'becoming'. In other words, heritage values, while referring to the past are actually present and future oriented* (Henry and Jeffery, 2008: 16).

UNESCO define cultural heritage as:

> *The entire corpus of material signs – either artistic or symbolic - handed on by the past to each culture…cultural heritage gives each particular place its recognizable features and is the storehouse of human experience – it includes built heritage, archaeology, cultural landscapes and moveable heritage* (UNESCO, 1989).

The reference to *material signs* relates this definition of cultural heritage to tangible elements and these are what will be mainly dealt with in this research. The intangible heritage of places was subsequently recognised by UNESCO's Convention for the Safeguarding of Intangible Cultural Heritage in 2003 which defined intangible heritage as:

> *The "intangible cultural heritage" means the practices, representations, expressions, knowledge, skills – as well as the instruments, objects, artefacts and cultural spaces associated therewith – that communities, groups and, in some cases, individuals recognize as part of their cultural heritage…transmitted from generation to generation, is constantly recreated by communities and groups in response to their environment, their interaction with nature and their history, and provides them with a sense of identity and continuity…*(UNESCO 2003)

The modern practice of conservation traces its roots back to Ruskin's *Seven Lamps of Architecture* in 1849. Ruskin's appeal to employ preventive measures rather than large scale interventive restorations is a key principle of the conservation profession today, as illustrated by the *cautious approach* advocated in the Burra Charter (ICOMOS, 1999).

The basic principles of the conservation and restoration profession were first laid down in the Venice Charter of 1964 including concepts such as appropriate use, context and authenticity (Committee of the 2nd International Congress of Architects and Technicians of Historic Monuments, 1964). This was also the meeting that agreed to the establishment of the International Council for Monuments and Sites (ICOMOS) an advisory body to the UNESCO World Heritage Committee (Petzet, 2004). Subsequent agreements have built on this to create the legislative and professional protections that are recognised as best practice today. Important amongst these was the Council of Europe's Convention for the Protection of the Architectural Heritage of Europe in 1985 which informed the development of protective legislation in Ireland, and the 1994 Narra Document which broadened international understanding of the concept of authenticity in terms of diverse cultural perspectives (Jukka Jokilehto, 1995).

Article 2 of the Venice charter states that conservation should have recourse to *all the sciences and techniques* that can aid in the analysis treatment and monitoring of historic structures (Committee of the 2nd International Congress of Architects and Technicians of Historic Monuments, 1964). Since the 1960s conservation science as a discipline that informs treatments has grown, but it remains a field that relies on multi-disciplinary research from diverse disciplines including engineering, building physics and geomorphology. The highest standards in documentation, choice of materials and adherence to the principle of reversibility are expected in modern conservation practice (ICOMOS, 1999).

3.1.2. Cultural heritage value and cultural significance

In 2005, the Council of Europe adopted a framework convention outlining the 'value' of cultural heritage to society in terms of sustainability, cultural diversity and prevention of conflict (Council of Europe, 2005). This document refers to cultural heritage on a regional and national level however, and a more specific approach is required for evaluating and managing value at site level. The process of conserving individual assets requires prioritisation of certain examples above others, based on an assessment of their 'value' (Cassar, 2009). A comprehensive site based understanding of values is also required to ensure appropriate conservation measures in order *to retain the cultural significance of a place* (ICOMOS, 1999: 2.1). The terms *value* and *significance* are sometimes used interchangeably.[1] For the purposes of the current research, the Getty usage of the terms was adopted i.e. cultural significance is *the importance of a site as determined by the* ***aggregate of values*** *attributed to it* (de la Torre, 2002: 3). Determining the value of heritage, either natural or cultural, is a complex issue. There may be many different values present, (e.g. social, scientific, aesthetic) and judgments are often politically loaded (de la Torre, 2002). The Burra Charter explanatory notes for Article 1 recommend a cautious approach to conservation, recognising that cultural significance may change as a result of continuing history or of new information (ICOMOS, 1999).

3.1.3. World Heritage designation

The World Heritage Convention of 1972 established a framework for international co-operation in the protection of cultural and natural heritage (UNESCO, 1972). Article 1 of the

[1] The Burra Charter 1999 defines **cultural significance** as *aesthetic, historic, scientific, social or spiritual value for past, present or future generations* the term **cultural significance** is synonymous in the Charter with **cultural heritage value**.

Convention defines cultural heritage as; monuments, groups of buildings, or sites (the latter including elements of archaeology and landscape). In order to establish which heritage assets should be included on the list of World Heritage, the concept of **Outstanding Universal Value (OUV)** was introduced. The criteria for determining OUV have been modified over the years, but it continues to be the measure by which sites are listed, rejected or even, as in the case of Dresden in 2009, delisted (UNESCO, 2009).

The most recent change to the criteria was accomplished in 2005 when the natural and cultural criteria were merged (Bandarin, 2007). This unified list of ten criteria came into use in 2007 and is intended to reflect a more holistic approach toward heritage identification and management (Bandarin, 2007: 42). The criteria for evaluating OUV of cultural heritage sites are based on the tangible remains of immovable material heritage and require assessment of integrity (wholeness) and authenticity (credibility). Not everything within a World Heritage site contributes to OUV (ICOMOS, 2010: 3) and heritage of national and/or local significance is also noted in the Management Plan of a WHS e.g. the Battle of the Boyne site in Brú na Bóinne (Duchas 2002). By applying a system for the definition of values a WHS can be utilised as a model for evaluating other monuments and sites of national or local importance.

The World Heritage Convention (1972) does not specifically mention climate change as it was not an issue at the time of writing. States Parties are obliged to protect their sites from damaging impacts however. Arguably, this could be interpreted as an obligation for States Parties to the World Heritage Convention to support the United Nations Framework

Convention on Climate Change (1992), so as to prevent future climate threats from occurring (Gruber, 2008).

3.1.4. Summary

In summary, conservation and management of cultural heritage deals with a diverse set of assets that embody a shifting set of socially constructed values. Heritage managers are dealing from day to day with the conservation of sites that may be thousands of years old and this perspective sets the sector apart in terms of the willingness to take an intergenerational approach to risk (Cassar, 2005). The work of professionals within the field is informed in large part by a series of international agreements such as the Venice and Burra Charters and agencies such as UNESCO and ICOMOS.

The determination of appropriate policy for managing and conserving cultural heritage assets is based on achieving a balance between scientific knowledge and an understanding of the values present (ICOMOS, 1999). Assessment of place based heritage values, and thereby cultural significance, is an essential part of the conservation and management decision making processes. Values may be based on social, artistic, scientific or other grounds and may be considered in relation to local, national or international scales. At an international scale, the World Heritage Convention provides a clear set of criteria by which cultural heritage can be assessed for Outstanding Universal Value. The case studies adopted in this thesis are both World Heritage sites and as such have a clearly defined set of heritage values (Department of Environment Heritage and Local Government, 2008, Duchas the Heritage Service, 2002).

3.2. CLIMATE CHANGE

3.2.1. What is climate change?

Short-term atmospheric changes that occur at a local level can be described as 'weather'. Over a long period, i.e. 30–100 year climate-norm, this weather becomes defined as a regional climate. Annual variations from the climate-norm are referred to as 'climatic variability'. If climates alter over a 30–100 year span however, this is considered long-term 'climate change'. At its simplest, climate change is *a change in the average climate (or its variability) from one averaging period to the next* (i.e. 30 years) (Parry and Carter, 1998: 5).

The United Nations Framework Convention on Climate Change (UNFCCC) define climate change as follows (United Nations Conference on Environment and Development, 1992):

> *A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods* (Article 1).

The Intergovernmental Panel on Climate Change (IPCC) established under the UNFCCC uses a wider definition that does not differentiate between natural and anthropogenic climate change:

> *Climate change may be due to natural internal processes or external forcing, or to persistent anthropogenic changes in the composition of the atmosphere or in land use* (IPCC WGIII, 2001: Appendix II glossary)

3.2.2. The debate

The issue of climate change has been hotly debated since the *United Nations Framework Convention on Climate Change* (1992 Rio de Janeiro) recognized that climate change was a problem and that Global governance was required to reduce greenhouse gases. The Intergovernmental Panel on Climate Change (IPCC) was formed by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to assess the international body of science related to global climate change (Intergovernmental Panel on Climate Change, n.d.). The IPCC provide regular Assessment Reports that synthesise and comment on the state of knowledge in the field. The Fifth Report (AR5) will be published in 2014. In its Fourth Assessment Report, *Climate Change 2007*, the IPCC left no room for debate on the reality of climate change:

> *Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level* (Pachauri and Reisinger, 2007: 1.1).

In the face of mounting evidence the climate change debate has largely moved on from denying climate change to debating causes and consequences (Schneider et al., 2010, AlJazeera, 2013). Schneider (2010) categorises the various factions as:

- Those that deny climate change is influenced by human activities;
- Those that assert it may be occurring but is of no consequence;
- Those that argue mitigation will have no effect or be too costly to implement.

In the Fourth Assessment Report the IPCC also stated that the observed rise in temperature was *very likely* to be the result of anthropogenic activities, namely the increase in greenhouse gases in the atmosphere (Pachauri and Reisinger, 2007). What is now undeniable, given the mounting evidence and worldwide scientific consensus, is that we are living through a period of rapid global climate change.

3.2.3. Archaeology and climate change science

'Climate change archaeology' is defined by Van de Noort as *the contribution of archaeological research to modern climate change debates* (Van de Noort, 2011: 1039). Proxy records such as pollen, sphagnum macrofossils and tree rings are a rich source of information regarding past climatic and environmental conditions (Brown, 2008). Archaeological research that includes palaeoclimatic or palaeoenvironmental research can therefore contribute to assessments of long-term climate change and this dataset is considered in the Assessment Reports of the IPCC Working Group I (Van de Noort, 2011).

Within the field of archaeology there is also a growing interest in understanding how past responses of human populations to climatic change can inform adaptation today (Pearson, 2008, Rowland, 2008, Van de Noort, 2011, Rockman, 2012). Archaeological evidence suggests that climate change is often associated with shifts in social, cultural and economic activities, political upheaval, conflicts and the movement of populations (Brooks et al., 2009). There may be a tendency to over-simplify this link however, and the attribution of any change in the archaeological record to changed climate must be treated cautiously (Brown, 2008).

> *The extent to which climate changes caused a societal response in agriculture and settlement will remain a source of continued debate* (Monk, 2012).

As Van de Noort argues, the value of archaeology's contribution to resilience studies is not in the particulars of how past communities adapted, but in the *pathways* they followed (Van de Noort, 2011). These pathways could be used as *adaptation models* (Rockman, 2012). Van de Noort suggests a framework, based on the coupled human environment system, to allow archaeologists to contribute to the modern climate change debate:

> *By offering long-term perspectives on human interrelationships with climate change, archaeology is well placed to enhance an understanding of the socio-ecological resilience of communities and their adaptive capacity*. (Van de Noort, 2011: 1046).

Key Concept 1.

The 'coupled human-environment system' and anthropogenic pathways of resilience are significant in the determination of both past and present vulnerability to climate change.

3.2.4. Determining future climate

Climate *prediction* is an attempt to describe the actual climate conditions that may occur in the immediate future based upon current and past conditions, i.e. weather forecasting. Climate *projection* is the result of an attempt to model how the climate system may respond to various atmospheric conditions in the near and far future. Climate projections are created using sophisticated computerised climate models. These models require assumptions about greenhouse gas concentrations in the future, provided by the emissions scenarios developed by the IPCC (figure 3.2). The IPCC family of emission scenario (SRES) present a variety of 'imagined' futures dependant on socio-political and economic factors (Pachauri and Reisinger, 2007).

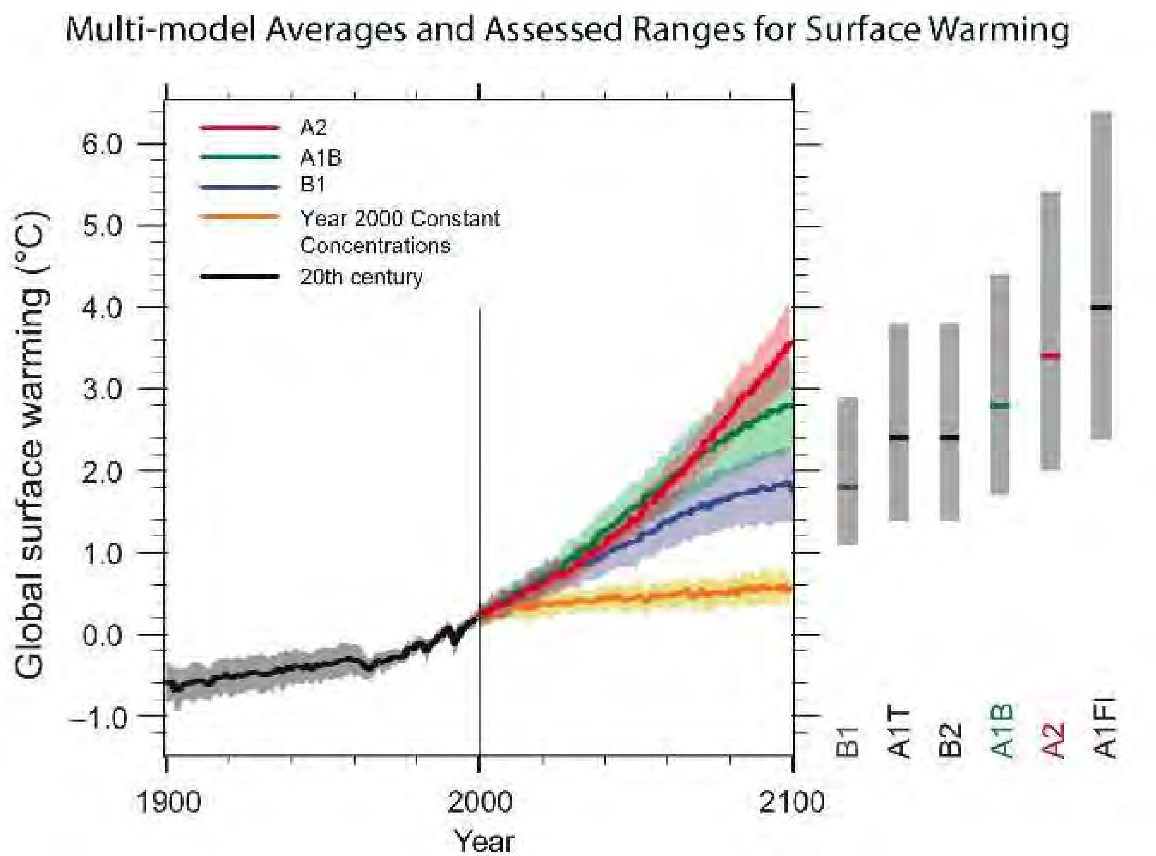

Figure 3.2. Illustration of projected global temperature rise under IPCCs A1/A2/B1 future emission scenarios

Global climate models (GCM) are used to project how the earth's systems (atmosphere, oceans and cryosphere) will respond to the conditions outlined in the various emission scenarios. The GCMs provide coarse scale assessments at low resolution and do not account for factors such as topography. The Regional climate models (RCM) downscale the GCM projections to high resolution grids (e.g. 10Km), allowing for more specific projections (figure 3.3). The need for downscaling for impacts studies is increasingly recognized because site specific data can differ considerably from the GCM aggregate (Smith et al., 2010).

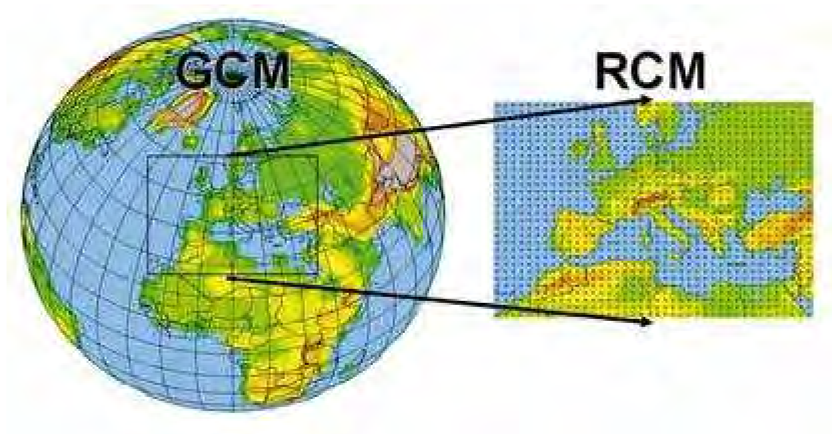

Figure 3.3. Downscaling from Global Climate Models to Regional Climate Models (http://www.wmo.int/pages/themes/climate/images/ 15.5.2013)

3.2.5. Uncertainty and the Precautionary Principle

The degree of uncertainty in climate science, as to how exactly the global climate system will respond to rising temperatures, is compounded by the fact that future levels of greenhouse gases depend on unknown policy choices and economic development scenarios (Schneider et al., 2010). The magnitude of future climate change therefore depends on two unknowns: how the human population will act, and how the earth's climate system will respond. The range of possible uncertainty in regional downscaled projections has been demonstrated by researchers comparing different global climate models with the reference period of 1960–1990 (figure 3.4) (Kjellström, 2011). The lack of consensus amongst climate change experts makes it hard for archaeologists to know which scenario is likely, nonetheless they must begin to address the most probable impacts (Rowland, 1992). Orell argues that the concept of predicting future climate is based in culturally formed ideas of symmetry and rationality and not in the reality of how complex natural systems actually operate (Orell, 2012). He suggests we should use models and data to *outline* possible scenarios and develop flexible and robust systems that can cope with a variety of outcomes.

> *Even if the future is obscured at least we can use our wisdom to prepare for it* (Orell, 2012).

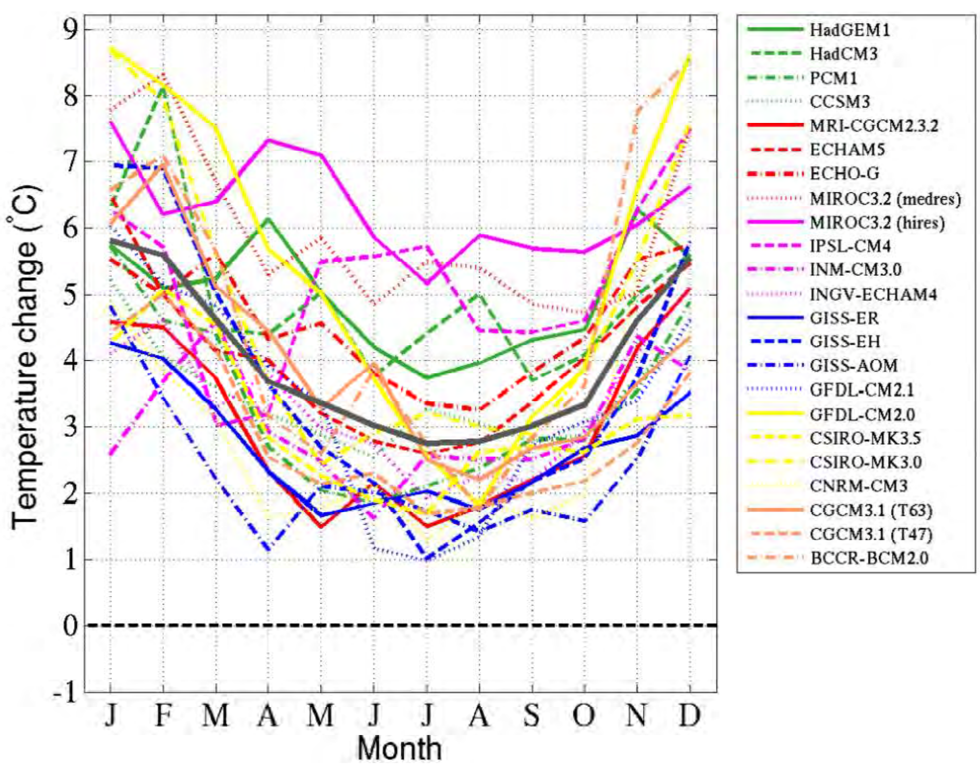

Figure 3.4. Uncertainty at the regional scale demonstrated by comparing temperature change in Northern Sweden from 1961–1990 (black line) with projections for 2071–2100 by a range of different RCMs under the A1B scenario (Kjellström, 2011)

A number of authors also point out that it would be unwise, even irresponsible, to wait for absolute proof before making recommendations to combat climate change (Sweeney et al., 2002, Gruber, 2008, Cassar et al., 2006, Schneider et al., 2010). The imperative to act in the absence of certainty relates to the 'Precautionary Principle' in international law; for example in Article 191 of the Treaty of the European Union. This principle aims at ensuring a high level of environmental protection by enshrining the concept of preventative action in cases where scientific evaluation identifies a risk, but cannot determine it with certainty (European Union, 2012).

Article 15 of the United Nations *Rio Declaration on Environment and Development*, 1992 states:

> *Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost effective measures to prevent environmental degradation* (United Nations, 1992)

The responsibility to take action is especially grave in the case of non-renewable resources such as cultural heritage (Gruber, 2008).

> *Our archaeological heritage can neither be 'moved' nor 're-created'. It is a finite resource which, once lost, is gone forever* (Edwards and O'Sullivan, 2007: 4).

3.2.6. Projections for Ireland

Regional Climate modelling (RCM) for Ireland has been carried out in parallel by the *Climate for Ireland* (C4i) project at Met Eireann and University College Dublin and also by *The Irish Climate Analysis and Research Unit* (ICARUS) at Maynooth University. Applying medium emissions scenarios both C4i and ICARUS models predict warming of greater than 2^{o}C by the end of the century in Ireland, with significant changes in precipitation amounts and distribution (Fealy and Sweeney, 2007, Sweeney et al., 2003, McGrath and Lynch, 2008). The greatest increase in temperature is projected for the summer period in the east and south-east of the country. ICARUS projects July temperatures will be 2.5^{o}C warmer by 2055 and a further 1^{o}C warmer in 2075 (Fealy and Sweeney, 2007, Sweeney et al., 2003). Warmer temperatures will likely result in an increased atmospheric moisture content and resultant heavier rainfall (Bates, 2010). Both projects predict wetter winters, with an overall increase of 11–15% in rainfall, but significant regional differences. For example, C4i December precipitation values for the far future (2070–2099) show a 10% elevation for the south-east and 25% for the north-west. Summer rainfall projections also show a large range. C4i project a national decrease in rainfall averages of 10%, ICARUS put this figure at 25% with up to a 40% reduction in the east (Sweeney et al., 2003, McGrath and Lynch, 2008).

The frequency of intense storms over the Atlantic is predicted to grow by approximately 15% with even greater increases in winter and spring. The location of the cyclone activity is also predicted to move further south in the Atlantic than at present which will increase its direct impact on land (McGrath and Lynch, 2008, McGrath et al., 2005). The resultant risks of storm surge, flooding and erosion will be magnified by elevated sea levels (Kelly and Stack, 2009). The Department of the Environment suggest a mean annual sea level rise to 2030 of about 2mm/yr, placing approximately 1500Km of coastline under threat from erosion of between 0.2–2m/year (Department of Environment and Local Government, 2001). Research combining climate projections with long-term crustal movements suggests that by 2050 RSL could be as much as 4.5–6.5mm/yr in the southwest and 3.3–5.3mm/yr in the northeast (Edwards and O'Sullivan, 2007). The softer coasts in the south east, and in particular the small inlets where long-term human settlement has often been focused will be very susceptible to erosion while dune coasts in the west may become unstable and release wind-blown sand (Department of Environment and Local Government, 2001, Devoy, 2008).

3.2.7. Summary

Climate change is an alteration in atmospheric climate measured over averaging periods of 30 years or more. The evidence that climate change is underway is unequivocal, although there is still some debate as to the causes and appropriate response. Archaeology is already playing an important role in the efforts to understand past climate change, its impacts on the environment, and to a lesser extent the pathways taken by affected human populations. Future climate change is projected by computer models using imagined socio-economic scenarios for the near and far future. Uncertainty is inherent in the projections due to weaknesses in the models and the variety of possible scenarios. Faced with the possible loss of non-renewable heritage resources decision makers can refer to the uncertainty principle in taking preventive action without the need for absolute proof. The regional projections for Ireland suggest that in the medium to far future temperatures will be higher, rainfall will be heavier (especially in autumn and winter) and there will be longer dry periods (especially in summer and in the south and east). This is supported by long-term trends in rising temperatures and increased rainfall already noted for the latter half of the twentieth century (Dwyer, 2012). In addition, sea level rise (anything from 2–6mm/year) and an increase in Atlantic storms and wave heights are expected.

3.3. THE DEVELOPMENT OF RESEARCH ON 'CLIMATE CHANGE and CULTURAL HERITAGE'

In 1992, Rowland raised the urgent need for heritage practitioners to address the issue of climate change impacts and wrote of a general lack of awareness of what was then termed 'greenhouse issues' (Rowland, 1992). In 1996 Pearson and Williams wrote the following;

> *It will be very difficult to convince governments of the threats to the cultural environment, and of the range of options available to reduce the impact of climate change, if substantial work is not carried out in the next 10 years* (Pearson and Williams, 1996: 126).

Unfortunately this statement has proved to be accurate and cultural heritage is not considered as an affected sector within any of the IPCC Assessment Reports because they consider that *the body of research is too small* (Cassar, 2013). This is problematic as the IPCC influence policy at national and international level.

In 2009 the Australian government published a report on the vulnerability of Australia's natural and cultural World Heritage properties to climate change. This report concluded that the state of knowledge related to impacts on the built heritage is limited at best and frequently non-existent.

> *...the amount of time and research devoted to the effects of climate change on World Heritage values is disproportionate between the natural and cultural values. A broad-scale state-of-the-art vulnerability assessment is required across all properties and values* (Australian National University, 2009: 33).

3.4. TOWARDS ASSESSING THE POTENTIAL IMPACTS OF CLIMATE CHANGE ON CULTURAL HERITAGE

Published analyses of the potential impacts of climate change on cultural heritage tend to use one, or a combination, of the following techniques:

1. Expert led: Use of expert judgment to theorise on potential impacts of projected climate change. Examples of this approach are the World Heritage expert advisory group *Report 22* (Colette, 2007b), the review of Australia's World Heritage sites (Australian National University, 2009), the report by the Norwegian Directorate for Cultural Heritage (Riksantikvaren, 2010) and the report by the Irish Heritage Council in combination with Failte Ireland (Kelly and Stack, 2009).

2. Stakeholder led: In this approach consultation with stakeholders is used to produce a hypothesis of potential impacts. Rooted in experience and knowledge of past events and the effectiveness of the response, this provides a more place specific analysis than the previous 'expert led' approach. Examples are the scoping study by UCL *Climate Change and the Historic Environment* (Cassar, 2005), the National Trust's *Shifting Shores* reports (National Trust, 2005b, National Trust Northern Ireland, 2007) and work with Indigenous land owners in Australia (McIntyre-Tamwoy and Buhrich, 2012, McIntyre-Tamwoy et al., 2013).

3. Mapping and/or Modelling: Various combinations of computer software applications can be utilised to produce an analysis of the impacts of projected climate change. Examples are the use of Geographical Information systems to

create risk maps (Hunt, 2011, McNeary, 2010), or the use of simulation and modelling software to mimic future environmental response (Kincey et al., 2008, Huijbregts et al., 2012).

4. Material Specific Studies: Utilises material science and the study of deterioration mechanisms as the basis for understanding how projected climate change may impact on cultural heritage. Examples include work on stone (Smith et al., 2010, Bolton, 2007, Bonazza et al., 2009) and on archaeological artefacts (Elberling et al., 2011).

Figure 3.5. The destabilization of frozen ground threatens archaeological buried evidences of nineteenth century whalers' settlements on Herschel Island Territorial Park (Colette, 2007a: 59)

3.4.1. Expert Led

This approach is exemplified in the 2007 World Heritage Report 22 *Climate Change and World Heritage*, the outcome of an expert Advisory Group meeting (Cassar et al., 2006, Colette, 2007b). It utilises expert judgement to determine how future climate change may impact on heritage values worldwide. The report emphasises the interconnection between the physical and social impacts of climate change, suggesting that the way people interact with their heritage and the relevance and value of that heritage to their lives, may alter with climate change.

Subsequently, several similar desk top studies have been conducted (Australian National University, 2009, Cuffe Fitzgerald, 2010, Berghall and Pesu, 2008). At a regional level the Nordic project, *Effects of Climate Changes on Cultural Monuments and Sites*, was co-ordinated by the Norwegian Heritage Board and considered cultural heritage in Finland, Sweden, Norway, Denmark, Iceland and Greenland (Riksantikvaren, 2010). In Ireland the Heritage Council commissioned a report on potential impacts of climate change for building stone, which utilised expert knowledge of past deterioration (Bolton, 2007). The subsequent Heritage Council report on the impacts of climate change for coasts and waterways called on multi-disciplinary expertise (Kelly and Stack, 2009).

This form of assessment is relatively efficient as it does not involve significant primary research. The results are generalised however, and require interpretation before they can be applied to individual sites. Case studies are therefore used within the World Heritage report to illustrate the theoretical issues (Colette, 2007b). The World Heritage Committee (29

COM 7B.a) requested that the World Heritage network of sites be used to demonstrate best practice in relation to climate change management and raising of public awareness (Cassar et al., 2006). This was accomplished in part by the publication of *Case Studies on Climate Change and World Heritage*, a publication that used case studies to communicate the issues in an engaging way (Colette, 2007a).

The World Heritage report utilises a one page matrix to communicate the potential train of causation from climate factor to loss of heritage value. This format has been repeated by others (Kelly and Stack, 2009, Huckerby et al., 2008: 84–85) and was adapted within this thesis in an attempt to clarify multiple possible impacts (section 3.5.5.).

3.4.2. Stakeholder Led

This approach shares much in common with the above method but tends to be a more localised or site specific assessment and utilises theoretical perspectives rooted in the experience of stakeholders. Some studies contain an element of stakeholder consultation or opinion but are not focussed on this element, such as the World Heritage report (Colette, 2007b) or English Heritage's coastal risk assessment (Hunt, 2011). The University College London scoping study commissioned by English Heritage is a good example of the concept, using a mixture of site based assessments, stakeholder workshops and questionnaires (Cassar, 2005). The questionnaire outlined possible impacts and predicted responses and was sent to scientific and heritage experts and site managers (Cassar and Pender, 2005). Central to the study is the concept that heritage managers' observations and concerns provide a good indicator of future risk.

The National Trust conducted a series of reviews of their coastal estates in Wales, England and Northern Ireland. They utilised regional and site specific data for accelerating coastal erosion to assess possible future impacts (National Trust, 2005b, National Trust Wales, 2007, National Trust Northern Ireland, 2007). In this case the Trust were the stakeholders and they were able to tap into a wealth of data on the condition of their estate and on past climatic events and responses in making their assessment (National Trust, 2005b).

3.4.3. Mapping and Modelling

The modelling and/or mapping of climate change risks and impacts has been carried out at different scales and using varying degrees of computation. At its simplest, Geographical Information Systems (GIS) can be used to map data and visually monitor differences over time, as in the case of the Scythian burials of Golden Mountains of Altai (Gheyle, 2009). English Heritage combined GIS data from Rapid Coastal Zone Assessment Surveys (RCZAS) with flood and erosion projections to assess the risks of climate change to coastal properties (English Heritage, n.d.). Local geology, staff observations and condition reports were used to refine the results (Hunt, 2011). Thus, an element of stakeholder and expert input was combined with the GIS mapping to produce the evaluation of risk.

The ability of GIS to overlay mapped heritage sites with risk maps for erosion or flooding has been utilised in other reports. In Sweden, a desk top study combined locations of prehistoric remains with maps for future water table levels in order to predict sites at risk (Nilsson, 2009). In another example, the US National Park Service combined desk top mapping using a geological Coastal Vulnerability Index with site visits by experts to assess risks to the Gulf Islands National Seashore (Toscano, 2004). Although limited to assessing risks that can be mapped, such as flooding and coastal erosion, this case study sensitive approach using GIS can directly aid decision making.

Various types of modelling have also been combined with mapped data to provide scenario building, as was done in the case of the Trent and Ouse river valley.

> *The interrogation of the archaeological, geological and landform assemblage datasets within a GIS allows the construction of a terrace sequence model that also serves as a map of archaeological potential (and vulnerability) and is transferable to other temperate river valley systems* (Howard et al., 2008a: 1050).

The analysis produced risk factors for each mapped site to guide mitigation and adaptation responses in the future (Kincey et al., 2008, Howard et al., 2008b).

The most extensive published research in this field is the European Union Framework Programme (FP) 6 project *Global Climate Change Impact on Built Heritage and Cultural Landscapes* or *Noah's Ark.* This project aimed to assess the overall risk to Europe's monumental heritage posed by climate change (Brimblecombe and Grossi, 2006, Sabbioni et al., 2006). The project modelled parameters of interest for cultural heritage such as number of freeze thaw cycles and relative humidity fluctuations, termed 'heritage climatology' by Brimblecombe (2010b). The project combined this future data with damage functions for specific materials in order to produce both risk and damage maps for European built heritage over the next century (Sabbioni and Bonazza, 2010). In addition to the final Risk Atlas for

European heritage, the working groups also published the detailed reports Deliverables 06–15 online (Sabbioni et al., 2010, Noah's Ark, n.d.).

The results of Noah's Ark will be complemented in 2014 by the final results of the Climate for Culture (CfC) FP7 project. Climate for Culture is the largest project funded by the EU in the area of climate change and cultural heritage with a budget of €6 million and 27 partners from across Europe (Climate for Culture, 2013). The project is focused on indoor environments and moveable cultural heritage. CfC is utilising a combination of historic data, surface and environmental monitoring, case studies, climate modelling and building simulations (Huijbregts et al., 2012). One of the main project outputs is expected to be an online decision support tool. This tool will allow end users to calculate the potential impacts of projected climate change[2] on a specific building or collection type in any part of Europe using an interactive database (Leissner and Kilian, 2013).

> *For the first time ever regional climate models with a high resolution of 10x10 km are therefore being developed and coupled with whole building simulation tools to identify the most urgent risks for specific regions* (Climate for Culture, 2013).

Of key importance is the undertaking by the Commission that the assessment produced should be submitted as a European contribution to IPCCs future reports (European Commission, 2010).

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[2] Based on high resolution REMO model climate projections under two scenarios, IPCCs A1B emission scenario and RCP4.5. The latter is a scenario to be published in the forthcoming IPCC AR5 report in 2014 described as: *a scenario of long-term, global emissions of greenhouse gases, short-lived species, and land-use-land-cover which stabilizes radiative forcing at 4.5 Watts per meter squared (approximately 650 ppm* CO_2 *equivalent) in the year 2100 without ever exceeding that value* (http://www.climateforculture.eu/index.php?inhalt=project.climatechange [retrieved 23.5.2013])

3.4.4. Material Science

At the basis of many of the above assessments is an empirical understanding of how environmental parameters interact with heritage materials to cause deterioration. This understanding has been constructed under current climatic conditions however, and may not necessarily hold true in a changed future (Bolton, 2007). For example, Smith and his colleagues identified a knowledge gap centred on the effects of changing seasonal wetting patterns for stone deterioration mechanisms, especially biological growth and salts (Smith et al., 2011, Smith et al., 2010, McCabe et al., 2010). To address the question of 'deep wetting' a project monitoring moisture penetration in test walls was established in Derrygonnelly in Northern Ireland (section 5.2). Exposure trials were also carried out across Northern Ireland to study the potential effects of altered rainfall for biological growth (Smith et al., 2010). In addition, a desk based review of biological growth on stone buildings and monuments was conducted using a database of condition surveys (Adamson et al., 2010). The survey indicated that stone type was less important than climatic controls for biological activity. In order to account for micro-climatic conditions that affect the presence of moisture, and thereby biological activity, site specific studies would be necessary (Cutler et al., 2013).

One of the strategies of the Noah's Ark project was to use damage functions to predict the impact of future climate change on specific materials (wood, glass, metals and stone) (Brimblecombe and Grossi, 2009, Tidblad, 2009). Damage functions are probabilistic cause-effect relationships established for specific materials under known conditions and can be utilised to estimate the deterioration of materials under future conditions. For example, the Lipfert damage function for estimating the dissolution of limestone in clean rain (the Karst effect) (Bonazza et al., 2009). The translation of these engineering functions to aged heritage materials and their extrapolation over long periods can be problematic however (Brimblecombe, 2010a).

The *Parnassus* project, *Protecting Cultural Heritage from Flood and Driven Rain* funded under the Science and Heritage Programme in the UK and co-ordinated by University College London (UCL) is currently underway. The aim of this project is to quantify the risks of climate change on built heritage, focussing on flooding and driving rain, and to determine appropriate responses (UCL, 2013). The project utilises building simulations, stakeholder consultation and climate modelling but also has a significant empirical element. The experimental work involves conducting testing of traditional materials (mortar, timber, masonry) under extreme wetting and drying conditions to determine material failure levels (Stephenson, 2013). Test walls will also be subjected to simulated wind-driven rain in order to determine parameters for structural damage (UCL, 2013). The final results of the Parnassus project are expected in 2014.

3.4.5. Summary

In summary, the research approach to assessing impacts of climate change is multi-facetted. Although four approaches have been identified, in reality many of the projects use them in combination. The advantage of the expert and stakeholder led approaches is in their ability to consider the complex range of interacting variables involved. The gradual and catastrophic impacts of climate change in addition to the indirect and socio-economic impacts are all factored into many of the studies outlined above. The stakeholder based research also involves expert knowledge holders but tends to a more place specific result. This specificity may make it more useful for decision makers at a local level. All projects utilise climate model projections to some extent but complex building simulations, GIS mapping and heritage climate modelling are tools illustrated by some of the larger projects such as CfC and Noah's Ark. GIS mapping may be available to heritage managers but as yet the computational requirements for advanced simulations are not widely accessible. The need for downscaled material specific studies on climate change impacts has been identified in the literature but this type of research will take some time to produce results (Smith et al., 2010). Site specific studies are also necessary in order to account for localised microclimate effects.

Key Concept 2.

There is a gap in the literature in relation to site specific studies and there is a need for an assessment methodology that can be implemented by cultural heritage professionals. This type of assessment is currently missing from the literature, although there is recognition of the importance of site specific factors.

3.5. DIRECT IMPACTS OF CLIMATE CHANGE FOR CULTURAL HERITAGE

In the previous section approaches taken to assessing potential impacts of climate change were examined. The indirect effects caused by climate change mitigation and adaptation strategies are detailed in section 3.6. The direct physical impacts predicted in these studies include gradual effects of environmental change and catastrophic losses from extreme weather. These direct impacts are discussed below in relation to four elements of heritage; coastal, archaeological, built and landscape.

3.5.1. Coastal heritage

Many of the losses due to climate change are likely to occur at the coast (National Trust, 2005b, Flatman, 2009, Pearson, 2008). Rowland refers to it as the 'battlefront' (Rowland, 2008). Coastal heritage includes land based sites, intertidal sites and underwater or submerged sites. The direct impacts include sea level rise (SLR), storm events and greater wave energy leading to flooding, coastal erosion and coastal squeeze. Kelly and Stack see coastal erosion as the key threat amongst these and note that part of the challenge will be dealing with the often conflicting demands for protection of coastal assets (Kelly and Stack, 2009). The high water mark and inter tidal zone are the areas that maintain the most aggressive environment for stone decay, and with erosion and SLR more monuments will find themselves within this environment (Bolton, 2007). Tidal influences are liable to be felt at higher reaches of river systems and could cause significant flooding in previously immune areas (Chapman, 2002). Saline intrusion will also impact historic structures and archaeological deposits (Pearson and Williams, 1996, Chapman, 2002).

While increased erosion may expose submerged wrecks and coastal archaeology, the extreme weather could inhibit their documentation and excavation (Kelly and Stack, 2009). In a survey of cyclone damage to archaeological sites in the Pacific islands, for example, it was found that the greater frequency of these events led to increased destruction as there was no time for protective deposition of sediment or growth of vegetation to occur (Spennemann, 2004).

In relation to underwater preservation, the pH of the oceans is a concern. The average value until pre-industrial times was 8.0. Since then a global average drop of 0.1 has occurred. Unmitigated CO_2 emissions could cause the global pH to decrease by 0.4 by 2100, a level unknown for about 20 million years (Turley and Findlay, 2009). Colder waters can dissolve more CO_2 and the acidification will therefore be greatest in polar and sub polar regions (Riksantikvaren, 2010).

3.5.2. Archaeology

Buried archaeological evidence survives due to the maintenance of conditions that inhibit deterioration mechanisms (Cronyn, 1990). Preservation is best where agents of decay such as water and oxygen are excluded or limited i.e. arid, frozen or anaerobic waterlogged (Caple, 2004). Unfortunately however, even minor alterations to a burial environment can trigger deterioration mechanisms, thereby leading to the destruction of subsurface remains. For example, rising temperatures may encourage microbial deterioration of organics (Chapman, 2002) as would exposure to oxygenated water due to heavy rainfall (Bjordal et al., 2006). Assessing the potential impacts of future climate change on the archaeological resource is complicated by the fact that the conditions and processes involved in burial preservation are poorly understood (Cassar, 2005, Van de Noort et al., 2001).

Changes in water quality, saline intrusion or altered redox potential, will alter established preservation conditions. Anaerobic environments, associated with excellent conservation of waterlogged artefacts and palaeological evidence, are especially vulnerable to changes in water levels (Chapman, 2002). Heritage professionals surveyed on climate change impacts by UCL in believe that organic deposits close to the surface are likely to be lost before they can be recorded (Cassar, 2005). The drying of soils will also allow impact inorganic objects due to the greater penetration of oxygen e.g. corrosion of metal artefacts (Riksantikvaren, 2010).

Figure 3.6. Archaeological remains in the Golden Mountains of Altai: burial mounds (kurgans), Bronze-Age stelae and stone circles. The melting of permafrost threatens the conservation of grave goods and human remains (Colette, 2007a: 62)

Research from MIT Boston shows that moderate alterations in rainfall patterns may have dramatic impacts on groundwater recharge (Chandler, 2008). The exact effects depend on factors such as soil, vegetation, rainfall amount and frequency, and there will therefore be large regional and local variations. Evidence from Crannogs in Scotland suggests that rainfall events can rapidly change *in situ* conditions through the introduction of oxygenated water (Lillie et al., 2008). Saturation alone is therefore no guarantee of long-term stability, especially given predications for increasingly seasonal and extreme precipitation.

In Northern latitudes, increasing annual precipitation may mean soils become more waterlogged. This potential benefit may be offset by an increase in freeze thaw cycles however, and a reduction in permafrost due to rising temperatures (figure 3.6) (Prowse et al., 2009, Blankholm, 2009).

Physical effects on the surface will have impacts on buried archaeology. In Ireland for example increasingly wet conditions predicted for winter with less chance for soil to dry out, means that the level of damage from livestock and machinery on agricultural land is likely to increase (Gormley et al., 2009). Landslides, increased fluvial erosion or scouring by pluvial flooding could all result in complete loss of deposits (Kincey et al., 2008, Howard et al., 2008b). Increased wind could erode sites where the soils are dry, sandy or close to the surface (Riksantikvaren, 2010). The discovery of new sites due to erosion (Caffrey and Beavers, 2008) or the melting of snow and ice is likely to accelerate with climate change (Riksantikvaren, 2010). This material will rapidly decompose after exposure unless found and conserved. Thus, climate change impacts may offer both an opportunity and a challenge to archaeologists (Riksantikvaren, 2010).

3.5.3. Built heritage

Built heritage encompasses structures with variations in scale, materials, states of occupation and decay. Research to date in relation to built heritage and climate change impacts has a strong focus on Europe. Issues relating to built heritage in tropical or desert climate are not well represented. The main exceptions to this are the World Heritage publications (Colette, 2007a, Colette, 2007b).

The parameter of most concern to those involved in historic buildings, according to a survey of English professionals, is increased rainfall (Cassar, 2005). Increased frequency of wind driven rain may result in an increase of abrasion and dissolution rates (Cassar, 2005). For example, wind driven rain leading to the erosion of sandy brick construction is already a problem for the National Trust property of Blickling Hall, Norfolk (National Trust, 2005a). Potential effects of increased rainfall and flooding are also the focus of the Parnassus project (UCL, 2013).

Flood waters can erode foundations and damage structural fabric and the heavy flotsam carried in floods has potential to cause mechanical damage (Pospisil, 2013). The extent of flood damage depends on the depth, length of time and pressure exerted by flood waters (Cassar, 2005). In general however, the major damage to historic structures is likely to occur in the drying-out period. Prolonged periods of wetness, especially if associated with winter warmth, have implications for a number of decay mechanisms including salts and biological action (Bolton, 2007, Smith et al., 2004).

Higher rainfall and rising water levels will increase moisture content of soils and potentially lead to weakened building foundations, subsidence, erosion and even landslide. Conversely, long dry summers with lowered water tables may damage building foundations (Berghall and

Pesu, 2008). Flash flooding may affect desert areas, but an increase in desertification is the main concern for heritage in these regions e.g. Chinguetti Mosque Mauritania (Cassar et al., 2006).

Figure 3.7. High waters in Venice are becoming more frequent and climate projections suggest that Venice could be flooded on a daily basis by the end of the century (Colette, 2007a: 71)

The potential for large losses due to severe storms is borne out by the historic literature. The worst recorded storm in Ireland of 6th January 1839 resulted in trees 10–12 miles inland being covered with salt and 20–25% of the housing stock in Dublin being damaged (Sweeney, n.d., Sweeney et al., 2008). The effect in the West of Ireland was equally devastating:

Scarcely a house in Westport town or neighbourhood escaped uninjured from the storm...Some fifteen hundred trees were broken and torn up by their roots in the Marquis of Sligo's demesne. The stabling and farmyard at Westport House were much damaged (Delaney, 1995: 1).

Europe's historic buildings are predominantly made of stone and efforts to conceptualise the impacts of climatic change on stone decay reveal the complex, episodic processes involved (Warke et al., 2004, Viles, 2002). Deterioration due to the presence of salts is likely to increase in western Europe due to an increase in critical humidity fluctuations (Brimblecombe and Grossi, 2006, Grossi et al., 2011). Predicted increased winter wetness may also lead to deeper penetration of salts facilitating continuous recession (Smith et al., 2004, McCabe et al., 2010). Smith emphasizes the seasonal aspects of climate change for Northern Ireland as being key to a changing pattern of deterioration including the current understanding of salt damage as being a near surface phenomenon (Smith et al., 2011).

Shifts in biological growth are expected. The main control for all types of biological growth is the availability of moisture (Smith et al., 2010, Adamson et al., 2010, Cutler et al., 2013). There are known tolerable ranges for certain organisms, for example mould will only grow at humidity higher than 70% (Martens, 2012). Growth is also exponentially dependant on temperature once the threshold moisture value is reached (given by Sedlbauer's model) (Martens, 2012). In the future it is likely that species that cannot tolerate the drier summers will be less common while the annual increase in temperature will be particularly advantageous to frost sensitive species (Bolton, 2007). Shifts in pests are also predicted. In

2005 termites were found at two National Trust properties in Devon (National Trust, 2005a). Invasive species such as termites could have serious implications for the future preservation of historic timber and other organic materials in the British Isles if they became widespread due to milder winters.

Time of surface wetness is a concern for chemical deterioration of building stone in urban areas as the deposition of pollutants happens more readily if the surface is wet (Bonazza et al., 2009). Warmer wetter winters are therefore a potential risk for this form of chemical attack. The Arrhenius equation refers to chemical reactions accelerating at higher temperatures, indicating rising temperatures may increase chemical degradation reactions such as oxidation and hydrolysis, although again, the reality will be more complex (Fassina, 2010). With improvements in air quality, the implications of clean rain erosion on calcareous stones has received attention (Bonazza et al., 2009). Noah's Ark used the Lipfert damage function (section 9.3.6.) to predict increasing surface recession in areas of high rainfall such as the mountains of central and northern Europe (Bonazza et al., 2009).

3.5.4. Cultural Landscapes

Cultural landscapes may be especially at risk from climate change because of the complex interdependencies between culture and nature in these environments (Gruber, 2008). The many disparate elements contained within landscapes also makes them extremely difficult to preserve as a whole (Cassar, 2005). Changes to landscapes may occur through ecosystems responses such as plant distribution, the loss and/or gain of species and altered growing seasons (Sweeney et al., 2002, Australian National University, 2009). The National Trust produced Gardening in the Global Greenhouse with the Royal Horticultural Society in 2001. They report that changing growing conditions have already affected the management of properties such as Trelissick in Cornwall where the garden is now open all year (National Trust, 2005a).

Figure 3.8. Chavín is located in the Cordillera Blanca of Peru, at the confluence of the Mosna and Wacheqsa rivers is at risk from increased glacial-melt (Colette, 2007a: 61)

Climate change may cause, or accelerate, changes in land use practices (Caneva, 2010). In Ireland there is concern for traditional field systems, hedgerows and stone walls (Sweeney et al., 2008). In Scandinavia, increased temperatures mean timberlines are moving higher and leading to associated root damage to buried archaeology and moisture related damage to built heritage at these high altitudes (Berghall and Pesu, 2008). Competition for water during drier summers is likely to place pressure on landscapes and wetland ecosystems (Cassar, 2005). Landscape effects are not solely limited to rural locations, for example, city-scapes such as gardens and tree lined streets may also be affected by drought conditions (Pearson 2008).

Landslides, ground heave and subsidence are phenomena likely to occur more frequently due to intense rainfall or increased glacial melts (figure 3.8) (Colette, 2007a). High winds are also a concern for cultural landscapes and when combined with waterlogged soils, tree throw is a risk as rooting is less secure (Riksantikvaren, 2010). In Ireland, bog-bursts are likely to be more frequent as dry periods are followed by heavy rainfall (Sweeney et al., 2008).

The Irish American Climate Project produced a report that emphasized the cultural importance of the Irish landscape and discussed some possibilities for how climate change may alter these values. The issues raised included alterations in landscape colours and light quality, changes to field systems and the loss of iconic species such as the curlew and salmon. These changes impact material cultural heritage by altering the existing ‘sense of place’. There are resultant implications for intangible culture which expresses landscape through art, poetry and music:

> *People go to places to feel things, experience things, get a sense of place. Those feelings are difficult to put into words…with Irish music you express some of those feelings…that feeling you get when you look at the scene is right there in the music* (Sweeney et al., 2008: 8)[3].

3.5.5. Summary and Matrix

The impacts of climate change may be sudden and catastrophic, or may represent a gradual change in deterioration processes. The key factor of concern for both natural and cultural heritage managers questioned by UCL researchers was water (Cassar, 2005); *too much, too little, or in the wrong place* (Cassar, 2013). In terms of built heritage, damage from catastrophic weather related events such as floods and storms are likely to increase at the same time as a gradual alteration in deterioration mechanisms is occurring. Materials science has been utilised to evaluate the latter, with a notable focus in the literature on Europe and stone buildings. Losses are likely to be high in soft or low-lying coastal areas, where the combination of increased severe storms and SLR could lead to catastrophic erosion and flooding. The changes occurring in the burial environment will be the most difficult to quantify. Permafrost deposits are clearly under threat from rising temperatures (Elberling et al., 2011) and in the future other burial environments, such as peat bogs, may no longer be considered stable (Jones et al., 2006).

[3] Traditional musician Martin Hayes

Climate Change Effect	Controlling parameters	Potential Impacts on Archaeological Heritage		
		Cultural Landscape	**Structures & Features**	**Buried deposits**
TEMPERATURE • Increased annual temperatures • Reduction in freeze thaw • Increased summer max • Increased surface temperature	Temperature Moisture Radiation	Change/loss of habitats & species Spread of new species Lengthening of growing season Changes in land use	Increased biological growth &/or changes in species Reduction in freeze thaw weathering Increased urban pollution effects (summer) Increased thermal weathering	Accelerated micro-biological activity Altered rate of chemical reactions
RAIN • Storms • Prolonged heavy rainfall • Flooding • Increased water flow • Altered water table • Prolonged dry periods	Rain intensity & duration Rain volume Catchment hydrology (i.e. flooding can be caused by rain elsewhere)	Erosion Silting of river beds Change/loss of habitats & species Loss of vegetation Deterioration of water quality Landslides Changes in agricultural practice Deterioration of peatlands Increased risk of fires Increased recreational use Pollution/contamination	Mechanical erosion Chemical erosion (dissolution) Change in humidity cycles (salts) Increase in time of wetness (salts & microbiological growth) Rising damp Subsidence (landslip) Increased recreational use Changes in surface deposition & washing of pollutants Soiling	Physical erosion Changes in soil chemistry & pH Accelerated deterioration of waterlogged organic deposits Plough damage Collapse/loss of stratigraphy (drying/loss organics) Landslide (saturation)
WIND • Wind driven rain • Wind pressure • Wind driven particulates • Gusts & changes in wind direction.	Wind speed Wind direction Rain intensity & duration	Erosion Rock fall Tree throw	Surface erosion & abrasion Increased penetration of water (leading to salt movement) Increased time of wetness (microbiological growth & salt movement) Physical damage & collapse	Erosion of earthen monuments/soil cover Physical damage from tree throw
		Additional Coastal Impacts		
INCREASED SEA TEMPERATURE • Rising Sea Levels • Cyclones • Coastal flooding	Temperature Ocean currents	Inundation by sea water Erosion Saline intrusion (soils and water table) Migration of human population Tree throw	Inundation with sea water Mechanical erosion Saline intrusion & rising damp Increase in salt weathering	Erosion of sites (exposure &/or loss) Sedimentation of sites Changes in soil chemistry and pH Submersion Increased salinity
WIND • Wind transported salts • Wind driven sand • Increased wave heights • Storm surge	Wind speed Wind direction Surface pressure	Erosion of sand dunes Coastal erosion Saline intrusion Inundation with sea water	Increased penetration of salts & salt weathering Sand blasting Inundation with sea water Erosion of foundations Structural damage/loss	Exposure &/or erosion of sites in sand dunes, underwater and intertidal areas Saline intrusion Submersion

Table 3.1. Matrix of potential impacts for cultural heritage values of climate change in a temperate climate (direct effects).

In assessing impacts it may be more relevant to express the 'direction of change', increasing or decreasing, rather than trying to quantify loss (Brimblecombe, 2010a). While there is a great deal of agreement in the literature over possible impacts, the complexities and uncertainties involved tend to overshadow this. In an attempt to address this lack of clarity a visual cause-effect matrix has been compiled by the author for impacts relevant to the termparate climate zone within which Ireland lies (table 3.1). The matrix represents the most common impacts of concern mentioned in the literature with the exception of some issues for extreme climates (i.e. melting permafrost or desertification). It takes a generalized approach and the case study applications (chapters 7 & 8) highlighted the existence of gaps. For example, due to its terrain and location, the impact of extreme weather on the health & safety of visitors and on the ability of staff to conduct conservation works would be of major concern at Skellig Michael.

Similar matrices/tables of impacts have been compiled in the literature (Cassar et al., 2006, Kelly and Stack, 2009, Colette, 2007b, Huckerby et al., 2008)[4]. The original contribution of the Matrix developed in this thesis is that the values of cultural landscape, built heritage and buried archaeology are included as separate categories. The elements considered are the climate change effect (e.g. reduced freeze thaw cycles) the controlling parameters (e.g. temperature and moisture) and the potential impacts on archaeological heritage values (landscape, built or buried). The Matrix is intended as a tool for step 3 of the Vulnerability

[4] Colette, A. Ed. (2007). Table 1 p.25 *Principal climate change risks and impacts on cultural heritage*, presents three categories; *climate indicator* (e.g. temperature change), *climate change risk* (e.g. changes in freeze thaw) and *physical, social and cultural impacts on cultural heritage*.
Kelly, B. and M. Stack (2009). Table 6.3 p.97 *Summary of impacts on cultural heritage of Ireland's coast and inland waterways*; four climate effects (temperature; precipitation and hydrology; RSL and storms; and adaptation) related to land based, underwater and indirect impacts on coastal and inland waterways.

Framework (see chapter 6); to aid in the identification of hazards for each value under the future climate. The intention in compressing the impacts onto one page was to create a visually clear reference tool for heritage managers. Interpretation of the Matrix relies on understanding heritage values and how they interact with the environment. Many of the interactions involved are synergistic and localised effects, such as microclimates and human intervention, will also buffer the effect of atmospheric climate.

> **<u>Key Concept 3.</u>**
>
> **The effective interpretation of impacts theory, including the Matrix developed here, requires site specific application and local knowledge.**

NB Social and intangible context

Although the Matrix concentrates on the direct impacts of climate change on the physical heritage, the social context within which sites are being managed should not be ignored.

> *The complex relationship between physical social and cultural impacts of climate change on heritage conservation has to be considered when assessing threats by the most significant climate parameters* (Cassar, 2009: 6).

In order to adapt to a changing environment certain ways of doing things may have to change and there is a cultural cost implicit in this, cultural traditions may therefore be the first casualty of the climate change adaptation process (Ford and Smit, 2004).

3.6 INDIRECT IMPACTS OF CLIMATE CHANGE FOR CULTURAL HERITAGE

Where climate change policy fails to give adequate consideration to impacts on heritage, the results could be extremely damaging (Flatman, 2009, Murphy et al., 2009). The greatest and most immediate losses in the historic environment from climate change may be caused by poorly planned mitigation and adaptation actions.

> *Presently, the greatest impact of climate change upon the historic environment is not change itself but rather fear of change* (Flatman, 2009: 7).

Coastal defences, flood engineering and energy generation are likely to affect cultural heritage on coasts and waterways (Murphy et al., 2009, Kelly and Stack, 2009). Public concern over land loss in Ireland is already leading to hard engineering solutions that may impact on archaeological heritage (Edwards and O'Sullivan, 2007). Past experience has shown that human interference in the coastline can be catastrophic to coastal heritage (Sistermans and Nieuwenhuis, n.d.). In terms of riverine archaeology, human adaptation measures such as drainage and flood relief schemes may be equally as damaging as climate change (Kincey et al., 2008, Howard et al., 2008b).

The current drive to increase the energy efficiency of buildings through retrofitting has the potential to be extremely destructive for the built environment (Cassar, 2009, Berghall and Pesu, 2008). The CIS Tower project in Manchester, where a listed 20th century building was re-clad in photovoltaic cells, illustrates the potential for conflict between architectural conservation and climate change mitigation (Hudson, 2007). Hudson sees a danger that the political pressure to mitigate climate change may become so overriding that substantial changes are made to historic buildings for minimal CO_2 savings. In a similar trend, the growth of renewable energy developments may be compromising landscapes and maritime archaeology (Christoff, 2008, Berghall and Pesu, 2008, Flatman, 2012b).

The challenge is to formulate strategies that create the right balance between the reduction of green house gas emissions (GHG) and the preservation of cultural heritage (Flatman, 2012b). Institutions such as ICOMOS[5], English Heritage and Historic Scotland are committed to achieving this through careful adaptation supported by research (English Heritage, 2008a, Historic Scotland, 2012, ICOMOS, n.d.). For example, English Heritage issues guidance on re-use and adaptation of historic structures and on managing renewable energies to minimise impacts on the historic environment (English Heritage, 2005, English Heritage, 2006, English Heritage, 2008b). While the built heritage lobby have demonstrated that reuse and retrofitting is cost effective and energy saving (Preservation Green Lab, 2011), the case for the protection of cultural landscapes and archaeology has still to be made (Flatman, 2012b).

> *Nowhere in government, industry or popular debate has the critical question been asked – does the "clean" energy provided by wind, wave solar and other "renewable" energy facilities "offset" the damage to archaeological sites that will occur through the large-scale construction of such facilities?* (Flatman, 2012b: 179)

3.6.1. Summary

In summary, the most immediate indirect threat to cultural heritage from climate change comes from mitigation and adaptation policies that have not fully considered the implications on heritage resources of schemes such as energy generation or flood and erosion defences. The heritage sector must therefore actively and urgently engage in policy development to ensure the value of cultural heritage is recognised. At the same time however, the sector must not abdicate its responsibility to contribute towards energy conservation.

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[5] This is the subject of a newly established International Scientific Committee (ISC) on Energy and Sustainability (ISCES).

3.7. CAUSE AND EFFECT – THE EVIDENCE BASE FOR CLIMATE CHANGE

In 2005, the World Heritage Centre circulated a questionnaire to all State Parties to gather information on impacts and responses related to climate change and listed properties. Of the eighty five countries that responded, 72% felt that climate change had already impacted on their sites. Out of the one hundred and twenty five sites named as being under threat, seventy nine were natural or mixed properties and forty six cultural (four of these being cultural landscapes) (Cassar et al., 2006). These results suggest that there is already widespread recognition amongst those managing World Heritage properties of the potential impacts of climate change and also that this extends beyond ecological effects to cultural heritage sites.

Within the literature, there is a division between those who are cautiously attributing observed changes to climate change and those who maintain it is too early to do so. The uncertainty in attributing specific issues to climate change is illustrated by the example of *Teredo Navalis*. This shipworm has become established in the Southern Baltic Sea where it is considered an alien species and is now threatening underwater archaeological remains. Some researchers suggest that this is due to increasing water temperatures and salinity caused by climate change (Wreck Protect, n.d.). The link with climate change is disputed however, with other scientists arguing that the spread of the ship worm has more to do with reduced pollution levels than water temperatures (Riksantikvaren, 2010, Berghall and Pesu, 2008).

Coastal erosion is another area where a cautious approach is appropriate (section 5.3).

Climate driven coastal change is merely one process that impacts upon the coastal archaeological resource…determining a direct link between observable change at the coast and climate change is presently impossible (Flatman, 2009: 7).

The complex interactions that occur within marine and land based environments mean that climate change will often be only one of several actors within a system. For example, groundwater changes may be caused by abstraction for domestic, agricultural or industrial use, and climate change represents only one additional factor (Howard et al., 2008b). In south east England monitoring data indicated that increasing summer droughts were to blame for subsidence damage. These figures were revaluated after visual assessment found the problem was, in many cases, due to clay shrinkage caused by tree roots (Cassar and Hawkings, 2007). Accurately determining cause and effect relationships therefore requires a thorough holistic assessment.

The future lies in developing long-term multidisciplinary research teams that monitor and react to climate change (Moss, 2010: 16).

3.7.1. Summary

In summary, the evidence base for confidently attributing observed impacts to climate change is not yet available. This is partly due to masking by historic processes, and partly because of a lack of suitable data from monitoring.

Key Concept 4.

A long-term and holistic approach towards the identification of climate change impacts on cultural heritage is necessary.

3.8. THE IMPLICATIONS OF CLIMATE CHANGE FOR CULTURAL HERITAGE MANAGEMENT

Within the literature that deals with cultural heritage and climate change several themes specific to management are evident.

3.8.1. Embedding heritage concerns in adaptation and mitigation policy

Raising awareness of cultural heritage preservation issues amongst policy makers in local and national government is necessary in order to ensure that appropriate systems are put in place and maintained (Berghall and Pesu, 2008, Flatman, 2012b). *An Taisce*, the National Trust for Ireland, have been highly critical of successive Irish Governments' failures to set targets for the reduction of carbon emissions and use of 'light touch regulation' in relation to planning and industry (An Taisce, 2013). This lack of legislation leads to uncertainty about future developments. It is projected however that by 2050 90% of Ireland's emissions will be from agriculture (Nix and Lumley, 2013). This could indicate that the farming sector, rather than large-scale renewable energy developments, may be targeted in future mitigation policies. The National Climate Change Adaptation Framework for Ireland provides a mandate to the various departments, agencies and councils to develop and publish sectoral and local adaptation plans by mid 2014. Heritage is listed as one of eleven key climate sensitive sectors and the lead agency is the Department of Arts Heritage and the Gaeltacht (Department of the Environment, 2012). The Heritage Council aim to input into the sectoral plans for heritage under the National Adaptation Strategy but at present no progress has been made (Kelly, 2013, Kelly, pers. comm.).

The process of lobbying and communication needs to be constant if heritage is to be embedded in policy as the political climate, public opinion and professional judgements all evolve over time (Flatman, 2012a). For example, in East Wemyss on the Fife coast the preferred coastal defence policy in the 1998 Shoreline Management Plan was to ‘selectively hold the defence line’ to save industrial and archaeological resources (Beech and Thornton, 2003). In the 2011 plan however, this changed to ‘no active intervention’, in regard to those same assets (Mouchel, 2011). In the future, increasing competition for resources to battle the effects of climate change may result in the re-evaluation and possible downgrading of cultural heritage (Egloff, 2006). Christoff argues that the ‘heritage community’ need to identify and publicise threats from climate change in order to engage public opinion and encourage appropriate policy and action before it is too late.

> *...should conditions deteriorate significantly in the future, the likelihood of being able to compete successfully against more fundamental claims for resources to provide food, transport and shelter in order to preserve cultural heritage will be small* (Christoff, 2008: 42).

Coordination with relevant public bodies is recommended to deliver integrated solutions (Cassar, 2005). This may be difficult given the different scales of decision making involved but is essential to avoid creating further problems (Berenfeld, 2008, Cassar, 2009). This is illustrated by coastal erosion, where risk assessment is conducted at local level yet planned responses must consider the whole coast. A decision to employ hard-engineering solutions in one place could prevent localised erosion while displacing the problem further down the coast (Kelly and Stack, 2009).

The need to create links and to pool knowledge and resources between natural and cultural heritage practitioners and policy makers is also emphasised in the literature (Chapman, 2002, Rowland, 2008, Moss, 2010). Cultural heritage would potentially benefit from partnering with the larger and more high profile natural heritage lobby. Chapman suggests that archaeological concerns could be integrated into protective measures taken under ecological grounds, for example in habitat creation in wetlands (Chapman, 2002). Sharing knowledge and information between heritage sites is certainly one option for maximising limited resources. The World Heritage Centre encourages twinning of similar sites to share expertise, in particular from the developed to the developing world (Boccardi, 2009).

Key Concept 5.

Identification of threats from climate change to individual sites is important in order to engage public opinion and encourage appropriate policy and action.

3.8.2. Managing change

Modern conservation practice has already moved away from *the rigidity of arresting change to the flexibility of managing it* (Melnick, 2009: 41). The Burra charter, for example, recognises that *all places and their components change over time at varying rates* (ICOMOS, 1999: 2). Given the potential effects of rapid global climate change the profession may need to develop a new understanding of what 'managing change' means (Melnick, 2009). It may be the case that a fundamental shift in ethos is required in some branches of conservation. For example, the National Trust have already recognised that management plans for their parks and gardens, predicated on the concept that the natural environment will remain unchanged, are unsustainable (National Trust, 2005a).

Given the uncertainty surrounding climate change, management policies must be framed that are flexible, and able to be constantly refined (Cassar, 2009, Rowland, 2008). Management strategies should also recognise that the impact of climate change on society may result in changed needs and demands from the communities using heritage (Christoff, 2008). Melnick (2009) proposes three options for cultural landscape managers confronting the issue of climate change:

1. First, one can resist the change, a short-term solution in most cases.
2. Second, one can enhance the system's capacity to cope with the change. For example, reducing some of the existing pressures on heritage could enhance resilience and lessen the affect of climate change (Cassar et al., 2006).
3. The third option for managers is to facilitate the transformation of the system to a new state which is more compatible with a changed climate. For example, by changing the vegetation to drought resistant varieties or introducing flood barriers. The challenge would be to maintain the integrity and authenticity of the heritage values at the same time, and designations such as World Heritage may restrict this form of adaptive response (Woodside, 2006).

The issue of inevitable loss and the need to prioritise resources is touched on by many authors (Murphy et al., 2009, Rowland, 2008, Kelly and Stack, 2009, Melnick, 2009). There is a common thread throughout the literature that the biggest management decisions of the future may entail allowing loss to occur (Cassar, 2005). One of the clearest methods advocated for prioritisation of the conservation response is the triage approach, which outlines three categories for decision making (Berenfeld, 2008):

1. Doomed sites i.e. record and loose;
2. Sites to be saved *at any cost*;
3. Sites that may be saved by forward planning and an interdisciplinary approach.

Part of adaptive management would be the incorporation of climate change concerns into disaster preparedness planning. The International Centre for the Study of the Conservation and Restoration of Cultural Property, ICCROM, produced a manual for UNESCO aimed at raising awareness amongst World Heritage site managers of risk preparedness (ICCROM., 2010). The manual provides a methodology for identifying, assessing and reducing risks to hazards, including climate change.

Successful heritage adaptation measures can take years to research, fund and carry out therefore it is vital to start that process early so that managers are not caught in a catastrophic situation unprepared (Caffrey and Beavers, 2008). The Directorate for Civil Protection and Emergency Planning in Norway has established a programme to assist municipal authorities prepare for climate change impacts (Haugen and Mattson, 2011, Risan et al., 2011). The research was published as a web resource to which municipal authorities and property owners could refer when planning and decision making (see www.klimakommune.no). It includes fact sheets on likely impacts, suggested monitoring strategies and possible adaptation and mitigation responses. This project translated impacts theory into practical solutions for heritage managers and owners and demonstrates the advantages of web based tools which are flexible, accessible and readily updated.

Key Concept 6.

Heritage management in a changing environment requires forward planning based on a flexible and easily refined assessment of climate change and its implications.

3.8.3. Preservation in situ

Preservation *in situ* entails leaving archaeological deposits intact, to be studied by non-destructive methods and as a resource for future generations (Council of Europe, 1992). Given the high cost of full scale excavation, leaving archaeology *in situ* is also preferable on economic grounds (Vibeke Martens, pers. comm.)[6]. It cannot be considered a sustainable solution however, unless the environmental conditions favouring preservation are known to be stable (Martens, 2010). As burial conditions are likely to alter due to climate change a reassessment of current policy favouring preservation *in situ* is required (Van de Noort et al., 2001). Where protection *in situ* is not possible, rescue excavation prioritised by prior archaeological testing is a possible solution (Spennemann, 2004). Rescue plans may also be needed for specific materials such as prehistoric wooden track-ways threatened by peat desiccation (Bjordal et al., 2006, Denison, 2002).

In assessing buried archaeology, the uncertainty inherent in dealing with climate change impacts is compounded by a lack of knowledge regarding existing conditions (Chapman,

[6] See section 5.5

2002, Van de Noort et al., 2001). Chapman stresses that the first step must therefore be monitoring schemes that increase our understanding of the effects of change within the burial environment. *Theories and models may change through time, but the data collection needs to begin now* (Chapman, 2002). The Qajaa study in Greenland demonstrates a site based approach to monitoring the impacts of climate change on archaeology, in this case organic deposits preserved in permafrost (Elberling et al., 2011). The project combined atmospheric climate measurements with monitoring of the burial environment and laboratory experiments to gain an understanding of how climatic factors influence organic decomposition. This information was then combined with climate projections to model future conditions at the site, and to determine whether the deposits could continue to be preserved *in situ* (Hollesen et al., 2012).

3.8.4. Conservation practice

Existing conservation theory and practice is founded on knowledge and experience of the occurrence of deterioration under current and past conditions. Conservation practitioners may therefore need to reconsider accepted approaches given projected environmental changes (Bolton, 2007). Altered perceptions of damage also have implications for stakeholder based assessments. For example, the changed aesthetics and physio-chemical nature of surface weathering may require a review of 'acceptable soiling' as well as of basic maintenance regimes (Bonazza et al., 2009, Bolton, 2007, Grossi and Brimblecombe, 2007). Smith points out that those changing environmental conditions will cause increasingly complex decay scenarios. While conservation science is catching up there is a risk of inappropriate treatments being used. For example, conservation practitioners faced with new problems may experiment with techniques that do not recognise the underlying causes and instead exacerbate decay (Smith et al., 2010).

3.8.5. Monitoring

Detailed long-term monitoring is necessary to understand the direction and magnitude of change in the environment, and to devise management strategies to deal with that (Rowland, 2008). Monitoring is also a tool for looking at the effectiveness of adaptation and conservation measures, and an intrinsic part of adaptive management (Cassar et al., 2006). The fact that climate change is only identifiable over time periods longer than 30 years is problematic because this is significantly longer than the normal funding scales for research projects (Brimblecombe, 2010c). There are also practical issues with establishing long-term monitoring projects. Staff change over, missing samples and lost data are some of the problems encountered by monitoring projects (Huisman and Mauro, 2011, Williams, 2011).

Long-term monitoring is necessary however in order to recognise the gradual processes related to climate change. For example, one of the recommendations of the Australian National University report for improving the resilience of heritage values is the implementation of site based monitoring (Australian National University, 2009).

> *It is essential that managers of properties develop a system to report and monitor climate effects on World Heritage values, and that this information be shared among stakeholders and managers alike* (Australian National University, 2009: 36).

Hurd proposed basic weather stations be set up at important heritage sites and that the Australian Government could take the lead and establish a national community based programme to monitor listed heritage places (Hurd, 2008).

In Ireland, the call for a national network came from the natural heritage sector, recommending co-ordination across agencies in the use of indicators:

> *...a national strategy for environmental observations centred on the issue of climate change…a network of long-term ecosystem monitoring sites* (Sweeney et al., 2002: 49).

Many of the indicators proposed for ecological monitoring could be applied to cultural heritage (section 9.3.5.) demonstrating the scope for national networks that include natural and cultural heritage sites (Sweeney et al., 2002).

There is an information gap identified for coastal archaeology in particular, and a stated need for more regional, periodic and site specific monitoring schemes such as the English Heritage Rapid Coastal Zone Assessments (Flatman, 2009, Edwards and O'Sullivan, 2007, Flatman, 2012b). In addition to tracking change as it occurs, monitoring is important in creating a baseline understanding of the heritage resource prior to quantification of risk and/or loss (Kelly and Stack, 2009). For example, the Kakadu Landscape Change Projects in Australia's Northern Territory have been recording observed changes in the environment of the park for 50 years, which provides baseline data for ongoing monitoring and adaptation (Pearson, 2008).

In relation to burial environments, monitoring is required firstly to establish a better understanding of the mechanisms of preservation and, following this, of how environmental changes are impacting on this system (Martens, 2010). Although this type of monitoring is extremely urgent given the vulnerability and current lack of visibility of the material, it is also very complex. The types and condition of artefacts, the soil chemistry, hydrology and geology will all be relevant and yet the monitoring solutions must account for this while being minimally invasive (Van de Noort et al., 2001, Caple, 2004).

> **<u>Key Concept 7.</u>**
>
> **Monitoring over periods of 30 years or more is required to understand the direction and magnitude of climate change, and its implications for heritage management.**

3.8.6. Maintenance and repair

In many cases the most severe effects of climate change will be felt where it is coming on top of existing stresses (Cassar and Pender, 2005, Australian National University, 2009). For cultural heritage, many of the impacts can be ameliorated by maintenance or targeted conservation (Pearson, 2008). Thus, maintenance and condition monitoring are key to the planning and management of climate change impacts into the future (Cassar and Hawkings, 2007).

> *While the scientific community is researching, gathering data and deciding how and what adaptations have to be made to mitigate the effects of Global Climate Change…maintenance should be at the top of the agenda for action now* (Hurd, 2008: 46).

Despite the fact that funding of a regular maintenance programme would be more cost-effective than a cycle of neglect followed by episodic conservation treatments, funding for capital projects is often easier to source than for ongoing maintenance (Hurd, 2008).

With increased weathering the repair cycle on buildings is likely to become shorter and this more frequent intervention increases the risk that original materials and historic features will be lost, thereby affecting authenticity (Berghall and Pesu, 2008). Adaptations such as increasing historic rainwater disposal systems could be harmful to both buildings and archaeology (Cassar, 2005). Historic infrastructure such as bridges and dams or reservoirs may need to be upgraded to cope with increased pressures (Pearson and Williams, 1996). Thus conservation works (pre or post event) on historic structures may be necessary but require careful management (Kelly and Stack, 2009). Concepts of authenticity and integrity may need to be revisited as a consequence of these conditions. The need to adapt historic buildings for energy conservation is one of the future challenges in this regard (Cassar, 2009, English Heritage, 2008b).

3.8.7. Summary

In the face of the challenges of climate change, heritage practitioners must firstly ensure that local and national policies take account of cultural heritage. It is important to entrench heritage concerns in planning at this stage to avoid the scramble for resources when challenging conditions occur. Accepting loss and the taking of hard decisions about what can and should be saved will have to be part of the planning process (Melnick, 2009). Partnering with natural heritage offers a potential strategy for achieving greater recognition for cultural heritage at policy level.

Managing and conserving cultural heritage in a changed climate may require a shift in focus and ethos for the heritage practitioner. For example, preservation *in situ* as a strategy for managing archaeological resources may need to be reconsidered. To inform this transformation, baseline condition surveys, research on burial preservation conditions and long-term monitoring of deterioration patterns on heritage are all necessary. Maintenance to increase resilience can be carried out immediately where funding is available. Adaptation measures may also be necessary but can prove challenging in terms of maintaining heritage value. Thus, flexibility in both methods and approach will be needed in the future.

3.9. CONCLUSIONS

The determination of appropriate policy for managing and conserving cultural heritage assets should be based on obtaining a balance between scientific knowledge and an understanding of heritage values. At an international scale, the World Heritage Convention provides a clear set of criteria by which cultural heritage can be assessed for Outstanding Universal Value.

Climate change is measured over averaging periods of 30 years or more. The evidence that climate change is underway is unequivocal, although there is still some debate as to the causes and appropriate response. Given the uncertainty surrounding climate change, management policies must be flexible, and open to constant refinement.

A literature review of the immediate discipline of climate change impacts on cultural heritage resulted in the identification of a number of **Key Concepts.** These concepts informed and shaped the research conducted in this thesis:

1. That the *'coupled human-environment system' and anthropogenic pathways of resilience are significant in the determination of vulnerability to climate change* this concept is reflected in the development of the Vulnerability Framework (chapter 6) which addresses heritage sites as 'systems' and considers adaptive capacity within the measure of vulnerability..
2. That there is a *need for a site based vulnerability assessment methodology that can be implemented by cultural heritage professionals* this concept is reinforced by primary research (chapters 4 and 5) and will be answered by the development of the Vulnerability Framework (chapter 6).
3. That the *effective interpretation of impacts theory, including the Impacts Matrix developed in this chapter, requires site specific application and local knowledge,* a concept illustrated by the case study assessments (chapters 7 and 8).
4. That a *holistic approach towards the measurement of climate change impacts on cultural heritage is necessary,* a concept that lead to the development of a multi-disciplinary Toolbox of Indicators (chapter 9).
5. That *identification of threats from climate change to individual sites is important in order to engage public opinion and encourage appropriate policy and action* (revisited in chapter 4).
6. That *heritage management in a changing environment requires forward planning based on a flexible and easily refined assessment of climate change and its*

implications, influencing the design of the Vulnerability Framework and Toolbox of Indicators as transferable and sustainable site based tools (chapters 6 & 9).

7. That *monitoring over periods of 30 years or more is required to understand the direction and magnitude of climate change, and its implications for heritage management*, a concept that led to the focus on indicators and subsequent design of the LegIT(chapters 9 & 10).

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CHAPTER 4.

INTERNATIONAL PRACTICE

4.1. INTRODUCTION

A two-stage method was designed to investigate current international practice in the assessment and monitoring of climate change vulnerabilities (section 2.5). The first stage involved questioning experts and managers with experience in the field internationally. This was intended as a fact finding mission and the information was sought by using a targeted questionnaire. The second phase, detailed in chapter five, entailed site visits and in-depth interviews at a small number of exemplar projects. In keeping with the guiding paradigms of constructionism and pragmatism the purpose was to understand, through the experience and opinions of those working in the field, which methods were most practical and transferable.

4.2. QUESTIONNAIRE DESIGN AND IMPLEMENTATION

4.2.1. Design

The reliability and validity of the questionnaire was established by undertaking a rigorous design and testing procedure (section 2.5.1). Before administering the questionnaire the questions were piloted to ensure that they would yield answers in a relevant and useable format.

4.2.2. Administration

The target population was defined as those who were addressing or researching the impacts of climate change on cultural heritage internationally. The respondents are listed alphabetically in table 4.1. The initial sample frame was the published literature and major research projects such as Noah's Ark and Climate for Culture (CfC) (section 3.4). This 'judgemental' sample was then added to by referrals from respondents, the 'snowball sample' (section 2.5.1). The process of making initial contact and arranging and conducting the interview was time consuming and often subject to delay (mainly due to scheduling problems). Where possible the questionnaire was conducted by phone, in ten cases the participants preferred to self-administer the questionnaire and this was facilitated (Appendix 4).

Table 4.1. Respondents to questionnaire listed alphabetically

Name and Country	**Profile**
Ashley-Smith J. (Dr) England	Freelance conservation consultant and partner within Climate for Culture (CfC).
Baker P. (Dr) Scotland	Research Fellow, Centre for Research on Indoor Climate and Health, Glasgow Caledonian University. Partner in Engineering Historic Futures and CfC.
Barr, S. Norway	President ICOMOS International Polar Heritage Committee.
Blankholm, H. P. (Prof) Norway	Institute of Archaeology and Social Anthropology, University of Tromsø. Polar archaeology expert.
Broström, T. (Prof) Sweden	Professor in conservation, research area sustainable management of cultural heritage, Gotland University. Partner in CfC

Name and Country	**Profile**
Burmester, A. (Prof Dr) Germany	Director, Doerner Institut Munich. Partner in CfC.
Camuffo, D. (Prof) Italy	Research Director at the National Research Council of Italy, Professor of “Environmental Physics” and “Physics for Conservation” at the University of Padua, the Polytechnic of Milan and the Cignaroli Academy, Verona. Partner in CfC.
Dawson T. (Dr) Scotland	Manager of SCAPE and Shorewatch community monitoring of coastal erosion.
Faylona, P. Philippines	National Museum of the Philippines, Forum UNESCO Universities and Heritage member with declared interest in climate change.
Fjaestad, M. Sweden	Member of steering group at Karlstad University for Scandinavian network on climate change and cultural property.
Flatman, J. (Dr) England	County Archaeologist and Senior Lecturer, Surrey County Council and UCL. Author (Flatman, 2009) ‘A Climate of Fear: Recent British Policy and Management of Coastal Heritage’ *Public Archaeology*
Gronnow, B. (Prof) Denmark	Research Professor, National Museum of Denmark. Polar archaeologist and researcher Qajaa monitoring project, Greenland.
Haefner, K. Germany	Chief Conservator Bayern State Castles and Gardens. Partner in CfC.
Hurd, J. England	ICOMOS President Advisory Committee. Author (Hurd, 2008)‘Preparing for climate change: the importance of 'maintenance' in defending the resilience of cultural heritage.’ *Historic Environment 21*
Hyslop, E. (Dr) Scotland	Deputy Director of Conservation, Historic Scotland. Author *A Climate Change Action Plan For Historic Scotland 2012–2017*

Name and Country	**Profile**
Martens, V.V. Norway	Researcher, Norwegian Institute for Cultural Heritage on project titled *Archaeological Deposits in a Changing Climate. In Situ Preservation of Farm Mounds in Northern Norway*
Matthiesen, H. Denmark	Senior Researcher National Museum of Denmark. Expert on in situ monitoring, researcher on Qajaa monitoring project Greenland.
McIntyre-Tamwoy, S. (Dr) Australia	Senior Research Fellow in archaeology and anthropology James Cook university, Cairns. Author (McIntyre-Tamwoy, 2008) 'The impact of global climate change and cultural heritage: grasping the issues and defining the problem.' *Historic Environment 21*
McNeary, R. and Westley, K. (Dr) N. Ireland	Research Associates, University of Ulster, Coleraine, Centre for Maritime Archaeology (CMA). Principal investigators on Climate Change and Cultural Heritage in Northern Ireland NIEA project.
Morales, O.O.B. (Dr) Mexico	Head of Department of Microbiology and Biotechnology, Autonomous University of Campeche Mexico. Research interest in climate change and microbiological growth on stone.
Murphy, P. England	Historic Environment intelligence Officer (Climate Change) English Heritage. Author (Murphy et al., 2009) 'Coastal Heritage and Climate Change in England: Assessing threats and priorities.' *Conservation and Management of Archaeological Sites* 11

Name and Country	Profile
Pearson, M. (Dr.) Australia	Managing Director, Heritage Management Consultants Pty Ltd, and former Chair ACT Heritage Council, Australian Capital Territory, Australia. Author (Pearson, 2008) 'Climate change and its impacts on Australia's cultural heritage.' *Historic Environment* 21 and co-author (Pearson et al., 1998) *Environmental indicators for national state of the environment reporting - Natural and Cultural Heritage*.
Pender, R. (Dr) England	English Heritage Conservation Department, Building Conservation + Research Team. Researcher on English Heritage publication *Climate Change and the Historic Environment* (English Heritage, 2008)
Rajčić, V. (Prof) Croatia	Professor, Faculty of Civil Engineering University of Zagreb. Partner with CfC.
Rockman, M. (Dr) USA	Climate Change Adaptation Coordinator for Cultural Heritage Resources, U.S. National Parks Service. Author (Rockman, 2012) "The Necessary Roles of Archaeology in Climate Change Mitigation and Adaptation" in *Archaeology in Society: Its Relevance in the Modern World*.
Roe, D. (Dr) Australia	Archaeology Manager, Port Arthur Historic Site Management Authority, Tasmania, Australia
Sabbioni, C. (Prof) Italy	Institute of Atmospheric Sciences and Climate, CNR, Bologna. Lead partner Noah's Ark, TeACH, and Executive Board EU Joint Programme Initiative for cultural heritage
Van Schijndel, A.W.M. (Dr) Netherlands	Assistant Professor, Eindhoven University of Technology. Partner in CFC.
Wainwright, I. U.K.	Broker Sales Director Ecclesiastical Insurance, partner in Engineering Historic Futures and Noah's Ark

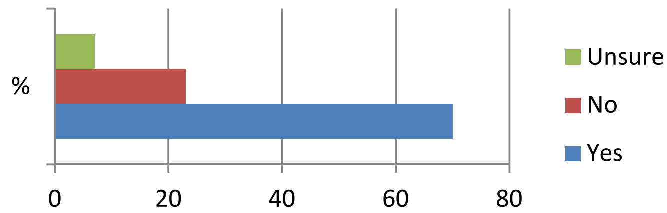
Name and Country	**Profile**
Wu, P.S. (Prof) Taiwan	Assistant Professor, National Cheng Kung University, Taiwan. Conducting research on climate change risks to cultural heritage.

4.2.3. Analysis

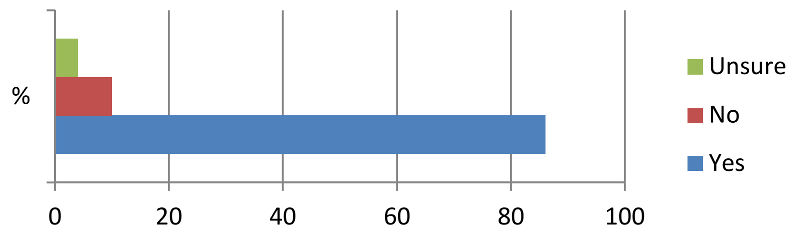
The analysis of the questionnaires was twofold. Firstly, the closed answers (yes/no/unsure) were tallied, a summary of the results are presented in table 4.2. Patterns were noted in the responses and along with additional explanatory comments provided by respondents these were collated into the accompanying text. Additional comments made by respondents (i.e. those not factually related to specific questions) were subjected to a thematic study. The themes identified were added to or refined as the data-set expanded (section 2.5.1.) and the number of respondents referring to each theme was noted (figure 4.1). The thematic analysis examines the conditions that frame and form the factual responses (constructivist paradigm), i.e. the social, economic and political context within which the respondents are operating.

Table 4.2. Nominal analysis of responses to international practice questionnaire

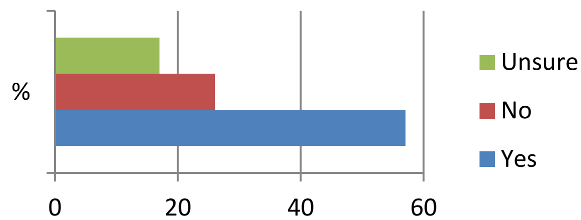
Q1. Have you assessed the vulnerability of any cultural heritage to potential climate change impacts or not?



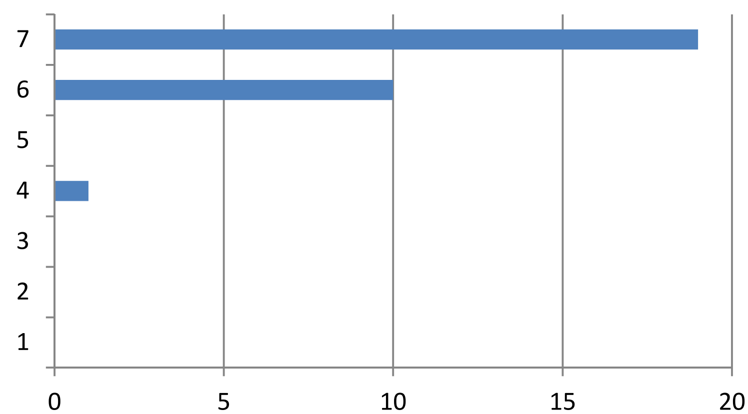
Q2. Do you know of work carried out by others to assess the vulnerability of cultural heritage to potential climate change impacts?



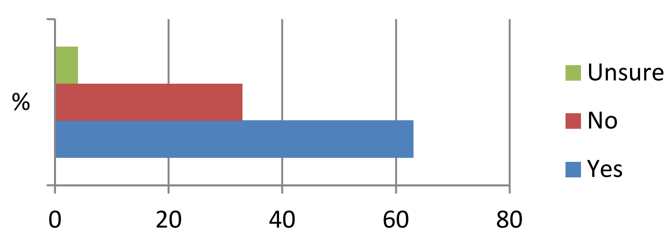
Q3. In your work have you noted any impacts on cultural heritage which you attribute to climate change?



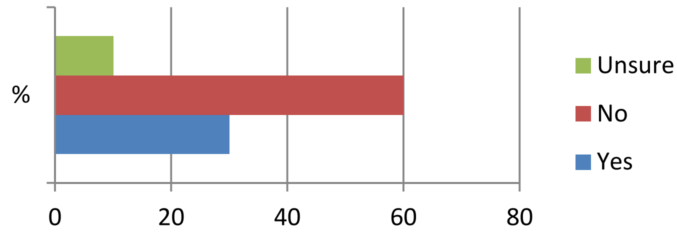
Q4. How important is ‘on site’ monitoring for understanding the impacts of climate change on cultural heritage on a scale of 1 (low) to 7 (high)?



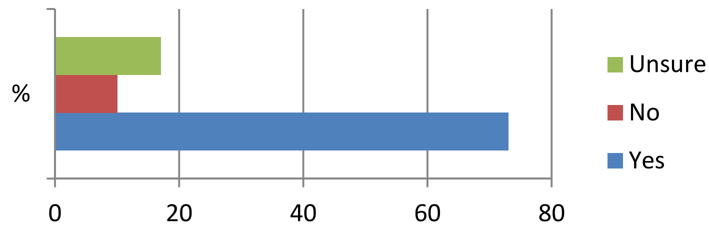
Q5. Have you implemented any site level monitoring for the potential impacts of climate change?



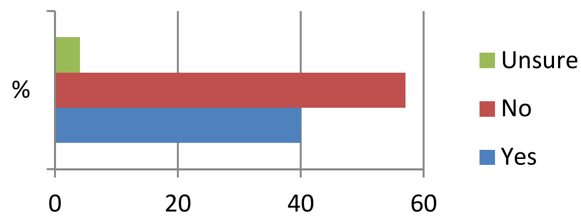
Q6. Do you know of any national schemes to monitor the potential impacts of climate change on cultural heritage?



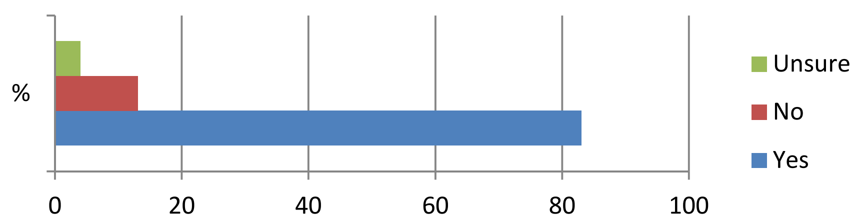
Q7. Do you know of any international research or development in monitoring the potential impacts of climate change on heritage?



Q8. Do you know of any monitoring tools for cultural heritage that are designed to function over the timescale used for climate change measurement (30–100 years)?



Q9. Do you (or others within your institution) have future plans to assess and/or monitor climate change impacts on cultural heritage?



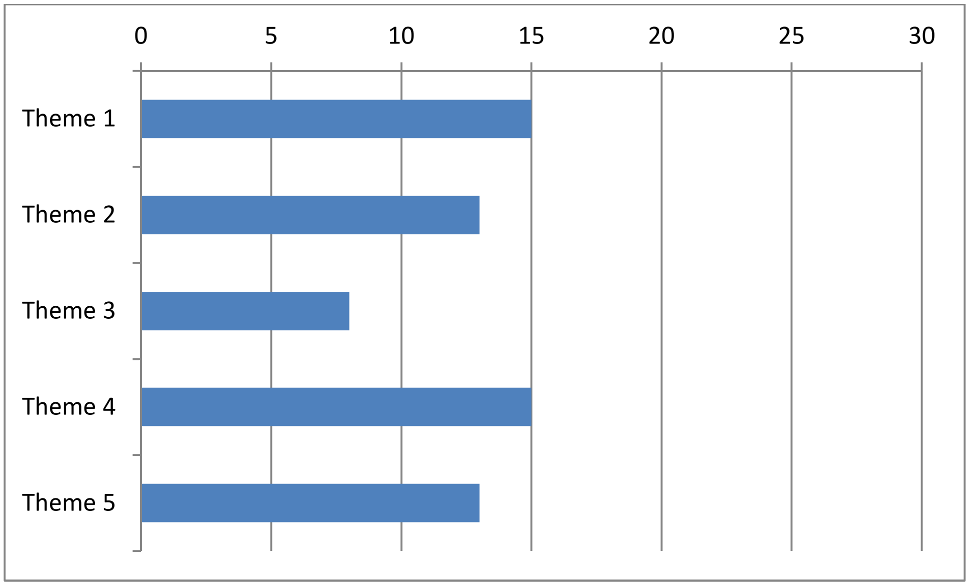


Figure 4.1. Number of respondents concerned with each identified theme.

4.3. ASSESSING VULNERABILITY TO CLIMATE CHANGE: QUESTION 1 & 2

Questions one and two were designed to establish if assessments of the vulnerability of cultural heritage to climate change were being carried out, and if so, what methodologies were being used. The response was very positive, most respondents had personally carried out assessments and also knew of work by others to do so. This was not unexpected as the respondents were chosen for their involvement with the topic of climate change and cultural heritage. The number of positive responses would, in all probability, be much lower in a random sample of heritage professionals. The methodologies used by those who had carried out vulnerability assessments (the majority of which are unpublished) generally fell into one of three categories and reflect the findings of the literature review (section 3.4):

- Short-term monitoring followed by computer simulation

- Risk mapping
- Stakeholder assessment

1. **Monitoring and computer modelling/simulation:** Recording of the environment and conditions at case study sites was mentioned by eight respondents. In four of these the intention was to use short-term monitoring data and computer modelling to simulate the site's environment. The computer simulations would then be run using a future climate projection in order to extrapolate the potential effects of climate change (van Schijndel, pers. comm., Sabbioni, pers. comm., Matthiesen, pers. comm., Martens, pers. comm.). Preliminary details are available on some of the work referred to (Elberling et al., 2011, Climate for Culture, 2013) and one study has been published in full (Cassar and Hawkings, 2007). This method will be explored further in relation to the exemplar case study Archaeological Deposits in a Changing Climate (section 5.5.2).
2. **Risk mapping:** Six respondents referred to desk based reviews, three of which involved elements of GIS and risk mapping. The only published work mentioned was English Heritage's Coastal Estate Risk Assessment (Hunt, 2011). The other projects were: a desk based review for local government in the UK in 2009 (Flatman, pers. comm.); a Noah's Ark style risk mapping for Taiwan city recently completed (Wu, pers. comm.); a GIS based risk mapping project for archaeology in N. Ireland (McNeary, pers. comm.); and two projects that were in the planning stages, one in Sweden (Fjaestad, pers. comm.) and one in the USA (Rockman,

pers. comm.).

3. **Stakeholder assessments:** Stakeholder or community based assessments were carried out by three respondents, one in the UK and two in Australia. The UK example involved heritage professionals and has been dealt with in the literature review (Cassar, 2005). One of the Australian examples engaged with Indigenous communities in assessing potential impacts of climate change on cultural practices (McIntyre-Tamwoy, pers. comm.). In the other, the World Heritage site of Port Arthur, a combination of observational data, in-house knowledge and external expertise was used to assess threats from erosion and inundation (Roe, pers. comm.). The involvement of stakeholders in conducting evaluations will be explored further in relation to the exemplar case study of SCAPE in Scotland (section 5.3.).

There were other approaches that do not fit within the above methodologies. One respondent carried out risk assessments for insurance purposes and this is an area with potential for development given the cost implications of claims. One respondent indicated that informal assessments were being made and two indicated that assessments for other impacts could also apply to climate change. This last point, the overlap between climate change and other impacts, was also referred to by those that answered ‘unsure’ to question one. While these individuals had assessed the impact of the environment on cultural heritage they could not say definitively if it was attributable to climate change. This issue will be discussed further under theme one (section 4.5).

The respondents knowledge of work carried out by others to assess the vulnerability of cultural heritage to climate change (question two) was fairly representative of the major publications on the topic. The large EU funded projects (Noah's Ark and CfC) were mentioned most along with English Heritage and research at University College London (UCL). The new information gained from the questionnaire responses was in individual references to low profile, unpublished, or forthcoming projects. These included the work of individuals who were added to the sample (snowball sampling) and two projects that were subsequently chosen for in depth study (Archaeological Deposits in a Changing Climate, Norway and SCAPE, Scotland).

In summary, while the majority of the respondents had conducted assessments for climate change impacts there was a wide diversity in the approaches taken. None of the respondents indicated that they had used or were aware of any clearly defined methodology for assessing vulnerabilities to climate change at a site level. While CfC and Noah's Ark have created a model for the activities undertaken within those projects (simulation models and mapping respectively) they require a high level of expertise and computer capabilities that may not be available to heritage managers (section 3.4). Elements of a site based approach are evident in the stakeholder assessments but no specific method is being used.

Key Finding 1

These results corroborate the literature review in identifying the need for site based methodologies to assess climate change impacts.

Figure 4.2. View of Fort Jefferson on one of the Keys of Dry Tortugas National Park in Florida (image from www.culturecoach.biz 2013)

4.4. IMPACTS OF CLIMATE CHANGE: QUESTION 3

Question three was designed to find out whether respondents were already able to identify climate change impacts on cultural heritage. Only slightly more than half of the 30 respondents believed they could attribute impacts to climate change. Of those that answered 'no' or 'unsure' three gave no reason and the rest all maintained it was too soon to do so e.g. *it would be unscientific to attribute any short-term observation to an uncertain long-term phenomenon such as climate change* (Wainwright, pers. comm.). What is notable is that many of those who answered 'no' then went on to refer to impacts they have noted, suspecting them to be climate change related but feeling it was too soon yet to determine this. This issue, the difficulty in attributing impacts to long-term climate change processes, will be discussed in more detail under theme one (section 4.5).

Of those who believe they are already seeing climate change impacts, the Polar and Sub-Polar regions provide the most alarming evidence: loss of permafrost, erosion, and material decay (i.e. corrosion, organics decay) are all reported by respondents working in Norway, Greenland and the Antarctic (Barr, pers. comm., Blankholm, pers. comm., Gronnow, pers. comm., Pearson, pers. comm.). Coastal erosion and the subsequent loss of coastal heritage are the effects most widely attributed to climate change. This affects all coastlines but is probably most dramatic in the Polar and Sub Polar regions where thawing of the sea ice and permafrost accelerates losses (e.g. Greenland, Gronnow, pers. comm.). In North America Rockman (pers. comm.) cited the Dry Tortugas National Park (figure 4.2) in the Florida Keys. This site currently requires extensive maintenance and repair due to the effect of long-term wind and water exposure (not directly attributable to climate change) and planning for the future must account for climate change projections – both for sea level rise and changes in storm intensity and frequency. Cape Hatteras lighthouse (figure 4.3) was moved inland by the US National Parks in response to the threat of coastal erosion (Caffrey and Beavers, 2008). Other examples given were the coastal sites of Neolithic Orkney in Scotland (Hyslop, pers. comm.) and the coast of Australia (Blankholm, pers. comm.) referring to a study on increasing erosion of indigenous sites in Sydney harbour. In Scandinavia, Scotland, Taiwan and Mexico (Fjaestad, pers. comm., Rajčić, pers. comm., Broström, pers. comm., Hyslop, pers. comm., Wu, pers. comm., Ortega Morales, pers. comm.) there is an increase in microbiological activity reported (including greening of stone, mould growth and timber decay). Camuffo and Pender (pers. comm.) put forward the notion that climate change is likely to impact the cultural landscape sooner than it will impact built heritage i.e. via coastal erosion, drying of peat lands and the introduction of new pests. Other potential impacts mentioned by respondents were increasing energy costs, adaptation response development such as new coastal defences, flaking of wall paintings, heavier than normal rainfall causing leaks, flash floods and erosion, increased stone throw, increased insurance claims for extreme weather, cyclones, drought and fires.

Figure 4.3. In 1999 the Cape Hatteras lighthouse was moved inland by the National Parks Service to protect it from ongoing coastal erosion (Caffrey and Beavers, 2008) (image from The Virginia Pilot http://media.hamptonroads.com 2009)

In summary, the responses to question three highlighted areas where cultural heritage is most vulnerable to climate change impacts i.e. Polar and Sub-Polar regions and coastal zones. The majority of respondents are already seeing damage caused by changes in the environment. Whether these can be attributed to climate variability or long-term climate change is a matter the respondents were divided on however, and is a key conceptual issue for any research on the topic of climate change.

4.5. THEME ONE

IDENTIFYING CAUSE: CLIMATE CHANGE OR CLIMATE VARIABILITY?

Theme one considers participants views on when (if at all) we can reliably point to climate change as the root cause of any observed impacts. As noted above, many of the respondents argued that it is too soon to attribute perceived effects to climate change rather than climate variability or other environmental forcers (with the possible exception of Polar regions where the shrinking ice can be directly related to temperature). In addition, one has to allow for non-environmental influencing factors such as inappropriate developments or inadequate maintenance (Wainwright, pers. comm., McNeary, pers. comm.).

Some of the ambiguity surrounding the issue is also due to the uncertainty of climate change projections (Burmester, pers. comm.) and to the difficulty in downscaling them meaningfully to local level (Wu, pers. comm.). In addition there may be a lack of clarity amongst stakeholders as to what climate change will mean to them in real terms (McIntyre-Tamwoy, pers. comm.). In Australia, a three stage approach was taken to clarify the issue and engage the Aboriginal community in assessing vulnerabilities (McIntyre-Tamwoy et al., 2013, McIntyre-Tamwoy and Buhrich, 2012):

1. Presenting climate change scenarios
2. Discussing potential impacts,
3. Obtaining feedback on how the community envisioned this affecting their cultural practices.

Many communities will contain valuable knowledge on how climate has changed in the past and how that has affected their culture. This ethnographic approach is akin to the resilience studies of archaeological data outlined in the literature (section 3.2.3.). The value of the approach is in scenario building, yet it still has to rely on future climate models to establish the likely parameters. Future improvements in climate modelling and projections will hopefully serve to address some of these concerns but uncertainty will always be present in any predictive models (section 3.2.4.).

The questionnaire results are in agreement with the literature (section 3.8.5) on the need for long-term data to demonstrate whether we are seeing short-term effects of climate variability or a lasting change. One of the benefits of monitoring could be the reduction of current uncertainty regarding the cause of observed deterioration. For some professionals charged with caring for heritage assets the root cause of any effect is an academic question however. Pearson (pers. comm.) echoed several others with the following comment:

> *I don't care whether it's climate change; I care whether cultural heritage is being impacted. If we have a pattern where cultural heritage is being impacted more frequently then we have a problem to address regardless of the cause.*

The desire to disconnect cause and effect in this context is in part a pragmatic decision by respondents to focus on matters within their professional remit. For some it is also a reaction to the politicisation of climate change, and this will be discussed further under theme five.

In summary, analysis of the questionnaire responses led to the identification of a common problem surrounding causality, i.e. how to ascertain whether an observed impact is caused by climate change rather than another environmental actor. There were two solutions suggested by respondents:

1. Seek to manage the impacts without identifying the root cause.
2. Gather long-term data in the hope of future clarification of causality.

This issue will be discussed further in relation to theme two and the exemplar projects (section 5.4.).

4.6. THE VALUE OF MONITORING: QUESTION 4

Question four was designed to measure the importance given to on site monitoring for understanding the impacts of climate change on cultural heritage. The respondents were asked to rank this importance on a scale of 1 (low) to 7 (high). Only one respondent scored the importance lower than either 6 or 7, and nineteen opted for the maximum value of 7. One can say therefore that there is agreement amongst those questioned on the high importance of monitoring climate change impacts: *Monitoring is absolutely necessary in order to go from guessing to knowing* (Matthiesen pers. comm.). This finding would seem to contradict the slightly ambivalent attitude to climate change research noted in theme one. The tension arises from those that believe in monitoring but feel that remedial action cannot wait for its results i.e. proof of cause.

There were several reasons given for the importance of monitoring. Understanding the rate and nature of climate change impacts is seen as a tool in the prioritization of resources and in developing general adaptation and management strategies. The need for site specific monitoring was also seen as crucial by respondents because micro-climates and orientation at the monument level will interact with the regional climate to determine deterioration.

> *Subtle differences will impact on rock art sites, all management is geared towards what people know of existing conditions at those sites and very small changes* [in the environment] *will in fact have an impact* (McIntyre-Tamwoy, pers. comm.).

Monitoring is also seen as a tool that can be used to convince policy makers and funding bodies that there is a need to address the issue of climate change. Reliable long-term data is required in order to demonstrate a pattern and prove that events are not merely episodic. *Monitoring is as much a tool in arguing the political question as in really showing the impacts* (Pearson, pers. comm.). Of course monitoring is not an end in itself, it is pointless to monitor unless action can be taken as a consequence, either to protect or to record before loss. If no action can be taken on the basis of the monitoring data then its acquisition has essentially been a waste of resources (Dawson, pers. comm., Roe, pers. comm.).

Key Finding 2.

Practitioners agree that long-term site-based monitoring is essential to establish patterns of impacts and determine causality.

4.7. CURRENT MONITORING PRACTICE: QUESTION 5, 6, and 7

Questions five, six and seven were designed to find out what site level monitoring is currently being implemented, either by the respondents themselves or by other projects they are aware of (nationally or internationally). Given the high level of importance placed on monitoring in the previous question it was surprising to find that while nineteen out of the thirty respondents said that they had implemented some monitoring, only nine knew of other schemes to do so within their country. At this point it is worth looking in more detail at the replies of the nineteen respondents that had implemented site level monitoring for climate change impacts.

1. Five of the nineteen responses referred to the monitoring of environmental parameters, mostly atmospheric climate but also indoor and sub soil conditions. Not all of these projects were established specifically for climate change, but the data is being collected over the long-term and is therefore highly appropriate for this use.
2. A further four respondents were engaged in damage monitoring specifically for impacts related to climate change i.e. coastal erosion, thawing permafrost, microbiological decay and flood damage.
3. In another five cases condition assessments and surveys are now being reinterpreted in this vein. This is a legitimate approach provided the time horizon is sufficient for

climate change.

4. Finally, two of the responses referred to short-term monitoring, of environmental parameters and object response, for use in simulation tools. This does not constitute monitoring of climate change impacts however as the real dataset is only a few years in length.

There are, therefore, a wide variety of interpretations about what 'monitoring climate change impacts' means. This is understandable given the diversity of the heritage resource and the research interests involved. Unfortunately it also means there is often confusion when the topic is raised even, as in this case, with experts in the field. This is manifested in the fact that the same types of projects are often considered differently by individual respondents. Thus, Flatman, McIntyre-Tamwoy, and Rockman (pers. comm.) all referred to SCAPE although Dawson (who directs the SCAPE project) does not attribute the impacts he monitors to climate change. The lack of a common perception of the problem is related to the difficulty differentiating between climate change and weathering and is addressed in theme two (section 4.8).

The techniques outlined by those carrying out specific climate change monitoring are similar to those used for measuring damage caused by other factors, human or environmental. One commonality noted is that the respondents who had conducted monitoring (Q5) had also (with only 3 exceptions) conducted some type of prior risk or vulnerability assessment (Q1). Also, in most of the examples given, the monitoring of impacts was quite simple such as surveys; condition assessments; photographic documentation (including aerial and time-lapse photography); laser scanning; and visual monitoring of physical markers. The shared characteristic of most of these techniques is their repeatability, which allows change over time to be recorded.

The main change from previous schemes is an increased emphasis on including climatic parameters. While monitoring of the indoor climate in museums and historic buildings has been standard practice for several decades, the installation of outdoor climate stations at monuments is still quite rare. The reported implementation of this form of monitoring is directly tends therefore to be directly related to concerns over climate change. Projects that included an element of outdoor climate recording at heritage sites were reported in the UK (Baker, pers. comm.), in Greenland (Gronnow, pers. comm.), in Central Asia (Hurd, pers. comm.) and in Norway (Martens, pers. comm.). The most widespread project involves 12 earthen archaeological sites across North Africa and Central Asia where simple climate stations have been installed and the data is downloaded by local volunteers (Hurd, pers. comm.). In six of these sites soil moisture is also being recorded as they are near large bodies of water.

The projects within respondents' home countries, mentioned in response to question six, were generally those where existing condition assessment procedures could be expected to note changes e.g. National Monuments Watch in Norway or Field Monuments Wardens in Northern Ireland. The National Museum in Greenland was the only institution reportedly planning a national monitoring program focused specifically on climate change related impacts to heritage sites. In this project they are concerned with the erosion and thawing of archaeological deposits. The scheme is proposing to take the research study on Qajaa, by the National Museum of Denmark, as a model (see section 3.8.3.). The pilot project is expected to focus on the region around Nuuk, the capital city of Greenland (Gronnow, pers. comm.). Unfortunately this work was in the early phase of development and the coordinator did not feel able to participate in the questionnaire when contacted in 2012 (Knudsen[1], pers. comm.).

In question seven, respondents were asked what site level monitoring they knew of internationally. Although twenty-two responded positively, the answers did not produce much new information i.e. they mostly referred to the research reviewed in chapter three. The confusion regarding what constitutes climate change monitoring is again evident in the fact that Noah's Ark was mentioned several times and yet the Noah's Ark project did not address the topic of monitoring (section 3.4.3.).

In summary, there was unanimous agreement, in response to question four, that monitoring of climate change is important. Respondents identified monitoring as a significant tool for several levels of decision making:

1. Site level i.e. knowledge of micro-climates
2. Policy level i.e. assigning resources, designing adaptation strategies.
3. Political level i.e. accessing funding

The variety of approaches mentioned in response to questions five, six and seven illustrate the lack of a common interpretation of 'monitoring climate change impacts'. In general terms it can be said that the monitoring described tended to be implemented

[1] Pauline Kleinschmidt Knudsen, National Museum of Greenland, paaliit@natmus.gl, 24.1.2012.

followed a risk assessment, involved simple easily repeatable methods and included atmospheric climate measurements.

Key Finding 3.

There is a lack of specific climate change monitoring projects in practice, and a certain degree of confusion on what such projects should entail.

4.8. THEME 2

MONITORING IMPACTS: CLIMATE CHANGE OR WEATHERING?

This theme examines the difficulty many respondents had differentiating between monitoring climate change impacts versus other environmental factors (see also section 5.4.2.). This is closely related to the conceptual uncertainty of theme one, but concerns a very practical question, i.e. when does measured 'weathering' become a 'climate change impact'? Fourteen respondents alluded directly to this issue. Furthermore, when asked if they knew of monitoring for climate change impacts, many respondents pointed to monitoring schemes that were not designed as climate change monitoring projects. The question arising from these responses is how climate change related impacts can be distinguished within the monitoring data. As Ashley Smith (pers. comm.) said, *monitoring of some kind must be good but linking cause and effect may be more difficult*.

There is a general sense that climate change is expected to change the rate and pattern of environmental impacts but not their nature.

> [We have] *just got to consider that new driver of change as being possibly climate change as well, but I think all the usual monitoring and care regimes for cultural heritage will automatically mop this up because they are all looking at the long-term* (Pender, pers. comm.)

This is a common view but it does not account for the uncertainty inherent within future climate projections. With rising temperatures it is possible, for example, that freeze thaw processes will cease for some parts of Europe but become problematic in areas unaccustomed to winter thaws. Monitoring is therefore necessary to clarify these uncertainties.

The lack of national strategies or best practice models is seen as a problem by respondents and the need for leadership in this respect was identified (Rockman, pers. comm.). Flatman (pers. comm.) remarked that he did not know of anyone carrying out long-term monitoring on sites partly because people didn't know what they should be doing or what others were engaged in:

> *I would love for some national or international organisation to develop a checklist for 5 or 10 easy steps which we could most usefully monitor and if there was some national or international monitoring system where everyone fed in data that could get some very useful information* (Flatman, pers. comm.).

Meteorologists measure climatic parameters on a daily basis but look at patterns over 30–100 year periods when speaking of climate change (section 3.2.1.). The same differentiation between monitoring climate change impacts and monitoring the impacts of weather could be made within the heritage profession. We could say therefore that the identification of climate change impacts depends primarily on the length of the data sample, i.e. it will be detected in 'long-term weathering patterns'.

> *Timescale of measurements will be long in order to see climate change impacts. Need to measure climate conditions locally* [and] *other impacts that can influence changes to cultural heritage* (Baker, pers. comm.).

4.9. SUSTAINABLE SOLUTIONS: QUESTION 8

Question eight asked respondents if they knew of any monitoring tools for cultural heritage that were designed to function over the timescale used for climate change measurement (30–100 years). Twelve respondents knew of some method they felt would function on this timescale. More than half of these were referring to traditional field work methods i.e. field visits and observation. Pender (pers. comm.) felt that most standard care and monitoring regimes for cultural heritage could be utilized because they automatically take a long-term perspective (theme 3). Over half of those monitoring climate change (Q5) were not aware of any tools that could function over the timescale required, highlighting the confusion surrounding this topic.

In Australia, the form for the State of Environment (SOE) condition reporting on heritage includes consideration of climate change impacts (Pearson, pers. comm.). These surveys are repeated every 5 years and to date there are 3 cycles of data covering 15 years. The process is based in current legislation however, and is therefore reliant on political whim.

Future politicians could change the legislation in which case the SOE process may cease. As Pearson (pers. comm.) pointed out, *I know of very few legislative regulatory processes that last that long* (i.e. 30–100 years).

The EU funded TEACH project was referred to by Sabbioni (pers. comm.) as the outputs will include tools to measure how blackening on buildings changes as a function of climate parameters. Airborne and terrestrial laser scanning was also mentioned but with the caveat that at the moment it remains too costly and specialized to be widely applied (McNeary, pers. comm.). Other proposed solutions were erosion markers; photography; changes in stone hardness (from baseline value); GIS mapping (for catastrophic loss); smart monitoring tools (Krüger, 2011); and material samples buried for decay process monitoring. The majority of respondents could not identify any sustainable solutions however, although they agreed it was a requirement. *We need simple solutions which can be left quietly and unobtrusively for long range analysis survey data* (Flatman, pers. comm.).

Low-tech easily repeatable visual assessment techniques were by far the most common proposed solution (given by nine respondents). This was primarily because none of the participants were able to identify a sensor or monitoring equipment that can continue to function over the 30–100 year period. An alternative approach taken by Hurd was to use cheap easily replaceable equipment and rely on well motivated local people to ensure continuity over time. This, he argued, can be accomplished by mobilising groups within civil society. In one example, in Kazakhstan, three sites are being monitored by the

Kazakh-Turkish University in Turkestan. The project has run for seven years and is likely to continue because of the university engagement. Hurd (pers. comm.) argues that institutions such as universities and schools or local heritage groups can sustain the human resource commitment that is required for long-term monitoring. The coastal monitoring projects of SCAPE, detailed in the following chapter, illustrate ways this can be managed through its use of local heritage groups and crowd sourcing (section 5.3.).

Key Finding 4.

There is a need for the design and promotion of sustainable monitoring solutions.

4.10. THEME THREE

TIME HORIZONS

Several respondents mentioned unique contributions that cultural heritage professionals could make to the field of climate change research and management. In particular, due to the long-term perspective of the sector, it would seem to be ideally positioned to consider climate change impacts. Respondents also pointed to the potential use of historic and archaeological data to help understand what may happen under future conditions because *it is easier to assess the past than the future* (Fjaestad, pers. comm.). The monitoring of insurance claims made by Anglican Churches in the UK for example could call on 100 years worth of data for analysis (Wainwright, pers. comm.). As a national spread of information relating to a similar building type this represents a valuable resource. Most national museums and many historic properties have indoor environmental data, in some cases this dates back to the late 1800s, a resource being utilized already by the CfC project (Burmester, pers. comm.). The detailed examinations routinely carried out on historic properties in care are likely to flag changes before they are noted by owners of private or modern properties (Pender, pers. comm.).

Historic data may also be combined with current short-term monitoring to verify the future projections produced by climate models. At the Qajaa archaeological site in Greenland researchers are looking at survey data from the 1800s and 1930s and combining it with current data and climate modelling software in order to predict how the site may change in the future (Gronnow, pers. comm., Matthiesen, pers. comm.). In addition, they have compared the state of preservation of organic artefacts recovered recently with those accessioned by the museum in the 1930s and earlier (Gronnow, pers. comm.).

The historic environment can also play a role in influencing public awareness about climate change (Pender, pers. comm.). In the UK, some historic gardens have had to change planting regimes that date back to the 1700s because of an altered growing season. These gardens often have long-term written phenomenological records and are in a good position to communicate the impacts of climate change to a wider audience. The long-term view taken by heritage professionals also means that there is an awareness of the inevitability of loss within the profession. There is, especially in archaeology, a tradition of preservation by record when loss is inevitable.

We know we can't save everything and we have a process for saying goodbye…we may have something to teach other sectors (Rockman, pers. comm.).

4.11. FUTURE PLANNING: QUESTION 9

The final question was whether respondents had plans for the future to assess and/or monitor climate change impacts. Twenty five responded in the affirmative but the majority of those referred to existing projects or had nothing specific planned. Apart from the projects in Greenland and Norway mentioned above, there were four other new projects being planned.

1. A PhD on climate change and Rock Art in Australia.
2. Risk mapping for all historic estates in Yorkshire by English Heritage.
3. Design of a nationwide response framework and institutional structures to direct future work and funding in the US National Parks Services.
4. A proposed Nordic project, possibly also with Russia, to look at archaeological sites in perma-frost regions of northern Europe.

The nature of this research area can thus be said to be largely aspirational at the current time. It is encouraging that there is an appetite for developing projects but how many more will come to fruition is hard to gauge.

4.12. THEME 4

FUNDING CONSTRAINTS

Cultural heritage is often seen as a low priority for government support and, due to the global financial crisis of recent years, funding has become a critical problem. The issue of the lack of finance for new projects was cited as a barrier to research and monitoring of climate change impacts by over half of the respondents. The inability to access funding when more research is clearly needed into this global issue is forcing heritage managers into being reactive rather than proactive in their response to conservation (Pender, pers. comm.). Several respondents spoke of ongoing cuts and of the inability to commit to any long-term projects as future funding levels are so uncertain (Haefner, pers. comm., Pender, pers. comm., Murphy, pers. comm., Hurd, pers. comm.). In other cases while the funding may be guaranteed, it was limited in time. Generally in 3–5 year tranches that matched the political cycle (Martens, pers. comm., Matthiesen, pers. comm., Rockman, pers. comm., Pearson, pers. comm.). This short-term budget planning process is not suited to creating and maintaining long-term projects. Burmester and Hurd (pers. comm.) also pointed to the problem of being unable to analyse existing data because of a lack of funding for staff. Many museums have decades of environmental records, but there is no-one to analyse it and develop an overall view. While complaints about under-funding are ubiquitous in the public sector, there is a serious risk that the crisis in funding will detrimentally affect the capacity of sites to cope with climate change impacts. John Hurd (pers. comm.) who works with heritage sites in several countries stated that in many cases they *haven't even got the budget to do maintenance which is the first line of defence against extreme climate.* Involving unpaid volunteers in research and monitoring is thus crucial to the continued operation of many projects (Dawson, pers. comm., Blankholm, pers. comm., Murphy, pers. comm., Hurd, pers. comm.). Public engagement is also important for the future of heritage funding: *if the public are not interested in what we do, why should they pay for us to do it* (Dawson, pers. comm.).

Lack of funding is also cited as one reason why so much of what is mentioned is aspirational in nature (Sabbioni, pers. comm., Rockman, pers. comm., Wu, pers. comm., Morales, pers. comm., Pearson, pers. comm.). The under-financing of cultural heritage is an international theme. The need to convince governments and funding bodies of the value of this non-renewable resource in order to secure financial support was also mentioned by several respondents in this context (Haefner, Wainwright, Hyslop, Pearson). This relates to the next topic to be discussed, the socio-political context surrounding climate change research.

4.13. THEME 5

THE POLITICAL AGENDA

Cultural heritage is part of the public domain and, as such, it operates in a politicised arena. The ramifications of this were mentioned by respondents, mainly in relation to negotiating financial or policy support. Several respondents reported unwillingness at government levels to tackle issues that operate far outside of the election term especially because in times of scarce financial resources cultural heritage is not considered a priority (Flatman, pers. comm., Camuffo, pers. comm., Murphy, pers. comm., Wu, pers. comm.).

This in turn effects the funding cycles for national and international projects, which are commonly tied to the same 3–5 year term. Short-term thinking is therefore endemic in policy and funding decisions due in part to a political desire for immediate results.

In the specific case of climate change, some respondents felt that there was a level of fear and/or denial amongst policy makers, both in relation to the scale of the problem and the possible impacts (Flatman, pers. comm., Pearson, pers. comm.). Others put a perceived lack of political engagement down to either disinterest or lack of awareness (Camuffo, pers. comm., McIntyre-Tamwoy, pers. comm., Rockman, pers. comm.). Whatever the reason, cultural resources are often left out of the dialogue on climate change impacts.

Many respondents allude to the need to challenge this traditional thinking and have already made efforts at awareness raising (Rockman, pers. comm., Hyslop, pers. comm., Wu, pers. comm., Morales, pers. comm., Pearson, pers. comm.). One example of this is the U.S. National Parks service where efforts are underway to have cultural resources considered by the Landscape Conservation Co-operatives. These organisations relate to the Department of Interior's eight *Regional Climate Science Centres* and have an overarching ecosystems focus although some integration of cultural heritage into their projects is slowly being developed (Rockman, pers. comm.). Historic Scotland has published an action plan on climate change to promote awareness of the different issues involved and other efforts have been made at local government level and through ICOMOS (Barr, pers. comm., Morales, pers. comm., Pearson, pers. comm.). Wu (pers. comm.) advocates the use of downscaled, Noah's Ark style, risk mapping as a tool to raise political awareness and support: *government always want to have visible results such as maps, these help to persuade them step by step.*

Climate change, and whether it is humanly-induced, remains a highly politicized issue involving many powerful vested interests. Some respondents have tried to disassociate themselves from the debate on climate change by focusing on the degradation of cultural heritage without speculating on its underlying cause (Dawson, pers. comm., Pearson, pers. comm., Roe, pers. comm.). In the experience of these respondents tying their research to climate change, particularly the concept of anthropogenic or human induced climate change, proved a handicap because it can be a politically controversial and socially divisive topic.

This leads to the question as to whether the identification of climate change impacts has any value for the conservation of heritage assets.

- As deterioration and loss of cultural heritage is a natural and inevitable process of change and…
- As heritage professionals cannot conceivably prevent the climate from changing…

Is there any practical purpose in differentiating between the impacts of climate change and normal climate effects?

The respondents to the questionnaire clearly believed that an understanding of climate change effects was critical.

> *The nature of the impacts associated with changing climate are not restricted to different rates of weathering but will include changing patterns of weather events (storms etc) as well as processes* (Roe, pers. comm.).

Thus the implications for future management may be significant, a finding reflected in the literature (section 3.8.2.). The high level of support for undertaking monitoring to determine the nature of climate change impacts (section 4.6.) demonstrates the consensus of opinion amongst respondents on the subject.

> *A precise understanding of underlying causes is not required by heritage managers; they need to know what aspects of climate are changing and how this will affect the places they are managing* (Roe, pers. comm.).

In most cases however, the desire to implement monitoring remains an aspiration.

> *We need to monitor it in enough volume and at the right level over a long period in order to get the empirical data that we need to make the right decisions, at the moment people are making decisions based on a lot of assumptions and hearsay rather than facts* (Wainwright, pers. comm.).

The politicisation of climate change could even prove an advantage, providing a platform from which heritage professionals can both argue for the accumulation of data and promote a conservation agenda (section 3.8.1.).

Key Finding 5.

Lack of resources and political disinterest in the topic is a challenge for heritage professionals - data from monitoring is seen as a valuable resource both for raising awareness and lobbying support.

4.14. CONCLUSIONS

The questionnaires were designed as a fact finding tool for the investigation of international practice in assessing and monitoring climate change impacts on heritage sites. The replies showed that impacts attributed to climate change are mainly being noted in Polar and coastal regions. The replies also demonstrate a lack of site based vulnerability assessment methodologies in use. There is almost unanimous agreement among respondents that monitoring is a high priority, yet less than half are currently engaged any such activities. When asked for examples of long-term monitoring tools, respondents generally felt that low tech solutions would be most suitable. Under-financing was a common complaint as were the short-term budget cycles which inhibit planning of long-term projects. In some cases the shortfall is affecting routine maintenance and is therefore a very serious problem likely to be exacerbated by climate change. The politicisation of climate change means that heritage professionals working in this arena are likely to meet scrutiny and criticism from a wider audience than usual. The key findings from the questionnaire in relation to the assessment of climate change impacts are listed below.

Key Findings

1. A gap exists which the development of a site based assessment methodology would address (see chapter 6).
2. Long-term site-based monitoring is essential to establish patterns of impacts and determine causality. This should feed back into active management of impacts, a concept reflected in the management model developed in this thesis (figure 11.4).

3. There is a lack of climate change monitoring in practice: The uncertainty in distinguishing between the impacts of climate change and climate variability is reflected in the confusion surrounding what constitutes monitoring of climate change impacts. This confusion is likely to greatly increase in the wider profession unless clarity on what might constitute monitoring of climate change impacts is reached amongst those engaged in research in this area.
4. There is therefore a need for the design and promotion of sustainable monitoring solutions. This problem will be addressed in chapter 9 and 10.
5. Lack of resources and political disinterest in the topic must be tackled by heritage professionals and data from monitoring could prove a valuable resource both for raising awareness and lobbying support. Some respondents found that heritage issues became sidelined when associated with climate change and had therefore stepped back from the topic.

The questionnaire results suggest a role for an international organisation that could make recommendations on the type of monitoring that should be conducted at heritage sites and could co-ordinate the results. There may also be a role for the creation of an international charter that would establish the requirement for long-term monitoring. One possible model for such a programme is the long-term materials testing undertaken at sites across Europe under the *International Co-operative Programme on Effects on Materials including Historic and Cultural Monuments* **(**ICP) (Swerea KIMAB AB, 2009).

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CHAPTER 5.

EXEMPLAR PROJECTS

5.1. INTRODUCTION

The myriad of impacts climate change may have on cultural heritage are discussed in the literature (section 3.5.) but there remains uncertainty as to how these can be examined at site level (section 4.7.). In this section four international endeavours to address the monitoring of potential climate change impacts on cultural heritage assets are examined. The chosen projects, located in north-west Europe (figure 5.1), address key topics for the current case study sites and for heritage resources in general. The projects selected, based on feedback from the expert questionnaire, are:

1. Future Climate Change; the nature and scale of impact upon masonry (Climate change and the 'greening' of masonry: implications for built heritage and new build): This project focuses on monitoring the effect of increased wetting of stone in Northern Ireland.
2. Scottish Coastal Archaeology and the Problem of Erosion (SCAPE): This charity in Scotland addresses the problem of the loss of heritage sites to coastal erosion.
3. "Påverkan på runinskrifter" or Runic Inscriptions as Cultural and Natural Environmental Indicators: This project by the Swedish National Heritage Board is investigating whether the loss of stone surface detail can be used as an indicator for atmospheric conditions.

4. Archaeological Deposits in a Changing Climate: This research in Norway focuses on monitoring preservation conditions within the burial environment and understanding how this may change under future climatic conditions.

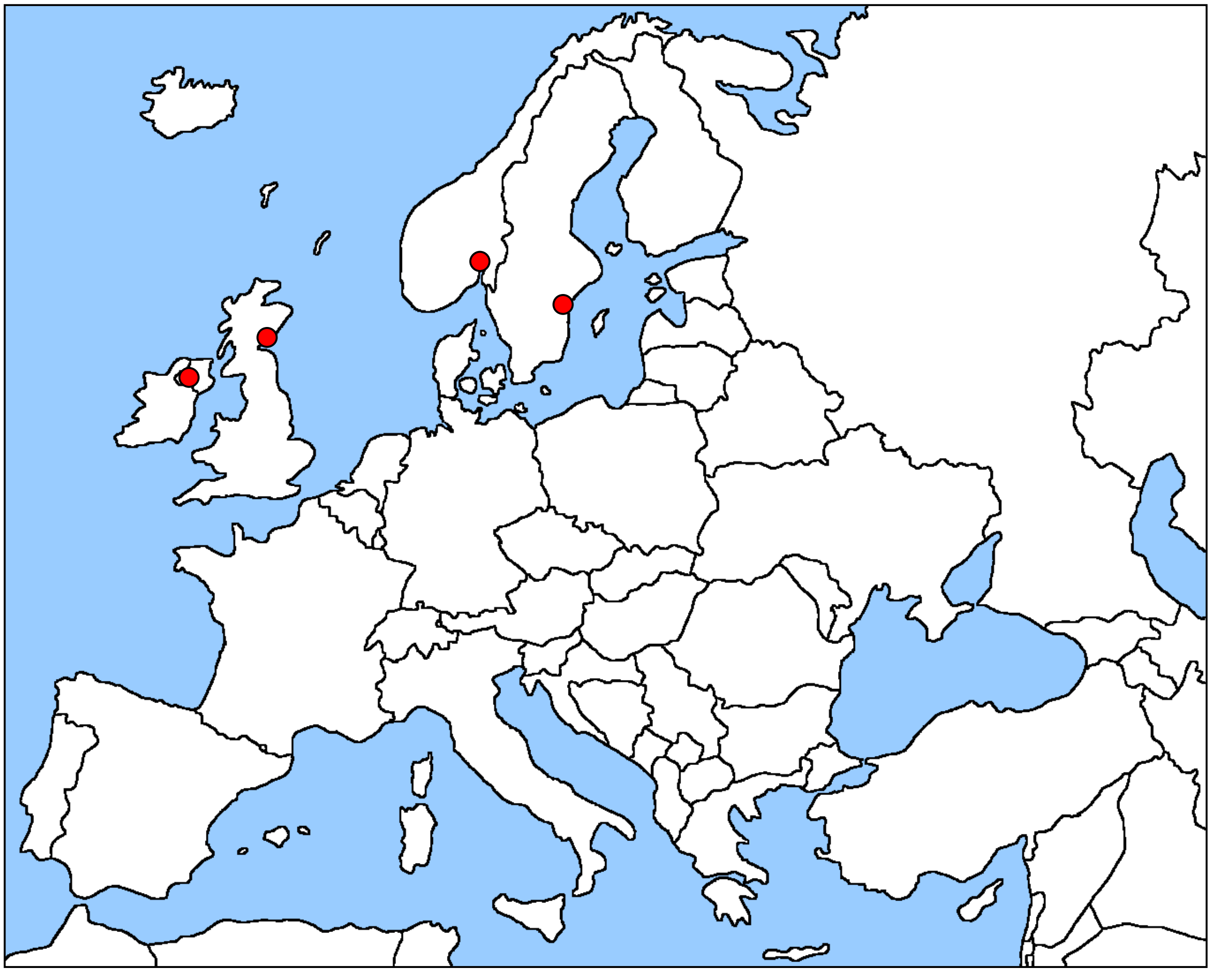

Figure 5.1. Locations visited for exemplar projects research; Derrygonnelly Northern Ireland, St. Andrews Scotland, Oslo Norway and Nyköping Sweden (www.youreuropemap.com)

5.2. FUTURE CLIMATE CHANGE: THE NATURE AND SCALE OF IMPACT UPON MASONRY

This project by the School of Geography, Archaeology and Palaeoecology, Queens University Belfast (Principal Investigator (PI), Prof. Bernie Smith) and the Oxford University Centre for the Environment (PI, Prof. Heather Viles) focuses on understanding processes that control stone decay and how they relate to climatic parameters. It encompasses the monitoring of masonry and climate in parallel. The research is focussed on increased 'time of wetness' in stone, an issue of major concern in Ireland given future climate scenarios (Smith et al., 2004, Smith et al., 2010) (section 3.2.6.). The case study data was collected during a visit to Derrygonnelly in February 2012 including an interview with Dr Stephen McCabe, Department of Geography, Queens University Belfast (Post Doctoral Research Fellow on the project).

5.2.1. Background – deep wetting in stone

Climate change in Northern Ireland, and other parts of north-west Europe, may result in 'deep wetting' of stone due to more prolonged periods of rainfall as well as intense wind-driven rain (Smith et al., 2004, Smith et al., 2011). Smith (PI on the project) and his colleagues believe that after prolonged heavy rainfall (the 'deep wetting' event), while the surface may dry, a reservoir of water remains deep within the stone, evaporation being insufficient to move moisture from the interior. This scenario represents an addition to the current understanding of 'time of wetness' and the test walls at Derrygonnelly are being used to monitor it within real world conditions (Smith et al., 2011). The location of Derrygonnelly was chosen as it has one of the wettest climates in Northern Ireland (McCabe, pers. comm.).

The impact of prolonged and deep wetting is important for stone conservation both in relation to the behaviour of salts and for micro-biological activity (Adamson et al., 2010). Levels of micro-biological activity on stone in Northern Ireland have been linked to time of wetness although the relationship is not straightforward (Smith et al., 2010, Adamson et al., 2010, Cutler et al., 2013). Salt weathering is normally related to wetting and drying cycles that cause crystallisation pressure quite close to the surface. Long periods of saturation increase the mobility of soluble salts however, and once drying does take place, 'hot-spots' of salt deep within stone blocks may arise (McCabe, pers. comm.). This pattern is expected under the increased seasonal extremes projected for Ireland's future climate (McGrath and Lynch, 2008). The chemical action of salt solutions is also of concern, with pH around 8 or 9 potentially causing the dissolution of quartz (McCabe, pers. comm.). This changing pattern of decay represents a major future threat, as chemical dissolution weakens the grain boundaries during prolonged wetting in winter and is followed by crystallisation pressure at depth during the summer (McCabe et al., 2010).

5.2.2. Methodology

The aim of the test walls at Derrygonnelly is to match the meteorological data for the site with internal stone moisture data, something that has not yet been attempted in heritage research (McCabe, pers. comm.).

> *When we started this project we just had this very simple idea that, in terms of climate change, one day Belfast might look like Derrygonnelly and that's why we put a*

building here [to study] what architects are going to have to deal with when there is more rainfall (McCabe, pers. comm.).

The test hut at Derrygonnelly, built in 2009, consists of a corrugated metal hut supporting a weather station and thinly mortared sections of stone wall (Figure 5.2). Three different stones are set into gaps cut in the walls on each side of the hut. The stone is 50cm at its thickest point and includes a projecting ledge to imitate the string course often found in historic buildings (figure 5.3).

Figure 5.2. Test hut at Derrygonnelly, February 2012

Figure 5.3. South-west wall showing 3 types of stone, February 2012

Holes have been drilled on the interior of the walls and moisture probes inserted at 5, 15 and 25 cm from the outer surface. Two types of probes are used: a commercially available capacitance probe and a two pronged resistivity probe developed by Queens (figure 5.4). The Technical aspects of monitoring moisture in stone were a challenge to overcome for the team:

> *It's all very well talking about how what is going on out here [weather conditions] affects what is going on with the stone but actually being able to monitor what is going on in the stone was a real issue for us* (McCabe, pers. comm.).

The group are also in the early stages of developing fibre optic probes for moisture monitoring (Smith et al., 2011).

Figure 5.4. Detail of internal face of stone wall showing two types of embedded moisture sensors, February 2012

Additional monitoring techniques utilised at the test hut include:

- Colorimetry: a colour meter provides early indications of biological growth due to changes in hue and lightness (see section 10.10.4).
- Gas permeability: a gas permeability meter can be used to monitor biological growth and salts on the surface as both will reduce the permeability of the stone pores to a puff of gas.
- Thermal imaging: bedding layers in stone will dry at different rates, and temperature gradients (related to moisture content) can be detected by a thermal camera.
- Protimeter: measures moisture on the surface of the stone.

- Electrical Resistance Tomography: this tool maps moisture with depth, using sensors attached to the stone surface. It provides a snapshot in time of the moisture profile in the wall, not continuous monitoring. The method may stain certain stone types however, and should be tested on an inconspicuous area first (figure 5.5 and 5.6).

In addition to the test walls at Derrygonnelly the project have also constructed a 4-sided exposure experiment in Belfast. This has moisture sensors embedded close to the surface of the stone to measure event related wetting. The Belfast exposure provides complementary data to Derrygonnelly, so that both seasonal responses related to deep wetting and daily responses related to individual events can be studied (McCabe, pers. comm.). Of key interest for the researchers is showing how those two systems (surface and stone interior), relate to one another.

5.2.3. Implementation

Results from the test hut at Derrygonnelly indicate that the best data source for stone moisture content is provided by the internal resistivity probes (McCabe, pers. comm.). After one year of operation two very different environmental systems were notable (McCabe, pers. comm.).

1. The exposed south-west wall is subject to driving rain. Initially moisture was within the outer 5cm of the stone and subject to evaporation, once the 5cm threshold was passed however (the point where evaporation is no longer effective) water quickly penetrated deep into the stone.

2. The north-east wall is sheltered and precipitation never penetrated past the 5cm ‘threshold’ therefore surface evaporation continued to overcome the movement of moisture inward (i.e. no deep wetting event).

Figure 5.5. Staining from electrical resistance tomography, February 2012

In addition to improving our understanding of wetting and drying cycles under given meteorological conditions, these results highlight the importance of localised factors such as aspect and exposure.

We can show relationships between rainfall, temperature and what is going on in the stone but it is much more complex than that…[we] *must also account for the effects of radiation, wind, aspect, position and so on* (McCabe, pers. comm.).

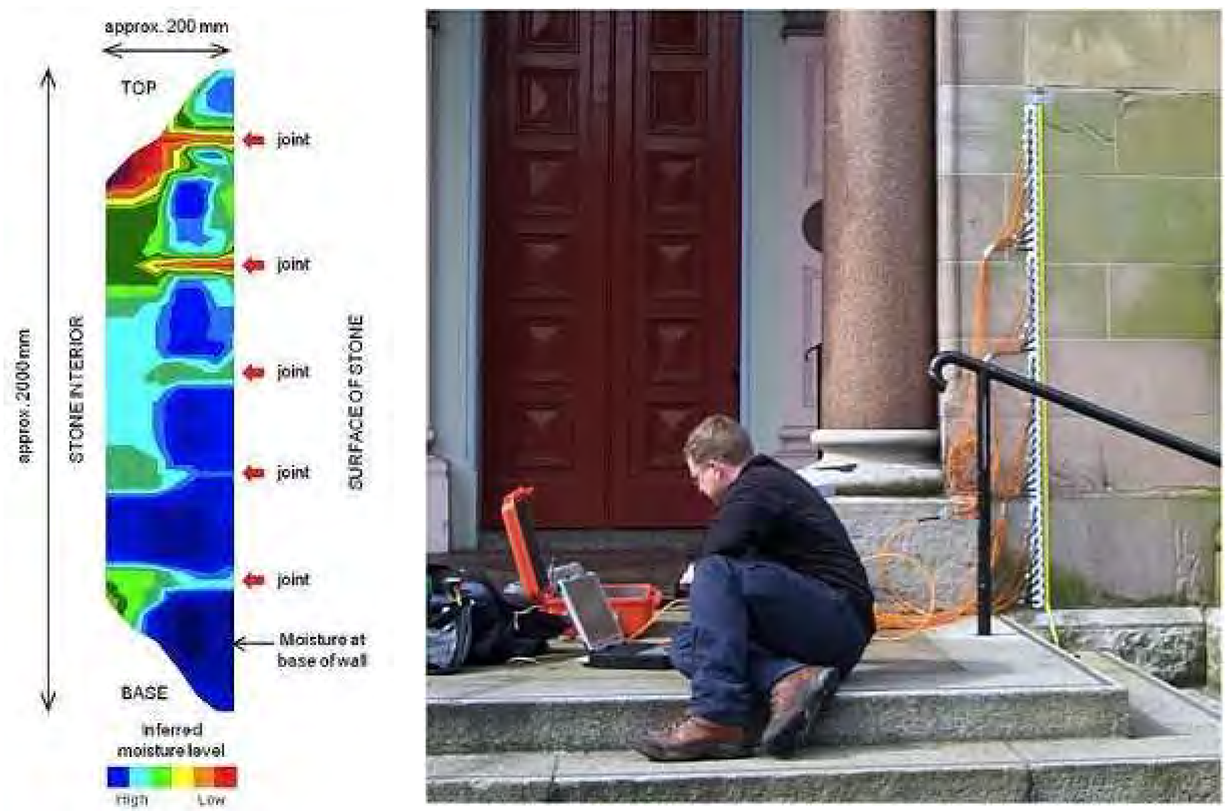

Figure 5.6. Non-destructive 2D electrical resistance tomography (ERT) being used to map moisture distribution within masonry by researchers from the school of Geography, Queens University, Belfast (www.qub.ie/)

5.2.4. Barriers to success

The results from Derrygonnelly have been very promising for our understanding of deep wetting of stone and its likely occurrence under future climate conditions. The team are actively engaged with heritage authorities such as Historic Scotland and also with the Building Research Establishment (BRE) in the UK. Despite this, the future of the test-hut is not secure as funding remains an issue. The research group aim to keep Derrygonnelly going over the long-term and see it as a priority to secure the necessary finance. If possible, they would also like to expand to other locations. The current research grant for Derrygonnelly runs out in 2013 (McCabe, pers. comm.).

> *We are collecting site specific data but with climate change Belfast might one day look like Derrygonnelly, so there is transferability, ideally we would have test walls dotted around the UK and be able to map change…we would need approximately £50,000 for each one which makes it pretty difficult* (McCabe, pers. comm.).

5.2.5. Transferability

Although the resources in terms of finance and expertise mean that the test wall methodology is not easily reproduced, the non-destructive monitoring equipment tested on the stone could be readily transferred to heritage sites. To that end Queens have published a 'non-destructive scientific toolkit' that lays out how these techniques could be used in conjunction with laser scanning (Meneely et al., 2009).

The final results of the project will undoubtedly be of great interest to those caring for stone buildings. This research should allow conservators to predict with greater certainty how future changes in rainfall will affect moisture content and its associated deterioration processes in stone.

5.3. SCAPE ST ANDREWS SCOTLAND

Scottish Coastal Archaeology and the Problem of Erosion (SCAPE) was founded in 2001 to research, conserve and promote Scotland's coastal archaeology (The Scape Trust, 2012). Due to climate change coastal losses are expected to increase substantially in the next century (Kelly and Stack, 2009, National Trust, 2005). Although not established to monitor climate change impacts *per se* this organisation has pioneered several innovative solutions to address the loss of heritage from coastal erosion. The case study data was gathered during a two day stay in St Andrews in April 2012, including an in depth interview with manager Tom Dawson and visits to local sites in danger.

Figure 5.7. Land slip onto the beach below St Andrews Castle, April 2012

5.3.1. Background – coastal erosion

Scotland's inhabited coastline is over 15,000 km long and has a rich diversity of archaeological and historical sites (Dawson, In Press-a). Although coastal erosion has been causally linked with climate change (Lees, 1998, Dawson, 1998) SCAPE have consciously avoided making this connection. In part this is because the debate surrounding climate change science can distract attention from the fact that coastal erosion is an urgent and current problem (figure 5.7) (Dawson, pers. comm.). The long-term nature of climate change also means that many of the sites SCAPE is concerned with may have disappeared before impacts like sea level rise (SLR) take effect (Dawson, pers. comm.).

Figure 5.8. Storm damage to modern pier at Boddin Limekiln, April 2012

Currently the main risks to coastal heritage are from storm surge (figure 5.8) and temporary sea level rise (associated with spring tides, low pressure and high onshore winds) (Dawson, pers. comm.). For example in 2005 fifty metres of the coastal edge of Baile Sear was removed in a single storm. Dawson therefore argues that incremental SLR and coastal erosion are less problematic than damage caused by individual events (Dawson, pers. comm.). The implication of this is that much loss will be episodic in nature and therefore attempts to predict the 'rate of coastal erosion' could be rendered inaccurate by a single event.

Figure 5.9. The warning signs are there, St Andrews, April 2012

5.3.2. Methodology – professional survey and community stewardship

In 1996 Historic Scotland started their Coastal Zone Assessment Surveys (CZAS) of archaeological assets. The surveys combine desk based study and field walking and are carried out by professional archaeologists (Historic Scotland, 1996). As of 2012 approximately 40% of Scotland's coast had been documented (Dawson pers. comm.). SCAPE is responsible for managing the CZAS in Scotland and making the resultant data available. Given limited resources it is unlikely that 100% of Scotland's vulnerable coastline will ever be subject to CZAS. There is also a legitimate argument that it would be more effective to use the limited funds for action on sites already identified as at risk, rather than to continue surveying new areas.

> *The simplest thing to do is to carry on doing surveys, make lists, make management plans, make priorities…but* [if you] *don't actually do anything by the time you get finished the sites on your priority list will be washed away. The leap has to be made and we have to start doing something* (Dawson, pers. comm.).

In 2001 SCAPE took over Shorewatch in conjunction with the Council for Scottish Archaeology (Fraser et al., 1998) (www.shorewatch.co.uk). Shorewatch is an innovative approach to involving volunteer groups with professional archaeologists in the recording and monitoring of coastal archaeology. SCAPE employs professional archaeologists and geomorphologists to undertake CZAS. Shorewatch volunteers are trained, often at the same time, to undertake subsequent monitoring and survey of these areas. The success of this award winning project demonstrates one way that modern coastal communities can play an important role in helping to record and preserve their heritage.

Scotland's Coastal Heritage at Risk is a new project launched by SCAPE in 2012 (http://scharp.co.uk/). This online venture presents the CZAS information in an interactive database using a Geographic Information System (GIS). The website encourages the public to suggest corrections to the surveys, some of which are now twenty years old. The web based database is flexible and easily updated; as such it is the ideal vehicle for managing records on the dynamic coastal environment.

> *We are asking members of the public to go out and look for sites that are near them and then tell us what the condition is like because we know this stuff* [CZAS] *is out of date, this is crowd sourcing, we are asking the public to check all 12,000 sites for us and tell us if they are still there* (Dawson, pers. comm.)

Table 5.1. Definition of vulnerability classes (Dawson, In Press-b)

Vulnerability Class	**Description**
1	Any distance from coast edge, definitely eroding (either coastal or Aeolian erosion)
2	Any distance from coast edge, at risk of erosion (record not specific but possibility that site is vulnerable)
3	Within 10m of coast edge or in dunes – stable, but may erode in future
4	Within 10m of the coast edge or in dunes – stable and unlikely to erode
5	More than 10m from the coast edge and stable

The monuments in the database are graded according to a system devised by Dawson. He combined a study of erosion risk (table 5.1), with an assessment of archaeological value, to create a priority ranking by which sites could be sorted (Dawson, In Press-b). From the original list of 12,000 sites this system prioritised approximately 1,000 monuments identified as being of high to medium risk.

Figure 5.10. SCAPE partnered the Bressay community project to excavate (top) and rebuild (bottom) the eroding Burnt Mound of Cruester, Bressay, Shetland (www.shorewatch.co.uk)

5.3.3. Implementation

The small amount of money available to SCAPE for archaeological projects means that action to preserve and/or record the sites is often not possible. Sites monitored by local Shorewatch groups have been lost without any intervention having been taken, leaving the volunteers feeling disappointed and angry (Dawson, pers. comm.). As a consequence of such negative volunteer experiences SCAPE decided to reduce the focus in Shorewatch on monitoring and concentrate on selecting individual sites for research i.e. excavation, documentation and/or restoration. In these projects professional archaeologists and local volunteers work together. The solutions used include relocation and reconstruction of threatened structures (e.g. Bronze Age Bressay, figure 5.10), preservation by record using laser scanning (e.g. Boddin limekiln, figure 5.11), and excavation in advance of loss (e.g. Brora saltpans) (The Scape Trust, 2012).

Scotland's Coastal Heritage at Risk is designed to run over 3 years (2012–2015) during which time the public will be asked to visit and update records for any of the 12,000 sites in the database. Users can revise the location of a site, alter or add to the text, add comments, or even make a new record if unrelated features are visible (entries will be moderated by SCAPE). The data can be submitted using downloaded survey forms or directly through a Smartphone. SCAPE created a Smartphone App that will direct the user to the site and geo-locate photographs they upload. The app has a multiple choice recording form that both describes the site and asks for information. Intensive surveys or mini-excavations will also be undertaken on a limited number of sites and the public can make nominations for where this work should be done (Dawson, pers. comm.).

Figure 5.11. Boddin Limekiln showing undercutting and collapse due to wave action, Tom Dawson in foreground, April 2012

5.3.4. Barriers to success

Finance is a constant struggle for SCAPE. With funding granted annually Dawson is on what he describes as a hamster wheel, spending much of one year sourcing money for the next. Funding is also an issue for local and national authorities when it comes to making decisions on threatened monuments, as illustrated by Scurdie Ness beacon. The beacon has been partially eroded by wave action, but to repair and defend the original structure would be more than twice the cost of building it anew (figure 5.12).

Figure 5.12. The 1780 Scurdie Ness navigation beacon, April 2012

With limited resources available, the extent to which people value heritage assets will inform management decisions (section 3.1.1. and figure 5.13). Dawson argues that there is currently a lack of clarity on the issue, yet he does not believe that extending the existing system of scheduling (national heritage protection designation) would be an effective response. In addition to the extra burden such a move would place on state agencies, the licensing requirements could also create a barrier to anyone wishing to investigate sites at risk of disappearing without record. There is an added problem in attempting to value archaeological assets as the extent of the resource is often unknown:

…we have archaeological sites that we suspect are really important but we don't know until we dig them…what we are asking people to do is place value on something when we don't actually know what it is that they are valuing (Dawson, pers. comm.)

Figure 5.13. *Ad hoc* attempts to prevent erosion occur at local level regardless of Shoreline Management Plans e.g. the deposition of building rubble and garden waste by owners of Scurdie Ness Lighthouse, April 2012

5.3.5. Transferability

The CZAS system is specifically Scottish but similar coastal surveys have been carried out in England and Wales (Dawson, pers. comm.), providing a snapshot of coastal heritage at the time. The potential usefulness of this baseline information must however be balanced against the costs of surveying an entire coastline. The evidence from Scotland is that the surveys should not be seen as an end in themselves but as a catalyst for decision making in terms of coastal protection or the recording of threatened sites. A gradual shift has occurred in the focus of SCAPE away from working with community groups on survey and monitoring and more to action. Given sufficient resources, SCAPE would like to do this in tandem with further CZAS (Dawson, pers. comm.). This community led approach to management of coastal archaeology is transferable given appropriate resources and sensitive design. SCAPE's supportive style of tailoring solutions to suit individual communities would seem to be central to its success. On the other hand engaging communities in open-ended monitoring with no fixed outcome is likely to be counterproductive.

> *The main failing of Shorewatch was in raising expectations with local groups who think that if they are going out and monitoring sites that we are going to do something, and then we don't* (Dawson, pers. comm.).

Lessons learned from Shorewatch in this respect led SCAPE to the targeted approach taken in *Scotland's Coastal Heritage at Risk.* The lifetime of this project is set at three years and the desired outcomes are clearly defined. If it succeeds in engaging the public in coastal heritage monitoring, the crowd sourcing aspects of this web-project are *hugely transferable* (Dawson, pers. comm.).

5.4. RUNIC INSCRIPTIONS AS CULTURAL AND NATURAL ENVIRONMENTAL INDICATORS SWEDEN

Runic is a Scandinavian script used most prolifically in the Viking Age. Today it survives mostly on carved stones scattered across Sweden, Norway and Denmark but concentrated in the area around Stockholm (National Heritage Board Sweden, 2007, Löfwendahl, 2007). Rune stones are a rich source of information about Viking Age society and language. In most cases the Swedish examples remain outdoors, in or near their original positions (figure 5.14).

Figure 5.14. Rune stones at Kolunda Eskilstuna, May 2012

In the case of runic inscriptions, as with the carvings at Brú na Bóinne, the loss of even a small amount of material can be catastrophic. The rune stone monitoring project is concerned with measuring surface loss as an indicator of environmental factors such as pollution and climate change. The case study data was collected in May 2012 during field work in the vicinity of Nyköping with Helen Simonsson and Laila Kitzler Åhfeldt of the Swedish National Heritage Board.

5.4.1. Background

The Rune Stone project has been revised several times since its inception and the Heritage Board is currently considering whether it can be reconfigured to monitor climate change impacts (Simonsson, pers. comm.). It originated in the 1980s with the "Air pollution and cultural environment" programme which included rune stones in the national indicators for air quality (Simonsson, 2012). In 2005, as part of a multi-agency programme, the Heritage Board once more proposed runic inscriptions as suitable national indicators for the impact of environmental factors on the built environment (Swedish Environmental Protection Agency, 2011). In 2008 the relocation of the Heritage Board and resultant change in personnel caused the project to be abandoned until 2012, when the newly configured Heritage Board began to re-evaluate the use of rune stones as indicators.

5.4.2. Methodology

The rune stone indicator project is currently under review and at the time of the interviews and site visits no methodology had been put in place. Past methods and results are being evaluated by Helen Simonsson, a stone conservator with the Heritage Board (Simonsson, 2012). The Swedish rune stones have a great wealth of historic recording, some of which dates back over 400 years (National Heritage Board Sweden, 2007). In addition the Heritage Board receives annual reports from their network of volunteer ‘rune wardens’ (Simonsson, pers. comm.). Since 1987 systematic documentation of the rune stones to record weathering has been carried out but with varying methods being employed (Simonsson pers. comm.). The aim of the most recent version of the project (2005) was to quantify deterioration by assessing the number of runes that were intact and, by comparing this to past records, to calculate weathering rates (National Heritage Board Sweden, 2007, Löfwendahl, 2007). Documentation included data on the local environment, object condition, climate measurements from local meteorological stations and photographic records.

Figure 5.15. Tent set up over a rune stone for 3D visual scan, Södermanland, May 2012

Figure 5.16. Helen Simonsson (standing) and Laila Kitzler Åhfeldt conducting 3D scanning of a rune stone, Södermanland, May 2012

In the 2012 project plan Simonsson poses several questions which are very pertinent for those considering monitoring climate change impacts (Simonsson, 2012):

1. Have methods already implemented yielded useful information? Simonsson (pers. comm.) commented in interview that the documentation to date yields information on the rate of deterioration but not on the cause.
2. Exactly what parameter is to be monitored; the cause (environment) or the effect (deterioration)?
3. Are specific objects of interest or general patterns?
4. Are specific materials of interest or specific environments?

Since 2011 the Runic Inscription Project has been recording stones with a high resolution 3D visual scanner (figures 5.15 and 5.16). Similar to laser scanning, this produces an extremely accurate copy of the stone surface (Åhfeldt, pers. comm.). The working proposal for the new rune stone indicator project is to enter all of the available information, including historic records and 3D scans, into a publically available database.

Theoretically it should then be possible to create a time line for each stone in the database, to understand what events have impacted upon its condition. Statistical analysis of patterns within the dataset, relating to specific environmental or climatic parameters, should also be possible (Simonsson, pers. comm.). Some stones have been moved during their history however, the surrounding vegetation may have changed and many of the events affecting their current condition will not have been recorded. Given the many unknown and inter-related variables, isolating the effect of any single environmental parameter is therefore improbable. This refers to the problem raised by the questionnaire analysis (section 4.5.), namely how can the effects of climate change be distinguished from the many other variables that contribute to deterioration?

5.4.3. Implementation

Results from previous monitoring of the rune stones suggests that between 1987 and 2006 12% of inscriptions were lost (Simonsson, 2012). In 2001 a Heritage Board report concluded over time stones reach a 'tipping point' from where degradation accelerates rapidly (Löfwendahl et al., 2001). Although it could be expected that sandstone and limestone would reach this point faster than granite, the study unexpectedly found that the gneiss[1] showed the greatest material loss (Figure 5.17). The authors suggested that this may have been due to careless handling but this finding was reviewed in 2007 and the cause was re-attributed to inappropriate cleaning methods (Simonsson, pers. comm.). This example demonstrates the difficulty conservators have determining the cause of historic damage, and also the value of systematic documentation and monitoring.

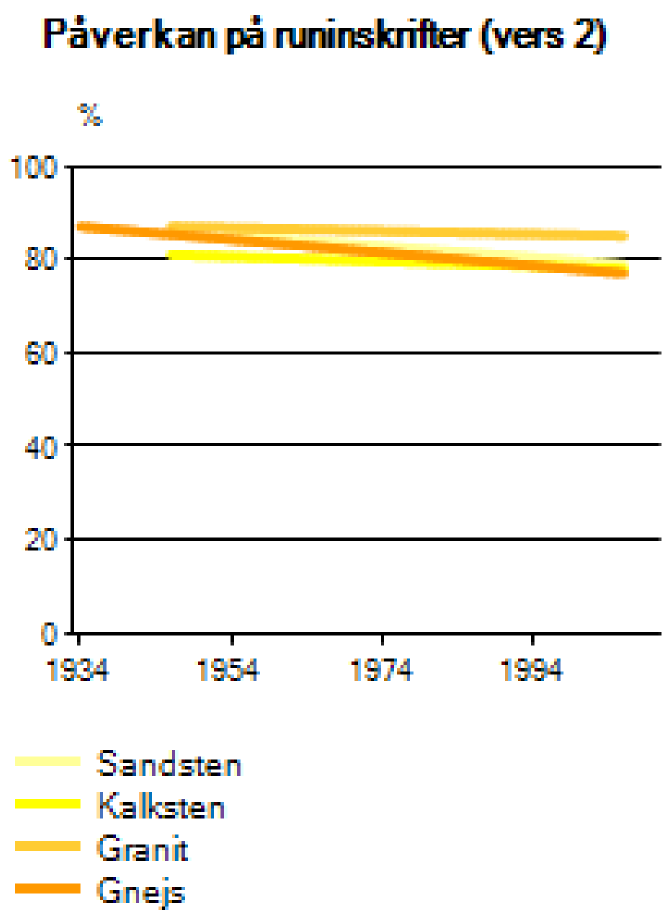

Figure 5.17. The proportion of intact runes from 1934–2009 divided by material (sandstone, limestone, granite and gneiss) (www.miljomal.se/)

[1] Gneiss is a metamorphic rock, it is generally considered very durable, for example it is the stone used to pave footpaths in Turin Italy.

In 2011, and again in 2012, 3D visual scanning of selected rune stones was conducted in the field (figure 5.18). Two researchers using this method over a period of two weeks are able to scan between 15 and 20 objects. The post field processing of the data and statistical analysis is generally the most time consuming part of this type of recording and requires specialist knowledge (Åhfeldt, pers. comm.).

Figure 5.18. 3D scanning in progress; reference point stickers are placed on the stone to enable the software to knit individual sections together (Daly 2012).

5.4.4. Barriers to success

The documentation of runic inscriptions in relation to the study of environmental parameters was initially conceived of in the 1980s and during the following 30 years efforts to systematically record the stones have been abandoned and revisited several times. The political interest in environmental indicators switched from pollution to climate change, funding streams altered, staff members left and the Heritage Board itself was relocated and restructured. The history of the project highlights the difficulty of sustaining research over the long-term, namely that continuity of all the necessary elements (interest, finance, expertise) is rarely possible.

There are also significant difficulties with choosing and interpreting indicators (Adger et al., 2004) and these are well illustrated by this project.

> *There is a clear conflict or contradiction between the desire to have a monitoring and evaluation process that is concrete and easy to grasp and to communicate to politicians and the public and the desire to have an evaluation that covers several aspects of the environmental process* (Anna Larsson quoted in Simonsson 2012).

The unexpected result regarding gneiss rune stones illustrated the difficulties extrapolating causal links from observed damage. In her evaluation of the project Simonsson writes that this is *an example of the risk of using unrepresentative or too small a sample size* (Simonsson, 2012). Using aged samples with an unknown history, such as the rune stones, adds to the uncertainties that are already involved in interpreting indicators. It is hoped the Legacy Indicator Tool (LegIT) developed within this research project will go some way to solving these issues (section 10.3).

5.4.5. Transferability

The concept of using the rune stones as indicators for climate change is still being developed and it is therefore too early to assess transferability. The tools used such as 3D scanning and condition assessment are easily transferable however, given the appropriate skills and equipment. Laser scanning is increasingly common as an imaging technology, for example researchers at DIT are developing new modelling applications in built heritage recording (Dore & Murphy, 2012). English Heritage have recently published advice and guidance on the application of laser technology (English Heritage, 2012) and at Brú na Bóinne the Discovery Programme have already scanned an orthostat at Knowth (Shaw, 2012). Expertise in continuous monitoring using 3D laser scanning is also growing and the potential of this method has been demonstrated on New College Oxford (Meneely et al., 2008) .

The problems that the rune stone project has encountered reflect many of the key issues for research in this area, i.e. the sustainability of long-term studies, the question of what to monitor and the challenge of attempting to link observed data to climate change. At the heart of the current redesign of the project there remains a fundamental question, namely *how can causal relationships be reliably made between observed damage and climate change?* (Simonsson, pers. comm.). This theme was raised by expert respondents (chapter 4) and a possible solution borrowed from ecology will be proposed in a later section (9.2.5.).

5.5. ARCHAEOLOGICAL DEPOSITS IN A CHANGING CLIMATE: IN SITU PRESERVATION OF FARM MOUNDS IN NORTHERN NORWAY

The Norwegian Institute for Cultural Heritage Research (NIKU) in Oslo have recently established a research project entitled ‘Archaeological Deposits in a Changing Climate; In Situ Preservation of Farm Mounds in Northern Norway’ or ‘In Situ Farms’ for short. During October 2012 the researcher on this project, Vibeke Vandrup Martens, was interviewed in Oslo.

Figure 5.19. Medieval cemetery beside church of St. Mary in Oslo. Monitoring point marked by manhole cover under which data-logger is housed, October 2012

5.5.1. Background

Farm mounds are settlement sites where human activity over a few thousand years has resulted in the build up of deposits several metres thick (NIKU, 2012). The preservation of archaeological materials is often excellent and the mounds are a rich source of knowledge about the rural economy and society in Norway. The plan for the 'In Situ Farms' project is to combine archaeological assessment and environmental monitoring with climate modelling to predict how climate change will affect the *in situ* preservation of archaeological deposits (Martens, 2012a). At present in Norway a number of urban deposits in Oslo, Bergen and Trondheim are being monitored (Martens, 2012b, Matthiesen, 2008, Petersen and Bergersen, 2012) the new study will extend this research to rural areas (Martens, pers. comm.) (figures 5.19 and 5.20).

Figure 5.20. Location of auger holes where monitoring probes are to be inserted, Vestre Strete, Oslo. Vibeke Vandrup Martens in background at Medieval street level with reconstructed Medieval house outlines, October 2012

5.5.2. Methodology

Monitoring conditions in the burial environment is a requirement in Norway prior to, after, and during any works that may disturb archaeological deposits (Norwegian Directorate for Cultural Heritage, 2012). Should alarming results be shown by the monitors, secondary testing would be conducted to confirm the findings and then NIKU would recommend a course of remedial action to the Directorate (Norwegian Directorate for Cultural Heritage, 2012). Currently NIKU has two strategic research projects dealing with in situ monitoring:

- In Situ Preservation of Archaeological Remains in the Unsaturated Zone
- In Situ Farms

Both are concerned with characterizing the unsaturated zone where the majority of archaeological deposits are found, and where water and oxygen content fluctuates (Martens, 2010).

Over four years (January 2012 – December 2015) the In Situ Farms project aims to:

1. Monitor the burial environment at selected sites.
2. Combine this with data from nearby meteorological stations to characterize climate influences on subsoil conditions.
3. Use the above research to generate computer simulations of burial conditions under future climate scenarios.

By characterizing the deposits and simulating their responses to environmental factors the project aims *to provide the archaeologists at the County Councils and the archaeological museums with new knowledge and methods on how to sustainably manage these very important cultural heritage sites* (Martens, 2012a).

The Norwegian Standard NS 9451:2009 outlines how archaeological deposits should be assessed and monitored for both 'current state' of preservation and 'preservation conditions' (Norwegian Directorate for Cultural Heritage, 2012). *Parameters that provide information on the speed at which archaeological materials are decomposing and on the extent to which oxygen has reached the cultural deposits* should be examined (Norwegian Directorate for Cultural Heritage, 2012: 20) (table 5.2). The assessment is multi-disciplinary involving paleobotanists, geophysicists geochemists, and archaeologists (Martens, pers. comm.). Field monitoring is conducted by taking samples and inserting probes into the soil in section (figure 5.21) or auger holes or into dip-wells. Above ground monitoring of subsidence using periodic surveying of fixed stations is also required under the Standard (Norwegian Directorate for Cultural Heritage, 2012).

Table 5.2. Methods for assessing preservation conditions; Norwegian Standard NS 9451:2009 (Norwegian Directorate for Cultural Heritage, 2012)

Measuring in water	**Measuring in soil**
Field Work	Field Work
Temperature	Temperature
pH/acidity	pH/acidity
Oxygen levels	Humidity/ soil moisture content
Conductivity	Conductivity
Lab work	Lab work
Sodium, potassium, calcium, magnesium, ammonium, iron, manganese, chloride, sulphate, sulphide, pH, conductivity, redox evaluation.	Dry matter content, loss on ignition, pH, conductivity, matrix potential (pF), porosity, sulphate/sulphide, iron II/iron III, ammonium/nitrate, redox evaluation.

NIKU are collaborating with Jørgen Hollesen from the National Museum in Copenhagen who has been instrumental in the development of simulation software for Qajaa in Greenland (Martens, pers. comm.). The one dimensional CoupModel, 'coupled heat transfer model for soil-plant-atmosphere systems', was used for Qajaa (Hollesen, pers. comm.). The computer model simulates heat and water flow for different atmospheric and soil conditions. It has been used to describe and predict the influence of climate changes on soil conditions including the varying effect on different layers of stratigraphy (Hollesen et al., 2010).

Figure 5.21. Installing monitoring equipment at Åker gård, Hamar, Hedmark; probes measuring soil temperature and water content (Martens 2007) working in section allows exact placement of probes within the stratigraphy

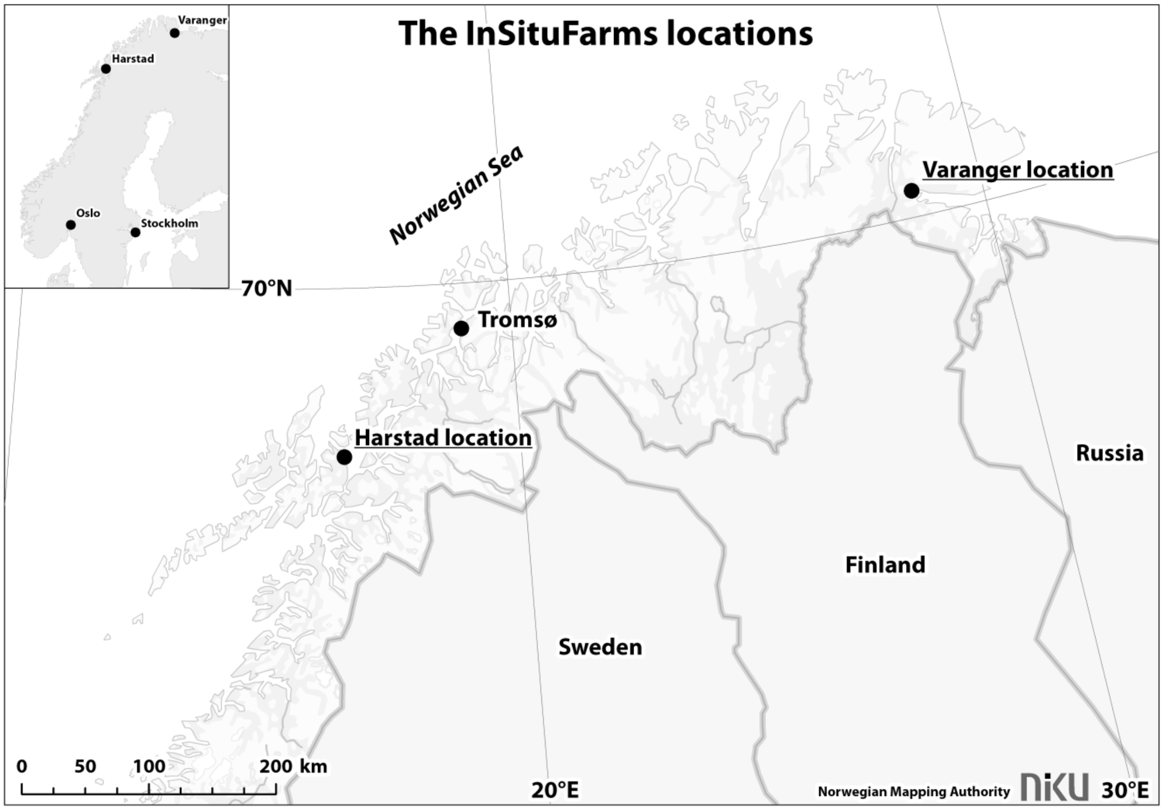

Figure 5.22. Map showing location of Bankgohppi (Varanger) and Saurbekken (Harstad) sites (courtesy of Troels Petersen, NIKU)

5.5.3. Implementation

The chosen case study sites are Saurbekken in Harstad town, Troms County and Bankgohppi in Karlabotn, Finnmark County, both in the far North of Norway (figure 5.22). In order to minimise disturbance to the archaeology, and to reduce costs, the project aims to co-ordinate installation of monitors with other excavations. Unfortunately this means the project has little control over scheduling. For example, installation at Saurbekken was initially planned to co-ordinate with road works but after a year of construction delays an alternative point for installation of monitoring equipment was made (Martens, pers. comm.). The mound at Saurbekken has been recorded in 3D (ground laser scanning) and surveyed with geo-radar (figure 5.23). It is planned to repeat the laser-scan in 3 years to see if any change has occurred. The concern is that altered drainage patterns due to the road improvements may cause loss of organic material, leading to collapse.

The second case study, Bankgohppi, is a Stone Age research excavation. Although not a farm mound, this permafrost site was chosen as it has excellent organic preservation in the unsaturated levels, and is in a rural location unaffected by development. At the time of writing field work had not yet commenced on this case study.

Figure 5.23. 3D laser scanning of Saurbekken farm mound, Troms (Martens 2012)

5.5.4. Barriers to success

Martens cites continuity of personnel, funding and research interest as the main barriers to creating long-term monitoring projects for the burial environment (Martens, pers. comm.).

For example in Åker gård where monitors were installed in 2007 when the member of staff responsible left, and was not replaced, there was no-one on site to collect data (Martens, pers. comm.). The equipment continues to function and the data is currently downloaded by a NIKU employee who lives close to the site; this means the project is now reliant on one individual's goodwill. In another example in Nedre Langgate in Tønsberg dip-wells were being monitored for almost 10 years (1998–2007) but when the datalogger stopped working it was not replaced. In this case research priorities had changed in the intervening period and the funds were diverted towards other sites as a result (Martens, pers. comm.).

5.5.5. Transferability

Environmental monitoring of deposits is a useful tool for assessing preservation conditions and in tracking how these may be changing. The results are only effective however if they feed into appropriate management actions. The concept behind monitoring *in situ* is that if burial conditions worsen dramatically then an excavation can be carried out to prevent loss of the resource (i.e. preservation by record). The Norwegian Standard NS9451:2009 states that heritage management authorities *can require preventative actions to be undertaken in order to protect the cultural deposits* (Norwegian Directorate for Cultural Heritage, 2012: 5). Despite this statement it may be difficult to convince the state to rip up a new road or order a developer to tear down a building because archaeological deposits beneath them are no longer stable (Martens, 2011). The challenges for the future are in meeting the costs of ongoing monitoring and reacting effectively should conditions deteriorate (Martens, pers. comm.).

5.6. CONCLUSIONS

The aim of conducting the exemplar project field work was to establish a perspective on 'smart' international practice by investigating different approaches to monitoring climate change impacts on archaeological heritage. The fact that most of the projects were newly established at the time of investigation in 2012 reflects the reality that this arena of research is still in its infancy. Findings relevant to the current study are summarised below.

5.6.1. Future Climate Change; the Nature and Scale of Impact upon Masonry

Queens University Belfast

- ❖ This project concerns short-term high-tech monitoring of stone moisture content and atmospheric climate.
  - ➢ Aims to correlate short-term monitoring data with climate projections in order to predict future trends for masonry buildings.
    - ▪ Will provide proven correlations between stone conditions and climate fluctuations.
      - • Supports interpretation of LegIT (chapter 10).
    - ▪ Proven that localised issues of aspect may be more influential than regional climate.
      - • Illustrates importance of site specific assessment of exposure (section 6.7.2.).
    - ▪ Demonstrates variety of monitoring techniques and the use of specific non-destructive tools suitable for monitoring built heritage.
    - ▪ Finance is problematic.

5.6.2. SCAPE

- The SCAPE Trust Scotland is conducting long-term qualitative monitoring of national coastal assets.
  - Aims to protect and record heritage at risk from coastal erosion
    - Demonstrates the value of community stewardship and crowd sourcing in the monitoring of heritage.
    - Illustrates that monitoring alone, unsupported by appropriate remedial action, is unsustainable (section 4.6.).
    - Considers climate change as an added stressor in the long-term, but not material to the current losses from erosion.
      - Has found the debate surrounding climate change distracts public attention from the immediacy of the problem (section 4.13).
    - Finance is problematic.

5.6.3. Runic Inscriptions as Cultural and Natural Environmental Indicators

- The Swedish National Heritage Board is conducting long-term monitoring of rune stone degradation.
  - Aim to calculate rates of stone weathering and use this as an indicator of environmental change.
    - Considers the potential of stone as an indicator for climate change.
      - Closely related to concept of LegIT.
    - Demonstrates the problems involved in sustaining long-term monitoring on a national scale.

            - Identifies need to carefully consider the aim and outcome before designing a monitoring scheme if it is to be useful and sustainable (sections 10.3 and 10.9).
        - Considers the problem of interpreting cause from observed effects (sections 4.5. and 9.2.5.).
        - Demonstrates the use of 3D scanning to record objects *in situ*.

5.6.4. In Situ Farms

- ❖ The Norwegian Institute for Cultural Heritage Research is conducting short-term monitoring of rural burial environments and atmospheric climate.
    - ➢ Aims to use this data to simulate future burial preservation under climate change scenarios.
        - Will provide proven correlations between burial conditions and climate fluctuations.
            - Evidence for future evaluations of the sensitivity to climate change of buried archaeology (section 6.7.1.).
        - Demonstrates *in situ* monitoring techniques and tools (e.g. Norwegian Standard).
        - Illustrates the combination of short-term monitoring with computer simulation tools to predict long-term conditions.
            - Provides an alternative solution to the problems of sustaining long-term monitoring (section 4.9.).

Many of the issues raised by the exemplar project field work reflected findings from the literature review and questionnaire analysis. The information gathered in this chapter demonstrated different practical solutions to the issue of climate change monitoring. The direct implications from the field visits were:

1. Localised/site specific factors are extremely significant in determining the patterns of climate change impacts (section 5.2.3.).
2. Monitoring schemes must be designed with clear objectives; the ultimate aim being to feed into management action (section 5.3.3. and 5.5.5.).
3. Indicators for both cause (environmental parameter) and effect (deterioration impacts) are likely to be relevant (section 5.4.2.).
4. There are recognised and as yet unresolved problems in establishing causality and sustainable long-term monitoring (section 5.4.3., 5.4.4. and 5.5.4.).

The findings from the field work influenced the development of a 'smart practice' assessment framework and indicator based monitoring detailed in the following chapters.

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CHAPTER 6.

VULNERABILITY ANALYSIS, THEORY AND DEVELOPMENT

Although it is conceptually quite simple to envisage the impact of climate change on individual processes, the difficulty comes in trying to weigh up the importance of different impacts (Viles, 2002 410).

6.1. INTRODUCTION

The literature review (section 3.5.) illustrated that the impacts of climate change on heritage values are dynamic and complex (figure 6.1). Assessing these factors therefore requires a multi-facetted approach capable of addressing the many variables and uncertainties involved. It will be argued in this chapter that 'vulnerability analysis' answers these requirements. An exploration of the theoretical development of vulnerability analysis and of the methods documented in the literature will be carried out. The methodology chosen and its adaptation to the current purpose will then be detailed. The ultimate aim in carrying out the assessment is to enable the development of appropriate and effective management responses (i.e. adaptation and mitigation).

6.2. VULNERABILITY and CLIMATE CHANGE

The use of vulnerability analysis to assess climate change impacts came to the fore in 1992 when the Coastal Zone Management Subgroup of the Intergovernmental Panel on Climate Change (IPCC) published its methodology for vulnerability assessment of coastal regions to

Sea Level Rise (SLR). The perceived success of the methodology prompted the IPCC to adopt the same approach for non-coastal sectors (Hinkel and Klein, 2006). Assessing *vulnerabilities* to climate change, as opposed to carrying out risk analysis, has become a common approach in many sectors (e.g. economy, ecology) since the IPCC issued its Third Assessment Report (TAR) (Hinkel, 2011, Adger, 2006, The Allen Consulting Group, 2005). The TAR report recommends vulnerability assessment as a precursor to developing adaptation responses to climate change impacts.

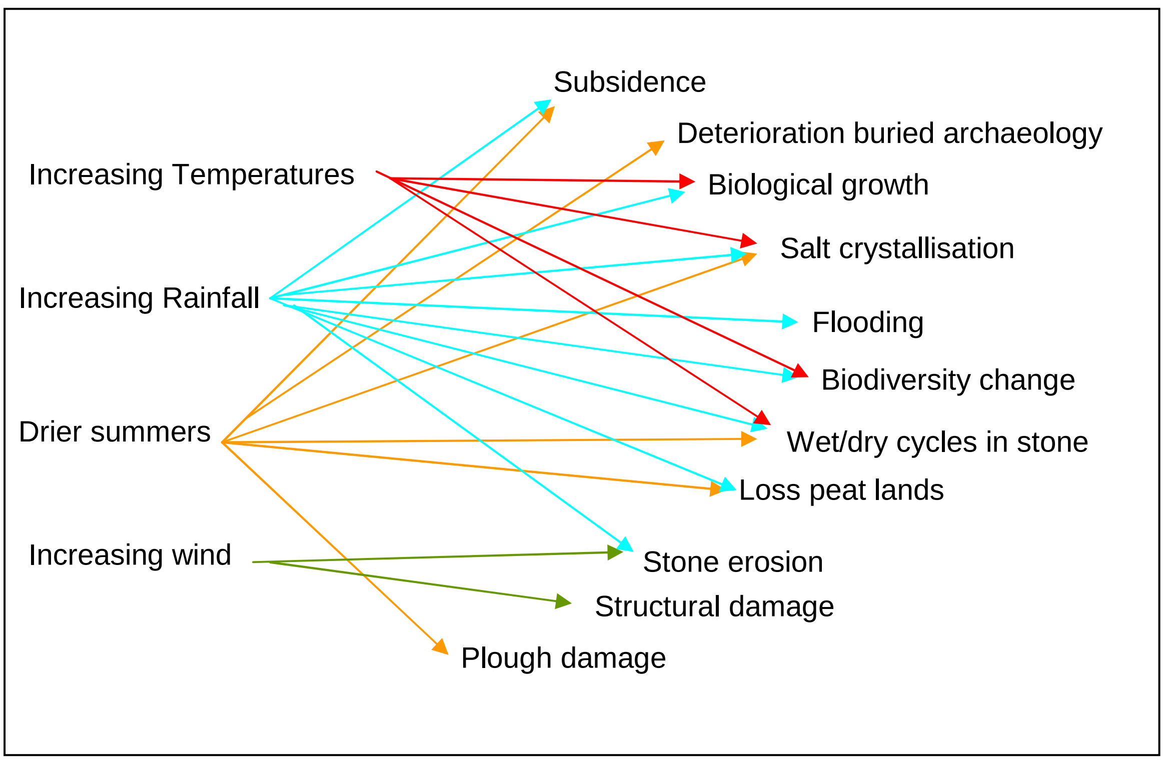


Figure 6.1. Multiple interactions: Climate change factors and impacts (Daly et al., 2010)

The TAR definition of vulnerability is widely referred to in the literature (Adger et al., 2004, The Allen Consulting Group, 2005, Hinkel and Klein, 2006, Ford and Smit, 2004). It defines vulnerability as:

> *The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity* (McCarthy et al., 2001: Annex B).

While this definition states that vulnerability is a function of exposure, sensitivity and adaptive capacity it has been criticised for failing to explain this relationship or to give direction to those seeking to apply the theory into practice (Adger et al., 2004, Hinkel and Klein, 2006). The result of this lack of clarity is that while the terminology is common across studies (i.e. exposure, sensitivity and adaptive capacity), methods of analysis can vary quite substantially.

Despite the ambiguity in the IPCC definitions, vulnerability assessments are increasingly being used as a precursor to framing policy and adaptation for climate change (Hinkel, 2011). Given the lack of guidance in the theoretical definitions, methodologies have instead developed based on the individual case being considered and are increasingly complex, multi-disciplinary analyses (Hinkel and Klein, 2006). The terminology should reflect this development in practice, and some authors have suggested the need to move away from the 'one size fits all' approach when framing definitions (Hinkel, 2011, Hinkel and Klein, 2006).

6.3. CONCEPTUAL DEVELOPMENT OF VULNERABILITY ANALYSIS

As a growing field with multi-disciplinary origins it is not surprising that there are a variety of approaches described as vulnerability assessment. Currently formulations stem from the needs of each individual case and there is no single recognized way of analysing cause and effect within socio-ecological systems (Adger, 2006). The multiple concepts and applications published in the literature can be confusing for an individual attempting to conduct an assessment.

Ford and Smit concluded from their literature survey that there were two basic approaches to vulnerability: biophysical and social (Ford and Smit, 2004). In the **biophysical** approach vulnerability is conceptualised as a pre-existing condition determined by exposure and sensitivity to hazard, it is similar to risk but differs in the absence of probability as a function (Adger et al., 2004). In the **social** approach vulnerability is dependent on the social, political and economic determinants that control resistance and recovery i.e. adaptive capacity. Adger argues that the IPCC definition fails to resolve the issue of whether vulnerability is social or biophysical (Adger et al., 2004). A growing number of researchers combine the social and biophysical however, and that is the approach favoured for the case study analyses in chapters 7 and 8 (Turner et al., 2003b).

Reviewing the conceptual literature Hinkel identified six purposes for which vulnerability assessment and indicators have been implemented (Hinkel, 2011). Out of these, he found only one that demonstrated what he considered an appropriate application of vulnerability assessment. That is, to identify vulnerabilities at a local or narrowly defined system level where deductive arguments could be used to select indicating variables and inductive arguments to assess and evaluate them (Hinkel, 2011). This is essentially a case study approach, as proposed in this thesis (section 2.3.1.). For large scale assessments Hinkel suggests that simulation models would be a better approach. This argument is borne out to some extent by the successful application of modelling and computer simulation in large regional studies such as Noah's Ark and Climate for Culture (CfC) (section 3.4.).

Stakeholder experience and perception is central to the vulnerability assessment concept i.e. quantitative measures complementing stakeholder-led or qualitative assessments of vulnerability in context (Adger, 2006). Schröter argues that the success of any vulnerability analysis must be measured not purely on its scientific merit but also on the usefulness of the end product to stakeholders. The ultimate goal being to inform the decision makers about options for adapting to the effects of global change (Schröter et al., 2005). It is perhaps for this reason that case-studies predominate in the field although other techniques such as historical narratives, contextual analysis and statistical analysis are sometimes used (Moss et al., 2001).

6.4. COMPARISON BETWEEN PLACES

Decision makers are often interested in how vulnerability of sectors or regions compare, in order to prioritise the allocation of resources (Hinkel and Klein, 2006). Accounting for the very specific localised factors that influence vulnerability yet still accommodating cross-comparisons is a problem struggled with in the literature (Adger, 2006). Attempts to quantify vulnerability by creating mathematical formulas allow for comparative assessments but cannot account for the local socio-ecological or cultural factors (Hinkel and Klein, 2006).

The Tyndall Centre for Climate Change in the UK examined the possibility of producing diagnostic indicators that could be compared between countries. The variables allowed assessment of vulnerability in human populations and the calculation of a global vulnerability index (Adger et al., 2004). Indicators can aid comparative analysis but should never be used in isolation however (section 9.2.4.). For example, human resources are intrinsic to the adaptive capacity of heritage sites, thus a comparative indicator could be the number of employees. In some institutions however, the availability of trained volunteers greatly increases adaptive capacity and this would not be quantified by the indicator.

The aim of this thesis is primarily to analyse vulnerability at individual site level but it would be helpful for decision makers if results could be compared between places. The methodology chosen will therefore be applied to two disparate case study sites to illustrate how this may be possible.

6.5. VULNERABILITY WITHIN A SYSTEM

Vulnerability analysis entails a holistic approach examining 'whole systems' in terms of the complex interactions that take place and their capacity to adapt. This multi-dimensionality allows the role of social, political and economic structures to be taken into account. While risk assessments concentrate on the 'multiple effects of a single stress' and food security studies on the 'multiple causes of a single effect', vulnerability attempts to analyse the entire system (Schröter et al., 2005). Recognizing that humans and the environment are inextricably linked, analysts assess this 'coupled human-environment system' in their calculation of vulnerability. The concept of the social-ecological system is that human action and social structures are integral to the environment so that any distinction between social and natural systems is arbitrary (Adger, 2006). This approach is therefore appropriate within the overarching constructionist philosophy of this research (section 2.2.).

Vulnerability deals with complex systems and some ‘simplifying assumptions’ are necessary in practice. This can leave analyses open to criticism of being reductionist and arbitrary. For this reason transparency and testing as well as regular review are essential i.e. *the process of thinking about the problem* [must be] *iterative, participatory and ongoing* (Adger et al., 2004: 23). Verification of vulnerability assessment findings can be made by comparison with other relevant studies or by consensus among stakeholders that the results are plausible (Adger et al., 2004). In this research project stakeholder review was selected to refine and verify the results of the case study assessments (section 2.6.2.).

6.6. VULNERABILTY OR RISK ANALYSIS?

Risk can be defined as *the combination of the probability of a consequence and its magnitude* (Willows and Connell, 2003: 43). Following the identification of the risks, a ranking system is created based on probability and consequence values. This entails agreement on the criteria used to prioritise dangers however, and determination of acceptable risk is often political:

> *…values and uncertainties are an integral part of every acceptable-risk problem. As a result, there are no value-free processes for choosing between risky alternatives* (Douglas and Wildavsky, 1982: 4).

This argument, that there are no objective methods to assess risk (as even the quantitative statistical models rely on data which is value laden), fits the constructionist perspective of this thesis. Risk assessment requires knowledge about the future and consent on what is 'acceptable loss'. In terms of the current enquiry this highlights the difficulty of assessing risk when our knowledge about climate change in the future is uncertain and consent on how to react is contested (Daly, 2008). The advantage of the vulnerability approach over traditional risk analysis is that it does not rely solely on an evaluation of exposure and sensitivity to hazards, but also on the internal ability of a system to adapt and recover i.e. its ability to be sustainable (Turner et al., 2003a, Luers et al., 2003).

6.7. TERMINOLOGY – THE THREE ELEMENTS OF VULNERABILITY

> *The one size fits all label 'vulnerability' is not suitable, because it disguises the wealth of different types of problems addressed and methods applied* (Hinkel, 2011: 206).

The three elements of vulnerability are sensitivity, exposure and adaptive capacity. An important part of the current undertaking is to clarify how these general terms can be interpreted in relation to cultural heritage. To do this, existing terms and definitions have been adapted by describing them specifically in relation to heritage systems. The terminology and theory in relation to indicator variables will be discussed in chapter nine.

6.7.1. Sensitivity

The IPCC Third Assessment Report (TAR) defines sensitivity as follows:

> *Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct or indirect* (McCarthy et al., 2001: Annex B).

In terms of cultural heritage the sensitivity we are concerned with is that of the identified heritage values. In practical terms this can be estimated on one or more of three nested scales:

- Individual artefact
- Structure or assemblage
- System

These three headings correspond with the UNDP approach for measuring adaptive capacity and thus provide a tested framework for looking at the elements of vulnerability (GEF Global Support Programme, 2005). The three levels may be understood as follows:

1. <u>Artefact:</u> Micro level effects, largely dependent on material properties e.g. the sensitivity of stone to biological colonisation.
2. <u>Assemblage/structure</u>: Effects on built heritage or archaeological assemblages (e.g. shipwreck, burial) assessed mainly on the basis of physical condition or integrity e.g. the sensitivity of structures to wind damage.
3. <u>System:</u> Comprehensive assessment of effects within the wider system, including environmental or organisational fragility e.g. the sensitivity of waterlogged burial environments to changes in precipitation.

By combining the IPCC definition with experience of heritage assessments the following definition for the sensitivity of cultural heritage to climate change is proposed:

> ***Sensitivity is the degree to which an identified heritage value is affected, either adversely or beneficially, by [climate-related] stimuli. The effect may occur at artefact, assemblage or system level.***

6.7.2. Exposure

The IPCC definition of exposure speaks only of climatic variations and not other changes in the environmental system brought about by climate effects (The Allen Consulting Group, 2005):

> *The nature and degree to which a system is exposed to significant climatic variations* (McCarthy et al., 2001: Annex B)

If we again consider the three different scales (used here in reverse order):

1. System: Exposure will be determined by atmospheric variables and influenced by geography e.g. coastal or inland. Probable future conditions of exposure under climate change are given by downscaled model projections.
2. Assemblage/structure: At the level of built heritage issues such as topography and surrounding environment will moderate exposure to atmospheric climate.
3. Artefact: At this level issues of aspect potentially have a greater influence on exposure than atmospheric conditions (section 5.2.3.).

Thus the following working definition is constructed for the exposure of cultural heritage to climate change:

> ***Exposure is the degree to which an identified heritage value is exposed to climatic variations and their related impacts. It is determined by environmental conditions (physical and atmospheric).***

6.7.3. Adaptive Capacity

Adaptation is defined by Adger as *adjustments in a system's behaviour and characteristics that enhance its ability to cope with external stress* (Adger et al., 2004 34). Unlike exposure and sensitivity, this is not an inherent quality of the system and deliberate efforts to increase the capacity to cope with (or avoid) the impacts of climate change are possible (The Allen Consulting Group, 2005). The IPCC defines adaptive capacity as:

> *The ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences* (McCarthy et al., 2001: Annex B).

This applies for any system and does not need to be reworded for the current application. The United Nations Development Programme names four strategic areas where adaptive capacity should be analysed and these were adopted for use in the case study assessments (sections 7.3.4. and 8.3.4.) (GEF Global Support Programme, 2005):

- Information and knowledge
- Policies and programmes
- Implementation

- Monitoring/feedback

6.7.4. Vulnerability

The IPCC definition of vulnerability (section 6.2.) (McCarthy et al., 2001: Annex B) was altered based on concerns and needs identified by research for this thesis. The following definition is proposed for the vulnerability of cultural heritage to climate change:

> ***Vulnerability is the degree to which an identified cultural heritage value is susceptible to, or will be adversely affected by, effects of climate change, including climate variability and extremes. Vulnerability (V) is a function of exposure (E), sensitivity (S), and adaptive capacity (AC) as represented by the equation MV = (E + S) – AC.***[1]

6.8. THE EIGHT STEP METHOD

Amongst those involved in research into vulnerability assessments are the Environmental Vulnerability Assessment (EVA) group at the Potsdam Institute for Climate Impact Research and the Research and Assessment Systems for Sustainability Program (RASSP) at Harvard University. Scientists from these two Institutions developed an eight step method to guide vulnerability assessments. The method was published in 2005 by Schröter, Polsky and Patt and was recommended by the UNESCO report on strategies for managing climate change (Colette, 2007). Unlike some vulnerability techniques, this is a 'place-based' approach, designed for specific stakeholders. One advantage of this is the potential it allows for public and collaborative professional involvement (Turner et al., 2003a).

[1] Where MV is the measure of vulnerability.

Luers criticises the approach suggesting that it is not possible to quantify the vulnerability of a place, and that focus should be on selected variables and sets of stresses as they are easily translatable to other locations (Luers et al., 2003). The problem with the Luers approach is in its mathematical method. It requires quantification of variables such as sensitivity and threshold damage which are not objectively quantifiable in relation to heritage values.

Based on workshop discussions amongst researchers in the field, Schröter first proposed five criteria which a successful vulnerability assessment should fulfil. The following list has been adapted from the published article (Schröter et al., 2005).

1. *The knowledge base engaged for analysis should be varied and flexible.* This entails collaboration with stakeholders and local knowledge holders as well as experts.
2. *Assessments should be place-based with an awareness of the nesting of scales* i.e. carried out at a local scale but referencing regional or international issues where relevant.
3. *The global change drivers examined should be multiple and interacting.* Recognizing the complex nature of interactions within a system is central to this type of analysis. Non-climatic factors such as socio-economic developments and land use changes should be considered alongside atmospheric conditions.
4. *Vulnerability assessment should allow for differential adaptive capacity.* This differential is largely in the human part of the coupled system due to resources, political barriers, social barriers and so on.
5. *The information should be both prospective and historical* with a balance between past experience and future projections.

In order to satisfy these five criteria the authors go on to propose an eight step methodological framework for conducting vulnerability assessments (Schröter et al., 2005):

1. *Define the study area together with stakeholders (spatial and temporal)*
2. *Get to know the place over time*
3. *Form a hypothesis on who is vulnerable to what.*
4. *Develop a causal model of vulnerability*
5. *Find indicators for the elements of vulnerability*
6. *Operationalize*[2] *model of vulnerability* (i.e. apply the model and validate the results)
7. *Project future vulnerability*
8. *Communicate vulnerability creatively*

Despite UNESCO's recommendation the only application of this eight step vulnerability framework to cultural heritage to date, aside from research by this author, has been in an unpublished Master's thesis from University College London (Woodside, 2006, Daly et al., 2010, Daly, 2008).

6.9. VULNERABILITY ASSESSMENT IN PRACTISE

Primary research indicated that the use of clearly defined 'Vulnerability' methods is not common in the heritage field, and that assessments tend to fall into one of three categories: monitoring and simulation, risk mapping or stakeholder assessment (section 4.3.). Published

[2] Vulnerability cannot be directly observed as it is a theoretical phenomenon therefore the term 'operationalize' is used in place of 'measure' (Hinkel, 2011).

examples illustrate the lack of methodological clarity discussed previously (section 6.3.). The US National Park Service's vulnerability assessment of coastal heritage resources in the Gulf Islands illustrates this. It takes a 'biophysical' approach using a combination of desk top mapping and site visits to produce the assessment (Toscano, 2004). Although there is a strong place based element in this assessment, the final result takes very little account of socio-economic factors involved, and is not very different to risk analysis.

In another example, the Great Barrier Reef (GBR) Marine Park World Heritage site in Australia produced a vulnerability analysis of the site to climate change impacts (Marshall and Johnson, 2007). The analysis is qualitative, based on past vulnerabilities and expert judgement, and adaptive capacity is considered in relation to Indigenous culture and coastal industries. In the *Summary of Impacts* however each impact is assessed according to vulnerability, certainty and timeframe, more akin to the probability and magnitude rankings of risk analysis than vulnerability theory, despite the terminology.

6.9.1. Vulnerability of intangible heritage

Ford and Smit (2004) conducted a vulnerability study of the traditional practices of Arctic communities to climate change. They produced a research framework for assessing social vulnerability based on a two stage approach (figure 6.2). In stage one, current vulnerability is assessed by documenting exposure and adaptive capacity. In stage two, future vulnerability is estimated based on predicted climate change exposure and likely adaptive responses (based on stakeholder responses in stage one). Sensitivity is not included as it is considered part of biophysical assessment. The adaptive capacity of material cultural heritage is restricted however, having values rooted in concepts of authenticity and integrity of the fabric. Thus, the exclusion of sensitivity from this assessment limits its transferability to heritage sites.

The question of how far back in time one should go to assess past responses is addressed in this study and the conclusion is that this will be determined by both the relevance of past conditions to the current situation and on the reliability of the data (Ford and Smit, 2004).

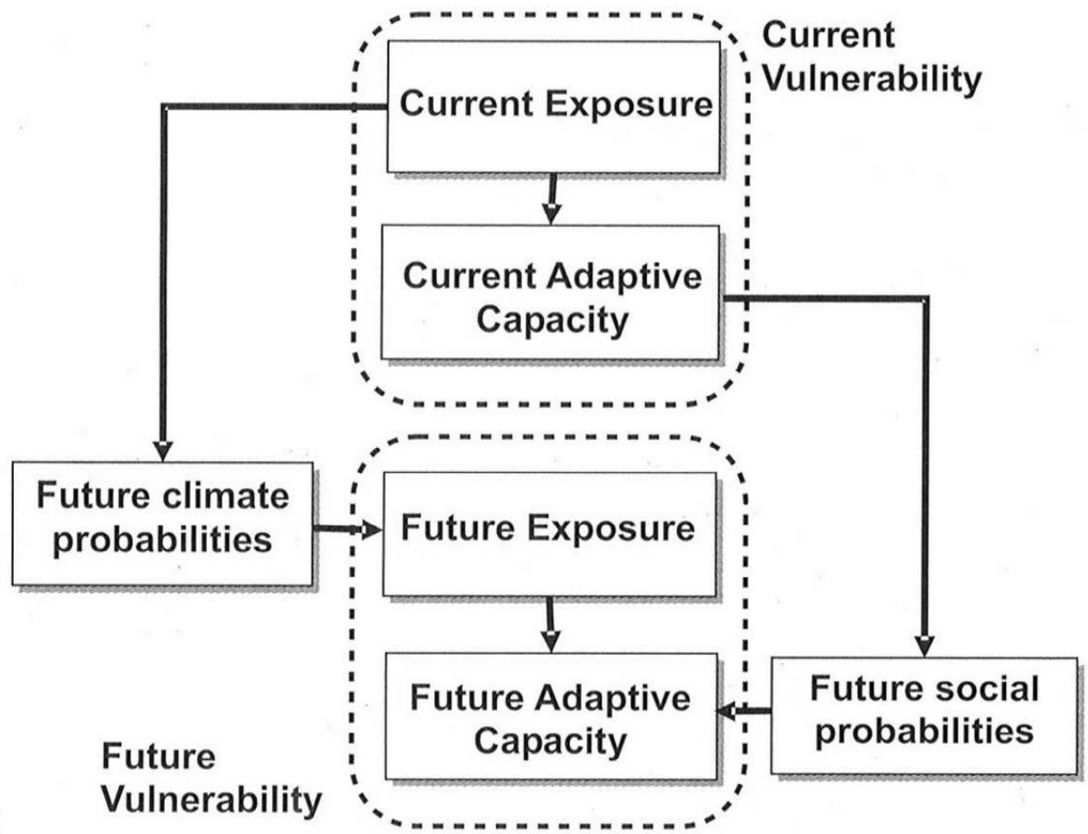


Figure 6.2. The analytical framework developed by Ford and Smit (2004)

6.9.2. Vulnerability of built heritage: Application of the eight step method

In his Master's thesis for University College London (UCL) Robert Woodside applied the Schröter methodology to an assessment of the Tower of London World Heritage site (Woodside, 2006). Woodside chose to focus on key climatic threats and to analyse them in detail. In the textual method he elucidates the interplay between heritage values, climate and the three elements of vulnerability in a descriptive qualitative manner. The assessment is weighted by grading both the cultural assets that contribute to the Outstanding Universal Value (OUV) of the site, and the stakeholder contributions (management are *critical*, landowners *important* and visitors *contributory*).

The method Woodside applies differs from Schröter as there is no causal model of vulnerability, instead the initial assessment of adaptive capacity, exposure and sensitivity is based entirely on qualitative data (table 6.1). The assessment of sensitivity is based on material properties, nature of the assemblage and condition. Adaptive capacity is divided by Woodside into the *physical capacity* of the site to adapt without loss of cultural value and the *social capacity* of the management systems to cope (section 9.3.1.). The requirements of World Heritage to embody defined values (OUV), and maintain authenticity and integrity may affect these capacities differently (Woodside, 2006):

1. World Heritage status increases management and legislative protection thereby potentially increasing social capacity.
2. World Heritage status restricts the ability to adapt physically thereby potentially reducing physical capacity.

Woodside calculates initial vulnerability without considering quantifiable indicators. He argues that indicators should relate to overall vulnerability rather than individual elements of it (i.e. sensitivity, exposure and adaptive capacity). This has practical benefits in terms of simplifying the calculation of vulnerability but does not account for any variance that may exist in the relevance of each contributing element.

6.10. VULNERABILITY FRAMEWORK DESIGN

> *There is a desperate need for tools that can assess risks to archaeological sites from environmental threats* (Holden et al., 2006: 80).

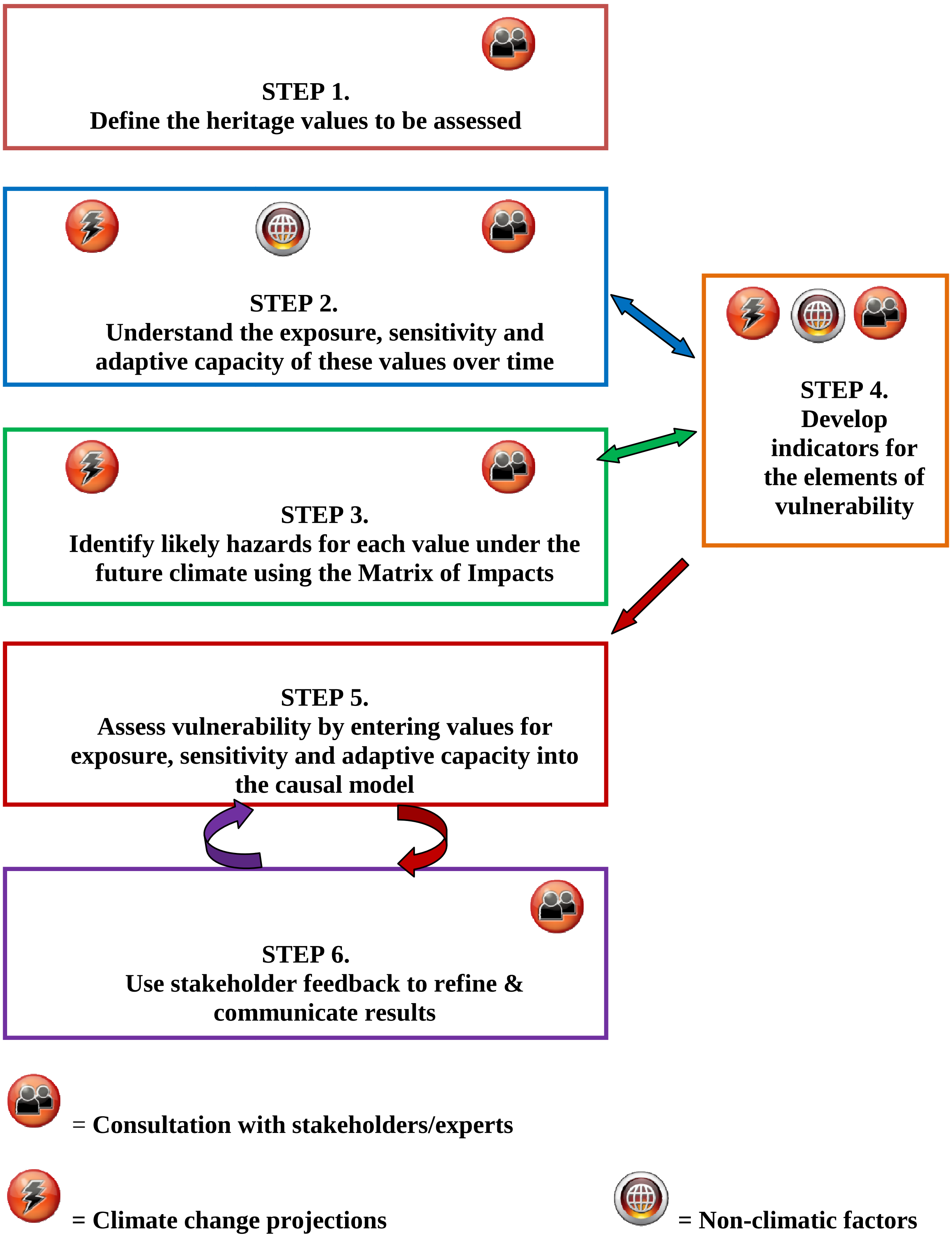
Following on from the work of Schröter and Woodside a **six stage Framework** for assessing the vulnerability of cultural heritage to climate change was developed for implementation at the case study sites (table 6.1). The key contributions of this Framework are:

1. The introduction of specific tools for use in conjunction with the Framework i.e. the **Matrix of Impacts** and the **Causal Model**.
2. The choice of terminology that focuses on **heritage value**.
3. The introduction of **Stakeholder Review** as a means to refine and validate the results.

Table 6.1. Comparison of proposed 6 STEP VULNERABILITY FRAMEWORK with previous examples by Schröter (2005) and Woodside (2006)

8 STEP FRAMEWORK (Schröter et al., 2005)	**WOODSIDE's 5 STEPS (2006)**	**6 STEP VULNERABILITY ASSESSMENT FRAMEWORK**
Define study area	Define study area	**Define the heritage values to be assessed**
Get to know the place over time (understand exposure, sensitivity and adaptive capacity)	Define the significance of the asset	**Understand exposure, sensitivity and adaptive capacity of these values over time**
Hypothesize who is vulnerable to what	Identify most likely hazards	**Identify likely hazards for each value under future climate using the Matrix of Impacts**
Develop a causal model of vulnerability (exposure, sensitivity, adaptive capacity)	Assess exposure and sensitivity Assess adaptive capacity	**Develop indicators for the elements of vulnerability**
Find indicators for the elements of vulnerability	Quantify vulnerability and develop indicators	**Assess vulnerability by entering values for exposure, sensitivity and adaptive capacity into the Causal Model (table 6.2)**
'Operationalize' model of vulnerability		**Use Stakeholder Review to refine and communicate results**
Project future vulnerability		
Communicate vulnerability creatively		

Figure 6.3. SIX STEP VULNERABILITY FRAMEWORK FOR CULTURAL HERITAGE



6.10.1. STEP ONE. Define the heritage values to be assessed

This requires knowledge of the nature and extent of the values which are considered important for the heritage site. Spatial boundaries should be determined. For example, are views important or specific elements of the landscape? The case study sites are World Heritage properties and therefore have clearly defined boundaries and described values as part of the UNESCO requirements for designation.

6.10.2. STEP TWO. Understand exposure, sensitivity and adaptive capacity of these values over time

Vulnerability is a function of three elements (exposure, sensitivity and adaptive capacity) and the widest possible range of primary and secondary sources should be used to gain an understanding of these factors (Turner et al., 2003b). At the case study sites this included both published and unpublished documentation, repeated site visits and interviews with stakeholders (chapters 7 and 8). Site visits develop a first-hand understanding of the relationship between the heritage values and the surrounding environment, such as topography, aspect, patterns of wear, and land use. Ideally the site should be visited in different seasons to ascertain any areas prone to seasonal effects such as flooding or frost. Stakeholders may include heritage professionals, researchers, site staff, local residents or visitors. They should represent a wide breadth and depth of knowledge. Future climate conditions can be ascertained from a suitable Regional Climate Model (RCM). Downscaled RCM projections with a resolution of 10 Km^2 were utilised for the case studies. The data was provided by the Max Plank Institute under the auspices of Climate for Culture from REMO 2009 regional climate model. Recent evaluations of its transferability demonstrated it to be good at simulating temperature and precipitation in general and particularly so over Europe (Jacob et al., 2012). The downscaled regional models all inherit certain biases from the global models and although more precise for topographic variables they therefore contain an equal level of uncertainty.

6.10.3. STEP THREE. Identify likely hazards for each value under future climate using the Matrix of Impacts

The production of a vulnerability hypothesis (*who is vulnerable to what?)* must be based on knowledge of the heritage values and of the likely impacts of climate change. The potential hazards for each heritage value under the projected future climate can be identified with the aid of the Impacts Matrix (table 3.1). This was developed from research in the literature and from expert interviews. It focuses on impacts that are theorized for archaeological sites in temperate zones, relying on evidence and experience of past weathering in order to ‘imagine’ possible future impacts. In the case study analyses each stakeholder was shown a version of the matrix and asked to select the impacts they considered relevant. Their responses were used to create a ranking of hazards (e.g. table 7.6).

Although it is proposed that the Matrix should be used as a reference when developing the vulnerability hypothesis, it must not be viewed as a definitive list of all potential impacts. In addition to indirect impacts which are not included (section 3.6.), individualised parameters such as topography, aspect and material properties must also be accounted for separately by the user. The uncertainty of the climate change model projections means that any hypothesis formulated on the basis of these future scenarios will need to be kept under constant review.

6.10.4. STEP FOUR. Develop indicators for the elements of vulnerability

Indicators should be place based and relate to the key elements of exposure, sensitivity and adaptive capacity of heritage values to climate change impacts (Schröter et al., 2005). Quantifiable indicators for measuring vulnerability to climate change have been outlined in other disciplines and it may be possible to adapt some of these ideas to cultural heritage (Moss et al., 2001, Sweeney et al., 2002, Forbes and Liverman, 1996). The selection and application of indicators and the design and implementation of a site specific tool for stone recession will be discussed in later sections of this thesis (chapters 9 and 10).

6.10.5. STEP 5. Assess vulnerability by entering values for exposure, sensitivity and adaptive capacity into the Causal Model

A Causal Model developed by the author on the cause to consequence orientation (table 6.2) is proposed for this step (Daly, 2008). In the model sensitivity (S) and exposure (E) to hazard are positive values and adaptive capacity (AC) is negative. The 'measure of vulnerability' (MV) is then calculated; a positive value indicating vulnerability and a negative one resilience. The scale is a basic 1–3 range, where 1 is low.

Table 6.2. Causal Model for site specific evaluations of vulnerability to climate change impacts

Matrix Input	**Indicators**	**Exposure (E)**	**Sensitivity (S)**	**Adaptive Capacity (AC)**	**Measure of Vulnerability (MV)**
Impact of concern	*Ind. E.* *Ind. S.* *Ind. A.C.*	1 to 3	1 to 3	1 to 3	MV = (E+S) - AC

In order to run the model for the case study sites, values for sensitivity, exposure and adaptive capacity were ascertained by interrogating the primary and secondary data. There were significant gaps in the data due to several factors. Firstly the lack of detailed monitoring on the sites makes establishing baseline values very difficult. Secondly many heritage values are socially constructed and therefore the objective quantification of loss is often not possible (section 2.2). In these instances the data gap was addressed by consulting stakeholder expertise. The model relies on the person entering the data having a high level of knowledge gathered in steps 1–4 to produce a credible set of values. The application of indicators provides a quantifiable support for the qualitative assessment. This expert driven approach can be accused of producing subjective outcomes but, as discussed previously that does not mean it is invalid (section 2.2).

6.10.6. STEP 6. Use stakeholder review to refine and communicate results

The main difference between this Framework and the earlier 8 step methodology is in the approach to validation. Schröter suggests operating the model under current conditions in order to demonstrate its validity. Given the difficulties in obtaining quantifiable data appropriate to cultural heritage however, test-running the model in this way is unlikely to be informative. It was decided therefore that Stakeholder Review of the results would be used to provide validation. Appropriate feedback mechanisms will need to be developed to suit the requirements of each group of stakeholders. At the case study sites the stakeholders were sent hard copies of the final results and asked to complete a feedback form (Appendix 2).

Dialogue with stakeholders throughout the assessment process ensures a final product that is both credible and relevant (figure 6.3). Communication of the final results should be through presentations, publications, summary reports and direct feedback to the contributing stakeholders. To establish an easily understandable and comparable ranking of vulnerabilities, standard colour coding for expressing 'significance of change' should be adopted when communicating summary results (figure 6.4) (ICOMOS, 2010).

VALUE OF HERITAGE ASSET	SCALE & SEVERITY OF CHANGE/IMPACT				
	No Change	Negligible change	Minor change	Moderate change	Major change
For WH properties Very High – attributes which convey OUV	SIGNIFICANCE OF EFFECT OR OVERALL IMPACT (EITHER ADVERSE OR BENEFICIAL)				
	Neutral	Slight	Moderate/ Large	Large/very Large	Very Large

Figure 6.4. Colour coding recommended by ICOMOS for expressing the significance of change (ICOMOS, 2010)

6.11. THE PROBLEM OF VALUE and RANKINGS

The aim of the vulnerability assessment is to be as comprehensive as possible so that an understanding of the system-wide 'structure of vulnerability' can be gained (Adger et al., 2004). Further assessments may choose to focus on specific values and impacts highlighted by the first general analysis. In larger more complex sites, an element of selection may be necessary from the start (Woodside, 2006).

In order to set priorities it is necessary to make certain judgements as to the relative value of a heritage asset and the degree to which that will be diminished by any given impact. The measure of vulnerability (MV) does not include a weighting for these factors thus the priorities it sets may need to be reassessed. ICOMOS recommends that *the weight given to heritage values should be proportionate to the significance of the place and the impact of the change upon it* (ICOMOS, 2010: 2-1-5). Thus in the case of World Heritage properties most weight should be given to impacts on heritage values that contribute to the OUV. There is an element of value ranking present in the assessment of 'physical' adaptive capacity as this is likely to be inversely proportional to the heritage value i.e. for assets critical to OUV small changes may be considered detrimental (section 6.9.2.).

Frequency of stakeholder responses was used to rank impacts for the case study assessments. This alone is not a reliable indicator however, as some stakeholders will be more knowledgeable than others about specific topics. Woodside assigned a weighting to the stakeholders themselves, and used that as a multiplier to create a ranking of impacts. The weighting of stakeholder input relies on a subjective assessment of the value of one person's views over another however. It is unlikely to be a palatable task for site managers when processing contributions by their colleagues and peers and therefore it is not suggested as part of the methodology. It is important nonetheless to be aware of the issue of competency when drawing conclusions from the views of stakeholders.

6.12. CONCLUSIONS

Vulnerability assessment takes a system-wide approach. It considers stakeholder input, socio-economic and institutional factors in addition to the physical hazards of climate change. This means vulnerability assessments can accommodate the lack of accuracy inherent in future climate projections better than the statistical approach of risk analysis. For the same reason they are also better suited to the subsequent development of adaptation measures (Adger et al., 2004). The flexible multi-disciplinary approach of vulnerability analysis suggests that it is a 'smart' management practice (section 2.5.).

Vulnerability analysis is well suited to cultural heritage management. The emphasis on case study assessment, on taking a holistic approach and including capacity for adaptation to change all contribute to this suitability. There are a wide variety of applications and methodologies in the literature, some are more akin to risk assessment but utilise the terminology of vulnerability. This lack of clarity in terminology was also evidenced in the questionnaire research (section 4.3.). In creating working definitions of the key terms and a conceptual six step Framework, this chapter goes some way towards clarifying the issues for those interested in conducting a vulnerability assessment on cultural heritage. The following chapters will demonstrate the application of these theoretical developments in relation to the case study sites of Skellig Michael (chapter 7) and Brú na Bóinne (chapter 8).

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CHAPTER 7.

VULNERABILITY ANALYSIS OF SKELLIG MICHAEL

Both the Skelligs are pinnacled, crocketed, spired, arched, caverned, minaretted; and these gothic extravagances are not curiosities of the islands: they are the islands: there is nothing else (Shaw, 1910).

7.1. INTRODUCTION

In the previous chapter the theoretical basis underlying Vulnerability Analysis and the conceptual Framework developed for conducting assessments on heritage assets were outlined. In this chapter, and the following one, the six step Framework will be applied to the two case study World Heritage sites (Skellig Michael and Brú na Bóinne respectively). The aim is to test the efficacy of the method in order to facilitate its transfer to other sites. The Vulnerability Framework, as developed in this thesis (section 6.10.), involves 6 steps:

1. Define the heritage values to be assessed.
2. Understand the exposure, sensitivity and adaptive capacity of these values using a variety of sources both historic and contemporary.
3. Identify likely hazards for each value under the future climate using the Impacts Matrix (table 3.1).
4. Develop indicators for the three elements of vulnerability i.e. sensitivity, exposure and adaptive capacity.
5. Assess vulnerability by entering values for exposure, sensitivity and adaptive capacity into the causal model.

6. Use stakeholder review to refine and communicate results (section 2.6.1.).

7.2.

STEP 1. DEFINE THE HERITAGE VALUES TO BE ASSESSED

7.2.1. Site description

Skellig Michael is one of two World Heritage sites in the Republic of Ireland. It is located on a precipitous rock in the Atlantic, 11.6 km from the coast of county Kerry (figure 7.1). The sea creates a natural boundary for the World Heritage property. Characterised by its extreme environment and the Early Christian dry stone monastic structures, the landscape shaped human settlement and was in turn altered by that interaction. In addition to its cultural value, the island is home to breeding colonies of many species of bird, some of which are endangered and protected. The monastic enclosure on the north peak is built on man-made terraces and consists of dry stone walls, beehive huts, two boat shaped oratories, a later mortar built church and a collection of stone cross slabs (figure 7.2). The monastery is still reached today by one of the three original dry stone staircases that are all largely intact (figure 7.3). In addition there is a hermitage on the more inaccessible south peak consisting of a number of small terraces and dry stone structures. There are also two lighthouses and associated structures considered important for local and national heritage (Department of Environment Heritage and Local Government, 2008) and which are intrinsic to the maritime landscape. The predominant stone of construction is Devonian sandstone, sourced on the island. The only deep archaeological deposits are located in the monastery, outside of that buried archaeology is limited (Bourke et al, 2011).

Figure 7.1. Site location and survey of island of Skellig Michael showing the main elements (Department of Environment Heritage and Local Government, 2008)

Figure 7.2. Cross slabs and dry-stone beehive huts in monastic enclosure, north peak, August 2010

7.2.2. Values present at the site

In 1996 Skellig Michael was listed as World Heritage under two of UNESCO's criteria for Outstanding Universal Value (OUV) (Department of Environment Heritage and Local Government, 2008):

Criteria (iii) As it bears *exceptional testimony to a cultural tradition* for the evidence of Early Christian ascetic monasticism.

Criteria (iv) As *an outstanding example of…an architectural ensemble* [and] *landscape* for the collection of dry stone architecture, which is integrated within the island's topography.

In addition to the OUV for which Skellig Michael has been designated, the lighthouse structures are significant in terms of national heritage value (section 7.2.1) and the avian population is protected under EU and national legislation[1]. The vulnerability of the World Heritage property will be analysed at three levels taking account of both national and WH values:

1. Cultural Landscape (iv)
2. Monastic structures & features (iii & iv)
3. Buried deposits (iii)

Figure 7.3. Steep topography and dry stone Medieval staircases that characterise Skellig Michael, August 2010

[1] NHA under Irish Wildlife Acts 1976–2000 & SPA under the EU Birds Directive 79/409/EEC (Department of Environment Heritage and Local Government, 2008).

7.3.

STEP 2. UNDERSTAND THE EXPOSURE, SENSITIVITY AND ADAPTIVE CAPACITY OF THESE VALUES OVER TIME

This step requires that the assessor gains an understanding of the site over time, with a particular focus on conservation and management issues. Where the site manger is conducting the assessment with colleagues, much of the required information will be known to them already. Where the assessor has limited experience of the site, as in this present study, stakeholder interviews are vital in building the case study. These interviews were augmented by desk based research and two visits to the site (2010 & 2012).

NB When undertaking an assessment, large amounts of qualitative data are gathered by the assessor as a foundation for their evaluation. In this chapter, and in chapter eight, much of that raw data is presented in order both to illustrate the process and to ensure transparency. This does, however, lead to large chunks of data in tables (e.g. table 7.7) or within the text. As the evaluation process proceeds the tables become increasingly simplified to increase readability, in these instances the background data can be found in earlier sections.

7.3.1. Stakeholder interview procedure

Stakeholders were identified from those who have a detailed knowledge of Skellig Michael, either through their work or research. This includes Office of Public Works (OPW) employees that reside on the island during the summer season and professionals involved in archaeological and conservation works (table 7.1). Where possible the interview was conducted in person or by phone. In a few cases the participants preferred to self-administer the questions and this was facilitated. The structured interview consisted of six questions all relating to the past impacts of climate on the heritage of Skellig Michael, and how this may change in the future (Appendix 2). The interviewees were provided with a simplified version of the Impacts Matrix to help them identify issues of concern under a changed future climate (Appendix 2).

Table 7.1. Stakeholders consulted for Skellig Michael research 2010–2012

Name	**Institution**	**Details**
Lynch, Ann (Dr)	National Monuments, Dept of Arts Heritage and the Gaeltacht	Senior Archaeologist, has excavated on Skellig Michael and is a member of the Skellig Michael Implementation Group (SMIG)
Harris, Bob	OPW	Chief guide on Skellig Michael
O'Halloran, Claire	OPW	Guide on Skellig Michael
Lavelle, Des	Boatman & author (Lavelle, 2004)	Running passenger boat service to Skellig Michael for over 40 years
Bourke, Edward	National Monuments, Dept of Arts Heritage and the Gaeltacht	Archaeologist for Skellig Michael and member of the SMIG
Rourke[2], Grellan	OPW	Skellig Michael Site Manager and Senior Conservation Architect
O'Leary, Jack	Malachy Walsh & Partners	Consultant engineer for Skellig Michael
Connolly, Michael (Dr)	Kerry County Council	County Archaeologist, conducted surveys of Skellig Michael.

[2] Unlike the other respondents Grellan Rourke gave an in depth interview (2010), and at a subsequent meeting of OPW conservation architects was present where the Impacts Matrix was discussed (2011).

Name	**Institution**	**Details**
Ryan, Michael (Dr)	Adjunct professor of archaeology at University College Dublin and Trinity College Dublin	Chair of Skellig Michael Expert Advisory Academic Group
O'Shea, Patrick	OPW	Chargehand and mason, Skellig Michael

Additional input was sought from Michael O'Sullivan, consultant geologist and Paul Whelan, lichenologist (author of a survey of lichens on the island), in their specific field of expertise. Unfortunately attempts to include a National Parks and Wildlife respondent were unsuccessful.

7.3.2. Exposure

Exposure of cultural heritage is the degree to which an identified heritage value is exposed to climatic variations and their related impacts. It is determined by environmental conditions (physical and atmospheric).

The current climate of Skellig Michael is characterised by mild temperatures and extreme wind and rain. Climate projections used to assess future conditions were provided by the Max Plank Institute in Hamburg. The projections were generated within the Climate for Culture (CfC) FP7 project using a REMO model and the IPCC A1B scenario. Managers must be cognisant of the emissions storyline underlying climate projections and that they may not indicate the 'worst case scenario'. In this case CfC chose a medium–low emissions storyline representing a fairly positive view of the future.

Table 7.2. Summary of projections for Valentia Observatory from the REMO model using the IPCC AR4 A1B scenario (calculated in Microsoft Access Jan 2013)

Period	Temperature 30 year Average (at 2m)	No. of Freeze Events i.e. non-consecutive days <0°C	July Precipitation Average (mm/hour)	December Precipitation Average (mm/hour)	Intensity of Rainfall (No. of days ppt. >5mm/hr)
1960–1991	10 ºC	15	0.17 mm	0.54 mm	344
2070–2101	11.5 ºC	1	0.17 mm	0.52 mm	474
Projected Change	**↑ 1.5 ºC**	**↓ 93%**	**No change**	**↓ 4%**	**↑ 38 %**
Period	**Wind Speeds (m/s) July Average & Min/Max (at 10m)**	**Wind Speeds (m/s) December Average & Min/Max (at 10m)**	**Wind Direction by % (at 10m)**	**Ground Surface Temperature (July) Max, Min & Standard Deviation**	
1960–1991	Average: 5.27 Max 16.9 Min 0.16 Std. D. 2.16	Average: 7.85 Max 21.4 Min 0.19 Std. D. 3.43	N 17% E 11% S 28% W 44%	Max 25.5ºC Min 7.85ºC Std. D. 2.39	
2070–2101	Average: 5.28 Max 14 Min 0.19 Std. D. 2.15	Average: 7.85 Max 20.4 Min 0.24 Std. D. 3.44	N 17% E 10% S 26% W 47%	Max 27ºC Min 8.67ºC Std. D. 2.35	
Projected Change	**↑0.2% Av.** **Std. D. ↓0.5%**	**No change** **Std. D. ↑0.4%**	**E ↓ 1%** **S ↓ 2%** **W ↑ 3%**	**↓ 1.6% (Std. D.)**	

Lola Kotova of Max Plank and CfC included the two case studies within the REMO model and extracted the generated data for use within the current study. The location of Skellig

Michael (-10.3218996 longitude, 51.4618984 latitude with 185m elevation) was not within the parameters of the regional model however, and outputs for the meteorological station of Valentia Observatory (-10.3189086 longitude and 51.8458462 latitude) approximately 28kms north-east of Skellig Michael were chosen as the nearest available (Kotova, pers. comm.). Eleven parameters selected by CfC Partners were modelled in REMO. In addition to the standard parameters of temperature, precipitation and radiation the data includes specific concerns for heritage such as RH, surface temperature and wind direction.

Table 7.3. Intensity of precipitation projections for Valentia Observatory from the REMO model using the IPCC AR4 A1B scenario (calculated in Microsoft Access Jan 2013)

No of days/quarter with rainfall >5mm/hr	Jan–Mar	Apr–Jun	Jul–Sep	Oct–Dec
1960–1991	72	43	89	140
2070–2101	118	46	106	204
Projected Change	**↑ 64%**	**↑ 7%**	**↑ 19%**	**↑ 46%**

REMO data has been shown to have good correlation for temperature but precipitation is likely to be underestimated (Max Plank Institute, 2010). The model was run for three periods: 1960–91; 2020–51; and 2070–2101. For the purposes of the vulnerability assessment it was decided to focus on likely change in this century, so the control period (1960–91) was compared with the far future period (2070–2101) (tables 7.2 & 7.3). The REMO projections suggest that the future climatic parameter of most concern for Skellig Michael will be an increase in the intensity of rainfall. The reduction in freeze thaw events predicted is positive, but as the incidence of this is already low (<1/annum) any reduction has limited significance. Results from the REMO model suggest there will be no significant change in surface temperature associated with thermoclastic weathering[3]. The average and standard deviation in wind speeds showed no future change either.

Table 7.4. Storm surge projections for Ireland (McGrath and Lynch, 2008, 22)

Table 3: Differences in the surge elevation between the future (2031-2060) and control run (1961-1990).

Station Name	50 cm<Hsurge<100 cm % Change in frequency	99 percentile % Change in height	Maximum Surge % Change in height
Dublin Bay	14.7%	5.45%	5.6%
Wicklow	21.9%	2.22%	13.98%
Arklow	20.1%	2.27%	11.1%
Wexford Bay	18.98%	2.44%	12.36%
Waterford	20.6%	2.44%	-7.69%
Cork Harbour	10.6%	0.01%	-17.76%
Dingle Bay	24.93%	2.33%	20.88%
Shannon Estuary	25.50%	4.76%	10%
Sligo Entrance	30.53%	6.38%	-5.08%
Lough Swilly	19.2%	3.7%	-10.88%
Donegal Bay	24.80%	6.12%	6.87%
Clew Bay	31.20%	6.38%	6.42%
Galway Bay	25.93%	6.52%	73.2%

The Climate for Ireland (C4I) consortium projections suggest that cyclonic conditions (including low pressure) on the Atlantic will result in a 25% increase in frequency of extreme storm surge events and 10% increase extreme wave heights on the south-west coast (McGrath and Lynch, 2008) over the next century. The C4I group used a 3D storm surge model (driven by wind speed, sea level pressure, precipitation, evaporation and radiation and heat fluxes) at a horizontal

[3] Noah's Ark calculated sensitivity to thermal weathering in stone using a damage function; $\delta = E\lambda\Delta T$
Where δ is the internal tension (MPa); E is the modulus of elasticity of the stone; λ is the thermal dilation coefficient of the stone; and ΔT is the daily surface temperature change.
INSTITUTE OF ATMOSPHERIC SCIENCES AND CLIMATE 2007. Deliverable 12. *Noah's Ark; Global Climate Change Impact on Built Heritage and Cultural Landscapes*:101.

resolution of 7Km (table 7.4). Validation of the model showed a high degree of correlation between observed and modelled storm events although for severe events the model had a tendency to underestimate the severity (McGrath and Lynch, 2008: 18).

Combining future projections with evidence gathered from stakeholders and secondary research it was possible to summarise the exposure of Skellig Michael to the main climatic parameters (wind, rainfall and temperature) and their associated impacts (table 7.5).

Table 7.5. Evaluation from research of the Exposure of heritage values in Skellig Michael to climate change impacts[4]

Climatic parameter & Impact	Degree of Exposure	Comment
Wind – contributes to rock fall, soil erosion, stone throw, mechanical action with water, transportation of salts. Also prevents boat landings (access for staff and visitors) (Ryan pers. comm.).	Predominant winds are from west and south and this is likely to continue - the main monastery is sheltered (unless wind easterly); the hermitage is exposed. Winds have carried salt spray 160m to cover monastery in salt crystals but exposure of monuments to salt damage is low as the few decorated cross slabs are effectively sealed with Lichen cover (Pavia and Bolton, 2001) (Rourke, pers. comm.).	Those working on the island noted a shift to northerly winds (NE/NW) between 2005 and 2012 making conservation work more difficult and colder. In 2013 winds shifted to predominantly south westerly (Rourke, pers. comm.).

[4] List of impacts based on Matrix developed from literature (table 3.1)

Climatic parameter & Impact	**Degree of Exposure**	**Comment**
Atlantic storms & Sea level rise – mechanical damage (waves/wind/rain), salt loading & boat landings.	Ocean Models suggest 25% increase in frequency of extreme storm surge events and 10% increase extreme wave heights on the south-west coast (McGrath and Lynch, 2008).	During past storms the lighthouse glass has been smashed and the light put out, approximately 200 feet above sea level (Rourke, pers. comm.).
Rainfall – Increased rainfall may results in soil erosion, rock fall, mechanical weathering, dissolution, saturation & collapse.	Increase in intense rainfall (days with >5mm) by 38% is predicted, the greatest number of these events will be in winter.	Increased or more severe rainfall and resultant water action will have an effect on both the surviving structures and intermittent, thin soil cover (Connolly pers. comm., O'Leary pers. comm.).
Rainfall – Decreased rainfall in summer may lead to drought, vegetation die back, soil erosion & rock fall.	The REMO model does not show any decrease in summer rainfall although this is suggested by other projections e.g. ICARUS GCM model for Valentia suggests a 35% reduction in July average (Fealy and Sweeney, 2007).	The shift to more intense and sporadic rainfall combined with higher temperatures may lead to occasional drought.
Temperature – Increased temperatures may impact on natural heritage, microbiological growth on stone, and freeze thaw weathering.	Atmospheric temperature rise is modulated on Skellig by the surrounding ocean. Nesting birds are exposed to any change that affects food stocks. Exposure to freeze thaw is predicted to decrease by 93%.	For avian food stocks the temperature of the sea is most significant.

Climatic parameter & Impact	**Degree of Exposure**	**Comment**
Radiation – thermoclastic weathering is caused by warming and cooling of stone surfaces creating thermal stress and eventual mechanical decay of stone.	Surface temperature fluctuations are projected to show a slight decrease of 1.6% (standard deviation) suggesting this impact will not worsen. This form of damage has been recorded on the South peak, especially on the west side (Rourke, pers. comm.).	In Malta daily fluctuations in air temperature of 4^{o}–8^{o}C resulted in differentials at south-easterly facing stone surfaces of between 20^{o}–30^{o}C (Corrosion and Metals Research Institute Sweden, 2006).

Figure 7.4. Vegetation and soil erosion due to visitor traffic on steps to monastery August 2010

Figure 7.5. Stainless steel gate erected on Skellig Michael and destroyed by winter storms, now on display in the Skellig Visitor Centre, Portmagee, August 2012

7.3.3 Sensitivity

Sensitivity of cultural heritage is the degree to which an identified heritage value is affected, either adversely or beneficially, by [climate-related] stimuli. The effect may occur at artefact, assemblage or system level.

The impacts identified by stakeholders were numerically ranked according to the number of respondents concerned with each one (table 7.6). This involved a simple tally, weighting of responses according to expertise could improve the analysis (section 7.4.1.).

Table 7.6. Skellig Michael climate change impacts ranked in order of significance; based on number of stakeholders stating concern (for each impact)

Order of Concern	Cultural Landscape	Structures & Features	Buried Deposits
1	• Soil Erosion		
2		• Structural damage	
3		• Soil erosion (destabilisation of foundations)	
4	• Change/loss of habitats & species • Landslide/soil movement	• Increased penetration of water • Increased penetration of salts and salt weathering	• Erosion & exposure
5	• Loss of vegetation • Run off (water flow that washes out features) • Rock fall & erosion		• Subsoil instability
6		• Access • Landslip (pressure from saturated soil) • Surface abrasion (wind & rain)	
7	• Saline intrusion • Wave damage	• Wave damage • Changes in lichen colonies • Dissolution • Increased biological growth • Increased recreational use	• Loss of stratigraphic integrity

Based on research and stakeholder interviews a number of recurring issues in respect to the sensitivity of heritage values on Skellig Michael were noted and these 'key sensitivities' are described and illustrated below as a precursor to evaluating vulnerability (table 7.7).

Table 7.7. Discussion of the main potential sensitivities to climate change impacts for the heritage values of Skellig Michael identified from primary and secondary research

Impact	Mechanism	Comment
Cultural Landscape		
Rock Falls and **soil movement** are a feature of the steep inclines, extreme weather and shallow soil cover on the island.	Geology - the cleavage planes in the bedrock allow weathering and erosion to take place rapidly and result in large cleavage blocks falling on a constant basis (O'Sullivan, pers. comm.). The most recent large rock fall was in 2011 on north steps. Frost - splits the stone Heavy rain - softens the soil. Dry conditions - loosens stones. Wind - moves stones.	One major fall seriously damaged the lighthouse road (Lynch, pers. comm., Rourke, pers. comm.). Rock fall is caused by the combination of *a highly fragile rock type and a highly erosive environment* but on the geological scale current levels of climate change are unlikely to be significant (O'Sullivan, pers. comm.).
Soil erosion is caused by similar conditions as rock fall and may occur in tandem.	Heavy rain - erodes exposed soil and saturates vegetation & root system that anchors soil causing land slip. Dry conditions - ground cover dies back exposing soil to erosion. Wind - erodes exposed soil.	Puffin and rabbit burrowing further undermine soil cover (O'Halloran, pers. comm.) as does visitor traffic along main routes to and from monastery (figure 7.4).

Impact	**Mechanism**	**Comment**
Pluvial flooding i.e. mechanical damage by water run-off after heavy rain.	Heavy rain - water flow carving channels in the soil (gullying), moving stones and damaging infrastructure.	This has occurred on the lighthouse roadway (O'Leary pers. comm., Bourke, pers. comm.).
Wave damage can be both mechanical (figure 7.5) and chemical (salt dosing).	Atlantic storms - wave heights up to 50m (O'Sullivan, pers. comm.). Above this mechanical damage is unlikely but salt dosing may occur from sea spray.	E.g. waves have damaged infrastructure and even put out the light at the top of the lighthouse (Rourke, pers. comm., Ryan, pers. comm.).
Vegetation change due to higher temperatures and altered rainfall patterns.	Drought, overwatering and heavy salt dosing caused by storms - implicated in loss of vegetative ground cover. Loss of vegetation is known to rapidly accelerate soil erosion and increase rock fall. Grass and ragwort (invasive species) are now more prolific.	E.g. predominant sea pink died back to be replaced by sea campion in 1970s (Lavelle, pers. comm., Harris, pers. comm.). Sea campion died back on SE slopes in the 1990s due to salt dosing (O'Shea, pers. comm., O'Halloran, pers. comm., Harris, pers. comm.).

Impact	**Mechanism**	**Comment**
Bird Species are liable to be affected by temperatures in the sea around Skellig Michael.	Sea water temperature - affects supply of food for breeding colonies - if this occurs for four years in a row population could be impacted (O'Halloran, pers. comm.).	E.g. Approx 5 years ago *puffins were coming in with pipe fish as opposed to sea sprats which were harder for chicks to eat* (Harris, pers. comm.[5]).
Structures & Features		
Stone throw - dry stone masonry.	High winds - lift off stones. Annual need to repair and consolidate.	Conservation practise is to use sacrificial courses of modern replacement masonry to protect original material (Ryan, pers. comm.).
Collapse of dry stone walls - the history of the site has been one of subsidence and collapse (Rourke, pers. comm.).	Heavy rain - saturates retained material increasing pressure on base of walls. Heavy rain or drought combined with animal burrowing - loosens footings of structures leading to subsidence	In some parts of monastery the wall has been rebuilt four times since the early Christian period (Bourke, pers. comm.).
Mechanical action of water gradually destabilises structures.	Heavy rain and wind - Rain washes soil into and through dry stone walls, washes mortar out of walls (lighthouse period structures).	E.g. on the South peak the original soil in the garden terrace was washed out causing collapse (O'Shea, pers. comm.).

[5] Harris states that the bird population is currently healthy and the diet has returned to normal; *I believe direct impact of changes in climate on bird populations on Skellig would be very difficult to determine* (Harris, feedback form, 10.6.2013).

Impact	Mechanism	Comment
Mechanical action of waves erodes and destabilises structures located below approx. 200 feet (Rourke, pers. comm.).	Wave action - mechanical erosion of Early Christian rock cut steps & accelerated washing out of mortar from lighthouse period walls.	The action of the waves has removed the mortar from the seaward face of the lighthouse roadway, which is now treated as a dry stone wall to allow for nesting birds (figure 7.7).
Mechanical damage by visitors: visitor traffic on the steps and within the monastery results in loosening and movement of the dry stone structures (figure 7.6).	Higher temperatures could mean altered visitor patterns and a longer tourist season resulting in increased mechanical damage caused by visitor traffic.	E.g. constant loosening of stones on main visitor routes; the surface wear on paving in the monastery (Rourke, pers. comm., Harris, pers. comm.).
Access to the island by staff and visitors is weather dependent.	High winds & storms - boats cannot dock. Restricted access will affect the ability to carry out maintenance and conservation works. Conversely, reduced footfall will result in less mechanical damage.	The OPW keep records of boat landings, which are weather dependant. For example in 2009 there were 44 days without landings (Skellig Michael Implementation Group, 2009).
Vegetation change – plant growth within walls is an issue that requires constant maintenance (O'Shea, pers. comm.).	Higher Temp - increased and/or changed plant growth and microbiological growth (including lichens). Rare lichens on Skellig are important for biodiversity (Whelan, pers. comm.).	Control of plants is by hand, herbicides cannot be used on the island due to the birdlife (Rourke, pers. comm.).

Impact	**Mechanism**	**Comment**
Thermoclastic weathering – large temperature differentials at the stone surface can lead to mechanical failure.	Increased summer temperatures - mechanical damage to stone induced by thermal stress.	Thermal stress on stone causing crumbling has been recorded on the south peak (Rourke, pers. comm.).
Buried Deposits		
Collapse of the subsoil in the monastery where the main archaeological deposits survive.	Heavy rain or drought - due to saturation pressure and water percolation (Bourke, pers. comm.) or loosened footings of structures leading to subsidence.	Effect worsened by animal burrowing.
Erosion of the shallow soil cover.	Rain & wind - as above.	Outside of main monastery very little archaeological material remains (Bourke, pers. comm., Rourke, pers. comm.).

7.3.4. Adaptive Capacity

The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (McCarthy et al., 2001).

Adaptive capacity is analysed under four headings suggested by the UNDP (GEF Global Support Programme, 2005). It is also important to consider the capacity of a site at the different scales that can affect it i.e. local and individual as well as national and institutional.

1. Policies & Programmes
2. Information & Knowledge
3. Implementation
4. Monitoring/feedback

Figure 7.6. Tourists and OPW guide Claire O'Halloran in the main monastic enclosure of Skellig Michael August 2010

Policies & programmes

Management Structures: The Department of Arts Heritage and the Gaeltacht[6] (DAHG) is responsible for overall policy and World Heritage liaison. The OPW is responsible for the implementation of the Management Plan and the day to day running of the property and the National Parks and Wildlife Service manage natural heritage protection. UNESCO recommended the appointment of a site manager to co-ordinate between the various agencies and stakeholders and drive forward the management plan and in late 2011 Grellan Rourke took on this role (UNESCO, 2007, Rourke, pers. comm.). Under the Skellig Michael Management Plan 2008–2018 a site management team overseen by the Skellig Michael Implementation Group (SMIG)[7] was established with members from both OPW and DAHG (Department of Environment Heritage and Local Government, 2008). Their stated aim is to maintain the OUV of the site by ensuring compliance with both the management plan and World Heritage requirements.

Visitor management: This is the responsibility of a Principal Officer in OPW. Due to increasing numbers of visitors and associated damage, OPW instigated a license system with local boatmen in 1994. The average number of visitors during the season is now 11,100 (Department of Environment Heritage and Local Government, 2008). In 1987 an official guide service was introduced and the guides currently reside permanently on the island during the tourist season (approximately May–September). Visitor access outside of this period is not officially permitted but is virtually impossible to police (UNESCO World Heritage Centre, 2006, UNESCO, 2007). The guides provide health and safety advice as

[6] The State heritage function was moved from the Department of Environment and into the Department of Arts in 2011.

[7] Members included in the stakeholder interviews were Dr Ann Lynch, Edward Bourke & Grellan Rourke.

well as monitoring visitors in the monastery and providing information but there can be issues of overcrowding within the monastic enclosure (O'Halloran, pers. comm., figure 7.6) and balancing the integrity of the site with visitor safety is an ongoing issue.

Legislative Protections: The site is protected under the National Monuments Act 1930–2004 and all works are subject to consent from the Minister of Arts Heritage and the Gaeltacht. It is also protected, along with the neighbouring island of Small Skellig, under Ireland's Wildlife Acts 1976–2000 as a Statutory Nature Reserve for its seabird breeding habitat and as a proposed Natural Heritage Area (NHA). In addition, it is a Special Protection Area (SPA) under the EU Birds Directive 79/409/EEC (Department of Environment Heritage and Local Government, 2008).

Information & knowledge

Climate Change: The 2008 Management Plan for Skellig Michael makes specific reference to concerns regarding climate change impacts (Department of Environment Heritage and Local Government, 2008). It states that changes in the direction of winds and increasingly adverse weather conditions have already affected the capacity to carry out conservation works and visitor access on the island. The Implementation Group recommends scientific climate recording (Skellig Michael Implementation Group, 2009).

Human Resources: The conservation of the site is currently undertaken by a multi-disciplinary team within which there has been a great deal of continuity. The project is led by a conservation architect, an archaeologist a District Works Manager and a NPWS ranger.

The works are carried out by stone-masons skilled in dry-stone work and consultant specialists are involved as required. Many of these individuals have worked on the site for twenty or thirty years and have an intimate understanding of the property that is very valuable when it comes to ensuring its ongoing preservation. Works are planned before each season, the main aim being to stabilise the structures with minimal intervention. Plans are discussed with National Parks and Wildlife representatives if there may be impact on the breeding birds, and with the Expert Advisory Committee (Rourke, pers. comm., Department of Environment Heritage and Local Government 2008).

Implementation

Conservation & maintenance: Some repairs to the monastic structures were carried out in the 1880s and 1930s (ICOMOS, 1996). The current programme of conservation and archaeological works began in 1978 (Bourke and Hayden, 2011, Bourke et al., 2011). Conservation is managed by the Senior Conservation Architect for OPW in conjunction with the Senior Archaeologist of the DAHG. The need to consider nesting birds in some cases delays operations (Department of Environment Heritage and Local Government, 2008). The 20th century works included the removal of some 19th century additions; surveying and excavation; and restoration and consolidation of the dry stone walls, terraces and structures (ICOMOS, 1996). In some cases concrete has been used to reinforce dry stone walling, especially if the foundations were weak or there was excessive pressure from the retained material (Department of Environment Heritage and Local Government, 2008). In 2007 controversy surrounding the conservation measures undertaken, particularly those carried out in the late 20th century on the south peak, lead to a UNESCO-ICOMOS Reactive Monitoring

Mission. The mission concluded that although the works had radically transformed the appearance of the remains, the OUV of the site remained intact but academic publication of the work was set as a priority (UNESCO, 2007). This requirement was partially fulfilled by publication of the archaeological excavations in 2011 (Bourke et al., 2011).

Figure 7.7. Conservation of retaining wall for roadway from pier to monastery steps (Small Skellig visible in background) August 2012

Monitoring/feedback

All works on Skellig Michael have been preceded by surveys, film and photographic documentation so there is an extensive archive of the property now held by OPW (Rourke, pers. comm.). In 1982 a photogrammetric survey 1:1000 of the island was completed and in

2007 this was updated by a LiDAR survey. The LiDAR provides high definition (100 points/m^2) coverage for the structures on the north and south peaks, providing excellent baseline recording. Surveys of the geology and the lichen have also been conducted (Department of Environment Heritage and Local Government, 2008, Skellig Michael Implementation Group, 2009). Planned future actions in the management plan include a vegetation survey (A20); inclusion on census of grey seals (A21); monitoring important bird species (A17); and extending the Special Protection Area to include the sea between the two islands (A28) (Department of Environment Heritage and Local Government, 2008).

There is no structured monitoring regime for the cultural heritage on the island. Condition assessment occurs on an ad hoc basis as part of the annual maintenance programme. In practice this works quite well as the same individuals have worked on the site for a long period but as this situation may change in the future, a more systematic approach would be preferable. There are unique challenges to undertaking monitoring on Skellig including the seasonal access, extreme weather and the heterogeneous nature of the dry stone architecture (Rourke, pers. comm.). The Management Plan's stipulated approach for adapting to climate change under Objective 11 is to undertake close monitoring and observation followed by regular maintenance (Department of Environment Heritage and Local Government, 2008). The plan states that a framework for monitoring climate change will be developed in conjunction with ICOMOS Ireland (Action 57) and those possible impacts of climate change on the site will be monitored with a view to development of the National Climate Change Strategy (Action 58).

Subsequent to the drafting of the management plan ICOMOS Ireland did produce a set of recommendations for the monitoring of climate change at the heritage sites of Clonmacnoise and Brú na Bóinne, however, Skellig Michael was not included (Daly et al., 2010). The main reason the site did not feature was the stated difficulty of establishing and maintaining technological monitoring systems on the island (Rourke, pers. comm.). The practicalities of having a climate station on Skellig due to the extremely high winds, which have destroyed infrastructure previously, mean that alternative solutions will need to be found. Logistical issues with accessing the island and the availability of services make equipment failure and repair a potential minefield of problems. Maintaining continuity is also problematic when there is a separation between those gathering the information and those processing it. For example, guides on the island were taking rainfall measurements for a period but had no subsequent knowledge of what was done with the data or why the project ended (Harris, pers. comm.). Any monitoring solution for Skellig Michael will need to address all of these issues if it is to succeed in gathering long-term data. The employment of indicators, including a specific stone indicator tool installed at the site as part of this research, may go some way to addressing these issues (chapters 9 and 10). The Met Eireann station at Valentia is a Global Atmospheric Watch station, linked to a phenological garden. The proximity of this to Skellig Michael has potential for development in terms of integrating data analysis (Sweeney et al., 2002).

7.4.

STEP 3. IDENTIFY LIKELY HAZARDS FOR EACH VALUE UNDER THE FUTURE CLIMATE USING THE MATRIX OF IMPACTS

This step requires assessors to imagine how, under projected future climate conditions, the values of the site might be affected. The Matrix developed in chapter 3 (table 3.1) provides a reference tool to aid this process.

7.4.1. Application of Impacts Matrix – Observations by stakeholders

In the interviews, stakeholders were shown a simplified version of the Matrix and asked to mark impacts they considered relevant to Skellig Michael (see Appendix 2). The responses of the stakeholders were collated and those impacts identified by respondents are listed in table 7.6 in order of frequency. This exercise revealed some weaknesses, both in the Matrix and in applying the simplified form for stakeholder review. The simplified matrix used for interviews contained only potential impacts without the climate parameters. While the intention was to make it more accessible for respondents, removing the cause-effect link actually resulted in a lack of clarity (e.g. does concern for 'increased water penetration' relate to damage by salts, biological growth or dissolution?). For this reason in future assessments it is suggested that the full Impacts Matrix be employed.

The exact interpretation of the terminology in the Matrix also varied depending on the respondent's background. Therefore, wherever possible, descriptive clarification was sought. For example, when a respondent refers to landslide being a problem but then goes on to describe redeposition of material by water it can be understood that they are actually referring to pluvial flooding or soil erosion. Technically landslide is a catastrophic event and landslip a localised small scale feature, but both relate to failure of slope rather than the washing away of surface material (Meehan, pers. comm.). The exercise also demonstrated some gaps within the Matrix, and by association, in the existing research literature from which it was developed (chapter 3). As a result of the case study applications the Matrix was added to and the terminology clarified where possible but it should still be considered as a guide, not a definitive list.

Finally, the assessor has to consider that the stakeholders were in many instances considering the issue of climate change impacts for the first time. While they all had a wealth of knowledge of the site, familiarity with issues surrounding climate change varied greatly. Interpretation of stakeholder responses is the responsibility of the expert assessor. Thus, this person must use the original contributions together with collected data in a measured way. Where a stakeholder is commenting on an area within their expertise however, such as a geologist commenting on landslide risk, this would not require further comment.

7.5.

STEP 4. DEVELOP INDICATORS FOR THE ELEMENTS OF VULNERABILITY (exposure, sensitivity and adaptive capacity)

The topic of selecting and using indicators is discussed in chapter 9. Assessors must attempt to find the most useful indicators for the impacts with which they are concerned and this can be challenging. The indicators proposed for ongoing evaluation at Skellig Michael are outlined in table 7.8.

Table 7.8. Proposed indicators of vulnerability for Skellig Michael to potential climate change impacts

Impact	Indicator	Proxy for	Functional Relationship
Erosion of soil	% vegetation cover	Exposure to soil erosion	↑ % cover = ↓ exposure
Subsoil instability	Number of animal burrows	Sensitivity of structures and archaeological deposits to disturbance	↑ number = ↑ sensitivity
Pluvial flooding - mechanical damage by water flow	Volume of material moved	Sensitivity of monuments and landscape to water flow	↑ amount of material = ↑ sensitivity
Collapse caused by water pressure	Time taken for surface water to drain after rainfall	Exposure of monastic walls to saturation pressure	↓ time = ↓ exposure
Destabilisation of foundations after heavy rain	Condition of soil cover	Exposure of structures to destabilisation	↑ erosion, cracking etc. = ↑ exposure
Wave damage – salt dosing and mechanical action	% vegetation die back on south east slope	Exposure landscape to increased frequency and severity of storms/waves	↓ % cover = ↑ exposure
Change in biodiversity	Species survey (birds, lichens)	Sensitivity of natural heritage to changing climate	↑ change = ↑ sensitivity
Changes in biodiversity	Implementation of actions from management plan (A14–28 including extending SPA, dealing with invasive species and cooperation with NPWS)	Adaptive capacity (planning and mitigation)	↑ actions implemented = ↑ adaptive capacity
Changed microbiological growth	Lichen survey Stone cube indicator tool.	Sensitivity of microbiological organisms to changes in climate	↑ change = ↑ sensitivity

Impact	Indicator	Proxy for	Functional Relationship
Increased salt loading of stone	Stone cube indicator tool	Exposure of stones to salt weathering	↑ incidence = ↑ exposure
Structural damage by wind – stone throw	Number of stones dislodged outside of visitor areas/season	Sensitivity of structures to damage by wind	↑ volume = ↑ sensitivity
Surface weathering by wind and rain	Stone cube indicator tool	Exposure of monuments to surface erosion	↑ measured loss = ↑ exposure
Disruption of access to island	Number of boat landings	Adaptive capacity re. conservation and maintenance regime	↓ landings = ↓ adaptive capacity
Increased visitor pressure	Length of season Number of boat landings	Exposure to mechanical damage	Longer season = ↑ exposure
Increased visitor pressure	Implementation of actions from management plan (A30–41 including establish defined annual season and study visitor trends and impacts)	Adaptive capacity (planning and mitigation)	↑ actions implemented = ↑ adaptive capacity
All	Human and civic resources = No change in professional staffing levels.	Adaptive capacity (management)	Stagnant recruitment = ↓ adaptive capacity

7.6.

STEP 5. ASSESS VULNERABILITY BY ENTERING VALUES FOR EXPOSURE, SENSITIVITY AND ADAPTIVE CAPACITY INTO THE CAUSAL MODEL

This is the point at which all the research generated during the previous 4 steps is amalgamated to produce an evaluation. Assessors must interrogate the data and use their expert judgement to evaluate **sensitivity**, **exposure** and **adaptive capacity** on a scale of 1 (low) – 3 (high). A simple cumulative model based on one previously developed by the author (Daly, 2008) was used (table 7.9). The assessment is presented in detail (table 7.10) and the results are also summarised to facilitate communication (table 7.11).

Table 7.9. Causal Model for site specific evaluations of vulnerability to climate change impacts (Daly, 2008)

Matrix Input	**Exposure (E)**	**Sensitivity (S)**	**Adaptive Capacity (AC)**	**Measure of Vulnerability (MV)**
Impact of concern	1–3	1–3	1–3	V = (E+S) - AC

7.6.1. Example of criteria for evaluating the elements of vulnerability

Sensitivity

- Damage history
- Material characteristics
- Protective factors (reducing)
- Compounding factors (increasing)
- Tolerance range

Exposure

- Climate projections
- Aspect
- Topography

- Situation
- State/condition

Adaptive Capacity

- Can existing management strategies and procedures moderate effects?
- Are management procedures sufficiently flexible?
- Is there realistic potential for implementing adaptation measures (e.g. availability of finance, human resources)?
- Will key values be reduced i.e. can the loss be coped with?
- Is there an awareness of or engagement with the issue?

Table 7.10. Calculation of the Measure of Vulnerability of Skellig Michael heritage values to the projected impacts of climate change - utilising research on indicators, sensitivity, exposure and adaptive capacity.

Climatic Parameter	Sector or W. H. Value	Impact	Indicator	Sensitivity	Exposure	Adaptive Capacity	Measure of Vuln.
Radiation	Cultural landscape, Structures & features	Thermoclastic weathering	Temp. differential at stone surface	Low (only seen to occur on south peak)	Low (slight reduction in radiation predicted)	Low	Low (1)
Rainfall	Buried Deposits	Erosion & exposure	% vegetation cover	Low (deposits in monastery)	Low (sheltered in monastery)	Medium (excavation)	Low (0)
Rainfall	Buried Deposits	Drying & loss of organics/ stratigraphy	Survey levels	Low (lack of organics)	Low (deep deposits)	Medium (excavation)	Low (0)
Rainfall	Buried Deposits	Subsoil instability	Survey levels	Medium (deposits in monastery)	Medium (wall collapse)	Medium (loss not critical)	Medium (2)

Climatic Parameter	Sector or W. H. Value	Impact	Indicator	Sensitivity	Exposure	Adaptive Capacity	Measure of Vuln.
Rainfall	Cultural landscape	Soil erosion	% vegetation cover	High (shallow soil & steep topography)	High (drier summers and more intense rainfall)	Medium (control of visitors)	High (>3)
Rainfall	Cultural landscape	Landslip	Caine's threshold	Low (rock fall and soil erosion occurs preferentially)	Med (intense rain & sea spray)	Low	Med
Rainfall	Cultural landscape	Pluvial Flooding (water run off)	Material moved	Low (only in paved areas or roadway)	Low (few paved areas)	Low (no drainage infrastructure)	Low (1)
Rainfall	Structures & features	Pressure & collapse	Drainage of surface water	High (history of wall collapse)	High (rainfall and runoff)	High (conserva-tion)	High (3)
Rainfall	Structures & features (esp. steps)	Soil erosion & destabilisation	No. of burrows	High (foundation of shallow soil & vegetation)	High (rainfall)	High (maintenance regime)	High (3)
Rainfall	Cultural landscape	Loss of vegetation drought	% vegetation dieback	High (shallow soil poor moisture retention)	Low (predictions for summer rain)	Low (slow to recover)	High (3)
Storms – extreme rain & waves	Cultural landscape	Loss of vegetation (salt or overwatering)	% vegetation dieback	High (previous occurrences)	Medium (dep. altitude & aspect)	Low (slow to recover)	High (>3)
Temperature	Cultural landscape	Change/loss of species	Species survey	Medium (4 years for population	High (important nesting	Medium (puffins adapted diet)	High (3)

Climatic Parameter	**Sector or W. H. Value**	**Impact**	**Indicator**	**Sensitivity**	**Exposure**	**Adaptive Capacity**	**Measure of Vuln.**
				affected)	site)		
Temperature & rainfall	Structures & features	Changed microbiological growth	Lichen survey/ cubes	Low (few decorated surfaces)	Medium (no regulation possible)	Low (treatments restricted)	Medium (2)
Temperature & rainfall	Structures & features	Salt crystallisation	Cubes	Low (no history of salt damage)	High (incr. of salt cycles)	Medium–low (protective lichens)	Low–Medium (1/2)
Wind	Structures & features	Structural damage	No of stones dislodged	High (common occurrence)	High (High on S med. on N)	High (sacrificial courses)	High (3)
Wind & rainfall	Cultural landscape	Rock fall and erosion	Volume dislodged	High (common occurrence)	High (wind)	Low (topography)	High (>3)
Wind & rainfall	Structures & features	Mechanical weathering/ abrasion	Cubes	Low (no fine details)	High (High on S med. on N)	Medium (loss not critical)	Medium (2)
Wind & SLR	Structures & features	Wave damage	Condition	Low (little monastic remains)	Medium (only lower level)	Medium (conservation of walls)	Low (1)
Wind & SLR	Structures & features	Access	No. of boat landings	High (history of problems)	High (wind)	Low (no other access)	High (>3)

7.7. STEP 7. REFINE AND COMMUNICATE RESULTS

7.7.1. Summary of results

The monastic heritage of Skellig Michael developed in an extreme environment and is well suited to severe climatic conditions because of its sympathetic relationship with the landscape. By contrast the lighthouse period additions, more complex mortar built structures, are more likely to suffer from any increase in extreme weather. The main vulnerabilities identified for the island's entire built heritage relate to destabilisation caused by rain and wind. For the monastic structures this is closely tied to the wider issue of water saturation, soil movement and erosion within the landscape.

> *The aggression out on the Skelligs with regard to rain and wind is that it erodes; it washes out the mortar from walls, it tries to return every structure out there to what it would have been naturally much faster than on mainland* (O'Leary pers. comm.).

There is relatively little by way of undisturbed archaeological deposits outside of the central monastic enclosure and this is reflected in the vulnerability assessment. In the cultural landscape complex interactions between rainfall, wind and animal activity may result in loss of vegetation, soil erosion and rock fall. The predicted increase in temperatures due to climate change is likely to impact upon the natural heritage more than cultural remains. There is evidence already of a change in the availability of fish species possibly due to rising sea temperatures, and of the nesting birds changing their diet accordingly (Harris, pers. comm.). It is conceivable that the importance of the Skellig islands for avian preservation will increase due to negative impacts on breeding sites elsewhere. Should this happen it could add to existing restrictions on maintenance and conservation work to structures in nesting areas, thereby indirectly compromising the resilience of the cultural heritage.

Table 7.11. Summary for decision makers of predicted climate change vulnerabilities for Skellig Michael to 2101 based on research and evaluation (table 7.10)

	Buried Deposits	*Structures and features*	*Cultural Landscape*
Impacts for which Vulnerability is High (priority 1)		• Pressure collapse • Erosion of foundations • Structural damage by wind • Access	• Soil Erosion • Loss of vegetation • Change (loss/gain) of species • Rock fall
Impacts for which Vulnerability is Medium (priority 2)	• Subsoil instability	• Changed microbial growth • Mechanical abrasion • Infrastructural changes[8]	• Landslip
Impacts for which Vulnerability is Low		• Salt crystallisation • Thermoclastic weathering[9]	• Wave damage • Damage by water run-off

7.7.2. Stakeholder review

The completed assessment was circulated to stakeholders for comment (Appendix 2) and the feedback was divided into four categories (table 7.12):

1. **No changes:** The stakeholder was happy with all personal attributions and was in agreement with the results of the assessment. No alterations or amendments suggested. For example feedback from one respondent stated the assessment was *comprehensive and well documented* (Ryan, feedback form, 7.6.2013).

[8] Added following stakeholder review.

[9] Although overall this is low, the West face of the South peak is extremely vulnerable to this form of weathering (Rourke, pers. comm.)

Table 7.12. Breakdown of stakeholder feedback

Stakeholder	**1. No changes**	**2. Minor changes**	**3. Major changes**	**4. No response**
Bourke, Edward				
Connolly, Michael (Dr)				
Harris, Bob				
Lavelle, Des				
Lynch, Ann (Dr)				
O'Halloran, Claire				
O'Leary, Jack				
O'Shea, Patrick				
Rourke, Grellan				
Ryan, Michael (Dr)				

2. **Minor changes:** The stakeholder was in agreement with the results of the assessment but had some minor corrections of fact and/or clarification of opinion to suggest. These corrections are not detailed as they have no implications for the assessment results. The changes were made immediately and are incorporated into the above text.

3. **Major changes:** The stakeholder suggested amendments or corrections which had possible implications for the final assessment results. In this case the comments and resultant actions taken are detailed (sections 7.7.3. and 7.7.4.).

4. **No response:** The stakeholder did not respond to the request for feedback. Following postage of the hardcopy form and draft text, non-responsive stakeholders were subsequently sent Email reminders and finally contacted by phone. In a few cases no response was forthcoming.

7.7.3. Suggested major changes - amendments with implications for the final assessment

Adaptation

Bob Harris suggested that existing pressures to improve visitor amenities and access could be intensified at Skellig Michael by the impacts of climate change. In his opinion, increased erosion and rock fall, or greater difficulty in landing due to storms, would be likely to force infrastructural changes (Harris pers. comm.). These changes, such as hand rails on the steps, are currently being resisted in order to preserve the unique and original aspect of the island landscape. The indirect impact of these adaptations could be a reduction in the integrity and OUV of the site (Harris, pers. comm.).

Thermoclastic weathering

Grellan Rourke identified the west facing terraces on the south peak as having a high exposure and known sensitivity to thermoclastic stone decay. Rourke agreed that the general vulnerability to thermal weathering was low but suggested that the particular vulnerability of the south peak be noted.

Pluvial flooding/water runoff

Rourke disagreed with this being ranked as high in the final calculation of vulnerability. He stated that in his experience the peat soil on the island absorbs rainfall and that water runoff or pluvial flooding only affects paved areas in the monastery (Rourke, pers. comm.). The weight of the absorbed rainfall causes pressure collapse and slippage but this is not related to surface water.

7.7.4. Response to feedback and implications for practice

- Harris raised a concern that pressure to make the island more tourist friendly could be exacerbated by climate change impacts. This indirect impact of climate change on the cultural landscape was not factored into the original vulnerability assessment (table 7.10). The sensitivity of the landscape values to any structural intervention is extremely high given the architecture and ecology of the island. The exposure at the moment is low as the management are resistant to adding infrastructure, but this could come under intense pressure in the future if the climate worsens conditions for visitors. Adaptive capacity is low as there is very little that can be done to mitigate the effects of modern structures on the medieval landscape.

Table 7.13. Assessment of vulnerability of Skellig Michael to infrastructural adaptation

Climatic Parameter	**Sector or W. H. Value**	**Impact**	**Indicator**	**Sensitivity**	**Exposure**	**Adaptive Capacity**	**Measure of Vuln.**
Rainfall & wind	Cultural landscape	Infrastructural changes	Management planning	High (3)	Low (1)	Low (1)	Medium (2)

The Measure of Vulnerability to this indirect impact of climate change is therefore calculated as medium (table 7.13). This was added into the final summary of vulnerabilities for Skellig Michael (table 7.11).

> **Implication for practice:** Indirect impacts of climate change are not included in the Impacts Matrix, this makes them harder for stakeholders to consider. Future improvement of the Framework could include consideration of a matrix or similar for indirect impacts.

- The differential in vulnerability between the south peak and the rest of the island to thermoclastic weathering was addressed by inserting a footnote into the summary results. This clarified that there is one localised area where the built heritage is regarded as having 'high' vulnerability to this effect.

> **Implication for practice:** This raises the general issue of how to account for micro-climates within assessments. In the case of the assessment of Skellig Michael the climate measurements used were for Valentia Island, the nearest weather station. This is likely to be slightly different to the micro-climate that exists on the island itself however (Rourke, pers. comm.). The installation of equipment to monitor climate conditions on the island would go some way to clarifying the suspected differences. Rourke is in favour of installing monitors providing they are discreet and can function without human intervention in the off season. The choice of indicators must also take the

existence of micro-climates into account. The installation of the LegIT in three different locations on the island, including one on the South peak, is one example of how this can be addressed.

- To address the comments on pluvial flooding by Rourke the calculation of vulnerability was revised taking into account that surface run off mainly occurs in paved areas in the monastery and the lighthouse roadway. This reduced the ranking of this impact in the final results from high to low (table 7.14).

Table 7.14. Re-Assessment of vulnerability of Skellig Michael to pluvial flooding: Initial calculation of Vulnerability (top line) revised (bottom line in bold) following feedback

Climatic Parameter	**Sector or W. H. Value**	**Impact**	**Indicator**	**Sensitivity**	**Exposure**	**Adaptive Capacity**	**Measure of Vuln.**
Rainfall	Cultural landscape	Pluvial Flooding (water run-off)	Material moved	*Medium (some damage in past)*	*High (steep topography)*	Low (no drainage infra-structure)	*High*
				Low (only in paved areas or roadway)	**Low (few paved areas)**	As above	**Low**

7.8. CONCLUSIONS

In this chapter a preliminary assessment of vulnerabilities for the World Heritage Site of Skellig Michael to climate change was carried out using the six step Vulnerability Framework developed in this thesis. The assessment combined current theory on climate change impacts with downscaled REMO projections, site based research and stakeholder consultation. The results provide an indication of future priorities but need to be regularly reviewed and supported wherever possible by scientific monitoring, not least because of the uncertainty inherent in climate change projections. The installation of climate monitoring equipment and collection of scientific data on precipitation, wind, temperature and radiation will be vital for gaining a more precise understanding of the micro-climate that exists on the island. Experience suggests that the weather on Skellig tends to be more extreme and intense than on the mainland (Rourke, pers. comm.). If this is shown to be the case it has implications for interpretation of the climate change projections.

The application of the Framework and Impacts Matrix to a practical case study site illustrated some of the strengths and weaknesses. In the next chapter the robustness of the Framework will be tested further by repeating the process on a different set of values at the World Heritage Site of Brú na Bóinne.

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CHAPTER 8.

VULNERABILITY ASSESSMENT OF BRU NA BOINNE

8.1. INTRODUCTION

In this chapter the Vulnerability Framework (figure 6.3) was applied to the case study site of Brú na Bóinne, where a very different set of values and environmental concerns to those of Skellig Michael are present. Application of the Framework to two different case studies is intended to test and improve its flexibility as a management tool.

8.2.

STEP 1. DEFINE THE HERITAGE VALUES TO BE ASSESSED

8.2.1. Site description

Brú na Bóinne is one of two World Heritage Sites (WHS) in the Republic of Ireland. It is located in the north-east, 9km from the coast at Drogheda. The designated World Heritage property and buffer zone cover approximately 3,300 hectares encompassing 93 recorded monuments protected under national heritage legislation[1] (figure 8.1). Characterised by the bend in the River Boyne where it encounters a hard shale ridge the area also includes several wetland habitats and rare species protected under EU legislation.[2]

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[1] National Monuments Act 1930-2004

[2] Protected sites include Special Areas of Conservation under Annex I (habitats) & Annex II (species) of the EU Habitats Directive 1992 and Special Protection Areas under EU Birds Directive 79/409/EEC.

Figure 8.1. Recorded monuments in core and buffer zones of Brú na Bóinne. (Duchas 2002, 18)

There are 31 known Megalithic passage tombs at Brú na Bóinne, dating to the time around 3,000 BCE. In the main tombs of Knowth, Newgrange and Dowth many of the large stones (orthostats), in the passage, chamber, and around the exterior, are carved with designs (figure 8.2). The majority of the stone used by the Neolithic builders is greywacke or green grit, Palaeozoic sandstone. There are 400 known pieces of rock art from Brú na Bóinne and when this is compared to only 200 from all similar sites in Western France the importance of the site for Megalithic art is clear (Eogan, 1986). The cultural landscape of the site spans the history of human habitation in Ireland, from Neolithic flint scatters to World War II defences

(Duchas the Heritage Service, 2002). Some of the most significant historic elements include the Battle of the Boyne site and Ireland's earliest inland canal system. The Neolithic topography and sight lines linking the monuments are still in evidence thanks to the persistence of traditional mixed farming (figure 8.3). The most important of the views is from Newgrange to the ridge lying east of the Boyne, from where the mid winter sun penetrates the central chamber at dawn.

Figure 8.2. Entrance at Newgrange showing roof-box and carved entrance stone K1

8.2.2. Values present at the site

In 1993 the Archaeological ensemble of the Bend of the Boyne was listed as World Heritage under three of UNESCO's criteria for Outstanding Universal Value (OUV) (ICOMOS, 1993):

Criteria i: As a *masterpiece of human creative genius* for the Megalithic rock art collection.

Criteria ii: Because it *exhibits an important interchange of human values over a span of time.* In particular the archaeological and extant remains that indicate continuity of settlement from the Neolithic to Late Medieval period.

Criteria iv: As an *outstanding example…which illustrates a significant stage in human history* for the Megalithic passage tomb assemblage.

Using these criteria the vulnerability of the World Heritage property will be analysed at four levels:

1. Rock art (i)
2. Passage tomb structures (iv)
3. Buried deposits (ii) and (iv)
4. Cultural Landscape

NB Cultural Landscape

Unlike Skellig Michael, Brú na Bóinne is not an officially designated World Heritage Cultural Landscape. The likely reason for this is that the revised criteria (iv), referring to Cultural Landscapes, was only introduced in 1992 at which stage the nomination process for Brú na Bóinne would already have been underway. Despite this lack of official designation, subsequent national and UNESCO documents do place considerable emphasis on the site as a cultural landscape (Smyth, 2009, UNESCO-ICOMOS, 2004, Duchas the Heritage Service, 2002).

> *Without a doubt, the outstanding universal value attached to Brú na Bóinne is largely attributable to the ambiance there, which is integral to all three criteria. That ambiance is created by the totality of sights, sounds, and other sensory input presented to a person in the landscape* (Comer, 2011: 5).

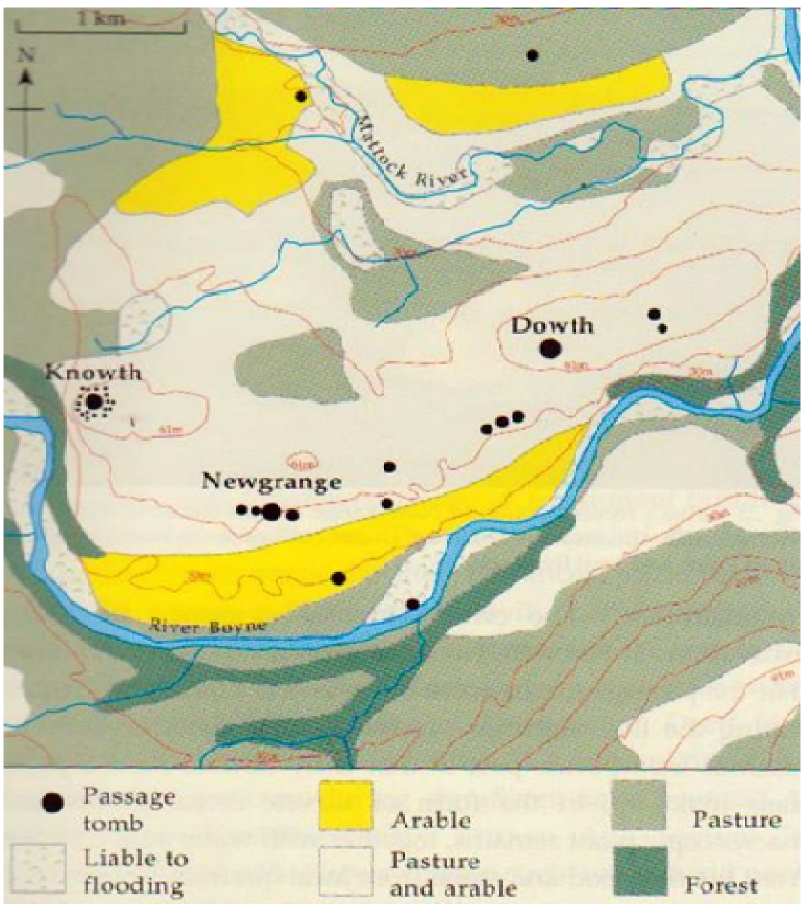

Figure 8.3. Neolithic land use pattern (Stout 2002, 31)

8.3.

STEP 2. UNDERSTAND THE EXPOSURE, SENSITIVITY AND ADAPTIVE CAPACITY OF THESE VALUES OVER TIME

As with Skellig Michael, desk based research and site visits (2008, 2009, 2010, and 2012) were combined with stakeholder interviews to create a rounded understanding of the site. Some primary research gathered by the author for a Masters in World Heritage thesis was also utilised (Daly, 2008).

Figure 8.4. View of cultural landscape at Brú na Bóinne, February 2008

8.3.1. Stakeholder interview procedure

Stakeholders were defined as those who have a detailed knowledge of Brú na Bóinne, either through their work or research. This includes Office of Public Works (OPW) employees and professionals involved in archaeology and conservation works (table 8.1). Where possible the interview was conducted in person or by phone, in a few cases the participants preferred to self-administer the questions and this was facilitated. The structured interview consisted of six questions relating to how climate has, and may in the future, impact on the heritage of Brú na Bóinne. The interviewees were shown a simplified version of the Impacts Matrix to help them identify issues of concern under future climate change (Appendix 2).[3]

Table 8.1. Stakeholders consulted for Brú na Bóinne listed alphabetically

Name	**Institution**	**Details**
Brady, Conor (Dr)	Lecturer in archaeology Dundalk Institute of Technology	Undertaking landscape based archaeological fieldwork in the Brú na Bóinne area
Chadwick, Jill	Architectural Conservation Officer, Meath County Council, Abbey Road Navan	Member of Brú na Bóinne management plan steering committee.
Comer, Douglas (Dr)	Principal, Cultural Site Research and management Inc. Maryland USA. Co-President and Expert Member, ICOMOS International Scientific Committee on Archaeological Heritage	Author of expert report for An Bord Pleanála: *Brú na Bóinne World Heritage Site N2 Slane Bypass; Heritage Impact Assessment* (2011)
Cumming, William	National Inventory of Architectural Heritage, Dept of Arts Heritage and the Gaeltacht	Senior Architectural Advisor, previously Senior Conservation Architect, Brú na Bóinne

[3] Dolan, Guinan, McMahon & Lumley were interviewed prior to developing the Matrix, they were provided with it during follow up contact to review/update their comments.

Name	**Institution**	**Details**
Dolan, Ana	National Monuments Service, OPW	Senior Conservation Architect for Brú na Bóinne
Gowen, Margaret	Consultant Archaeologist Margaret Gowen and Company	ICOMOS representative on management plan steering committee
Guinan, Loretto (Dr)	Heritage Officer, Meath County Council	County advisor on heritage and member of management plan steering committee
Lewis, Helen (Dr)	Lecturer in archaeology University College Dublin	Member of INSTAR project undertaking landscape characterization of river Boyne
Lumley, Ian	Heritage Officer, An Taisce	An Taisce own the Boyne canal
Lynch, Ann (Dr)	Senior archaeologist National Monuments, Dept of Arts Heritage and the Gaeltacht	Excavated in Brú na Bóinne
Lynch, Annette	Conservation Ranger, National Parks and Wildlife Service, Navan	Monitoring compliance with natural heritage protection legislation for NPWS
McMahon, Paul	Senior Conservation Architect, OPW	Previously with responsibility for Brú na Bóinne
Meehan, Robert (Dr)	Consultant geologist, Talamhireland	Research on Boyne valley paeleo-geology
Ritchie, Marc	Architectural Conservation Advisor, Architectural Heritage Advisory Unit, Dept of Arts Heritage and the Gaeltacht	Member of steering committee for management plan
Tuffy, Clare	Office of Public Works (OPW)	Service Manager, Brú na Bóinne Visitor Centre

8.3.2. Exposure

Exposure of cultural heritage is the degree to which an identified heritage value is exposed to climatic variations and their related impacts. It is determined by environmental conditions (physical and atmospheric).

Table 8.2. Summary of projections for Brú na Bóinne from the REMO model using the IPCC AR4 A1B scenario (calculated in Microsoft Access Jan 2013)

Period	Temperature Average (at 2m)	No. of Freeze Events i.e. non-consecutive days <0ºC	July Precipitation Average (mm/month)	December Precipitation Average (mm/month)	Intensity of Rainfall (No. of days ppt. >5mm/hr)
1960–1991	9.38ºC	127	87.3mm	92mm	84
2070–2101	11.1ºC	19	81.6mm	105.3mm	159
Projected Change	**↑ 2 ºC**	**↓85%**	**↓ 7%**	**↑ 14%**	**↑ 90 %**

Period	Wind Speeds (m/s) July Average & Min/Max (at 10m)	Wind Speeds (m/s) December Average & Min/Max (at 10m)	Wind Direction by % (at 10m)	Ground Surface Temperature (July) Max, Min & Standard Deviation	Cloud cover % Average for December
1960–1991	Average: 4.29 Max 12.4 Min 0.18 Std. D. 1.89	Average: 5.67 Max 16.9 Min 0.26 Std. D. 2.51	N 12 E 15 S 29 W 45	Max 26.6 ºC Min 7.6 ºC Std. D. 2.97	75%
2070–2101	Average: 4.46 Max 13 Min 0.21 Std. D. 1.97	Average: 5.68 Max 15.4 Min 0.39 Std. D. 2.46	N 11 E 13 S 26 W 50	Max 30 ºC Min 9.5 ºC Std. D. 3.01	77%
Projected Change	**↑ 4% Av.** **↑ 4% Std. D.**	**↑ 0.2% Av.** **↓2% Std. D.**	**N ↓ 1%** **E ↓ 2%** **S ↓ 3%** **W ↑ 5%**	**↑ 1.3% (Std. D.)**	**↑ 3%**

Table 8.3. Intensity of precipitation projections for Brú na Bóinne from the REMO model using the IPCC AR4 A1B scenario (calculated in Microsoft Access Jan 2013)

No of days/quarter with rainfall >5mm/hr	Jan–Mar	Apr–Jun	Jul–Sep	Oct–Dec
1960–1991	12	16	33	23
2070–2101	10	27	72	50
Projected Change	**↑ 17%**	**↑ 69%**	**↑ 118%**	**↑ 117%**

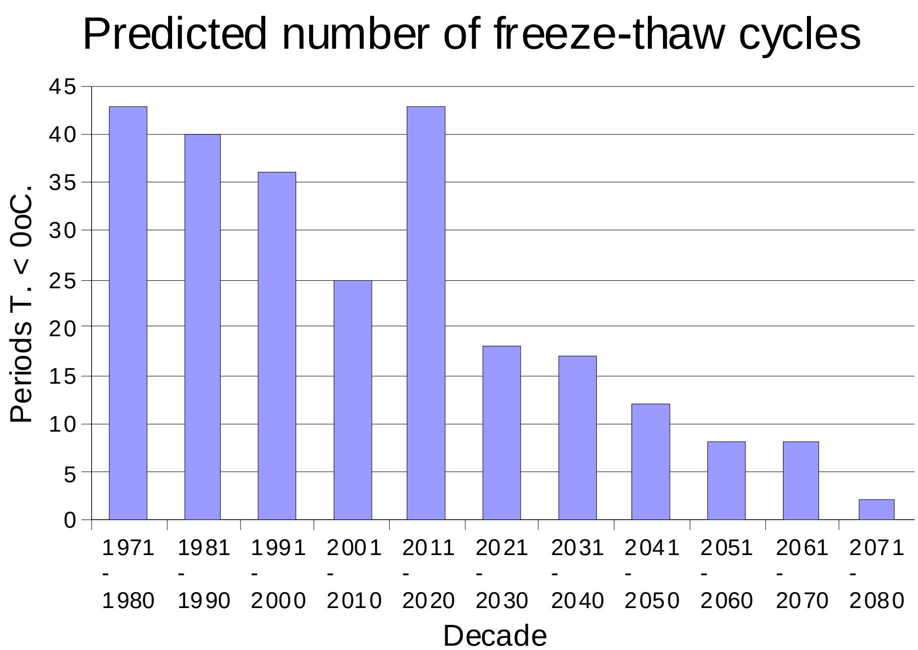

Figure 8.5. Number of freeze-thaw periods at Dublin airport projected by the ICARUS ensemble model using the A2 scenario (presented as decadal averages) (Daly 2008)[4]

The future climate projections were provided by the Max Plank Institute Hamburg under the auspices of the Climate for Culture (CfC) project. The data was generated in a REMO model using the IPCC A1B scenario. The site of Brú na Bóinne was modelled (-6.4463 longitude, 53.694567 latitude) for eleven 'heritage climate' parameters as defined by CfC Partners. The

4 This graph was created using datasets provided by Rowan Fealy, ICARUS, National University of Maynooth, Ireland.

model was run for three periods: 1960–91; 2020–51; 2070–2101. For the purposes of the vulnerability assessment the control period (1960–91) was compared with the far future period (2070–2101) (tables 8.2 and 8.3).

The REMO model projections suggest a decline in freeze thaw events of 85% by the end of the century. This is supported by climate projections from the ICARUS project in Maynooth (figure 8.5) and is a positive development for the site, where frost damage of the rock art is a major concern. There is a major shift in the rainfall patterns projected, with very significant increases in heavy rainfall events, and a less dramatic but significant seasonality i.e. drier summers and wetter winters. The drier summer conditions, combined with ground surface temperatures projected to rise by 2–3^{o} C in summer, have implications for soil conditions; impacting agriculture, natural heritage and buried deposits.

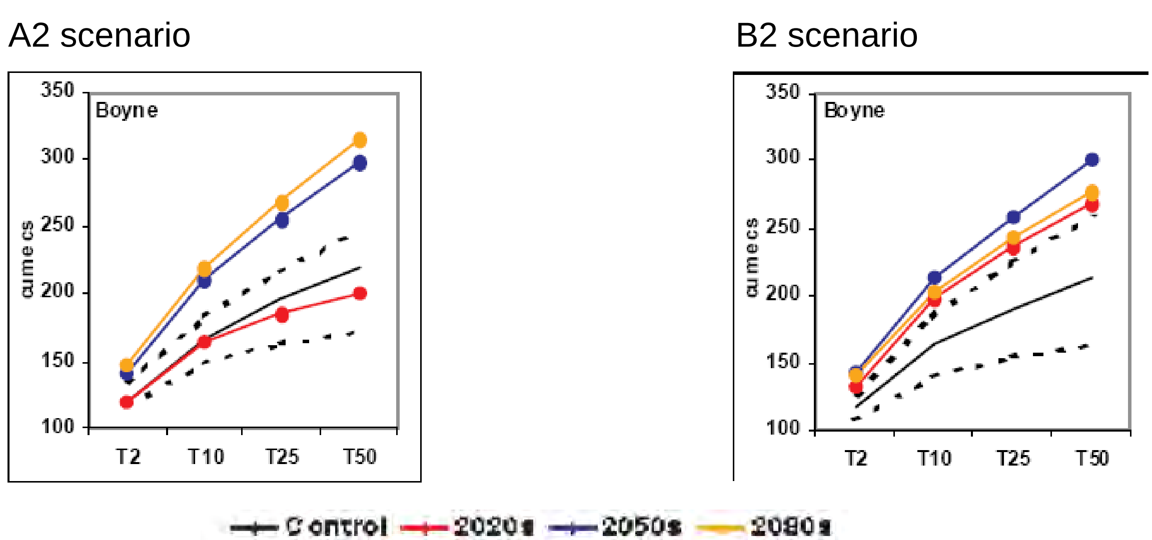

Figure 8.6. Changes in the magnitude of selected Boyne flood events for each future time period under the A2 & B2 emissions scenarios (Sweeney et al., 2008)

Future flooding on the Boyne was modelled by Sweeney, analysing four flood events of increasing magnitude according to the frequency of occurrence i.e. flood expected every 2, 10, 25 and 50 years. The results suggest that the high magnitude flood events on the Boyne will become more frequent by 2050, with a 47% increase in the 50 year flood event expected by the end of the century (Sweeney et al., 2008) (figure 8.6).

Combining the above projections with evidence gathered from stakeholders and secondary research it was possible to summarise the exposure of Brú na Bóinne to the main climatic parameters (wind, rainfall and temperature) and their associated impacts (table 8.4).

Table 8.4. Evaluation from primary and secondary research of the Exposure of heritage values in Brú na Bóinne to climate change impacts [5]

Climatic parameter and impact	Degree of exposure	Comment
Wind – impacts include tree throw, structural damage to buildings, particulate abrasion of surfaces, soil erosion and wind driven rain (abrasion, dissolution, increased penetration of water). Climate projections suggest an increase in summer wind speeds. Wind direction remains predominantly westerly.	External stones facing west are currently the most exposed to weathering by wind and wind driven rain as the prevailing winds are north-westerly to south westerly. This pattern is predicted to continue. Exposure to wind is high for the Megalithic tombs due to their elevated position.	The coverings at Knowth protect the kerbstones during the winter months, reducing their exposure. The REMO model does not predict a great increase in wind speed but suggests that where this occurs it may be during the summer months.

[5] List of impacts based on Matrix developed from literature (table 3.1)

Climatic parameter and impact	Degree of exposure	Comment
Rainfall – impact on flooding, landscape use, wetting and drying patterns, salt and microbiological activity. Summer drought leading to vegetation die back, soil erosion, subsidence and deterioration of water quality. The REMO model shows drier summers and wetter winters. The greatest change in precipitation is in increased intensity.	There is a 90% rise in the number of days where rainfall is projected to exceed 5mm/hour. July–September will see the greatest escalation in heavy rain, followed by October–December. The decrease in summer volume (July) at 7% is significant when combined with 2–3^{o} C. Rise in ground temperatures.	Concrete canopies at Knowth and Newgrange partially shelter the kerbstones from horizontal rain. Although volume remains constant the shift towards short periods of intense rainfall will alter wetting and drying cycles considerably. Concern for K1, the exposed entrance stone at Newgrange (Cumming, pers. comm.).
Sea Level Rise (combined with heavy rainfall) – Winter (December) rains, causing seasonal fluvial flooding are predicted to increase by 14% and the number of days where rainfall >5mm/hour in the autumn/winter period is predicted to increase by 200%. Global sea level rise of 0.5m could bring tidal waters approximately 500m further upriver e.g. when sea levels were 4m higher (3,500 BCE) the Boyne was tidal as far as Glenmore (Stout, 2002).	Winter flooding occurs below 20m (OPW *Benefiting Lands* indicate the 10–20m level) affecting 10% of recorded monuments; many are structures built on the river or canal such as weirs, mills and bridges, and as such may be resilient to flooding see Dept of Environment, SAC map, 2006, site code 002299 (Duchas the Heritage Service, 2002). Sweeney predicts more frequent high magnitude	Meath Local Authority flood reports mention four stretches of the river Boyne between Slane and Drogheda which flood once or twice per year (Meath County Council, 2006). From 2011–2016 OPW are undertaking the Flood Risk Assessment and Management Studies for Ireland (FRAM) and will eventually generate predictive flood maps for each catchment. Preliminary results of the

Climatic parameter and impact	Degree of exposure	Comment
	flooding on Boyne (figure 8.6) (Sweeney et al., 2008).	Boyne study are available online (Office of Public Works, 2013).
Radiation – thermoclastic weathering is caused by warming and cooling of stone surfaces creating thermal stress and eventual mechanical decay of stone.	REMO suggests rise in surface temperature of 2–3^{o} C. Standard deviation changes by only 1.3% into the far future suggesting large temperature differentials will not occur.	
Increased temperatures (combined with pollutants) - Endothermic chemical reactions (including acid hydrolysis of stone) accelerate at higher temperatures. A 10^{o}C rise has been associated with a doubling of hydrolysis and solubilisation rates (Bortz and Wonneburger, 2000). Higher temperatures are likely to alter the rate and type of microbiological growth. Exposure to pollutants (primarily SO_2, NO_x and O_3) and water is required for the chemical decay of stone; there is also a direct link between nitrogen oxides and the decay of stone by biological processes such as bacteria (McMahon, 2005).	None of the passageways are sealed therefore airborne levels of pollutants may be equal. Deposition rates are likely to vary according to location (due for example to the cleaning action of rain). The nitrogen deposited by gaseous nitrogen compounds (e.g. NO_2, N_2O and NO) stimulates biological growth and leads to increased biomass production, including that of 'weed' lichens (Paul Whelan, lichenologist, pers. comm.).	The present exposure to SO_2 is estimated as low due to strict environmental protection; total emissions of SO_2 were reduced by almost 60% nationwide between 1990 and 2003 (O'Leary, 2006). In 2012 Panda Waste applied for permission to build a biomass furnace and waste treatment plant approximately 4Km from Newgrange (McDonald, 2012) if this proceeds exposure is likely to increase.

Climatic parameter and impact	Degree of exposure	Comment
Hotter and drier summers (leading to land use change) – Combination of reduced summer rainfall and warmer temperatures has lead to predictions of a shift to arable farming for the east of Ireland (Sweeney et al., 2003).	Large amount of private land dedicated to farming within the World Heritage property. Between 2000 and 2010 the area of farmed land in Co. Meath increased by approximately 5% while the area dedicated to cereals and other crops went from 16% of the total to 19% (Central Statistics Office, 2013a)[6].	NPWS monitor the river and banks up to 2.5m on improved grasslands, further if there is a flood plain or scrub/woodland. (Annette Lynch, pers. comm.).
Freeze thaw - freeze-thaw cycles are equated with wet frost periods when temperatures fall below 0^{o}C .	The REMO model suggests an 85% reduction in the temperatures necessary for freeze-thaw weathering to occur. This is in line with other research e.g. Noah's Ark (Grossi et al., 2007) and ICARUS (figure 8.5).	Exposure to freeze-thaw action is highest for the external kerbstones at Newgrange and Dowth. At Knowth measures to wrap the stones in winter should reduce exposure to these effects although their effectiveness has not been measured (Dolan, pers. comm.) (figure 8.7).

[6] Exact figures are 179,540 hectares of farmland, 28,920 hectares dedicated to cereals and other crops in 2000 census and 191,846 hectares of farmland with 37023 under crops in 2010 census.

Figure 8.7. Main passage tomb (site 1) at Knowth with protective wrappings over the kerbstones, February 2008

8.3.3. Sensitivity

> *Sensitivity of cultural heritage is the degree to which an identified heritage value is affected, either adversely or beneficially, by [climate-related] stimuli. The effect may occur at artefact, assemblage or system level.*

The impacts identified by stakeholders were numerically ranked according to the number of respondents concerned with each one (table 8.5).

Table 8.5. Brú na Bóinne climate change impacts ranked in order of significance; based on number of stakeholders stating concern (for each impact)

Order of Concern	Cultural Landscape	Structures and Features	Buried Deposits	Rock Art
1			> Plough damage	
2	> Changes in land use			
3	> Change/loss of habitats & species > Erosion	> Erosion > Flooding		

Order of Concern	Cultural Landscape	Structures and Features	Buried Deposits	Rock Art
4	>Flooding	> Destabilisation of foundations > Increased loading pressure		
5	> Saline intrusion > Tree throw	> Increased penetration of water/time of wetness > Increased salts & salt weathering > Physical damage & collapse		> Changes in lichens > Changes in pollutants > Increased time of wetness > Increased penetration of salts and salt weathering
6	> Deterioration of water quality > Lengthening of growing season > Loss of vegetation > Change in fluvial characteristics			> Increased biological growth > Surface abrasion
7	> Silting of river bed	> Subsidence	> Accelerated &/or altered microbiological deterioration > Changes in soil chemistry/biota/structure > Erosion & exposure > Flooding > Physical damage from tree throw > Submersion	
8	> Increased recreational use > Landslide > Change in groundwater table > Storm damage		> Loss of stratigraphic integrity > Salt water intrusion > Sedimentation > Sub-soil instability	> Increased recreational use

Based on research and stakeholder interviews a number of recurring issues with respect to preserving heritage values in Brú na Bóinne were noted as significant. There is a degree of overlap between cultural landscape and the other categories. This is due to the fact that cultural landscape encompasses all the structures, monuments and buried archaeology as well as the natural heritage. In the detailed evaluation (table 8.6) general sensitivities described under landscape criteria are refined in relation to specific elements i.e. structures, buried deposits and rock art.

Table 8.6. Evaluation from primary and secondary research of sensitivity to climate change impacts for heritage values of Brú na Bóinne

Impact	Mechanism	Comment
Cultural Landscape		
Land Use - Alterations in agricultural practices resulting from climate change may impact on the nature of the mosaic landscape, wetland ecosystems and preservation of soil cover. Many of the monuments are fairly small and low-lying and could become physically and visually less accessible, limiting the ability to monitor (Ritchie, pers. comm.).	Hotter drier summers could lead to a shift from mixed to arable farming - Removal of hedgerows (mosaic landscape) Plough damage Soil erosion Irrigation in summer affecting water table and wetland ecosystems. Production of bio fuel crops e.g. elephant grass would hide monuments, removing visual links and views and impairing access (Chadwick, pers. comm.).	In October 2011 removal of hedgerows combined with heavy rain caused a ploughed field of newly picked potatoes to wash across the road into the Visitor Centre causing enormous damage (figure 8.8) (Tuffy, pers. comm.).

Impact	**Mechanism**	**Comment**
Ecological Change – loss or change of habitats and/or species affecting biodiversity (also change in vegetation) There has been no paleoclimatic study so cannot use past response (Meehan, pers. comm.).	Higher annual Temperatures and altered rainfall patterns – likely to affect breeding patterns in animals, the arrival of new species, and the growth cycles of flora – key species are salmon, River Lamprey, otter and kingfisher (Annette Lynch, pers. comm.).	Some monitoring carried out by volunteers in *An Taisce* and Birdwatch Ireland but no comprehensive study has been undertaken.
Erosion – of earthen monuments, the river bank and the farmland is possible with increased episodes of severe weather. Alterations to the river bank would impact on otter and kingfisher sites (Annette Lynch, pers. comm.).	Heavy rain can lead to gullying and erosion where vegetation has been removed, or has died back following drought. Intensification of agriculture with bigger fields could increase sensitivity to erosion.	Geologically stable glacial till, low risk of landslide but human activity could make it vulnerable to erosion (Meehan, pers. comm.).
River flooding – Increased intensity of seasonal flooding is likely on the Boyne floodplain and flooding may occur in areas currently not susceptible. The Boyne corridor is naturally very dynamic and there has always been movement of the	Rain – increased volumes or intensity of rainfall within the Boyne catchment would lead to higher flood levels and stronger more destructive water flow (figure 8.9). Possible effects are erosion; physical damage by flotsam; structural collapse; tree throw; contamination by water borne pollutants; soiling; and debris deposition.	One local farmer reports flood waters in recent years reaching higher levels (Redhouse, pers. comm.) In 2005 high Spring tides and seasonal flooding caused breach of the spine bank separating the canal and river at Oldbridge (McLoughlin, pers. comm.).

Impact	**Mechanism**	**Comment**
river edge e.g. the current Site B on the floodplain may have been a braided island at one stage (Brady, pers. comm.).		
Saline intrusion – movement of sea water far up the Boyne would have implications for the ecosystems and would be very problematic if this resulted in marine salt being introduced to the structures affected by floodwaters.	Sea level rise in conjunction with high tides could increase the reach of salt waters within the Boyne, possibly as far as the WHS. This may not be the first time either; it is thought that in the Neolithic period Newgrange was accessible by boat from the coast (Brady, pers. comm.).	Seals have already come up as far as Brú na Bóinne to fish for salmon (Tuffy, pers. comm.) In the Holocene period SLR possibly changed the length and flow of the Boyne, and may have resulted in the loss or damaging of some sites (Lewis, pers. comm.).
Deterioration of water quality – impacting on chemical and biological processes within the ecosystems, burial environment and flooded monuments.	Heavy rainfall and drier summers - increased run off from agricultural land and possible summer shortages. Sensitivity is being reduced by the Water Framework Directive improving water quality (Meehan, pers. comm.).	Key issue for NPWS, now and potentially in future, is water quality and pollution (Annette Lynch, pers. comm.).
Tree throw – causing structural damage, exposing buried archaeology and altering the landscape character e.g. the tree at Dowth	Heavy rainfall and high winds – tree roots are less secure in saturated ground, combined with wind this could result in increased tree fall.	Currently happens more in summer when trees heavy with leaves (Tuffy, pers. comm.).

Impact	Mechanism	Comment
(figure 8.10) is part of the identity of the monument (Gowen, pers. comm.).		
Change in groundwater table and hydrology – the flow and course as well as the salinity and silt load of the river may alter, affecting buried and extant heritage. Fluctuations could impact ecology, cause structural subsidence, and compromising archaeological preservation.	Altered rainfall pattern combined with anthropogenic factors such as drainage schemes, flood defences, irrigation systems, and development using impermeable surfaces.	Rainfall pattern alone is unlikely to alter the water table over short time periods as it is influenced more by annual volume, i.e. overall recharge will be similar every year regardless of when it falls provided the volume remains similar (Meehan, pers. comm.).
Buried Deposits		
Changes in land use and Plough damage – Majority of monuments within the WHS are on farmland and earthen structures are particularly sensitive to agricultural activity.	Hotter drier summers could lead to a shift from mixed to arable farming - ploughing associated with the predicted shift to arable crops endangers archaeological evidence as do deep rooted crops such as some bio fuels.	Protective heritage and environmental legislation regulations restrict disturbance of Recorded Monuments yet damage is occurring from ploughing (Brady, pers. comm.).
Changes in burial conditions – altered microbiological activity, changes in soil chemistry, pH, biota and structure.	Rainfall and atmospheric temperature influences the soil conditions. If changes occur in the water table or the river becomes more saline this would	*If there are changes in preservation conditions we may lose the dryland resources available for landscape history studies*

Impact	Mechanism	Comment
Alterations in the preservation equilibrium could cause accelerated deterioration and loss of archaeological resources.	also impact on affected areas. In addition microbiological activity and soil chemistry will be affected by agricultural practices especially in relation to the introduction of pollutants i.e. from fertilizers or pesticides.	*(e.g. soil data, molluscan data, and sedimentary history of the valley). This would be a great failing of heritage studies and is not an unforeseeable result of climate change*. (Lewis, pers. comm.).
Erosion and Exposure – erosion of sites may result in partial exposure e.g. gullying of earthen mounds; or it may result in complete loss e.g. site on river bank. In some cases it may reveal a previously unknown feature.	Heavy rain and increased river flow - erosion of soil especially where vegetation has been removed, or has died back following drought. *Only when you strip the vegetative cover* [incl. grass] *that glacial till becomes unstable* (Meehan, pers. comm.).	Every field in the WHS has archaeological potential, with concentrations in some areas such as around Newgrange (Cumming, pers. comm., Brady, pers. comm.). Careful management of land use is the best way to stop erosion, and land use plans must be entered into with the co-operation of landowners (Brady, pers. comm.).
Flooding and submersion - As stated in relation to the wider landscape, possible effects include erosion, physical damage by flotsam, structural	Rain – increased volumes or intensity of rainfall within the Boyne catchment would lead to higher flood levels and stronger more destructive water flow and seasonal flooding may come to affect areas currently not	Re-sedimentation of sites may also occur with the deposition of flood debris and silt.

Impact	Mechanism	Comment
collapse, tree throw, contamination by water borne pollutants, soiling and debris deposition.	susceptible.	
Tree throw – disturbing and exposing archaeology beneath the fallen trees.	Heavy rainfall and high winds as above – sensitivity highest in forestry (limited to the eastern boundary of the WHS), in other cases damage will be localized due to single trees. Age and root structure may increase the severity of damage.	Areas that were forested 20–40 years ago did not undergo any prior archaeological assessment and would require monitoring in future if thinning or replanted is carried out (Brady, pers. comm.).
Structures and Features		
Erosion – in respect of earthen monuments and structures possible with increased episodes of severe weather.	Heavy rain and increased river flow (see flooding) - erosion of soil especially where vegetation has been removed, or has died back following drought.	Animal activity may contribute e.g. livestock trampling and breaking grass cover.
Flooding - Increased intensity of seasonal flooding may affect structures near the river, possibly destabilizing foundations, causing physical damage by flotsam, contamination by water borne pollutants, soiling and debris deposition.	Rain – increased volumes or intensity of rainfall may lead to erosion by flood waters, prolonged saturation of weight bearing orthostats causing deterioration and internal structural collapse.	

Impact	**Mechanism**	**Comment**
Structural damage/collapse – destabilization of foundations, weakening of structural stone orthostats and slippage of the cairn mounds may occur. The cairns already collapsed through soil creep in antiquity so have a known sensitivity.	Extreme rainfall and flooding – increased time of wetness, increased loading/pore pressure Sudden changes in water content are more important than annual increases. The slope, material properties and layer composition of the cairns will determine their sensitivity to slippage. Determination of sensitivity of the two largest cairns is complicated by modern interventions in the original structures. Wetting and drying of clays in summer may cause increased ground movement and result in subsidence (Woodside, 2006).	Pressure cracking at Newgrange can be seen in the corbelled roof (Gowen, pers. comm.) and the collapse at Newgrange (north face) in 1980s indicates that the structure is sensitive to water pressure (Duchas the Heritage Service, 2002). A conservation report on the orthostats at Knowth noted splitting and disintegration due to loading placed on the saturated stones (Ellis, 1997). The STEP project noted extensive damage to individual stones within the passage and chamber at Knowth due to settlement or subsidence. That report suggests that the fractures indicated recent movement, demonstrating that instabilities can still occur (Office of Public Works, 1993).

Impact	Mechanism	Comment
Cloudiness - the effect on the winter solstice at Newgrange is a special concern.	Increased rainfall does not necessarily mean fewer clear dawns. The REMO model projections are for a 2% increase in cloudiness which is not a significant change.	Records are kept at the Visitor Centre and since 1967 the sunrise has entered the chamber every year on at least one morning over the solstice period with the exception of 2000 (when freezing fog obscured the dawn all week) (Tuffy, pers. comm.).
Rock Art		
Biological growth – microbiological growth on stone surfaces causing aesthetic, chemical and physical alteration and loss. Any obscuring of the decorated surfaces would represent a significant aesthetic loss.	Rainfall (deep wetting) and higher temperatures (longer growing season) – increase in volume and species of microbiological growth. Greywhacke is quite non-porous but as OUV is based on aesthetic values sensitivity is described as high.	Studies at other OPW properties and anecdotal evidence suggest that growth is increasing, and becoming more diverse, due to either air quality or climate (Sevastopulo, pers. comm., McMahon, pers. comm.).
Changes in pollutants – pollutants initiate chemical reactions causing loss of surface detail.	Increased temperatures – acid hydrolysis is an endothermic reaction which will accelerate at higher temperatures. Sensitivity of greywacke to chemical decay from common pollutants is known empirically to be lower than porous rocks such as limestone.	Requires presence of pollutants – in general air quality is improving (O'Leary, 2006) however, if Panda Waste builds a biomass furnace and waste treatment plant 4Km from Newgrange this could change (McDonald, 2012).

Impact	Mechanism	Comment
Wet-dry cycles - Greywacke is structured from bedding planes with a concentration of clay matrix at the interfaces. The clay interstices are sensitive to expansion and contraction during wet-dry cycles and this eventually will lead to delamination and granular disintegration (Polish Academy of Sciences, 2006).	Heavy rain and higher ground water, flooding and increased temperatures - increase in near surface wetting and drying of both internal and external carved stone. Condensation forms on internal orthostats when warm air enters and cools on the stone surfaces (Tuffy, pers. comm.) - likely to increase with higher yearly temperatures.	Visitors raise the R.H. in Newgrange, particularly on wet days by brushing against orthostats in damp clothes. In 2006 mosquitoes were breeding in the passage and chamber at Knowth, indicating the presence of standing water (Tuffy, pers. comm.).
Salts – Mechanical damage from soluble salts, causing spalling and crumbling of surface.	Heavy rain and higher temperatures - Noah's Ark predicts a substantial increase in the annual frequency of crystallisation events (Grossi et al., 2011). Smith predicts deeper wetting and salt reservoirs increasing salt damage (Smith et al., 2004).	Greywhacke thought to have low porosity but penetration and crystallisation may occur at clay interstices. In STEP condition summary some stones showed serious damage from alkaline salts (Office of Public Works, 1993). Salts may migrate from the concrete which is *oozing* (Tuffy, pers. comm.).

Impact	Mechanism	Comment
Surface abrasion – abrasion by wind and rain causing loss of surface detail.	Wind driven rain or particulates – physical erosion of exposed carvings. Resistance to abrasion of Gallstown greywacke = 88.3%. AAV 11.7, Test EN 1097-8 (Celtest Company Ltd, 2007).	The predominant greywacke are estimated to have low sensitivity to mechanical weathering based on abrasion resistance tests.
Freeze thaw action – mechanical damage due to expansion of water within stone as it freezes.	Higher annual temperatures – likely to reduce freeze thaw events.	The laminate nature of greywacke makes it sensitive to this type of decay.

Figure 8.8. Visitor Centre treatment plant flooded with soil and potatoes after heavy rain in October 2011 (Tuffy 2011)

8.3.4. Adaptive Capacity

> *The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences* (McCarthy et al., 2001)

Adaptive capacity is analysed under four headings (GEF Global Support Programme, 2005).

1. Policies and Programmes
2. Information and Knowledge
3. Implementation
4. Monitoring/feedback

Figure 8.9. Boyne in flood, November 2009 (Tuffy 2009)

Policies and programmes

Management Structures: Newgrange, Knowth, Dowth and the Visitor Centre are state owned and managed by the OPW, who carry out any necessary conservation works. Responsibility for managing the World Heritage property, the majority of which is on private lands, lies with the Department of Arts Heritage and the Gaeltacht (DAHG). The management structure is further complicated by the fact that the National Commission of Ireland for UNESCO is run by the Department of Education. The resultant lack of clarity on the division of responsibilities was noted by a joint UNESCO-ICOMOS Mission to the WHS (UNESCO-ICOMOS, 2004). This Mission flagged the need for two management appointments: a site manager (OPW) and a World Heritage officer (DAHLG).[7] From 2010, deteriorating economic circumstances have led to a hiring freeze within the public sector and a site manager has never been appointed. Work on revising the existing Brú na Bóinne World Heritage Site management plan and associated action plan commenced in 2011 (Ritchie, pers. comm.). The lack of management resources and the failure to implement many of the actions outlined in the previous management plan are effectively eroding adaptive capacity.

Visitor Management: The Brú na Bóinne Visitor Centre controls the flow of people to Newgrange and Knowth and provides an exhibition space and visitor facilities. Newgrange is open throughout the year, visitor numbers are limited at 625/day, and in the summer months is frequently sold out. The weather does not affect the number of visitors but in cold or wet weather the tight passageway undergoes more mechanical impact due to visitors wearing bulky, damp clothes and carrying umbrellas (Tuffy, pers. comm.).

[7] Although the mission was specifically dealing with Brú na Bóinne the same management framework also applies to the WHS of Skellig Michael

Legislative Protections:

The Special Areas of Conservation (SAC) protected under the EU Habitats Directive 1992 and Special Protection Areas (SPA) protected under EU Birds Directive 1979, are monitored by the National Parks and Wildlife Service (NPWS). The NPWS co-ordinate with local landowners to ensure appropriate land use practices (Lynch, pers. comm.).[8] The canal is owned by An Taisce, the National Trust for Ireland. They must be notified of water extraction from the Boyne and have the power to take preventive measures in order to protect the flow (Lumley, pers. comm.). Archaeological monuments on private land are protected from any interference under the National Monuments Act 1930–2004. Enforcement of this legislation is lacking in some cases however, Stout writes that henge monuments below Newgrange continue to be ploughed annually even though to do so is unlawful (Stout, 2002). Some farmers are resentful of bureaucratic interference in their practices and purposefully avoid participating in environmental schemes such as REPS in order to limit inspections of their lands (Redhouse, pers. comm.)[9]. Capacity to mitigate the consequences of climate change on agriculture is dependent therefore on having good relations between the site management and landowners in addition to appropriate and enforceable legislation.

Meath County Council and Louth County Council share responsibility for planning in and around the World Heritage property. The majority of the WHS falls within the County of Meath where the County Development Plan provides for protection of views, sites and monuments. Louth County Council's statutory development plan currently contains no

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[8] The EU regulated Rural Environmental Protection Scheme (REPS) was the main tool used by the State for agri-environmental conservation as it provided financial top-ups to farmers using sustainable practices. This scheme was changed in 2013 to the Agri-Environment Options Scheme (AEOS) and is managed by the Department of Agriculture.

[9] Willie Redhouse, Newgrange farm, interviewed by phone (1/2/2008)

specific policies or objectives regarding the WHS. If development affects cultural or natural heritage the Planning and Development Act 2000 requires consultation with relevant State prescribed bodies, in the main this is DAHG. Planning applications within the WHS are also referred to other prescribed bodies such as An Taisce, the Heritage Council and Failte Ireland (Ritchie, pers. comm.). As the controversy over the N2 Bypass showed however, these protections are not sufficient to prevent developments that are damaging to the OUV (Comer, 2011). Despite the economic recession, between 2006 and 2011 the population of County Meath increased by 13% (Central Statistics Office, 2013b). Continued population growth is likely to increase the exposure of heritage to developments as planners strive to meet an ever expanding demand.

Figure 8.10. View of Dowth tumulus from the south-west (February 2008)

In 2004 a joint monitoring mission by the UNESCO World Heritage Centre and ICOMOS reported that despite the existence of protective legislation *development has taken place both within the core area and the buffer zone, some of it intrusive* (UNESCO-ICOMOS, 2004). The challenge for the Local Authority and DAHG is to balance the needs of heritage protection with those of a living landscape and expanding population. Improving engagement with local and non-governmental stakeholders is vital to ensure the most successful outcome for conservation management in the face of all challenges, including climatic ones (Guinan, pers. comm.).

Figure 8.11. Kerbstones at Newgrange south-east side: Excavated area in foreground with cantilevered shelter; unexcavated area behind with stone faced concrete revetments on both the mound and ditch (cut through cairn collapse) (April 2009)

Information and knowledge

Climate Change: The capacity for a World Heritage site to adapt to climate change is, in the first instance, dependent on institutional awareness. The focus of research to date has been on the archaeological potential and the Research Framework (Smyth, 2009) largely continues this trend. It has no reference to conservation among its eighteen objectives, although it does consider it as an 'individual research question' (No.32: 83). The lack of resources for conservation research and monitoring at Brú na Bóinne impairs the ability of conservation professionals to make informed decisions (Dolan, pers. comm.). Other gaps occur in relation to landscape study i.e. the soil, fluvial history and paleoclimatic data, all necessary in assessing the potential sensitivity of the archaeological record and predicting how future changes in climate may affect the landscape (Lewis, pers. comm., Meehan, pers. comm.) The ability to cope with new challenges (including but not restricted to climate change) and to plan effective adaptation and mitigation strategies will continue to be hampered by these knowledge lacunae.

Over the years conservation works on the passage tombs have been carried out at several junctures but there are issues with the conservation archive including recording and availability of data on these interventions. These include lost reports and unpublished material or incomplete recording (Dolan, pers. comm., Cumming, pers. comm.). In the past some of the damage to monuments has also occurred due to lack of awareness of the significance of the individual site and the potential impacts of farming or development activities:

Once the impacts of climate change become apparent it is critically important that the local community, including farmers, and those managing the WHS on behalf of the State, should be educated on how to address the emerging situation (Ritchie, pers. comm.).

Communication with stakeholders may need to be followed with more concrete solutions such as increasing the amount of State owned land or targeted research excavations (Ritchie, pers. comm.).

Human Resources: The experts caring for the WHS are off-site, divided between different state agencies and different offices, all of which reduces the capacity for close inter-disciplinary partnerships. For example, responsibility for all WHS related policy matters rests with DAHG while the conservation architects with responsibility for conservation of the State owned monuments are at OPW.

Population: Small farmers are central to maintaining the mosaic landscape characteristic of Brú na Bóinne and their population demographic is potentially of concern in terms of maintaining this landscape system. Currently in Co. Meath only 982 of the 4544 small farm holders are under the age of 45 (Central Statistics Office, 2013a).

Implementation

Conservation and Maintenance: The current constraints on conservation come from a need to reconcile the sometimes conflicting requirements of public access and preservation (Dolan, pers. comm.). Weathering of the exposed rock carvings by freeze-thaw action has been a major concern and during the closed period at Knowth the stones are wrapped (figure 8.7). As Newgrange is open all year it is only feasible to cover the entrance stone (K1) at night. The issue of replacing some of the most important stones with replicas was left undecided in the last management plan pending a comprehensive assessment, which has yet to be carried out (Duchas the Heritage Service, 2002).

Newgrange and Knowth are heavily altered from their original state due to excavation and restoration. In both cases concrete housing has been erected over restored sections of the passage to relieve loading pressure. In Newgrange the original cairn material was replaced after excavation together with concrete slurry (O'Kelly, 1982). At Knowth Polystyrene blocks were inserted to relieve loading on the internal structures that had no concrete housing (Cumming, pers. comm., Dolan, pers. comm.). After drainage problems caused a collapse at the rear of the mound at Newgrange in the 1980s, steel gabions were inserted behind the kerb at both Newgrange and Knowth (O'Kelly, 1982, Duchas the Heritage Service, 2002). Cantilevered concrete slabs were also inserted in both sites to protect the kerbstones from direct rainfall (figure 8.11.) although their effectiveness has not been quantified (Duchas the Heritage Service, 2002). The concrete canopies over the passageways are a potential future problem as their lifespan is unsure and accurately ascertaining their integrity would be very invasive and require considerable resources (Dolan, pers. comm.). The lifespan of expanded polystyrene is indefinite but guaranteed for at least 100 years (ICC Flowtech, n.d., Kremer, 2003). The scale of intervention at Knowth and Newgrange is such that it is impossible to be confident in how they will respond to environmental conditions (Gowen, pers. comm.).

Monitoring/feedback

The Science and Technology for Environmental Protection (STEP) programme 1990–1993 used Newgrange as one of two case-studies in stone deterioration and conservation. The interim recommendations of the project included measurements of possible subsidence, environmental monitoring inside the tomb and improvement to the protection for kerbstones from rainfall runoff (Office of Public Works, 1993). The aim of the STEP project was to set up environmental monitoring stations at several OPW sites but it was unfortunately discontinued when EU funding came to an end (McMahon, pers. comm.). Approximately twenty years ago baseline photographic documentation of the carved stones was carried out, with the intention of monitoring surface weathering, but was never repeated. More recently some of the stones have been laser scanned (Shaw, 2012), and this may form the baseline for monitoring in the future (Dolan, pers. comm.).

Although it was a key objective of the 2002 Management Plan (Duchas the Heritage Service, 2002) there is no formal monitoring scheme in place for the Brú na Bóinne properties. Guides and OPW staff provide an informal service in this regard by reporting any problems as they are encountered. In 2004, a joint monitoring mission was sent by the UNESCO World Heritage Centre and ICOMOS to report on the impact of a planned waste incinerator in Duleek. It recommended that OPW develop a methodology for monitoring the state of conservation of the monuments particularly in relation to the effect of pollutants. The requirement for ongoing monitoring of the site in partnership with stakeholders such as An Taisce has also not been realized (Lumley, pers. comm.). The lack of systematic monitoring at Brú na Bóinne means that little is known about the extent of exposure to the various forms of deterioration and adaptive capacity is low as a result. The lack of a conservation and/or disaster plan and the fact that the majority of monuments are on private land all serve to further reduce adaptive capacity at the site.

8.4.

STEP 3. IDENTIFY LIKELY HAZARDS FOR EACH VALUE UNDER THE FUTURE CLIMATE USING THE MATRIX OF IMPACTS

This step requires personal judgment on how, under projected future climate conditions, the values of the site might be affected. The Matrix developed in chapter 3 provides a reference tool to aid this process (table 3.1). In the interviews, stakeholders were shown a simplified version of the Matrix and asked to mark impacts they considered relevant. The responses of the stakeholders were collated (table 8.5) and the assessment of vulnerability was carried out on these selected impacts.

8.5.

STEP 4. DEVELOP INDICATORS FOR THE ELEMENTS OF VULNERABILITY (exposure, sensitivity and adaptive capacity)

The topic of selecting and using indicators is discussed in chapter 9. Assessors must attempt to find the most useful indicators for the impacts with which they are concerned and this can be challenging. The indicators proposed for ongoing evaluation at Brú na Bóinne are outlined in table 8.7.

Table 8.7. Proposed Indicators of Vulnerability for Brú na Bóinne to potential climate change impacts

Impact	**Indicator**	**Proxy for**	**Functional Relationship**
Mechanical abrasion of surfaces by wind and/or rain	Cube indicator tool	Sensitivity of rock art to mechanical weathering.	Change in surface roughness
Flooding	Water level and flow on Boyne measured by OPW at Slane and Roughgrange stations.	Exposure of monuments to fluvial flooding	↑ level = ↑ exposure
Chemical action	SO_2 conc. = 2µg/m^3 mean daily value Kilkitt, 2006 (O'Leary, 2006)	Exposure of rock art to temperature accelerated chemical deterioration.	↓ SO_2 conc. = ↓ exposure
Microbiological growth	1. Cubes indicator tool 2. Nitrates conc. = 4µg/m^3 mean hourly value Kilkitt, 2006 (O'Leary, 2006).	Exposure of rock art to biological growth.	1. Colour change 2. ↑ NO_X conc. = ↑ exposure
Reduction in freeze thaw weathering	Periods T < 0^{o}C = 85% reduction by 2070–2100.	Exposure of rock art to freeze thaw weathering.	↓ nos freezing periods = ↓ exposure
Changes in agriculture and land use – plough and root damage	% tilled farmland county Meath (2010 census) = 19%	Exposure to disturbance (archaeological remains)	↑ % = ↑ exposure
Deterioration of water quality	EPA water quality testing	Exposure of cultural landscape to run off and pollution	↓ quality = ↑ exposure

Impact	Indicator	Proxy for	Functional Relationship
Soil erosion	% hedgerows	Sensitivity of landscape to pluvial flooding and erosion	↓ % = ↑ sensitivity
Salt weathering	Cube indicator tool	Exposure to salt cycles	Surface loss attributable to salts
Conservation approach	Information resources: Research and monitoring implemented	Adaptive capacity (conservation).	Lack of monitoring & research = ↓ adaptive capacity
Management system	Human and civic resources = No change since 2004 in professional staffing levels.	Adaptive capacity (Management).	Stagnant recruitment = ↓ adaptive capacity
Increased demands on water levels in summer e.g. changes in hydrology	Population growth = 18% from 2002–2006 (Central Statistics Office, 2013b).	Adaptive capacity in management of natural resources (Planning and mitigation).	↑ % = ↓ adaptive capacity
Changes to biodiversity	Monitor species e.g. moths (www.biodiversityireland.ie)	Sensitivity to change in biodiversity.	↓ Species = ↑ sensitivity.

8.6.

STEP 5. ASSESS VULNERABILITY BY ENTERING VALUES FOR EXPOSURE, SENSITIVITY AND ADAPTIVE CAPACITY INTO THE CAUSAL MODEL

This is the point at which all the research generated during the previous 4 steps is amalgamated to produce an evaluation (table 8.8). Assessors must interrogate the data and use their expert judgment to evaluate sensitivity, exposure and adaptive capacity on a scale of 1 (low) – 3 (high). This preliminary vulnerability assessment for Brú na Bóinne identifies areas which are expected to be most affected by climate change and are a priority for monitoring (Table 8.9). The time scale adopted is the one used by the climate change models i.e. to the end of this century. As before, the results must be kept under review and supported wherever possible by scientific monitoring.

Table 8.8. Calculation of the Measure of Vulnerability of Brú na Bóinne heritage values to the projected impacts of climate change - utilising research on indicators, sensitivity, exposure and adaptive capacity.

Climatic Factor	**Sector or W. H. Value**	**Impact**	**Indicator**	**Sensitivity**	**Exposure**	**Adaptive Capacity**	**Measure of Vuln.**
Rainfall	Cultural Landscape	Deterioration of water quality – runoff, silting	EPA water testing	Medium (valuable wetlands)	Medium (intense rain)	High (Water Framework Directive)	Low (1)
Rainfall	Cultural Landscape & archaeology	Changes in hydrology/ water table	Population pressure +18% (adaptive capacity)	Medium (valuable wetlands)	Low (recharge is based on annual volume)	Medium (An Taisce & NPWS powers)	Low (1)
Rainfall	Cultural Landscape, archaeology & structures and features	Erosion	% hedgerows	Medium (high along river or ploughed land)	Medium (Incr. intense rain)	Medium (manage land use)	Medium (2)
Rainfall	Cultural landscape, Structures & features	Flooding (fluvial & pluvial)	Water levels on Boyne (OPW)	Low (survived existing flooding)	High (Prediction for incr. flood)	Low	High (3)

Climatic Factor	**Sector or W. H. Value**	**Impact**	**Indicator**	**Sensitivity**	**Exposure**	**Adaptive Capacity**	**Measure of Vuln.**
Rainfall	Structures & features	Collapse	Monitoring of mound, chambers & orthostats	Medium (evidence of some movement)	Medium (Incr. intense rain)	Medium (structural intervention possible)	Medium (2)
Sea Level Rise	Cultural Landscape, archaeology & structures	Saline intrusion and deposition of salts		Medium (high for structures)	Low (at extreme limit)	Low (no facility to mitigate)	Low (1)
Temperature	Rock Art	Cryoclastic weathering	$T < 0^{o}C$ = reduced 85% by 2070–2100.	High (current problem)	Negative-Reducing by 85%	Medium (winter wrapping)	Low (1)
Temperature	Rock Art	Thermoclastic weathering		Low (not known)	Low (small change)	Low (during summer season)	Low (1)
Temperature & Rainfall	Archaeology	Altered preservation conditions	Soil testing	Medium (ecofacts)	Medium (varies on location)	Medium (research framework)	Medium (2)
Temperature & Rainfall	Cultural landscape	Ecological change	Bio diversity e.g. Moth traps	High (high value)	Low (pred. not severe)	Medium (NPWS control)	Medium (2)
Temperature & Rainfall	Rock Art	Accelerated chemical weathering	Cubes & SO_2 conc.	Low (stone type)	Low (rural location) – Medium (Panda plant)	Low (no monitoring)	Low (1) – Medium (2) dep. on waste plant proposed
Temperature & Rainfall	Rock Art	Increased biological action	Cubes & Nitrates conc.	Medium (aesthetic OUV)	Medium (varying with aspect)	Low (no climate control possible)	High (3)
Temperature & Rainfall	Rock Art	Wet dry cycles		Medium (structure of stone)	Medium (internal & external)	Medium (wrappings, canopies)	Medium (2)
Temperature & Rainfall	Rock Art	Salt cycles	Cubes	Low (no evidence of sensitivity)	High (wet dry cycles)	Low (no climate control)	Medium (1)

Climatic Factor	**Sector or W. H. Value**	**Impact**	**Indicator**	**Sensitivity**	**Exposure**	**Adaptive Capacity**	**Measure of Vuln.**
Temperature & rainfall (summer)	Archaeology	Plough damage (and related e.g. root damage)	Tilled farmland (e.g. Meath in 2010 = 19%)	High (area of high potential)	Medium (currently 19% arable)	Low (diff to restrict ploughing even on monuments)	High (>3)
Temperature & rainfall (summer)	Cultural Landscape	Land Use	% hedgerows	High (mostly farmland)	Medium (projected changes)	Medium (engagement with NPWS)	High (3)
Wind & Rainfall	Cultural landscape, archaeology and structures	Tree throw		Medium (dep on location)	Medium (intense rainfall)	Medium (tree felling, emergency excavation)	Medium (2)
Wind & Rainfall	Rock Art	Mechanical weathering	Cubes & Abrasion resistance = 88.3%	Medium (stone type vs. low relief carving)	Medium (wind speed & direction)	Medium (winter wrappings)	Medium (2)

8.7.

STEP 7. REFINE AND COMMUNICATE RESULTS

8.7.1. Summary of results

The main vulnerabilities for Brú na Bóinne centre around two issues: land use and flooding. These are predicted to affect the buried deposits, landscape and structures. Erosion and tree throw are the next most significant impacts to also affect all of the above values. In addition buried deposits face changes in preservation conditions, the landscape faces ecological change and the built structures, under increased mechanical pressure, may experience some collapse. In terms of the rock art it is biological activity that comes out as the main issue followed by changes in mechanical weathering, wetting and drying patterns, salt cycling and surface abrasion (table 8.9).

Table 8.9. Summary for decision makers of predicted climate change vulnerabilities for Brú na Bóinne to 2099

	Rock Art	*Buried deposits*	*Structures and Monuments*	*Cultural Landscape*
Impacts for which Vulnerability is High	! Changes in biodeterioration	! Changes in agriculture (ploughing, crops)	! Flooding (fluvial & pluvial) ! Structural collapse[10]	! Flooding (fluvial & pluvial) ! Changes in land Use
Impacts for which Vulnerability is Medium	! Wet dry cycles ! Abrasion ! Salt damage	! Changes in burial conditions ! Erosion ! Tree throw	! Erosion ! Tree throw	! Erosion ! Ecological change ! Tree throw
Impacts for which Vulnerability is Low	! Accelerated chemical weathering ! Cryoclastic weathering ! Thermoclastic weathering	! Changes in hydrology/ water table ! Saline intrusion	! Saline intrusion	! Changes in hydrology/ water table ! Deterioration of water quality ! Saline intrusion

8.7.2. Stakeholder review

As with Skellig Michael, the completed assessment was circulated to stakeholders for feedback (Appendix 2). Stakeholder feedback was divided into four categories (table 8.10) and analysed as described for Skellig Michael (section 7.7.2). When the suggested

[10] Raised from 'medium' to 'high' based on stakeholder feedback.

amendments or corrections had implications for the calculation of vulnerability, they were detailed (sections 8.7.3 and 8.7.4).

Table 8.10. Breakdown of stakeholder feedback

Stakeholder	1. No changes	2. Minor changes	3. Major changes	4. No response
Dolan, Ana		■	■	
Lynch, Ann (Dr)	■			
Lynch, Annette		■		
Tuffy, Clare		■		
Brady, Conor (Dr)		■	■	
Comer, Douglas (Dr)				■
Lewis, Helen (Dr)		■		
Lumley, Ian	■			
Chadwick, Jill		■		
Guinan, Loretto (Dr)				■
Ritchie, Marc		■		
Gowen, Margaret		■	■	
McMahon, Paul				■
Meehan, Robert (Dr)		■		
Cumming, William		■		

8.7.3. Suggested major changes - with implications for the final assessment

Structural sensitivity

Due to excavation and subsequent restoration during the twentieth century the tombs of Knowth and Newgrange have been subject to substantial structural alteration. Margaret Gowen felt that the assessment of sensitivity and exposure did not make sufficient reference to the scale of these modern structural interventions. The consequences of this re-engineering for the movement of water and the implications for stability and burial conditions are unknown (Gowen, pers. comm.). The issue of structural additions, in particular with reference to the use of concrete and the potential drainage issues were discussed with OPW conservation architects (Cumming, Dolan and McMahon) during the assessment process. Although the use of steel gabions behind the kerb and the introduction of Polystyrene into the mound at Knowth are intended to address some of the loading and drainage issues, there has not been any testing of the efficacy of these.

Management capacity

In reference to discussion of the legislative protections preventing the N2 Slane Bypass and its implications for adaptive capacity (section 8.3.4.) the point was made by Dr. Conor Brady that there are a host of developments constructed within or very close to the World Heritage property, which have been very damaging. These include the M1 Motorway Bridge, the Indaver incinerator, and Irish Cement Phase 3 (Brady, pers. comm.). This point highlights the lack of a coherent management plan catering adequately for the needs of the WHS and the local residents, and implies the adaptive capacity due to legislative protections may be very low.

Bias in results

Ana Dolan, conservation architect for the WHS, felt that there was not enough emphasis on structures and features, and on possible destabilisation by landslide or storms. With reference to the ranking of impacts (table 8.5) compiled from stakeholder interviews, it was suggested that the results were biased towards archaeological concerns as plough damage is the most frequently mentioned impact (Dolan, pers. comm.).

8.7.4. Response and implications for practice

- The comments from Margaret Gowen and Ana Dolan indicated that the assessment of Brú na Bóinne may not have taken enough cognisance of structural issues relating to the architecture of the passage tombs. The fact that two stakeholders made this point adds weight to the opinion. The strategic management role held by Ana Dolan as Senior Conservation Architect for the site also gives these comments added significance. It was therefore decided to reflect this feedback by changing the vulnerability of structures and monuments to *structural collapse* from 'medium' to 'high' in the final summary results (table 8.9).

    - **Implication for practice:** Ranking and/or weighting of individual responses by the assessor(s) is necessary in considering how to react to stakeholder feedback (requires flexibility and judgement).

- Although specific reference had not been made within the text to the developments raised by Dr Brady, the assessment of adaptive capacity based on legislative protections was already low: *protections are not sufficient to prevent developments that are damaging to the OUV* (section 8.3.4.). Therefore, although the information from feedback reinforces this assessment it does not necessitate any change in the final calculation of vulnerability.

- **Implication for practice:** The implications of new information must be gauged within the context of the overall assessment. As above, this requires flexibility and judgment on the part of assessor(s).

- There was a perception of bias towards archaeology. To address this issue would require collaboration with the stakeholder concerned to identify whether new respondents could be found to balance the list. Of the fifteen stakeholders consulted, five were archaeologists. The addition of further interviewees was not possible in this instance.

  - **Implication for practice:** Clarity and detail in analysis is necessary in order to avoid any suspicion of bias in the final result.

  - **Implication for practice:** Sufficient time and energy should be allocated to the stakeholder review process to allow for frank exchange and for the implications of the responses to be investigated fully, including the possible inclusion of new stakeholder contributors.

8.8. CONCLUSIONS

The cultural heritage of Brú na Bóinne encompasses varied components with very different levels of exposure and sensitivity to climate change. During the course of research the response of certain elements of the OUV to climate change risks were established as being of primary concern. The largest passage tombs have been radically altered in the last century and their response to climate change may be very different to that of the rest of the Megalithic landscape. The cultural landscape has absorbed environmental change during the past five millennia and has proved to be very durable. Human interference in the structure of the environment, such as altering land use practices or developments that interfere with the hydrology, could have a negative cascading effect on this durability (Comer, pers. comm.). In many instances, climate change will act as a contributing factor rather than principle cause of deterioration. Development and farming practices followed by visitor numbers are the main pressures currently concerning stakeholder respondents. To carefully monitor and manage the impact of human induced change may be the most effective way of ensuring resilience to the future impacts of climate change.

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CHAPTER 9.

INDICATORS

9.1. INTRODUCTION

The case-study methodology for assessing climate change vulnerabilities developed in the previous chapters allows heritage managers to identify priorities for monitoring and adaptation at individual sites. One key element of the assessment process is the selection and use of quantifiable indicators. In this chapter indicator theory will be explored further and a multi-disciplinary approach to their selection and implementation for measuring climate change impacts on heritage values will be examined. As climate change is measured in 30–100 year periods, it is evident that impact monitoring should operate over a similar timescale, as a legacy for the future (Brimblecombe, 2010). *In situ* monitoring techniques however, often require levels of staff involvement, funding or equipment maintenance that are unsustainable over a century (Daly et al., 2010). The possibility that indicators may provide a sustainable alternative to direct monitoring will be explored.

9.2. INDICATOR THEORY

9.2.1. Defining indicators

Indicators may be defined as quantifiable variables that, because of an established functional relationship, can be used as proxies for process not directly observable or involving interactions over a long period, as in the case of climate change (Moss et al., 2001). They can be based on physical, biological, chemical or socio-economic variables that represent the elements within a complex system (Pearson et al., 1998). It is vital that those chosen are scientifically sound, understandable to stakeholders and clearly defined (Schröter et al., 2005).

Vulnerability cannot be measured directly as it is a theoretical concept rather than an observable phenomenon (Hinkel, 2011). Indicators serve to quantify the elements of vulnerability, sensitivity, exposure and adaptive capacity, via the described functional relationship. In its simplest form this is a direct scalar relationship between the measurable indicator (e.g. temperature) and theoretical concept (e.g. exposure to freeze-thaw weathering). Thus, Noah's Ark described the functional relationship:

> *Exposure to freeze thaw weathering = Number of rainy days (ppt>2mm & T>0* ^{o}C*) followed by days with mean temperature below -1* ^{o}C (Grossi et al., 2007: 277).

Hinkel stresses that the term indicator should be used to refer to the whole function and not the proxy alone. A variable is only an indicator when it is linked by an established functional relationship to another variable, as in the freeze thaw example (Hinkel, 2011). Hinkel also distinguishes between what he terms 'harm indicators' and 'vulnerability indicators'. Harm indicators are those that evaluate current condition and do not include a forward looking aspect, while vulnerability indicators are indicators of possible future harm (Hinkel, 2011). Thus 'vulnerability indicators' should concentrate on variables that can provide warning signals of impending problems. The predictive element of the *indicator model is simple, often linear, and not explicit in time* (Hinkel, 2011: 206). For example, in this thesis the predictive element is provided by the use of future climate projections to inform the functional relationships.

There is also a differentiation between 'primary' and 'secondary' indicators in the literature. According to Sweeney primary indicators of climate are the instrumental measurements, what is referred to in this thesis as 'direct monitoring' (Sweeney et al., 2002). Secondary indicators are the supplementary climate record, such as butterfly recording or phenological observations. This secondary data-set is of most use where primary or direct measurements are not being collected.

9.2.2. Applying indicators

Indicators can either be specific or general, the choice depends on the purpose and scale of the assessment. With general indicators (e.g. food security, human and environmental resources, national economic growth) comparison between systems or places is possible, although a large sample size is required for these to be meaningful (Adger et al., 2004). For the case study approach taken in this thesis (chapters 7 and 8) site specific indicators for defined heritage values were of more relevance.

Indicators used in a vulnerability analysis should relate to one of the three elements of vulnerability (Schröter et al., 2005).

1. Exposure
2. Sensitivity
3. Adaptive capacity

Each indicator will therefore represent one aspect of vulnerability rather than its totality. In defining indicators for the case study sites it was possible to find quantifiable variables and to objectively measure their functional relationship for only a limited number of impacts (tables 7.8 and 8.7). In many instances the proxy-relationships defined were based instead on broadly observed trends. Lack of site-specific data, uncertainties regarding climate change and the esoteric nature of heritage values contributed to making the identification of indicators a very challenging part of the vulnerability assessment process. The main purpose of indicators is to provide a *theoretically sound and technically feasible way of assessing vulnerability and resilience to a first approximation* (Moss et al., 2001: xi). Their value is therefore not in the complete and accurate quantification of a system's vulnerability, but in providing directions for future research and priority setting. Indicators simplify a complex reality and communication is their major function (Smeets and Weterings, 1999). Despite the difficulties obtaining quantitative data and the subjectivity of some of the functions, the indicators defined for the case studies were useful in obtaining and communicating that ‘first approximation’ assessment (for example table 8.8).

9.2.3. Choosing indicators

Indicators must be relevant to the stated objectives, be quantifiable (i.e. capable of being measured), verifiable (i.e. repeatable by others) and suitable for comparative analysis over time (Elliott, 1996). For the purposes of vulnerability analysis indicators should be place based and relate to the key elements of exposure, sensitivity and adaptive capacity (Schröter et al., 2005). Each indicator will detect change on a different scale and the appropriate timing will depend partly on what is being measured (Pearson et al., 1998).

Before selecting indicators (or monitoring solutions) it is essential to understand the aims, objectives and restrictions applicable (Forbes and Liverman, 1996):

- What are the key objectives e.g. measure current conditions, measure rate at which conditions change, help predict future behaviour?
- What are the spatial and temporal limits applicable e.g. frequency of assessment?
- What are the potential causes of error in interpretation of results?
- Who will use the final results i.e. scientific or management purposes?
- What is the overall context and how does the research contribute i.e. economic, social and logistical issues?

The deductive approach, utilised in this thesis, is to select indicator variables on the basis of a theoretical relationship (Adger et al., 2004: 18). This defined relationship must be rooted in knowledge of the interactions and processes involved. Once the indicators are applied they can be evaluated inductively, based on statistical evidence.

9.2.4. Limitations

While indicators are valuable as a communication tool and in providing a point of departure for research, they cannot capture the system in depth nor provide information on complex phenomena such as non-linear responses (Hinkel, 2011). Hinkel also argues against generalising from indicators suggesting that they are only relevant at a local narrowly defined level where the inductive deductive cycle can be utilised in their selection and evaluation, as in this thesis (section 2.3.). As Luers et al point out the choice and weighting of indicators is subjective (Luers et al., 2003), therefore the best way to ensure validity is to develop a transparent and rigorous selection process (Hodge, 1996). The shortcomings of the chosen indicator must also be made clear. Adger suggests three criteria for evaluating the choice of indicators which are suited to the pragmatic approach of this thesis (Adger et al., 2004):

1. Validity of theory i.e. the described functional relationship.
2. Appropriateness of indicator e.g. scale, timing, availability.
3. Reliability of data e.g. collection method, source, margin of error.

9.2.5. Equifinality

The difficulty in distinguishing the effects of climate change from other forms of environmental change, or normal climate variability, was identified earlier in this thesis (sections 4.5., 4.8. and 5.4.). The concept of *equifinality* describes this problem i.e. having the same result from different events or processes (Merriam-Webster Dictionaries, 2013). The need to disentangle causality is common to all disciplines where impacts of climate change are being considered, for example by specialists studying sea level rise or those tracking the migration of bird species (Nicholls et al., 2009, Fiedler, 2009). The Natural Science approach to addressing equifinality is to gather a wide range of long-term comparative data (Humphries, 2009). Forbes suggests that a 'Minimum Data-Set' of indicators should be created for specific objectives and that conclusions should never be based on single indicators in isolation (Forbes and Liverman, 1996). The impacts of climate change on cultural heritage systems are liable to be highly complex, dependant both on people's responses, local conditions and the heterogeneous nature of heritage values (Henry and Jeffery, 2008). The fact that the climate change signal is not projected to be obvious in most regions until the end of this century means that uncertainty will remain part of any analysis (Mikolajewicz, 2013). Despite the problems in interpreting causal links, monitoring is widely held by heritage professionals as a necessary first step in understanding environmental change, as was seen from the questionnaire responses (section 4.6.).

In summary, indicators are quantifiable variables that can be utilised as proxies for measuring the elements of vulnerability, exposure, sensitivity and adaptive capacity. Vulnerability indicators provide a direction for research or warning of future problems but are not as accurate as direct monitoring. The selection of appropriate variables and definition of the functional relationship are essential for ensuring reliability. Creating a set of indicators for long-term data collection is recommended to address the problem of equifinality.

9.3. INDICATORS and CULTURAL HERITAGE

Although indicators are used systematically in natural heritage management they are not often applied to the cultural heritage sector. In Australia however this cross-over has occurred in State of the Environment (SoE) reporting (Pearson et al., 1998). In *Environmental indicators for national state of the environment reporting – Natural and Cultural Heritage* (Pearson et al., 1998) the Organisation for Economic Co-Operation and Development (OECD) framework was used (Sweeney et al., 2002). This characterises indicators according to condition (C), pressure (P) or response (R). For the purposes of the current research the OECD categories can be loosely understood in relation to the three elements of vulnerability i.e. condition approximates to sensitivity, pressure to exposure and response to adaptive capacity. In this chapter a multi-disciplinary approach has been taken in order to create a preliminary set of indicators for cultural heritage sites. The proposed indicators relate to the three elements of vulnerability but the functional relationships are not defined here. The choice and employment of indicators should be done on a site specific basis (chapters 7 and 8).

Figure 9.1. Emergency preparedness can increase adaptive capacity (photo www.bcdailybuzz.com 2013)

9.3.1. Adaptive Capacity indicators

The focus of the Australian report is on condition (sensitivity) and response (adaptive capacity) (Pearson et al., 1998). Woodside divided indicators of adaptive capacity into two groups (Woodside, 2006) (section 6.9.2.):

- *Physical capacity* or the ability of the site to adapt without loss of value e.g. fabric, condition, definition of values.

- *Systematic capacity* or the ability of the management systems to cope e.g. skills, finances.

Response indicators link mainly to physical adaptive capacity as they concern resilience or the ability to respond to change without loss of value (Redman and Kinzig, 2003). Adequate response will effectively reduce exposure and sensitivity to impacts, therefore adaptive capacity indicators may also be relevant for these elements of vulnerability. A series of indicators have been compiled (table 9.1) that can be related to the four strategic areas for assessing capacity i.e. information, policy, implementation and monitoring (section 6.7.3),

Table 9.1. Example of conservation and management indicators for cultural heritage (Pearson et al., 1998, Woodside, 2006, Daly, 2008).

Impact	**Indicator**	**Method**
All	Knowledge/Understanding of heritage resource (Information resources)	Numbers of listed monuments Numbers of monuments regularly assessed Availability of management and/or conservation plan Monitoring Research
	Integrity of heritage resource	Number of places destroyed or damaged Number assessed as being in good, average or poor condition
	Planning, mitigation and adaptation activity	Maintenance regime Level and frequency of conservation intervention Implementation of management and/or conservation plans

Impact	Indicator	Method
	Financial resources	Funding for conservation Funding of heritage bodies Insurance Maintenance regimes
	Human resources	Numbers of trained practitioners/courses Access to skilled professionals Institutional support Involvement of local population/stakeholders
	Legislative Protection	Number of statutory mechanisms actively used to protect heritage Planning restrictions
	Status of heritage (social and cultural capital)	Awareness among population of value of heritage Engagement by local stakeholders Promotion nationally and internationally
	Emergency response systems (figure 9.1)	Availability of an effective emergency plan Historic/statistical records for event related damage e.g. flood or fire

9.3.2. Landscape indicators

Geoindicators can be defined as *measures of surface or near surface geological processes and phenomena that vary significantly over periods of less than 100 years and that provide information that is meaningful for environmental assessment* (Berger, 1996: 6). They are already used in environmental reports and there is scope for their application to heritage, especially in terms of the exposure and sensitivity of cultural landscapes.

Climate models for Ireland project an increase in intense rainfall (section 3.2.6.) raising concerns over impacts such as flooding, erosion and landslip. Water discharge, which is related to channel width and depth, can be used as an indicator for riverine erosion. Where stream flow gauges include monitoring of channel bed-level this can also provide information on the rate of erosion or aggradations as it provides an indication of changes within the river basin (Osterkamp and Schumm, 1996). For example, there are two water level and flow gauges close to Brú na Bóinne, one upriver at Slane and one at Roughgrange (close to Newgrange), which could provide an indication of exposure to this impact.[1]

Soil erosion can be estimated from vegetation change, one example would be the measurement of earth beneath the root collar of an old tree (Osterkamp and Schumm, 1996). When choosing a location to monitor it is important to select sites where there is known sensitivity i.e. existing evidence of erosion or sedimentation. In many countries data sets of water and sediment discharges exist for as much as a century and these can be used as a valuable baseline with which future trends can be compared (Osterkamp and Schumm, 1996).

[1] The Environmental Protection Agency (EPA) are responsible for co-ordinating the collection of water quantity data in Ireland in co-operation with Local Authorities, OPW, the geological survey of Ireland (GSI), the Electricity Supply Board (ESB), Met Eireann and the Marine Institute ENVIRONMENTAL PROTECTION AGENCY. 2011. *http://www.epa.ie/* [Online]. [Accessed 27.06.11 2011]..

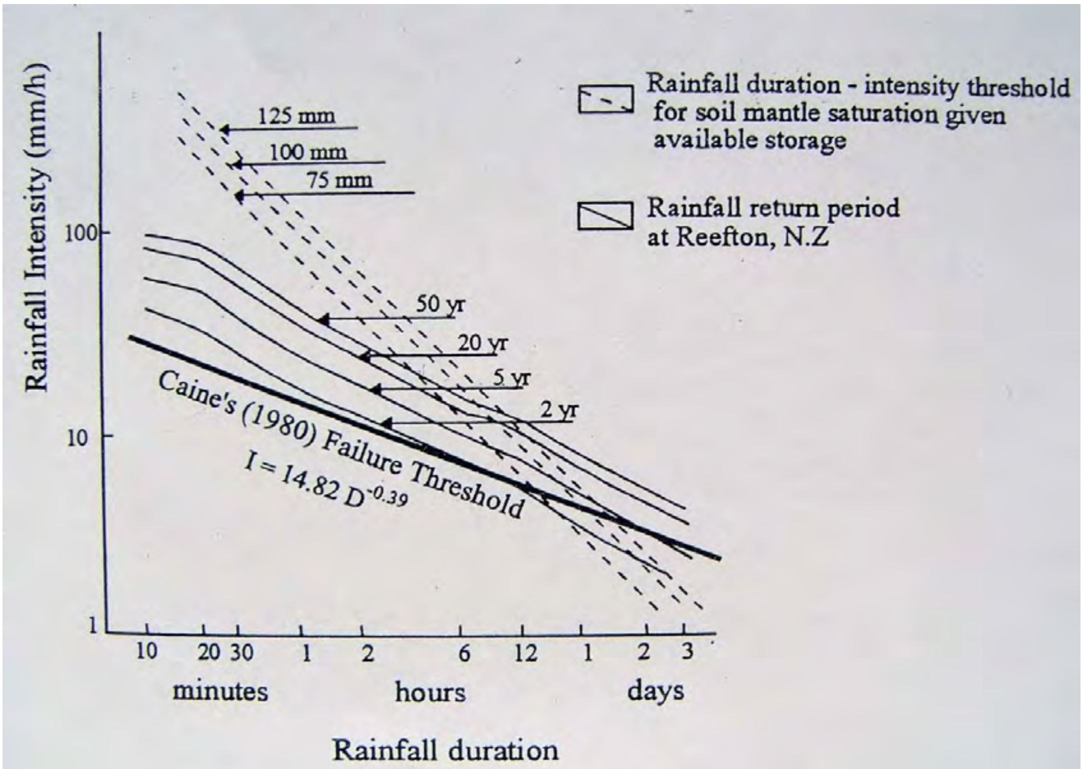

Figure 9.2. Caine's rainfall intensity threshold for triggering landslides (also showing intensity-duration curves from New Zealand and soil mantle saturation curves) (Dikau et al., 1996: 173).

Projections for warmer drier summers with more sporadic rainfall have led to predictions that in Ireland 31% of raised bogs will be lost by 2055 due to climate change (Jones et al., 2006). The Irish Peatland Conservation Council monitors water levels and suggests 30cm or less (from the surface) as a reliable threshold depth for the survival of sphagnum mosses. They recommend a combination of monthly hydrology monitoring with vegetation surveys (% sphagnum cover) every 6–10 years (Duggan[2], pers. comm.). Simple wells can be made using plastic pipes inserted in the peat and water levels checked by hand with a dip stick or weighted string ‘plopper’ (Irish Peatland Conservation Council, 2013). In the case of

[2] Richella Duggan, Conservation and Database Officer, Irish Peatland Conservation Council, bogs@ipcc.ie (4.2.2010).

peatlands, the palaeo-record can provide valuable evidence of past climate and environmental response, which in turn may be utilised as an indicator for sensitivity and possible future behaviour (Warner and Bunting, 1996).

Figure 9.3. Lyrecrompane Co. Kerry, landslide of elevated blanket bog, August 2008 (photo http://friendsoftheirishenvironment.net/ 2009)

The relationship between rainfall intensity and duration for the triggering of shallow slides and debris flows is expressed by Caine's failure threshold (figure 9.2). According to this formula, a rainfall intensity of 14.82mm/hour lasting longer than 25 minutes could trigger a landslide. As the rainfall intensity and duration values move towards Caine's failure threshold the exposure is therefore said to increase (Dikau et al., 1996). Noah’s Ark cite a different figure based on experience from landslides in Singapore where 100mm of rain delivered over a period of 6 days (i.e. 15–20mm/day) was sufficient to trigger small slides (Institute of

Atmospheric Sciences and Climate, 2006). Records of past landslide events can be utilised to assess soil stability issues, yet with extreme climate events previously stable areas may be affected. Sensitivity to landslide is determined by a combination of soil type and slope properties (e.g. gradient, drainage, land cover). Human activity such as land cutting or drainage schemes may also increase sensitivity. Of the 117 documented landslide events in Ireland, 63 have involved peat as the major material, in both upland blanket and lowland raised bogs and extreme rainfall is often a factor in these events (figure 9.3) (Creighton, 2006).

Figure 9.4. High water mark (secondary indicator for flooding) Lady's Island, Co. Wexford, February 2013

A concept that has potential to be developed within the heritage sector is the elaboration of 'cultural' geoindicators. Edmunds raised this in terms of relating a baseline indicator for groundwater levels to the behaviour of the human population. His suggestion was that patterns of traditional use of water by indigenous peoples, who have adapted to cycles of drought over centuries, would provide a good indicator for water availability and climatic influence (Edmunds, 1996). Research into patterns of cultural practices could thus provide data for establishing indicators based on human behaviour. The potential of cultural or social indicators was described more recently in relation to the contribution of archaeology to understanding environmental change (Rockman, 2012). This is described by Rockman as the 'human barometer'.

Table 9.2. Example of geoindicators for impacts on landscape

Impact	**Indicator**	**Frequency**	**Method**	**Other Indicators**
Fluvial flooding and Erosion	Water level and flow	Hourly	Automated gauges	Channel bed level High-water mark (figure 9.4)
Pluvial flooding and Erosion	Vegetation change / cover Volume of material moved	Seasonal	Aerial photography Visual assessment	% hedgerows

Impact	Indicator	Frequency	Method	Other Indicators
Deterioration of water quality	Ground water testing		Conducted by EPA	Freshwater dependant species e.g. otter, kingfisher
Deterioration of peatland	Water level Sphagnum moss	Monthly 5 yearly	Dipstick Species survey	Palaeo-record Aerial survey
Landslide/ collapse	Caine's threshold Peat condition	Event related Seasonal	Linked to meteorological measurements	Survey levels Time taken for surface water to drain
Disturbance to buried archaeology	Agricultural practices e.g. % tilled land	Annual	Aerial or field survey Data collected by agencies e.g. Census	

9.3.3. Indicators in the burial environment

The use of soil parameters to indicate archaeological preservation *in situ* was discussed previously in relation to the Norwegian project *Archaeological Deposits in a Changing Climate* (section 5.5). While burial preservation is dependent on many variables those most affected by climate are soil chemistry, temperature and water supply. Piezometric levels, widely used for national monitoring of groundwater, can also act as indicators for archaeological preservation (Edmunds, 1996). Where the existing network does not coincide with site locations, on site monitoring can be established.[3] At the Sutton Common archaeological site in England for example, the position, shape and fluctuation of the water table was measured using piezometers (Holden et al., 2006). Changes in the water table are not considered problematic in terms of preservation unless they fall outside of the existing pattern of fluctuations (Holden et al., 2006). Once this happens the degree of impact will depend upon the ability of the soil to retain moisture and its permeability to oxygen. Using water level as an indicator of exposure to deterioration therefore requires a time series of measurements and an understanding of the local soil conditions.

It is important to tap into existing resources before developing new programmes; many countries carry out groundwater monitoring and may also test for other indicators of interest. Understanding the methodology utilised by the primary collectors is vital when using borrowed data however. For example some water quality tests use pumped samples of mixed origin and would have no value for a site based analysis (Edmunds, 1996).

Decreased recharge or increased abstraction rates during hotter and drier summers may lead to an increase in the salinity of groundwater, the main indicator for exposure to this impact is the level of Chloride (Cl) (Edmunds, 1996). Measurements of conductivity and water chemistry can be used to indicate dissolved ions, if combined with precipitation measurements this can also inform on the hydrology of the site (Williams, 2011). Williams writes that reduction potential (Eh) and acidity (pH) are used by most projects to indicate exposure to climate related deterioration mechanisms. A stable reducing environment

[3] In Ireland the Environmental Protection Agency implement the National Water Framework Directive, assessing groundwater quality and levels and the Geological Society of Ireland hold details of all the aquifers.

(0mV<Eh>-200mV) is an indicator of good conditions for organic preservation while neutral pH around 8–6 is associated with good general preservation (Holden et al., 2006, Lillie et al., 2008).

> *Most projects use the presence of a non-fluctuating near neutral pH and redox values between +100 and -400mV as an indicator of good preservation conditions* (Williams, 2011: 3) .

Micro-organisms are the main agent of organic decay in the burial environment and have potential as indicators that has yet to be developed due to lack of detailed understanding (Holden et al., 2006). Experiments with archaeological wood from Greenland showed that deterioration is exponentially related to temperature (Hollesen et al., 2012). Thus a 1^{o}C rise in soil temperature equates to 11–12% increase in rate of wood decomposition. The availability of oxygen and water are required for the decomposition reaction but the functional relationship of these factors was not determined. A simpler possibility for assessing the organic preservation within a burial environment is the periodic processing of cores to compare percentages of environmental remains e.g. plant macrofossils or *coleopteran* (beetles). Attempts to relate botanical remains to the preservation of artefacts in the Netherlands did not find a clear correlation however and further research is required before use of this indicator (Huisman and Mauro, 2011). Similarly, attempts to relate bone histology to soil conditions found preservation of archaeological bones can vary greatly within one site and was best assessed using a combination of techniques (Jans et al., 2002). This raises the importance of the functional relationship discussed earlier i.e. monitoring of indicators can only be useful if there is an idea of the meaning of any change (Holden et al., 2006).

Figure 9.5. Close up of prepared wood samples on spiked rod and complete set prepared for insertion in soil (Gregory et al., 2008)

Monitoring soil characteristics requires specialist equipment and the costs may be prohibitive. A low cost alternative for organic materials is the use of sacrificial wood samples, buried on site and retrieved periodically (figure 9.5) (Gregory et al., 2008). The wood samples are subjected to simple microscopic study to determine degradation patterns (identifying the presence and type of micro-organisms) as well as wood density measurements. This offers a relatively low cost and zero maintenance set of indicators for exposure to ongoing biological deterioration processes, and one that can be employed at multiple locations and levels (Gregory et al., 2008).

Table 9.3. Example of indicators for burial preservation (Edmunds, 1996, Holden et al., 2006, Williams, 2011, Gregory et al., 2008, Huisman and Mauro, 2011)

Impact	**Indicator**	**Frequency***	**Method**	**Other Indicators**
Change in groundwater level	Water level Fluctuations	Daily / 3 months	Piezometric meter Dip wells	Soil moisture content
Altered reduction potential	O_2 Eh (redox)	6 months	Conductivity meter	Fe^{2+}
Altered recharge rates	Cl	2 years	Field or lab testing	
Water quality	HCO_3, Cl pH	6 months	Field or lab testing	Conductivity NO_3
Altered microbiology	Bacteria, Enzyme activity, Microbial activity		Field or lab testing	Soil temperature
Soil chemistry and salinity	pH, Cl, Conductivity		Field or lab testing	

Impact	**Indicator**	**Frequency***	**Method**	**Other Indicators**
Deterioration of organic artefacts and ecofacts	Buried wood samples Eh Organic content in soil		Microscopic and density analysis Field or lab testing	Assessment of excavated organics

*Frequency is only given if recommendations have been given in the literature

9.3.4. Indicators for the coastal zone

Loss or damage of cultural heritage due to coastal change is one of the main concerns in the both the literature and questionnaires (sections 3.5.1. and 4.4.). There are a number of possible indicators that policy makers can use to alert themselves to possible future loss and these are dealt with in the relevant scientific literature (Forbes and Liverman, 1996, Morton, 1996, Young et al., 1996, Liu et al., 2013, Souza Filho et al., 2006, Universitat Autonoma de Barcelona and G.I.M. Geographic Information Management NV, 2002). Coastal processes that affect a given site are complex and even for experts it may be difficult to attribute measured changes to a single cause such as climate change (Forbes and Liverman, 1996).

In order to assess shoreline change Young (Young et al., 1996) developed a methodology using qualitative data. By repeated photographic and descriptive assessments using a checklist of geoindicators he suggests that non-experts can monitor shoreline change in a scientifically valid and inexpensive way. The authors agree that detailed instrumental monitoring is preferable but argue that financial backing for decade long monitoring projects is difficult: *tools that can be of immediate application may be of a more far-reaching consequence than sophisticated methods relying on instrumentation and long-term, quality data-bases* (Young et al., 1996: 203).

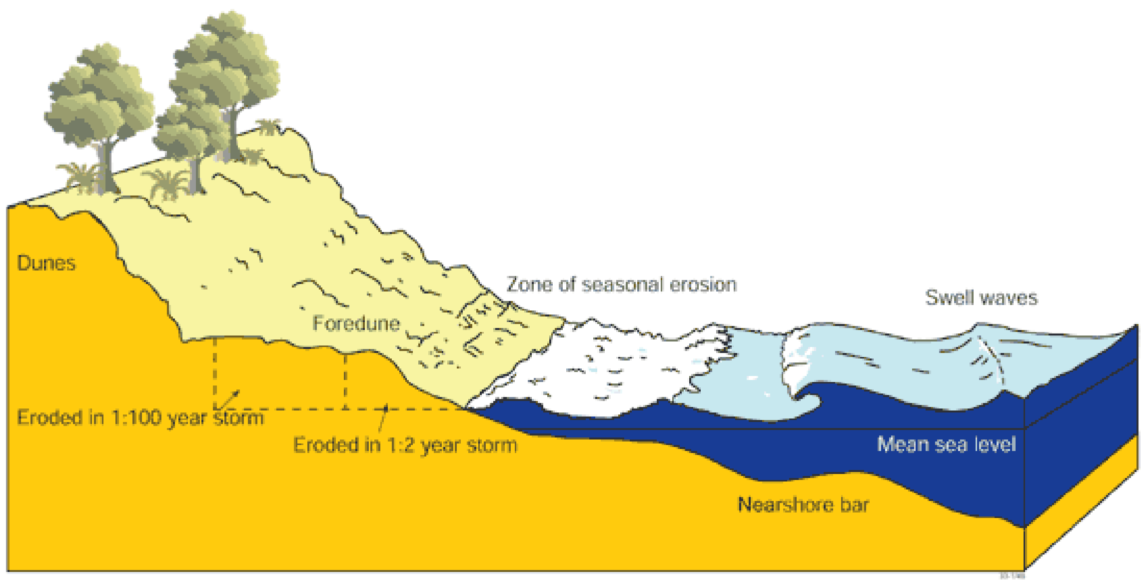

Figure 9.6. Cross-section of a sandy beach showing volume of sediment eroded in high-magnitude storms (1:100 year) compared to seasonal events (figure from http://www.ozcoasts.gov.au/indicators/beach_erosion.jsp 2013)

Morton is more cautious about using qualitative data and argues that only quantitative, long-term analyses are truly reliable (see table 9.4). Geoindicators have been applied to archaeological resources in Queensland, to map climate change risk using dune formation, sea level rise and shoreline position (Rowland, 2008). From this study Rowland concluded that although most of the changes identified were within the expected norm, indicators were capable of clearly demonstrating future deviations from this pattern.

Table 9.4. Example of indicators for coastal change (Morton, 1996, Universitat Autonoma de Barcelona and G.I.M. Geographic Information Management NV, 2002, Blasco et al., 1996)

Indicator	**Measurement**	**Other Indicators**	**Measurement**
Shoreline position (figure 9.6)	Ground survey, Remote sensing, (e.g. aerial photography) Beach profile	Beach width, morphology and composition, Erosion hotspots	Field measurement, Mapping
Wetlands distribution	Ground survey, Aerial photography	Water levels, Salinity (water and soil), Sedimentation	Water level, Flood levels, Chemical analysis, Surface height
Water level change	Tide gauges, Direct sea level measurement	Storm surge height, Storm duration and frequency	Tide gauges, Pressure sensors[4], High water survey
Mangroves	Remote sensing (satellite and aerial images), Field survey		
Investments on coastal protection	Financial resources deployed	Capital at risk (human, economic, ecological etc.)	

[4] One millibar (100 Pa) difference in atmospheric pressure can result in a tidal height change of 10mm (CUFFE FITZGERALD, A. 2010. Climate Change and Shoreline Built Cultural Assets; The Preparation of a Vulnerability Atlas. The Heritage Council).

9.3.5. Biological indicators

Instrumental recording of climate has long been supplemented by secondary biological indicators that are climate dependant (Fiedler, 2009). These often have the advantage of reflecting local micro-climates and are relevant for the composition of cultural landscapes, biodiversity and intangible heritage values e.g. flagship species.

Phenological observations are proven to be good natural indicators for climate change (Menzel et al., 2006) and are relatively easy to establish. At the National Trust Trelissick estate in Cornwall for example, records of the plants in flower on the 1st of January have been made for 25 years (The National Trust, 2005). The Phenological Network in Ireland was first established in the 1960s for the *study of the timing of recurring natural events* such as flowering, leaf burst and leaf drop (Department of Botany Trinity College Dublin, 2011). There is already half a century of data available and the network is currently being expanded. Continuity and storage of this data is secure due the involvement of permanent institutions such as the National Botanic Gardens and Trinity College Dublin.

The Phenological Network also publishes data sets on migration and egg laying of certain bird species that are closely linked to spring temperatures. The National Biodiversity Centre and Irish Phenological Network have created a website where members of the public can report phenological observations (www.phenology.biodiversityireland.ie). This mobilises the voluntary sector and also promotes environmental awareness and public engagement. Edible plants may offer another possibility for data gathering. In Japan a recent study identified six edible plants that would be suitable for use in a long-term volunteer-based system, monitoring climate change using plant distribution (Higa et al., 2013). The study of niche species such as lichens offers another possibility. Interpreting life cycle and growth rate observations requires expert input. For example in the case of lichens, combining survey with laboratory analysis will generally be necessary (Viles and Pentecost, 1994).

Figure 9.7. The Irish Butterfly Monitoring Scheme (photo www.biodiversity.ie 2012)

The EPA report on indicators for climate change recommends the use of moths and butterflies (Lepidoptera) (Sweeney et al., 2002). Lepidoptera are ideal indicators of climate change as they are relatively easy to identify and contain a large number of species which are indicative of various habitat types. A study of the first dates of appearance of the adults, and the number of generations per year can provide useful comparative data (Tubridy[5], pers. comm.). The Biodiversity Centre run the Irish Butterfly Monitoring Scheme developed in

[5] Dr. Mary Tubridy & Associates, Ecological consultant, by Email, 2/2/2010

conjunction with volunteers (figure 9.7).[6] The value of volunteers was highlighted in relation to coastal monitoring (section 5.3) and collection of indicator data offers further possibilities for engaging public participation in heritage management.

Flagship species such as the Atlantic salmon on the Boyne can provide indications of changing environmental conditions, but in many cases the effect is complex. The salmon for example may be declining in the Boyne because of over-fishing at sea, pollution, sedimentation of spawning beds or rising temperatures due to climate change (Sweeney et al., 2002). Many flagship species have a powerful symbolic function and as such are important indicators for intangible cultural values. Selecting a visible and culturally significant indicator species (e.g. swallows, geese or the cuckoo) is therefore important not merely for ease of observation but also because these species have a cultural resonance (Fiedler, 2009).

Table 9.5. Example of biological indicators for climate impacts (Sweeney et al., 2002, Menzel et al., 2006, Letcher, 2009, Viles and Pentecost, 1994)

Impact	**Indicator**	**Frequency (yrs)**	**Method**	**Other Indicators**
Changes in growth conditions - Temperature	Tree development phases e.g. leaf burst, flowering, leaf drop	Seasonal	Phenological network	Plant distribution

[6] http://irishbutterflymonitoringscheme.biodiversityireland.ie/

Impact	Indicator	Frequency (yrs)	Method	Other Indicators
Changes in growth conditions - Precipitation	Agriculture e.g. % crops irrigated, grass production, potato yield	Seasonal	Data collected by agencies i.e. Teagasc or Dept. of Agriculture	Plant distribution
Changes in growth conditions – Temperature and Precipitation	Lichens i.e. niche species and rate of growth	5 yearly	Survey and laboratory analysis	Atmospheric NO_x (implications for growth)
Changes in species behaviour - Temperature	Arrival dates of swallows Butterfly and moth populations	Spring Daily	Volunteer recording Moth traps	Bat hibernation Bird egg laying
Changes in biodiversity	Population surveys – flora and fauna	All above	All above	Invasive species

9.3.6. Indicators for the built environment

Many of the environmental indicators already mentioned will be relevant to built heritage in terms both of 'sense of place' and of physical processes. At the micro-scale however, there are additional concerns that need to be considered as the structural and material properties of built heritage are key factors in understanding sensitivity and exposure to changing climatic conditions (Sabbioni et al., 2006).

Within conservation science dose-response or damage functions have been developed for some materials and/or types of object, in an attempt to predict how environmental conditions contribute to decay mechanisms (Martens, 2012). Essentially these are equations that describe how a number of different variables act together to produce an effect. For example Noah's Ark used the Lipfert function[7] to determine the erosion index of carbonate stones, the variables being rainfall and pollutant concentration (Brimblecombe and Grossi, 2009). The individual variables that contribute to formulating a damage function may have potential as indicators for sensitivity to a given effect. To isolate one variable would greatly reduce the scientific accuracy, yet if the functional relationship defined by the formula allows a linear correlation, it may be possible.

In the case of carbonate stone in Europe, Noah's Ark came to the conclusion that clean rain was the most important parameter in the Lipfert function and they simplified it accordingly (Bonazza et al., 2009) (section 10.9.2.). Recent comparison between rates of measured erosion and dose response predictions demonstrated that while the magnitude of change was very different the function was accurate at estimating the patterns of change i.e. increasing or decreasing (Inkpen et al, 2012). Work package 4 of the Climate for Culture project deals with the use of damage functions for indoor climates and their utilisation in the definition of climate control standards (Climate for Culture, 2013). The project utilises an approach that

[7] Lipfert function: **$-dx/dt = 18.8R + 0.016[H+]R + 0.18(VdS[SO_2] + VdN[HNO3])$.** Where -dx/dt is the surface recession per year (μm/year), 18.8 is the solubility of $CaCO_3$ in equilibrium with 330 ppm CO_2, R is the rainfall (m/year), 0.016 is the constant valid for precipitation pH in the range 3–5, [H+] is the ion concentration (ion/l) evaluated from yearly rain pH, 0.18 is the conversion factor from (cm/s) (μg/m^3) to μm, VdS is the deposition velocity of SO_2 (cm/s), [SO_2] is the SO_2 concentration (μg/m^3), VdN is the deposition velocity of HNO_3 (cm/s), and [HNO_3] is the HNO_3 concentration (μg/m^3).

combines damage functions with computer simulations to produce risk analysis (Huijbregts et al., 2012). The final results, including decision support software using specific damage functions, are due in 2014.

Table 9.6. Relative humidity thresholds for crystallisation of various salts (Haugen and Mattson, 2011)

Salt	**RH_{eq} at 0°C**	**RH_{eq} at 10°C**	**RH_{eq} at 20°C**	**RH_{eq} at 30°C**
Sodium Carbonate (Na_2CO_3)	-	-	82	84.3
Sodium Chloride (NaCl)	75.5	75.7	75.5	75.1
Potassium Sulphate (K_2SO_4)	98.8	98.2	97.6	97
Sodium Sulphate (Na_2SO_4)	-	-	93.6	87.9

Predictions for an increase in wetting and drying cycles have lead to concern over salt damage due to climate change (Cassar et al., 2006, Smith et al., 2004). Haugen lists the 'equivalent relative humidity' for several common salts i.e. the value at which they will crystallise out of solution (table 9.6) (Haugen and Mattson, 2011). These threshold values mean that relative humidity (RH) values can be used as an indicator of exposure to salt damage. For example, Noah's Ark heritage climate maps for salt crystallisation were based on projections of the number of times each year that the 75.5% RH transition point for Sodium Chloride (NaCl) was crossed (Brimblecombe and Grossi, 2006, Grossi et al., 2011). Actual exposure will also depend on the concentration in solution and physical characteristics of the object.

In relation to biological growth, while moisture is often the decisive criteria for germination and growth in Southern Europe, temperature has been the limiting factor in Northern latitudes (Brischke et al., 2010). In Northern Europe wooden buildings are common, and one of the main concerns in this regard is that warmer winters will result in increased biological decay (Haugen and Mattson, 2011). At 80-85% RH mould germination and growth can occur for most species at temperatures between 0^{o} and 40^{o}C (Gobakken, 2010). The rate of growth will be highest around 20^{o}–28^{o}C, suggesting that temperature could be used as an indicator for biological decay (Martens, 2012). REMO projections for the case study sites project a significant increase in the incidence of higher temperatures and RH, suggesting that both internal and external spaces will see increased growth rates, for example the germination of fungi (table 9.7).

Table 9.7. Comparison between recent past and far future periods of germination conditions for fungi according to Sedlbauer's theory (Martens, 2012)

Number of days projected to reach Sedlbauer 1–2 day summer germination conditions of 20^{o}–30^{o}C & 90–100% RH for fungi on porous organic substrate	
Skellig Michael	**Brú na Bóinne**
1960–1991 1 day 2070–2101 46 days = 4,500% increase to far future	1960–1991 11 days 2070–2101 86 days = 780% increase to far future

Stone buildings are known to respond to higher precipitation volumes by increased biological growth (primarily algal). Thus the monitoring of greening has been suggested as a secondary indicator for climate change (McCabe et al., 2011). The known sensitivity of sandstone to biological colonization, together with the existing body of research into the behaviour of the stone under varying environmental conditions, makes it an ideal indicator (McCabe et al., 2011). Alterations in the occurrence and distribution of lichens are expected under future climate change and there is evidence that this process has already begun. For example, in the Netherlands warmth loving oceanic lichens are expanding and boreal lichens reducing (Aptroot, 2009). Unlike other forms of microbiological growth lichens are visually obvious and can be measured relatively easily (figure 9.8). The process of interpreting observed differences in any form of biological growth *vis a vis* climate change is likely to be highly complex (Viles and Pentecost, 1994, Cutler et al, 2013).

Figure 9.8. Limestone headstones with golden and grey crustose lichens (photo http://www.britishlichensociety.org.uk/ 2013)

The possibility of using the condition of historic stone as an indicator of future performance has been investigated in the literature (Scheffler and Normandin, 2004, Curran et al., 2004). Historic deterioration has also been assessed to determine past environmental conditions (Brimblecombe and Grossi, 2009, Andre, 2006). The use of gravestones and stylistically dated carvings to assess weathering rates dates to the nineteenth century (Andre, 2006, Inkpen et al., 1994, Geikie, 1880). The concept has also been applied to Megalithic monuments to demonstrate that post-megalithic weathering can override geological weathering (Pope and Miranda, 2004). The rate and pattern of stone weathering may alter under future conditions and is of particular concern for Brú na Bóinne where the rock art is considered to be of Outstanding Universal Value (chapter 8). An indicator for stone recession, which was developed within this study, will be detailed in the following chapter. The concept is to expose a fresh sacrificial stone sample and take measurements over time in order to track patterns of deterioration. The advantages of this system are that the complete history of weathering will be known and that the object can be measured *ex situ*.

Changes in insurance payouts could potentially be used as an indicator for catastrophic climate change effects on buildings (Grontoft, 2009). While archaeological heritage is not necessarily insured there is a long tradition of ecclesiastical insurance for historic churches and that could prove useful in this regard (Wainwright, pers. comm.).

Table 9.8. Example of indicators for built heritage (Haugen and Mattson, 2011, Corrosion and Metals Research Institute Sweden, 2006, Andre, 2006, McCabe et al., 2011, Grossi et al., 2011, Bonazza et al., 2009)

Impact	**Indicator**	**Frequency (yrs)**	**Method**	**Other Indicators**
Biological decay of wood	Temperature and RH	Daily	Instrumental	Moisture content of wood
Salt crystallisation	RH	Daily	Instrumental	Temperature
Microbiological growth on stone	Indicator species e.g. lichens Temperature and RH	Annual Annual	Specialist Visual and/or instrumental	Atmospheric NO_x Sensitive materials i.e. quartz sandstone
Chemical erosion of carbonate stone	Rainfall volume	Annual	Lipfert Function	SO_2 HNO_3
Stone weathering rates	Dated stone surfaces e.g. tombstones	5 years	Visual	Lichens (figure 9.8)
Structural damage – storm, flooding etc.	Repair costs	Annual	Annual budgets, insurance company data	Insurance claims for historic buildings

9.4. EXISTING RESOURCES

In some situations data from indicators can offer an alternative to installing monitoring equipment if staff and funding are limited. If heritage managers are concerned about climate change impacts but are without the resources required to establish site specific monitoring they may be able to benefit from data sets collected within other disciplines. Some of those relevant in the Irish context are listed below but others may be available and it is important to keep an open mind on possible interdisciplinary links (see table 9.9). Capitalising on this capacity for interagency collaboration leads to what Bardach terms 'smart practices' and forms part of the flexible and pragmatic management approach favoured in this thesis (Subirats and Gallego, 2001). In many cases the data is provided free or for a nominal fee, public agencies in particular should be able to negotiate co-operative arrangements. Good communication with the primary collector is essential when choosing to use indicator data from external agencies in order to ensure it is fit for purpose. Timing is also important and data should only be requested when it is required in order to ensure it is as up to date as possible (RPS, 2012).

Table 9.9. Example of sources for indicator data (RPS, 2012, Daly et al., 2010)

Name	Resource	Contact
C4i (climate for Ireland)	Climate change research and projections for Ireland	www.c4i.ie
Central Statistics Office	Population, land use, economic growth etc.	www.cso.ie
Coillte	Forestry database	www.coillte.ie

Name	**Resource**	**Contact**
Irish Marine Institute	Marine weather buoys data and mapping service online, includes wave height, water temperature, wind and RH. Also data on other marine research e.g. shellfish stocks, algal bloom etc.	www.marine.ie
Environmental Protection Agency	Environmental factors e.g. water quantity and quality, air quality, natural heritage and climate change.	www.epa.ie
Geological Survey of Ireland and the Irish Landslides Working Group	Mapping geology incl. soils and groundwater aquifers. National Database of landslide events	http://www.gsi.ie (landslide database not currently available)
Inland Fisheries	Fish counts and species present	www.fisheriesireland.ie
Irish Weather Network	Data from privately owned weather stations	www.irelandsweather.com
Local Authorities	Development plans include information on landscape assessments, protected areas, cultural assets, water quality testing, species surveys etc.	Local authority websites
Met Eireann	Database of historic and current meteorological measurements	www.met.ie
National Biodiversity Centre	Database of flora and fauna including annual counts	www.biodiversity.ie
National Oceanography Centre UK	Short term tidal level and storm surge predictions for British Isles. Historic records for same.	www.pol.ac.uk

Name	Resource	Contact
National Parks and Wildlife	Information on protected species and habitats	www.nps.ie
National Roads Authority	Automatic weather stations located along main routes	Data available online from www.irelandsweather.com
OPW	Hydrometric gauges data, flood mapping and flood risk management	http://www.opw.ie
Teagasc	Agriculture incl. soils, crops etc.	www.teagasc.ie
The Phenology Gardens Network Ireland	Records for phenological observations from 1960s	Trinity College Dublin Botany Dept. College Green Dublin 2 proctoh@tcd.ie

9.5. CONCLUSIONS

Indicators are an important part of the vulnerability assessment process. They also have potential as a secondary data source to complement data from direct monitoring. The choice and selection of indicators can be difficult however, and validation relies on the process being both detailed and transparent. Indicators are useful in simplifying the characteristics of vulnerability into a measureable variable but this process can be criticised as reductionist or arbitrary. The selection and use of indicators should be a participatory process, open to criticism and review (Adger et al., 2004).

In some instances a lack of detailed scientific information on interactions being examined makes definition of the functional relationship difficult (Sweeney et al., 2002, Holden et al., 2006). The current lack of long-term data collection at a scale relevant for individual sites may also be a problem. Nonetheless the value of indicators is recognised across different disciplines and it can be expected that both research and data collection will improve to reflect this in time (Pearson et al., 1998, Sweeney et al., 2002, Elliott, 1996, Gregory et al., 2008).

By taking a multi-disciplinary approach to the selection of indicators cultural heritage managers are already able to take advantage of a wide variety of long-term secure data-sets collected for diverse purposes (table 9.9) which they can utilise when applying the Vulnerability Framework (section 6.10.). The collection of indicators presented in this chapter form a Toolbox from which managers can select according to their needs. The initial Toolbox can be updated and expanded and through reflexive use is likely to become increasingly relevant to the specifics of cultural heritage. In the next chapter the creation of an indicator tool to address concerns over the effects of climate change on stone surfaces at the World Heritage Sites will be discussed.

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CHAPTER 10.

LEGACY INDICATOR TOOL ‘LegIT’

10.1. INTRODUCTION

In the previous chapter the concept of vulnerability indicators was explored, and a number of possible data sets for use with cultural heritage were outlined. Finding relevant indicators (especially material-specific ones) remains a complex challenge for those undertaking site-based assessments. During the course of the current study it was decided to investigate the possibility of creating an indicator specifically for tracking the weathering of stone in heritage sites. The result was the development of a Legacy Indicator Tool or ‘LegIT’ for use in the case studies. The design, implementation and preliminary results of the LegIT trial are described in this chapter.

The majority of Ireland’s pre-eighteenth-century heritage buildings are constructed from local stone (Pavia and Bolton, 2001). At the two case study sites stone is also the main material of construction. Preventing the loss of the stone surface, and resultant reduction in detail of the carvings, is a priority at Brú na Bóinne. Therefore every winter the kerb at Knowth is wrapped in protective covers (figure 10.1). On Skellig Michael Old Red Sandstone is the main material, and its deterioration affects both the built structures and the island itself.

Figure 10.1. Protective coverings on the decorated kerbstones at Knowth, February 2012

Direct monitoring is the most accurate method to ascertain the rate and scale of loss due to weathering (Daly et al., 2010). Optical 3D scanners (section 5.4.) or laser scanners are tools that can be utilised both for detailed recording of fine carvings and for building scale analysis (Dore & Murphy, 2012, Meneely et al., 2009, English Heritage, 2012). For example a decorated orthostat from the Knockroe Western Tomb was scanned by the Discovery Programme while undergoing conservation treatment (Shaw, 2011). The point cloud produced by a laser scanner can vary in precision, in the case of the equipment used to record carved detail on the Knockroe orthostat an accuracy of 0.13mm was possible. At present this style of high-tech, expert-led monitoring, requires a level of funding and technical capability that may be difficult for heritage sites to maintain given current funding shortfalls (section 4.12.). In addition confident attribution of observed deterioration to climate change will require a century of data. Any method chosen should therefore be easily repeatable over the long-term, and in this context low-tech solutions may be more appropriate (section 4.9.).

The issue of sustainability of monitoring procedures over the period of climate change *vis à vis* staffing, equipment and funding, is vital in the selection of appropriate monitoring solutions (Daly et al., 2010). The stone indicator devised during this study has been designed to address these issues. Based on the research tradition of using sample exposures (section 10.2.1.), it is designed to answer questions specific to climate change impacts. The aim in designing the tool was to create an indicator capable of:

1. Tracking some of the effects that a changing climate will have on the weathering of stone surfaces i.e. changing patterns of recession or microbiological growth
2. Providing a legacy for the future i.e. a tool that is sustainable over a period of 100 years required to measure climate change

10.2. BACKGROUND

10.2.1. Stone exposure

The exposure of fresh stone allows study of stone decay patterns under real-world environmental conditions without compromising the integrity of historic monuments. Short-term exposure trials have been used in many scientific studies for understanding decay patterns and thus for predicting future behaviour (Turkington et al., 2003, Young and Urquhart, 1998, Tiano, 2006b). To date, most exposure trials have been conducted to investigate pollution effects and have often focused on calcareous stone (Baedecker and Reddy, 1993, Eureka Project, 2000, Cooper et al., 1991). The vast majority are also short-term projects, and even in the long-term studies, the longest period any sample is exposed for is approximately eight years (Viles et al., 2002, Inkpen et al., 2012a).

Figure 10.2. International Co-operative Programme (ICP) stone test samples on rotating carousel, Katowice, Poland (Tidblad, 2009)

One of the most extensive exposure trials is that carried out by the International Co-operative Programme (ICP) in which the effects on materials, including historic and cultural monuments, were monitored (Swerea KIMAB AB, 2009, Tidblad, 2009). The ICP exposed standardised materials at a network of test sites across Europe between 1987 and the present. The stone tests have been conducted on Mansfield sandstone and Portland limestone blocks (50x50x8mm) fixed to a rotating carousel (figure 10.2) (ICP Materials Programme Centre, 2006). The British National Materials Exposure Programme (NMEP) ran from 1987–1995 and fed into the ICP programme. These samples were assessed according to a variety of criteria, including weight, salt content, colour change and were also observed by Scanning Electron Microscopy (Viles et al., 2002). In addition, the Buildings Research Establishment (BRE) has data from studies of Portland limestone blocks (100x100 x75mm) dating from 1955 in which the blocks were measured once per year (Yates, 2003). It can be difficult to compare exposure studies given the variety of methodologies employed although Yates suggests this may be managed using a volume to surface area ratio translation (Yates, 2003).

Figure 10.3. Concrete *Asterixe* at Fraunhofer Institute, Holzkirchen, December 2010

The Fraunhofer Institute for Building Physics has a collection of natural and artificial stones (including concrete) that have been exposed in both rural and urban locations in Germany for 25 years (approx.1985–2010). These *Asterixe* stones were cut into a standard asymmetric shape that provided a range of surfaces similar to those found on monuments: recesses, projections, smooth and ridged surfaces (figure 10.3). The aim was to produce weathered material for later research on conservation treatments such as the application of hydrophobic coatings or consolidants, and not to study the weathering *per se* (Kilian[1], pers. comm.).

Figure 10.4. Limestone sample and runoff catchment unit, STEP programme, Trinity College Dublin (Cooper et al., 1991)

The STEP project exposed samples at locations across Europe, including Dublin city centre, to determine the rate of dissolution of stone as a consequence of pollution (Cooper et al., 1991). Again the focus was on Portland limestone. The STEP samples were exposed in standardized micro-catchment units and the runoff was collected and analysed to accurately quantify the amount of loss (figure 10.4). At Queen's University in Northern Ireland, Turkington exposed blocks of sandstone (50x50x10mm) on north-facing racks to study pollution effects (assessed using visual and chemical analyses) (Turkington et al., 2003). Queen's has also carried out sandstone exposure trials related to 'greening' or microbiological growth effects (Adamson et al., 2012), and the test walls at Derrygonnelly

[1] Ralf Kilian, Fraunhofer Institute for Building Physics IBP.

discussed in chapter five (section 5.2.) are being used to study 'deep wetting' (Smith et al., 2010, McAllister, 2011).

10.2.2. Damage correlation

Damage functions[2] are hard to extrapolate over long time periods based on limited evidence and the fact that extrapolation of non-linear functions can produce unreliable results (Brimblecombe, 2010a). Dose-response functions[3] offer an alternative approach by looking at the *direction of change*, whether a process is increasing or decreasing, as illustrated by a dosimeter. Dosimeters, the devices that demonstrate exposure through physical change, are frequently utilised in moveable heritage conservation. The Oddy test for corrosion using metal coupons (Art Conservation Research Center, 2009) and the blue wool fading standards (British Standard 1006 1990) are two of the most common. Dosimeters are designed to provide an early warning signal. They are often composed of materials similar to those of the heritage objects being studied, but which are more sensitive and will react faster (Rosenberg et al., 2010). Recently, the EU has funded a number of projects that developed dosimeters for indoor environmental monitoring including MIMIC, ERA, PROPAINT and SENSORGAN (Rosenberg et al., 2010). In general all of these studies take a common approach, comparing samples aged in the laboratory under known conditions with site-exposed samples. Although the process was not replicated with the LegIT, the dosimeter concept of using a sacrificial object to indicate the effects of environmental conditions and to provide an early warning signal, was central to the tool design (section 10.3.1).

[2] Damage functions are mathematical equations used to represent the relationship between damage and the contributing factors.
[3] Dose response functions explain the link between change in a dosimeter and exposure to specific hazard.

10.2.3. Embedded monitoring

Monitoring methods currently in use, both for climate and deterioration, tend to fall into three categories.

- Expert driven e.g. laser scanning or laboratory analysis.
- Quantitative measurements e.g. automatic sensors of varying technological complexity.
- Qualitative e.g. condition survey.

There is no long-term monitoring strategy at either of the two case-study sites. This is not unusual for heritage sites where changes in funding streams, management plan cycles, personnel and political interest can contribute towards a lack of sustainable monitoring projects (sections 4.12. and 4.13.). It has been stated elsewhere (Brimblecombe, 2010b) that what is needed for climate change monitoring at heritage sites is a form of embedded monitor. This could be either a passive object or a high-tech piece of equipment that would continue to gather and store data without maintenance or management requirements.

The consensus of expert opinion is that there is a need for monitoring (section 4.6.), and that simple low-cost methods would prove the most sustainable (section 4.9.). This research provided a motivation for the decision to develop an indicator tool that could be embedded at heritage sites in Ireland to focus on the impact of climate change on stone. The concept was presented at a meeting with Senior Conservation Architects at Office of Public Works (OPW) offices in Dun Sceinne Dublin on the 10th March 2011 and those present agreed that an embedded tool for long-term monitoring would be of value (Dolan, McMahon, O'Shaughnessy and Rourke, pers. comm.).

> …*you know they* [cubes] *will decay and of course they will, but it is the way the process accelerates that will alert you* (O'Shaughnessy, pers. comm.).

The tool successfully addressed several requirements as expressed by the group:

1. The need to understand site specific micro-climates.
2. The need for simple solutions that can be used without constant specialist input. A problem had been experienced with handling laser scan data (Dolan, pers. comm.).
3. The need for an evidence base to assist lobbying for resource allocation and political support.

10.3. CREATING AN INDICATOR TOOL

It was decided to develop a sacrificial object that could register changes in the severity and/or magnitude of weathering patterns specific to stone surfaces, reflecting concern over the loss of surface detail. The tool will track the *direction* of any change by illustrating actual weathering as it occurs. Over time, by relating the condition of the object to climate data, it will contribute to an understanding of the influence of climate change on these patterns (i.e. any increase or decrease in incidence and severity). The assessment of climate change impacts will require 30–100 years of data collection, equal to the period referred to as the 'climate norm' by meteorologists, and the LegIT is therefore designed as a legacy for future decision makers.

10.3.1. Design

Table 10.1. Advantages and Disadvantages of two options for indicator

	Advantages	**Disadvantages**
Option 1. **Single object measured**	• Simple to prepare. • Create one sample, install and leave. • Will continue to function without intervention.	• Relies on regular and detailed measurements for comparative analysis. • Loss = total loss i.e. vandalism, failure etc. • Slow process
Option 2. **Consecutive objects compared *'trend monitor'***	• Loss of one is only loss of fraction of data. • Time specific. • Uniformly degrade. • Creates a bank of physical samples that can be used by future researchers i.e. valuable comparative material.	• Results may be misleading depending on the interval for replacement and the sensitivity of the artefact. • Cumulative deterioration leading to catastrophic failure is not measured. • Relies on replacement and safe storage of samples over a long period of time.

Two different options for the embedded indicator were considered:

Option 1: Exposure of a selection of sensitive/representative materials in accurately calibrated cubes subject to periodic documentation/visual assessment. Over time, the relative condition of the samples will contribute to understanding the impacts of weathering mechanisms when assessed in combination with climate data.

Option 2: Exposure of a manufactured artefact, such as a ceramic cube, that would be replaced annually. Over a long period comparison between the databank of weathered cubes will reveal trends in deterioration caused by climate impacts i.e. a trend monitor.

Comparing both options (table 10.1), the key drawback for the trend monitor is that the regular replacement would be difficult to ensure into the far future. On the other hand, the single measured object will maintain its value even if measurements are discontinued for a period. It was therefore decided to pursue option one.

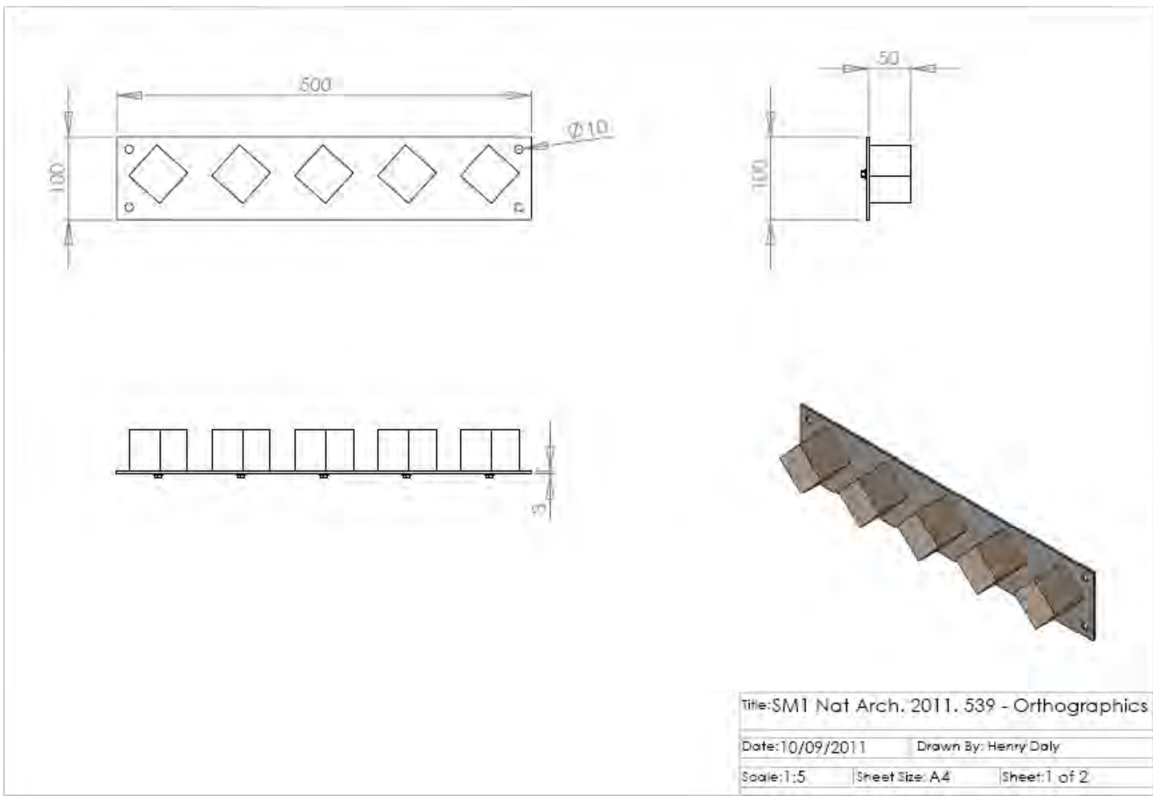


Figure 10.5. Design of the LegIT (drawing by H. Daly 2011)

The final design consists of five cubes attached to a stainless steel plate (figure 10.5). Three identical plates were mounted horizontally at each case study site (figure 10.6). The indicator had to be visually unobtrusive and easy to handle, and this led to the decision to restrict the size of the cubes to $50mm^3$. This decision means that the data collected is limited to near-surface effects. Smith has argued that deep wetting is an important factor in stone-deterioration mechanisms (Smith et al., 2004) and Goudie (Goudie et al., 1997) emphasizes that salt solutions at depth cause chemical breakdown, paving the way for later damage. Because it was considered unfeasible to handle and mount blocks on a masonry scale, these processes will not be reflected. The cube shape was chosen for practical reasons as it is easy to cut and being equal on all sides it allows directionality in weathering to be measured.

Figure 10.6. Skellig Michael LegIT plate No. 1 *in situ*, from left to right: concrete, brick, Peakmoor, Portland, Old Red Sandstone (August 2013)

10.3.2. Natural and manufactured cube materials - Site specific and reference

In the selection of samples, it was important to balance site-specific concerns with the need for scientific baseline data. There are five cubes on each plate, four reference cubes common to all sites and one site-specific cube (figures 10.7 and 10.8).

At each monument, the **site specific cubes** were made from stone as similar as possible to that used by the original builders. In the case of Skellig Michael, stone was sourced by OPW from the World Heritage property (Old Red Sandstone). In Brú na Bóinne Greywhacke from the same stratigraphical unit as that used by the tomb builders was sourced from a modern quarry at Gallstown (Corcoran and Sevastopulo, 2008). Historic Wicklow granite was used for Dublin Castle and two local sandstones were selected for Clonmacnoise and the Rock of Cashel (chosen and provided by OPW).

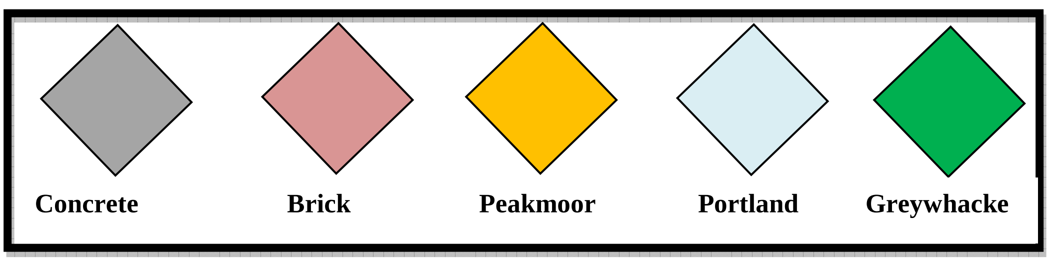


Figure 10.7. Diagram of cubes on Brú na Bóinne LegIT

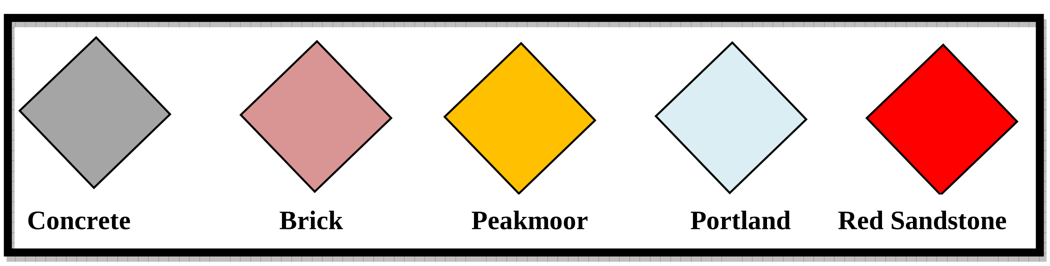


Figure 10.8. Diagram of cubes on Skellig Michael LegIT

The reference materials included two natural stones and two manufactured materials. The **natural reference cubes** chosen were Portland limestone and Peakmoor sandstone, both of which have previously been used in weathering research (Turkington et al., 2003, Yates, 2003, Viles et al., 2002, McAllister, 2011).

- Peakmoor is a medium grained, non-calcareous, quartz sandstone, considered to be durable with good weathering properties (Block Stone Ltd, 2012).
- Portland is an oolitic limestone, creamy/white in colour, its fine texture makes it popular for carvings and mouldings as well as masonry and cladding (Albion Stone, 2012). BRE calculated the recession rate for Jordan's basebed Portland limestone of between 3 and 4 mm per 100 years, but this could be higher in severe exposures or on the edges of stonework (Albion Stone, 2012).

The **manufactured reference cubes** selected were a poured concrete and a machine-made historic brick. Brick is a common component of many heritage structures. Substantial concrete engineering solutions have been made to the archaeological monuments at Brú na Bóinne and Skellig Michael. In addition, the two materials offer an interesting contrast in their weathering patterns compared with the natural stone as they demonstrate different sensitivities to weathering (Chandler, 1991).

- Concrete provides a standardisable sample with known composition and, unlike natural stone, the degradation of cement tends to a linear path (Gaspar and de Brito, 2008). A concrete most representative of common concrete (medium strength and aggregate) with no additives was selected. Concrete is composed of a cementatious paste and an aggregate, the combined properties of these ingredients determines the way in which it weathers. The concrete used was poured by CEMEX Ltd. in Wexford. It has a compression strength of 25–30 MPa and an aggregate size of 10mm (CEMEX 20116841). Chemical processes such as hydration changes and carbonization will continue to occur in the samples over time, independent of the action of weathering, (Gaspar and de Brito, 2008).

- The historic brick was manufactured by the Dolphin's Barn Brick and Tile Co. which operated from 1900 to 1940 in Dublin (Roundtree, 1999).

10.3.3. Reference cubes - materials characterisation

The relationship between geomorphological properties and weathering processes is highly complex and is addressed at length in the scientific literature on stone weathering (Prikryl and Smith, 2007). Samples of the reference cube materials were tested by the Building Research Institute (BRE) in 2013 for porosity, saturation coefficient, water absorption and density (table 10.2). These reference cubes will act as a control for the site-specific stone and allow for comparisons between different sites. The testing by BRE quantifies some of the characteristics controlling the susceptibility of different materials to weathering.

Porosity: Pore space as percent of total volume (porosity) will determine wetting and drying rates for the cubes and therefore will affect biological growth, freeze thaw and salt action. Water is also a controlling factor in the chemical decay mechanisms affecting concrete e.g. alkali-silica reaction (Andrade et al., 1999). According to BRE the most porous of the reference materials is brick followed by Portland stone (table 10.2). The size and distribution of pore spaces is also important. For example, very large pores (as in the brick) will be less susceptible to the physical stresses exerted by salts (McKinley and Warke, 2007).

Table 10.2. Results of materials testing (BR141 1989) conducted by BRE on samples of the reference cube materials (Building Research Establishment, 2013)

BRE Material tests results (BR141 1989)	**Porosity** % by volume	**Saturation Coefficient**	**Water Absorption** % by mass	**Apparent Density** Kgm^{-3}
Portland Limestone (Jordan's Basebed)	18.35	0.73	6.07	2208
Peakmoor Sandstone	12.79	0.66	3.66	2309
Brick	39.19	0.75	17.47	1675
Concrete (CEMEX 20116841 8.00 M3 c25/30 10 CEM IIB S2 WRA-07)	14.86	0.76	4.97	2263

Saturation coefficient: A high-value saturation coefficient indicates that a material has a high proportion of fine pores allowing water to be absorbed by capillary action. According to BRE Digest 420, a value > 0.85 would indicate a stone of low durability, while < 0.65 would be extremely durable (Ashall,[4] pers. comm.). In the case of brick, a saturation coefficient of 0.75 would be an assurance of durability but in fact some bricks measuring as high as 0.85 demonstrate good durability (due to the manufacturing process) (Robinson, 1982). The results for the Peakmoor cube of 0.66 suggest it will prove to be quite durable. Results for the other materials are inconclusive as they all measure around 0.75, the region where saturation coefficient on its own is an unreliable guide to durability (Ashall, pers. comm.).

[4] By Email; Geoff Ashall, Principal Consultant, Building Technology Group, Building Research Institute (BRE), Garston, UK (6.3.2013)

Water absorption: Very small pores do not absorb water, therefore water absorption characteristics, when combined with porosity and saturation coefficient, can be used to build a picture not only of the quantity of pores but also information about the pore size (Winkler, 1997). The resistance of stone to salt damage decreases as the proportion of fine pores increases (Clifton, 2008). When considering the three characteristics of the tested samples, it would appear that concrete is the material most at risk to salt damage, as it has the highest saturation coefficient and relatively low absorption. Concrete is an aggregate material however which makes this interpretation less reliable than it would be for natural stone. With greater absorption the exposure to deterioration mechanisms requiring water increases. In brick the limits for good performance are said to be between 15 – 17% absorption and the reference sample is just outside this range (Robinson, 1982).

Density: The density of a material is a measure of the aggregation of the mineral grains and therefore of its permeability to liquids and gases. In general stones with low densities are softer and easily weathered, those below $1700Kgm^{-3}$ are considered too soft for building stone, while those above $2200Kgm^{-3}$ should be quite durable (Robertson, 1982). The brick displays a low density, suggesting it will be the least strong, but all the other materials tested were above $2200Kgm^{-3}$ although in the case of Portland it was only just over this threshold.

Summary

Based on the BRE test results it is expected that the brick and limestone will weather faster than the Peakmoor and concrete. The apparent larger pore size (based on absorption coefficient) of the brick may mean that salt crystallization cycles will be less damaging. It is the softest material (based on density) and likely to be most sensitive to mechanical recession while Portland (being a calcareous stone) will be most susceptible to dissolution. Biological colonization is also related to the physical and chemical character of the substrate, for example close-grained rocks (those with higher densities) will have low colonization rates because the hyphae cannot penetrate the surface (Cooper et al., 1991).

10.3.4. Support

The stones require an inert support that will not interfere in any way with weathering mechanisms. It must be stable over a minimum of 100 years and ideally for much longer. Initially, several materials were considered including resins, plastics and corrosion-resistant metals such as titanium (Ti), stainless steel and aluminium (Al). The choice was quickly reduced to stainless steel or titanium.

Table 10.3. Relative corrosion pitting rates after 4–5 years of exposure in a marine atmosphere for copper (Cu), aluminium (Al), 316 stainless steel, and titanium (Ti) (Boyd and Fink, 1979).

	Cu	***Cu-zinc alloy***	***Al alloy***	***316***	***Ti***
Corrosion Rate	.095	.028	.01-.025	.0013	Nil

In general, high-strength stainless steel austenitic grades (e.g. 304 and 316) are resistant to the marine atmosphere, considered to be the most aggressive natural environment for metals (Boyd and Fink, 1979). In tests by the British Stainless Steel Association grade 316 took 260 years to develop pits of 1mm depth in a marine environment (British Stainless Steel Association). Crevices, shielded areas and high temperature welds are the only potential areas of weakness. Unlike stainless steel, titanium is not susceptible to crevice attack or pitting and is one of the most corrosion-resistant metals available. The cost of titanium is approximately three times that of stainless 316 however, and as that expense was not justifiable, on the basis of corrosion-resistance tests (table 10.3), stainless steel was selected. The galvanic effect of combining two metals means that the fixings chosen were also 316 stainless, otherwise corrosion of the less noble metal would be likely (Boyd and Fink, 1979).

10.3.5. Fixings

Various options including adhesive, demountable brackets and screws with rawlplugs were considered. The system finally selected is a stainless steel 316 nut and bolt (figure 10.9). The nut is fixed with adhesive into a hole drilled in the base of the stone. This nut will then provide the thread for screwing the stone onto the plate (using the bolt). There are two main advantages to this system. Firstly, the stones are completely demountable. Secondly, there is no internal pressure on the stones from the fixing, as there would be using a traditional screw and rawlplug technique.

The long-term stability of the adhesive used is vital to the longevity of this system, and research was undertaken to establish what would be the best option. In terms of strength and adhesion of two disparate materials (steel and stone) epoxy resins offered the best choice. These resins are commonly used as structural adhesives in industry, and have been developed with diverse properties. Unfortunately enquiries directed at the manufacturer produced very little data on long-term properties. While the resins are tested for industrial purposes, they are not guaranteed for more than 20–30 years and there is no knowledge of their properties over longer periods (Baines[5], pers. comm.).

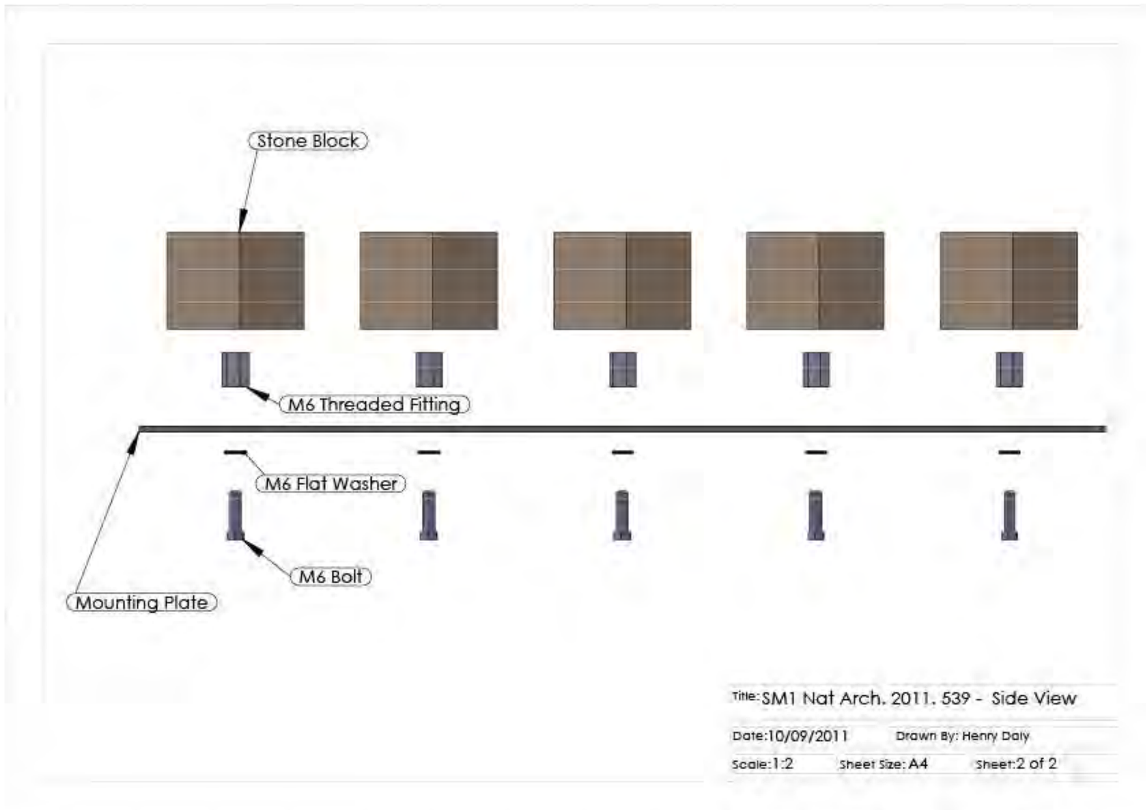


Figure 10.9. Exploded side view of LegIT fixing system (drawing by H. Daly 2011)

The recommendation from Huntsman, manufacturers of Araldite epoxy resins, was to try Araldite 2015 or 2014 and to maximise the bond by abrading and degreasing the steel surface (Chouvet[6], pers. comm.). The data sheet for Araldite 2014 shows that it has a lap shear strength of >20Mpa on stainless steel joints and a high glass transition temperature (Tg) of 85°C. Unlike most epoxies it exhibits a good resistance to water. After 90 days in water at 60°C no change occurred in its lap shear strength and after the same period in water at 90°C

[5] By phone; Paul Baines, Specialist Sales Engineer, Huntsman Advanced Materials, UK (29.8.2011)
[6] By Email; Laurent Chouvet, Field Promotion & Technical Support, Adhesives, Composites and Tooling, Huntsman Advanced Materials, Basel, Switzerland (31.8.2011)

there was a reduction of strength of only 20% (Huntsman Advanced Materials, 2009). In comparison, Araldite 2015 has a lap shear strength of >15Mpa on stainless steel joints, a lower Tg than 2014 (67°C), and lower water resistance (Huntsman Advanced Materials, 2008). On balance, it was decided that the superior water resistance of 2014 made it the better choice for use in the tool as damp conditions would be prevalent for much of the time.

The degreased and abraded stainless steel (316) nuts were fixed into the pre-drilled holes in the base of the cubes using Araldite 2014. The exceptions are those of B1, B2 and B3 on the Skellig Michael plates. In their cases, an acrylate adhesive, also produced by Huntsman, Araldite (2021A) was used. This was undertaken during the initial stages of the project and although the adhesive secured the nuts in place it was found to be difficult to work with. The thixotropic properties of 2014 subsequently proved a much better alternative.

Figure 10.10. Set up for 3D profile scanning using touch probe, Dublin Institute of Technology, April 2013

10.4. MEASUREMENT

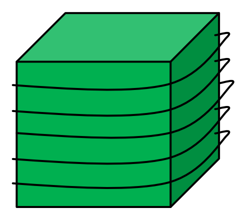
It is intended that once the cubes are installed on heritage sites they should be periodically (every 3–5 years) demounted and measured to monitor surface deterioration. The tool has been designed for long-term exposure however, therefore if this regime is interrupted or abandoned, assessment can begin again at a far-future date. In an attempt to future-proof the measurements a combination of low and high tech methods were employed (table 10.4).

Table 10.4. Measurements carried out on cubes before and during exposure trial

Method and requirements	**Procedure**	**Comment**
Photography Location: demounted and indoors Requirements: 30–40 minutes/plate personnel time. Requires daylight lamp, digital camera, tripod, indoor space, grey background, scale.	Digital colour photographs, macro setting, daylight bulb from top left plus ambient daylight, cm scale, identifying number, and grey background. Each exposed face taken (numbered 1–5)*****. Cube photographed at 0 and 45 degrees to camera i.e. straight on and with corner forward (except top).	Low tech, low cost, can be done on site once indoor area with power source is available. Comparison will be visual not quantifiable.
Surface roughness (Ra) Location: Demounted in laboratory (e.g. Renishaw Metrology Lab DIT Bolton St.)	This instrument draws a fine stylus over the surface of the object (figure 10.11). The profile of the surface is magnified through software and quantified as Roughness Average (Ra) in µm, accurate	This highlights any changes in surface characteristics, e.g. smoothing as the lay is eroded or roughening as the surface becomes granulated. Standard deviation in the Ra measurements can be used to

Method and requirements	Procedure	Comment
Requirements: 3 hours/plate personnel time. Equipment – Diavite DH-6 or similar (machine with a laser probe could be substituted). Industry standard settings used = Lt 4.80 trace length and Lc 0.8 cut off filter (ignores >0.8mm).	to .01mm. 10 measurements taken on each exposed face (1–5). Large holes or cutting ridges are avoided. If obvious lay measurements are taken perpendicular to it. If not measurements taken perpendicular to edge of the cube, from the centre outwards. High tech but does not require experienced operator. Images available from software (figure 10.17).	indicate homogeneity of the surface. The main disadvantage of the stylus contact method for Ra measurement is that it will not function on extremely rough or pitted surfaces. For the freshly cut cubes this was not an issue but in future it may be problematic. Substitution with laser probes would address this however (Swantesson, 1994).
Colour meter Location: Demounted in the laboratory (Teagasc Food Research Centre, Ashtown), however it would be possible on site with portable device Requirements: Approximately 4 hours/15 cubes (personnel time). Ultra Scan Pro USP1577 Hunter Lab. Mode #3	On the earliest samples (Skellig Michael) three measurements were taken on each face. It was subsequently decided that five points would supply a more representative sample. Values for brightness (L*) redness (a+) and yellowness (b+) are taken. Average values are calculated from the five points by the Ultrascan – as exact locations cannot be returned to averages are better for comparison.	Colorimetry has successfully been used as a measure of biomass on stone (Young and Urquhart, 1998, Adamson et al., 2012). Visual assessment of staining, micro-biological growth etc. must accompany this assessment and interpretation of results would benefit from expert input. Up to 90% of soiling on sandstone may be due to microbiological growth (Young and Urquhart, 1998).

Method and requirements	Procedure	Comment
RSEX or similar (reflectance specular excluded, 0.390 inch aperture, nominal). Free access provided by Teagasc.		
Callipers <u>Location:</u> Demounted but possible to do in situ on site. <u>Requirements</u> Vernier callipers	Digital Vernier callipers. Measurements taken in three dimensions (width, depth and height). Three measurements taken in each case. Recorded according to the faces of the stone being measured i.e. 1/3, 2/4 and 5/6(base)	Measurements accurate to +/- 0.1mm. Repetition will not be exact in terms of placement of calliper jaws. Comparison will be between measurements, quantifiable but of low accuracy.
Weight <u>Location:</u> In laboratory (Teagasc Food Research Centre Ashtown) but possible to do on site if suitable balance available. Allow minimum of two weeks air-drying after demounting. <u>Requirements:</u> Digital laboratory scales (measure to 0.00g).	The demounted stones (including internally fixed nut) are weighed on a digital scale. The weights are taken in grams and rounded to two decimal places. The stones must be completely dry before weighing; calibration using a RH meter can ensure this before the weights are taken.	The requirement for calibration of the stones to standard RH could delay this method of assessment for several weeks after demounting. Rapid drying is not advised however (i.e. using an oven etc.) as that could damage the stones.

Method and requirements	**Procedure**	**Comment**
3D profile scanning Location: Demounted in laboratory. (DIT Bolton St. Room 101 Engineering Lab.) Requirements: 2 hours/plate personnel time. Renishaw Cyclone Series 2 SP600M machine or similar. Used Tracecut programme (figures 10.10 and 10.12)	The surface under the cubes was set as Z0. The profile parameters were as follows: Metric; probe dia 6.002; chordal tolerance 0.1; start point X10 Y10 [chosen as safe zone]; Rapid Z 100.0; nominal pitch 2; initial direction Y; search distance 100; scanning speed 1000.0; probe deflection 0.5. Profiling done in Z plane in increments of 5–10mm (i.e. 45, 40, 35, 30, 20, 10). A minimum of 5 profiles were made around four faces of each block (1–4). Profiles stored as DXF lines and arcs in CAD.	The CAD software will compare profiles over time, calculate change and can produce visual overlays that show the progression of loss. The data can be read as a series of measurements (x y and z co-ordinates) ideally these should be extracted for archiving as CAD may become obsolete in the future, this is not a simple procedure however (see Appendix 6).  40mm 35mm 30mm 20mm 10mm **Illustration of profiles**

***A circular mark was drilled on the base of each cube and the measured faces are numbered clockwise from this mark 1–4 with the top surface as 5. The base is not measured except with callipers.

In addition to the methods above other options trialled included taking a series of point measurements using a touch probe Co-ordinate measurement machine (CMM) and 3D laser scanning of the entire cubes. Some measurements were carried out using these techniques but they were not found to be feasible due to requirements such as the use of expert operators and problems accessing the equipment at an affordable cost. The current commercial recording systems which combine laser scanning with digital photo-modelling have been proven to meet with accuracy requirements for recording and surveying but are outside of the scope of this study (Beraldin et al., 1997, Bernardini and Rushneier, 2002, Jacobs, 2000). The final choice of methods provides a series of complementary, non-destructive measurements of surface properties that are achievable on a low budget and require little operator expertise or high-tech equipment.

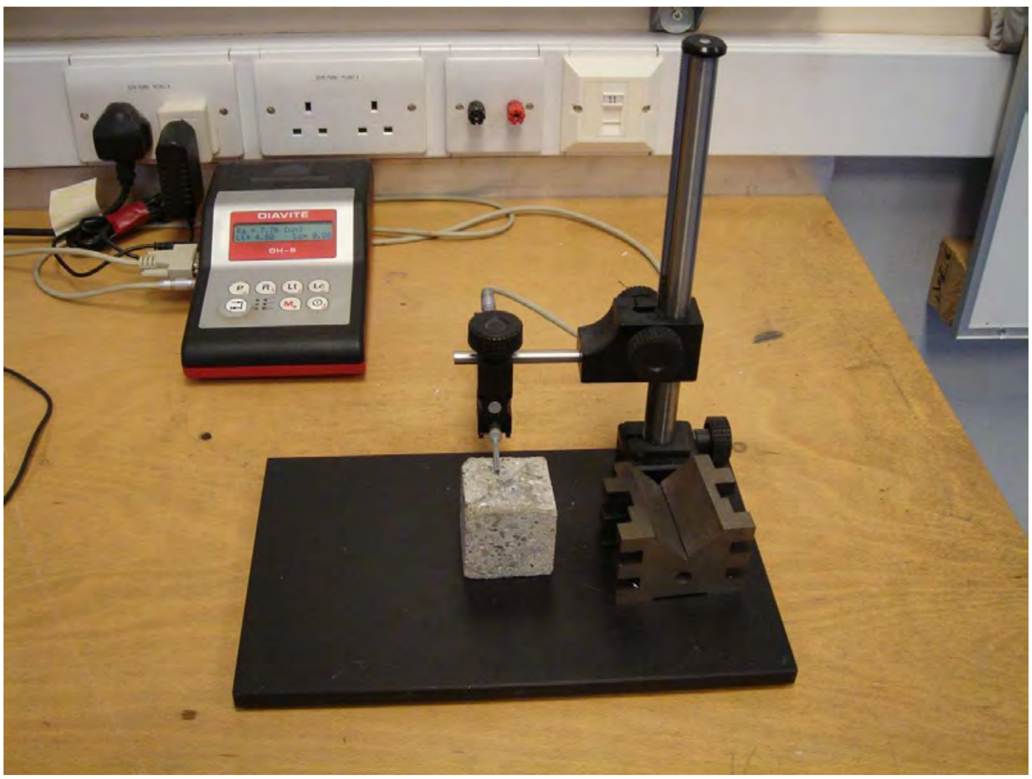


Figure 10.11. Set up for surface roughness measurement with the Diavite DH-6, Dublin Institute of Technology, April 2013

10.5. INTERPRETATION

Interpretation of observed changes in the cubes and their relationship to climatic factors will not be possible until a minimum of 30 years from now (i.e. in 2043). Differences detected will then be interpreted in relation to climate measurements for the same period, relying on expert judgement. This expert opinion will be rooted in decades of stone weathering research and process-based classifications for decay (Smith et al., 2005, Winkler, 1997, Pavia and Bolton, 2001, Tiano, 2006a).

Figure 10.12. Conducting 3D profile measurements with Renishaw Cyclone Series 2 SP600M, Dublin Institute of Technology, April 2013

One example of how such a process may evolve is the 30 year project at St Paul's Cathedral on surface erosion and surface change (including accretion) measurements (Inkpen et al., 2012b, Trudgill and Viles, 2001, Trudgill, 1982). The study utilised microerosion meters[7] (MEM) to measure changes in surface elevation of a limestone balustrade, concentrating on near-horizontal surfaces (Inkpen et al., 2012b). The results indicated that there was a general decrease in erosion rates attributable to an improvement in air quality in London during the same period. The rate of surface change decreased from the 1980s to the 1990s but data from 2010 shows a slight rise again, attributable to micro-biological growth (Inkpen et al., 2012b). There was also a pattern observed relating to variations in rainfall (Trudgill and Viles, 2001). The association between rainfall quantities and surface loss was not a simple linear one, rather the authors found a curvilinear correlation *where each rainfall increment, of say 1000mm* [decrease], *corresponds to progressively less erosion* (Trudgill and Viles, 2001). In assessing the cubes, it is unlikely that linear relationships between climate variables and weathering processes will be established. What is expected (as demonstrated by the above example) is that long-term data will allow trends and correlations to be determined (section 10.9.).

10.6. TRANSMISSION TO THE FUTURE

The LegIT is designed to be as self-explanatory as possible using standardized 50mm cubes and including materials that will weather at different rates. No matter how clearly damage can be read from the tool itself however, contextual information will be needed to maximise this communication (Kornwachs, 1999). In order to ensure that all the relevant information about the LegIT will be available for future generations of conservators, it was necessary to

[7] This method uses a dial gauge to record changes in surface elevation relative to control points (metallic markers) located on the object. Accurate to 10µm.

consider the possibilities for archiving the data. The Irish Meteorological Service (Met Eireann) collects and stores climate data from the national network of stations and it is highly probable that this will continue far into the future.

Figure 10.13. Engraved label on Brú na Bóinne stainless steel plate: abbreviated site name (BnB), plate number (3) and National Archives reference number (2011/62)

Object- and site-related data requires the same level of careful planning and centralized archiving so that, in the future, it will be readily available to researchers. Digital information is particularly problematic in terms of longevity. Technology changes so rapidly that the software and hardware necessary to read stored data quickly become obsolete and constant migration from one format to another is required. This is unsustainable and will result ultimately in the loss of much information. In as much as practicable all of the data related to the LegIT will therefore be lodged in paper format with the National Archives, an institution with permanent status. However, in some cases digital data does not lend itself to being transferred to hard copy (Appendix 6). The accession number of the archived files is engraved on the steel plates, thereby linking the physical tool and its accompanying data in an enduring manner (figure 10.13).

10.7. CONCEPTUAL ISSUES

> *Exposure trials provide an important link between knowledge of decay processes derived from laboratory-based experimentation and observed decay of stone buildings and monuments* (Turkington et al., 2003: 1205).

The exposure of fresh stone allows the study of stone decay patterns under real-world environmental conditions, but there are a number of issues that need to be considered. Initial rapid weathering of newly exposed surfaces is generally followed by slower on-going deterioration. Thus, exposure trials using fresh samples do not replicate the current weathering of historic stone (Baedecker and Reddy, 1993, Turkington et al., 2003). Turkington (2003) argues that short-term exposure trials can be useful for explaining *decay patterns* and thus for predicting future behaviour, but that long-term *decay rates* cannot be reliably extrapolated. One could argue however, that exposure trials could provide that information if carried out over the long-term. The main aim of the tool is to create a point of reference for future research. As such it is not expected to yield significant results earlier than 2043. The tool meets many of the conditions outlined for a *proxy dosimeter* for the impacts of climate change on cultural heritage as outlined by Grontoft (Grontoft, 2009).

Another issue in the interpretation of the indicator cubes is that the results may be misleading because, in general, *surface decay and soiling do not show a clear, linear progression over time* (Viles et al., 2002: 228). This means that a lack of visible degradation could be followed by sudden and catastrophic loss. Material loss over time therefore reveals the rate of 'erosion' but cannot give a comprehensive view of 'weathering' given the complex interactions that occur at different levels beneath the surface (Turkington et al., 2003, Inkpen et al., 2012a). Surface analysis methodologies for describing changes in the stone, such as surface roughness, overlook internal chemical changes that may in fact be driving decay. To fully understand these, samples would need to be taken at depth, a process not possible given the small size of the cubes. These unseen reactions can result in unexpected loss of the surface and in turn make recession measurements redundant. The small mass of the cubes means they cannot reflect the range of internal processes present in masonry stone and are in fact more comparable to sculptural stone i.e. artefacts or architectural details. The advantage of this however is that they are likely to be more responsive to fluctuating temperature and moisture cycles than large blocks. This sensitivity to climatic influences should therefore make the cubes a good early indicator of surface weathering patterns.

The interpretation of measured and observed changes in the cubes raises the issue of equifinality (section 9.2.5.). For example, microbiological growth may increase in the future but can we know if this is due to climate change or to the presence of increased oxides of nitrogen (NO_x) in the atmosphere? Recession by the end of the century may be occurring at a faster rate than before, but will this be due to the increase in rainfall, to atmospheric pollution or to internal weakness in the stone itself? Thus, there is a need to account for the contribution of factors other than those of direct interest (Inkpen et al., 1994). The cross comparison of results between the unpolluted marine atmosphere of Skellig Michael, the urban atmosphere of Dublin Castle, semi-urban Cashel and the rural sites of Brú na Bóinne and Clonmacnoise should help in the interpretation of the contribution of pollution, including NO_x levels. Similarly, if the rates of degradation of the majority of samples from one site demonstrate the same trend, the likelihood is that it is environment-related rather than due to weaknesses in the individual cube. Effects limited to a single material may be more difficult to generalise, nonetheless the more sensitive stones such as Portland provide an early warning system that should not be quickly dismissed.

Another issue in the use of sample exposures for assessing climate-change impacts is the difficulty in extrapolating from one stone to another. Stone decay is determined by the properties of the stone itself as well as the environmental conditions. Each material reacts differently and within stone types, even within single blocks, structural and mineralogical variations can be significant (Warke et al., 2004, McKinley and Warke, 2007). This problem is faced in all studies where original material is not used, out of respect for the integrity of the monument. The tool is designed to be used as an 'indicator', however direct monitoring remains preferable. The cubes are a sacrificial indicator and therefore it is necessary that they be more sensitive than the monument itself, so they can act both as a warning and a testimony. This sensitivity to climatic influences should make the LegIT a good, early indicator of weathering patterns. It is one step on the long journey towards understanding how climate change may impact on our heritage and is intended as a legacy for the future.

10.8. IMPLEMENTATION OF THE LegIT AT THE CASE STUDY SITES

Figure 10.14. Skellig Michael plate No. 3 (SKM3) being removed for measurement, August 2012

Sourcing the stone materials, cutting and preparing the cubes, undertaking baseline measurements, and manufacturing and engraving the steel plates all proved to be logistically and financially challenging. In Skellig Michael, the additional issue of limited accessibility and poor weather in 2011 meant that only one of three plates (SKM3) was installed as planned, the remaining two being positioned during the 2012 season (figure 10.14). In 2011 the Department of Arts Heritage and the Gaeltacht[8] granted the sum of €3,000 for

[8] Formerly Department of Environment, Heritage and Local Government granted from the Environment Fund,

manufacturing the indicator tool. This allowed production of 15 plates for installation at a total of five nationally important heritage sites under the care of the OPW.

Table 10.5. Details of indicator tools installed at Brú na Bóinne and Skellig Michael

Plate/tool Number	Site	Location	Aspect	Date installed
SKM1	Skellig Michael	Rock shelf beside Upper lighthouse	North facing, sheltered by rock face	Summer 2012
SKM2	Skellig Michael	Hermitage on South peak	No data	Summer 2012
SKM3	Skellig Michael	Sloping rock face above monastery on North peak	South facing slope, exposed situation (figure 10.14)	Summer 2011
BnB1	Brú na Bóinne	On top of Newgrange tumulus	East-west orientation, exposed on all sides	February 2012
BnB2	Brú na Bóinne	On side of main tomb at Knowth	South side of tumulus - plate has an east-west orientation	February 2012
BnB3	Brú na Bóinne	On side of main tomb at Knowth (figure 10.15)	North side of tumulus, plate has east-west orientation	February 2012

Installation began at Skellig Michael in 2011 and at Brú na Bóinne in 2012 (table 10.5). The LegIT was extended to Clonmacnoise, the Rock of Cashel and Dublin Castle in 2013. Detail about these sites is not included in this thesis, which focuses on the two case studies. Three plates were fixed onto horizontal surfaces at each site. The exact location of each plate was chosen in conjunction with the OPW with due regard to security, accessibility and visual

Architectural and Archaeological Projects.

impact, as well as to the research question being addressed. Potential impacts of maintenance or conservation measures were also considered e.g. use of herbicides affecting biological growth. Past exposure studies have often included a set of sheltered samples to observe dry deposition effects (Turkington et al., 2003, Lefevre et al., 2007). This was not replicated due a lack of suitable sheltered locations and constraints on the number of plates achievable. It is something that should be considered in future (Killian, pers. comm. 6.11.2012).

It is intended that the cubes be measured every 3–5 years under the auspices of the OPW. Within the time constraints of the current research project it was only possible to obtain measurements for one year of exposure on four plates - one on Skellig Michael and three at Brú na Bóinne. This was due to adverse weather conditions in 2011 which delayed the installation of plates on Skellig Michael.

10.8.1. Issues encountered

During this first year problems in design and other issues were encountered. When the plates were retrieved for measurement after one year it was apparent that some of the stones had loosened slightly in position (figure 10.15). This led to the concern that over time the cubes could be lost. When the stones were remounted therefore the washers were removed in order to increase the threading connection between the bolt and the nut inside the stones.

In Knowth, a concrete cube was broken in position, either a result of a flaw in the poured block or of physical impact of some kind. When all the cubes from Brú na Bóinne were examined after one year deep cracks were noticeable in three. The Greywhacke was worst affected (G1/G2/G3), two Portland cubes (P2/P3), one concrete (C3) and one Peakmoor (PK3) also demonstrated hairline cracks.

Figure 10.15. Brú na Bóinne plate No. 3 (BnB3) (Knowth) showing variance in orientation of cubes after one year exposure, February 2013

The cracks tend to radiate from the drilled hole, suggesting they are stress fractures from the drilling, and opened significantly after one year of weathering (figure 10.16). If the fracturing was allowed to proceed catastrophic loss would occur rapidly. To prevent this, the cracks were consolidated by injection of a low viscosity epoxy resin. This was justified as the cubes are intended to track near surface effects only. It suggests a need to review the design of the fixing system in the future however, to find a method that does not entail drilling into the stone but is demountable.

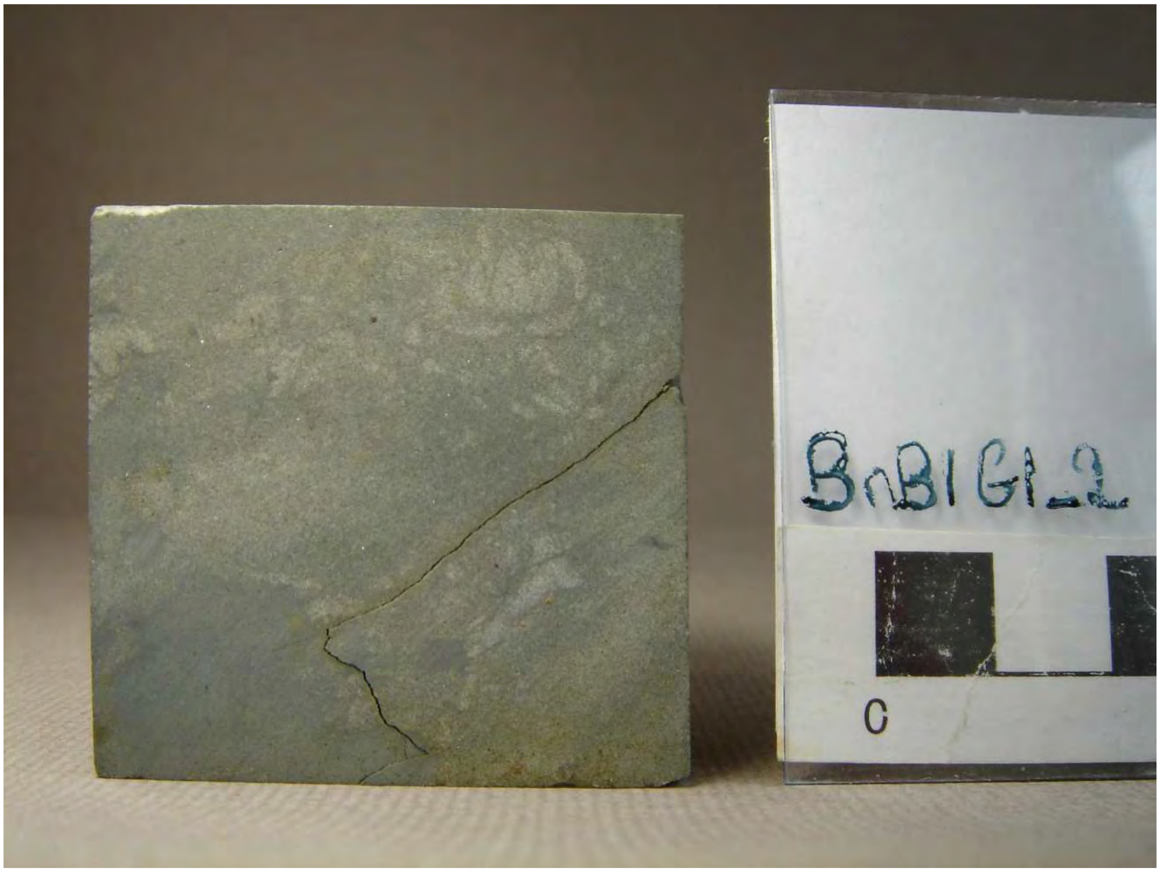


Figure 10.16. Brú na Bóinne plate No. 1 (BnB1) Greywhacke cube showing stress fracture, February 2013

In September 2012, a cube of Portland (P1) was reported as missing from the Newgrange plate (figure 10.17). The cube was not found nearby, suggesting that it was removed deliberately. The OPW are aware of people occasionally trespassing on the mound despite their efforts to prevent it (Willie Foley OPW, pers. comm.). Replacement of the lost cube was effected in February 2012; ideally the plate would be better moved to a more secure location on site. In the future, ongoing measurement and replacement of lost/damaged cubes will be left within the remit of OPW. A copy of all relevant data and a protocol for this process will be submitted to OPW to facilitate this task.

Figure 10.17. Brú na Bóinne plate No. 1 (BnB1) showing gap where Portland cube (P1) was removed and tampering with position of brick cube (B1), February 2013

10.9. EXPECTED OUTCOMES

To demonstrate if deterioration measured on the cube surfaces is due to normal weathering or to the effects of climate change will require long-term data collection. Analysis of the cubes will show over time whether the processes of surface weathering are being altered by climate change or not. The possible impacts of future climate change on heritage values have been discussed in the literature review (section 3.5.) and specific concerns for the two case study sites identified through vulnerability assessment (section 7.6. and 8.6.).

The tool is designed to capture the surface and near surface effects on built heritage materials of:

1. Salt crystallisation cycles.
2. Physical and chemical surface recession.
3. Micro-biological activity.

These are issues noted by Noah's Ark as being of primary concern in Western Europe given future climate projections (Sabbioni and Bonazza, 2010). Research in Northern Ireland suggests that increased seasonality in wetting and drying of stone will alter patterns of salt damage and that microbiological growth will be affected by increasingly wet periods in autumn and winter (Adamson et al., 2010, Cutler et al., 2013).

Table 10.6. Limestone and sandstone properties (Institute of Atmospheric Sciences and Climate, 2007, Smith, 1999, Building Research Establishment, 2001)

	Resistance to salts $NaSO_4$ test	**Compressive strength (MPa)**	**Modulus of elasticity**
Limestone	34.63% wt loss *Portland Jordan's basebed*	52.8 *Portland Jordan's basebed*	3–27
Sandstone	1.07% wt loss *Peakmoor*	72.5 *Peakmoor*	10–20
	-0.48% wt loss *Devonian old red sandstone (Callow Hill)*	153.4 *Devonian old red sandstone (Callow Hill)*	10–14 *Greywhacke*

In order to understand what can be expected from the cubes in the near and far future given current climate projections for Ireland it is necessary to look in more detail at the impacts which the cubes can measure.

10.9.1. Salt crystallisation cycles

Salt weathering is dependent on fluctuations in temperature and relative humidity (RH). Predicting how it will be affected by climate change is difficult however, as there are many interacting factors at play (Viles, 2002). The physical effect of salt crystallisation cycles will depend on the type of salt (crystallisation pressure), the pore size and distribution within the substrate, and the depth at which crystallisation occurs (Oguchi et al., 2006). Of the materials tested (table 10.2) brick is by far the most porous (39%) yet has a saturation coefficient similar to the other materials, suggesting that many of its pore spaces are large and not likely to be affected by salt crystallisation pressure. The British Stone List gives results for resistance to salts using a sodium sulphate test (BS EN 12370). The BRE found that Portland has an extremely low resistance to this form of weathering (table 10.6) (Building Research Establishment, 2001).

Table 10.7. Comparison of the number of times Relative Humidity values are at the crystallisation threshold for NaCl between the periods 1960–1991 and 2070–2101 (REMO model projections)

75.1% ≤ RH ≤ 75.7%	**Skellig Michael**	**Brú na Bóinne**
Projected change to the far future	↓13.5%	↓4%

Noah's Ark used the phase change of sodium chloride (NaCl) that takes place at 75.5% RH as a means of assessing probable crystallisation cycles in the future (Grossi et al., 2011).

Using data from the Hadley Regional Climate Model HADCM3 (50Km resolution) produced in 2005 and the A2 scenario, Noah's Ark projected an increase in the frequency of crystallisation events in Western Europe due to drier summers. The 2012 REMO model data (10Km resolution, A1B scenario) for the two case study sites produces differing results, projecting a decrease in the crystallisation of NaCl (table 10.7). The difference in projections may be explicable due to the different scenarios used (A2 is a higher emissions scenario than A1B) and the higher resolution of the REMO model (Kotova[9], pers. comm.). Given the uncertainty inherent in all models it is difficult to say which projection is more probable (Mikolajewicz[10], pers. comm.). The more recent and higher resolution REMO data is preferred here but is used with caution. Noah's Ark also predicted an increase in hydration cycles and damage due to transitions of sodium and magnesium sulphates, which exert a high hydration pressure (Institute of Atmospheric Sciences and Climate, 2007). Sodium sulphate is one of the salts that is commonly implicated in salt weathering of concrete (Aggregate Research, 2010).

Table 10.8 Summary of expected outcomes for salt weathering on cube tool 2012–2101

Impact	**Assessment Method**	**Period**
Surface recession: Loss caused by salt crystallization pressure	<u>Primary:</u> 3D profile and Ra <u>Secondary</u> Weight Photography	**Near Future (to 2020)** Salts present in fresh stone together with pore size and distribution will determine the initial occurrence of salt weathering. Most susceptible are likely to be Portland and brick (see table 10.2)

[9] Lola Kotova, Max Plank Institute, pers. comm. CfC Workshop, Ham House, Richmond, Surrey, April 18 2013.
[10] Uwe Mikolajewicz, Max Plank Institute, as above.

Impact	Assessment Method	Period
	(freshly exposed stone and salt efflorescence)	**Medium term (to 2050)** Surface porosity of stones is likely to alter due to weathering; salt loading from atmosphere will also change the availability of soluble salt (especially in Skellig Michael). Salt action is likely to increase in this period.
		Far Future (to 2101) The REMO data suggests a slight reduction in NaCl crystallisation. Projections by Noah's Ark and research into deep wetting at Queens suggest salt damage will increase. The expected outcome is very unclear.

10.9.2. Physical and chemical recession

One could expect that, after an initial period when the freshly cut stone erodes more quickly, in the near future the annual recession of the cubes will stabilise (Turkington et al., 2003). The recession of carbonate stones in rainwater is due to both dissolution (chemical erosion) and mechanical removal of grains (physical erosion) (Baedecker and Reddy, 1993). When pollution reduces the pH of rainwater, this increases the quantity of material lost by dissolution. Higher concentrations of CO_2 will also have this effect. In Skellig Michael, dissolution will be unrelated to atmospheric pollutants unlike the urban samples in Dublin Castle. Future comparisons between these sites should be of interest. Higher temperatures also slightly favour chemical weathering (Viles, 2002, Bortz and Wonneburger, 2000). Laboratory experiments suggest that pH does not affect the physical loss of grains in carbonate stone, and that this effect is purely mechanical (Baedecker and Reddy, 1993).

Given projections for the shift towards shorter periods of heavy precipitation (table 10.9), it is expected that the recession rate caused by the physical action of rain, including wind driven rain, will increase. Increased recession rates are probable especially where the cubes are positioned in exposed locations. Aspect will be crucial for this type of damage as wind direction is influential. It is also likely that this effect will be seen initially on the corners and edges of the cubes and on the softer materials such as Portland, brick and Peakmoor.

Table 10.9 Precipitation change at the case study sites between the periods 1960–1991 and 2070–2101 (REMO model projections provided by Max Plank Institute & CfC)

Case Study	**Precipitation volume**	**Intense precipitation** (No. of days ppt. >5mm/hr)
Brú na Bóinne	1.6% increase projected for far future	90% increase projected for far future (from 84 to 159 days)
Skellig Michael	0.26% increase projected for far future	38% increase projected for far future (from 344 to 474 days)

The abrasion resistance[11] of Peakmoor has been measured at 26.8 and of Portland Base Bed at approximately 25 (Albion Stone, 2012, Block Stone Ltd, 2012, Building Research Establishment, 2001). Gallstown Greywhacke by contrast, geologically similar to the stone used by the builders of Newgrange, has an abrasion resistance of 11.7[12] (Corcoran and Sevastopulo, 2008). Harder stones such as Greywhacke, concrete (compression strength 25–

[11] EN1341 tests the abrasion resistance of stone for construction applications. Values <23.0 are considered suitable for use in heavily trafficked areas i.e. are resistant to abrasion.

[12] EN 1097-8 Gallstown greywhacke tested for use as a road aggregate

30MPa) and Old Red Sandstone will be much slower to evidence recession (Celtest Company Ltd, 2007, Corcoran and Sevastopulo, 2008).

Table 10.10. Summary of expected outcomes for surface recession from mechanical and chemical action of rainfall for period 2012–2101

Impact	Assessment Method	Period
Surface recession: Rainfall Mechanical or chemical (dissolution)	Primary: 3D profile and Ra Secondary: Weight and callipers Other: Photography	**Near Future (to 2020)** Fresh cut stone erodes quickly at first when exposed and then comes towards equilibrium. Has been detected during five year exposures using weight loss (Yates, 2003)
		Medium term (to 2050) Rate of loss likely to stabilise after the initial period. Weathering tests under current climatic conditions give a recession rate for Portland (Jordan's basebed) limestone of 3 to 4mm every century (Albion Stone, 2012).
		Far Future (to 2101) Increase in intensity of precipitation likely to be reflected in an increased rate of recession due to the mechanical action of rain, especially where exposed to predominant winds (i.e. Southerly in Skellig Michael, Westerly in Brú na Bóinne). The projected increase in rain volume is negligible thus the Karst effect (clean rain dissolution) is unlikely to increase although the effect of more intense rain on this process is unclear.

The surface recession of carbonate stones due to dissolution in clean rain (Karst effect) or due to pollutants (acid rain or dry deposition) was considered by Noah's Ark in light of future climate projections and pollution trends (Bonazza et al., 2009). In processing data for the Lipfert function to calculate dissolution the conclusion was reached that clean rain was in fact the driving factor. This allowed Noah's Ark (Brimblecombe and Grossi, 2009, Bonazza et al., 2009) to simplify the function for mapping surface recession to:

$$L = 18.8R$$

L = surface recession in µm/year.

18.8 = solubility of $CaCO_3$ in equilibrium with 330ppm CO_2.

R = precipitation amount in m/year.

Precipitation projections do not indicate a significant volume increase however (table 10.9) and precipitation intensity (projected to change by 40–90% at the case study sites) is not factored into the Lipfert function. As already discussed (section 10.2.2), damage functions can be unreliable when extrapolated over a long period of time. Comparison between erosion rates derived from the Lipfert function and measured erosion rates for the period 1980–2010 at St Paul's in London was carried out by Inkpen et al (2012a). They showed that although there was a large discrepancy in magnitude between the two sets of data, measured erosion being at least 2.5 times greater than predicted, the relative patterns of change were consistent. Therefore dose-response functions should be used to indicate 'direction of change' rather than absolute quantification.

10.9.3. Microbiological activity

Microbiological growth on stone includes algae, fungi and lichens. Once growth occurs on stone surfaces, it tends to encourage the retention of moisture and therefore further growth, establishing a ‘positive feedback loop’ (McCabe et al., 2007). Sandstone is known to be particularly susceptible to biological colonization as *its mineral and pore characteristics are especially bioreceptive* (McCabe et al., 2011: 167). Biological activity can be physically and chemically destructive for example surface recession caused by lichens has been estimated at between 0.5–3mm/century depending on the characteristics of the stone (Cooper et al., 1991). Yet there is also evidence that stone may be protected by surface growth, for example Cutler et al (2013) found evidence of a bioprotective role for algal films. Unlike previous exposure trials the LegIT will provide an opportunity to study long-term effects of biological growth.

> *Exposure tablets have been exposed for as little as a year and so would be expected to have less well developed biological activity on their surfaces. This would suggest that any bioprotective/biodeteriorative roles would be relatively poorly developed on exposure tablets* (Inkpen et al., 2012a: 479)

Test exposures of sandstone in Scotland and Northern Ireland found that aspect played an important role in algal growth, with rates being highest on north facing surfaces due to moisture retention and solar radiation (Adamson et al., 2012, Young and Urquhart, 1998). There is no consensus on whether seasonality is an issue however. Researchers in Scotland found growth was greatest during autumn and winter (Young and Urquhart, 1998) while in Northern Ireland it was concluded that there was no seasonal influence (Adamson et al., 2012). In Scotland the length of time for sandstone samples to reduce to 25% lightness value (L*) from algal growth was estimated at 6–22 years (Young and Urquhart, 1998). Darkening can be due to forms of soiling other than biological growth however, and it is important to also refer to measurements of greenness (*a) and visual examination (Cutler et al., 2013).

Noah's Ark calculated the relationship between climate and annual growth of biomass on stone. They developed the following exponential model (Gómez-Bolea et al., 2012):

$$B = e\,(-0.964 + (0.003P) - (0.01T))$$

B = biomass per area in mg/cm^2.

P = yearly mean of precipitation in mm.

T = yearly mean of temperature in ^{o}C.

Table 10.11. Temperature, precipitation and estimated biomass production for the case study sites in the periods 1960–91 and 2070–2101 using an exponential biomass model developed by Noah's Ark (Gómez-Bolea et al., 2012)

	Average Temperature over 30 year period (^{o}C)	**Average precipitation over 30 year period (mm/hr)**	**Biomass = e(-0.964+ (0.003P)–(0.01T))**
Skellig Michael	1960–1991 10.10^{o}C 2070–2101 11.54^{o}C *= 14% increase to far future*	1960–1991 0.334mm 2070–2101 0.335mm *= 0.26% increase to far future*	1960–1991 B = e(-1.063998) 2070–2101 B = e(-1.078395) *= 1.4% increase to far future*
Brú na Bóinne	1960–1991 9.38^{o}C 2070–2101 11.13^{o}C *= 18.6% increase in T to far future*	1960–1991 0.120mm 2070–2101 0.122mm *= 1.6% increase in ppt. to far future*	1960–1991 B = e(-1.05744) 2070–2101 B = e(-1.074934) *= 1.7% increase in Biomass to far future*

Applying this function to the case study sites using REMO data (table 10.11) indicates there will be a 1–2% biomass increase during the far future period. However the equation derives from research in Spain where high temperatures correspond with high evaporation rates and therefore restricted biological growth (Brimblecombe, pers. comm.). For this reason, the formula implies that lower temperatures result in greater growth. This is not necessarily the case for northern climates however, where temperatures in winter can be low enough to retard growth (Haugen and Mattson, 2011). Research on algal greening in Belfast noted a negative correlation with the stone surface temperature, but found it only explained 14% of the variance (Cutler et al., 2013). Cutler (2013) suggests that moisture levels are likely to be integral to the distribution of algal films but also that the relationship between moisture and growth is not straightforward. Growing-season temperature, numbers of warm days or annual time of wetness, are other possible indicators for micro-biological growth in Ireland's climate (Cutler et al., 2013, Brimblecombe, pers. comm.).

Table 10.12. Summary of expected outcomes for microbiological activity for period 2012–2101

Impact	**Assessment method**	**Period**
Microbiological Growth	Primary: Colour measurement. Secondary: Photography. Other: Surface texture (Ra).	**Near Future (to 2020)** Colour change in most cubes has been found after 1 year exposure, indicating algal growth. Peakmoor sandstone exhibits most rapid colonization as do north facing surfaces (section 10.10). In Northern Ireland lichens on rural samples were noted by end of second year (Adamson et al., 2012).
		Medium term (to 2050) Weathering will make less porous rocks vulnerable to colonization. North facing surfaces probably will experience most rapid growth.

Impact	Assessment method	Period
		Far Future (to 2101) With increased temperature and precipitation, the rate of microbiological growth is likely to increase during winter/autumn. Growth may continue with higher level species, and/or a change in the colour of microbiological growth may occur, indicating altering profile of species. Future levels of atmospheric NO_x will contribute to this effect but are unlikely to affect Skellig Michael due to its location.

10.10. RESULTS

At present, results are available for one year of exposure at Brú na Bóinne (BnB1, BnB2, BnB3) and Skellig Michael (SKM3). The data from these measurements is presented below to demonstrate how, in the future, results may be compared over time to build a picture of surface weathering processes. Further methods of manipulating the data may develop to study the *relative proportions and directions of change* (Brimblecombe, 2010a).

10.10.1. Dimensional change: Vernier callipers

Vernier callipers are extremely accurate manual measuring tools with a margin of error of just 0.05mm (Department of Physics Southern Methodist University, 2010). The problem with using them for comparative measurements over time is that the cubes are not completely regular and therefore the positioning of the calliper jaws is responsible for some if not all of the differences noted. Thus, there are both gains and losses shown after one year of exposure.

In 53 of the 54 comparative measurements, the magnitude of change does not exceed 0.3mm (and in most cases is considerably less). From these results, it is possible to suggest a margin of error of +/- 0.3mm when using the callipers for repeat assessments in the future.

Table 10.13. Vernier Calliper measurements for cubes from Skellig Michael plate no. 3 for one year exposure 2011–2012

ID	**2011 measurements (mm)**			**2012 measurements (mm)**			**Difference between 2011 and 2012 measurement averages**
RED SANDSTONE							
SK3RS3 1/3*	47.75	47.42	47.78	48	48	47.5	- 0.183mm
SK3RS3 2/4	46.22	46.18	45.9	45.4	45.9	46.3	- 0.23mm
SK3RS3 5/base	46.67	46.23	46.54	46.3	46.26	46.6	- 0.09mm
PEAKMOOR							
SK3PK3 1/3	48.09	47.48	47.92	48.2	48.14	47.86	+ 0.23mm
SK3PK3 2/4	49.72	49.25	49.11	49.8	49.32	49.1	+ 0.05mm
SK3PK3 5/base	48.63	48.68	48.71	48.6	48.6	48.6	- 0.07mm
PORTLAND							
SK3P3 1/3	50.98	50.99	50.09	50.96	51	51	+ 0.02mm
SK3P3 2/4	50.89	51.02	50.35	51.02	51.1	51.06	+ 0.06mm
SK3P3 5/base	50.09	50.35	50.24	50	50	50.04	- 0.22mm
BRICK							
SK3B3 1/3	48.12	47.74	47.4	47.5	47.9	48.3	+ 0.15mm
SK3B3 2/4	44.44	45.6	46.63	44.4	45.8	46.6	+ 0.04

ID	2011 measurements (mm)	2012 measurements (mm)	Difference between 2011 and 2012 measurement averages
SK3B3 5/base	47.14 47.86 47.94	47.9 47.9 47.2	+ 0.02mm
CONCRETE			
SK3C3 1/3	48.89 48.98 49.9	48.7 49.4 48.8	- 0.29mm
SK3C3 2/4	50.66 51.62 51.13	51.3 51.7 51.08	+ 0.22mm
SK3C3 5/base	50.96 50.17 50.34	51.1 50.2 50.9	+ 0.24mm

*****A circular mark was drilled on the base of each cube and the measured faces are numbered clockwise from this mark 1–4 with the top surface as 5. The base is not measured

Table 10.14. Vernier Calliper measurements for cubes from Brú na Bóinne for one year exposure 2012–2013

ID	2012 measurements (mm)	2013 measurements (mm)	Average difference between 2011 and 2012 (mm)
PEAKMOOR			
BnB1 PK1 1/3	48.84 49.41 49.48	48.9 49.3 49.6	+0.02
BnB1 PK1 2/4	48.03 48.08 48.07	48.1 48.1 48.2	+0.07
BnB1 PK1 5/base	47.25 47.7 47.4	47.5 47.3 47.8	+0.08
BnB2 PK2 1/3	49.95 49.48 49.17	49.3 49.6 49.9	+0.06
BnB2 PK2 2/4	48.85 49.17 48.87	48.7 48.9 49	-0.1
BnB2 PK2 5/base	49.63 49.15 49.12	49.1 49.7 49.6	+0.17
BnB3 PK3 1/3	46.75 46.71 46.81	46.9 46.9 46.9	-0.14
BnB3 PK3 2/4	50.03 49.27 48.69	49.9 49.6 48.7	+0.07
BnB3 PK3 5/base	47.7 47.94 47.89	48 48 47.8	+0.09

ID	2012 measurements (mm)	2013 measurements (mm)	Average difference between 2011 and 2012 (mm)
PORTLAND			
BnB1 P1 1/3	51.78 51.72 51.76	*Lost during 2012 Replaced with BnB1 P4*	
BnB1 P1 2/4	50.18 50.11 50		
BnB1 P1 5/base	51.17 51.15 50.92		
BnB1 P4 1/3		51.1 51.2 51	
BnB1 P4 2/4		49.9 50 50	
BnB1 P4 5/base		51 50.9 51.1	
BnB2 P2 1/3	50.8 50.8 50.92	50.8 50.9 51.1	+0.09
BnB2 P2 2/4	50.99 50.97 51.09	50.9 51.1 51	-0.02
BnB2 P2 5/base	49.88 49.9 49.85	50 50 50	+0.12
BnB3 P3 1/3	50.91 50.95 50.89	51 51.1 51	+0.08
BnB3 P3 2/4	50 49.93 49.87	50 50.2 49.9	+0.1
BnB3 P3 5/base	51.06 51.04 51.01	51.1 51.2 51	+0.06
GREYWHACKE			
BnB1 G1 1/3	46.52 46.48 46.6	46.5 46.6 46.8	+0.1
BnB1 G1 2/4	47.3 47.44 47.58	47.4 47.6 47.7	+0.13
BnB1 G1 5/base	45.49 45.27 45.39	45.4 45.3 45.3	-0.05
BnB2 G2 1/3	47.33 47.62 47.94	47.3 47.5 48	-0.03
BnB2 G2 2/4	47.94 46.05 44.07	48 46 44	-0.02
BnB2 G2 5/base	45.29 45.39 45.27	45.4 45.3 45.2	-0.02

ID	2012 measurements (mm)	2013 measurements (mm)	Average difference between 2011 and 2012 (mm)
BnB3 G3 1/3	46.62 45.92 45.17	46.7 46 45.3	+0.1
BnB3 G3 2/4	48.07 47.39 46.79	48 47.6 46.8	+0.15
BnB3 G3 5/base	45.48 45.28 45.39	45.4 45.7 46	+0.95
BRICK			
BnB1 B1 1/3	46.07 45.93 46.26	46.3 46.1 45.6	-0.09
BnB1 B1 2/4	44.5 44.43 44.41	44.5 44.6 44.7	+0.15
BnB1 B1 5/base	47.53 47.34 47.42	48.6 48.5 47.6	+0.8
BnB2 B2 1/3	46.12 46.84 47.34	46.3 46.5 47.3	-0.07
BnB2 B2 2/4	47.97 47.65 47.42	47.9 47.8 47.5	+0.05
BnB2 B2 5/base	45.76 45.35 44.76	44.9 45.7 45.8	+0.17
BnB3 B3 1/3	45.73 46.2 46.65	45.7 46.1 46.8	+0.01
BnB3 B3 2/4	45.3 45.73 46.02	45.3 45.8 46.3	+0.12
BnB3 B3 5/base	43.68 43.8 43.65	44 43.6 43.8	+0.09
CONCRETE			
BnB1 C1 1/3	49.84 50.73 50.93	49.8 50.8 51	+0.03
BnB1 C1 2/4	51.83 51.47 50.71	51.8 51.5 50.7	-0.01
BnB1 C1 5/base	48.11 48.46 48.76	48.6 47.8 48.5	-0.14
BnB2 C2 1/3	50.91 51.67 50.68	*Broken in situ 2012 Replaced with BnB2 C4*	
BnB2 C2 2/4	48.02 48.35 47.86		
BnB2 C2 5/base	50.74 49.97 50.7		
BnB2 C4 1/3		51.4 51.4 51.5	

ID	2012 measurements (mm)	2013 measurements (mm)	Average difference between 2011 and 2012 (mm)
BnB2 C4 2/4		48.2 48.8 49	
BnB2 C4 5/base		50 49.9 49.5	
BnB3 C3 1/3	49.57 49.74 49.65	49.6 49.6 49.9	+0.05
BnB3 C3 2/4	50.51 51.47 52.11	50.6 50.7 52.1	-0.23
BnB3 C3 5/base	47.84 48.77 48.01	48.4 48.1 48.8	+0.23

10.10.2. Weight change

After one year of exposure it was expected that little or no change in weight would be registered.

The cubes from Skellig Michael (SK3) exhibit little change with the exception of the Portland (-1.38g) and concrete (+4.54g). The cubes were weighed one week after being retrieved from the island and it may be that some residual moisture was present which would account for elevated weights on all but the Portland. Following this result a minimum of two weeks air drying was stipulated before weighing (table 10.4). The loss registered for the Portland cube may be significant but comparative measurements from the other plates on Skellig are required before one can say if this effect is peculiar to the particular cube or related to environmental factors.

In the case of Brú na Bóinne small quantities of weight loss were identified in most cubes, mostly <1g. The exceptions to this were B1 (+0.43g) and the concrete cubes C1 and C3 (+1.76g and +1.67g). The small gain in weight of the brick may be due to soiling but the gain in the concrete is more significant and mirrors the weight increase of C3 from Skellig Michael. The hydration reaction responsible for curing fresh concrete can continue for up to 20 years, increasing the strength of the material as it does so (Cemex USA, 2013). These internal chemical reactions may be the explanation for the weight gain noted in all of the concrete cubes.

Table 10.15. Weights for cubes from Skellig Michael plate no. 3 for one year exposure 2011–2012

ID	2011 weights (g)	2012 weights (g)*	Weight gain/loss between 2011 and 2012
SK3B3	166.8	166.92	+ 0.12g
SK3C3	281.7	286.24	+ 4.54g
SK3P3	279.87	278.49	-1.38g
SK3PK3	260.66	261.06	+ 0.4g
SK3RS3	269.45	269.81	+ 0.36g

*Taken off site 14/8/12 air dried one week, possibly not enough

Table 10.16. Weights for cubes from Brú na Bóinne for one year exposure 2012–2013

ID	2012 weights (g)	2013 weights (g)	Weight gain/loss between 2012 and 2013 (g)
BNB1B1	163.07	163.5	+0.43
BNB1C1	284.93	286.6	+1.67
BNB1G1	275.95	275.8	-0.15
BNB1P1	289.12	*Lost in situ*	
BNB1PK1	253.93	253.9	-0.03
BNB2B2	165.96	165	-0.96
BNB2C2	276.6	*Broken in situ*	

ID	2012 weights (g)	2013 weights (g)	Weight gain/loss between 2012 and 2013 (g)
BNB2G2	273.58	273.5	-0.08
BNB2P2	287.08	286.4	-0.68
BNB2PK2	270.08	269.8	-0.28
BNB3B3	162.64	162.1	-0.54
BNB3C3	278.34	280.1	+1.76
BNB3G3	273.59	273.5	-0.09
BNB3P3	283.51	283.2	-0.31
BNB3PK3	250.15	250.0	-0.15
BnB1P4	*Replacing P1*	289.99	N/A
BnB2C4	*Replacing C2*	279.07	N/A

10.10.3. Surface roughness

Ten measurements were taken on all five exposed faces and these were combined to give:

- Average surface roughness (Ra) per cube
- Standard deviation of Ra values per cube

The Ra value quantifies surface texture in µm, it does not reflect pits or crevices. Higher values equate to a rougher surface (figure 10.18). The standard deviation will illustrate the heterogeneity of the surfaces. A low deviation indicates clustering of values around the mean and therefore a relatively homogeneous surface. It may also be useful to calculate the skew[13] in values once the cubes have been in place for several years; this is likely to become more positive as small steps will gradually occur in the surface (Swantesson 2005). The method of

[13] The skew is a measure of the asymmetry of a distribution. A positive value means that there is a longer tail to the right, while a negative value means that there is a longer tail to the left (Swantesson, 2005: 18).

data analysis chosen was influenced by research on geological micro-mapping using surface roughness measurements (Swantesson, 1994). Over time, weathering is likely to change the surface of the cubes and both these values will be useful to illustrate this phenomenon. After one year of exposure, changes were found to have occurred.

Figure 10.18. Graph demonstrating difference between surface roughness profiles for brick (A.) Old Red Sandstone (B.) and Portland (C.). Shows a single measurement (1 of 50) from cubes on plate No.1 Skellig Michael, taken before exposure on site (2011)

The concrete and Portland cubes in Skellig exhibit the greatest increase in Ra or roughening of their surfaces. These materials also returned the highest Ra in the Brú na Bóinne measurements however, the magnitude of change for that site is much less (e.g. BnB P2 & P3 at 15–17% compared with SKM P3 at 40%). To date, as with all the results, there is insufficient data to draw conclusions from the observed changes.

Table 10.17. Surface roughness (Ra) results for cubes from Skellig Michael plate no. 3 for one year exposure 2011–2012

ID	No of Measurements	Average Ra 2011 (µm)	Standard Deviation of Ra 2011	Average Ra 2012 (µm)	Standard Deviation of Ra 2012	% change in Ra
SK3 B3	50	8.8	2.02	9.48	1.68	↑7.7%
SK3 C3	50	5.78	2.57	7.83	2.39	↑35.5%
SK3 P3	50	9.28	1.57	12.98	1.99	↑40%
SK3 PK3	50	11.67	1.68	12.84	2.08	↑10%
SK3 RS3	50	3.57	1.12	4.3	1.3	↑20.5%

Table 10.18. Surface roughness (Ra) results for cubes placed at Brú na Bóinne for one year exposure 2012–2013

ID	No of Measurements	Average Ra 2012 (µm)	Standard Deviation of Ra 2012	Average Ra 2013 (µm)	Standard Deviation of Ra 2013	% change in Ra
BnB1B1	50	5.89	1.51	6.12	1.62	↑4%
BnB2B2	50	7.79	1.84	8.27	1.94	↑6%
BnB3B3	50	6.13	1.47	5.44	1.48	↓11%

ID	No of Measurements	Average Ra 2012 (μm)	Standard Deviation of Ra 2012	Average Ra 2013 (μm)	Standard Deviation of Ra 2013	% change in Ra
BnB1C1	50	5.98	1.82	7.07	1.77	↑18%
BnB2C2	50	6.44	1.62	*Broken*		
BnB3C3	50	6.42	1.89	7.4	1.81	↑15%
BnB2C4	50	*Replaces C2*		5.99	2.12	
BnB1G1	50	2.26	0.71	2.55	0.66	↑13%
BnB2G2	40–50	2.01	0.73	2.48	0.64	↑23%
BnB3G3	50	1.86	0.58	1.85	0.5	↓0.5%
BnB1P1	50	6.55	1.29	*Lost*		
BnB2P2	50	6.85	1.47	8.03	1.97	↑17%
BnB3P3	50	7.97	1.84	9.13	1.75	↑15%
BnB1P4	50	*Replaces P3*		6.7	1.47	
BnB1PK1	50	9.7	1.55	10.55	1.93	↑9%
BnB2PK2		10.18	1.85	10.8	1.7	↑6%
BnB3PK3		10.8	1.52	10.1	1.8	↓6.5%

10.10.4. Colour change

Colour change was measured with a spectrometer using the L*a*b* colour space system where L* represents lightness and a* and b* represent hue (figures 10.19 and 10.20). The red/green spectrum is represented by a* values: +a* is the red direction and –a* is the green direction (Konica Minolta, 2003).

Reduction in lightness has occurred in all samples. In SKM3 the reduction is less pronounced than in some of the Brú na Bóinne plates. This may be related to aspect. SKM3 is south facing and would therefore be expected to have a low rate of microbiological growth. This would appear to be supported by some of the results from Brú na Bóinne where the south facing BnB2 plate is also exhibiting less change in lightness values than BnB1 and BnB3 (for all except the Greywhacke cubes).

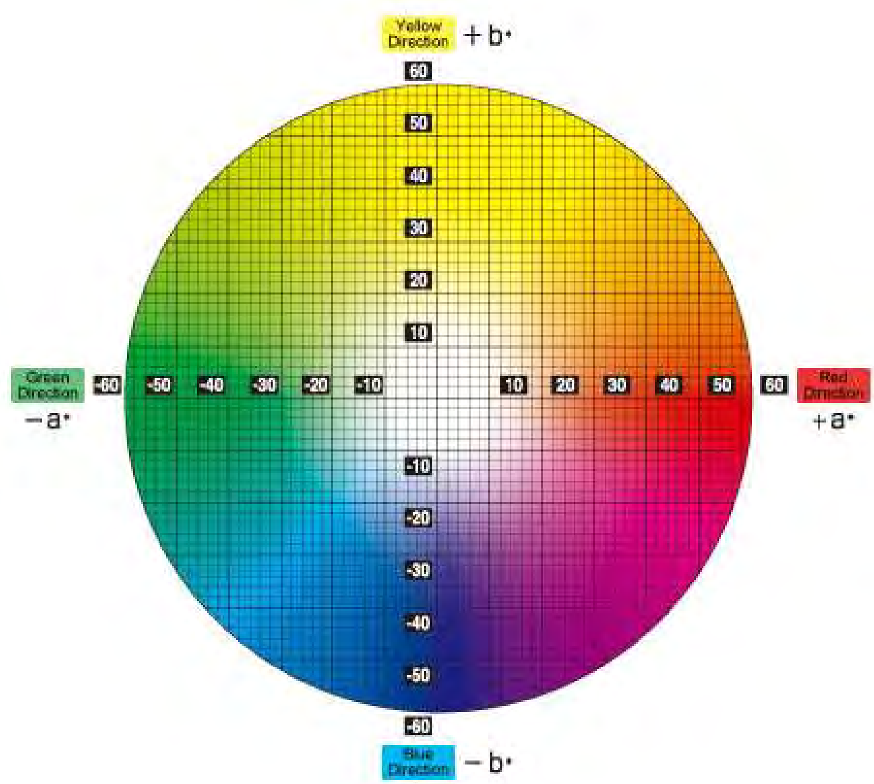


Figure 10.19. L*a*b* colour specification system chromaticity diagram illustrating a*b* colour space at a constant L* value: +a* red direction; -a* green direction; +b* yellow direction; and –b* blue direction (Nippon Denshoku Industries Co, 2007)

Although some cubes do demonstrate greening (demonstrated by a reduction in a* values), the picture is by no means consistent. Many samples have actually moved higher on the red spectrum with increasing a* measurements. In exposure tests Adamson (2012) noted a larger inconsistency in greening than in darkening across sandstone samples. Despite the fluctuations she was able to observe a clear north/south pattern in the a* results. Interpreting the fluctuations in a* Adamson points to the presence of red/orange algae that compete along the same colour axis and obscure the green signal (Adamson et al., 2012). In the experiments conducted by Adamson, the red algae were seen to grow preferentially on limestone. In the case of Greywhacke from Brú na Bóinne however, visual examination suggests that the minor increase in redness is due to soiling on the stone. This highlights the fact that a single dataset should not be viewed in isolation and that visual examination (including comparison of photographs) will play an important role in future interpretation. Young and Urquhart (1998) concluded that reduction in lightness (L*) was a more reliable measure of biological growth that greening (-a*). More recently however, Adamson (2012) has argued that L* and a* should be seen as complementary datasets and that this will lead to a more reliable detection of patterns of change due to biological growth. In general the material that has been most affected by microbiological growth, according to both L* and a* values, is Peakmoor sandstone. In Brú na Bóinne these cubes exhibit both a large degree of darkening and a significant reduction (approx 50%) in a* values i.e. movement towards green on the spectrum.

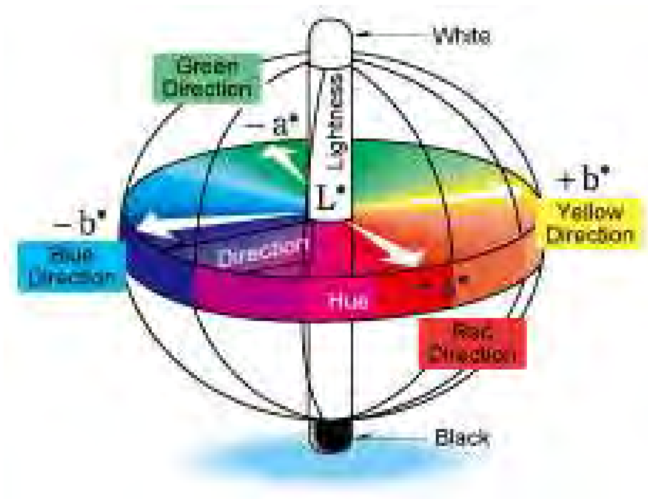


Figure 10.20. L*a*b* colour specification system 3 dimensional sphere illustrating lightness (L*) as well as colour. L* is increasing in the white direction and decreasing in the black direction (Nippon Denshoku Industries Co, 2007)

Table 10.19. Colour (*L and *a) results for cubes placed at Skellig Michael plate No. 3 for one year exposure 2011–2012

ID	No of measure-ments	Average L* 2011	Average a* 2011	Average L* 2012	Average a* 2012	ΔL* 2011–2012	Δa* 2011–2012
SK3B3	15/25	71.13	2.71	66.27	3.19	↓4.86	↑0.48
SK3C3	15/25	65.3	0.47	63.06	0.61	↓2.24	↑0.14
SK3P3	15/25	81.37	1.65	77.8	1.11	↓3.57	↓0.54
SK3PK3	15/25	69.31	3.87	66.66	3.01	↓2.65	↓0.86
SK3RS3	15/25	51.65	0.7	47.35	1.08	↓4.3	↑0.38

Table 10.20. Colour (*L and *a) results for cubes placed at Brú na Bóinne for one year exposure 2012–2013

ID	No of measure-ments	Average L* 2011	Average a* 2011	Average L* 2013	Average a* 2013	ΔL* 2012–2013	Δa* 2012–2013
BnB1B1	25	73.41	3.59	59.1	3.77	↓14.31	↑0.18
BnB2B2	25	64.87	3.3	56.27	2.98	↓8.6	↓0.32
BnB3B3	25	72.38	3.45	58.26	3.97	↓14.12	↑0.52
BnB1C1	25	65.82	0.5	60.6	0.47	↓5.22	↓0.03
BnB2C2	25	65.68	0.52	*Broken*			
BnB3C3	25	66.83	0.32	60.15	0.06	↓6.68	↓0.26
BnB2C4	25	*Replaces C2*		64.6	0.62		
BnB1Pk1	25	69.62	3.76	55.66	1.99	↓13.96	↓1.77
BnB2Pk2	25	69.49	3.59	60.02	1.85	↓9.47	↓1.74
BnB3Pk3	25	70.06	3.62	56.55	1.67	↓13.51	↓1.95
BnB1P1	25	80.63	1.52	*Lost*			
BnB2P2	25	80.07	1.61	73.45	1.64	↓6.62	↑0.03
BnB3P3	25	80.17	1.52	71.69	0.54	↓8.48	↓0.98
BnB1P4	25	*Replaces P1*		81.65	1.36		
BnB1G1	25	50.06	-2.51	49.43	-2.45	↓0.63	↑0.06
BnB2G2	25	50.32	-2.41	49.26	-2.36	↓1.06	↑0.05
BnB3G3	25	48.48	-2.51	47.8	-2.42	↓0.68	↑0.09

10.10.5. Dimensional change: 3D profiles

The profiles taken by the 3D scanner represent dimensional measurements in the XY direction at fixed Z interval values (table 10.4). The accuracy of the Renishaw Cylcone touch probe scanner is greater than +/- 2µm (Renishaw, 2006). The measurements are saved as DXF files for use in computer animated design (CAD) software. Dimensional change can be calculated by the software comparing XY co-ordinates for the same Z profiles over time. The CAD software can also be used to produce outlines of the cube profile at set Z values; overlaying these allows visual evaluation of the progression of loss (figure 10.21).

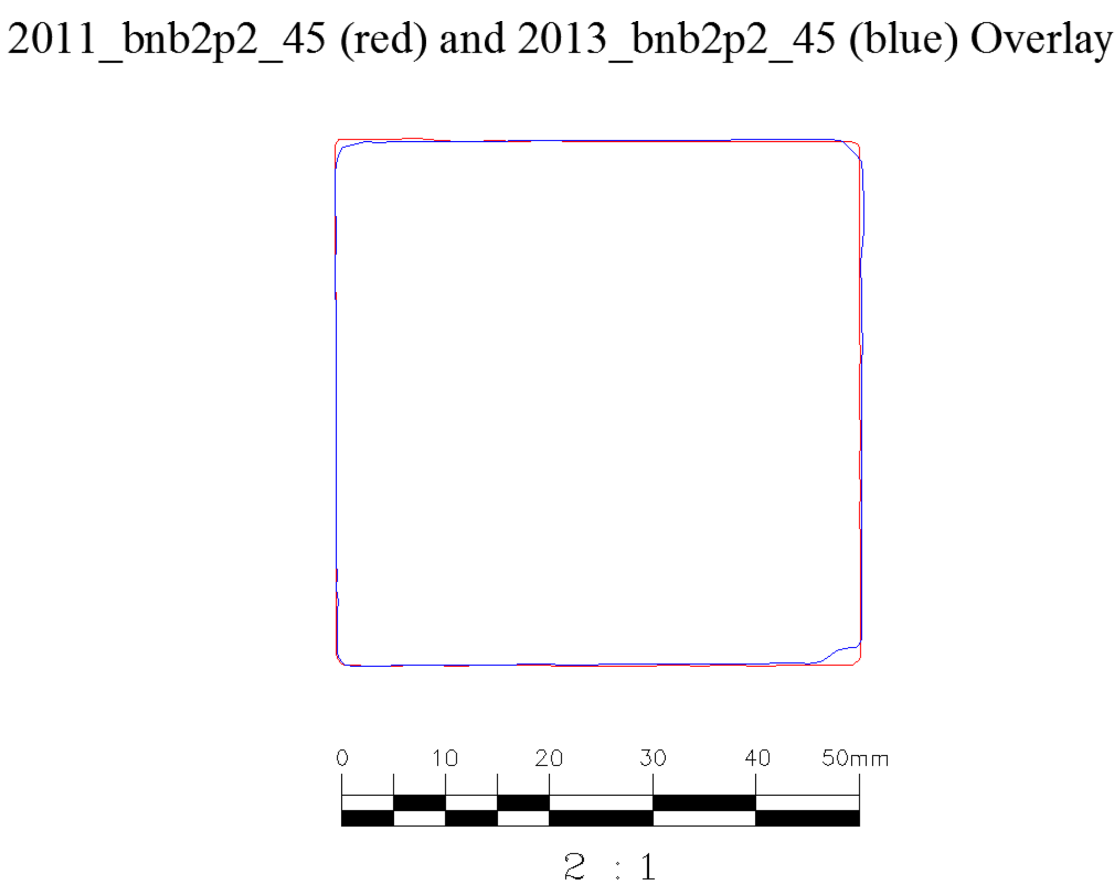


Figure 10.21. 'Best-fit' alignment of 2011 and 2013 profiles of Brú na Bóinne, plate 2, Portland cube 2 (BNB2P2) taken at 45mm from base. Red line represents 2011 measurements: Blue line 2013 measurements (image by Conor Dore)

Processing of the first year of profile measurements in CAD was carried out with the assistance of Conor Dore at DIT. Conor suggested various methods for comparing the 2011 and 2012 data. A visual best-fit alignment was considered first, achieved by overlaying cube profiles (moving and rotating one cube to match the second cube profile). A visual best-fit alignment of the cubes lacked accuracy however, as it relied on the operator's perception of visual references points. Instead a scientific or mathematical approach was adopted.

Mathematical matching of two irregular objects such as the recorded cube profiles proved a difficult task however, as there were no defined common points that could be used to match the objects (due to erosion of corners etc). To overcome this, a best-fit line was calculated for each edge of each cube resulting in a best fit rectangle that was then fitted to each irregular cube profile. Each best-fit rectangle contained four straight lines with defined corners that could be used to align the irregular cube profiles recorded at different times. The full technical details of this procedure can be found in Appendix 5.

The processing of the first set of profile measurements (2011–2012) demonstrated a problem with the procedure for data collection. Namely, that for accurate comparison over time, common control points are required. In the absence of these reference points, the technique of mathematical best-fit was utilised (Appendix 5). The best-fit alignment produced is useful for illustration purposes and some loss was observable (figure 10.21). It is not sufficiently accurate for detailed comparative analysis however (Dore, pers. comm.) and was also an extremely time-consuming procedure.

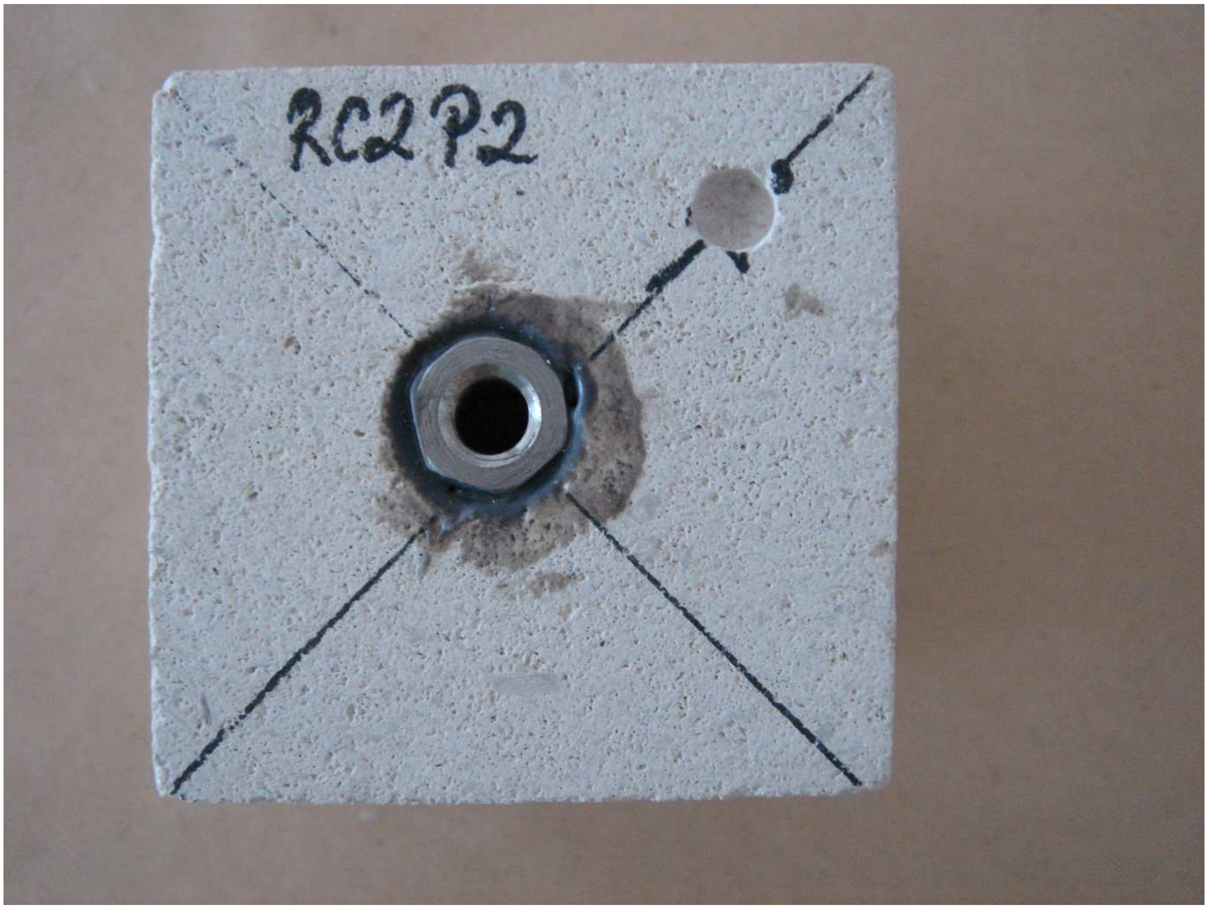


Figure 10.22. Base of cube showing sunken stainless nut and drilled reference point (top right corner) suggested control points for future 3D scanning.

The establishment of fixed reference points that can be returned to at each point in time when the cubes are measured is problematic as the surfaces and corners are subject to weathering. The solution that is proposed is to use the internal circumference of the steel nut as a control (figure 10.22). The reference point marked on the base of each cube can be used to ensure correct orientation. As the steel nut's circumference will remain unchanged it will allow accurate comparison over time. This method will require that the cubes be measured upside-down so that these points can be noted by the scanner prior to taking each profile.

10.11. CONCLUSIONS

The process of undertaking vulnerability assessments requires the identification of relevant indicators (chapter 9), yet this can prove challenging as suitable data sets are not always available. Given the predominance of stone within the case study sites, the development of an indicator relevant to the weathering of stone surfaces was therefore determined to be a priority. The short-term exposure of fresh stone is a common method for determining initial rates of weathering, when processes are at their most rapid. Long-term studies of weathering rates tend to be based on dateable historic samples such as gravestones. The newly created LegIT attempts to combine these two traditions by creating a fresh baseline for long-term measurements. To ensure sustainability, careful thought was given to the choice of materials, design of the tool and the manner of data retrieval and archiving. Surface recession, salt crystallisation and microbiological growth are the deterioration mechanisms the tool aims to track. Although based on the existing scientific tradition of using exposed samples, the LegIT is original in that it has been designed for the measurement of long-term exposure. It is also original in its use of multiple materials (including manmade) and in being embedded in at heritage sites. The main threat to the sustainability of the LegIT, as experienced during the first year of exposure, is human interference and vandalism. A second design issue, relating to the drilling of certain stone types, can be addressed in future by altering the manufacturing method.

The potential for tailor-made indicators as additional tools in the heritage manager/conservator’s arsenal has been demonstrated by this work. While scientific monitoring and high-tech sensors provide valuable data their use is not always feasible, given either limited resources or extended time-scales. This is particularly relevant when discussing climate change, as the periods being studied are inter-generational. Shortcomings with the LegIT approach have been discussed but nonetheless, it is anticipated that over time useful results will be gained. It is also intended that feedback from experts and end-users should go towards improving the design of the tool and perhaps result in its use at heritage sites outside of Ireland. This tool can therefore be proposed as a prototype model with the emphasis on the design of laboratory measurements as elaborated. Further work will be required to improve the design and address the issues encountered during on site trials.

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CHAPTER 11.

CONCLUSIONS

Climate change will cause severe disruption to society…It will damage or destroy many historic assets and may significantly impair the ability of future generations to understand and enjoy their cultural heritage (English Heritage, 2008:10)

11.1. INTRODUCTION

This thesis set out to study the issue of climate change from a heritage management perspective. The significance of climate change for cultural heritage preservation has been highlighted by international organisations and there is a growing body of literature on the subject. This is an under-researched area however, and a number of topics have yet to be addressed. From a management perspective, the lack of transferable systems for site based assessment and monitoring is significant, and this identified need provided a starting point for the research.

This thesis developed from research conducted by the author for ICOMOS Ireland and commissioned by the then Department of Environment, Heritage and Local Government. The question it sought to address was *how can cultural heritage managers gain an understanding of the impacts of climate change on sites in their care*? From this question, two interlinked research aims were framed:

1. To determine what method is most appropriate for assessing the potential vulnerabilities to climate change at site level.
2. To determine which monitoring solutions are capable of measuring the impacts of climate change on heritage values.

The constructionist philosophy underlying the research and the methods used were described in chapter two. A pragmatic approach engendered flexibility in the choice of methods and activities, including the tailoring of vulnerability theory to meet the needs of heritage management. Vulnerability theory examines the 'human-environment system' and is thus a good fit with the constructionist/phenomenological concept of meaning being produced by the interaction of subject and object. This understanding of meaning or value as created, rather than inherent, was also reflected in the development of the Vulnerability Framework. The proposed six step Vulnerability Framework focuses on cultural values and stakeholder perceptions; it is a flexible tool that allows for adjustments in this relationship.

The background research activities undertaken for this thesis were:

- Survey of the current state of knowledge through literature review, conferences, workshops and the Climate for Culture (CfC) PhD group (chapter 3).
- Survey of current practice through questionnaires with international experts (chapter 4).
- Investigation of four exemplar projects (chapter 5).

These activities provided insight on a rapidly developing topic, but one where a number of gaps exist in terms of understanding, assessing and monitoring climate change impacts on cultural heritage.

Following from the background research a theoretical approach was chosen that combined vulnerability and indicator theory. This led to the two complementary strands of primary research pursued for the remainder of the thesis (figure 11.1).

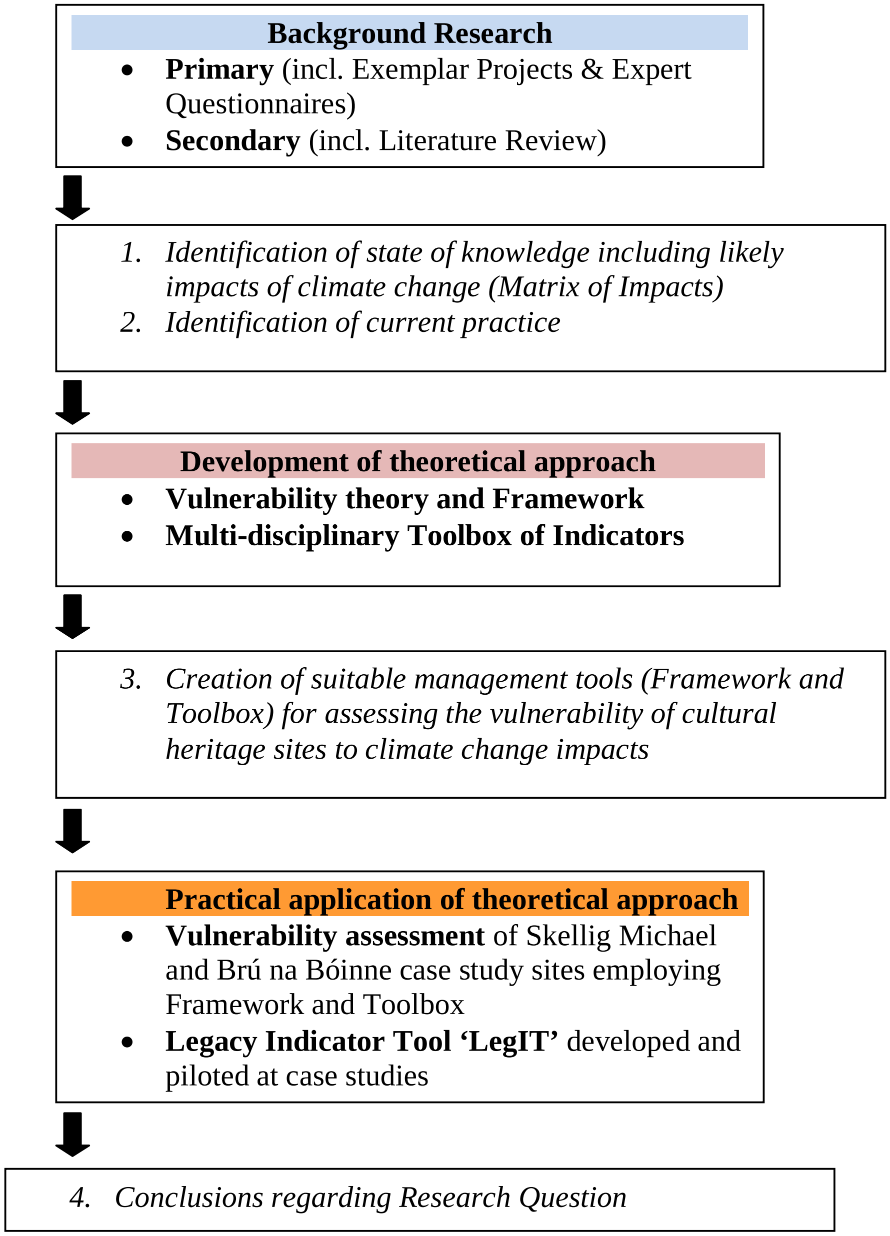

Figure 11.1. Relationship of research strands to development of completed thesis

The terminology and methodology for conducting a vulnerability assessment were defined in chapter six alongside the development of a six step Framework suitable for cultural heritage purposes. This Vulnerability Framework was then piloted at the case study sites of Skellig Michael and Brú na Bóinne (chapters 7 and 8). The final analysis utilised stakeholder contributions and feedback to ensure relevant results. In tandem with the development and testing of the six step Framework, a Toolbox of Indicators for use both in assessing vulnerabilities and monitoring climate change was created (chapter 9). The subsequent development of the Legacy Indicator Tool (LegIT) addressed an identified gap in the Toolbox by providing an indicator for surface weathering (chapter 10).

In this chapter the main discoveries relating to the research objectives outlined in chapter one are discussed. This is followed by an exploration of the central research problem in light of these findings, including a summary of the original contribution made by this thesis. The theoretical implications of the conclusions reached are subsequently outlined in order to locate the work in terms of related disciplines. The practical implications for heritage management are also described. This practical section includes a checklist for managers considering undertaking a vulnerability assessment. Finally, the implications of the thesis findings for further research are discussed.

11.2. ACHIEVEMENT OF RESEARCH OBJECTIVES

The objectives stated in chapter one (section 1.2) provided the lines of enquiry for this thesis. The findings in relation to those objectives are summarised below.

11.2.1 Objective 1. To ascertain the potential effects of climate change on cultural heritage in Ireland

General projections for Ireland by Met Eireann and ICARUS, and downscaled projections from CfC's REMO data for the case study sites, were utilised to gain an understanding of possible future climate conditions under medium-emissions scenarios (sections 3.2.6, 7.3 and 8.3). The literature review indicated the impact of changed rainfall patterns as a key issue (Smith et al., 2010, Cassar, 2005) and this was reflected in the case study assessment results (sections 7.7 and 8.7). At Skellig Michael the main issues predicted relate to increased intensity of rainfall and summer droughts causing destabilisation of structures and soil erosion. At Brú na Bóinne, with the exception of flooding, the main issues were not with the direct affect of rainfall but with its influence on processes i.e. land use, micro-biological growth, wet/dry cycles and salt crystallisation.

The literature dealing with the impacts of climate change on cultural heritage outlines a myriad of potential effects. Interpreting which of these is relevant to any given site requires an understanding of both the processes involved and the values being protected (section 3.5). Following a review of the literature the most likely effects of climate change were compiled into an *Impacts Matrix* (table 3.1). This differs from similar matrices in the literature (Cassar et al., 2006, Kelly and Stack, 2009, Colette, 2007) by considering impacts according to heritage value. The Matrix is based on environmental parameters, indirect impacts caused by anthropogenic adaptation or mitigation measures must be considered separately (section 7.7.4).

The case study applications highlighted the existence of gaps in the Matrix, due in the main to the generality of the published analyses. While the existing literature is valuable in providing a conceptual framework, there is a lack of specificity (i.e. case studies, scientific research and long-term monitoring) for developing a convincing analysis (Daly, 2011a). In the case of buried archaeology in particular there are acknowledged gaps in research and in the understanding of environmental conditions (Van de Noort et al., 2001;

Holden et al., 2006). Issues particular to individual sites are also difficult to account for within a Matrix. For example the specific structural interventions at Brú na Bóinne or problems of access at Skellig Michael.

11.2.2. Objective 2. To identify suitable methodologies for the assessment of potential climate change impacts on cultural heritage sites

Findings from the questionnaire analysis (section 4.3) suggested that existing assessment methods were based on computer simulation, risk mapping or stakeholder assessment. Methodologies rooted in risk analysis theory, and involving some or all of the above techniques, were the most common form of site based assessment featured in the literature (section 3.4) (Marshall and Johnson, 2007, Toscano, 2004). The final selection of a *vulnerability assessment* methodology in this research therefore represents a departure from current trends. Although commonly utilised as a precursor to developing adaptation and mitigation measures in sectors such as ecology, vulnerability assessment is largely untried within the heritage sector (Hinkel, 2011, Adger, 2006, The Allen Consulting Group, 2005, Woodside, 2006).

Vulnerability differs from risk analysis in taking a systems based approach and accounting for adaptive capacity, thereby giving the assessment a management focus. It also differs in not requiring an assessment of probability and this is entirely appropriate given the uncertainty involved in climate change. The application of vulnerability assessment to natural and cultural heritage was called for by the authors of "Implications of Climate Change for Australia's World Heritage Properties: A preliminary assessment":

> *A broad-scale state-of-the-art vulnerability assessment is required across all properties and values* (Australian National University, 2009: 33).

The choice of vulnerability assessment is further justified by the fact that it is a method recommended by both IPCC and UNESCO ((McCarthy et al., 2001, Colette, 2007).

11.2.3. Objective 3. To synthesise existing knowledge and identify current international practice

The findings from the international expert questionnaires and exemplar project interviews indicated that accepted 'smart practices' have yet to be established within the field of climate change and cultural heritage management. This was illustrated by the fact that three[1] out of the four exemplar projects visited in Europe were either still in development or had yet to produce results (chapter 5).

One of the key issues raised by the primary research was the practical problem of separating climate change impacts from amongst the other environmental processes affecting heritage (sections 4.8 and 5.4). This problem of 'equifinality' had not been indicated as a significant issue within the cultural heritage literature. The need to disentangle causality is addressed in ecology however (Nicholls et al., 2009, Fiedler, 2009), where the proposed solution is to gather a wide range of long-term comparative data (Humphries, 2009).

The expert questionnaire responses indicated that long-term monitoring involved difficulties in collecting and managing data (section 4.9). The international exemplar projects subsequently illustrated some possible approaches to this problem:

1. <u>Future Climate Change, the nature and scale of impact upon masonry, N. Ireland:</u> Monitoring of new artefacts (i.e. test walls) in order to extrapolate processes to

[1] The projects referred to are: Future Climate Change, the nature and scale of impact upon masonry, N. Ireland; Runic Inscriptions as Cultural and Environmental Indicators, Sweden; Archaeological Deposits in a Changing Climate, Norway. The fourth project which has been established since 2001 is SCAPE, Scotland.

heritage assets (section 5.2) - **short-term monitoring to create a theoretical model of future deterioration.**

2. SCAPE, Scotland: Mobilising volunteers for data collection (section 5.3) - **field survey sustainable due to public participation.**
3. Runic Inscriptions as Cultural and Environmental Indicators, Sweden: Utilising heritage artefacts that have a long history of documentation as indicators of environmental change (section 5.4) - **long-term condition monitoring in order to determine environmental change.**
4. Archaeological Deposits in a Changing Climate, Norway: Monitoring the burial environment to aid computerised simulation of future conditions (section 5.5) - **short-term monitoring in order to inform computer simulation**.

In addition to a shortage of long-term solutions, these findings illustrate the lack of a common structured approach. This is problematic because it suggests comparison of results between sites and regions will not be possible.

Conducting the case study assessments highlighted another issue not mentioned in the literature, namely the lack of awareness regarding climate change impacts amongst many stakeholders. In addition, where individuals or institutions are interested in engaging with the topic, there remains a large degree of uncertainty as to the severity or relevance of climate change impacts. The current lack of evidence regarding climate change effects combined with existing pressures on financial and human resources tends to result in the prioritization of more immediate problems (Daly, 2011a).

11.2.4. Objective 4. To develop a robust, transferable vulnerability assessment methodology that could facilitate analysis of potential climate change impacts at other heritage sites

Evidence from the literature pointed to a lack of clear terminology relating to vulnerability theory (section 6.2) and resultant confusion with risk assessment applications (section 6.6). It was concluded that the framing of vulnerability assessment terminology specifically in terms of cultural heritage was required. The definitions developed for *sensitivity* and *exposure* within this thesis clarify the use of these terms and relate them specifically to heritage assessments, an essential step toward creating a transferable framework (section 6.7). The IPCC definition of *vulnerability* was altered by the author to include a formula for calculating the Measure of Vulnerability (section 6.7.4).

The vulnerability methodology developed by Schröter (Schröter et al., 2005) and proposed by UNESCO (Colette, 2007) for use at World Heritage sites was found to require downscaling and adjustment, to account for the predominantly qualitative nature of individual heritage site assessments (section 6.9). This finding correlated with a previous application of the method to the Tower of London that was based entirely on qualitative data (Woodside, 2006). Following from the literature, and with the case study application in mind, a *six stage Vulnerability Framework* for assessing the vulnerability of cultural heritage to climate change was developed by the author (table 11.1). This method also reflects other impacts analyses within the literature as it combines elements of an expert led approach with stakeholder contributions (Cassar and Hawkings, 2007, Hunt, 2011, Cassar, 2005).

Table 11.1. Summary outline of the six step Vulnerability Framework developed in this thesis

6 STEP VULNERABILITY ASSESSMENT FRAMEWORK
1. Define the heritage values to be assessed
2. Understand exposure, sensitivity and adaptive capacity of these values over time
3. Identify likely hazards for each value under future climate using the Matrix of Impacts
4. Develop indicators for the elements of vulnerability
5. Assess vulnerability by entering values for exposure (E), sensitivity (S) and adaptive capacity (AC) into the Causal Model and calculating the Measure of Vulnerability (MV): $MV = (S + E) - AC$
6. Use Stakeholder Review to refine and communicate results

The results of the assessment of vulnerability of Brú na Bóinne and Skellig Michael were reviewed and sanctioned by stakeholders (section 7.7 and 8.7). This process illustrated both that the Framework could return probable findings and that it is sufficiently flexible to allow refinement based on feedback. Application of the Framework to the case study sites also revealed some drawbacks of the stakeholder approach however, most of which centre around issues of communication. A solution for overcoming this would be to conduct the assessment within a workshop or focus group format. Unlike the structured interview technique used in this thesis, the focus group would allow the assessor to provide a detailed introduction to the topic and to generate discussion amongst the stakeholders.

The successful application of the Framework to two quite different case studies demonstrates the transferability of the method between rural sites in Ireland. Further testing would be necessary to ascertain its suitability for urban heritage or for different countries (see section 11.6.1).

11.2.5. Objective 5. To identify a toolbox that will inform and initiate the monitoring of climate change impacts at the case study sites of Brú na Bóinne and Skellig Michael.

Respondents to the expert questionnaire felt that monitoring of climate change impacts was very important (section 4.6). This reflects the literature where the requirement to achieve baseline data through monitoring is identified by several authors (Kelly and Stack, 2009, Edwards and O'Sullivan, 2007, Cassar et al., 2006). The questionnaire analysis also raised two issues in relation to monitoring that were not detailed in the literature. Firstly, although there was agreement on the importance of monitoring, there was no consensus amongst respondents on what to monitor, or indeed on what constituted 'monitoring for climate change'. Secondly, the issue of 'how' to monitor the long-term effects of climate change was seen to be problematic (section 4.9.). This is due in part to a lack of monitoring solutions sustainable over a 30–100 year period (Brimblecombe, 2010). A reliance on technological monitors for both climate measurements and condition assessment is potentially problematic in this regard (Burmester, pers. comm.). The sustainability of monitors is further compromised by short funding cycles, political timeframes and staff turn-over (section 4.12). Although monitoring methods are reported in the literature and were being used by some questionnaire respondents (section 4.7) the long-term sustainability of chosen solutions is rarely, if ever, mentioned. Initial research by the author for the ICOMOS Ireland SCCC resulted in the compilation of monitoring options for the sites of Clonmacnoise in county Offaly and Brú na Bóinne; yet the question of whether these would be sustainable remained unresolved (Daly et al., 2010).

The conclusion reached in this thesis is that indicators provide a practical solution to the problem of long-term monitoring of climate change impacts (Sweeney et al., 2002, Hinkel, 2011, Higa et al., 2013). By taking a multi-disciplinary approach it was possible to assemble a Toolbox of Indicators with potential for use on cultural heritage sites (table 11.2). Indicators are considered 'secondary monitors', i.e. they measure variables that can then be related to processes of interest. Utilisation of these, or similar, quantifiable indicators will allow comparison of the impacts of climate change between sites, regions and internationally.

Table 11.2. Categories of indicator included in the Toolbox (chapter 9)

Toolbox of Indicators
Conservation and Management Indicators e.g. human resources
Landscape Indicators (Geoindicators) e.g. water level
Coastal Indicators (Geoindicators) e.g. mangroves
Burial Environment Indicators e.g. pH
Biological Indicators e.g. butterflies
Built Heritage Indicators e.g. Relative Humidity (RH)

The process of selecting suitable indicators from those available illustrated that gaps exist regarding certain heritage values. In particular, the need for an indicator to track the effects of climate change on the weathering of stone surfaces was identified. As a result of this finding, the LegIT, an indicator for stone and related materials, was designed and installed at both case studies and at three other heritage sites in Ireland (figure 11.2).

Figure 11.2. LegIT SKM1 (visible in bottom left corner) installed on a rock shelf near the ruined Upper Lighthouse of Skellig Michael (August 2013).

The LegIT was designed to overcome identified problems with sustaining monitoring. Thus, it will function passively over the coming century and does not require maintenance. Results from the first year of exposure indicate that some surface change has already occurred i.e. colour, dimension and roughness (section 10.10). The interpretation of these changes in relation to climate change will require many more years of data however, and significant results are not expected from the LegIT until at least 2043. The Toolbox of Indicators, including the LegIT, will inform the monitoring of climate change impacts at the case study heritage sites of Brú na Bóinne and Skellig

Michael into the future. In conclusion, while the systematic use of indicators has not yet been accomplished in the field, their potential has been illustrated by this study.

11.3. RESEARCH QUESTION

The question addressed in this thesis is '*how can cultural heritage managers gain an understanding of the impacts of climate change on sites in their care?*' While a number of assessment methodologies are available in the literature, the vulnerability approach, analysing the coupled human-environment system, was selected as the most appropriate for heritage management. Within this thesis a six step Vulnerability Framework for conducting such an assessment was developed and applied to the case study sites. This illustrated the potential for managers to conduct a site based analysis that highlights areas of concern. The chosen indicators, including the LegIT, can be utilised to keep this assessment under review and as a means of tracking climate change on site.

11.3.1. Original contribution to knowledge

- **Development of a six step Vulnerability Framework:** The main contribution to knowledge of this thesis is in the development and testing of a methodology for identifying the vulnerability of cultural heritage values to predicted climate change - figure 6.3, p.239. The flexible six step process is intended to be transferable to other sites, both in Ireland and internationally. During the development and application of the Framework additional original outputs were generated:

- **Definitions:** The key terms of *vulnerability*, *exposure* and *sensitivity* were defined in order to clarify the use of this terminology and its application in the field of cultural heritage management.
- **Impacts Matrix:** A matrix of potential impacts for heritage values in a maritime temperate climate was created based on the literature and case study results (table 3.1: 106). The novel elements of this Impacts Matrix are in the separation of impacts according to heritage value and in the concentration on one climate zone.

- **Toolbox of Indicators:** The utilisation of indicators aids in reviewing vulnerabilities and presents a novel approach to the problem of long-term monitoring. The multi-disciplinary Toolbox of Indicators gathered in chapter nine is a contribution towards sustainable and transferable monitoring solutions for heritage sites i.e. 'smart practice' both in Ireland and internationally.

- **LegIT:** The development and installation of a Legacy Indicator Tool for tracking the weathering of stone and related materials is an original contribution to research and a tangible benefit to the management of the sites involved. The tool is intended as a legacy for future researchers and is the first long-term exposure trial to be initiated at heritage sites in Ireland. Funding from the Department of Arts Heritage and the Gaeltacht (formerly the Department Environment, Heritage and local Government) enabled the extension of the LegIT beyond the two case study properties to Clonmacnoise, Rock of Cashel and Dublin Castle, assuring both the robustness of the results and the validation of concept.

- **Archiving:** A National Archives reference number was obtained for the LegIT and engraving onto each steel plate. This original approach will ensure that the physical indicator is securely linked to the background information and analysis necessary for its future interpretation. It also ensures longevity of the data as part of the National Archives repository.

In summary, the Vulnerability Framework, Toolbox of Indicators and LegIT are the original results of this thesis project. They will aid decision makers with planning and prioritisation for the case study sites, facilitate comparative assessment of other sites in Ireland and have the potential for transfer to heritage sites worldwide.

11.4. THEORECTICAL IMPLICATIONS OF RESEARCH FINDINGS

Primary and secondary research indicated a lack of clearly defined risk assessment methods for analysing potential climate change impacts in the international cultural heritage field. The majority of assessments of future threats utilised computer simulation, risk mapping or stakeholder assessment methodologies (sections 3.4 and 4.3). Mapping of risk with GIS is useful on a broad scale but of limited application at site level. Computer simulations require technical expertise and large amounts of baseline data. The empirical approach of stakeholder or expert judgement assessments is therefore likely to be the most accessible option for individual managers. Without a systematic methodology to guide such assessments there can be no cross comparison however, limiting their relevance and making the results harder to validate. The development of a six step Framework for assessing vulnerabilities at site level has contributed to addressing this theoretical gap and has implications for international management practice. The

Framework adopts a coupled human-environment approach to assessing the impacts of climate change on cultural heritage, focussing on individual heritage values.

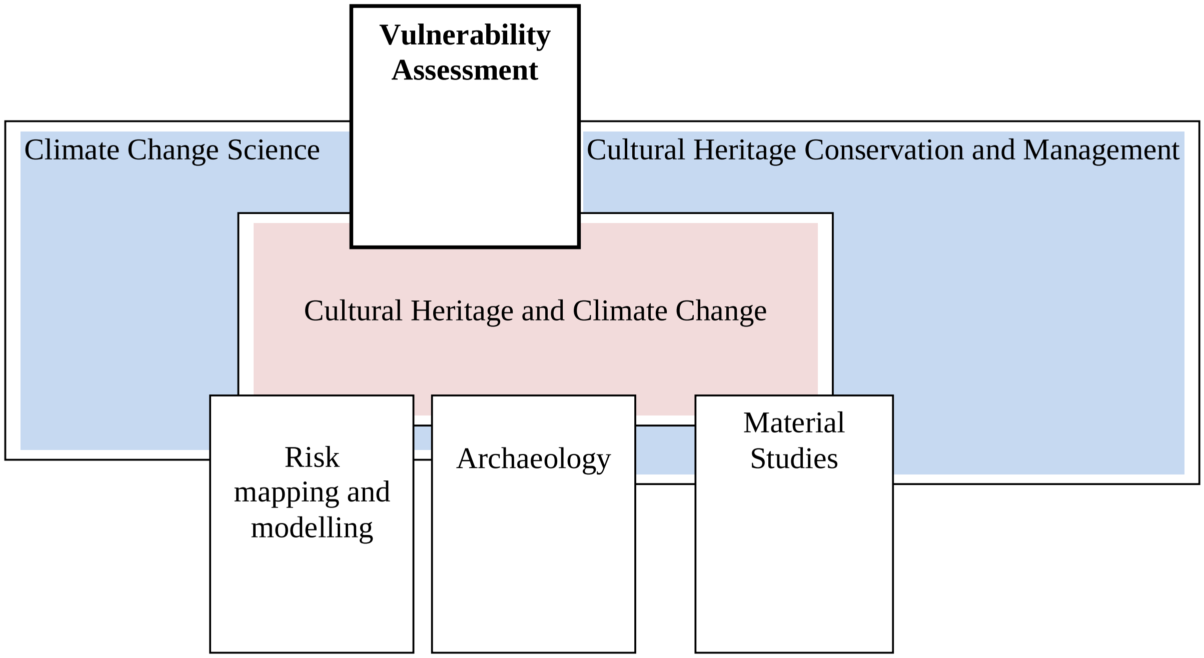

Figure 11.3. Modification of figure 3.1. ***Conceptual outline for body of knowledge*****: Blue = parent disciplines: Pink = immediate discipline; White = intersecting disciplines <u>now including Vulnerability Assessment</u>.**

11.4.1. Research contribution to conceptualisation of body of knowledge

The blending of vulnerability analysis and cultural heritage management disciplines within the thesis has resulted in the creation of two new theoretical approaches:

1. A **values based** approach to vulnerability assessment.

2. A **coupled human-environment systems based** approach to cultural heritage conservation and management.

As a result the theoretical perspectives of *vulnerability assessment* and *cultural heritage conservation and management* can be described as intersecting disciplines, within the field of *cultural heritage and climate change* research (figure 11.3).

11.4.2. Research contribution to defining the field

Problems in conceptualising and defining fundamental issues in the research field came to light during international expert consultation. The key theoretical dilemmas identified by respondents were:

1. How to identify climate change as the cause of an observed deterioration process when a single effect can have multiple causes (equifinality) (sections 4.8 and 5.4).
2. How to ensure the sustainability of monitoring and assessment solutions in the context of a 30–100 year climate period (section 4.9).
3. How to cope with uncertainty; both in terms of how the climate will change, and of what that means for cultural heritage (section 4.5).

The findings of the research have made a contribution towards addressing these problems at national and international level. The theoretical approach to equifinality proposed is borrowed from natural heritage i.e. long-term collection of multiple data strands. The Toolbox of Indicators and LegIT offer practical examples of how this may be achieved for cultural heritage. The study of indicators also offers a theoretical solution to the problem of sustainability. Creating inter-disciplinary partnerships for the sharing of data collection and storage is one of the smart practice activities recommended in this regard (Daly, 2011b). Uncertainty is inherent in the analysis of future events and at present the main theoretical position outlined in the literature is to operate according to the precautionary principle. The Vulnerability Framework and Toolbox of Indicators developed here provide heritage managers with suitably flexible and dynamic solutions that will cope with a variety of outcomes (Orell, 2012).

11.4.3. Contribution to cultural heritage management theory

The need for heritage managers to engage in forward planning based on a flexible and easily refined site based assessment of the implications of climate change, was identified in the literature (section 3.8.2). In addition to aiding the formulation of appropriate management policy, such assessments could also serve to engage public support and resources (section 3.8.1). The six step Vulnerability Framework developed and applied in this thesis offers a methodological approach that addresses these issues and can therefore be considered a contribution to management theory.

11.5. IMPLICATIONS FOR POLICY AND PRACTICE

Schröter argues that the success of any vulnerability analysis must be measured not purely on its scientific merit but also on the usefulness of the end product to stakeholders (Schröter et al., 2005). It is for this reason that a case-study strategy was utilised (section 2.3). The inductive-deductive research cycle of the case study application enabled the development of theory through experience (Moss et al., 2001). Employing multiple data strands, including stakeholder contributions and feedback, also facilitated validation of the vulnerability assessment results. The lack of certainty surrounding climate change means that any analysis of risk must be kept under review, and inclusion of quantifiable variables (indicators) builds this necessary flexibility into the Framework.

11.5.1. Implications for policy formulation

The need to include consideration of the impacts of climate change on cultural heritage within national and international adaptation and mitigation policies was noted in the literature (section 3.8.1). Through assessment of the World Heritage Sites and installation of the LegIT at these, and another three national heritage monuments, this thesis has made a contribution towards informing heritage policy in Ireland. The potential of the research to influence management policy was recognised by Dr. Michael Ryan, Chair of Skellig Michael Expert Advisory Academic Group:

> *This is a very useful piece of work and should help to form future protective policies for the island and its monuments* (Ryan, feedback form, 7.6.2013.).

The involvement of high ranking civil servants[2] as stakeholders in the assessments served to raise awareness amongst those who advise on national heritage strategy. Many of the contributors work in the Department of Arts Heritage and the Gaeltacht, which is the lead agency for developing a heritage adaptation plan under the National Climate Change Framework. The final version of this thesis will be communicated to all stakeholders and may, in turn, inform the drafting of an adaptation plan.

11.5.2. Implications for management practice

The suggested management application is of initial assessment utilising the six step Vulnerability Framework followed by ongoing review and monitoring using the Toolbox of Indicators (figure 11.4). Phase One of the management model requires gathering a toolbox of indicators and undertaking a six-step vulnerability analysis as illustrated at the case study sites, in order to develop appropriate adaptation strategies. Protective

[2] See table 7.1 & 8.1 for details on contributors and institutional affiliations.

measures taken in response to the initial assessment are likely to increase adaptive capacity at the site, thereby reducing vulnerability.

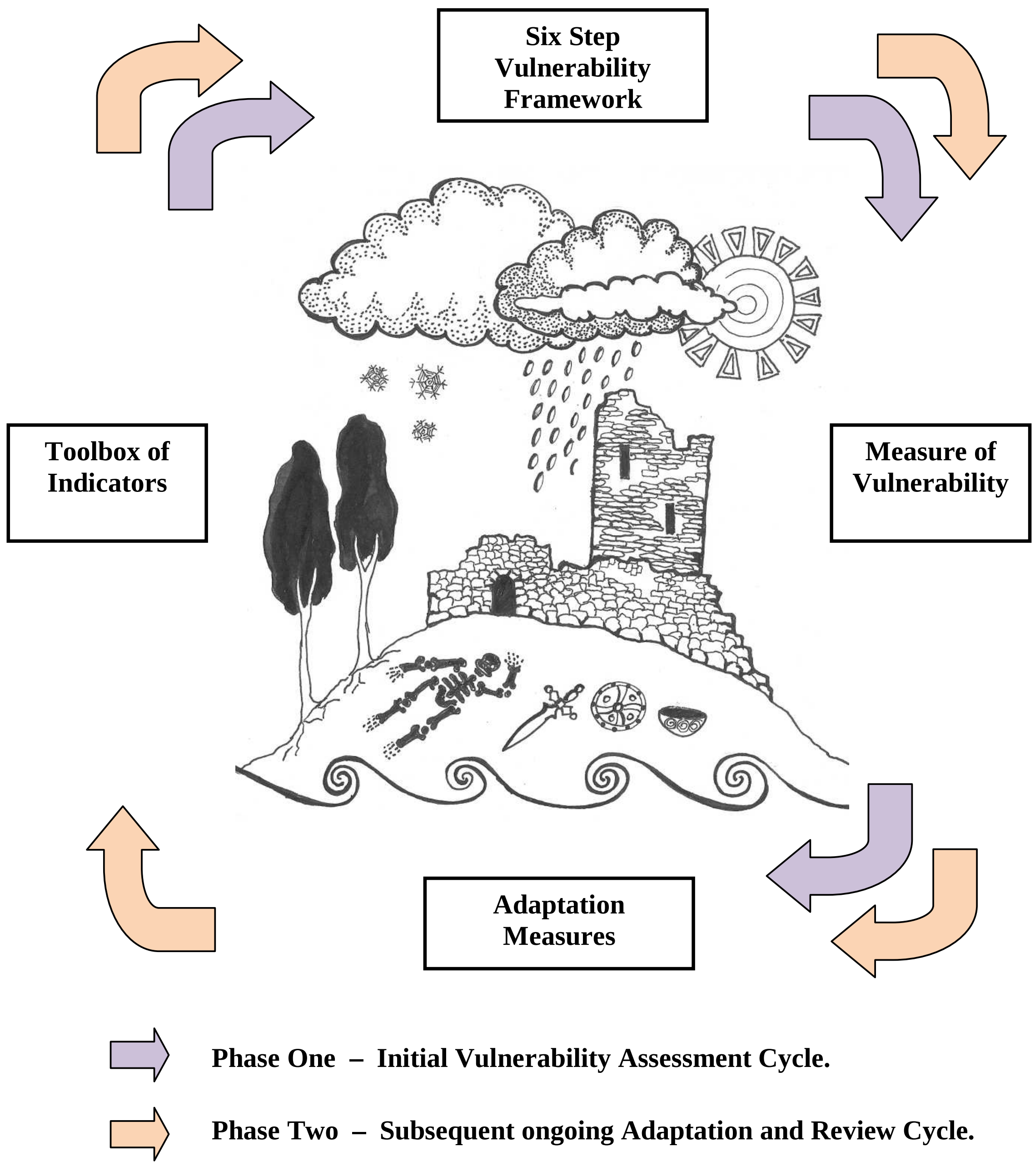

Figure 11.4. Management model for the application of the Vulnerability Framework and Toolbox of Indicators (drawing by Eileen Daly, 2013)

Phase Two entails the establishment of an ongoing cycle of review, utilising indicator data and the Framework to evaluate the performance of adaptation measures. The goal of the ongoing assessment is to inform decision makers on appropriate actions to improve resilience and reduce the measure of vulnerability. The theory surrounding the development of adaptation measures was not explored in this thesis and is suggested as an area for future research (section 11.6.4).

11.5.3. Checklist for implementation of the Vulnerability Framework

Managers wishing to assess vulnerabilities to climate change can employ the six step Framework and Toolbox of Indicators as developed and illustrated in this thesis. The assessment is based on stakeholder input and expert judgement and does not require a high level of financial resources. Lessons learned from applying the Framework to the case study sites have been utilised to create the following checklist for those attempting this process:

1. Administrative/institutional interest and support. The assessment will require a commitment of time for both the assessor and stakeholders and is not achievable without full support of the relevant authorities.
2. Access to high resolution downscaled climate model projections for the site location. Ideally the assessor would have access to one century of projections for hourly/daily values under the chosen scenario to include: precipitation, temperature, wind speed, wind direction, ground surface temperature and relative humidity.
3. Availability of climate measurements for the site location. The measurement of climate at the site - in particular of precipitation, temperature, wind speed and

direction - is preferable to using data from nearby Met stations. By recording climate on site local micro-climatic variations can be measured (section 7.7.4.).

4. Availability of multiple strands of current and historic data and stakeholder opinion. The assessor must not rely on personal knowledge of the site. The use of stakeholder focus groups is recommended as part of the consultation process to ensure a holistic assessment that reflects a variety of viewpoints.
5. An understanding, on the part of the assessor(s), of the potential impacts of climate change on heritage values. The Impacts Matrix provides a guide for direct impacts but requires interpretation based on an appreciation of the processes involved i.e. the complex interactions between climate conditions and materials response. Currently it does not include indirect impacts of climate change (section 8.7.4.).
6. A site based set of indicators. Selection can be made from existing sources including the Toolbox of Indicators and the LegIT. In some cases suitable indicators may not be available and may need to be developed to address site specific concerns.
7. Establishment of a programme for the regular monitoring of indicators into the future. The variables used to generate the initial assessment of vulnerability should be monitored and reviewed as appropriate.
8. Transparent evaluation process and communication of results. The evaluation will be based on the assessor(s)' judgement and stakeholder review. The use of two or more assessors with multi-disciplinary expertise may be an advantage in assuring the flexibility and judgement required (section 8.7.4.). Sufficient time must be allocated to the review process – for example to allow for inclusion of further respondents. Communication of the complex processes involved should utilise as

many diverse techniques as possible e.g. journal publication, online dissemination, summary results, visualisation etc.

9. Embedding of climate change activities within management policy. The repetitive cycle of reviewing monitored indicators, re-evaluating vulnerabilities and reformulating adaptive measures should be part of policy and included in site management plans.

11.5.4. Checklist for implementation of the LegIT

The LegIT is designed to track surface effects of climate on stone and related materials. The trial of the tool at the two case study sites suggested that surface changes will be measureable but also highlighted practical issues in relation to design and implementation. These included problems with the drilling method and issues of security and vandalism. Transferral of the LegIT concept beyond Ireland may also require some changes to the design in order to reflect regional concerns i.e. choice of different materials for the cubes. The following checklist outlines the key issues for those wishing to attempt this:

1. Ensuring the long-term survival and readability of the physical tool and associated data is a priority: Essential aspects towards achieving this are: the choice of high grade stainless steel support and fixings; the archiving of background information and measurements; Labelling with reference number linking the object to the archived data.
2. The use of a range of easily repeated measurement techniques: Emphasis should be placed on utilising multiple techniques and on those where the results can be archived in a printable format. This approach will minimise problems of lack of

access to expertise or of equipment obsolescence when researchers seek to repeat and compare measurements in the future.

11.6. SUGGESTED FURTHER RESEARCH

The results discussed above represent the product of a long process, yet many questions remain and new ones have developed. A number of queries arising from the findings of this thesis are suggested for further research.

11.6.1. Ascertain the transferability of the Vulnerability Framework

To ensure a transferable methodology that will allow comparison between sites and/or regions the Vulnerability Framework needs to be applied to different types of sites and in different countries. The development of new Impacts Matrices for various climate zones and heritage typologies should be undertaken in tandem with the application of the Vulnerability Framework. In addition the creation of a matrix type reference for considering indirect impacts, an issue raised during the Skellig Michael stakeholder review process, could be undertaken. It is expected that the flexible place based approach of the Framework will transfer readily. Historic Scotland has already expressed an interest in piloting the assessment method on the property of Tantallon Castle, on the Firth of Forth (Hyslop, pers. comm.).

11.6.2. Develop long-term monitoring solutions

The issue of long-term monitoring of climate change remains problematic. This research has suggested the utilisation of indicators as a solution. Indicators are not commonly applied in cultural heritage management however, and further research and development of heritage specific indicators will be necessary to ensure the availability of a comprehensive toolbox. The adaptation and transfer of the LegIT to different climatic environments and site types would be a valuable element in this process. The pilot phase of the LegIT (chapter 11) has demonstrated its potential as a heritage indicator and this should be built on with further research into improving its design and testing its transferability. This could be accomplished alongside the testing of the Vulnerability Framework on different sites.

The issue of how to sustain direct or primary monitoring on heritage sites, as distinct to monitoring indicators, remains unanswered by this research. It is one that deserves further exploration however, i.e. how much direct monitoring is needed and what tools can reliably deliver this data over a 100 year period?

The development of a co-ordinated international approach to the problem of sustainable monitoring would be beneficial. This could include the production of recommendations on the type of monitoring to be conducted and the collection and dissemination of results. The Climate for Culture project database is intended as an interactive tool for stakeholders and is currently hosted on the University of Eindhoven server (Smulders & Martens, 2013). There is perhaps a potential for creating partnerships that build on the CfC achievements. Such an initiative would require secure long-term support from the EU or other sources of heritage research funding. There is also scope for the creation of a professional standard or charter establishing the requirements for long-term monitoring. This would require co-ordination on an international level through an organisation such as UNESCO or ICOMOS.

11.6.3. Dissemination of results to end users

Dissemination of the results has been ongoing via communication with stakeholders, publications and presentations. The Indicator Toolbox and Vulnerability Framework are designed as practical management tools however, and the ideal format for reaching end-users around the world would be to publish these tools online. The creation of Web tools based on the research conducted would be a valuable contribution to the efforts to create international smart practice. In addition to accessibility, the Web format would allow for updating and improvements of the tools, using feedback from end users for example, or adding new indicators to the Toolbox. Existing websites, which aim to disseminate information on climate change tools, may be considered as models or even potential partners. Examples include:

- EU Climate for Culture project's online database (Smulders & Martens, 2013);
- Klimakommune advice website for local government in Norway that includes a section written by the Directorate of Heritage (NIKU) on suitable adaptation measures for heritage buildings (CICERO 2011);
- Climate Frontlines website launched by UNESCO as a grassroots Internet forum for communities affected by climate change (UNESCO, n.d.).

11.6.4. Develop adaptation strategies

The ultimate purpose of monitoring and assessing vulnerabilities is to inform management policy. The next step for those sites where vulnerabilities have been identified is to develop targeted response strategies. Research is needed to ensure that any adaptation measures taken are appropriate to the risk and do not pose a threat to the heritage values being protected.

11.6.5. Consideration of different scenarios

In this thesis, as in the CfC Project and Noah's Ark, climate change model projections driven by a medium-emissions scenario were utilised. To some extent this is a political compromise; if the research used a high-emissions scenario it could be more easily dismissed as extremist or alarmist. Given current emissions trends however, the global climate is on a trajectory that meshes with the higher scenarios (Mikolajewicz, pers. comm.) [3]. Future research could consider data from projections under both high and medium-emission storylines and examine whether the choice of scenario has a major impact on the outcome of the vulnerability analysis.

11.7. CONCLUSION

> *In a world where climate is changing, our heritage will be faced with a range of new pressures that are quite different to those experienced in the past. Management practices will have to evolve to reduce the impact of novel threats*…[and] *damage forms that are expected to be different from those of the last century* (Sabbioni et al., 2008: 3).

The research process that was undertaken in this thesis has yielded many original and useful results for cultural heritage managers who are concerned about climate change impacts. Primary and secondary research provided an overview of current international theory regarding climate change effects on cultural heritage. Combining this with downscaled climate projections and stakeholder knowledge facilitated a preliminary assessment of vulnerabilities for the World Heritage properties of Skellig Michael and

[3] Uwe Mikolajewicz, Max Plank Institute, CfC Workshop, Ham House, Richmond, Surrey, April 18 2013

Brú na Bóinne in Ireland. The results of the assessments will be kept under review by the Office of Public Works and it is recommended that the ongoing monitoring of indicators, including the LegIT, will be incorporated into management planning at both sites.

The Vulnerability Framework and Indicator Toolbox are a contribution towards international efforts to manage climate change impacts on cultural heritage. The development of a theoretical approach, and its application to two case studies, provides a 'road map' for those wishing to conduct vulnerability assessments on sites in their care. Increasing awareness of the issue of climate change amongst heritage managers is the first step towards creating international smart practice in this field and will be aided by communication and distribution of this research. The Framework and Toolkit have the potential for dissemination as online tools initiating site based assessments of climate change vulnerabilities within Ireland and further afield. The implications for future research include generalising the Vulnerability Framework to different site types in different regions, and researching the design and implementation of adaptation measures.

Heritage managers attempting to assess the potential impacts of climate change on cultural heritage sites have to grapple with many difficulties: non-quantifiable heritage values; unknowable archaeological resources; uncertain climate futures; and the poorly understood responses of a range of materials and environments. Nonetheless, these same individuals have a responsibility to future generations to rise to the challenge and address the threat of climate change. While not reacting in a hurried and ill thought out way, those responsible for protecting heritage can also not allow indecision and short-term thinking to prevent them from taking action. Striking the balance is the challenge for this generation of heritage practitioners, our success or failure will be measured by the next.

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APPENDIX 1. ESTABLISHING CURRENT PRACTICE

1. **Expert Questionnaire**

2. **Topics for Exemplar project interviews.**

1. Identifying Current Practice; Questionnaire

The term **Climate Change** here refers to mean a *significant variation in either the mean state of the climate or in its variability, persisting for an extended period* (IPCC).

Vulnerability is used here to refer to the *extent to which climate change may cause damage or harm to cultural heritage*.

1. If global climate change predictions are correct, then it is likely that cultural heritage will be affected over the coming century. Have you assessed the vulnerability of any cultural heritage to potential climate change impacts or not?

Yes/No/Unsure

If yes please outline how this was done:

2. At either national or international level, do you know of work carried out by others to **assess the vulnerability** of cultural heritage to potential climate change impacts?

Yes/No/Unsure

Please outline:

3. In your work have you noted any impacts on cultural heritage which you attribute to climate change?

Yes/No/Unsure

Please expand:

4. Please mark your opinion on the rating scale below. How important is 'on site' monitoring for understanding the impacts of climate change on cultural heritage?

	Low			Neutral			High
No opinion	1	2	3	4	5	6	7

5. Have you implemented any site level monitoring for the potential impacts of climate change?

Yes/No/Unsure

Please expand:

6. Do you know of any national schemes to **monitor** the potential impacts of climate change on cultural heritage?

Yes/No/Unsure

If aware please outline:

7. Do you know of any international research or development in **monitoring** the potential impacts of climate change on heritage?

Yes/No/Unsure

Please expand:

8. Do you know of any monitoring tools for cultural heritage that are designed to function over the timescale used for climate change measurement (30-100 years)?

Yes/No/Unsure

Please expand:

9. Do you (or others within your institution) have future plans to assess and/or monitor climate change impacts on cultural heritage?

Yes/No/Unsure

Please expand:

10. Any comments or points you would like to add?

2. Exemplar projects; Topics for discussion

1. **Perception of Problem**

   What is the identified problem being addressed, what are future key threats & issues.

   How does climate change fit in?

   What led to the identification of key issues, how were priories set?

2. **Methodology**

   What approach has been taken?

   What is new about it?

   What scale does it take?

3. **Implementation**

   Practical solutions implemented?

   What will be done with data - store and process and interpret?

   What is lifetime of the project?

   How well does it work and what are drawbacks?

   What resources does it require – set up and ongoing?

   What were the barriers encountered?

4. **Transferability**

   How suitable is this method for monitoring climate change impacts at site level?

APPENDIX 2. STAKEHOLDER CONSULTATION DOCUMENTATION

1. **Structured interview materials (Brú na Bóinne & Skellig Michael)**
2. **Sample feedback form (Brú na Bóinne)**

1. Stakeholder Consultation – Brú na Bóinne

1. To the best of your knowledge does climate impact on the cultural heritage of Brú na Bóinne?

Yes/No/Unsure

If Yes, please elaborate

2. Do you know of any impacts on cultural heritage at Brú na Bóinne in the past that can be related to climate?

Yes/No/Unsure

If Yes, please elaborate

3. As a result of global climate change the following is predicted for the East coast of Ireland over this century:

- *Drier summers*
- *Wetter winters*
- *Increased frequency and intensity of storms*
- *Changed rainfall pattern i.e. a shift to shorter more intense periods of rain*
- *Warmer winters and summers.*
- *Sea level rise*

The potential impacts of these climate changes on heritage are listed in table 1 (see attached document). On that table please mark all the impacts you consider relevant to Brú na Bóinne. If there are any impacts not listed please add those.

4. Based on table 1 and your own knowledge, please list the potential impacts of climate change which you consider of greatest concern for the cultural heritage of Brú na Bóinne (please limit your choice to 5 or less in each column):

Cultural Landscape	Structures Monuments	Buried Archaeology

Table 2. Impacts of concern for Brú na Bóinne

5. Based on table 2 and your knowledge of the site, please suggest three key impacts of climate change for the cultural heritage of Brú na Bóinne (choose from any column).

6. Please briefly describe the exposure and sensitivity of cultural heritage at Brú na Bóinne to these key impacts.

7. Any comments or points you would like to add?

Cultural Landscape	**Structures & Features**	**Buried deposits**
Change/loss of habitats & species Changes in land use Deterioration of peatlands Deterioration of water quality Erosion Flooding Increased recreational use Increased risk of fires Landslides Lengthening of growing season Loss of vegetation Migration of human population Saline intrusion Silting of river beds Tree throw Changes in fluvial characteristics Change in groundwater table	Changes in lichen colonies Changes in pollutants Destabilisation of foundations Dissolution Erosion Flooding Increase time of wetness Increased biological growth Increased penetration of salts & salt weathering Increased penetration of water Increased loading pressure Increased recreational use Physical damage & collapse Reduction in freeze thaw weathering Rising damp Storm damage Subsidence Surface abrasion Changes in fluvial characteristics	Accelerated micro-biological activity Changes in soil chemistry/ pH / biota / structure Desiccation of waterlogged organic deposits Erosion and exposure Flooding Loss of stratigraphic integrity Physical damage from tree throw Plough damage Salt water intrusion Sedimentation of sites Submersion Subsoil instability Changes in fluvial characteristics Change in groundwater table Changes in land use incl. use of river/water

Table 1. Potential Impacts of climate change on cultural heritage

Stakeholder Consultation – Skellig Michael

1. To the best of your knowledge does climate impact on the cultural heritage of Skellig Michael?

Yes/No/Unsure

If Yes please elaborate

2. Do you know of any impacts on Skellig Michael's cultural heritage in the past that can be related to climate?

Yes/No/Unsure

Please elaborate

3. As a result of global climate change the following is predicted for the Atlantic coast this century:

- *Drier summers*
- *Wetter winters*
- *Increased frequency and intensity of storms*
- *Changed rainfall pattern i.e. a shift to shorter more intense periods of rain*
- *Warmer winters and summers.*
- *Sea level and wave height increase*

The potential impacts of these climate changes on heritage are listed in table 1 (see last page). On that table please mark all the impacts you consider relevant to Skellig Michael (feel free to add to the list).

4. Based on table 1 and your own knowledge please list the potential impacts of climate change which you consider of greatest concern for the cultural heritage of Skellig Michael (please limit your choice to 5 or less in each column):

Cultural Landscape	**Structures Monuments**	**Buried Archaeology**

Table 2. Impacts of concern for Skellig Michael

5. Based on table 2 and your knowledge of the site, please suggest three key impacts of climate change for the cultural heritage of Skellig Michael (choose from any column).

6. Please briefly describe the exposure and sensitivity of cultural heritage at Skellig Michael to these key impacts.

7. Any comments or points you would like to add?

Cultural Landscape	**Structures & Features**	**Buried deposits**
Change/loss of habitats & species Changes in land use Deterioration of peatlands Deterioration of water quality Erosion Flooding Increased recreational use Increased risk of fires Landslides Lengthening of growing season Loss of vegetation Migration of human population Saline intrusion Silting of river beds Tree throw	Changes in lichen colonies Changes in pollutants Destabilisation of foundations Dissolution Erosion Flooding Increase time of wetness Increased biological growth Increased penetration of salts & salt weathering Increased penetration of water Increased loading pressure Increased recreational use Physical damage & collapse Reduction in freeze thaw weathering Rising damp Storm damage Subsidence Surface abrasion	Accelerated micro-biological activity Changes in soil chemistry & pH Desiccation of waterlogged organic deposits Erosion and exposure Flooding Loss of stratigraphic integrity Physical damage from tree throw Plough damage Salt water intrusion Sedimentation of sites Submersion Subsoil instability

Table 1. Potential Impacts of climate change on cultural heritage

2. **Feedback Form Brú na Bóinne Vulnerability Assessment**

Researcher's Name: CATHY DALY	
Faculty/School/Department: Real Estate and Construction. DIT, Bolton St.	
Title of Study: *Methodology for Assessing the Vulnerabilities of Archaeological Sites to Predicted Climate Change; focusing on Ireland's two World Heritage sites*	
To be completed by the Stakeholder NB Please use additional paper for answers as needed	
Have you read the results of the Brú na Bóinne vulnerability assessment? YES/NO Having considered the summary results (table 1 attached), would you recommend any specific amendments to the vulnerability assessment as stated. YES/NO If YES, please outline your suggested alteration(s) and indicate your reasoning for so doing. Do you agree in principle with the comments/information attributed to you within the text? YES/NO If NO, please outline your suggested corrections/alterations Any additional comments or factual corrections in relation to any of the processes or results described?	
Signed_______________________________________ Date: Name in Block Letters:	

Table 1. Summary of predicted climate change vulnerabilities for Brú na Bóinne to 2101 based on research and evaluation

	Rock Art	*Buried deposits*	*Structures & Monuments*	*Cultural Landscape*
Impacts for which Vulnerability is High	! Changes in biodeterioration	! Changes in agriculture (ploughing, crops)	! Flooding (fluvial & pluvial)	! **Flooding (fluvial & pluvial)** ! **Changes in land Use**
Impacts for which Vulnerability is Medium	! Wet dry cycles ! Abrasion ! Salt damage	! Changes in burial conditions ! Erosion ! Tree throw	! Structural collapse ! Erosion ! Tree throw	! **Erosion** ! **Ecological change** ! **Tree throw**
Impacts for which Vulnerability is Low	! **Accelerated chemical weathering** ! **Cryoclastic weathering** ! **Thermoclastic weathering**	! **Changes in hydrology/ water table** ! **Saline intrusion**	! **Saline intrusion**	! **Changes in hydrology/ water table** ! **Deterioration of water quality** ! **Saline intrusion**

APPENDIX 3. ETHICAL RESEARCH PROCEDURES & DOCUMENTATION

1. **Introduction for expert questionnaire interviews.**
2. **Introduction for stakeholder consultation interviews (at case studies).**
3. **Consent form for all respondents.**
4. **Sample DIT Ethics Committee Appendix 1 form; Subjects and/or researchers for exemplar interviews**
5. **Sample DIT Ethics Committee Appendix 1 form; Subjects and/or researchers for stakeholder interviews**

1. Introduction for expert questionnaire respondents

Thank you very much for agreeing to be interviewed. The following paragraphs provide an idea of the aim and structure of this survey.

The interview will be structured around a questionnaire. I have 10 questions to ask, depending on your answer, you may be asked to expand on some sections. The interview will take between 15 and 30 minutes. Should further clarification be required afterwards it can be done via Email.

The purpose of the interviews is to establish current practice in relation to the assessment and monitoring of climate change impacts on cultural heritage. The information will be used towards my PhD with the faculty of Real Estate and Construction at Dublin Institute of Technology. No opinions or information will be attributed to any individual in the thesis unless they have read and approved the relevant text. Any amendments or corrections required by named individuals will be undertaken before publication.

If you agree I would like to tape the interview. This is for my own record only as the taped interviews will not be published. The audio files will be encrypted and stored on a password protected computer. Following the completion of the research all recorded interviews will be destroyed.

I am required by the Dublin Institute of Technology Ethics Committee to ask you to indicate your agreement with the conditions outlined. Please indicate your consent to proceed by signing this form and return it in electronic or hard copy to the address below.

Signature & date:
Name & position:
Place of work:
Contact Email:

2. Introduction for case study stakeholders.

Thank you very much for agreeing to be interviewed. The following paragraphs provide an idea of the aim and structure of the interview.

Completing the questions should take approximately 20 minutes. The aim of the interview is to gain an assessment of the possible impact of climate change on Ireland's World Heritage sites. It should be based on the respondent's knowledge and experience of the heritage site alone, no prior understanding of climate change is required.

The information will be used towards my PhD with the faculty of Real Estate and Construction at Dublin Institute of Technology. Participants may be referred to by name within the thesis in relation to information or opinions given through the interview. In such cases named individuals will have an opportunity to read and approve the relevant text. Any amendments or corrections required by named individuals will be undertaken before publication. Participants are free to withdraw from the study at any time prior to publication.

If you agree I would like to tape the interview. This is for my own record only as the taped interviews will not be published. The audio files will be encrypted and stored on a password protected computer. Following the completion of the research all recorded interviews will be destroyed.

I am required by the Dublin Institute of Technology Ethics Committee to ask you to indicate your agreement with the conditions outlined prior to this interview. Please indicate your consent to proceed by signing the attached consent form and return it in electronic or hard copy to the address below. All correspondence will be kept in confidence.

Name & position:
Place of work:
Contact Email:

3. Consent form for all respondents

Researcher's Name: CATHY DALY	
Faculty/School/Department: Real Estate and Construction	
Title of Study: Assessing and monitoring the potential impacts of climate change on Ireland's World Heritage.	
To be completed by the respondent/interviewee	
3.1 Have you been fully informed/read the information sheet about this study? YES/NO 3.2 Have you had an opportunity to ask questions and discuss this study? YES/NO 3.3. Have you received satisfactory answers to all your questions? YES/NO 3.4 Have you received enough information about this study and any associated health and safety implications if applicable? YES/NO 3.5 Do you understand that you are free to withdraw from this study? • at any time • without giving a reason for withdrawing • without affecting your future relationship with the Institute YES/NO 3.6 Do you agree to take part in this study the results of which are likely to be published? YES/NO 3.7 Have you been informed that this consent form shall be kept in the confidence of the researcher? YES/NO	
Signed____ Date Name in Block Letters ____ Signature of Researcher ___________________________________ Date	

4. DIT Ethics Committee Appendix 1 form; exemplar interviews

Researcher's Name: *Caithleen* (use block capitals)	**Title:** *Daly*
Faculty/School/Department: *Real Estate & Construction Economics, Dept. Engineering & Built Environment*	
Title of Study: *Measuring and monitoring vulnerability to climate change in Ireland's heritage*	
2.1 Please specify the types of subjects involved in this study, e.g. healthy subjects, in-patients, clinic attendees, minors, and indicate the number of each type.	
Heritage professionals involved in projects being visited and studied for use as examples of best practice.	
2.2. How will you be recruiting subjects for the study? If controls are to be included please state how they are to be selected and attach a copy of the advertisement if used.	
Subjects are identified through the literature & through personal referral. They are chosen for their involvement with a specific project that is relevant to the aims of the PhD research.	
2.3. Specify the number of subjects to be used in this project, the selection criteria and the exclusion criteria.	
Approximately four projects will be studied, the number of human subjects interviewed will be between 4 & 8. Selected subjects (see above) will be contacted to see if they are willing to have their project included in the study.	
2.4. Specify whether any of the following procedures are involved:	
• Any invasive procedure *NO* • Physical contact *NO* • Any procedure that may cause mental distress *NO*	
Outline the procedures involved in your study. (If samples are to be taken state **type**, **frequency** and **amount** and whether this is part of their normal treatment. If Radiological Investigations are part of the procedure please indicate the number and frequency of exposures and total calculated dosage.)	
The collection of primary data via interviews: *Unstructured informal interviews. The subjects will be asked to describe the project, any obstacles they encountered and how transferable they think the method is.* *The interviews will be conducted in person by visiting the respondent's location.* *The interviewee will be contacted in advance to set up the visit and given an explanation of the purpose of the research.* *The interview will last at least one hour.*	

The interviewee will be asked for permission to record the interview for note-taking purposes. The recorded interviews will not be published.
The recorded interview will be transcribed. The transcribed interview will be stored with the recordings and will not be made available to anyone other than the researcher.

The interviewees will be given an opportunity to read the draft text that relates to their project and request changes before publication.

2.5. State the procedures which may cause discomfort or distress and the degree of discomfort or distress likely to be endured by the subjects.

No discomfort or distress is likely

2.6. State the potential risks, if any (to both the investigator, subjects, the environment and/or participants), and the precautions being taken to meet them.

Include information on hazardous substances that will be used or produced, and the steps being taken to reduce risks.
For any projects using Ionizing Radiation see SECTION 7.

It is a requirement that a formal signed Risk Assessment Form be provided-see SECTION 10 (i) to (v)

None

2.7 Is written consent to be obtained? ***YES***

If so, please use the CONSENT FORM (section 3)

If a form other than the Research Ethical Committee consent form is to be used, please attach a copy.

2.8. Are subjects to be included under the age of 18? ***NO***

If yes, please fill in the CONSENT FORM (section 4) for Research Involving 'less powerful subjects' and those under 18 years of age

2.9. Is neonatal material to be used in this study? ***NO***
If yes, please fill in SECTION 8 for Research Involving Neonatal Material

2.10. Will any payments be made to subjects? ***NO***   If **YES** give details:
2.11. Is any proportion of this payment being paid by a commercially sponsored organisation and if so by whom?   ***NO***
Organisation:
2.12 Signature details   **Researcher's Signature ___Cathy Daly________Title_____Ms__________**   **Date ____14.5.2012____________**

5. **DIT Ethics Committee Appendix 1 form; Subjects and/or researchers stakeholder interviews**

Researcher's Name: *Caithleen* (use block capitals)	**Title:** *Daly*
Faculty/School/Department: *Real Estate & Construction Economics, Dept. Engineering & Built Environment*	
Title of Study: *Measuring and monitoring vulnerability to climate change in Ireland's heritage*	
2.1 Please specify the types of subjects involved in this study, e.g. healthy subjects, in-patients, clinic attendees, minors, and indicate the number of each type.	
Heritage professionals and those involved with the two case study heritage sites e.g. archaeologists, conservators, managers, guides, academics & policy makers.	
2.2. **How will you be recruiting subjects for the study?** If controls are to be included please state how they are to be selected and attach a copy of the advertisement if used.	
Subjects are identified through the literature & through personal referral. They are chosen for their expertise/experience on the case study sites.	
2.3. **Specify the number of subjects to be used in this project, the selection criteria and the exclusion criteria.**	
The exact number is not yet known, it will be approximately 20. Selected subjects (see above) will be contacted to see if they would like to participate, involvement is based on availability.	
2.4. Specify whether any of the following procedures are involved:	
• Any invasive procedure *NO* • Physical contact *NO* • Any procedure that may cause mental distress *NO*	
Outline the procedures involved in your study. (If samples are to be taken state **type**, **frequency** and **amount** and whether this is part of their normal treatment. If Radiological Investigations are part of the procedure please indicate the number and frequency of exposures and total calculated dosage.)	
The collection of primary data via interviews: *Structured interview but with allowance for open discussion. The interviews can be conducted by phone, in person or self administered dependant on the person's preference* *The interviewee will be sent the list of questions and a short introduction to the process prior to the interview. The questions and introduction are attached here.*	

The interview will last approx half an hour.
The interviewee will be asked for permission to record the interview for note-taking purposes (not applicable if self-administered). The recorded interviews will not be published.
The recorded interview will be listened to and relevant sections will be transcribed.
The transcribed interview sections will be stored with the recordings and will not be made available to anyone other than the researcher.
If any comments or opinions are attributed to the individual within the final thesis they will be given an opportunity to change or remove same before publication.

2.5. State the procedures which may cause discomfort or distress and the degree of discomfort or distress likely to be endured by the subjects.

No discomfort or distress is likely

2.7. State the potential risks, if any (to both the investigator, subjects, the environment and/or participants), and the precautions being taken to meet them.

Include information on hazardous substances that will be used or produced, and the steps being taken to reduce risks.
For any projects using Ionizing Radiation see SECTION 7.

It is a requirement that a formal signed Risk Assessment Form be provided-see SECTION 10 (i) to (v)

None

2.7 Is written consent to be obtained? ***YES***

If so, please use the CONSENT FORM (section 3)

If a form other than the Research Ethical Committee consent form is to be used, please attach a copy.

2.8. Are subjects to be included under the age of 18? ***NO***

If yes, please fill in the CONSENT FORM (section 4) for Research Involving 'less powerful subjects' and those under 18 years of age

2.9. Is neonatal material to be used in this study? ***NO***
If yes, please fill in SECTION 8 for Research Involving Neonatal Material

2.10. Will any payments be made to subjects? ***NO*** If **YES** give details:
2.12. Is any proportion of this payment being paid by a commercially sponsored organisation and if so by whom? ***NO***
Organisation:
2.12 Signature details **Researcher's Signature _Cathy Daly ________Title_____Ms__________** **Date ____14.5.2012____________**

APPENDIX 4.
LISTS OF CONTRIBUTORS

Table Ap.4.1 Stakeholders consulted for Skellig Michael listed alphabetically

Name	**Institution**	**Details**	**Interview method**
Bob Harris	OPW	Chief guide on Skellig Michael	Face to face 16.8.10
Claire O'Halloran	OPW	Guide on Skellig Michael	Face to face 16.8.10
Des Lavelle	Boatman & author (Lavelle 2004)	Running passenger boat service to Skellig Michael for over 40 years	Face to face 10.9.12
Dr Ann Lynch	National Monuments, Dept of Arts Heritage and the Gaeltacht	Senior Archaeologist, has excavated on Skellig Michael and is a member of the Skellig Michael Implementation Group (SMIG)	Self admin 29.5.12
Dr Michael Connolly	Kerry County Council	County Archaeologist, conducted surveys of Skellig Michael.	Self Admin 18.6.12
Dr Michael Ryan	Adjunct professor TCD and UCD	Chair of Skellig Michael Expert Advisory Academic Group	Self Admin 18.9.12
Edward Bourke	National Monuments, Dept of Arts Heritage and the Gaeltacht	Archaeologist for Skellig Michael and member of the SMIG	By Phone 18.6.12
Grellan Rourke	OPW	Skellig Michael Site Manager and Senior Conservation Architect	Face to face 12.8.10
Jack O'Leary	Malachy Walsh & Partners	Consultant engineer for Skellig Michael	By phone 21.6.12
Patrick O'Shea	OPW	Chargehand and mason, Skellig Michael	Face to face 16.8.10

Table Ap.4.2 Stakeholders consulted for Brú na Bóinne listed alphabetically

Name	Institution	Details	Interview method
Ana Dolan	National Monuments Service, OPW	Senior Conservation Architect for Brú na Bóinne	Unstructured Interview for MA research 2.4.2008
Ann Lynch (Dr)	Senior archaeologist National Monuments, Dept of Arts Heritage and the Gaeltacht	Excavated in Brú na Bóinne	Self-admin 29.5.12
Annette Lynch	Conservation Ranger, National Parks & Wildlife Service, Navan	Monitoring compliance with natural heritage protection legislation for NPWS	Structured phone interview 27.6.12 (interviewed for MA research 2008)
Clare Tuffy	Office of Public Works (OPW)	Service Manager, Brú na Bóinne Visitor Centre	Structured phone interview 8.6.12 (interviewed for MA research 2008)
Conor Brady (Dr)	Lecturer in archaeology Dundalk Institute of Technology	Undertaking landscape based archaeological fieldwork in the Brú na Bóinne area	Structured phone interview 17.5.12
Douglas Comer (Dr)	Principal, Cultural Site Research and management Inc. Maryland USA Co-President and Expert Member, ICOMOS International Scientific Committee on Archaeological Heritage	Author of expert report for An Bord Pleanála: *Brú na Bóinne World Heritage Site N2 Slane Bypass; Heritage Impact Assessment* (2011)	Structured phone interview 10.1.13
Helen Lewis (Dr)	Lecturer in archaeology University College Dublin	Member of INSTAR project undertaking landscape characterization of river Boyne	Self admin 10.5.2012
Ian Lumley	An Taisce		Unstructured interview for MA research 5.4.2008
Jill Chadwick	Architectural Conservation Officer, Meath County Council, Abbey Road Navan	Member of management plan steering committee	Self-admin 28.5.12
Loretto Guinan (Dr)	Heritage Officer, Meath County Council	County advisor on heritage and member of management plan steering committee	Unstructured interview for MA research 3.4.2008

Marc Ritchie	Architectural Conservation Advisor, Architectural Heritage Advisory Unit, Dept of Arts Heritage and the Gaeltacht	Member of steering committee for management plan	Self-admin 5.6.12
Margaret Gowen	Consultant Archaeologist Margaret Gowen & Company	ICOMOS representative on steering committee for management plan	Structured phone interview 20.4.12
Robert Meehan (Dr)	Consultant geologist, Talamhireland	Research on Boyne valley paeleo-geology	Structured phone interview 2.7.12
William Cumming	National Inventory of Architectural Heritage, Dept of Arts Heritage & the Gaeltacht	Senior Architectural Advisor, previously Senior Conservation Architect, Brú na Bóinne	Structured phone interview 2.5.12

Table Ap.4.3 Respondents to Best Practice Questionnaire listed alphabetically

Name & Country	**Country**	**Details**	**Interview Method**
Ashley-Smith J. (Dr)	England	Freelance conservation consultant & partner within Climate for Culture project (CfC).	Self admin 6.10.11
Baker P. (Dr)	Scotland	Research Fellow, Centre for Research on Indoor Climate and Health, Glasgow Caledonian University. Partner in Engineering Historic Futures & CfC.	Self admin 13.9.11
Barr, S.	Norway	President ICOMOS International Polar Heritage Committee.	Phone 27.10.11
Blankholm, H. P. (Prof)	Norway	Institute of Archaeology and Social Anthropology, University of Tromsø. Polar archaeology expert.	Phone 1.12.11
Broström, T. (Prof)	Sweden	Professor in conservation, Gotland University. Partner in CfC	Self admin 3.11.11
Burmester, A. (Prof Dr)	Germany	Director, Doerner Institut Munich. Partner in CfC.	Phone 14.11.11

Name & Country	**Country**	**Details**	**Interview Method**
Camuffo, D. (Prof)	Italy	Research Director at the National Research Council of Italy, Professor of "Environmental Physics" and "Physics for Conservation" at the University of Padua, the Polytechnic of Milan and the Cignaroli Academy, Verona. Partner in CfC.	Face to face 13.9.11
Dawson T. (Dr)	Scotland	Manager of SCAPE and Shorewatch community monitoring of coastal erosion.	Phone 19.10.11
Faylona, P.	Philippines	National Museum of the Philippines, Forum Unesco Universities & Heritage member with declared interest in climate change.	Self admin 21.4.12
Fjaestad, M.	Sweden	Member of steering group at Karlstad University for Scandinavian network on climate change and cultural property.	Self-admin 4.10.11
Flatman, J. (Dr)	England	County Archaeologist & Senior Lecturer, Surrey County Council and UCL. Author (2009) 'A Climate of Fear: Recent British Policy and Management of Coastal Heritage' *Public Archaeology*	Phone 19.10.11
Gronnow, B. (Prof)	Denmark	Research Professor, National Museum of Denmark. Polar archaeologist & researcher Qajaa monitoring project, Greenland.	Phone 17.1.12
Haefner, K.	Germany	Chief Conservator Bayern State Castles and Gardens. Partner in CfC.	Self admin 23.9.11
Hurd, J.	England	ICOMOS President Advisory Committee. Author (2008) 'Preparing for climate change: the importance of 'maintenance' in defending the resilience of cultural heritage.' *Historic Environment 21*	Phone 20.1.12
Hyslop, E. (Dr)	Scotland	Deputy Director of Conservation, Historic Scotland. Author *A Climate Change Action Plan For Historic Scotland 2012-2017*	Phone 16.1.12
Martens, V.V.	Norway	Researcher, Norwegian Institute for Cultural Heritage on project titled *Archaeological Deposits in a Changing Climate.In Situ Preservation of Farm Mounds in Northern Norway*	Phone 22.2.12

Name & Country	**Country**	**Details**	**Interview Method**
Matthiesen, H.	Denmark	Senior Researcher National Museum of Denmark. Expert on in situ monitoring, researcher on Qajaa monitoring project Greenland.	Phone 20.1.12
McIntyre-Tamwoy, S. (Dr)	Australia	Post doctoral research fellow in archaeology & anthropology James Cook university, Cairns. Author (2008) 'The impact of global climate change and cultural heritage: grasping the issues and defining the problem.' *Historic Environment 21*	Phone 1.12.11
McNeary, R. & Westley, K. (Dr)	N. Ireland	Research Associates, University of Ulster, Coleraine, Centre for Maritime Archaeology (CMA). Principal investigator on Climate Change and Cultural Heritage in Northern Ireland NIEA project.	Self admin 2.11.2011
Morales, O.O.B. (Dr)	Mexico	Head of Department of Microbiology and Biotechnology, Autonomous University of Campeche Mexico. Research interest in climate change and microbiological growth on stone.	Google chat 29.2.12
Murphy, P.	England	Historic Environment intelligence Officer (Climate Change) English Heritage. Author (2009) 'Coastal Heritage and Climate Change in England: Assessing threats and priorities.' *Conservation and Management of Archaeological Sites* 11	Phone 19.12.11
Pearson, M.	Australia	Managing Director, Heritage Management Consultants Pty Ltd, and former Chair ACT Heritage Council, Australian Capital Territory, Australia. Author (2008) 'Climate change and its impacts on Australia's cultural heritage.' *Historic Environment* 21 & co-author (1998) Environmental indicators for national state of the environment reporting - Natural and Cultural Heritage. *Australia: State of the Environment (Environmental Indicator Reports).*	Phone 21.3.12

Name & Country	**Country**	**Details**	**Interview Method**
Pender, R. (Dr)	England	English Heritage Conservation Department, Building Conservation & Research Team. Researcher on English Heritage 2008 publication *Climate Change and the Historic Environment*	Phone 2.12.11
Rajčić, V. (Prof)	Croatia	Professor, Faculty of Civil Engineering University of Zagreb. Partner in CfC.	Self-admin 15.9.11
Rockman, M. (Dr)	USA	Climate Change Adaptation Coordinator for Cultural Heritage Resources, U.S. National Parks Service	Phone 8.12.11
Roe, D. (Dr)	Australia	Archaeology Manager, Port Arthur Historic Site Management Authority, Tasmania, Australia	Self Admin 20.4.12
Sabbioni, C. (Prof)	Italy	Institute of Atmospheric Sciences & Climate, CNR, Bologna. Lead partner Noah's Ark, TeACH, & Executive Board EU Joint Programme Initiative (JPI) for cultural heritage.	Phone 3.11.11
Van Schijndel, A.W.M. (Dr)	Netherlands	Assistant Professor, Eindhoven University of Technology. Partner in CfC.	Self admin 20.9.11
Wainwright, I.	U.K.	Broker Sales Director Ecclesiastical Insurance, partner in Engineering Historic Futures & Noah's Ark	Phone 28.10.11
Wu, P.S. (Prof)	Taiwan	Assistant Professor, National Cheng Kung University, Taiwan. Conducting research on climate change risks to cultural heritage.	Phone 24.2.12

APPENDIX 5.

TECHNICAL PROCEDURE TO ACHIEVE BEST FIT FOR 3D PROFILE DATA

By CONOR DORE

Calculation of Best-Fit Line for each Irregular Cube Edge

Coordinates of 9 to 10 points were measured at regular intervals for each edge of each cube from the CAD profiles (Figure Ap5.1). These coordinates were then exported from AutoCAD and copied to an Excel sheet (Figure Ap5.2) to calculate the best fit line through the points. The 9 to 10 points for each cube edge were plotted on a graph in Excel and a Trendline was used to show the best-fit line through these points (Figure Ap5.3). This Trendline function in Excel also provides the equation of the best-fit line which can be used to calculate coordinates of points on the best-fit line. Coordinates of the best-fit line were calculated in Excel (Figure Ap5.4) and then brought back into AutoCAD software to plot the best fit lines for each edge of each cube (Figure Ap5.5 to Ap5.9). This resulted in a best fit rectangle for each cube profile (Figure Ap5.9 and 5.10).

Alignment of Irregular Cubes using Best-Fit Rectangles

Now that a regular best-fit rectangle is available for each irregular cube profile it was possible to align cube profiles recorded in 2011 with the relevant cube profiles recorded in 2013 based on common defined corner points. These profiles were aligned using three common corner points on each best-fit rectangle (Figure Ap5.11). An align command in AutoCAD calculates the necessary transformation including a translation and rotation. The scale of the separate cube profiles being aligned was not altered during this transformation. When applying this transformation to overlay the best-fit cubes together, the irregular cubes were also moved with them resulting with the irregular profiles for each year overlayed together (Figure Ap5.12).

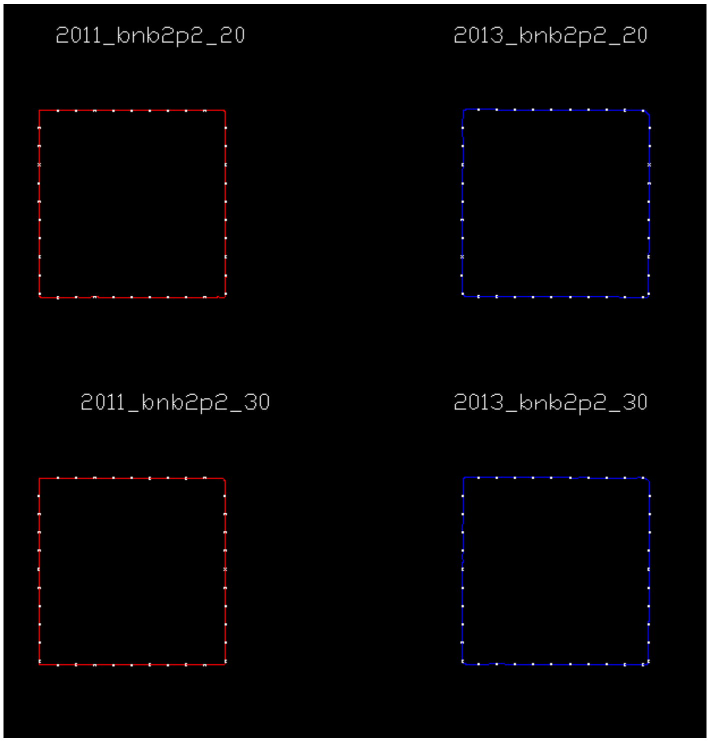

Figure Ap.5.1: Points taken at regular intervals on each cube edge which were used to calculate best-fit lines.

2011_bnb2p210 (Right Edge)

Cube Coordinates:	**X coordintates**	**Y coordintates**
	50.6741	-5
	50.6914	-10
	50.7079	-15
	50.6978	-20
	50.6901	-25
	50.7364	-30
	50.7479	-35
	50.7809	-40
	50.7975	-45
	50.7819	-50

Figure Ap.5.2: Coordinates of points on a cube edge imported into Excel for calculating best-fit lines.

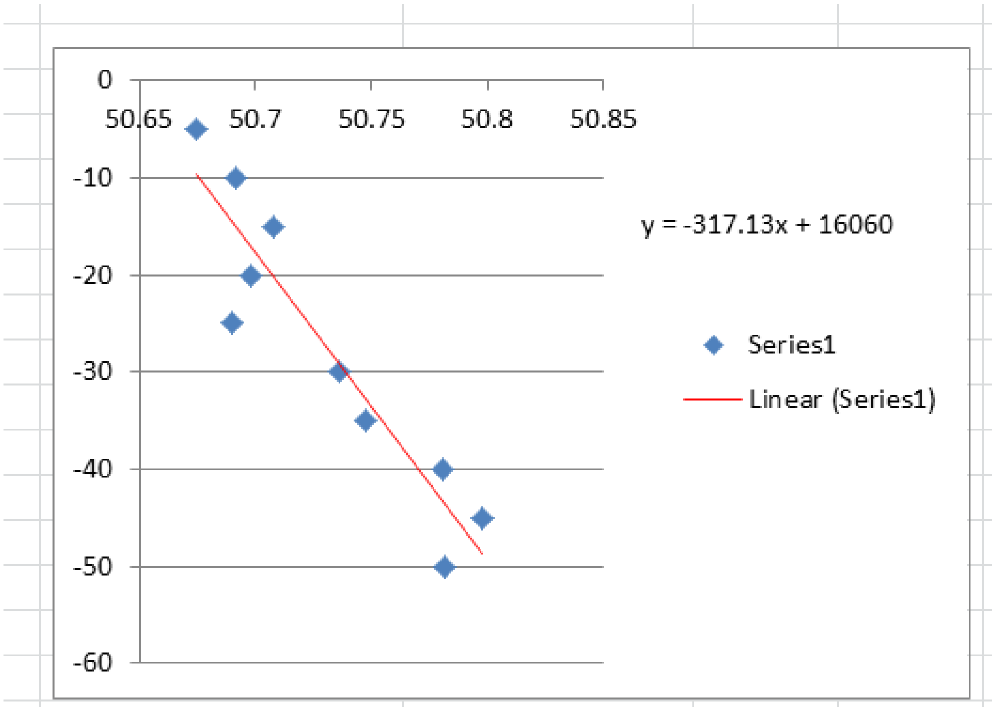

Figure Ap.5.3: Coordinates of a cube edge plotted on a graph in Excel showing best-fit line through points (trendline).

Equation of Best Fit Line:	y = -317.13x + 16060	
	-317.13	16060
Coordinates of Best Fit Line:	**X coordintates**	**Y coordintates**
	50.65745909	-5
	=(C20+-C24)/-B20	
	50.6889919	-15
	50.7047583	-20
	50.72052471	-25
	50.73629111	-30
	50.75205752	-35
	50.76782392	-40
	50.78359033	-45
	50.79935673	-50

Figure Ap.5.4: Calculation of coordinates on best-fit line using the equation of the best-fit line.

Figure Ap.5.5: Best-fit line plotted in AutoCAD (green) for irregular cube edge (red).

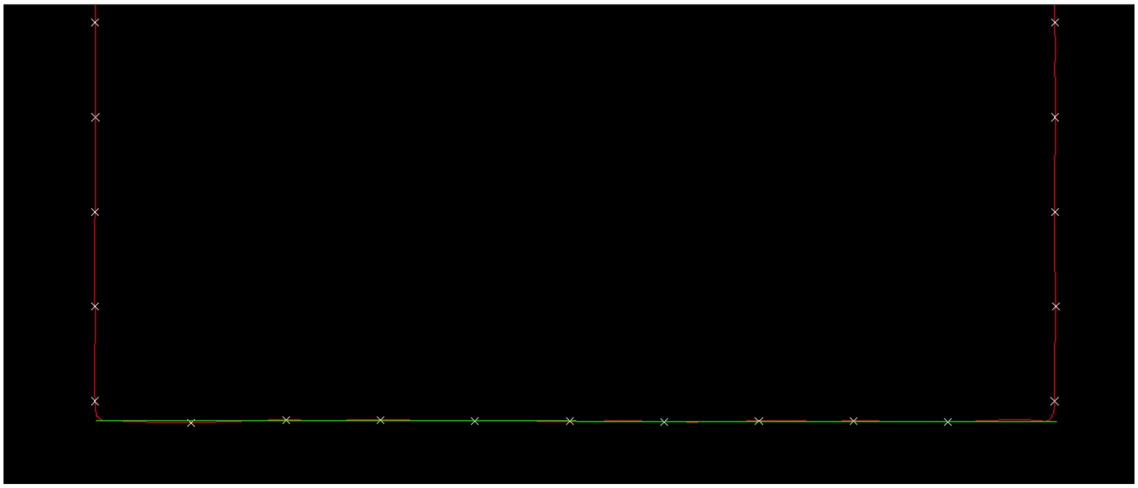

Figure Ap.5.6: Best-fit line plotted in AutoCAD (green) for irregular cube edge (red).

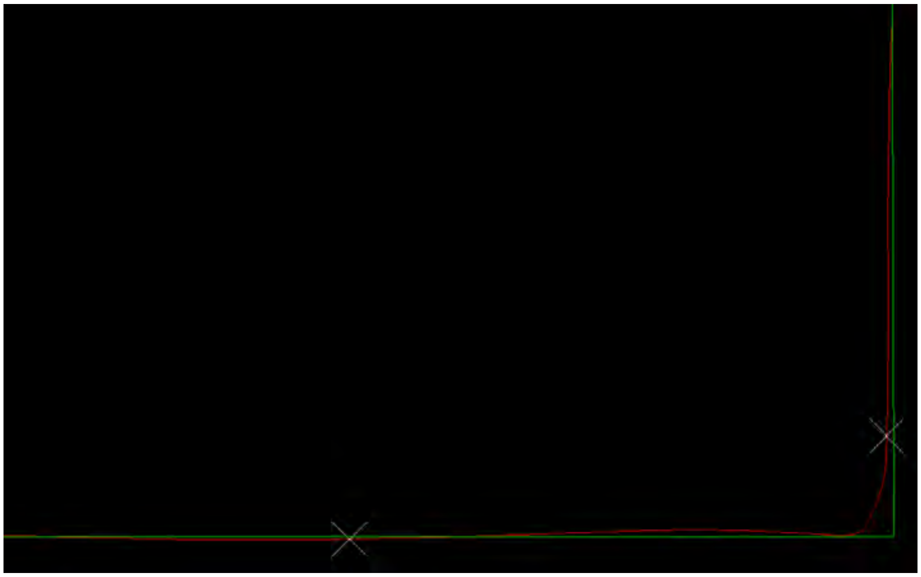

Figure Ap.5.7: Best-fit lines plotted in AutoCAD (green) for irregular cube edges (red).

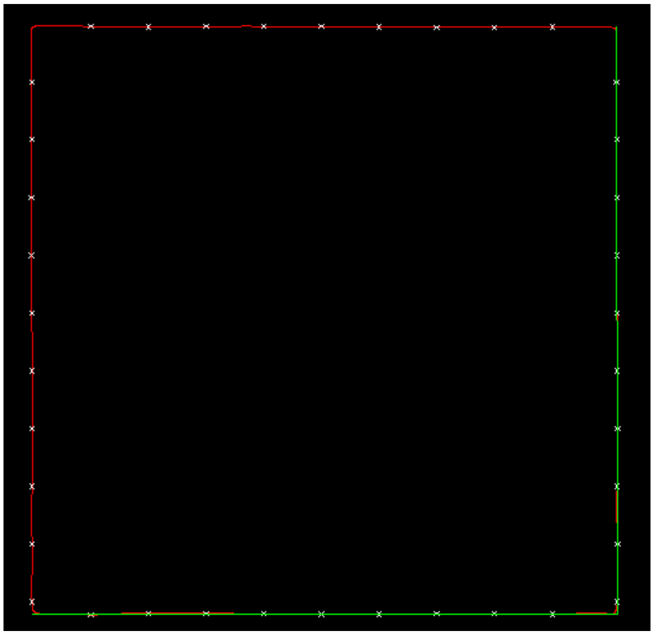

Figure Ap.5.8: Best-fit lines plotted in AutoCAD (green) for irregular cube edges (red).

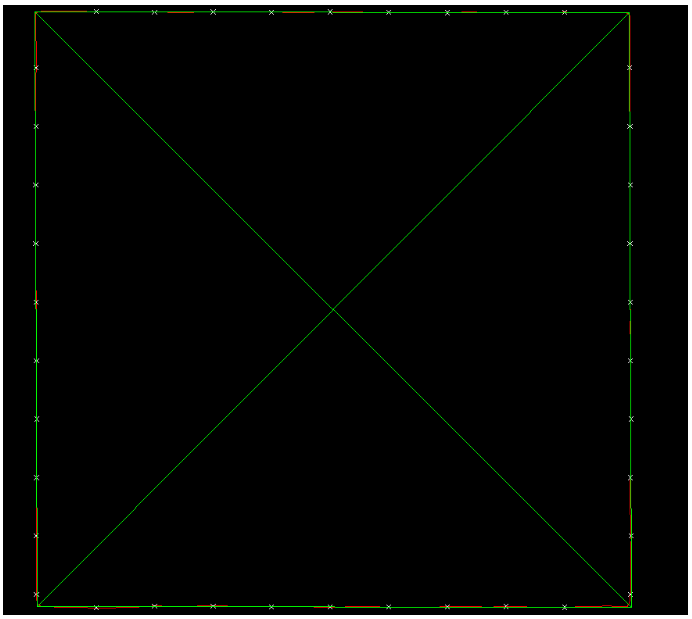

Figure Ap.5.9: Regular rectangle from best fit lines through irregular cube profile.

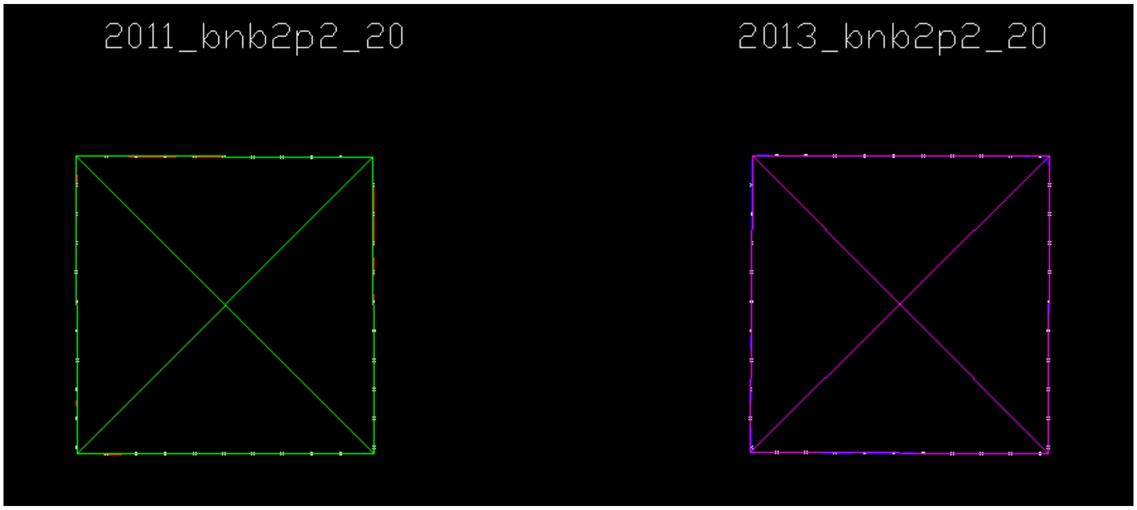

Figure Ap.5.10: Best-fit rectangles overlaid with irregular cube profiles for years 2011 and 2013.

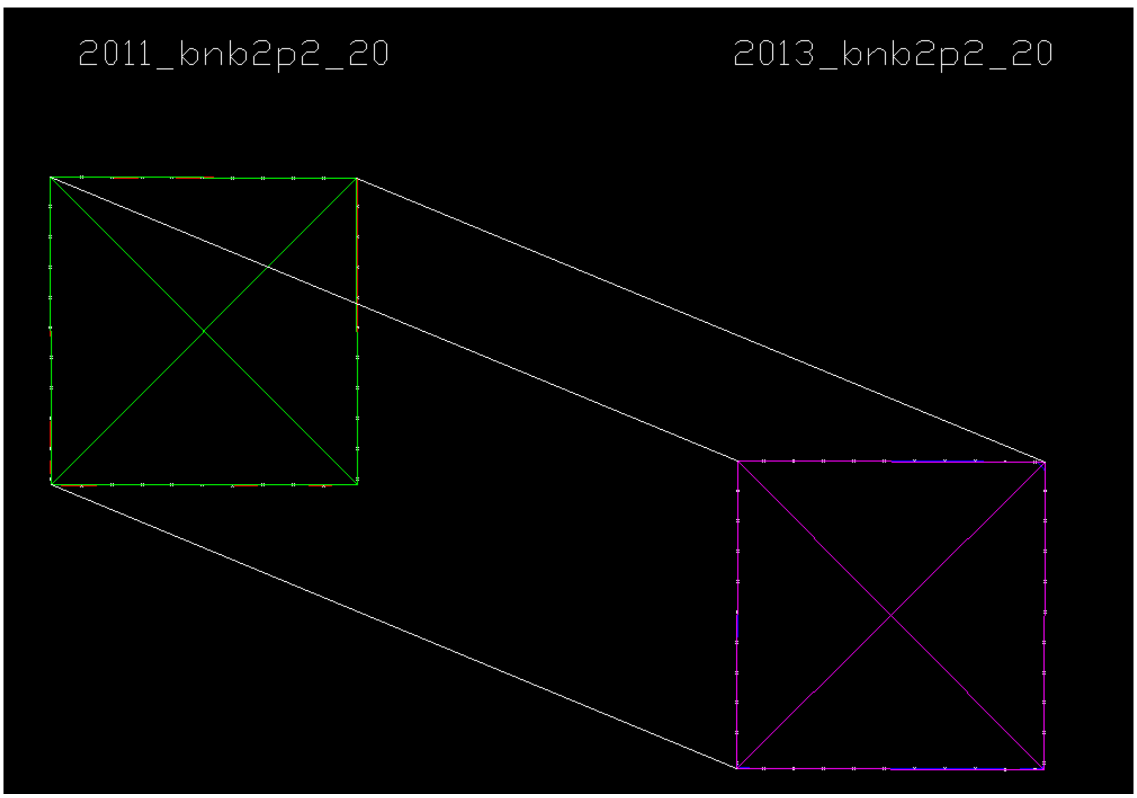

Figure Ap.5.11: Alignment of cube profile recorded in 2011 and 2013 using defined common corner points from best-fit rectangles on each.

2011_bnb2p2_45 (red) and 2013_bnb2p2_45 (blue) Overlay

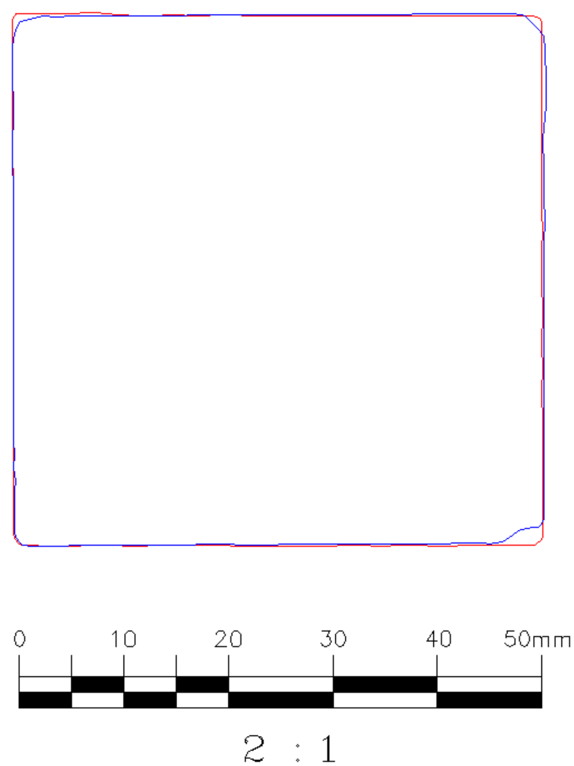

Figure Ap.5.12: Resulting alignment of cube profile recorded in 2011 and 2013 without best-fit rectangles.

APPENDIX 6.

ISSUES WITH ARCHIVING DXF DATA

In order to store the 3D scan data independent of commercial software it was decided to try and export co-ordinates for each cube profile for storage as a text file or excel document that could also be printed to hard copy for archiving. Unfortunately the process did not prove straightforward. The difficulty experienced in exporting co-ordinates from the DXF files was due to the fact that each profile is made up of line segments and arcs. For each arc segment the start and end point needs to be exported along with the centre point for the circle which defines the arc (Dore, pers. comm.). All co-ordinates can be automatically exported from CAD but without any organisation or descriptions for the points. Conor Dore suggested it would probably be impossible to redraw the cube profile again exactly in CAD with disorganised arc co-ordinates. Transferring from DXF files to a printable text format could therefore only be achieved by manually exporting the data and organising it accordingly. The table below shows an example of this for the "2011_bnb2p2_10" profile as created by Conor Dore. It contains 272 coordinates which have a number, easting, northing and description. The description specifies whether the coordinate is for a line segment, arc end point or arc centre point. These coordinates could be used to redraw the profile in CAD exactly as it is in the DXF files using lines and arcs. This process took approximately twenty minutes for one profile. Thus to transfer one set of measurements for all the LegIT cubes currently in use would take 150 hours.

Table Ap7.1. '2011_bnb2p2_10' 3D scan profile data DXF lines and arcs extracted (supplied by Conor Dore)

Point Number	Easting	Northing	Description
531	10.5441	-0.2664	line
532	12.5494	-0.2292	line
533	16.5864	-0.2483	line

534	28.8177	-0.2861	line
535	34.9192	-0.2496	line
536	36.9595	-0.2489	line
537	45.2009	-0.1714	line
538	50.6731	-4.7313	line
539	50.7081	-14.791	line
540	50.7341	-28.9821	line
541	50.748	-35.0422	line
542	50.7778	-39.0749	line
543	50.798	-45.1682	line
544	32.1395	-51.1299	line
545	36.2304	-51.0616	line
546	24.0349	-51.1493	line
547	28.0758	-51.1678	line
548	5.6457	-51.143	line
549	11.7594	-51.1127	line
550	-0.088	-36.7742	line
551	-0.1071	-40.8198	line
552	-0.0633	-30.6502	line
553	-0.1056	-34.714	line
554	-0.1141	-20.4695	line
555	-0.0373	-26.5566	line
556	-0.1235	-14.5125	line
557	-0.1553	-18.5258	line
558	10.0813	-0.2751	line
559	16.5864	-0.2483	arc endpoint
560	17.7063	-0.2604	arc endpoint
561	16.4089	-68.5567	arc centre
562	17.7063	-0.2604	arc endpoint
563	19.7368	-0.2517	arc endpoint
564	18.535	43.3667	arc centre
565	19.7368	-0.2517	arc endpoint
566	21.5291	-0.2414	arc endpoint
567	20.8699	-41.3816	arc centre
568	21.5291	-0.2414	arc endpoint
569	23.7243	-0.2458	arc endpoint
570	22.7848	78.1311	arc centre
571	23.7243	-0.2458	arc endpoint
572	26.8628	-0.2662	arc endpoint
573	24.7421	-85.1508	arc centre
574	26.8628	-0.2662	arc endpoint
575	28.8177	-0.2861	arc endpoint
576	28.5103	65.6816	arc centre
577	34.9192	-0.2496	arc endpoint

578	35.9944	-0.25	arc endpoint
579	35.4296	-76.895	arc centre
580	35.9944	-0.25	arc endpoint
581	36.9595	-0.2489	arc endpoint
582	36.4099	56.1423	arc centre
583	45.2009	-0.1714	arc endpoint
584	45.8381	-0.1844	arc endpoint
585	45.3019	-10.7833	arc centre
586	45.8382	-0.1844	arc endpoint
587	48.2053	-0.2215	arc endpoint
588	47.552	33.6908	arc centre
589	48.2053	-0.2215	arc endpoint
590	50.3651	-0.239	arc endpoint
591	48.9654	-39.684	arc centre
592	50.3651	-0.239	arc endpoint
593	50.5018	-0.3324	arc endpoint
594	49.9296	-1.0231	arc centre
595	50.5018	-0.3324	arc endpoint
596	50.5812	-0.4152	arc endpoint
597	50.1806	-0.7201	arc centre
598	50.5813	-0.4152	arc endpoint
599	50.6268	-1.1046	arc endpoint
600	42.7944	-1.2754	arc centre
601	50.6268	-1.1046	arc endpoint
602	50.6671	-3.7514	arc endpoint
603	-151.148	-5.5041	arc centre
604	50.6671	-3.7514	arc endpoint
605	50.6731	-4.7313	arc endpoint
606	-141.731	-5.4223	arc centre
607	50.7081	-14.791	arc endpoint
608	50.7045	-15.3045	arc endpoint
609	25.3167	-14.8681	arc centre
610	50.7045	-15.3045	arc endpoint
611	50.677	-18.097	arc endpoint
612	240.8437	-18.5731	arc centre
613	50.677	-18.097	arc endpoint
614	50.695	-19.8688	arc endpoint
615	120.7278	-18.2724	arc centre
616	50.6949	-19.8688	arc endpoint
617	50.7169	-21.7561	arc endpoint
618	-33.9216	-21.7978	arc centre
619	50.7169	-21.7561	arc endpoint
620	50.7031	-23.8088	arc endpoint
621	-91.2171	-21.826	arc centre

622	50.7031	-23.8088	arc endpoint
623	50.6845	-26.2646	arc endpoint
624	242.9683	-26.495	arc centre
625	50.6845	-26.2646	arc endpoint
626	50.7193	-28.237	arc endpoint
627	102.967	-26.3273	arc centre
628	50.7193	-28.237	arc endpoint
629	50.7341	-28.9821	arc endpoint
630	28.4195	-29.0522	arc centre
631	50.748	-35.0422	arc endpoint
632	50.737	-36.0719	arc endpoint
633	9.8072	-35.1209	arc centre
634	50.737	-36.0719	arc endpoint
635	50.7581	-38.2322	arc endpoint
636	83.4858	-36.8328	arc centre
637	50.7581	-38.2322	arc endpoint
638	50.7778	-39.0749	arc endpoint
639	28.9941	-39.1629	arc centre
640	50.798	-45.1682	arc endpoint
641	50.7854	-45.9992	arc endpoint
642	27.9372	-45.2369	arc centre
643	50.7854	-45.9992	arc endpoint
644	50.766	-47.8792	arc endpoint
645	91.588	-47.3607	arc centre
646	50.766	-47.8792	arc endpoint
647	50.7824	-50.627	arc endpoint
648	-153.587	-50.4749	arc centre
649	50.7824	-50.627	arc endpoint
650	50.634	-50.8802	arc endpoint
651	49.3529	-49.9591	arc centre
652	50.2181	-51.0714	arc endpoint
653	50.634	-50.8802	arc endpoint
654	49.7068	-49.4117	arc centre
655	49.9589	-51.1144	arc endpoint
656	50.2181	-51.0714	arc endpoint
657	49.9299	-50.1361	arc centre
658	47.6268	-51.1401	arc endpoint
659	49.9589	-51.1144	arc endpoint
660	48.0998	11.6819	arc centre
661	45.0483	-51.1442	arc endpoint
662	47.6268	-51.1401	arc endpoint
663	46.5624	-192.504	arc centre
664	43.6875	-51.133	arc endpoint
665	45.0484	-51.1442	arc endpoint

666	44.6645	-15.3084	arc centre
667	40.701	-51.0948	arc endpoint
668	43.6875	-51.133	arc endpoint
669	40.8747	-154.274	arc centre
670	36.7099	-51.0616	arc endpoint
671	40.701	-51.0948	arc endpoint
672	40.365	148.4686	arc centre
673	36.2304	-51.0616	arc endpoint
674	36.71	-51.0616	arc endpoint
675	36.4714	-64.095	arc centre
676	30.9405	-51.1544	arc endpoint
677	32.1395	-51.1299	arc endpoint
678	33.562	-150.228	arc centre
679	29.4842	-51.1729	arc endpoint
680	30.9404	-51.1544	arc endpoint
681	29.5355	1.9428	arc centre
682	28.0757	-51.1678	arc endpoint
683	29.4841	-51.1729	arc endpoint
684	29.7389	213.3592	arc centre
685	22.5274	-51.1369	arc endpoint
686	24.0348	-51.1493	arc endpoint
687	24.4396	89.1138	arc centre
688	18.5634	-51.1029	arc endpoint
689	22.5274	-51.1368	arc endpoint
690	17.1944	-442.284	arc centre
691	16.6424	-51.1209	arc endpoint
692	18.5634	-51.1029	arc endpoint
693	18.3022	-125.743	arc centre
694	14.9629	-51.1087	arc endpoint
695	16.6423	-51.1209	arc endpoint
696	16.0092	-22.6556	arc centre
697	12.8465	-51.0973	arc endpoint
698	14.9629	-51.1087	arc endpoint
699	13.7221	-84.8508	arc centre
700	11.7594	-51.1127	arc endpoint
701	12.8465	-51.0973	arc endpoint
702	11.6418	-4.6686	arc centre
703	4.9328	-51.1441	arc endpoint
704	5.6457	-51.143	arc endpoint
705	5.163	28.4283	arc centre
706	2.2364	-51.1211	arc endpoint
707	4.9328	-51.1441	arc endpoint
708	5.6238	187.7359	arc centre
709	0.4607	-51.0496	arc endpoint

710	2.2363	-51.1211	arc endpoint
711	2.7202	-17.002	arc centre
712	0.0771	-50.9792	arc endpoint
713	0.4607	-51.0496	arc endpoint
714	0.5729	-49.3588	arc centre
715	-0.0178	-50.4741	arc endpoint
716	0.0771	-50.9792	arc endpoint
717	1.5803	-50.4353	arc centre
718	-0.0371	-47.7572	arc endpoint
719	-0.0178	-50.4741	arc endpoint
720	79.1966	-48.5515	arc centre
721	-0.064	-45.7438	arc endpoint
722	-0.0371	-47.7572	arc endpoint
723	-43.1025	-47.3255	arc centre
724	-0.0795	-43.9783	arc endpoint
725	-0.064	-45.7438	arc endpoint
726	31.4655	-44.585	arc centre
727	-0.0957	-41.5828	arc endpoint
728	-0.0795	-43.9783	arc endpoint
729	-46.191	-43.0916	arc centre
730	-0.1071	-40.8198	arc endpoint
731	-0.0957	-41.5828	arc endpoint
732	21.4728	-40.8767	arc centre
733	-0.0986	-35.6018	arc endpoint
734	-0.088	-36.7742	arc endpoint
735	-37.602	-36.529	arc centre
736	-0.1056	-34.714	arc endpoint
737	-0.0986	-35.6018	arc endpoint
738	26.1576	-34.9527	arc centre
739	-0.0608	-29.7427	arc endpoint
740	-0.0633	-30.6502	arc endpoint
741	-51.7036	-30.0528	arc centre
742	-0.0402	-27.2564	arc endpoint
743	-0.0608	-29.7427	arc endpoint
744	87.1263	-29.2192	arc centre
745	-0.0373	-26.5566	arc endpoint
746	-0.0403	-27.2564	arc endpoint
747	-19.1116	-26.8271	arc centre
748	-0.146	-19.131	arc endpoint
749	-0.1141	-20.4695	arc endpoint
750	-55.2444	-21.1138	arc centre
751	-0.1553	-18.5258	arc endpoint
752	-0.146	-19.131	arc endpoint
753	14.5107	-18.6034	arc centre

754	-0.1282	-13.6532	arc endpoint
755	-0.1235	-14.5125	arc endpoint
756	-27.6214	-14.2337	arc centre
757	-0.1377	-11.633	arc endpoint
758	-0.1282	-13.6532	arc endpoint
759	61.5442	-12.3511	arc centre
760	-0.1333	-9.315	arc endpoint
761	-0.1377	-11.633	arc endpoint
762	-119.333	-10.2455	arc centre
763	-0.1216	-7.1827	arc endpoint
764	-0.1333	-9.315	arc endpoint
765	80.1851	-8.688	arc centre
766	-0.1495	-5.1311	arc endpoint
767	-0.1216	-7.1827	arc endpoint
768	-31.8404	-6.5881	arc centre
769	-0.1519	-3.4954	arc endpoint
770	-0.1495	-5.1311	arc endpoint
771	18.2077	-4.2871	arc centre
772	-0.166	-0.621	arc endpoint
773	-0.1519	-3.4954	arc endpoint
774	-30.0772	-2.2049	arc centre
775	-0.1418	-0.4042	arc endpoint
776	-0.166	-0.621	arc endpoint
777	0.5021	-0.5857	arc centre
778	-0.0917	-0.3008	arc endpoint
779	-0.1418	-0.4042	arc endpoint
780	0.1732	-0.493	arc centre
781	-0.0917	-0.3008	arc endpoint
782	-0.0501	-0.2605	arc endpoint
783	0.044	-0.3992	arc centre
784	-0.0501	-0.2605	arc endpoint
785	-0.0216	-0.2477	arc endpoint
786	0.0008	-0.3356	arc centre
787	-0.0216	-0.2477	arc endpoint
788	0.2744	-0.2081	arc endpoint
789	0.296	-1.495	arc centre
790	0.2744	-0.208	arc endpoint
791	2.6765	-0.2024	arc endpoint
792	1.6704	-83.5551	arc centre
793	2.6765	-0.2024	arc endpoint
794	5.0512	-0.217	arc endpoint
795	5.0862	199.4268	arc centre
796	5.0512	-0.217	arc endpoint
797	8.6923	-0.2686	arc endpoint

798	5.0285	-130.343	arc centre
799	8.6924	-0.2686	arc endpoint
800	10.0813	-0.2751	arc endpoint
801	9.5256	29.3113	arc centre