Historic England Research Report 13/2023

HARLOW CONSULTING

Approaches to Heritage Climate Change Risk Assessment: an integrative literature review

Final Report
April 2023

Clare Vokes, Jennifer Brennan, Ben Kehoe, James Legard, Ellie Moore

Historic England

Contents

Click on any line in the contents to take you to the relevant page.

The buttons at the bottom of each page will help you navigate this document. The home button will take you back to this page.

Tables and Figures

Glossary

AC	Adaptive Capacity
ALARP	As Low As Reasonably Practicable
ANH	Adapt Northern Heritage
BART	Bayesian Additive Regression Tree
BGLM	Bayesian Generalised Linear Model
BGS	British Geological Survey
BRT	Boosted Regression Tree
CCC	UK Committee on Climate Change
CE	Coastal Erosion
CERA	Coastal Erosion Risk Assessment
CF	Coastal Flooding
CHRI	Cultural Heritage Risk Index
CR	Coastline Retreat
CRV	Cultural Resource Vulnerability
CRVA	Cultural Resource Vulnerability Assessments
CVI	Climate Change Vulnerability Index
DSAS	Digital Shoreline Analysis System
ETCCDI	Expert Team on Climate Change Detection Indices
GCMs	Global Climate Models
GIS	Geographical Information System
HONO	Heart of Neolithic Orkney
HES	Historic Environment Scotland
ICCROM	International Centre for the Study of the Preservation and Restoration of Cultural Property
ICOMOS	International Council on Monuments and Sites
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
LCA	Landscape Character Areas
LCF	Landscape Character Features
MENA	Middle East and North Africa
MIVES	Integrated Value Model for Sustainability Assessment
MV	Measure of Vulnerability
NPS	National Parks Service
NRAP	Northern Rockies Adaptation Partnership
OLI	Operational Land Imager
OUV	Outstanding Universal Value
PIC	Properties in Care
RCMs	Regional Climate Models
RCP	Representative Concentration Pathways
RMP	Risk Management Process
SEPA	Scottish Environment Protection Agency
SLR	Sea Level Rise
SMART	Specific, Measurable, Achievable, Realistic, and Timely
STORM	Safeguarding Cultural Heritage through Technical and Organisational Resources Management
UNDRR	United Nations Office for Disaster Risk Reduction
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
VA	Vulnerability Assessment
VR	Vulnerability Rating
WHS	World Heritage Sites

Executive Summary

Background, aims and objectives

Heritage assets are under considerable threat from climate change. Risk assessment methodologies provide an important first step in identifying the nature and extent of climate change impacts and in defining appropriate adaptation strategies. However, there is as yet no agreed method of quantifying the risks posed by climate change to heritage assets either for England or internationally.

Historic England (HE), as part of its Climate Change Strategy is seeking to address this gap by establishing a methodology for assessing the risks to heritage assets posed by climate change. To inform the development of HE's risk assessment methodology, HE has commissioned an integrative literature review of English-language research related to the quantification of climate change risk to heritage assets.

The overall aim of the project is to identify whether there are current approaches to climate –change- related heritage risk assessment that are potentially appropriate for use in England.

Specific objectives that need to be met in order to realise the project aims are to:

i. search for current practices in climate change-related risk assessment from around the world;

ii. critically appraise and report on examples of practice in other countries for their applicability to heritage management in England;

iii. recommend any approaches that HE should consider adopting (with or without modifications), with any necessary caveats.

This research project will provide HE with much needed, up-to-date intelligence that will assist it in developing a robust approach to assessing climate change risks to heritage assets in England.

Methodology

A search strategy was developed which consisted of the following stages:

- Review and citation searching of existing literature reviews and meta-analyses on the topic of climate-related risk assessment methods for heritage assets.
- Conduct a series of targeted literature searches. Search terms were developed and open, wildcard and Boolean searches[1] were conducted to ensure the fullest range of possible hits.
- Review of the websites of national and international heritage organisations to identify any additional academic or 'grey' literature[2] not discovered through open searches.

The search strategy identified 500 sources which were collated into a master bibliographic spreadsheet. From this initial list of 500 documents, a process of source moderation was undertaken to identify a core of 116 academic and grey literature articles which proposed or described a process for assessing climate change risks to heritage assets.

The core articles were analysed using a bespoke 'analysis spreadsheet', which was used to map each source against the requirements of the most current approach to climate change risk assessment outlined by the Intergovernmental Panel on Climate Change (IPCC). By assessing each source against IPCC criteria, an understanding of the overall scope and completeness of each risk assessment methodology was developed. The results of this analysis process enabled the identification of the more comprehensive approaches to climate change risk assessment and those which may be more relevant to a UK heritage context.

1. Boolean searches involve the combination of single words and phrases using predefined operators to limit, broaden or define a search. The most common Boolean operators are AND, OR and NOT.

2. Grey literature refers to documents not produced by commercial publishers. This may include research reports, policy documents, white papers, guidelines, unpublished theses but it excludes academic articles.

Climate change risk assessments

Background research was carried out into current approaches to climate change risk assessments, used by organisations such as IPCC and the UK Committee on Climate Change (CCC). This provided the theoretical grounding in the foundational concepts of climate change risk assessments, which informed an analysis and critical appraisal of the methodologies identified.

The basic conceptual framework for climate change risk assessment has become relatively standardised. A typical approach, proposed by IPCC, is to quantify risk as the result of an interaction between three key determinants of risk: hazard, vulnerability and exposure.

Hazard is understood broadly as an event or occurrence which has the potential to cause harm to people, infrastructure and other assets.

Exposure is typically defined as the situation or location of people, infrastructure or other assets in a setting which could be affected by a hazard.

Vulnerability is a complex concept which encompasses two key aspects: 'sensitivity' and 'adaptive capacity':

- 'Sensitivity' refers to the susceptibility of a system to harm when exposed to the effects of a hazard, which influences the probability of damage occurring within the system.
- 'Adaptive capacity' refers to the qualities within a system that enables it to respond to change, maintain its functions and adapt to hazards.

This review analyses heritage-specific risk assessment frameworks through the lens of these concepts. This principally involves assessing whether climate change risk assessments for heritage make use of the IPCC's hazard-exposure-vulnerability framework for quantifying risk. However, this review also explores the extent to which heritage risk assessments consider the functions which underpin vulnerability, namely the sensitivity and adaptive capacity of a site.

Summary of main findings

Comprehensive approaches

The methodologies which propose the most comprehensive strategies for assessing climate change risks to heritage assets are those which employ the IPCC's hazard-exposure-vulnerability framework, but which also drill down into the components which underpin vulnerability (exploring a site's sensitivity and adaptive capacity), as well as taking into consideration the significance of heritage assets. These methodologies are generally based on individual sites (or a small selection of sites) and data collection methods typically involve engagement with stakeholders who are familiar with the specific site (site managers, local experts, the wider community of heritage users) as well as field studies and site observations.

Examples of this approach are the **STORM Risk Assessment and Management Tool**, the **Climate Vulnerability Index (CVI)** and the **US National Parks Service's (NPS) Cultural Resource Vulnerability Assessments (CRVAs)**.

The main disadvantage with these more comprehensive approaches is that they are difficult to scale up to collect data covering multiple sites over a larger geographic region. In all cases, these methodologies tend to use co-production methods to draw upon the knowledge and insights of local experts and stakeholders. While the use of local stakeholder input is undoubtedly a strength in acquiring a holistic view of risk, methodologies which are dependent on local stakeholder involvement are resource intensive and are difficult to scale beyond a small selection of sites.

'Less comprehensive' approaches

Generally, climate change risk assessments which attempt to cover a wider geographic scale – or which attempt to quantify risk for a wider range of heritage assets – often fail to fully integrate all of the determinants of risk which form part of the IPCC's framework. This review identified a number of climate change risk assessment methodologies which attempt to cover multiple sites over a wide geographic area, but which do not fully integrate the three standard determinants of risk (hazard, exposure, vulnerability). Usually, this is because insufficient consideration is given to the functions of vulnerability, most typically omitting considerations of a site's adaptive capacity.

Examples of methodologies which fall into this category are:

- Carmichael et al.'s, (2017) practical climate change risk analysis methodology designed for rangers and managers of cultural and archaeological sites in two national parks in Northern Australia.
- Cook et al.'s (2021) 'Landscape Vulnerability Framework', which assesses the vulnerability of archaeological heritage by situating archaeological sites within the context of their historic landscape.
- García Sánchez et al.'s (2020) proposed risk assessment methodology for multiple heritage coastal fortifications threatened by sea level rise in the Canary Islands.

Impact and hazard modelling

By far, the most common methodological approach to assessing and identifying heritage sites at risk is hazard modelling. This approach involves combining secondary data derived from climate change projection modelling (or historical data on climate-change related hazards) and geospatial data on heritage assets to model specific climate-related hazards and map them to the locations of heritage assets to identify heritage sites most threatened by climate change.

The advantage with these large-scale, data driven approaches is that they enable multiple climate change hazards to be easily studied over a wide geographical area (although in practice few of them look at multi-hazards). However, these approaches often fail to capture the granular, site-specific information – such as the condition of specific sites, the materials used, the financial and management resources available at site level – which are needed to carry out assessments of vulnerability and adaptive capacity.

This review did not identify a methodology which successfully leverages granular data about site vulnerability, capacity or significance for multiple sites over a large geographic area. As such, a suitable methodology for assessing climate change risks to multiple heritage assets over a wide geographical area was not found.

Conclusions and recommendations

Although this review has identified a number of well-developed climate change risk assessment methodologies for heritage assets, there does not appear to be a single, 'off-the-shelf' solution that can be easily adopted to meet Historic England's need for a robust, nationwide risk assessment.

While it may in theory be possible to combine the best features of several approaches – for instance, using a sampling approach to leverage more granular data on site vulnerability to enhance large-scale hazard mapping approaches – conceptual inconsistencies in the ways key determinants of risk have been used and defined make this process challenging.

Although the basic definitions of the three standard determinants of risk may seem clear enough in principle, once applied to practical risk assessment there are often significant implicit or explicit differences in the way that the terms are used or the boundaries drawn between them. These issues are particularly evident at the borderlines between hazard and exposure and between exposure and vulnerability, and in the precise definition and application of vulnerability.

A related problem is the lack of clear consensus over how to define and incorporate estimates of significance into the risk assessment process, as well as the practical difficulty of mapping significance in a way that can interact effectively with hazard distribution.

Given the implicit differences in the ways key concepts of risk have been used and applied across different risk assessment methodologies, it is recommended that further research be conducted. Specifically, what is recommended is the development of an appropriate concept model that clearly maps out all of the basic phenomena which underpin the principal concepts of risk.

There are likely two basic approaches to achieving this concept model. These can be described as 'top-down' modelling and 'bottom-up modelling':

- **Top-down modelling** involves starting with the broadest possible concepts and breaking them down into more basic, constituent phenomena. This approach would be particularly useful in appraising the existing IPCC risk framework and disaggregating the IPCC determinants of risk into more basic elements and underlying phenomena.
- **Bottom-up modelling** involves working upwards from the basic physical and socio-economic phenomena to develop complementary higher-level categories. The aim should then be to group the basic phenomena into higher-level classifications which represent the lower-level phenomena as completely as possible.

The two approaches should ideally be conducted simultaneously and iteratively, so that they can be used to cross-check each other, until they generate convergent results.

This concept model can then be mapped back against the existing literature to facilitate a like-for-like comparison of methodologies, enabling a judgement to be made about whether any single methodological approach is adequate. This process will also enable identification of the most significant gaps in the existing literature about climate change risk assessments in a heritage context.

The general principle is that the closer the research and modelling is to the fundamental physical and socio-economic phenomena involved, the less dependent it will be on having an adequate high-level conceptual framework in place.

In sum, therefore, the optimal way forward would seem to be establishing a number of research strands that feed into, challenge and refine each other iteratively, until their approaches and findings become fully convergent and complementary. Multi-strand research of this kind may also make it easier to identify overlaps in specific areas of research and modelling with other research agendas (potentially external to HE), opening the way to collaborative research with other agencies and institutions, leading to potential efficiencies of time and resource.

Introduction

Introduction

1.1 Project background

The UK heritage sector plays an important role in promoting climate and environmental resilience. In particular, the heritage sector can make a significant contribution to the Government's Net Zero Strategy through promoting the reuse and retrofit of old and traditional buildings, which can lead to reductions in operational carbon emissions of up to 84% (Historic England, 2021). Equally, historic parks and gardens play an important role in maintaining biodiversity and in enhancing environmental resilience, (Living with Environmental Change, 2016) while heritage spaces in general have the power to enhance personal wellbeing and promote good mental health (Historic England, 2020).

However, heritage assets themselves are under considerable threat from climate change. The hazards created by the UK's changing climate are many and varied and can impact different types of heritage assets in different ways. Historic and traditional buildings can be vulnerable to more extreme weather conditions, especially where such conditions encounter weaknesses in the building fabric, such as gaps in roofing, or where traditional approaches to design and choice of materials did not take into account the need to withstand such conditions. For instance, increased precipitation could lead to saturation of soils and overloading of gutters and downpipes, leading to a higher risk of moisture penetration through the building envelope, including masonry walls. Extreme fluctuations in weather are likely to lead to more severe freeze-thaw cycles, which can damage permeable materials and contribute to the disintegration of stone, brick and ceramic materials. More intense cycles of wetting and drying can also have serious structural implications for traditional buildings, caused by expansion and contraction of ground under foundations, particularly on clay soils (Sesana, E., et al, 2021). Warmer conditions, more intense precipitation and milder winters may also lead – both in themselves and as a secondary result of moisture penetration due to inadequate water handling – to increased risk of fungal and insect attack from both native and invasive species, with the latter themselves likely to become more numerous and problematic as a result of climate change.

Historic gardens and landscapes are also likely to experience negative impacts of climate change. Hotter and drier conditions are likely to stress native flora and fauna while also encouraging the spread of invasive plant and animal species. While this may create opportunities for the introduction of new crops, it also risks altering the traditional character of heritage parks and gardens, which are an important part of these assets' appeal (Bisgrove, R., Hadley, P., 2002). Indeed, climate change is already having an impact on England's heritage gardens. In January 2023, it was announced that the royal lawn at Sandringham would be replaced by a 'biodiverse garden' with species that are better able to withstand the impact of changing weather patterns. This is in response to the impact of warmer weather and excessive rainfall on the current expanse of lawn (BBC, 2023).

Increases in the frequency of extreme weather events, as well as catastrophic changes in the natural environment, such as flooding and rising sea levels, also present risks to heritage assets. Flooding is recognised as a risk to both coastal and inland heritage assets[3], and in 2011 around 70% of English Heritage Trust sites located in coastal zones were deemed to be at risk of coastal erosion (Hunt, A, 2011). Human responses to climate change can also introduce risks to heritage assets. For instance, while property-based flood defences may help to minimise flood damage to buildings, physical barriers may impact on their character. In some cases, flood damage responses promoted by insurance companies and contractors can affect the historic fabric by decreasing the fabric's ability to manage moisture and even breach listed building legislation (for example through unauthorised removal of flood-damaged timber or plaster) (Historic England, 2015).

Risk assessments provide an important first step in identifying more closely the nature and extent of the challenge posed by climate change. They are also the indispensable foundation for defining appropriate and effective climate change adaptation strategies. However, there is as yet no agreed method of quantifying the risks posed by climate change to heritage assets either in England or internationally. Cultural heritage value is largely overlooked by conventional climate-related risk assessments: in the third UK Climate Change Risk Assessment Report risks to cultural heritage are described as an area for which 'more action is needed', while the potential costs and damages associated with cultural heritage risks are denoted as 'not known' (H.M Government, 2022). According to a recent literature review, risk assessment tools that incorporate heritage are generally developed on a project-by-project basis, while academic research into risk assessment methodologies relating to cultural heritage is exceptionally limited (Crowley et al., 2022). The relatively small number of papers published on the topic have also been criticised for failing to draw on community-based knowledge, experience and values (Crowley et al., 2022).

Historic England (HE), as part of its Climate Change Strategy (Historic England, 2022a), is seeking to address this gap through its commitment to developing effective ways of quantifying climate-related risks to heritage assets. The establishment of a robust methodology for assessing the risk to heritage assets from climate change will serve to enhance HE's understanding of the threats to heritage assets – posed not only by climate change itself but by the human attempts to manage its consequences – enabling HE to ensure that risks to cultural heritage are fully accounted for in the fourth UK Climate Change Risk Assessment Report.

To inform the development of HE's risk assessment methodology, HE has commissioned an integrative literature review of English-language research related to the quantification of risk to heritage assets. The purpose of this research is to identify and critically appraise any recent evidence or existing methodologies relevant to assessing climate-related risks to heritage assets, which may have been developed by heritage professionals or organisations in other countries.

3. In 2013, 41 of Historic England's 362 inland estates were considered to be 'at high risk of flooding', with a further 20 at 'medium risk'. T. Pearson, (2013), English Heritage inland estate flood risk assessment (English Heritage).

1.2 Aims and objectives

The overall aim of the project is to identify whether there are accessible, current approaches to climate-change related heritage risk assessment that are potentially appropriate for use in England.

The objectives that need to be met in order to realise the project aims as completely as possible are to:

ii. search for current practices in climate change-related risk assessment from around the world;

iii. critically appraise and report on examples of practice in other countries for their applicability to heritage management in England.

iv. recommend any approaches that Historic England should consider adopting (with or without modifications), with any necessary caveats.

This research project will provide HE with much needed, up-to-date intelligence that will assist it in developing a robust approach to assessing climate change risks to heritage assets in England. The development of this risk assessment approach has important implications both for HE's actions in tackling climate change, but also in protecting places of cultural significance. The risk assessment methodology will allow HE to acquire a better understanding of the 'vulnerabilities, hazards and risks of harm to the historic environment' due to climate change and enable it to 'identify appropriate mitigations', strategic activities to which it is committed in its Corporate Plan (Historic England, 2022b).

The risk assessment methodology will also act as a useful tool for the broad range of individuals and organisations who are responsible for caring for England's heritage, providing heritage managers with the knowledge and information they need to make the decisions and preventative actions to manage, mitigate and adapt to the risks presented by climate change.

In this way, the development of the risk assessment methodology supports the third strand of HE's Climate Change Strategy, 'Adaptation', principally by helping to establish a toolkit that *'equips those who care for our heritage to plan for and manage decisions where some loss of, or transformative change to, heritage assets is unavoidable.'*

This research project therefore serves an important role in supporting HE in its actions to tackle the climate crisis, while at the same time providing the knowledge and information needed to protect places of heritage significance.

1.3 Scope

A key objective of the project was to identify as many relevant studies as possible published in the English language in the last 10 years – i.e., 2012 onwards.

The research focuses primarily on approaches to quantifying climate change risks to heritage assets. This review, therefore, considers only literature that sets out formal risk assessment processes, including approaches that are quantitative or semi-quantitative in emphasis; more generalised discussions of climate change threats have been excluded.

The term 'heritage asset' for this research comprises:

- buildings;
- ancient monuments;
- parks and gardens;
- battlefields; and
- wrecks.

For the purpose of this research, the following are out of scope:

- Conservation Areas;
- moveable heritage e.g., ships, aircraft, locomotives;
- museum and archival collections; and
- Intangible heritage.

1.4 Methodology

To ensure the most comprehensive coverage of the literature, we have not limited the literature search to a list of countries of interest. However, particular emphasis has been given to countries with a significance-led approach to heritage conservation, such as Australia and New Zealand. These countries adopt a significance-led approach, developed through the work of J. S. Kerr, 2013 on conservation planning. Priority was also given to countries which, like England, have substantial coastal heritage assets, such as the Netherlands and Denmark, but also Ireland, Scotland and Wales.

Included in scope for the literature search were:

- Academic literature: peer-reviewed journal articles, conference presentations; PhD theses/ dissertations;
- Existing climate change-related risk assessment methodologies;
- Government publications, reports and policy papers; and
- Evaluations and research reports by relevant heritage organisations.

The following were excluded:

- presentations and posters; and
- other media.

Background Research

The first stage was to undertake background research into two important elements of the research:

1. Risk assessment methods

2. Climate change hazards

The purpose of this stage was to build a firm understanding of these important aspects of the subject, both to assist the identification of relevant search terms and to provide a basis for the critical appraisal of the risk assessment methodologies identified in the literature.

The first stage of the background research was to develop a fuller understanding of current best practice in climate change risk assessment methodologies. This was achieved by reviewing recent literature on climate change risk assessments as well as the approaches of the Intergovernmental Panel on Climate Change (IPCC) and the UK Committee on Climate Change (CCC), to get a sense of the foundational concepts in climate change risk assessments (including risk, hazard/threat, severity, likelihood, exposure, vulnerability, impact, and resilience). A review of wider literature on climate change risk assessments was also undertaken to examine principal typologies (e.g., qualitative, quantitative, matrix-based, etc.), media and methods (including software, specialist equipment and monitoring, etc.), and typical data sources used. This initial research informed the development of keyword searches.

Subsequently, a typology was compiled of the different hazards posed by climate change to heritage assets. These hazards may include those associated with the action of weather conditions (such as precipitation or extreme temperature fluctuations) as well as those resulting from changes in the natural physical environment, both sudden (storm surges, floods, wildfire) and gradual (coastal erosion, permafrost thawing and changes in the properties of the oceans). Anthropogenic threats and hazards resulting from human responses to climate change have also been considered.

A review of recently published academic literature on climate change impacts to cultural heritage assets was undertaken to establish an initial, indicative list of the potential hazards associated with a changing climate which impact on heritage assets. Time constraints meant that this review was necessarily quite brief, and this list was compiled using the hazards identified in Sesana et al, (2021) and Orr et al., (2020) and consisted of:

- Temperature change
- Humidity
- Precipitation

- Wind
- Flooding (coastal)
- Flooding (general)
- Sea level rise
- Coastal erosion
- Storms
- Droughts/extreme heat
- Changes to ocean properties
- Slope instability and landslides
- Soil erosion

This list was not definitive and was used only to guide initial searches. As searches progressed, different risk assessment methodologies, addressing different kinds of climate-related hazards (wildfire, insect activity, solar radiation), were identified and incorporated into the review.
No hazards were specifically precluded from the review. The only exceptions to this were assessments focused solely on permafrost thawing, as this hazard was deemed to have limited direct impact on the UK climate (beyond indirect impacts associated with sea level rise and changing ocean properties).

Search Strategy

To ensure a comprehensive search which identified as much relevant, practicably accessible literature on the topic as possible, the search strategy employed a systematic, staged approach.

The first stage involved the identification, collation and review of existing literature reviews and meta-analyses on, or closely related to, the topic of climate-related risk assessment methods for heritage assets. Citation searches through bibliographies of these existing relevant literature reviews informed the development of a core list of references.

The second stage of the search strategy involved a series of targeted searches focused on literature relevant to the topic, to identify any research papers not cited in pre-existing literature reviews. A search grid (Table 1) was developed and used to combine terms for the three main groups of search terms (cultural heritage; risk assessments, climate change).

Table 1: Search terms

Term 1 Cultural heritage – synonyms and types	Term 2 Risk assessment – synonyms	Term 3 Climate change – synonyms
Primary search terms		
Heritage Cultur* Natur* heritage Monument Building Ruin Archaeologic* Wreck Marine Designed landscape Park Garden	Risk Assess* Assess* AND: Resilien* Vulner* Threat Hazard map*	Climate change Climate crisis Global warming Global heating Changing climate Environmental crisis

Open, wildcard and Boolean search terms were used in combination to ensure the fullest range of possible hits. Standard search engines (Google, Google Scholar) were deployed. Snowballing searches (sifting bibliographies and citations within works) then identified any further publications or literature relevant to the topic of assessing climate-related risks to heritage assets that had been drawn upon by previous authors in the field.

The third stage of the search strategy involved a review of the websites of relevant national and international heritage organisations, agencies and institutions with an interest in climate change and cultural heritage. The purpose of this third stage was to identify any relevant 'grey' literature which may not have been discovered through open and snowballing searches in stages one and two.
Priority was given to organisations which advocate a significance-based approach to heritage, including (but not limited to) the International Council on Monuments and Sites (ICOMOS), the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM), UNESCO and War Memorials Trust.

Source moderation

The search strategy identified 500 sources which were collated into a master bibliographic spreadsheet.

From this initial list of 500 documents, a process of source moderation was undertaken to identify a core of 116 academic and grey literature articles which proposed or described a process for assessing climate change risks to heritage assets. The first stage in source moderation was the removal of duplicate sources (112). Screening was then carried out on the remaining 388 sources. This involved reviewing the abstracts of the remaining sources to identify those most directly relevant to the research questions. Following the review of abstracts, 272 sources were excluded as not directly relevant. **Sources excluded at this point included:**

- Articles which did not explicitly discuss a methodology for assessing or quantifying risk. This included literature which focused only on monitoring climate change impacts on heritage assets, as well as articles which proposed broad stages for setting out risk evaluation processes.
- Articles which did not specifically address cultural heritage. This included sources which were more concerned with assessing the risk posed by climate change to natural systems (e.g., coral reefs, glaciers, woodland) or those more focused on the built environment in a more general sense (with no focus on heritage assets).
- Articles not specifically linked to climate change impacts, including those concerned solely with non-climate related natural disasters, such as volcanic or seismic activity.

Following screening and the process of eliminating articles which were not relevant to the project, a core of 116 main articles were identified and included in the review.

The process for source moderation is set out Figure 1.

Figure 1: Process for source moderation

Analysis and critical appraisal of sources

The process for analysing and critically appraising the risk assessment frameworks identified through the search strategy was informed by background research on current best practice in climate change risk assessment methodologies.

An 'analysis spreadsheet' was developed and used to map each source against the requirements of the IPCC's most current approach to climate change risk assessment. The IPCC's framework was chosen as the benchmark against which to map each risk assessment methodology, as this is the international standard for climate change risk assessment. Each source was examined to identify whether risk was quantified on the basis of the three standard determinants of risk – hazard, exposure, vulnerability used by the IPCC framework prior to 2022 (a discussion of the determinants of risk used in the IPCC framework is included in section 2.1) – as well as whether adaptive capacity was considered as part of the risk assessment framework. Adaptive capacity in the IPCC framework is a component of vulnerability, but is given separate consideration in a number of well-developed risk assessment approaches, in several cases after vulnerability has been assessed in more narrowly physical terms. In addition, consideration was also given to the extent to which the impact of human responses to climate change was explored, as this theme is now considered such an important potential source of problems that it has been included in the IPCC as a fourth determinant ("response") of risk since 2022, as well as to whether the methodology incorporated consideration of heritage significance in its assessment of risk.

The spreadsheet also recorded factual and thematic data about each source, including the data gathering methods used by each methodology; the heritage assets the methodology applied to; the climate change hazards it encompassed and the country in which it was developed and implemented.

Assessment of each source against the criteria outlined above informed an assessment of the overall scope and completeness of each risk assessment methodology. This analysis spreadsheet was then used as a basis for analysing each source in a consistent manner to determine how each method calculated and quantified risk (i.e., on the basis of all three determinants of risk plus adaptive capacity, or on the basis of just two or one), and whether heritage significance was considered. The results of this analysis process enabled identification of the more comprehensive approaches to climate change risk assessment. It also enabled an identification of those which may be more relevant to a UK heritage context, in part by informing an understanding of how significance is understood and assessed in each methodology. This process of analysis and critical appraisal, therefore, formed the basis of reporting and recommendations.

Climate change risk assessments and heritage: Key concepts

2.1. Climate change risk assessments

2.1.1 Current models and approaches

Risk assessments for climate change take many forms and make use of many different methodologies.

However, the basic conceptual framework for risk assessment has become relatively standardised. For example, a typical approach – and one used by organisations such as the Intergovernmental Panel on Climate Change (IPCC) and the UK Committee on Climate Change (CCC) – is to quantify risk as the result of an interaction between three key determinants of risk: hazard, vulnerability and exposure.

In their fifth climate change assessment report (AR5), the IPCC devised a risk framework which explicitly defines risk as a function of the interaction of hazard, vulnerability and exposure (in previous reports, exposure has been considered a component of vulnerability).

The Third UK Climate Change Risk Assessment (CCRA3) Report uses a methodology for quantifying climate change risk which is based on the IPCC's hazard-exposure-vulnerability framework.

Figure 2: AR5 IPCC Risk Framework

Taken from Simpson et al, (2022), ICSM CHC White Paper II

CCRA3 uses the IPCC framework to assess and assign magnitude scores for both present-day and future climate-related risks. Future risk scores are assigned for two time periods associated with the mid-century (2050s) and late-century (2080s), and for two scenarios, broadly consistent with 2°C and 4°C warming by the end of the century. Quantitative and qualitative evidence is gathered to assesses how vulnerability, exposure and hazards affect both current and future risks (Watkiss and Betts, 2021). Each key risk determinant will now be defined.

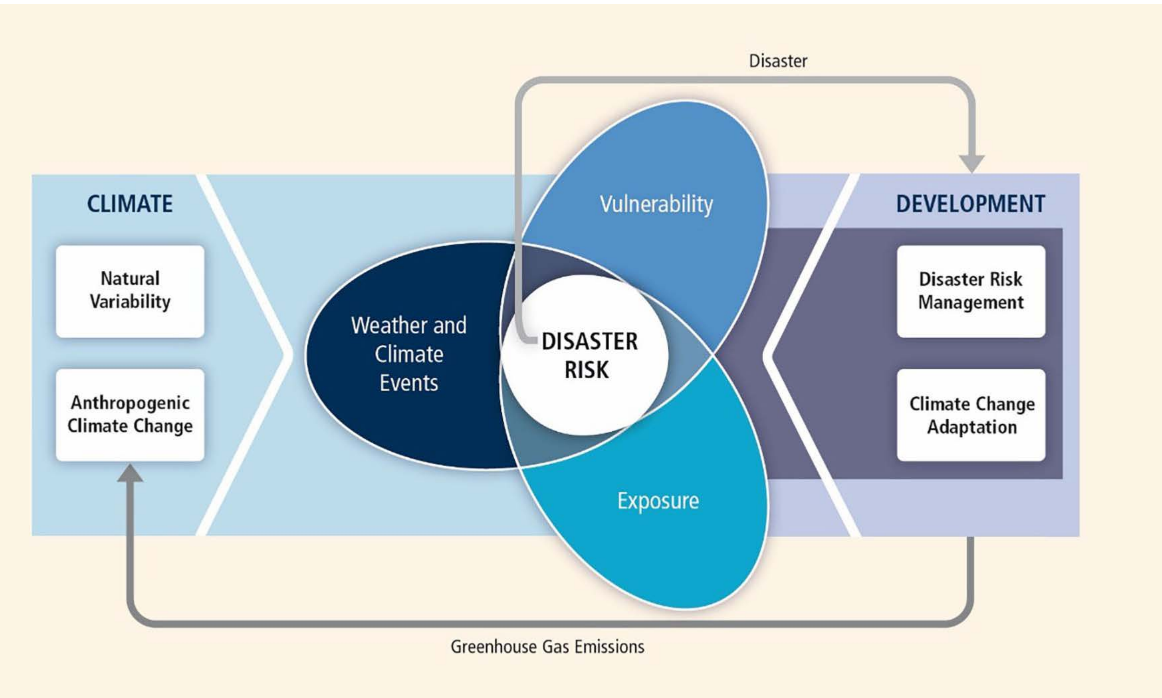


Figure 3: CCRA3 framework for quantifying risk

Source: IPCC, (2012), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Summary for Policymakers

Hazard

Hazard is understood broadly as an event or occurrence which has the potential to cause harm to people, infrastructure and other assets.

According to the IPCC, a 'hazard' is defined as *'The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.'* (IPCC, 2022a) This definition is also used in CCRA3.

Similarly, the United Nations Office for Disaster Risk Reduction defines hazard as *'A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.'* (UNDRR, 2021)

Exposure

Exposure is typically defined as the situation or location of people, infrastructure or other assets in a setting which could be affected by a hazard.

According to the IPCC, the term refers to: *'The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.'* (IPCC, 2022a) This definition is also used in CCRA3.

According to UNDRR, 'exposure' can be understood as *'the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas.'* (UNDRR, 2021). This slightly more complex definition considers 'situation' as well as 'location'. An annotation clarifies that assessing exposure may involve considering the number or types of the assets exposed to a hazard. The connection between these factors, and the degree of exposure, is clear enough in practice: if a million people live in an earthquake prone area, the exposure is greater than if there are just ten people; if you have a nuclear power station near a volcano there is more at stake than if there is a hydroelectric plant.

In literature published by heritage organisations about climate change, 'exposure' is often understood in this more wide-ranging way, for example as *'the proximity and sensitivity of attributes affecting the value of heritage. Exposure can be represented by several types of evidence: protected status (with accompanying description), databases or registries (including metadata), and local or Indigenous understanding.'* (Simpson et al, 2022).

Vulnerability

'Vulnerability' is a complex concept which is key to the characterisation of risk. According to the IPCC, vulnerability can be understood as *'the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm a nd lack of capacity to cope and adapt'* (IPCC, 2022a).

This definition is also used in CCRA3.

There are, therefore, two main aspects which underpin the concept of vulnerability:

- The 'sensitivity' of a system to the harmful effects of a hazard, and
- The 'capacity' of a system to cope with or adapt to the adverse effects of climate change.

(Quesada-Ganuza et al., 2021)

'Sensitivity' is defined as *'The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change.'* (IPCC, 2022a) 'Sensitivity' therefore refers to the susceptibility of a system when exposed to a hazard, which influences the probability of damage or other change occurring within the system.

'Adaptive capacity', on the other hand, is defined as *'the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take*

advantage of opportunities or to respond to consequences.' (IPCC, 2022a).

Adaptive capacity therefore refers to the qualities within a system that enables it to respond to change, maintain its functions and adapt to hazards. The adaptive capacity of a system can be derived from its inherent attributes, such as its physical and material characteristics, but it can also be influenced by anthropogenic factors, such as institutional planning, management and financial resources and defence infrastructure (Cook et al., 2021).

Earlier definitions of 'vulnerability' proposed by the IPCC present 'vulnerability' as the outcome of three sub-components: sensitivity, adaptive capacity and exposure. In its Third Assessment Report (AR3), the IPCC conceptualises vulnerability as a *'function of the sensitivity of a system to changes in climate (the degree to which a system will respond to a given change in climate, including beneficial and harmful effects),* ***adaptive capacity*** *(the degree to which adjustments in practices, processes, or structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change in climate), and* ***the degree of exposure of the system to climatic hazards.'*** (McCarthy et al., 2001, p. 89).

The concept of 'vulnerability' therefore embodies a complex terminological basis which has subsequently been inherited by numerous risk assessment frameworks. Some frameworks – assessed as part of this review – are termed 'vulnerability assessments' and quantify vulnerability as the outcome of 'exposure', 'sensitivity', and 'adaptive capacity'. These frameworks resemble very closely risk assessment frameworks. Others explore vulnerability as a determinant of risk, dependent on the two sub-components of 'sensitivity' and 'adaptive capacity'. **This review aims to explore the extent to which risk (and vulnerability) frameworks consider all of these various components (and sub-components) of risk.**

In heritage literature, understandings of vulnerability of heritage to climate change has largely been informed by research into the mechanisms and rates of material change affecting heritage assets. For instance, there has been analysis of salt weathering of inorganic materials used in the built environment (Simpson et al, 2022).

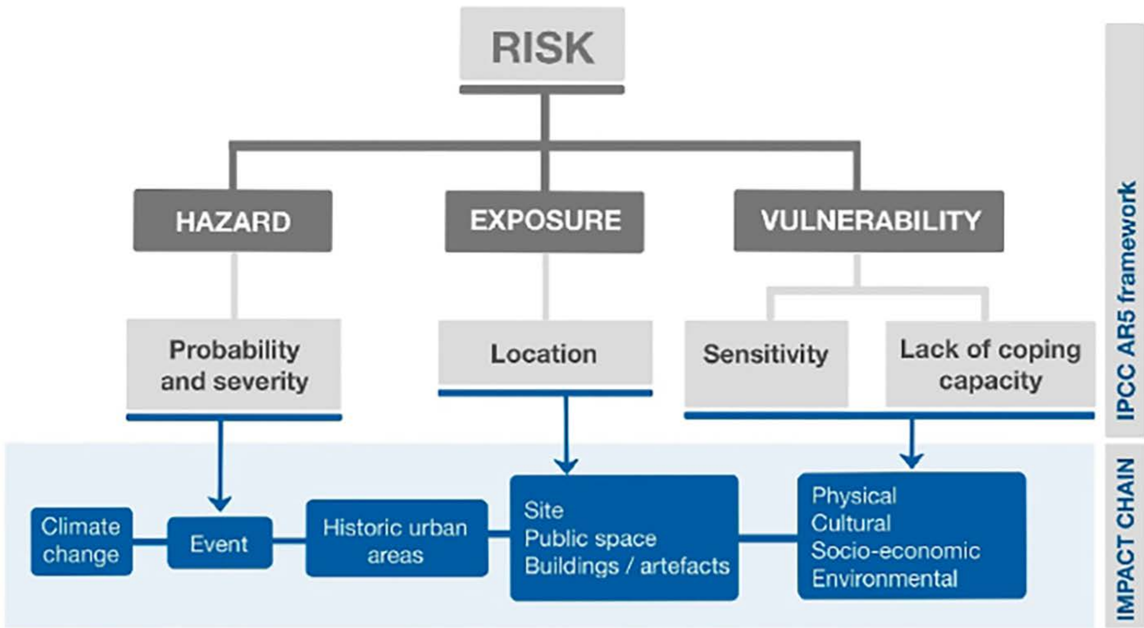
2.1.2 Hazard, Exposure, Vulnerability and Heritage assets

Mapping the concepts of 'hazard', 'exposure', and 'vulnerability' onto heritage assets is complicated, not least because there have been so few risk assessment frameworks which have attempted to quantify the risks presented by climate change to heritage assets.

Quesada-Ganuza et al. have proposed an 'impact chain for historic urban areas with a holistic vision,' which translates the standard risk-assessment concepts into an impact chain which incorporates cultural heritage and historic urban assets (Figure 4). This 'impact chain' gives a sense of how the principal concepts which underpin climate change risk manifest themselves in the historic environment.

Figure 4: Impact chain showing risk assessment concepts mapped to the historic urban environment.

Taken from L. Quesada-Ganuza et al. (2021), 'Do we know how urban heritage is being endangered by climate change? A systematic and critical review', International Journal of Disaster Risk Reduction, 65



2.1.3 New directions in climate change risk assessments

Since the sixth assessment report (AR6) in 2022 the IPCC has built on its tripartite risk framework of hazard-exposure-vulnerability and developed an inherently more complex view of risk. The IPCC's new framework takes into account the dynamic interactions among the various determinants of risk (including compound, cascading and aggregate risk – please see p.18 for further explanation), as well as considering risks arising from human responses to climate change.

Figure 5: Future directions of the IPCC risk framework incorporating 'responses'

Taken from: IPCC, (2022), Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Ch.1: Point of departure and Key concepts

In this more complex model of risk, human responses to climate change are conceptualised as a determinant in their own right, which can contribute to but also reduce climate change risks.

The risks associated with responses to climate change can arise from both the inability of a measure to achieve its intended objectives, as well as from the negative, unintended consequences of response implementation. Including climate change responses as potential determinants of risk also expands the scope of risk assessment to encompass positive and beneficial outcomes, not just negative, adverse ones (Simpson et al, 2021).

The IPCC conceptualise the risks associated with climate change responses as including both *'the possibility of responses not achieving their intended objectives or having trade-offs or adverse side effects for other societal objectives.'…'Response risks can originate from uncertainty in implementation, maladaptation, action effectiveness, technology development or adoption, or transitions in systems'* (IPCC, 2022b).

Although the IPCC does not offer an explicit definition of 'responses', the idea of responses to climate change overlaps with the concept of 'adaptation', which is defined by the IPCC as *'the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities.'* As adaptation essentially involves actions and change processes implemented in response to climate change in order to offset potential damages, adaptation can effectively be seen as a type of response to climate change. While it is not a key determinant of risk, risks can also arise from adaptation: risks may develop where adaptation does not achieve its intended objectives, or where unintended consequences result from inappropriate or maladaptive actions (Simpson et al, 2022).

The IPCC also incorporates the concept of resilience, which is defined as the *'capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.'* (IPCC, 2022b).

In addition to considering human responses to climate change as a determinant of risk, the IPCC's AR6 framework also considers the complex nature of interactions both between determinants of risk, and among multiple risk drivers within and across the determinants of a risk. **These complex interactions can be understood as:**

- **Compound:** when multiple hazards, such as concurrent heat and drought, interact with each other to increase the severity of risk.
- **Aggregate:** when risk is affected by the accumulation of multiple independent determinants of risk, such as when exposure to heatwaves has a disproportionate adverse effect on those with low income (economically vulnerable).
- **Cascading:** When one event or hazard triggers another (Simpson et al, 2021).

The IPCC defines compound risks as those which *'arise from the interaction of hazards, which may be characterised by single extreme events or multiple coincident or sequential events that interact with exposed systems or sectors'* (IPCC, 2022a).

Aggregate risk is described as a process of *'independent determinants of risks co-occurring', while cascading risk is understood as 'one event triggering another'* (IPCC, 2022b).

The CCRA3 framework also takes into consideration complex 'interacting' and 'cross-cutting' risks: *'This task investigates cross-cutting risk linkages and interdependencies for each risk and opportunity. The analysis of interdependences is considered in the magnitude scoring and has the potential to increase the score.'* (Watkiss and Betts, 2021).

A note on this report:

This review builds upon the theoretical content described above, and analyses heritage-specific risk assessment frameworks through the lens of the standard concepts that underpin climate change risk assessments. This principally involves exploring the extent to which heritage-specific risk assessments make use of the IPCC's hazard-exposure-vulnerability framework for quantifying risk.

However, this review also considers the extent to which heritage risk assessments consider the functions which underpin vulnerability, namely the sensitivity and adaptive capacity of a site. An assessment of these functions is essential to acquiring a holistic view of risk, as these components are foundational to understanding a site's vulnerability. Equally, by focusing on these two components of vulnerability, in addition to the three standard determinants of risk, attention will also be given to methodologies which are described as 'vulnerability assessments' – which incorporate 'exposure', 'sensitivity' and 'adaptive capacity', in line with the IPCC definition – but which in reality offer an effective means of calculating risk for heritage assets.

2.1.4 Approaches taken within UK nations towards climate change risk assessment

Scotland

In Scotland, the Climate Change (Scotland) Act 2009 (the Act) has placed duties on public bodies to contribute to emission reduction targets, deliver programmes for adaptation, to increase resilience, and to act sustainably. Historic Environment Scotland (HES) is identified as a 'Major Player' within the Act. HES has a role to quantify heritage assets affected by climate change. The Scottish Climate Change Adaptation Programme set out a role for HES to quantify these assets using GIS and to develop a climate change risk register for Properties in Care (PICs).

A Climate Change Action Plan (2012-17) was developed to:

- identify the range of climate risks across the HES estate, using GIS mapping;
- develop a baseline national risk register for the properties within the HES estate; and
- identify priority sites enabling detailed appraisal of risks and mitigating actions.

A climate change risk assessment undertaken in 2018 (Harkin et. al., 2018), used a desktop, GIS-based analysis of natural hazard risk to the 336 PICs, from identified threats including erosion and flooding. Exposure to risk for this purpose was defined as "exposure to a range of environmental threats/hazards with the potential to cause damage to the asset and its cultural significance". The GIS-based analysis combined asset management information with datasets on natural hazards, which were obtained from the British Geological Survey (BGS) and the Scottish Environment Protection Agency (SEPA).

Across all of the PICs, the geographical areas[4] were evaluated against a range of hazard data within an ArcGIS project. Existing data on HES' PICs was held as spatial boundary data in shapefile format identifying the extent of the area under HES' direct ownership or guardianship, which may differ from that covered by any legal designations. Spatial site boundary data was overlain with natural hazard datasets, with the intention of identifying the likelihood of the hazard occurrence at each property.

Six datasets were identified as having relevance:

1. Fluvial Flooding
2. Pluvial Flooding
3. Coastal Flooding
4. Coastal Erosion
5. Groundwater Flooding Potential
6. Slope Instability

Identification of the likelihood of the hazard occurring was achieved by assessing what the hazard was and what type of 'likelihood' score that particular dataset identified. Impact was assessed according to property type, staffing and visitor access. A score was assigned based on this analysis. A risk score was therefore calculated for each property by multiplying the impact and likelihood scores together.

4. For which HES had responsibility

Figure 6: Table showing the relationship between the likelihood score and corresponding datasets

Source: Harkin et. al, 2018

		Available datasets					
Likelihood	Probability	SEPA Fluvial Flooding	SEPA Pluvial Flooding	SEPA Coastal Flooding	SEPA Coastal Erosion	BGS Groundwater Flooding	BGS Landslides
5	1 in 10 chance	1 in 10 chance	1 in 10 chance	1 in 10 chance	165-175	C	E
4	1 in 100 chance	1 in 100 chance	1 in 100 chance	1 in 100 chance	150-160	B	D
3	1 in 1,000 chance	1 in 1,000 chance		1 in 1,000 chance	135-145	A	C
2	1 in 10,000 chance			1 in 10,000 chance	120-130		B
1	1 in 100,000 chance				105-115		A

The project methodology identified that, while some of the likelihood scores were relatively straightforward to assign, not all of the data was intended to be used to indicate the potential impact of a hazard, which made it more challenging. However, a 'likelihood' score was still assigned but with the caveat that the results should be used only on an indicative basis for screening purposes, that further site-level analysis would need to be undertaken to supplement this.

An impact scoring system was developed to ensure risk scores would be calculated and applied consistently. Scores were based on the physical impact to the monument fabric, and its surrounding grounds. **Two risk scores were created for each PIC:**

1. **Inherent risk:** multiplying the likelihood of the event occurring by the impact. Mitigants and controls are assessed to achieve modification of the impact score as a result of the situation on site, e.g., management, maintenance.
2. **Residual risk:** application of the mitigants and controls moves the inherent risk to the residual risk, i.e. the risk score after mitigations are taken into account.

Limitations exist due to reliance on datasets which were not designed for this specific purpose; HES collaborated closely with the data partners to identify and account for limitations, but it was not possible to fill all the gaps in datasets. **The principal limitations in the datasets were:**

- The Fluvial Flooding SEPA dataset was created to support flood risk management planning at a community level, and so was not intended for property level assessment. The results from this dataset are therefore 'indicative of the risk that may be experienced' at HES sites.
- The BGS slope instability dataset is concerned only with ground stability related to natural geological conditions. It does not cover man-made hazards, such as contaminated land or mining.

This project created a set of baseline data; it was acknowledged that the assessment was able to identify a level of current risk to PICs but that it is difficult to accurately assess future risk, within the context of a continually changing climate.

Building on the results of the climate change risk assessment, in 2021, HES launched its first climate change adaptation plan, setting out the climate risks identified and the response to these.

HES' risk assessment grouped 28 identified key climate risks into five categories:

1. Physical climate risks to the organisation's physical assets
2. Physical climate risks to the natural capital of Properties in Care (PiC)
3. Physical climate risks disrupting day-to-day operations
4. Varied climate risks impacting the safety and wellbeing of the organisation's people
5. Key transition risks that would likely impact delivery of core functions

This led to the development of ten priority actions to form HES' 'primary adaptation response'. Included within these actions was the integration of climate risk assessments organisation-wide, and to improve capability in data collection and analysis to be able to better monitor climate risks and to assess the impact of adaptation measures.

The climate change adaptation plan identified baseline information on roles and functions across all business areas, using a scoring system developed for the purpose which was recorded in a project workbook. Subsequent workshops, using a largely qualitative approach, refined the risks that had been identified, by developing sub-sets of risks, refining risk descriptions and gathering additional evidence to further test and validate the risks. The risks were ultimately categorised according to their level of urgency, shortfall in adaptation and perceived benefits of taking short-term action. Resources required and opportunities to work in partnership with other organisations were also discussed. The final plan included a monitoring, evaluation, and reporting schedule.

Wales

In 2012, a report was published which set out 'a strategic approach for assessing and addressing the potential impact of climate change on the historic environment of Wales' (Powell et. al 2012). Its aim was to identify and assess the sensitivity of historic assets to climate change, and to produce a risk assessment including likelihood and impacts of the identified risks.

The methodology was predominantly desk-based, spanning four main research activities:

1. Explore the vulnerability of the historic environment to current and future climate change
2. Assess the potential impacts of projected climate change on the historic environment of Wales
3. Review technical guidance, existing initiatives, programmes, and case studies that are currently monitoring and measuring the impact of climate change on the historic environment, within, but not exclusively confined to, the UK
4. Use the review to produce an assessment of how the anticipated climate changes may affect individual elements within the major asset types in order to assess their sensitivity to change

Assessment of the potential impacts involved, firstly, identification of historic assets potentially affected by climate change, which were plotted onto a matrix using four descriptions of climate change and eight potential outcomes of these changes:

Four descriptions of climate change:

1. Warmer mean temperatures
2. Hotter, drier summers
3. Warmer wetter winters/wetter summers
4. More frequent extreme weather

Eight outcomes of change:

1. Rise in sea levels
2. Longer growing season
3. Migration of pests and diseases into Britain
4. Drying out, desiccation and erosion of wetlands
5. Stress on some trees and plants
6. Drying and shrinking of clay soils
7. More flooding events
8. Frequent high winds/storms

Historic assets were broadly classified into 12 categories; some of which could span more than one category. A review of literature and technical guidance supplemented the desktop assessments which helped to determine what could be incorporated into adaptive strategies. **Asset impact matrices were then created for each historic asset category setting out:**

- Description of change
- Outcome of change
- Location: the area(s) to be affected by the change
- Impact on historic environment assets – consisting of a risk assessment score based on:
  - Scale: the extent of the impact on the historic environment caused by the outcome of change
  - Severity: the severity of the impact of the outcome of change on the historic environment
  - Sensitivity: the sensitivity of historic environment assets to change
- A qualitative risk assessment of historic assets
- Specific gaps in knowledge
- Responses to the outcomes of change
- Notes and references

Climate change impacts were then scored on a 1-5 scale, with severity of impacts also scored:

#	Description
1	Limited
2	Moderately limited
3	Moderate
4	Moderately extensive
5	Extensive

#	Description
+3	Large beneficial impact
+2	Moderately beneficial impact
+1	Small beneficial impact
0	Neutral
-1	Small negative impact
-2	Moderately negative impact
-3	Large negative impact

The report provides an explanation of how the impact scales were quantified:

"The extent of impact scale is arrived at by quantifying (or where this is not possible by estimating) the number of historic assets in a class and then estimating the number of assets in the class that are likely to be affected by the outcome of change. Thus if a class contains a large number of assets and all will be affected then the scale point would be five. If a class contains a large number, but only a few will be affected then the scale point would be 1 or 2. The severity of impact is a judgement based on expert knowledge and understanding of the historic environmental assets in Wales. Impacts can be both beneficial and negative depending on the particular nature of the asset under consideration and the predicted impacts from climate change. An indication of the overall significance of impact is obtained by multiplying the values calculating extent, severity, and sensitivity, rather than adding the score. The resultant score is used to identify high, medium or low risk to the asset" (Powell et. al 2012).

Score	Level of significance of impact (and nature of impact)
–75 to –36	high (negative)
-35 to –11	moderate (negative)
-10 to –1	small (negative)
0	neutral
1 to 10	small (positive)
11 to 35	moderate (positive)
36 to 75	high (positive)

Source: (Powell et. al 2012)

A number of matrices assessed risks to historic asset categories which were assessed using a set of scoring mechanisms to reach a measure of significant risk. Risks were also described qualitatively, including setting out any gaps in the evidence base.

Various limitations with the approach were identified, notably relating to generic, as well as specific, gaps in knowledge. Key generic limitations stemmed from the quality of data and how it was able to be used, as well as the evolving climate change variables and scenarios. Data quality varied greatly, with one notable concern being the coarseness of data used for impact predictions. It was challenging to factor in local environments as climate change scenarios are modelled at a national level. There were additional specific knowledge gaps relating to a wide range of environments including sites on farmland, foreshore sites, effects of pests and diseases in forestry and woodland, and the diverse nature of many historic assets making it harder to make predictions for each individual building with its unique traits.

In 2020, the Historic Environment and Climate Change in Wales Sector Adaptation Plan was published. This adopted the methodology set out by Powell et. al 2012 to assess future climate change and identified possible adaptation measures. It produced an updated risk assessment for nine categories of historic asset, considers the four descriptions of climate change and predicted outcomes before assessing the significant of those impacts ('extent', 'severity' and 'sensitivity').

Northern Ireland

Research was published in Northern Ireland in 2021 concerning the impacts of climate change on the historic built environment; the report was accompanied by a guide. **The report covers all categories and designations of the historic built environment in Northern Ireland, including:**

- Historic Buildings (Listed only);
- Conservation Areas
- Areas of Townscape Character
- Historic Parks, Gardens and Demesnes
- Industrial Heritage
- Scheduled Monuments
- Defence Heritage

The guide sets out five main factors considered to be key in determining the impact or likely risk to a heritage asset.

Figure 7: Factors determining impact or likely risk to a heritage asset

Source: Impacts of climate change on the historic built environment: a report and guide (Ulster Architectural Heritage, 2021).

The report emphasises the importance of understanding the building, structure and inherent factors that could have an impact on the building resilience, notably building type, mode of construction, building materials, and building site. It recommends current condition should be assessed, as well as all processes that exist for the structure's on-going management and monitoring.

In particular, the research recommends developing an understanding of how multiple factors may be working together to exacerbate the impacts of climate change. It further notes that climate change impacts will vary from structure to structure, and that individual risk assessments are essential for each unique asset.

This study highlights GIS as a critically important tool in on-going management of heritage assets and the impact of climate change on them, notably due to the ability to layer different types of data together such with the help of geolocation information, such as available data on rainfall, erosion, etc.

The study notes various gaps in datasets as key limitations. It also points out – as do other nations – that "there is no 'one size fits all' assessment of risk to heritage assets in the context of climate change".

2.2. Heritage and climate change in recent publications by the major heritage organisations

Although climate change and disaster risk management have been the focus of numerous publications by major heritage organisations over the past few decades, none of these global heritage bodies have developed a standard methodology for assessing climate change risks to heritage assets. Equally, heritage assets are not systematically examined as part of major national and international climate change risk assessments, such as the IPCC's Assessment Reports, or the UK's climate change risk assessment (CRA3). What this means is that there is a gap in both the heritage and scientific literature on climate change and risk assessment.

A review of some of the most recent publications by international heritage bodies serves to illustrate this gap. Published by UNESCO and the Advisory Bodies to the World Heritage Committee (ICCROM , ICOMOS and IUCN) in 2022, the most recent *Guidance and Toolkit for Impact Assessments in a World Heritage Context* represents a landmark document in managing the impact of major developments on globally important World Heritage sites. The objective of this document is to 'provide impact assessment guidance for World Heritage properties, using a framework that can be applied to both natural and cultural properties and to small- or large-scale projects, either within broader Environmental and Social Impact Assessments (ESIA), or as a standalone Heritage Impact Assessment (HIA)'. The guide 'fosters cross-sectoral, multidisciplinary collaboration to identify solutions for both protecting World Heritage sites and supporting good quality and appropriate development' and is at present the most up-to-date-reference on conducting and reviewing impact assessments for all World Heritage properties' replacing all previous documents (UNESCO et al., 2022).

However, the Guidance and Toolkit is primarily concerned with assessing and managing the impact of development within World Heritage Sites, but is not specifically focused on climate change. Principle nine of the Guidance does suggest that proposed actions should not be considered in isolation. Impact assessments should 'evaluate broader trends and cumulative impacts' and 'consider other past, present, or reasonably foreseeable future actions' It also states that climate change may 'make a World Heritage property vulnerable and amplify the impacts of a proposed action' (UNESCO et al., 2022, p.9).

Risk management has been a major focus of global heritage organisations in recent years. Yet, little attention has been given specifically to risk assessments (a key step in risk management) of climate change. ICCROM's *ABC Method: a risk management approach to the preservation of cultural heritage (2016), along with its Guide to Risk Management of Cultural Heritage*, provide heritage professionals with 'a methodology for studying risks in a simplified manner that does not require elaborate expertise for implementation' (ICCROM, 2017, p.5). ICCROM defines risk management as 'everything we do to understand and deal with possible negative impacts on our objectives'. The method moves through six stages to managing risk – context, identify, analyse, evaluate, treat, and monitor. By assessing risks that affect collections, buildings, monuments, and sites in their specific context more effective decisions can be made about the 'sustainable use and safekeeping of these heritage assets' (ICCROM, 2017, p.117).

Although ICCROM's publications describe risks that could be caused by climate change, such as floods, fire, and natural disasters, they don't address climate change as a specific risk or offer a specific risk management approach.

UNESCO has produced four main reports that specifically relate to climate change and heritage. Their most recent report, *World Heritage and Tourism in a Changing Climate* (UNESCO 2016), focuses on the increasing vulnerability of World Heritage sites to climate change and the 'potential implications for, and of global tourism' (UNESCO, 2016, p.5). The report underlines that climate change will have direct impacts and exacerbate existing stressors, having the potential to 'rapidly and permanently change or degrade the very attributes that make World Heritage sites such popular tourist destinations' (UNESCO, 2016, p.5). As well as being threatened by climate change, World Heritage sites and properties can also provide opportunities for 'climate mitigation and adaptation'. One example cited is 'well-preserved forests and coastal habitats [which] can help store carbon and provide vital ecosystem services, including natural protection against storms and floods' (UNESCO, 2016, p.5).

In 2014, UNESCO published *Climate change adaptation for natural world heritage sites: A practical guide* (UNESCO 2014). **The guide is intended to:**

- assist those responsible for the management of a natural World Heritage site to understand how climate change may affect those features of the site that contribute to its Outstanding Universal Value (OUV);
- offer a framework for putting site-level climate change effects into the management context;
- provide guidance on how to assess risk to the site's OUV;
- offer ideas for identifying and selecting options for responding and adapting to climate change.

(UNESCO, 2014, p.10)

This UNESCO guidance aims to set out a similar approach to that of a thorough and capable site manager. The guidance starts with understanding the complexity of the problem then moves to planning for adaptation (which includes guidance on topics such as measuring resilience, adaptation options and monitoring and evaluation). The guidance helps the reader to structure their thinking and offers worksheets and practical examples. (UNESCO, 2014).

Earlier UNESCO reports on climate change and heritage include a Policy Document on the Impacts of Climate Change on World Heritage Properties (UNESCO, 2008). This primarily focuses on 'providing the World Heritage decision / policymakers with guidance on synergies, research needs and legal issues. **It identifies the following future research needs for cultural heritage (UNESCO, 2008, p.11):**

- Understanding materials vulnerability
- Monitoring change
- Modelling and projecting climate behaviour
- Managing cultural heritage
- Preventing damage

The 2007 UNESCO two-part Climate Change and World Heritage publication, provides a report on predicting and managing the impacts of climate change on World Heritage and a strategy to assist State Parties to implement appropriate management responses. The document gives an overview of the main (physical, social and cultural) impacts of climate change on natural and cultural World Heritage and suggests appropriate measures to deal with them (UNESCO, 2007). **They state that the actions that need to be taken to safeguard heritage are threefold (UNESCO, 2007, p.40):**

1. **Preventive actions:** monitoring, reporting and mitigation of climate change effects through environmentally sound choices and decisions at a range of levels: individual, community, institutional and corporate.
2. **Corrective actions:** adaptation to the reality of climate change through global and regional strategies and local management plans.
3. **Sharing knowledge:** including best practices, research, communication, public and political support, education and training, capacity building, networking, etc.

Although these publications engage with issues of climate change and the potential threats to heritage assets, none of them offers a methodology for quantifying the risks posed by climate change.

Research findings: An overview of most recent climate change risk assessments specific to heritage assets

3.1 Summary of main findings

The methodologies which propose the most comprehensive strategies for assessing climate change risks to heritage assets are those which employ the IPCC's hazard-exposure-vulnerability framework, but which also drill down into the components which underpin vulnerability (exploring a site's sensitivity and adaptive capacity), as well as taking into consideration the significance of heritage assets. These methodologies are, however, generally restricted to individual sites or a small selection of sites. The most likely explanation for this is that comprehensive data on vulnerability and adaptive capacity – and information about heritage significance – is easier to gather when the focus is on an individual site. Data collection methods typically involve engagement with stakeholders who are familiar with the specific site in question (site managers, local experts, the wider community of heritage users) as well as field studies and site observations. Good examples of this approach are the STORM Risk Assessment and Management Tool and the Climate Vulnerability Index (CVI) as well as methodologies proposed by Sesana et al., (2020) and Daly (2014).

The disadvantage with these approaches is that they are difficult to scale up to collect data covering multiple sites over a larger geographic region. It is observed that, generally, climate change risk assessments which attempt to cover a wider geographic scale – or which attempt to quantify risk for a wider range of heritage assets – often fail to fully integrate all of the determinants of risk which form part of the IPCC's framework.

The most common methodological approach to assessing and identifying sites at risk is hazard modelling. This approach involves combining secondary data derived from climate change projection modelling (or historical data on geological, meteorological and climate-related changes) and geospatial data on heritage assets to model specific climate-related hazards and map them to the locations of heritage assets to identify heritage sites most threatened by climate change. These large-scale, data driven approaches enable analysis of climate hazards over large spatial areas. However, they typically omit information about site vulnerability, adaptive capacity, exposure and significance. The likely explanation for this is that information about vulnerability is typically site specific and there has yet been no methodology which successfully leverages data about site vulnerability, capacity or significance for multiple sites over a large geographic area.

3.2 Comprehensive approaches: Methodologies which consider the three standard determinants of risk (hazard, exposure, vulnerability), plus sensitivity, adaptive capacity and significance

This review identified a small selection of risk assessment methodologies specific to heritage assets which take a comprehensive approach to the quantification of climate change risks, by incorporating analyses of all three of the standard determinants of risk (hazard, exposure, vulnerability) as well as specifically considering the sensitivity, adaptive capacity and significance of sites. The principal limitation of these methodologies is that the process for calculating risk is generally dependent on site-specific information (in particular, information on specific site vulnerability, adaptive capacity and heritage significance) and so assessments are generally restricted to the level of individual heritage sites. Assessments typically involve engagement with local experts and heritage site managers based at the site, as well as with stakeholders and (sometimes) members of the public who are familiar with the site in question.

The site-based nature of these methodologies leads to challenges when attempting to scale up these assessments to incorporate multiple heritage assets.

To scale up, the whole assessment process needs to be replicated at subsequent sites, to gather the site-specific information needed to assess site vulnerability and adaptive capacity.

The summaries that follow serve to illustrate the challenges and opportunities of these more comprehensive, site-based approaches.

3.2.1 The STORM Risk Assessment and Management Tool

An important recent approach to risk assessment for heritage sites that takes account of all of the standard determinants of risk is the STORM Risk Assessment and Management Tool, developed by Dr Mohammad Ravankhah and his collaborators. This methodology has numerous strengths including a rigorous, top-down process for identifying hazards, which forms the basis of an initial hazard mapping process, along with a thorough procedure for quantifying risks based on assessments of an individual site's exposure, susceptibility and adaptive capacity. The specific module of the STORM model focused on risk assessment tool is, however, largely site-based with assessments of exposure, susceptibility and adaptive capacity dependent on information from expert stakeholders, usually those who are familiar with the site, such as conservators, managers, and dedicated volunteers. This is aptly demonstrated in the case of the Mellor Archaeology Trust where the STORM framework has been applied by volunteers of the trust.

The STORM model represents the outcome of a sustained research project that can be traced back in outline form to Ravankhah and Schmidt's 2014 paper on disaster risk assessment for cultural heritage sites (Ravankhah and Schmidt, 2014). At this early point, there was little specific attention to climate change and the authors largely adapted established disaster risk assessment protocols based on hazard, exposure and vulnerability to heritage by adding a step for assessing the value of the assets potentially impacted by the hazards. Thus, hazard and exposure assessment are complemented by value assessment, these last two being brought together in the category of 'exposure'. These then provide the foundation for the 'vulnerability' assessment, which can be either qualitative or quantitative.

The later publications by Ravankhah build on this early work to formulate an increasingly systematic and comprehensive approach, 'Safeguarding Cultural Heritage through Technical and Organisational Resources Management', abbreviated as STORM (Ravankhah et al., 2018, 2019, 2020a, 2020b). These papers set out an approach to risk assessment that continues with the hazard, exposure, vulnerability approach, but which includes consideration of adaptative and coping capacities as part of the vulnerability analysis. The process can be divided into two basic components: hazard identification and analysis, referred to as the 'Site Hazard Assessment module'; and the formal risk assessment itself, which considers the exposure and vulnerability determinants, including adaptative capacity, referred to as the 'Risk Assessment module'. The model also includes developing 'Risk Management Strategies' as a third stage or 'module' of the process, but this is beyond the scope of risk assessment itself.

Although the basic framework of the STORM model is familiar enough, the extremely thorough way in which it has been developed makes it a particularly interesting model. The first major component identified above, hazard identification and analysis, is discussed in considerable detail in Ravankhah et al, 'Integrated Assessment of Natural Hazards, Including Climate Change's Influences, for Cultural Heritage Sites: The Case of the Historic Centre of Rethymno in Greece'.

This paper notes at the outset that 'One of the main challenges in the STORM project was the large number of environmental hazards (sudden- and slow-onset) that may likely affect the project pilot sites.' It also points out that:

> *Vulnerability analysis of historic sites is a very complex and resource- consuming procedure; furthermore, the susceptibility analysis of historic structures to different hazards might need quite different methodologies and techniques.*

This means, to be practicable, risk assessment must be selective at the outset and establish which hazards are likely to be of most relevance.

The process of prioritisation and selection of hazards was carried out through a three-step process:

1. Identification of natural hazards, including climate change influences, likely to affect a study area;
2. Analysis of the natural hazards and threats through quantifying their severity, likelihood, and anticipated future changes; and
3. Evaluation of the natural hazards and threats to determine those that need to be integrated into the further risk assessment procedure and conservation strategies.

The identification process set out within the STORM approach is notable for its systematicity. Hazards are divided into geological, hydrometeorological, and biological, and further subdivided into fast- and slow-onset hazards. This enabled a large number of individual potential hazards to be identified within each of the six subcategories, many not adequately recognised by other climate-change related heritage risk assessments.

The hazards were then evaluated for their potential to affect specific heritage sites using semi-quantitative techniques (i.e. five point rating scales with qualitative descriptions or equivalents) to estimate the intensity of each hazard in relation to four criteria: severity; likelihood; relevance; expected intensity of impact. The process for hazard identification is set out in Figure 8.

For example, hazards were graded by probability of occurrence, on a scale from 1-5. The specific tabulation used for this process is highly imprecise. For example, 'likely' events having probabilities of 10% to <63% per annum, are classed as 'Once per ten years', when e.g., 62% probability implies more than once every two years. The ranges within each step are therefore enormous. Similar semiquantitative approaches were used for the remaining three criteria, translating qualitative estimates into numerical scores. Severity and likelihood estimates were based on historical data for the identified hazards, which were then modified on the basis of standard models of climate change and its impacts. The relevance and intensity of impact scores were intended to capture the potential degree of impact on specific sites, and were based on expert estimates. The resulting data were used to identify hazards likely to affect the heritage sites in the area of study. The likely future changes to selected hazards was then modelled in relation to predicted climate change.

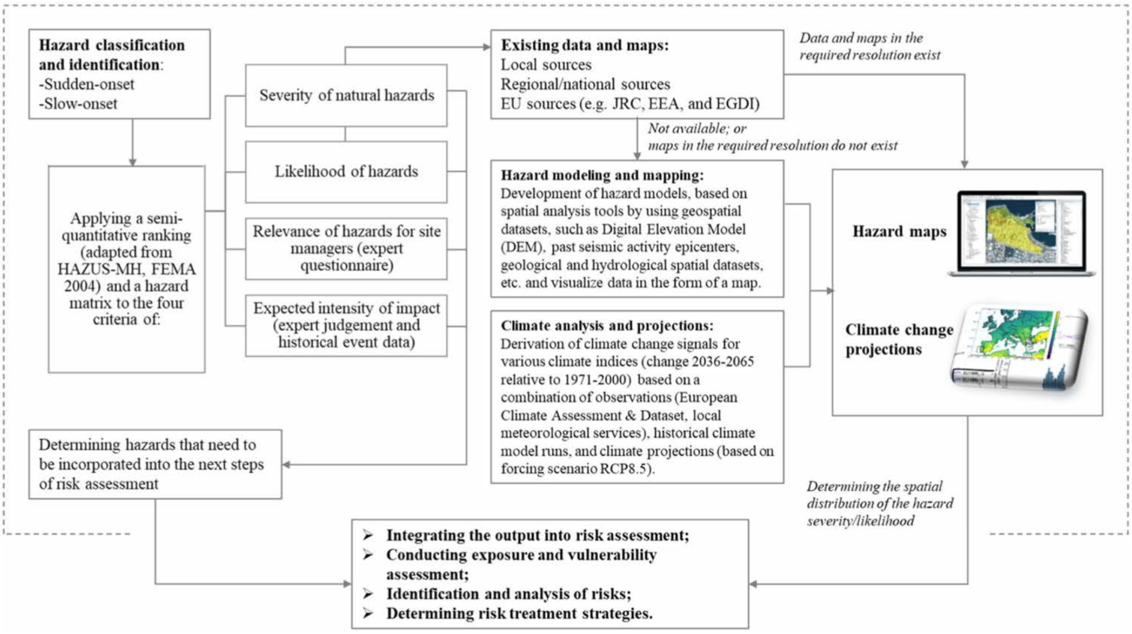


Figure 8: STORM Hazard identification process

Taken from: M. Ravankhah et al., (2020), A Multi-Hazard Platform for Cultural Heritage at Risk: The STORM Risk Assessment and Management Tool: IOP Conference Series: Materials Science and Engineering

The next stage consisted of developing hazard maps to show the spatial distribution of selected relevant hazards, with historical data and climate change modelling used to predict the likely intensity and prevalence of the hazard. Detailed modelling of the potential effects of climate change focused on RCP8.5, one of the most severe climate scenarios then modelled. There was a sophisticated process of downscaling to reduce the low resolution climate modelling data available to the scales needed to generate hazard mapping for individual heritage sites.

This was intended to give an upper bound estimate of the potential hazard. The resulting maps used the same five-level indices, represented by coloured green to red overlays, enabling the geographical areas most likely to be affected by the hazards to be readily identified. The likelihood and expected intensity scores of the different hazards were then mapped onto a single hazard analysis matrix (see Figure 9), giving a clear sense of their relative significance for the area.

Hazard analysis matrix			Event parameters (likelihood + severity + relevance to the site): Very low < 5.4	Low 5.4–7.8	Medium 7.8–10.2	High 10.2–12.6	Very high > 12.6
Expected intensity of impacts (a preliminary estimation)	Catastrophic	5					
	Major	4				Earthquakes	
	Moderate	3			Landslides Salinization Biological colonization Tsunamis	Wind	High waves Strong winds
	Minor	2		Rockslides Frost Snow loading	Coastal erosion Wind-driven particulates Tides Prolonged wet periods Humidity cycle changes Relative humidity shocks Surface runoff	Flash floods Coastal floods Wind-driven rain Solar radiation Prolonged dry periods Heat waves Cold waves	Intense rainfall
	Insignificant	1					

Figure 9: STORM Hazard Analysis Matrix

Taken from: M. Ravankhah et al., (2020), A Multi-Hazard Platform for Cultural Heritage at Risk: The STORM Risk Assessment and Management Tool: IOP Conference Series: Materials Science and Engineering

Following scoring, the ALARP (As Low As Reasonably Practicable) principle was used to identify the hazards to be considered in the detailed risk assessment. In practice, this means continuing to the more detailed second stage of formal risk assessment for the hazards in the high (red) and medium (yellow) zones. Low (green) hazards are not disregarded entirely, but in most cases should be managed through routine monitoring and conservation methods. This process is mapped out in Figure 10, below.

The hazard maps also make visible the extent to which individual monuments within the study area are liable to be impacted by the hazards.

The resulting analysis of the relative significant hazards then provides the basis for detailed risk assessment. These consider in much more detail the likely exposure and degree of vulnerability of the heritage assets to the identified hazards.

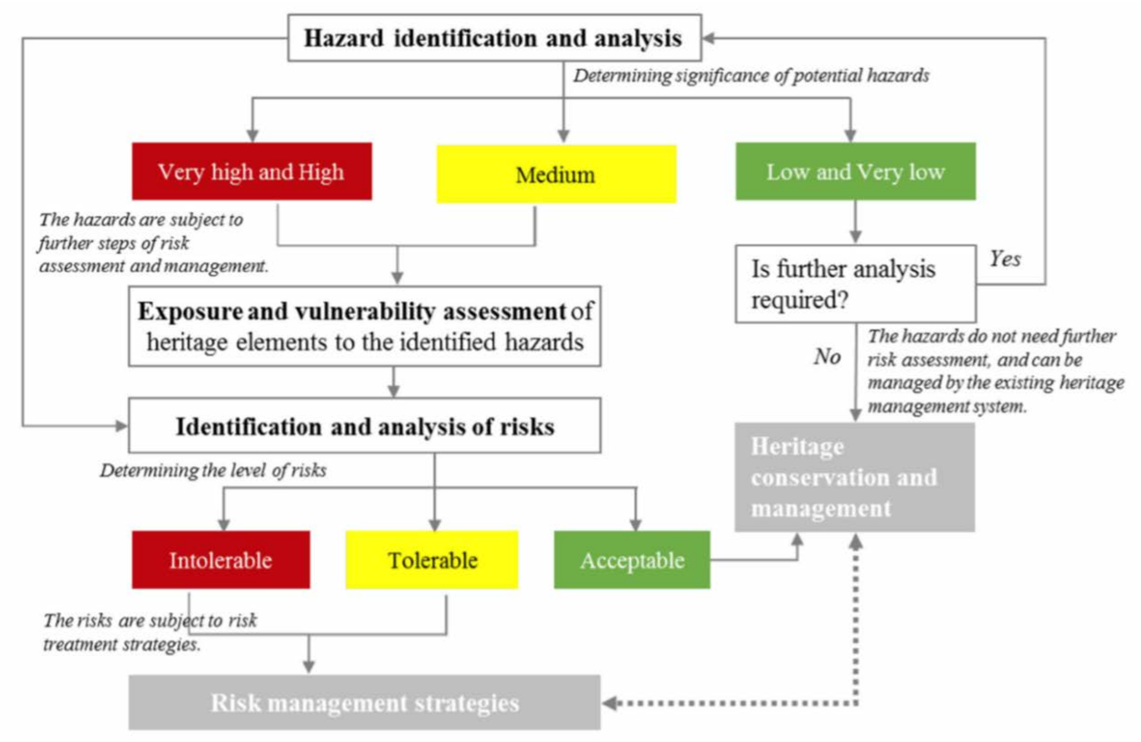


Figure 10: STORM Risk Assessment Process

Taken from: M. Ravankhah et al., (2020), A Multi-Hazard Platform for Cultural Heritage at Risk: The STORM Risk Assessment and Management Tool: IOP Conference Series: Materials Science and Engineering

This part of the process is only referred to in the outline in the 2019 paper but is considered more exhaustively in Ravankhah's 2020 papers. **These set out a risk assessment process with four basic components:**

- hazard analysis, derived from the previous 'site hazard assessment' stage of the process;
- exposure analysis;
- susceptibility analysis;
- capacity analysis.

The full STORM approach incorporates assessments of value or significance of heritage assets into the exposure analysis: the intention is that when risk assessing heritage assets, the relevant degree of exposure can only be conceived in terms of the significance of the assets or elements – the greater the value of the asset, the greater the potential exposure of 'heritage' to the hazard. **The model assesses significance through a very wide range of types of significance:**

1. Aesthetic
2. Architectural/technological
3. Historical
4. Archaeological
5. Economic
6. Educational
7. Scientific
8. Social
9. Environmental

For any given heritage asset, its significance in each of these categories is estimated using a variant of the standard five-point scale, from 'very low' (1) to 'very high' (5).

Vulnerability is essentially defined in terms of, and estimated through, the combined results of, the susceptibility and capacity analyses. **These are defined as follows:**

- **Susceptibility:** In the context of cultural heritage, susceptibility or sensitivity represents the extent to which a heritage asset might be adversely impacted by a hazard or threat.
- **Coping and adaptive capacity:** In the STORM project, coping and adaptive capacity describe the institutional capacity of existing heritage conservation and risk management systems to manage risks of natural hazards and threats to cultural heritage through structural and non-structural measures. Although coping and adaptive capacity are highly interconnected, coping capacity mainly reflects the ability to mitigate, respond to and cope with the sudden-onset disasters while adaptive capacity comprises the ability to adjust to slow-onset disasters in a long-term perspective.

The vulnerability analysis is based on the answers given in response to structured questionnaires by 'pilot site managers, expert partners familiar with the sites, and local and national organisations responsible for the protection of the sites'.

These analyses are then brought together in a three-stage process of 1) identifying risks; 2) analysing risks; and 3) evaluating risks.

As with previous stages, the approach is semi-quantitative, translating existing hazard data and estimates by relevant experts into five-point scales, with qualitative equivalents given to aid comprehension and accessibility.

The module was then presented as a web-based risk assessment tool, with rating scales, definitions and site descriptions embedded in the web pages.

The strengths of the STORM Risk Assessment and management tool lie in its comprehensiveness. It offers a thorough, top-down classification of hazards, incorporates all three standard determinants of risk, as well as susceptibility (i.e. sensitivity) and capacity (adaptive capacity) and develops assessments of the significance of individual sites.

There are a number of limitations. As well as being largely restricted to the level of individual sites when assessing exposure, vulnerability and capacity, the hazard mapping process largely fails to give a sense of the range of possibilities or the degree of certainty of the RCP8.5 estimate. A more dynamic approach, embracing a full range of possible scenarios would be potentially helpful (and perhaps more realistic). Furthermore, adaptive capacity is viewed only as a potentially positive determinant: there is no substantive consideration of the possibility that adaptation may itself have negative consequences – reflecting the fact that 'response' as distinct risk category was yet to be fully conceptualised in the standard IPCC model when the STORM model was developed. Finally, the actual processes used are not always very clearly or comprehensively described in the published papers on the project. There is also very little open access data related to the project and very little of the finer details of what has been done as part of STORM is publicly accessible. This makes detailed assessment of the adequacy of the techniques difficult to complete.

3.2.2 Vulnerability Assessments

This review also identified a small number of 'vulnerability assessments' which offer comprehensive approaches to assessing climate change risks on individual heritage sites. According to Carmichael et al., 'a vulnerability approach to risk assessment conceptualises vulnerability in terms of degrees of exposure and sensitivity to climate hazards and, additionally, upon the system's adaptive capacity over time (IPCC 2001, 2014).' (Carmichael et al., 2017).

Vulnerability assessment frameworks therefore draw upon the definition of 'vulnerability' set out by the IPCC as part of its Third Assessment Report (AR3), which sees climate 'vulnerability' as a function of:

a) the exposure of a system to climate hazards,

b) the sensitivity of system to changes in climate,

c) and the system's adaptive capacity.

(McCarthy et al., 2001, p. 89)

However, while the vulnerability assessments identified as part of this review take a comprehensive view of risk, they are limited in the same way as the STORM framework in that they are almost all concerned with producing site- or small area-based risk assessments.

A good example of this is the approach proposed by Sesana et al. (2020), which involves a five-step, integrated vulnerability assessment, based on the IPCC AR3 definition of 'vulnerability'. The approach was trialled at three World Heritage Sites in Europe and uses a process for assessing vulnerability based on qualitative assessments of a site's exposure, sensitivity and adaptive capacity. The assessment is based largely on secondary data sources and qualitative insights from expert stakeholders gathered through interviews. The assessment also takes into account significance by considering the values associated with the site.

The first step of the assessment involves understanding the values of the site using the site's Outstanding Universal Value. The second step involves using published literature and data sources to assess the exposure and sensitivity of the region in which the site is located. The third step is then to assess the exposure, sensitivity and adaptive capacity of the specific site to climate change. This step involves using literature and data but also qualitative interviews with local experts familiar with each site (site managers, academics). Assessment of the site's adaptive capacity is also performed in this step and this is done by categorising the information given by interviewees according to certain 'determinants of adaptive capacity' identified by the authors through secondary research. In the fourth step, overall vulnerability is assessed qualitatively by putting together the information gathered on exposure, sensitivity and adaptive capacity. **Vulnerability is represented by the following expression:**

Vulnerability = {exposure, sensitivity, adaptive capacity}

The final step consists of repeating periodically the assessment, given the variability of its components over time (Sesana et al., 2020). While Sesana et al. propose a comprehensive model for quantifying vulnerability, their article gives no information about how the exposure and sensitivity of each site is scored or graded, and there are no systematic instructions on how to bring together the information about exposure, sensitivity and adaptive capacity to calculate an overall assessment of vulnerability.

Similarly, Cathy Daly (2014), proposes a six-step, integrated vulnerability framework, also based on the IPCC AR3 definition of 'vulnerability', and trialled at two World Heritage case study sites in Ireland. Like Sesana et al., the first step of this framework is to identify and define the heritage values to be assessed. The second step is to assess the exposure, sensitivity and adaptive capacity of the values of the specific site. This step involves using both published data, but also interviews with stakeholders, to qualitatively describe the site's exposure and sensitivity to climatic parameters and assess the adaptive capacity of the site. **Adaptive capacity is here assessed through an analysis of the following four strategic areas:**

- Policies and Programmes (e.g., management structures, visitor management, legislative protections)
- Information and Knowledge (e.g., climate change, human resources, population)
- Implementation (e.g., conservation and maintenance)
- Monitoring/Feedback

The third step involves combining all of the evidence gathered in the second step to 'imagine' possible future impacts under projected conditions. The aim of this step is to identify likely hazards for each value under future climactic conditions using a matrix of impacts. The fourth step then involves the development of 'indicators' with which to measure certain key impacts of concern (e.g. lichen survey, extent of vegetation cover). Very little detail is given to how users of this framework would develop such indicators. The fifth step is to assess the overall vulnerability of the site by entering values for exposure, sensitivity, and adaptive capacity into a Causal Model (Table 2, below). In this model (developed by the author), sensitivity (S) and exposure (E) to each hazard are positive values and adaptive capacity (AC) is negative. The 'measure of vulnerability' (MV) is then calculated by combining scores for exposure and vulnerability and subtracting the score for adaptive capacity. The scale is a basic 1–3 range, where 1 is low. However, no information is given about how the qualitative descriptions of exposure, sensitivity and adaptive capacity (from the second step) are translated into numerical scores to be inputted into the causal model.

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

Table 2: Daly (2014): Causal model for site specific evaluations of vulnerability to climate change impacts

Taken from: Daly, C., (2014), 'A Framework for Assessing the Vulnerability of Archaeological Sites to Climate Change: Theory, Development, and Application', Conservation and Management of Archaeological Sites, 16:3

Table 3: Daly (2014): Example calculation of the 'Measure of Vulnerability' - erosion of buried deposits, Skellig Michael

Taken from: Daly, C., (2014), 'A Framework for Assessing the Vulnerability of Archaeological Sites to Climate Change: Theory, Development, and Application', Conservation and Management of Archaeological Sites, 16:3

Climatic parameter	Sector or W. H. value	Impact	Indicator	Sensitivity	Exposure	Adaptive Capacity	Measure of Vuln.
Rainfall	Buried deposits	Erosion & exposure	% vegetation cover	1 - Low (deposits only in monastery)	1 - Low (sheltered position)	2 - Medium (rescue excavation possible)	Low (0)

The final step is to use stakeholder review to refine and communicate results (Daly, 2014).

A key limitation of Daly's framework is that many of the processes used are not clearly or comprehensively set out. Very limited information is given for the third and fourth steps (through which participants 'imagine' possible future impacts under projected conditions and develop indicators with which to measure certain key impacts) and there is very little guidance on how the descriptive assessments of exposure, sensitivity and adaptive capacity are translated into numerical scores.

While Sesana et al. and Daly both propose quite comprehensive frameworks for assessing the vulnerability of heritage assets, they are both fundamentally limited in that assessments are based on individual sites. These frameworks are scalable only by repeating the process at different sites using data and stakeholders relevant to those sites.

3.2.3 The Climate Vulnerability Index (CVI)

Another important recent methodology for quantifying the vulnerability of heritage sites to climate change – which considers hazards, exposure, sensitivity, adaptive capacity and significance – is the Climate Vulnerability Index (CVI). The CVI is a rapid assessment tool created by two researchers at James Cook University in Australia, intended as a means of assessing the climate vulnerability of all types of World Heritage properties (natural, cultural, and mixed). It builds on the IPCC risk framework and proposes a risk assessment approach which systematically assesses a site's vulnerability to climate change, based on the site's Outstanding Universal Value (OUV) and an assessment of the site's exposure, sensitivity, and adaptive capacity with respect to key climate stressors (Jones et al., 2022). However, like all of the assessment approaches summarised so far in this chapter, the CVI is limited to site-based assessments as the whole vulnerability assessment is conducted via a workshop consisting of stakeholders who are knowledgeable about the specific heritage site.

There are two distinct stages of the CVI methodology. The first relates to assessing the vulnerability of the World Heritage site itself to climate change, exploring the impact of climate change on the key values associated with the site. **The second stage involves assessing the vulnerability of the wider community which lives around or near the site:**

1. OUV Vulnerability, assessing potential impacts on the key values for which the property is recognised; and
2. Community Vulnerability, based on economic, social, and cultural connections of the community (local, national, and international) associated with the World Heritage property, the dependency of the community upon the property, and the capacity of the community to adapt to climate change.

(Day et al., 2020)

The CVI methodology is undertaken as a collaborative workshop between diverse stakeholders (including site managers, researchers, dependent business owners, management agency representatives, as well as representatives from the local community), who jointly carry out the risk assessment process by following a series of set steps.

There are three foundational steps which participants must carry out before undertaking the CVI assessment:

1. Determine the key World Heritage values by analysing the Statement of Outstanding Universal Value for the relevant WH property.
2. From a predetermined list, establish the three key climate stressors likely to have the greatest impact on the WH values of the site, within a defined and agreed timeframe and climate future scenario (e.g., by 2050; RCP8.5)
3. Undertake a preliminary assessment of the current condition and trend of the key WH values of the property.

Once these initial steps are complete, workshop participants must then undertake the following eight steps to complete the CVI assessment:

1. Conduct a 'high-level risk assessment' by assessing the exposure and sensitivity of the site to the three climate stressors deemed to have the greatest impact on the site's key values, in accordance with an agreed timeframe and climate future scenario (e.g. 2050, RCP8.5). Exposure and sensitivity are assessed qualitatively using 5-point scales (exposure is assessed on a scale from 'very unlikely' to 'very likely' (see Table 4), sensitivity is assessed on a scale from 'very low' to 'very high' (see Table 5).
2. Use a predetermined 'Risk Matrix' worksheet (see Table 8) to identify the potential impact of each of the three key climate stressors on the key World Heritage values ('extreme', 'high', 'moderate', 'low').
3. Assess the 'adaptive capacity' of the site and its values in relation to the three climate stressors, by considering the local management response and scientific support available to the site.
4. Use a separate worksheet to determine the OUV Vulnerability of the site to the key climatic stressors (see Table 10, below).
5. Consider, and assess separately, the community's economic, social, and cultural (ESC) dependencies upon the World Heritage property.
6. Use a predetermined worksheet to determine the potential climate impacts on the ESC dependencies.
7. Consider, and assess separately, the level of ESC adaptive capacity within the community.
8. Use a separate worksheet to determine the Community Vulnerability component.

(Day et al., 2020)

When undertaking the 'high level risk assessment', workshop participants assess the level of exposure (which includes *'the nature, magnitude and rate of climatic and associated changes'*) of the key WH values to the three key climate stressors using the following scale:

Table 4: CVI: Categorical levels for assessing 'exposure'

Taken from: Day, Jon C. et al., (2019), Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site. An application of the Climate Vulnerability Index, Historic Environment Scotland

Exposure % based on IPCC[1,4]	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
	Very unlikely <10%	**Unlikely** 10–33%	**Possible** 34–66%	**Likely** 67–90%	**Very likely** >90%

Similarly, 'sensitivity' (*'i.e., the degree to which the OUV is affected, either adversely or beneficially, by climate variability or change'*) of the key WH values to the three chosen climate stressors is assessed using the following scale:

Table 5: CVI: Categorical levels for assessing 'vulnerability'

Taken from: Day, Jon C. et al., (2019), Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site. An application of the Climate Vulnerability Index, Historic Environment Scotland

Sensitivity based on IUCN[3]	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
	Very low All key WH values will remain essentially intact; overall condition of property is stable or improving	**Low** Some loss or alteration of a few of the key WH values will occur, but not causing persistent or lasting effects on OUV	**Moderate** Some loss or alteration of some of the key WH values will occur, but not causing a significant reduction of OUV	**High** Loss or alteration of many key WH values will occur, leading to a significant reduction of OUV	**Very high** Potential for major loss or substantial alteration of majority of key WH values, leading to substantial reduction of OUV

The CVI approach also involves applying modifiers to both exposure and sensitivity 'to account for temporal scale and trend (exposure), as well as the spatial scale and compounding factors (sensitivity).' *'The effect of the modifiers above Level 1 is to amplify the exposure and/or sensitivity (scaling by 1.0–1.3 in increments of 0.1 for each level), and thus increase the assessed risk. Modifiers are applied using the following scales'* (Day et al., 2019).

Table 6: CVI: Modifiers to assessed exposure

Taken from: Day, Jon C. et al., (2019), Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site. An application of the Climate Vulnerability Index, Historic Environment Scotland

Modifier	**Level 0**	**Level 1**	**Level 2**	**Level 3**
Exposure				
Temporal scale The frequency of event exposure	Intermittent (<1 event/ decade)	Occasional (1-5 events/ decade)	Frequent (5-10 events/ decade)	On-going
Trend The recent trend of the key climate driver	Decrease/static	Slow increase	Moderate increase	Rapid increase

Modifier	Level 0	Level 1	Level 2	Level 3
Sensitivity				
Spatial scale Extent (%) of WH property affected by climate driver at any one time	Restricted <10%	Localised 11–50%	Extensive 51–90%	Very widespread 91–100%
Compounding factors Is climate change likely to influence or interact with other non-climate stressors (e.g. invasive species) in the near future?	Very unlikely/ unknown	Low probability	Medium probability	High probability

Table 7: CVI: Modifiers to assessed sensitivity

Taken from: Day, Jon C. et al., (2019), Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site. An application of the Climate Vulnerability Index, Historic Environment Scotland

The 'compounding factors' modifier, which participants consider when assessing 'sensitivity', enables participants to think about the ways in which the main identified climate stressors may interact with other, non-climate related stressor, such as invasive species, increasing decay of materials (rot, mould, etc.); destabilisation of structures (e.g., earthquakes, subsidence, armed conflict), impacts of tourism. This part of the CVI framework therefore introduces discussion of how wider, non-climate related hazards may exacerbate and deepen the climate risks associated with a site.

The exposure and sensitivity scores are then entered into the following matrix, to determine the level of potential impact of each stressor:

Modified Exposure	Modified Sensitivity				
	Very low	Low	Moderate	High	Very high
Very unlikely	Low	Low	Low	Low	Low
Unlikely	Low	Low	Moderate	Moderate	Moderate
Possible	Low	Moderate	Moderate	High	High
Likely	Low	Moderate	High	High	Extreme
Very likely	Low	Moderate	High	Extreme	Extreme

Table 8: CVI: Risk matrix to assess potential impact from exposure and sensitivity

Taken from: Day, Jon C. et al., (2019), Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site. An application of the Climate Vulnerability Index, Historic Environment Scotland

To assess ‘adaptive capacity’, participants use the following table (Table 9). Local management capacity and scientific/technical support only contribute to the overall adaptive capacity if they are deemed to be effective in tackling the key climatic stressors (in the final row). If the resources available or technical knowledge are assessed as having no effect in addressing the climate stressors, adaptive capacity is null.

Table 9: CVI: Categorical levels for components of adaptive capacity

Taken from: Day, Jon C. et al., (2019), Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site. An application of the Climate Vulnerability Index, Historic Environment Scotland

	Level 1	Level 2	Level 3	Level 4
Local Management Capacity (i.e. resources, budget, knowledge) for management to respond at local level	No capacity and/or resources	Low capacity	Moderate capacity	High capacity
Scientific/Technical Support for management at local level	No support and/or scientific understanding	Low level of support	Moderate level of support	High level of support
Effectiveness to address the climate driver Extent to which adaptive capacity will effectively address the driver	Very low/ negligible level of effectiveness	Low level of effectiveness	Moderate level of effectiveness	High level of effectiveness

The overall OUV vulnerability of the site is then determined using the following risk matrix (Table 10), based on the potential impact and the adaptive capacity.

Potential Impact	Adaptive Capacity		
	High	Moderate	Low
Low	Low	Low	Low
Moderate	Low	Moderate	Moderate
High	Moderate	Moderate	High
Extreme	Moderate	High	High

Table 10: CVI: Risk Matrix to assess OUV Vulnerability from potential impact and adaptive capacity

Taken from: Day, Jon C. et al., (2019), Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site. An application of the Climate Vulnerability Index, Historic Environment Scotland

5. The following scores were used to grade probability and consequence: (a) Probability: 1 = exceptionally unlikely, 2 = very unlikely, 3 = unlikely, 4 = about as likely as not, 5 = likely, 6 = very likely. (b) Consequence: 1 = very low, 2 = low, 3 = moderate, 4 = high, 5 = very high, 6 = severe.

The methodology also uses a collaborative, co-production approach, which calculates risk by drawing upon the insights and views of experts and members of the local community. The CVI therefore makes effective use of 'on-the-ground knowledge of vulnerability, hazards and exposure', held by stakeholders who understand the local community and environment (Giliberto and Jackson, 2022). This process permits a more complex and holistic view of risk informed by experts as well as those who live by the heritage site who invest their own meaning in the place. The CVI is, therefore, a highly effective risk assessment methodology for an individual site or small group of sites. The challenge, however, is around scalability. While effective, the CVI methodology, with its collaborative workshop of local and community stakeholders, is also resource intensive. This means that the methodology cannot realistically be scaled up for a national assessment because of its emphasis on community involvement.

The CVI also differs from other vulnerability assessments by evaluating the site's OUV vulnerability and also 'community vulnerability' (the latter being based on the economic, social and cultural dependencies related to the WH property and the adaptive capacity to cope with climate change) that is applicable to all WH properties.

Examples of the application of the CVI – to the Heart of Neolithic Orkney (HONO) World Heritage Site and the Sukur Cultural Landscape, Nigeria – are included in Appendix 1.

The CVI has also been used as the basis for developing a more comprehensive risk assessment methodology which goes beyond assessing a site's climate vulnerability and which assists in the prioritisation of mitigating actions. This methodology has been recently developed by Chikodzi et al. (2022) for application to heritage sites within South African national parks. However, the process necessary to complete this methodology appears complicated and is not described very clearly.

Chikodzi et al. (2022) applied the CVI methodology to assess the vulnerability of heritage sites located within the Kruger, Mapungubwe and Table Mountain national parks in South Africa. They also developed a separate, additional risk analysis tool, which drew upon the results of the CVI process, to produce a more comprehensive assessment of climate change risks. The authors developed a seven-point, semi-quantitative risk analysis tool – designed to be used by site managers at the national parks – to rank and prioritise the main climate-related risks associated with the climate stressors identified through the CVI assessment. **Each risk was assigned score from 1 to 7 for:**

a. probability of the risk occurring and

b. consequence of the risk[5]

A risk value was calculated for each risk by multiplying the scores for probability and consequence. The risk values were then added together to give a score for 'cumulative risk' and Pareto analysis was undertaken using the cumulative risk to identify and prioritise the 'critical risks' responsible for over 80% of the identified risks. Once critical risks were identified, the authors then drew up a SMART (Specific, Measurable, Achievable, Realistic, and Timely) action list for the identified critical risks to help identify the most immediate mitigating actions. **For each critical risk, the SMART action list recorded the following information:**

- What must be done?
- Who will be responsible?
- What must be measured?
- When must it be complete?
- How often must progress be monitored?

Each action is also assigned a score for 'effort' and 'impact' (ranging from high to low) and assigned a description of the task ('thankless task', 'major project', 'quick win'). The information used in this Action list is then used to support prioritisation of actions (Chikodzi et al., 2022).

To summarise, the CVI is a useful methodology which effectively draws upon the knowledge of local stakeholders to calculate the vulnerability of individual heritage assets – and broader community vulnerability – through simple, user-friendly, graded assessments of exposure, sensitivity and adaptive capacity. However, its greatest strength – its co-production approach – also brings with it associated challenges around scalability. Its collaborative workshop approach is resource and time intensive, which limits the extent to which the CVI methodology can be scaled above the level of individual sites. While the CVI may be an effective site-based approach, it is arguably unsuitable as a national risk assessment methodology, due to its reliance on community involvement.

3.2.4 Cultural Resource Vulnerability Assessments (CRVAs) and the US National Parks Service

In 2022 the US National Parks Service (NPS) undertook a review of Climate Change Vulnerability Assessments (VAs) related to its Infrastructure, Natural Resources and Cultural Resources (Peek et al., 2022). The introduction to the review states that the most effective VAs are 'designed to contribute to and inform a planning process' (Peek et al., p.6). The methodologies of VAs reviewed included quantitative, qualitative, and mixed methods. The review identified some generalisations about the methods applied to different types of VAs, described in the box below:

- **Broad-scale, coarse-screening studies** are usually quantitative, and they use automated methods that process changes in temperature or other numerical metrics.
- **Hazard assessment IVAs** are almost by necessity quantitative because they rely on probabilities and often on engineering analyses.
- **Natural Resources Vulnerability Assessments** commonly combine quantitative and qualitative information, sometimes producing a specific numerical score, and sometimes a categorical ranking.
- **Climate exposure** is almost always a quantitative input (e.g., change in temperature, precipitation, or sea-level rise (SLR) determined from computer model), but sensitivity and adaptive capacity are often based on expert knowledge and are very frequently qualitative inputs.

(Peek et al., 2022, p14)

Perhaps of most interest to this literature review, chapter four centres on reviewing Cultural Resource Vulnerability Assessments (CRVAs). These CRVAs aim to understand how climate change impacts cultural heritage resources across America under NPS management, including 'archaeological sites, historic structures, cultural landscapes, and national historic landmarks' (Peek et al., 2022, p. 95). Seven near term recommendations are suggested that would build on the progress of the CRVA's reviewed (p.127-128). **These are set out in simplified form below:**

- Implementing data and resource sharing for cultural resources vulnerability researchers with future research scopes to include data sharing as part of deliverables.
- Simplifying the definition and usage of key vulnerability concepts and terms and making these consistent.
- Integrating CRVAs with natural resources and facilities.
- Allowing sufficient time and resource for park personnel to be involved in VA scopes of work.
- Incorporating VA concepts and methods into appropriate cultural heritage educational materials.
- Including ethnographic resources (or intangible Heritage) where available, as well as local community involvement in scoping, in CRVAs.
- Updating the study every 5 years.

The US National Park Service are already seeing the impacts of ongoing climate change on the archaeological sites, historic structures, museum collections, cultural landscapes, and ethnographic resources of the Colonial National Historical Park (Ricci et al.,2019).

For a 2019 report, the NPS cultural Resources Workgroup determined a list of priority sites within the Colonial National Historical Park through different methods (Table 11).

Each resource was allocated a vulnerability score based on its exposure and sensitivity to ten factors: sea level rise; groundwater change; soil chemistry; severe storms and flooding; erosion; precipitation; drought and temperature; increases in high wind events; run off; humidity. These scores were assessed in two ways: 'for sites that had specific geographic locations, exposure to these factors was determined by GIS mapping. For resources without unique geographic locations, a binary Yes/No response for each stressor within each focal area was given by subject experts' (Ricci et al., 2019, p.37).

Table 11: List of priority sites identified by NPS Cultural Resource Workgroup

Site	Method for determination
Priority archaeological sites and historic structures	Determined by expert judgement from park and regional staff.
Cultural landscapes	Identified using the Cultural Landscape Inventory.
Ethnographic resources in the park,	**To assess vulnerability the study considered four factors:** ■ archaeological sites of social, economic, or political significance, ■ tidal and non-tidal wetlands including marshes, ■ landscapes retaining a non-developed character, and ■ key plant and animal species These factors were developed by expert judgment with consultation in between the workshops from the Pamunkey Tribe Historic Preservation Officer.

Consideration was given to how each cultural resource could adapt in five categories of adaptive capacity: Physical Intrinsic (can adapt itself), Physical Technological (technology could be applied to adaption) Organisational, Social and Economic. For example, climate adaptations to collections and buildings may be expensive and therefore economic adaptation may not be possible (Ricci et al., 2019, p.38-39).

Through this process the Cultural Resources Workgroup observed that 'sites are already being lost to erosion and climate change factors' (Ricci et al., 2019, p.52). Their overall recommendation was that 'adaptation actions need to be implemented alongside ongoing planning processes'. Recommendations from the workgroup fell into two categories: planning and action.

Building on the previous report (Integrated coastal climate change vulnerability assessment: Colonial National Historical Park, Ricci et al., 2019) *The Method for Integrated Coastal Climate Change Vulnerability Assessment* (Ricci et al., 2019a) refines and summarises a method for conducting future assessments.

The goals of the vulnerability assessment are to help park managers:

- identify priority vulnerable resources/ assets to inform their adaptation planning processes;
- justify near term funding requirements to learn more about potential climate change vulnerabilities;
- inform investment prioritisation for resources that are highly vulnerable, but have a low ability to be conserved or to adapt (Ricci et al., 2019a, p.1).

The method uses existing data and expert knowledge of staff and partners which enables the vulnerability assessment to be done relatively quickly. The method is 'highly participatory' (Ricci et al., 2019a, p.1): it can involve NPS staff from park, regional, and Washington office levels and can invite participation from key stakeholders in local government, neighbouring partners, academics, and national groups. The NPS say that these actions 'provide support to move recommendations forward and broaden the conversation' and 'it cannot be overstated how valuable the social process is to the method, especially for working across divisions'.

The assessment tool used by the National Parks Service in this case follows the approach used by the IPCC and Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment (Glick et al. 2011). Ricci et al. (2019a) state that the significant difference in this method is that the framework does not treat adaptive capacity as a component of vulnerability. Their model is shared below (Figure 11) for reference:

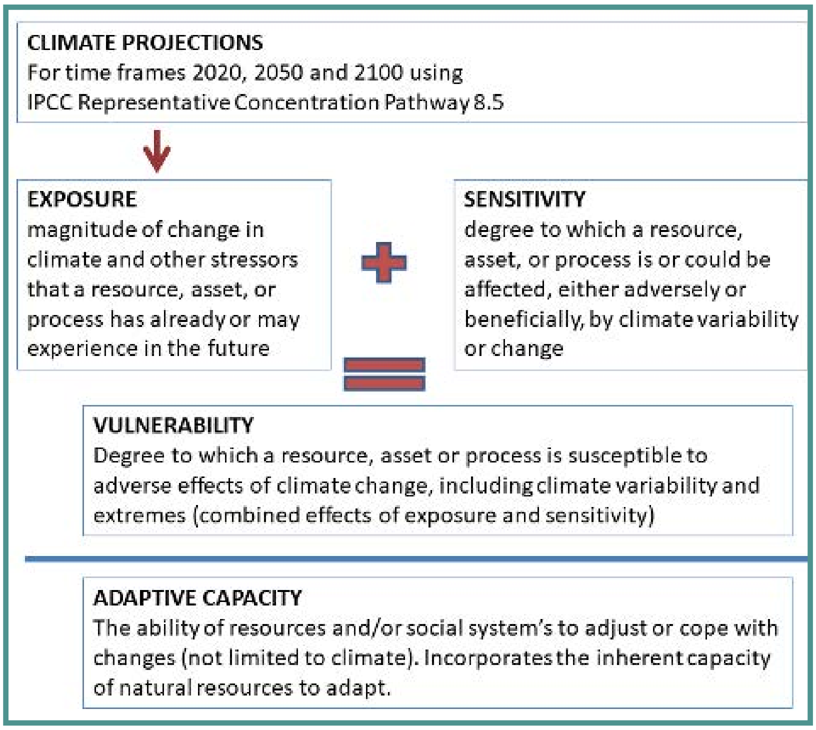


Figure 11: Ricci et al., 2019a: Overview of Climate Change Assessment Framework

Taken from: Ricci et al., (2019), Method for integrated coastal climate change vulnerability assessment

The vulnerability assessment is organised into nine steps 'beginning with the identification of resources and climate projections for three time periods followed by analysis of vulnerability and integration across priority issues' (Ricci et al., 2019a, p.ix).

Step 1: Identification of Resources and Goals

Step 2: Selection of Climate Projections

Step 3: Exposure Analysis

Step 4: Sensitivity Analysis

Step 5: Vulnerability Analysis

Step 6: Adaptive Capacity Analysis

Step 7: Integration Analysis and Recommendations

Step 8: Communicating Vulnerability

Step 9: Evaluation of Assessment Process

By the end of the process the following outputs are produced:

- **Vulnerability Assessment Report:** A detailed assessment report is produced for the park. It summarises the method and results, provides recommendations for next steps, and includes the raw data in the appendices.
- **GIS (Geographic Information System) Database:** All data is given to the park's GIS manager for record keeping and uploading to the system. There is the option to share the information.

(Ricci et al., 2019a, p.ix)

Johnson and Germano (2019) provide an overview of a vulnerability assessment (VA) model applied in the Pacific West Region (PWR) through three case studies. The case studies cover different landscapes from the State of Washington, the Territory of Guam, and Tinian, Commonwealth of the Northern Marianas Islands.

The PWR VA model incorporates published climate data and cultural resource documentation alongside information gained from collaboration with site staff and other consulting parties. This additional information on local natural systems, site condition, impacts, and management capacities helped to 'fill gaps in the published data by creating a clearer picture of local natural processes and observed changes' and provide a more complete picture of risk factors (Johnson and Germano, 2019, p.4). To capture this information, the team conducted, a questionnaire for site staff and other consulting parties, guided site visit and a structured workshop.

The VA in this article acted as a decision point in 'a larger process of developing and implementing an adaptation plan' (Johnson and Germano, 2019, p.13). It organised 'the best available information on significance, exposure, sensitivity, and management capacity to inform selection of management options'. It also identified areas where 'additional research, partnerships, or other site management support may be needed to implement treatment alternatives'. Due to the collaborative element of the VA, adaptation planning can address site-specific data gaps and be more responsive to local knowledge and capacities (Johnson and Germano, 2019, p.7).

Dante-Wood et al (2018) give an overview of vulnerability assessment work conducted in the Northern Rockies (USA) by the Northern Rockies Adaptation Partnership (NRAP). The NRAP is a science-management partnership who aim to 'provide the scientific foundation for operationalising climate change in planning, ecological restoration, and project management in the Northern Rockies' (Dante-Wood et al 2018, p4).

The NRAP region covers 74 million hectares, including northern Idaho, Montana, northwest Wyoming, North Dakota, and northern South Dakota. It also includes 15 national forests and 3 national parks across the U.S. Forest Service Northern Region and adjacent Greater Yellowstone Area (Dante-Wood et al 2018, p.1). NRAP conducted vulnerability assessments for key resource areas: water, fisheries, wildlife, forest and rangeland vegetation and disturbance, recreation, cultural heritage, and ecosystem services over 16 months. The method they used to complete the vulnerability assessments included (Dante-Wood et al 2018, p.5):

- Using scientific literature and expert knowledge to assess exposure, sensitivity, and adaptive capacity relative to key vulnerabilities in each resource area.
- Undertaking monthly phone meetings for each of the resource-specific assessments.
- Each assessment team identified key questions, selected values to assess, and determined which climate change models best informed the assessment.
- In some cases, assessment teams conducted spatial analyses and/or ran and interpreted models, selected criteria in which to evaluate model outputs, and developed maps of model output and resource sensitivities.

The NRAP explain that their vulnerability assessment provides 'information on climate change effects needed for national forest and national park plans, project plans, conservation strategies, restoration, and environmental effects analysis' (Dante-Wood et al 2018, p.5). The article talks about adaptation planning as an 'ongoing and iterative process' with implementation occurring at different times such as within the planning process or after the occurrence of 'extreme events and ecological disturbances (e.g., wildfire)' (p.6).

Again, as with the other USA-based vulnerability assessments there has been a focus on engagement with employees and partners. Engagement and communication with these groups and the general public is seen as an integral part of successfully responding to climate change.

This chapter has identified a number of comprehensive climate change risk assessment approaches for cultural heritage assets. These methodologies quantify risk by analysing all three of the standard IPCC determinants of risk, as well as considering site-specific sensitivity, adaptive capacity and heritage significance.

In all cases, these methodologies draw upon the knowledge and insights of local experts and stakeholders, often through collaborative, co-production methods such as workshops and qualitative interviews. While the use of local stakeholder input is undoubtedly a strength in acquiring a deep understanding of site vulnerability and, consequently, a holistic view of risk, methodologies which are dependent on local stakeholder involvement come with associated challenges around scalability. Indeed, the only way to scale up these site-specific approaches would be to repeat the process at multiple sites, which imposes a practical limit to their achievable geographical scale. The challenge is therefore finding a means of carrying out comprehensive risk assessments over larger scales and applying these methodologies to a portfolio of heritage assets in a given geographical region.

3.3 'Less comprehensive' approaches: Methodologies which consider two to three determinants of risk

This review identified a number of climate change risk assessment methodologies for heritage assets which are less comprehensive. That is, they offer methodologies for quantifying risk which do not fully integrate the three standard determinants of risk. Usually, this is due to the fact that insufficient consideration is given to the functions of vulnerability, most typically omitting considerations of a site's adaptive capacity. By failing to consider adaptive capacity, they fail to give a holistic assessment of vulnerability. This observation broadly aligns with the findings of recent literature reviews on the topic of climate change and heritage assets, which have concluded that most existing climate-related risk assessment frameworks for heritage assets only consider two or three of the determinants when quantifying risk (Crowley et al., 2022; Quesada-Ganuza et al., 2021).

In many cases, the methodologies which restrict the range of determinants attempt risk assessments over a larger geographic area or cover multiple heritage sites. However, there are also exceptions to this (Forino et al., 2016, which attempts to examine the vulnerability of a single heritage site without considering adaptive capacity).

The summaries that follow serve to outline these methodologies and describe some of their limitations.

Carmichael et al., (2017) propose a practical climate change risk analysis methodology for use by park rangers and managers of cultural and archaeological sites located within two national parks in Northern Australia, the Kakadu National Park and the Djelk Indigenous Protected Area. The methodology builds on an existing vulnerability assessment framework designed for application on coastal archaeological sites in France (Daire et al., 2012) and employs an in-situ field survey approach which integrates an assessment of the relative cultural value of sites with assessments of exposure and sensitivity to climate impacts. It incorporates a participatory research methodology, which draws upon the views of indigenous natural resource managers and custodians of rock art and midden sites, working in the two national parks. It involves these stakeholders in the risk assessment process through planning workshops, semi-structured interviews and participant observations.

The methodology proposed by Carmichael et al. offers a practical, useable framework for assessing climate change risks which can be employed by heritage resource managers at the local level. However, it has certain characteristics which limit the adaptability of this framework to the UK heritage context. The assessment variables used to carry out assessments of exposure and vulnerability are quite restricted and questions are specific to the context of Australian national parks. Furthermore, while the framework includes a consideration of 'adaptive capacity', assessments of adaptive capacity are not integrated into the overall process for quantifying risk.

The first part of the risk assessment process outlined by Carmichael et al. involves park rangers and resource managers assessing the significance of historic and archaeological sites in their care. Local rangers and heritage managers are asked questions which were developed to gauge the cultural significance of sites, based on three priority classes of evaluation (group identity value, historic value, and spiritual value). These classifications were based on ICOMOS categories of significance ('aesthetic, historic, scientific, social or spiritual value' – 'Social' is here defined in terms of 'group' or 'community identity'. Carmichael et al. state that *'although all classes of significance are important, spiritual value is graded as the highest priority and group identity value as the foundational priority. Group identity value is taken as a given for all middens and rock art and is the default position. If a site was not classified as culturally significant* *in terms of historical value but culturally significant in terms of spiritual value, it was rated class three.'*

Rangers/heritage managers were then involved in assessing each site's vulnerability and exposure. Exposure and sensitivity of the site is assessed through 15 exposure and sensitivity variables, each with three assessment options. The variables are shown in Table 12. Assessment options used in this model were: strong = 1, some = 0.6, and none = 0.2.

Scores for exposure and sensitivity are then added together to create a score for total exposure and for total sensitivity, respectively. The total score for sensitivity is then deducted from the total score for exposure to produce a total score for likelihood of loss or damage. This resulting score is then combined with the cultural significance scores for each site in a management priority matrix, giving rise to one of five possible management priorities: 'very low', 'low', 'medium', 'high' or 'very high'. An example is set out in Figure 12, below:

A—Exposure Hazard types	Variables
Human	Proximity of township or outstation Proximity of tourism or hunting/gathering Proximity of graded road or track
Climate change and extremes	Proximity to tidal edge/river Height above tidal edge/river Geomorphology: ◦ *Rock art*—gorge: location and breadth ◦ *Floodplain midden*—proximity of channel ◦ *Coastal midden*—proximity of river mouth
Biological	Feral animals and weeds—impact Native flora/fauna—impact Fire hazard—vegetation and detritus build up
Natural weathering	◦ *Rock art*—fading ◦ *Midden*—degree of deflation
B—Sensitivity Sensitivity factors	Variables
Nature of remains	◦ *Rock art*—ochre type ◦ *Midden*—structure
Nature of substrate	◦ *Rock art*—rock hardness ◦ *Midden*—doil type
Natural protection	◦ *Rock art*—rock overhang ◦ *Midden*—tree consolidation
Built protection	Fence—effectiveness
Legal protection	Site is (a) on Indigenous owned land or (b) listed under heritage protection legislation

Table 12: Carmichael et al (2017): Variables used for the assessment of exposure and sensitivity

Taken from: Carmichael, B. et al., (2017), 'Local and Indigenous management of climate change risks to archaeological sites', Mitigation and Adaptation Strategies for Global Change 23(2)

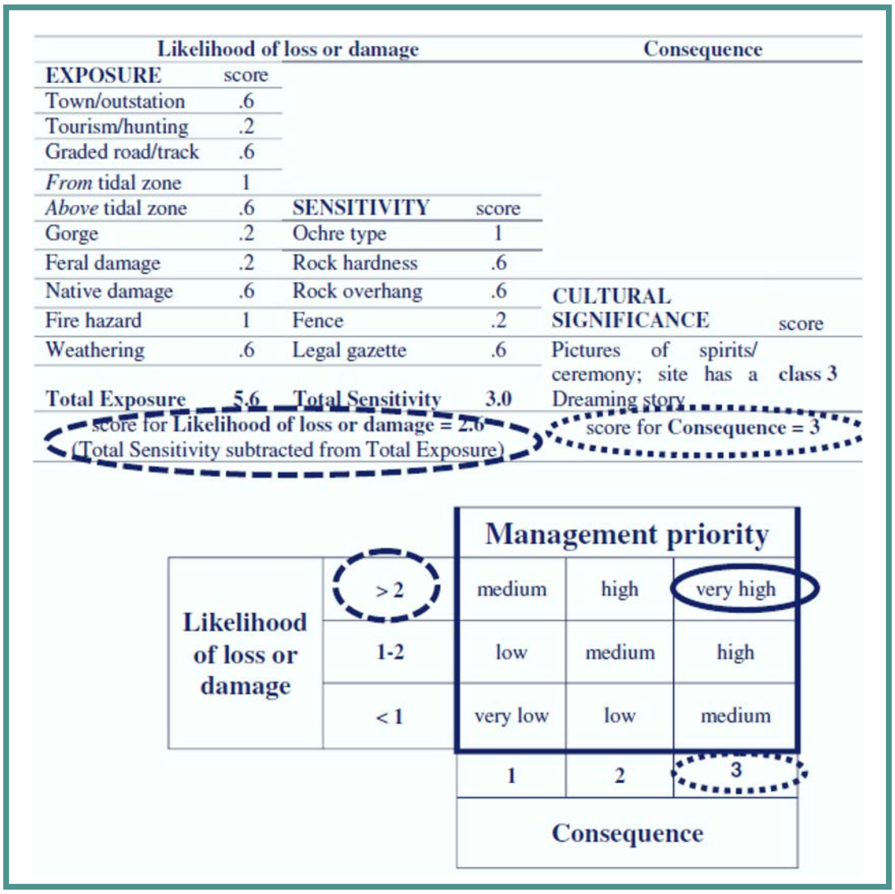


Figure 12: Carmichael et al. (2017): Model for calculating likelihood of loss or damage to heritage assets

Taken from: Carmichael, B. et al., (2017), 'Local and Indigenous management of climate change risks to archaeological sites', Mitigation and Adaptation Strategies for Global Change 23(2)

Assessment of adaptive capacity is focused on the adaptive capacity of the rangers themselves, rather than site adaptive capacity, and is also separate from the rest of the risk assessment process. Carmichael et al. set out the following rationale for assessments of adaptive capacity:

> ***We propose that adaptive capacity assessment focus on workshops discussing stakeholder adaptive capacity, held during the first step, the scoping phase, in the Cultural Site Adaptation Guide. During the third step, the option analysis phase, participants can more clearly focus on ways to increase stakeholder adaptive capacity and thus their overall level of resilience. Hence, assessment of adaptive capacity is not part of the risk analysis phase of the Cultural Site Adaptation Guide presented in this paper.***

One of the principal limitations of the methodology proposed by Carmichael et al. is the limited range of variables used in the assessments of exposure and sensitivity. The variables used to assess the exposure of historic and cultural sites are restricted to a selection of hazards which are specific to the climate and cultural heritage of Australian national parks (e.g., Rock art – gorge: location and breadth; coastal midden – proximity of river mouth). Furthermore, the assessment of 'sensitivity' is restricted to considerations of the physical attributes of the sites and their legal protection status. This assessment framework consequently lacks a comprehensive assessment of both vulnerability and adaptive capacity that can take into consideration not only the inherent, physical aspects of the site but also the human, economic and institutional capacity necessary to adapt to climate change, such as management and financial resources and institutional planning.

Carmichael et al. therefore offer a useful model – based on a sequence of key assessment variables – for thinking about climate change risk assessment across multiple heritage sites in a given region. However, the limitations outlined above mean that it is not immediately adaptable to the UK context.

The assessment methodology on which Carmichael's approach is based (Daire et al, 2012) is also limited in much the same way. Daire et al. propose a multidisciplinary approach to assess the vulnerability of archaeological heritage in the West of France. Their approach is based on a series of variables concerning both the threats (including *'anthropogenic, infrastructure, traffic/frequency of passage, human activity, biological erosion, and weathering')* *and the 'resistance capacity'* of the site ('resistance of the remains, local substrate and geomorphology, existing physical or legal protection').

The organising principle used for compiling these data is a standardised form that provides field archaeologists with an evaluation procedure that is based on an objective observation of the sites. A series of ten variables were used in the assessment of each site's vulnerability:

1. **Infrastructure:** this variable concerns the presence of private houses, buildings, camp sites, parking lots, etc.
2. **Traffic/frequency of passage:** concerns the presence of a country road, path, track, dirt track or lane used by pedestrians, bicycles, cars, etc.
3. **Activities:** concerns the presence of human activities linked to tourism (e.g., sailing), agriculture (ploughing), or industry (harbour, quarry, shellfish farming, etc.).
4. **Distance to the cliff:** concerns the distance between the archaeological site and the edge of the nearest cliff.
5. **Biological erosion:** takes into consideration the presence of tree roots, burrowing animals, or any other biological activity likely to disrupt the remains.
6. **Weathering:** concerns the exposure of the site to wave and wind action.
7. **Resistance of the remains:** concerns the evaluation of the physical resistance of the local remains (mechanical strength of the artifacts, raw materials and archaeological deposits) that can vary according to the nature of the remains (stones, sand, etc.), taphonomy of the site, etc.
8. **Resistance of the local substrate:** concerns the evaluation of the physical resistance of the local sediment or rock in which the artifacts and remains are embedded (hard rock, weathered rocks, soft rocks, clay, sand, etc.).
9. **Physical protection:** concerns the fences protecting the site or any equivalent structure (walling, barbed wire, etc.)
10. **Legal protection:** takes into account the presence or absence of potential legal protection on the site, linked to environment or heritage management, the nature of which varies according to French legislation.

Daire et al. offer the following explanation for these variables:

> *Variables 1, 2, and 3 are evaluated in terms of distance from the archaeological site. The closer the site to each type of anthropogenic threat, the more serious the threat is and the eventual consequences on the archaeological record. Variable 4 is also evaluated by the distance criteria, as well as variables 9 and 10, each with a range of 5 values, from less than 10 meters (which effectively means superimposition with the archaeological site) up to more than 500 meters (meaning that the criteria may be absent or the threat does not exist at the considered site). Variables 5, 6, 7, and 8 are evaluated in terms of intensity (or efficiency), from very strong to almost inactive.*

The overall vulnerability score is then calculated by adding together the scores for impacts (variables 1-6, above); then adding together the scores for resistance (variables 7-10); and finally subtracting the overall score for resistance from the overall score for impact.

The principal limitation of this approach is that it only focuses on a small number of potential hazards associated with environmental processes (biological erosion, weathering), while exposure is explored only in terms of proximity to a cliff edge. Like Carmichael et al., this methodology also fails to offer a full assessment of either the vulnerability or adaptive capacity of sites: the method focuses only on the inherent, physical characteristics of each site (resistance of the site remains and the local substrate) but does not consider the management and financial resources available at each site to respond to and adapt to climate change.

Building on the approach outlined by Daire et al., Cook et al. (2021) have proposed an alternative approach for assessing the vulnerability of archaeological heritage, based on a 'Landscape Vulnerability Framework', which attempts to situate archaeological sites within the context of their historic landscape. This framework is based on an assessment of the vulnerability of landscape character areas (LCAs) (which are based on 'Historic Landscape Characterizations').

The framework involves a two-step approach to assessing vulnerability. The first assesses the vulnerability of landscape character features (LCF). The second then scales up the results of the first assessment to consider threats to the LCAs. LCFs are parts of a landscape that influence the character of LCAs, such as drystone walls, historic military defensive features, and areas of ancient and plantation woodland. They also include archaeological "sites". **Five variables are considered in the vulnerability equation for the LCFs:**

- **a.** current levels of preservation
- **b.** resistance of the remains
- **c.** resistance of the local substrate
- **d.** the susceptibility of the LCF to projected temperature changes
- **e.** the susceptibility of the LCF to projected precipitation changes

According to Cook et al., variables a) and b) are intended to address the susceptibility and adaptive capacity of the LCF, variable c) is intended to address the exposure of the LCF, and variables d) and e) are intended to address the susceptibility of the LCF. Data for each variable are gathered through secondary sources – such as archaeological or monument databases, geological survey data and climate change projections – and also site visits.

The second step involves using results from the first step to calculate vulnerability of the LCA. **A vulnerability score for the LCAs is calculated using the following variables:**

- **a.** the vulnerability of the LCFs that characterise the LCA (the outcome of the first VI equation);
- **b.** the proportion of the LCA that is threatened by sea-level rise and inundation;
- **c.** the proximity of the LCA to an eroding stretch of shoreline;
- **d.** the susceptibility of the soil types in the LCA to erosion.

According to Cook et al., the latter two variables were chosen as indicators of the exposure of LCAs to climate change impacts, while the former three variables address the susceptibility and resilience of the character of the LCA.

Although this framework offers a novel approach by attempting to situate assessments of archaeological site vulnerability within the context of the vulnerability of the wider historic landscape, this framework is limited in similar ways to Daire et al. While this framework considers the level of site preservation, and so offers a somewhat more comprehensive assessment of sensitivity (as a function of vulnerability), the counterpoint to vulnerability is still limited to the inherent, physical characteristics of the site (resistance of remains; resistance of local substrate), meaning that there is no assessment of adaptive capacity. The framework also examines only a limited number of hazards (temperature, precipitation changes, sea level rise, coastal erosion) and exposure of the wider LCA is largely assessed in terms of proximity to eroding shoreline and erosion of soil types.

García Sánchez et al. (2020) have proposed a risk assessment methodology specifically designed to quantify and assign risk scores for multiple heritage coastal fortifications threatened by sea level rise in the Canary Islands. Risk in this methodology is quantified on the basis of assessments of each site's exposure and vulnerability to sea level rise. Exposure is divided into the three sub-categories, based on the site's exposure to coastal flooding (CF), coastal erosion (CE), and coastline retreat (CR). Field surveys and visual analysis were conducted to assess each site's material exposure, and level of exposure to each sub-category of exposure was graded from 1-4 ('low', 'medium', 'high', and 'very high').

Vulnerability of each site is calculated based on each site's 'sensitivity' and 'adaptive capacity'. The site's 'sensitivity' is assessed through an analysis of three areas: 'structural stability', 'external conditions', and 'damages'. Scores between 1-4 were given to each site, based on the percentage of the functional structure affected: less than 20% (assumable damage), 20–40% (reversible damage), 40–60% (high damage), and higher than 60% (irreversible damage). Adaptive capacity is assessed through a review of existing management tools. For these case studies, however, no investment resources, plans, or priorities of investment were found relating to climate change for coastal fortifications, so 'adaptive capacity' was not included in the risk scores assigned to these sites.

Risk is then calculated based on the following equation: ((Exposure x Sensitivity) – Adaptive Capacity). The following risk scores are then applied:

Risk	Risk Score	Characteristics
Very High	>28	- Unacceptable level of risk that requires immediate adaptation action
High	21–28	- Unacceptable level of risk which requires controls to reduce impacts
Medium	11–20	- Acceptable level of risk subject to regular passive monitoring
Low	0–10	- Acceptable level of risk

Table 13: Garcia Sanchez et al. (2020): Definition of Risk Scores according to exposure and vulnerability

Taken from: García Sánchez, F. et al., (2020), 'Cultural heritage and sea level rise threat: risk assessment of coastal fortifications in the Canary Islands' Journal of Cultural Heritage, 44

Although the model proposed by García Sánchez et al. quantifies risk based on the four determinants of hazard, exposure, vulnerability and adaptive capacity, there is no convincing method for quantifying adaptive capacity, as the case study assets identified no specific materials with which to assess each site's adaptive capacity. Furthermore, no mention is made of significance and the assessment methodology is not based on the heritage values of each site. The methods used to assess exposure and vulnerability are also entirely based on site visits and secondary data; there is no engagement with stakeholders (García Sánchez et al., 2020).

Forino et al. (2016) have proposed the Cultural Heritage Risk Index (CHRI) as an integrated risk assessment methodology, designed to assess climate change-related risk for cultural heritage. It was developed and trialled on a unique heritage site: the Burwood Beach Wastewater Treatment Works, located near the coast in Newcastle Australia, which contains important historic treatment buildings. **The methodology is based on four analytical steps:**

1. Hazard Analysis, which quantifies the physical characteristics of hazards;
2. Exposure Analysis, which 'identifies and maps underlying exposures of cultural heritage';
3. Vulnerability Analysis, which assesses the degree of susceptibility of those elements at risk which are liable to be exposed to the hazard;

4. Risk Analysis, which synthesises the scores resulting from the previous 3 steps and determines an overall, weighted numerical CHRI score for an individual heritage asset.

Risk to cultural heritage assets in this methodology is therefore quantified as a function of hazard, exposure and vulnerability. The adaptive capacity of the site is not taken into consideration.

The first step (hazard analysis) involves the quantification of hazards based primarily on secondary literature and data, such as archival and historical records, global climate modelling and meteorological data. The exposure and vulnerability scores, however, are calculated using relevant archival records and data sources combined with consultation with expert stakeholders. These include consultation with owners and site visits conducted by built environment professionals (such as structural engineers, architects, builders, conservation specialists). The exposure score is based on summing scores for the extent to which the asset is in current use (score out of ten) and for the probable a) direct and b) indirect economic impacts of losing the asset (each scored out of five). There is, notably, no consideration of the non-economic impacts of losing the asset, meaning that explicit consideration of non-economic heritage significance does not form part of the analysis.

The vulnerability analysis seeks to establish the predicted impact of a hazard on the heritage asset's significance (which is here seen as the primary reason for the site's listing) and encompasses three variables: structural condition, asset fabric condition, and historical damage. The structural condition denotes the degree to which the structure has sufficient integrity to withstand potential hazards. The asset fabric condition establishes the degree to which the asset materials can withstand potential hazards. Finally, historical damage examines how frequently an asset has been exposed to the hazard in the past. Vulnerability *'expresses the probability that the attributes (significance, authenticity) of a cultural heritage asset will be negatively impacted given a particular climate event.'*

It should be noted that vulnerability in these terms equates to the category of 'susceptibility' or 'sensitivity' found in many standard approaches to risk assessment.

The final score was based on summing the scores for the individual component analyses, and then assigning the scores (in a process unconventionally referred to in the paper as 'weighting') to the nearest point on a ten-point scale. Each of the points was then given a qualitative description that outlined the level of risk and degree of need for adaptive behaviour, from none, other than routine maintenance, to 'urgent and immediate intervention'.

3.4 Methodologies which consider one or two determinants of risk

3.4.1 Impact and hazard modelling

By far the largest number of methodologies reviewed here are large-scale hazard mapping and impact modelling studies focused on quantifying climate-change threats to heritage sites over large geographic areas.

Impact modelling methodologies are not strictly risk assessments as their objective is not to quantify risk for specific heritage assets, but rather to model specific hazards and map them to the locations of heritage sites. The purpose is to assist in the identification of sites likely to be the most threatened by climate hazards (such as coastal sites threatened by sea level rise, coastal erosion, coastal flooding). These methodologies mostly employ desk-based approaches and GIS methods, combining secondary data derived from climate change projection models (or historical data on climate change trends) and geo-spatial data on heritage sites, to map specific hazards to sites over large spatial areas.

This approach has been particularly important for researchers studying threats to coastal heritage sites over large geographical areas:

- Westley et al. (2021) used a geospatial database of maritime archaeological sites across the Middle East and North Africa (MENA) to map and quantify climate change threats (specifically sea level rise, coastal erosion and coastal flooding) to archaeological sites in the MENA region. This database (the Maritime Endangered Archaeology inventory) incorporates a disturbance/ threat assessment and information in the database is based on high resolution (<1 m) satellite imagery, supplemented by other data sources, including literature, historic imagery, historic maps, geophysical data, and field survey.
- Reimann et al. (2018) used data on the locations of UNESCO world heritage sites (WHS), combined with predictions on future flood risks and erosion risks associated with sea level rise derived from climate change projection models, to identify Mediterranean WHSs threatened by coastal flooding and erosion under four Sea Level Rise (SLR) scenarios from 2000 to 2100. The researchers specifically refrained from examining the vulnerability of individual WHS 'as local-scale data concerning the internal characteristics of a WHS such as heritage material or heritage inventory are not readily available and including those in the analysis goes beyond the scope of this first-order assessment.'
- Reeder-Myers (2015) used spatial modelling techniques which combined large-scale secondary data on coastal geomorphology, historic sea-level rise, coastal slope and historical erosion rates with data on archaeological site location to map hazards to sites and identify the most highly threatened coastal sites on two US coastlines. Reeder-Myers calculated 'cultural resource vulnerability' (CRV) for each archaeological site according to its position on the landscape (distance to shoreline and elevation), the degree of vulnerability of the nearest shoreline, and modern land use at the site.
- Marzeion and Levermann (2014) used sea level estimates for the next 2000 years and high-resolution topography data to compute which current cultural heritage sites defined by UNESCO will be affected by sea level rise at different levels of sustained future warming.
- In an earlier publication, Westley et al. (2011) examined the vulnerability of coastal archaeological sites to sea level rise in Newfoundland using a desk-based modelling exercise that made use of extant digital datasets

in a GIS environment. Westley et al. used predictions of global ocean volume change over the next century to estimate general patterns of future inundation and coastal erosion, to which they overlaid data on the distribution of known coastal archaeological sites to identify sites vulnerable to coastal erosion and coastal flooding caused by sea level rise.

Researchers have also used the same data-driven, hazard modelling approach to quantify inland flooding risks and identify heritage sites at risk from flooding from rivers:

- Van Meerbeck et al. (2017) developed strategies for mitigating risk of flooding exacerbated by climate change for the Via Iulia Augusta in Albenga, Italy. Flood risk was assessed by desk research and an onsite survey. The desk research consulted cartography, historic documents, climate data, books, scientific papers, satellite imagery and policy documents. Onsite surveys gathered heritage information using remote sensing tools, including unmanned aerial vehicles and GPS.
- A. Howard et al. (2016) used national climate change scenarios to model future river flow changes, the results of which were subsequently mapped against the locations of heritage properties in the Derwent Valley, to identify zones on the valley floor where pro-active mitigation might be required.
- J. J. Wang (2015) generated simulations of flood-prone areas based on varying precipitation scenarios, focused on New Taipei City in northern Taiwan, using GIS to overlay the locations of cultural heritage sites and create flood risk maps to identify cultural heritage likely to be affected by flooding.

Historic England's Coastal Erosion Risk Assessment (CERA) (2010-2011) and the inland flood risk assessment for the national collection (2013) can also be seen as fitting into this category of research. Both were desk-based risk assessments which made use of digital data in a GIS environment to map the extent of overlap between property boundaries and the predicted flood zones and coastal erosion patterns. Where there was no overlap, the sites were classified at low risk (Heathcote et al., 2017).

A number of researchers have also used the same approach to map multi-hazards to heritage sites over large geographic areas:

- M.M. Yagoub and Abdulla Amed Al Yammah (2022) used secondary data sources, including scenes from the Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor of 2020 covering the UAE which were downloaded from the United States Geological Survey (USGS) website. Remote sensing and GIS methods were applied to assess the spatial distribution of natural hazards (earthquakes, floods, and sea-level rise) and their proximity to heritage sites in the UAE.
- Saha et al. (2021), used secondary historic data on rock falls and debris falls, and geographic information on the location of heritage assets, to undertake multi-hazard susceptibility mapping of cultural heritage sites in the Eastern Himalayan region of the State of Sikkim, India, to identify cultural heritage sites' vulnerable to rock and debris falls caused by earthquakes. Multi-hazard susceptibility mapping was carried out using boosted regression tree (BRT), Bayesian additive regression tree (BART) and Bayesian generalised linear model (BGLM) methods, which took into account twenty-two conditioning factors along with seismic activity.

- Fenger Nielsen et al. (2020) undertook a 'multi-threat assessment' which used remote-sensing observations and climate projections to quantify and map climate-related threats to archaeological sites across Greenland and identify the most threatened sites.

The advantage that this large-scale, desk-based and data-driven approach offers is that multiple climate change hazards can be easily studied over a wide geographical area, enabling potentially vulnerable sites to be identified in a shorter space of time than would be needed for detailed field-based examinations. The main drawback, however, is that these approaches often fail to capture the granular, site-specific information – such as the condition of specific sites, the materials used, the financial and management resources available at site level – which are needed to carry out assessments of vulnerability and adaptive capacity.

The desk-based nature of these assessments, while permitting a wider geographical area to be included in the study, limits the scope of the assessment to characteristics that can be assessed remotely and across large areas, for instance, topographic slope angles, rates of relative sea-level rise, and tidal ranges of the nearest coastlines. The characteristics of the archaeological sites themselves, including the materials from which sites are constructed and current levels of preservation, are generally not captured in large, data-driven approaches (Cook et al., 2021). This means that impact modelling studies typically fail to take into consideration the sensitivity or adaptive capacity (and thus overall vulnerability) of individual sites, as well as the heritage significance of individual sites. Impact modelling focuses for the most part on quantifying and mapping hazards; exposure is considered only in terms of the site's proximity either to hazard zones mapped through climate projection models, or to coastal areas susceptible to hazards like sea level rise (Carmichael et al., 2017).

Heilen at al. (2018) have proposed a more comprehensive framework for impact modelling which attempts to incorporate consideration of site significance alongside the process of mapping climate change impacts onto the locations of heritage assets. **Heilen et al.'s framework is made up of five components:**

1. Development of vulnerability models predicting the extent, timing, and severity of climate change impacts.
2. Compilation, synthesis, and analysis of digital, geo-referenced information on heritage resource locations and attributes.
3. Development of locational models predicting the location of archaeological sites, according to site type, in unstudied or understudied areas.
4. Development of significance models predicting heritage values associated with particular resources.
5. Prioritisation of research, salvage, and preservation efforts.

The significance of individual heritage assets is addressed in this framework using 'significance modelling' tools. These tools use data on common site attributes (such as site size, types and counts of artifacts, presence or absence of features) to infer the *'information potential and potential traditional cultural sensitivity'* of heritage sites. Heilen et al. explain that:

> ***Significance models allow large numbers of sites, even ostensibly similar ones, to be rapidly and objectively differentiated according to their research potential and other values. Planning and management efforts can consider the entire resource base of a particular area as well as the cumulative effect of not just a single project under consideration, but all potential impacts that could occur in an area. This allows for a broad understanding of the distribution of resource values long before conducting formal field investigations, which in many cases are unlikely to occur before climate change impacts are rampant.***
>
> *(Heilen et al., 2018)*

However, while this framework may attempt to address the issue of heritage significance in impact modelling methodologies, it does not offer an effective means of capturing and assessing granular, site-based data on sensitivity or adaptive capacity.

3.4.2 Possible solutions – attempts to reconcile large-scale hazard mapping and site-based vulnerability assessments

The challenge of integrating large-scale, data-driven assessments which use desk-based approaches to map hazards over large spatial scales, on the one hand, with site-based assessments of vulnerability, on the other, is amply demonstrated through the recent EU-funded ProteCHt2save project. The Interreg Central Europe Project ProteCHt2save is an initiative which aims to improve the capacities of both the public and private sectors to mitigate the impacts of climate change and natural hazards on cultural heritage sites (including monumental complexes, historic buildings and related collections) in urban and coastal areas of Central Europe (Bonazza et al., 2021). **The project is focused on the development of two main tools which are designed to help build the resilience of cultural heritage assets in a changing climate:**

1. Development of large-scale hazard maps, based on data from climate models, of areas of Central Europe where cultural heritage is exposed to heavy rain, flooding and/or prolonged drought;
2. Vulnerability assessment of elements of monumental complexes and historic buildings (Bonazza et al., 2021).

ProteCHt2save, therefore, attempts to bring together the two approaches of regional hazard mapping and site-based vulnerability assessments. However, it largely fails to bring the two components together in an integrated methodology for assessing risk.

Hazard maps of large regions of Europe affected by the hazards of heavy rain, flooding and prolonged drought can be generated using data outputs from climate models, based on climate-extreme indices defined by the Expert Team on Climate Change Detection Indices (ETCCDI). The data which is used to generate these maps includes both historical climate data and climate projections at regional scales, for the near and far future, under Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios. Regional climate projections for the European continent are based on Global Climate Models (GCMs) driving an ensemble of regional climate models (RCMs) (Sardella et al., 2020).

The vulnerability assessment aspect of the ProteCHt2save project – undertaken at the level of individual historical sites – is based on vulnerability matrices, and is intended to be flexible and suitable for use by non-technical users, such as owners and managers of heritage assets. The vulnerability assessment component represents a simplified assessment, based on the concept of 'criticality'. Criticality is defined as *'any element/aspect in a cultural heritage system which affects its resilience.'* According to A. Bonazza, while mainstream definitions of 'vulnerability' typically encompass difficult to grasp concepts such as sensitivity, exposure and adaptive capacity, *'criticality is a more general term related to problems or issues easily identifiable by non-technical stakeholders.'* Vulnerability assessments based on key criticalities of the site are, therefore, easier to use for site managers and owners (Bonazza et al., 2021).

The proposed methodology, set out as part of ProteCHt2save, *'considers two main groups which characterise cultural heritage systems, namely managerial and physical criticalities.'*

'Managerial criticalities relate to those aspects which are not connected to the physicality of the assets but rather to their operation, administration and care. **Managerial criticalities include the following categories**':

- MC1- information concerning cultural heritage object
- MC2- funding availability and accessibility
- MC3- knowledge and awareness
- MC4- cultural heritage planning
- MC5- policy and regulations

Site managers/owners completing the vulnerability assessment are presented with tables with predetermined, colour-coded rankings of the various managerial criticalities (ranging from green to red i.e., from the least to most susceptible condition). They are then asked to position their heritage asset according to the rankings. An example concerning managerial 'knowledge and awareness' (MC3) is shown in Table 14.

Rank	Value
KA0	Knowledge and awareness are ensured
KA1	Lack of awareness
KA2	No knowledge sharing among different stakeholders
KA3	Lack of technical knowledge

Table 14: ProteCHt2save vulnerability assessment: Ranking and value description of MC3 'Knowledge and Awareness'

Taken from: Bonazza, A. et al., (2021), 'Safeguarding cultural heritage from climate change related hydrometeorological hazards in Central Europe', International Journal of Disaster Risk Reduction, 63

'Physical criticalities relate to aspects of the cultural asset involving its actual material composition and structural condition. For practical reasons, physical criticalities are categorized in relation to the type of hazard (flood, fire following drought periods, wind, heavy rain); their ranking is based on the evaluation of the sensitiveness of structures and elements to the effect of the specific hazard considered' **selected physical criticalities categories include:**

- PC1- flood
- PC2 - fire following drought periods
- PC3- wind
- PC4- heavy rain

An example for 'flood' is shown in Table 15.

Rank	Value
F0	Flood-resistant structures and buildings
F1	Structures made of materials with a high volumetric change due to moisture
F2	Structures made of materials that lose their strength to a great extent when subjected to moisture
F3	Structures susceptible to partial damage due to flooding

Table 15: ProteCHt2save vulnerability assessment: Ranking and value description of PC1 flood

Taken from: Bonazza, A. et al., (2021), 'Safeguarding cultural heritage from climate change related hydrometeorological hazards in Central Europe', International Journal of Disaster Risk Reduction, 63

Site managers/owners completing the vulnerability assessment then evaluate the physical criticalities of their own site against these colour-coding rankings (all from Bonazza et al., 2021).

The main limitation of the ProteCHt2save project is that it is not yet a fully integrated risk assessment methodology: it is a hazard mapping tool at broad territorial scale (based on climate data), which is followed by a simplified vulnerability assessment at individual site level, based on assessments of physical and managerial criticalities. The ProteCHt2save project represents great advancements in the field of identifying hazards and assessing vulnerabilities of individual heritage properties, but as yet it does not appear to propose a means of assimilating the results of the hazard mapping and vulnerability assessment exercises to provide an overall risk assessment for individual sites. In addition, its departure from the standard IPCC approaches to conceptualising vulnerability make it something of an outlier in the broader context of cultural heritage risk assessments.

A more comprehensive approach – which attempts to combine large-scale, data-driven approaches with site-specific assessments of vulnerability – is proposed by Westley in their broad-scale vulnerability assessment of coastal archaeological resources in Lough Foyle, Northern Ireland (Westley, 2019). Westley's methodology involved using secondary data and GIS-based software (Digital Shoreline Analysis System (DSAS)) to quantify local shoreline change and characterise present-day and future patterns of erosion. However, Westley's approach also involved field surveys to assess the condition of archaeological sites, as well as identifying unrecorded ones. Results from the DSAS and field surveys were then used as the basis for establishing an estimate of vulnerability for each site. This estimate of vulnerability was calculated based on the site's significance, condition and risk. A final vulnerability assessment was then calculated based on the assessments of site significance, condition and risk.

Westley's approach to assessing significance, condition and risk is outlined as follows:

- **Significance** is judged on the basis of *'the historic asset's rarity, period, potential to contribute to knowledge and group value, for instance whether it is an isolated example or part of a wider grouping.'*
- **Condition** is based on *'the physical appearance of the site as assessed by the field survey. For inland sites which were not surveyed, their physical appearance was based on the orthophoto evidence and extant HER records. Sites regarded to be in good condition appear largely intact and undamaged. Conversely, sites in poor condition are broken up, damaged or eroded out of context.'*
- Risk was based on the field survey combined with DSAS results. High-risk sites are those which are:

1. *'exposed in the intertidal zone (i.e., continuously impacted by waves and tides); or*
2. *located in exposed backshore sections where DSAS results indicate on-going erosion; or*

3. *located inland of the backshore edge, but based on DSAS results are predicted to erode in less than 5years.'*

Moderate risk sites are those located inland of the backshore edge, but based on DSAS results are predicted to erode in 5–10 years; while low-risk sites are similar but predicted to erode in>10 years.

Sites are then ranked on a scale of 1 to 3 (representing 'low', 'moderate', and 'high' respectively) for each of the categories of 'significance', 'condition' and 'risk', and the cumulative value is used to provide the final vulnerability estimate. According to Westley, *'effectively, the highest priority sites are high-significance sites in good condition but at high risk from erosion. Conversely, the lowest priority sites are low-significance sites in poor condition, and at low risk from erosion.'*

Westley's methodology seeks to bridge the gap between large-scale, data-driven approaches and site-based vulnerability assessments by combining a regional GIS-based mapping exercise with a sample of site visits. While this may offer a promising starting point for integrating vulnerability assessments into regional impact modelling approaches, there are a number of limitations in Westley's methodology. Firstly, while site visits may offer a means of analysing site vulnerability (or, more specifically, condition), the assessment of each site's vulnerability appears to be based on the site's physical appearance. Little consideration is given to the material sensitivities of the site to certain hazards (for instance, whether certain historic materials are more susceptible to damage or collapse when confronted with coastal erosion), and no mention is made of assessing the adaptive capacity of each site, in terms of the financial and managerial resources available to offset climate threats.

Furthermore, criteria for assessing and judging the condition is not clearly defined *('sites regarded to be in good condition appear largely intact and undamaged. Conversely, sites in poor condition are broken up, damaged or eroded out of context')*. Assessments of vulnerability are therefore based on subjective judgements of condition, which is something that Westley duly notes: *'It must be stressed that this is a subjective classification, and different researchers might classify each individual site differently or indeed develop classification schemes more applicable to their own study area and/or approach.'* (Westley, 2019).

Recent research focused on assessing the vulnerability of the historic environment to flooding events may offer some useful methodological approaches to integrate more granular assessments of vulnerability into large-scale, data-driven mapping approaches. To cite just one example, Stephenson and D'Ayala (2014) have developed a methodology for assessing the vulnerability of individual historic buildings to flood inundation, based on a set of 'descriptive parameters' which bring together the unique characteristics and intrinsic properties of a building that contribute to its flood vulnerability. **The descriptive parameters used in this assessment are:**

- age
- listed status
- use
- footprint
- number of storeys
- materials and structure
- condition

These parameters are used to profile the relative vulnerability of different historic buildings and building typologies, in order to determine the loss potential of the building. Each parameter is used to assess a different aspect of the building's vulnerability to flooding. According to

Stephenson and D'Ayala, age and listed status *'provide a measure of the value of the cultural asset',* while building use provides a measure of the building's revenue potential. *'The footprint of the building and its number of storeys provide the metrics of the asset at risk. The materials and structural system relate to the susceptibility of the building fabric to be damaged by flood, whilst the condition of the building is a measure of the resilience of the structure to the stresses placed upon it by the hazard.'* (Stephenson and D'Ayala, 2014).

For each parameter, a range of 'attributes' were identified and assigned a vulnerability rating (VR) on a scale from 10 to 100. Attributes with the lowest vulnerability were assigned a score of 10, while attributes with the highest vulnerability were assigned a score of 100 (Table 16).

Users of this methodology use the VR ratings in the table above to give an overall vulnerability score to the buildings they are assessing. For instance, an unlisted, Georgian, timber-framed building with three storeys in excellent condition would score 215 (10+55+70+70+10=215).

Table 16: Stephenson and D'Ayala (2014): Flood vulnerability descriptor ratings for individual heritage buildings

Taken from: Stephenson, V. and D'Ayala, D, (2014), A new approach to flood vulnerability assessment for historic buildings in England, Natural Hazards and Earth Systems, 14, 1035–1048

Table 1. Vulnerability descriptor ratings.

Descriptor	Response	VR
Age	Medieval/Tudor	100
	Jacobean	77.5
	Georgian	55
	Victorian	32.5
	Modern	10
Listed status	Grade I	100
	Grade II*	70
	Grade II	40
	Not listed	10
Storeys	4	100
	3	70
	2	40
	1	10
Construction	Earth	100
	Timber frame	70
	Brick masonry	40
	Stone masonry	10
Condition	Poor	100
	Good	55
	Excellent	10

The main limitation of this approach is that this methodology is designed primarily to assess building vulnerability to flooding. The VR scores for each attribute have been developed on the basis of damage caused to the building by flood inundation. If a different hazard was being studied, different VR scores would need to be used. For example, '*if freeze–thaw hazards were being studied, limestone masonry, which suffers particularly high levels of damage due to exposure to freeze–thaw action, would be considered more vulnerable than timber framing.'* (Stephenson and D'Ayala, 2014).

The limited scalability of this methodology also needs to be considered. This methodology is designed to be conducted on individual buildings. To use this methodology on a regional scale covering multiple buildings, users would have to assess the vulnerability of each individual building. Vulnerability values for individual buildings can then be collected together to determine a cumulative value for a specific area or region.

Gandini et al. (2018) have proposed a methodological framework for the vulnerability assessment of historic areas against flooding events, based on the MIVES (Integrated Value Model for Sustainability Assessment) method. Gandini's method is based on a building sampling approach, which attempts to find a balance between large-scale, 'macro' vulnerability assessments, which often fail to consider the vulnerability of individual buildings, and building-level, 'micro-scale' assessments, which are often costly and time-consuming. Gandini's proposed solution is to model the historic city through a statistical distribution of building characteristics in a determined area. The first step is to organise and categorise the building stock of a historic area into representative typologies. Next, more detailed, micro scale information is collected on a sample of buildings and the vulnerability of these buildings is calculated. This is then extrapolated to other buildings in the same category, creating a vulnerability assessment for a whole historic district (Gandini et al., 2018).

Once the buildings have been categorised, a 'requirements tree' approach is used to establish the 1) requirements, 2) criteria and 3) indicators needed to complete the vulnerability assessment for heritage buildings. According to Gandini et al., *'In the first levels – namely the requirements and criteria – general and qualitative aspects are defined, while in the last level – the indicators – concrete and measurable aspects are considered.'* (Gandini et al., 2018). This forms the basis of the vulnerability assessment.

For vulnerability assessments, the requirements are aligned to IPCC functions of vulnerability: 'sensitivity' and 'adaptive capacity'. According to Gandini et al., *'the sensitiveness requirement has the objective of assessing the degree to which a building is affected by an event. Depending on the conditions, typology and characteristics of the structure that is considered, its response to climate impacts varies. Criteria related to this requirement are therefore associated to the current state of the building, constructive critical elements, envelope characteristics, main use, and structural material. The requirement of adaptive capacity refers to the ability of a system to assume the potential effects of an event, overcoming its consequences. In this case, criteria refer to interventions, socio-economic conditions and the cultural value of the buildings. A visual representation of the 'requirements tree'* is set out in Figure 13.

While Gandini's sampling approach may offer a useful means of gathering and scaling up data on individual building vulnerability to the level of whole building typologies, the 'requirements tree' approach appears ponderous and the process is not clearly set out.

Thus, while this review has identified a number of approaches which attempt to reconcile large-scale data-driven approaches with micro-scale, site-based assessments of vulnerability, there appears to be no methodology which successfully leverages granular, site-level data on vulnerability and adaptive capacity, covering multiple heritage assets, to be used in large-scale, regional assessments. The sampling approach outlined by Gandini et al. (2018) would probably be the most effective means of achieving this, though the specific details of this approach remain problematic.

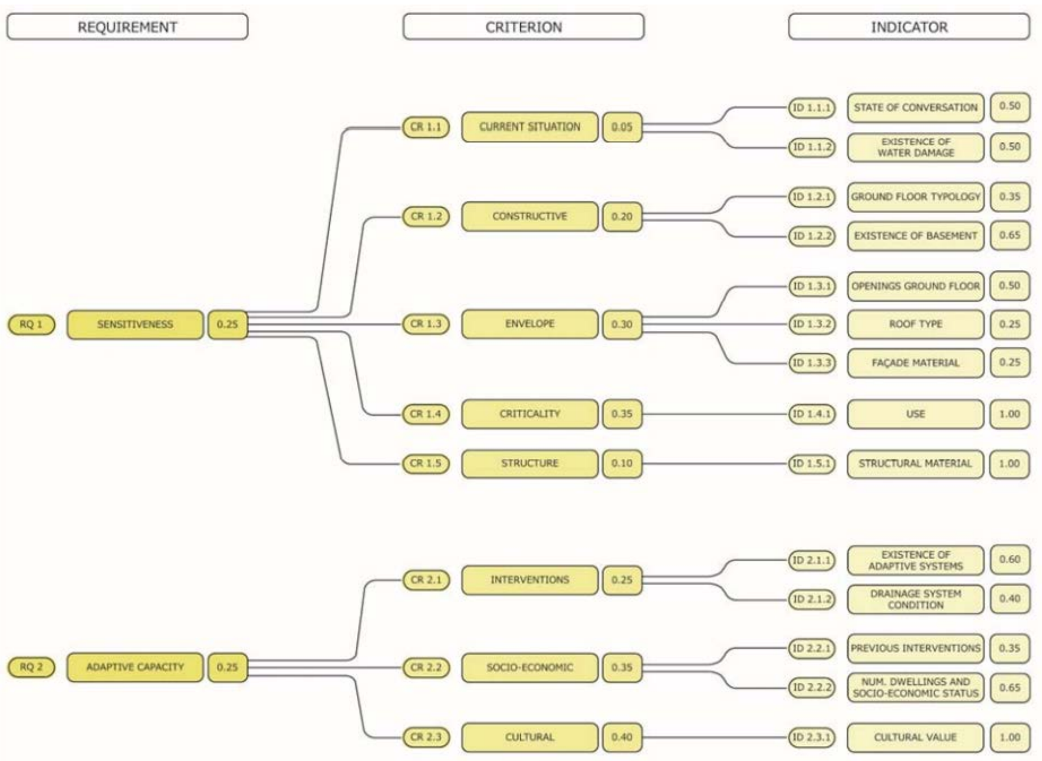


Figure 13: Gandini et al. (2018), Requirements Tree

Taken from: Gandini, A., et.al., (2018), 'Vulnerability assessment of cultural heritage sites towards flooding events', IOP Conf. Ser.: Mater. Sci. Eng.

3.5 Innovative approaches to heritage-specific climate change risk assessments

A more innovative approach to climate change risk assessments of heritage assets is presented in the Adapt Northern Heritage (ANH) Risk Management Process (RMP) (Boro et al., 2020). The RMP was developed to be used in northern global regions and is for application on 'historic places', for example: 'an ancient monument, a historic bridge, an old building ensemble, a designed garden, a cultural landscape, a spiritual place'. While there are a number of different RMPs that include a risk assessment stage, what sets ANH apart is the fact that the methodology for assessing risk is explicitly set out in detail as part of the broader risk management process.

The RMP is a largely bottom-up approach, encompassing a process of hazard identification and risk analysis which draws upon the knowledge of stakeholders who are familiar with the assets being assessed. While this can be seen as a strength, as it draws in the views of those most familiar with the site, it is also simultaneously a limitation in that the identification of relevant hazards depends wholly on the knowledge and awareness of local stakeholders who may not have sufficient familiarity with climate change hazards to provide robust information.

The RMP comprises eight steps (Figure 14) two of which relate specifically to the risk assessment process. Step 2 involves a process of identifying which are the main hazards and impacts affecting the heritage asset in question; step 3 involves analysing and rating risks.

One of the most innovative features of the RMP is that it offers three different working levels – standard, advanced and advanced plus – which enables users to undertake assessments at different levels of detail, depending on their purpose. The standard level represents *'initial and/or simple assessments and can be understood as a screening exercise, providing a general overview of the hazards, risks and adaptation measures relevant for a place.'* The standard level is the recommended starting point for assessment, with advanced and advanced plus levels building on this initial baseline assessment level. The Advanced Level '*adds considerable detail, making assessments more complex but also allowing us to investigate larger place in more depth.'*

Figure 14: Adapt Northern Heritage (ANH) Risk Management Process (RMP) - eight steps

Taken from: M. Boro et al., (2020), Assessing risks and planning adaptation Guidance on managing the impacts of climate change on northern historic places

Risk management preparation / review (part 1)	
1. **Define historic place(s)** for assessment, including cultural significance	*Chapter 2*
Risk assessment	
2. **Establish hazards and impacts** and relationship to climate change	*Chapter 3*
3. **Analyse and rate risks** and consider effect on cultural significance	*Chapter 4*
Adaptation planning	
4. **Identify adaptation measures**, including evaluation and appraisal	*Chapter 5*
5. **Develop adaptation strategy**, including collation of Climate Risk Management Plan	*Chapter 6*
Adaptation action	
6. **Design adaptation measures**	*not covered in this guide*
7. **Implemented adaptation measures**	*not covered in this guide*
Risk management preparation / review (part 2)	
8. **Evaluate adaptation progress**	*not covered in this guide*

The Advanced level adds additional components for consideration during risk assessment, for example the inclusion of a 'place element' (e.g., walls) and their material/ matter (e.g., stone, timber). Advanced Plus extends further, for example it may include the exploration of climate change data or enhanced description of the historic place as part of the risk assessment. An overview of the three levels is outlined in Figure 15.

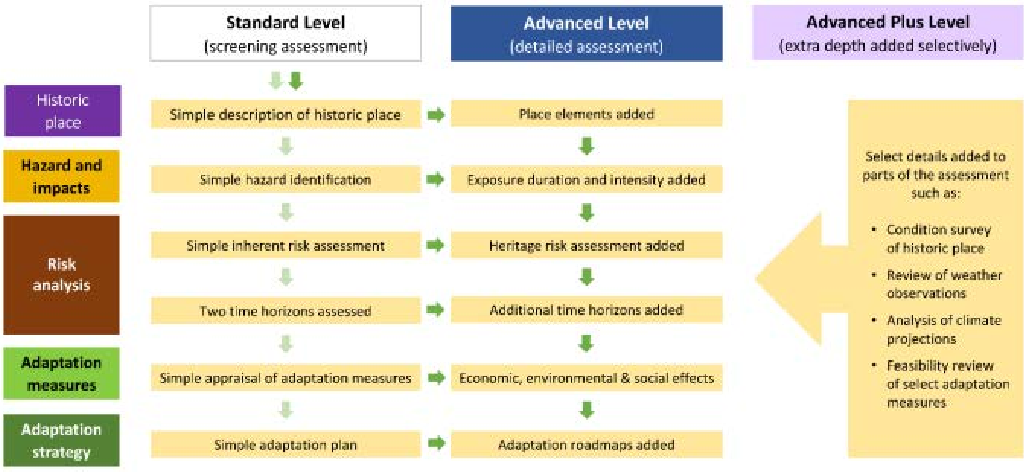


Figure 15: Adapt Northern Heritage (ANH) Risk Management Process (RMP): Working levels for risk analysis

Taken from: M. Boro et al., (2020), Assessing risks and planning adaptation Guidance on managing the impacts of climate change on northern historic places

Step 1 of the RMP involves the identification of the site of interest for the project: a single place, a group of places, or a place category. These are captured with location and boundaries, and a description of surroundings and wider environs. Cultural significance factors (e.g., any conservation policies, cultural heritage designations, and a rating of key cultural significance values) are captured at this stage. Additional background information can be gathered from stakeholder workshops.

Step 2 involves the identification of hazards and impacts relevant to the cultural heritage site. Unlike the STORM risk management tool, outlined in section 3.2.1, which proposes a top-down approach to the designation of hazards, the ANH process of establishing hazards is dependent entirely on the views of stakeholders who are familiar with each historic site. As stakeholders may lack extensive climate change knowledge, they are asked to identify relevant hazards by firstly reviewing the observed damages and deterioration which have occurred at the site. The idea is that local stakeholders should use their expertise and knowledge of the site to identify damage events and deterioration processes which have affected the site in the 'more recent past' ('recent past' is, however, never defined). Observed damages and deterioration are then recorded in a table (Table 17) and used as the basis for identifying relevant environmental hazards and climate drivers.

Observed damages and deterioration			
Damage and deterioration observed at historic place	**Impact type**	**Environmental hazard** relevant to observation	**Climate drivers**
	☐ damage ☐ deterioration		
	☐ damage ☐ deterioration		

Table 17: Adapt Northern Heritage (ANH) Risk Management Process (RMP): Observed damages and deterioration

Taken from: M. Boro et al., (2020), Assessing risks and planning adaptation Guidance on managing the impacts of climate change on northern historic places

At this stage, a score is applied to each identified environmental hazard – 'increase', 'decrease', 'no change' – but the guide does not specify the timeframe other than 'recent past'. The RMP does signpost to the ANH's additional sources of reference to assist the assessor with projected scores. Once hazards are scored, the observed and potential 'impacts' of each hazard on the site are described and recorded in a separate table (Table 18), with a rating for impact type (either 'damage' or 'deterioration').

Impacts on historic place		
Environmental hazard	**Impacts on historic place**	
Description of hazard	*Description of observed or potential impacts*	*Impact type*
		☐ damage ☐ deterioration
		☐ damage ☐ deterioration
		☐ damage ☐ deterioration
		☐ damage ☐ deterioration

Table 18: Adapt Northern Heritage (ANH) Risk Management Process (RMP): Impacts of hazards on historic place

Taken from: M. Boro et al., (2020), Assessing risks and planning adaptation Guidance on managing the impacts of climate change on northern historic places

All of the information recorded in the previous tables are then captured in a singular, overarching 'hazard register' which collates all of the data on 'hazards', 'climate drivers' and 'impacts' in one place, and which acts as the basis for the risk analysis.

In step 3, risks are analysed and rated, utilising the outputs from the previous steps. 'Inherent risks' are calculated by combining the severity an impact on a historic place and the likelihood of the impact to occur. The likelihood of an impact occurring is scored on a scale of 0-4 (0 'essentially impossible'; 1 'very unlikely'; 2 'unlikely'; 3 'likely'; 4 'very likely'). Severity of the impact is also scored on a scale of 0-4 (0 'insignificant'; 1 'minor'; 2 'moderate'; 3 'major'; 4 'catastrophic'). A matrix is then used to combine the scores for likelihood and severity to calculate the inherent risk (Figure 16).

Inherent risk rating matrix

Severity rating	Likelihood rating 0	1	2	3	4
4	0	4	8	12	16
3	0	3	6	9	12
2	0	2	4	6	8
1	0	1	2	3	4
0	0	0	0	0	0

Figure 16: Adapt Northern Heritage (ANH) Risk Management Process (RMP): Inherent risk matrix

Taken from: M. Boro et al., (2020), Assessing risks and planning adaptation Guidance on managing the impacts of climate change on northern historic places

Other steps can include adding time as a factor – comparing the risk at present to a future scenario. Risks are logged in a risk register, with a summary, time horizons, potential effect on cultural assets, etc. These are intended to be continuously reviewed to prevent a risk from becoming an issue.

Perhaps the most significant limitation of the ANH RMP is that the whole process – including identification of hazards – is dependent wholly on the knowledge of local stakeholders. The hazards and climate change drivers included in the risk analysis are limited by the knowledge and awareness of the stakeholders involved. Stakeholders are required to select climate drivers that are deemed 'relevant' to the historic place, opening up the possibility of omission or inclusion by error. This may be compounded by the fact that the framework depends heavily upon the 'observed' factor; i.e., that risks are identified primarily through known issues that have occurred, from assessment of causes to damage/ deterioration. Where changes are not immediately obvious, there is clearly a high probability that they will be omitted from the analysis.

Conclusions and Recommendations

4.1 Summary

Conclusions

- Although this review has identified a number of well-developed climate change risk assessment methodologies for heritage assets, there does not appear to be a single, 'off-the-shelf' solution that can be easily adopted to meet Historic England's need for a robust, nationwide risk assessment.
- This review identified two broad typologies of climate change risk assessments for heritage assets, both of which have distinct limitations: the most comprehensive risk assessment methodologies, which incorporate all of the standard determinants of risk, are generally site-specific and difficult to scale up; whereas larger-scale hazard mapping approaches typically depend on secondary datasets and often fail to capture granular data on the characteristics and vulnerabilities of specific sites.
- Although it may in theory be possible to combine the best features of several approaches – for instance, using a sampling approach to leverage more granular data on site vulnerability to enhance large-scale hazard mapping approaches – conceptual inconsistencies in the ways key determinants of risk have been used and defined make this process challenging.
- A related problem is the lack of clear consensus over how to define and incorporate estimates of significance into the risk assessment process, as well as the practical difficulty of mapping significance in a way that can interact effectively with hazard distribution.

Recommendations

- Given the implicit differences in the ways key concepts of risk have been used and applied across different risk assessment methodologies, it is recommended that further research be conducted. Specifically, what is recommended is the development of an appropriate concept model that clearly maps out all of the basic phenomena which underpin the principal concepts of risk.
- There are likely two basic approaches to achieving this concept model. These can be described as '**top-down**' modelling and '**bottom-up modelling**':
  - Top-down modelling involves starting with the broadest possible concepts and breaking them down into more basic, constituent phenomena. This approach would be particularly useful in appraising the existing IPCC risk framework and disaggregating the IPCC determinants of risk into more basic elements and underlying phenomena.
  - Bottom-up modelling involves working upwards from the basic physical and socio-economic phenomena to develop complementary higher-level categories. The aim should then be to group the basic phenomena into higher-level classifications which represent the lower-level phenomena as completely as possible.
- The two approaches should ideally be conducted simultaneously and iteratively, so that they can be used as cross-checks on each other, until they generate convergent results.
- This concept model can then be mapped back against the existing literature to facilitate a like-for-like comparison of methodologies, enabling a judgement to be made about whether any single methodological approach is adequate. This process will also enable identification of the most significant gaps in the existing literature about climate change risk assessments in a heritage context.

4.2 Main conclusions

The literature review has established there are many well-developed climate change risk assessment approaches designed specifically for cultural heritage, of which there are several that take explicit account of significance in the way that they assess risks. These are almost all founded on the existing standard tripartite 'hazard, exposure, vulnerability' schema for climate change related risk assessment, with or without consideration of adaptive capacity and its potentially positive and/or negative outcomes.

The principal limitations are that the most comprehensively developed climate change heritage risk assessment methodologies – STORM, CVI and the US National Parks Service's CRVA – have a primary focus on individual heritage sites, either singly or as a series of individual sites in a specific region, and are highly dependent on expert input on the specific characteristics of those sites. Risk assessment approaches with broader scope, on the other hand, tend not to take into account granular data on site vulnerability and adaptive capacity, critical factors when attempting to make realistic assessments of the risk to cultural heritage. The broader approaches also tend to be more restrictive in focus, generally considering fewer hazards, or fewer determinants of risk, or both.

Consequently, there does not appear to be a single 'off-the-shelf' solution that can be unproblematically adopted, either in its original, or in a slightly modified, form to meet HE's need for a robust, nationwide risk assessment approach. This implies that to develop large-scale assessments of the risk to heritage assets in England presented by climate change, it will be necessary to either:

a. substantially develop an existing approach;
b. combine the best features of several approaches to create a unified approach that avoids their individual weaknesses; or
c. develop a new approach from scratch, albeit one that will be strongly informed by the existing state of the art.

In general terms, there is a need to combine the scale of the hazard modelling approaches with the granularity of the more comprehensive, site-based approaches. In essence, this would involve bringing together the large-scale, data-driven hazard mapping methodologies, of the kind generally deployed with relatively limited numbers of hazards or risk determinants, with similarly large-scale modelling of the distribution, characteristics and susceptibility of the target heritage assets of the kind usually focused on single sites, or small groups of sites. It is possible that a sampling-based approach, of the kind described by Gandini et al. (2018), may offer a suitable means of leveraging the granular data on individual sites necessary to model the vulnerability of heritage assets over large spatial scales.

Conceptual challenges

While the most straightforward and economical approach might seem to be combining the most effective approaches to create a hybrid methodology, this is likely to present certain challenges. The most significant is that, while the basic definitions of the three standard determinants of risk may seem clear enough in principle, once applied to practical risk assessment there are often significant implicit or explicit differences in the way the terms are used, or the boundaries are drawn between them. These issues are particularly evident at the borderlines between hazard and exposure and between exposure and vulnerability, and in the precise definition and application of vulnerability.

Vulnerability is difficult, at first blow, to disentangle from 'sensitivity'. The baseline tripartite distinction of 'hazard, exposure, vulnerability' implies that vulnerability is an intrinsic feature of the target asset. But, vulnerability is itself often viewed as a compound phenomenon reflecting the combined results of two characteristics: 'sensitivity' and 'adaptive capacity'.

As we have seen in the review of the literature, the way that 'vulnerability' is defined or determined variously in different methodologies reflects these difficulties. In some cases, it is virtually synonymous with sensitivity/susceptibility (as in Forino et al., 2016), being seen as the result of basic, usually physical, features of the heritage asset(s) under consideration. In others, it is a high-level output of two or more lower-level determinants, and in some cases comes close to being synonymous with 'risk' itself (as in the CVI and RVA approaches).

Similar ambiguities and complexities are found in relation to approaches to defining and ascertaining 'exposure'. Perhaps the most straightforward and intuitively clear definitions of exposure are found in environmental science and epidemiology, where exposure is now simply considered to be 'contact between an agent and a target' (Zartarian et al., 1997). However, because of exposure's intrinsically inter-relational nature, it can be remarkably difficult in practice to define the boundaries between hazard and exposure, and between exposure and vulnerability. For example, when making a risk assessment, it is necessary to go further than simply ascertaining which hazard or hazards might potentially impact on the asset. It is also necessary to understand how far that hazard is likely to arise in a form liable to result in negative impacts. This is often conceptualised in terms of the location, frequency and intensity/severity of the hazard.

In addition, it is important to understand the extent to which the asset or class of assets are liable to be exposed to the hazard. This depends not only on the location, frequency and intensity/severity of the hazard, but also on the location, number and type of assets being assessed. Exposure assessment can then be defined as *'the process of estimating or measuring the magnitude, frequency, and duration of exposure to an agent, along with the number and characteristics of the population exposed.'*[6] Once the 'characteristics of the population exposed' are considered it is possible to blur the line into susceptibility/sensitivity/vulnerability.

It is not, therefore, always clear when something is 'highly exposed' to a hazard whether that reflects the intensity of the hazard, the vulnerability of the asset or agent, the temporal length of exposure, or some combination of these factors.

One consequence is that, while individual methodologies may present a modular approach to analysis or assessment that seems to correlate directly with the 'hazard, exposure, vulnerability, capacity' categories, such definitions are unlikely to be directly compatible across different methodological approaches.

The root of this problem seems to lie in conceptual ambiguities between different determinants and related usages of the terms involved. Hazard, exposure and vulnerability can be treated as absolutes (present or absent) or variables (present to some degree or intensity), concrete (a specific thing) or abstract (a class of things or a general characteristic), and similar concepts can be relevant at different levels of analysis – as we have seen is the case with sensitivity/susceptibility and vulnerability.

This implies that there remains a need for a systematic mapping of different usages of the basic concepts of risk, which then relates these usages back to the basic real-world phenomena to which they refer. It should then be possible to compare like-with-like to make reliable judgements of the optimal existing approaches to modelling the individual component phenomena.

6. https://www.epa.gov/expobox/exposure-assessment-tools-approaches.

The problem of significance

A related, but particularly important, challenge when developing cultural heritage related risk assessments is the lack of clear consensus over how to incorporate estimates of significance into the risk assessment process. Clearly, defining some artefact or practice as 'cultural heritage' in the first place involves complex and sometimes controverted or questionable value judgements. Even if we put aside for the moment the current challenges posed by 'contested heritage', there are basic problems with defining and understanding what significance really is and how its sources, dimensions and extent should be conceptualised. The few clearly developed methodologies for estimating significance for the purposes of risk assessment range widely in their approach to significance. Some focus on World Heritage Sites only and therefore construe significance in terms of the declared Outstanding Universal Value of the specific sites under consideration (e.g. Sesana at al. 2020, or the Climate Vulnerability Index); others attempt to measure significance using the ICOMOS categories of 'aesthetic, historic, scientific, social or spiritual value' (e.g. Carmichael et al. 2017); some consider, either directly as part of a significance assessment or indirectly through considering them as determinants of exposure or vulnerability, specific contributors to significance such as an asset's 'rarity, period, potential to contribute to knowledge and group value' (e.g. Westley, 2019); and a few develop more comprehensive approaches 'from the ground up', the most comprehensive being the STORM methodology for significance assessment (Ravankhah et al. 2020), with its nine distinct components or dimensions of significance.

Most significance assessment approaches used in existing models are also focused on estimating the significance of individual heritage assets; there is therefore a notable paucity of models for large-scale modelling of heritage significance.

There is also the practical difficulty of mapping significance in a way that can interact effectively with hazard distribution. This is because there is no direct or straightforward correlation between physical characteristics that make a building vulnerable to climate change related hazards and the sources of that building's cultural significance. This raises complex questions about how potential climate change impacts on significance are modelled: for example, it may be that a certain constructional type is particularly vulnerable to climate change related damage but does not include many outstandingly important individual structures. In such circumstances, how do we calculate the relative impact of potentially losing a large quantity of relatively less significant structures versus a smaller quantity of more important structures? This, moreover, points towards a further challenge, which is that the potential loss has the potential to alter the relative survival of specific types of heritage asset. Since rarity is widely recognised as a fundamental determinant of value in the field of heritage (for example in the criteria used to determine whether a building should be listed), as it is in economics, this implies not only that significance poses particular challenges to inclusion, but may need to be regarded as a dynamic quality with a recursive dimension: in the event of significant relative loss of a specific type of building, the remainder of that type will, by that very fact, become 'more' significant.

The question of empirical adequacy

Even if all conceptual challenges were adequately resolved, there are still significant methodological problems with some of the most seemingly comprehensive risk assessment approaches. A recurrent feature of the risk assessment approaches reviewed in this study is the use of relatively simple point-scale based scoring systems, which are then cumulated through simple addition or multiplication to give an overall risk score. While of some value as formalisations of intuitive judgments or necessary simplifications of continuous variables, in many cases it is not clear that there is any strong empirical basis for the types of quantification used. In most cases, the basic components of the risk assessment process, and their constituent elements, are given equal weights; no justification tends to be offered for this kind of straightforward equivalence between the components and subcomponents of the risk assessment process. Similarly, the way that, for example, the likelihood of a hazard impacting on an asset is translated from a chronological measure (e.g., likely to happen every ten, or fifty, years) into a scale can produce clusters that appear questionable – as when the STORM approach classes within the same frequency category events likely to happen every ten years with events likely to happen every year or more, meaning that a literal order of magnitude of difference is included in a single category.

In general, these approaches reflect the straightforward translation to the world of built heritage of risk assessment methods developed primarily for simple, accessible on-the-ground occupational health and safety risk assessments. A similar genealogy is reflected in the tendency to translate final results into simple, matrix-based presentations. Some kind of simplification of this kind may be appropriate for single sites. With larger scale risk modelling, of the kind Historic England is aiming to carry out, however, it is likely that this kind of presentation will fail to capture the issues adequately.

4.3 Recommendations

In the light of these issues, it seems clear there is a need for further research and development to produce a robust approach to large-scale risk assessment for cultural heritage in England.

One aspect of this is going to be to find ways of addressing the conceptual complexity of the field. The starting point is likely to be the development of an appropriate concept model for modelling climate-change driven risks to the historic environment. The aim of the exercise would be to develop a set of clear, comprehensible and stable concepts that are adequate to the phenomena being modelled. Ideally, the end result should be a model consisting of concepts that are, wherever possible a) mutually exclusive (avoiding unnecessary overlaps); b) clear and simple (unified as opposed to compound); and c) cumulatively exhaustive (covering, as far practicably possible, the whole field to be modelled).

While a systematic mapping exercise of this nature is beyond the scope of this research, it is possible to give some indicative suggestions for how this might be approached. In the first instance there are likely to be at least two basic ways of plotting out the range of concepts likely to be of relevance, **which can be thought of in simple terms as:**

- 'top-down modelling'
- 'bottom-up modelling'.

Top-down modelling

The first approach is to start with the broadest possible concepts and break them down. The initial aim should be to identify, as far as possible, initial categories that map out the specific concepts in a way that is clear, comprehensive and complementary. These categories can then be interrogated to break them down into constituent elements that should ideally have the same qualities of clarity, comprehensiveness and complementarity, repeating this pattern until an appropriately high level of specificity is reached.

This approach is perhaps best exemplified in the existing literature in the approach to hazard identification outlined by Ravankhah et al. as part of the STORM risk assessment tool (Ravankhah et al., 2019). This approach involves first breaking down 'hazards' into geological, hydrometeorological, and biological, then further breaking down each of these classes typologically, so that, for example, biological hazards were divided into those caused by plants, fungi and animals, and each of these subdivided again, so that animals were grouped into insects, birds and mammals, before individual types of animals were identified. Finally, the hazards were divided into fast and slow onset hazards. As we have seen, this resulted in a more comprehensive and, arguably, robust cataloguing of hazards than those obtained even by systematic cumulation of specific hazards considered in the prior literature.

This approach can also be used to critically appraise the completeness and conceptual coherence of the existing IPCC framework and develop it further to ensure it is adequate to underpin robust risk assessment methods. This would involve paying special attention to breaking down the basic high-level compound concepts (the IPCC's three or four major 'determinants of risk') into their constituent concepts, ensuring that categorical and variable concepts are disentangled. This should begin to capture the way that, for example, exposure and vulnerability are used in multiple ways that reflect different aspects and levels of the risk assessment process.

Bottom-up modelling

The second approach is the opposite of this: to work upwards from the basic physical and socio-economic phenomena of potential interest, seeking to be as exhaustive as possible, and then working upwards to develop complementary higher-level categories. **The phenomena that would have to be modelled in this way will include:**

- the primary phenomena of climate-related environmental change, i.e., the major climatic phenomena liable to be modified through increasing concentrations of greenhouse gases in the atmosphere (e.g., temperature, precipitation, wind flows, sea level rise);
- secondary phenomena of climate-related environmental change, i.e., the regional or local environmental changes induced by the primary phenomena (e.g., flooding, soil erosion and instability, wildfire, shift in climactic zones, changes to species distribution)[7];
- the nature and distribution of physical characteristics of the target assets liable to be impacted by the primary and secondary phenomena;
- the way that those physical characteristics relate to the significance of the target assets, which in its turn means developing a robust understanding of the relevant sources of each asset's heritage value;
- the socio-economic setting that determines the extent and ways that the target assets are used, maintained, and modified.

The aim should then be to group the basic phenomena in ways that reflect common properties but which have as few overlaps as possible, so that the higher-level classifications represent the lower-level phenomena as completely as possible.

A comprehensive model

The two approaches should ideally be conducted simultaneously and iteratively, so that they can be used as cross-checks on each other, until they generate convergent results. This will ensure that such phenomena are identified in a way which is systematic and rigorous and help ensure that the final result is a model that is as clear, complete and as practically applicable as reasonably possible.

When the comprehensive concept model is developed and mapped against existing literature, it should be possible to establish with confidence where and how existing approaches model the phenomena or relationships involved, as well as to identify with precision where there are gaps in the literature. Currently, given the extent of terminological inconsistency and confusion around the key climate change concepts and determinants of risk, it is difficult to ascertain with certainty, precisely where the gaps lie (and, consequently, where fit-for-purpose methodological models may exist) because like-for-like comparisons between different approaches are very difficult. The most significant gaps are likely to be around approaches to understanding significance and modelling of the vulnerability/susceptibility of heritage assets.

Approaches to significance are extremely variable, ranging from simple expert

7. Here we introduce the concept of primary and secondary phenomena as a means of conveniently categorising the various types of climate-related environmental change phenomena for the purposes of modelling. To be clear, this is not a concept that is introduced in the literature reviewed for this research, nor was it used as a means of developing the list of hazards used in our methodology referenced in section 1.4.

estimates of the global significance of individual assets to attempts to break down significance into multiple dimensions. Heilen et al.'s (2018) description of 'significance modelling tools' – which use data on common site attributes to support inferences about heritage significance – may offer a meaningful initial framework for modelling and understanding significance across multiple sites, but it is unknown how systematically this approach has been tested. It is also likely to be of value to consider revisiting the three dimensions of significance identified by James Kerr in his pioneering work on conservation planning (Kerr, 2017): 'ability to demonstrate', the way that the heritage asset can be used as a source of evidence; 'associational links for which there is no surviving physical evidence', dealing with reasons a site might be historically or culturally important regardless of whether that association has left tangible physical traces; and 'formal or aesthetic qualities', relating to the way that the sensory impressions (extending in some cases beyond the visual) made by the asset can contribute positively to human experience. Each of these can then be further broken down, along lines indicated by Kerr. Similarly, conceptualisation of the physical characteristics of target assets, an indispensable foundation for large-scale modelling of the potential impacts on heritage assets, seems to be extremely primitive at present, and largely carried out in a small number of individual projects.

It should be noted that there will almost certainly not be only one adequate way of breaking down or clustering concepts to form a full conceptual framework. This approach is therefore at least as much a way for HE to identify, from the possibilities, an approach that meets the specific needs for modelling the relevant phenomena and assessing risk in the context of the historic environment in England, but in a way that is as coherent and empirically adequate as possible.

In choosing a specific approach or group of approaches, it is also likely to be important to consider how far candidate approaches can be applied in a 'dynamic' way, that is to say approaches that can take into account **an evidence base that is likely to change because:**

- modelling of climate change and its impacts is likely to improve in both predictive power and resolution;
- there will be increasing clarity over whether political intervention is likely to reach the goal of substantially reducing greenhouse gas emissions;
- there are substantial potentially recursive (self-compounding) components in modelling impacts on heritage, most obviously that extensive loss of a particular class or type of heritage asset will have the effect of increasing the relative rarity of the survivors, potentially increasing their cultural heritage significance.

Development and selection of an adequate concept model that fulfils these requirements is likely to be challenging in certain respects, but it need not (indeed, probably should not) be carried out in its entirety prior to research into, and modelling of, the basic physical and socio-economic phenomena that will inevitably form the foundation of any more general approach to risk assessment.

Hazard mapping, for example, will be a technical exercise in its own right and will depend on concept modelling only to the extent that the latter may help identify potential hazards that may otherwise have been neglected. Similarly, careful research into the key physical characteristics of buildings that may make specific building materials or types especially vulnerable to climate change can be conducted fairly independently.

The general principle is that the closer the research and modelling is to the fundamental physical and socio-economic phenomena involved, the less dependent it will be on having an adequate high-level conceptual framework in place. Indeed, careful research and modelling of this kind can be a major contributor to the 'bottom-up' approach to defining that framework.

This kind of approach should begin as well to ensure that the modelling process is empirically adequate.

Where adequate conceptual frameworks become more important, however, is at the point where these specific models come to be combined into a broader, overall risk assessment. This is the point where it becomes necessary to combine the granular data into simpler, but still robust, quantifications of the probability of negative outcomes. This can only be done with a clear overview of how the various lower-level phenomena relate to and interact with each other. At this point in the modelling process, there may also be valuable lessons to be learned by looking beyond the specific literature on risk assessment for culture and climate change and considering the kind of approaches used in fields where extremely robust, fully quantified risk modelling is routinely undertaken. Obvious examples include nuclear and air safety, where intrinsically hazardous processes with the potential to cause large-scale harms have to be controlled sufficiently to bring risk within acceptable bounds. This kind of technical risk modelling would seem likely to be a potential source of empirically robust approaches to combining specific probabilities of particular types of phenomena into more general estimates of risk. There may be some benefit to exploring whether additional research into these types of risk assessment could be co-funded and co-commissioned with other interested bodies, such as CADW or Historic Environment Scotland.

In sum, therefore, the optimal way forward would seem to be establishing a number of research strands that feed into, challenge and refine each other iteratively, until their approaches and findings become fully convergent and complementary. Multi-strand research of this kind may also make it easier to identify overlaps in specific areas of research and modelling with other research agendas (potentially external to HE), opening the way to collaborative research with other agencies and institutions, leading to potential efficiencies of time and resource.

Appendix & Bibliography

Appendix 1: Applications of the Climate Vulnerability Index (CVI)

Application of the CVI to the Heart of Neolithic Orkney (HONO) World Heritage Site (April 2019)

The CVI methodology was applied to the Heart of Neolithic Orkney (HONO), a group of four sites on the main island (Mainland) of Orkney that represents one of the most complete and impressive Neolithic landscapes in western Europe.

The CVI methodology was undertaken as a collaborative workshop made up of experts and members of the local Orkney community (half of the 36 participants were from the community). The assessment was based on the impact of climate change stressors on eight key values specific to the HONO site, which were themselves based on the property's Statement of Outstanding Universal Value.

The participants considered the impact of various predetermined climate stressors and identified three stressors likely to have the greatest impact on the eight key values of the site (sea level rise, precipitation and storm intensity and frequency). A timescale of c. 2050 and a high-emission climate future scenario (RCP8.5) were selected to consider impacts. Participants then assessed the exposure and the sensitivity of the values of the site to the 3 stressors deemed to have the greatest impact on the site's OUV, using a five-point categorical scale (see Table 4 and Table 5).

Exposure to Sea Level Change and Precipitation Change was determined as very likely (>90%), and exposure to Storm Intensity and Frequency was determined as likely (67-90%). Sensitivity of OUV to all three drivers was determined as very high, indicating potential for major loss or substantial alteration of the majority of values comprising OUV. The overall potential impact, calculated on the basis of the scores for exposure and sensitivity, was determined as extreme (on a four-point scale, low to extreme) for all three key climate drivers.

Participants then assessed the adaptive capacity of the property and its management by considering the local management response and scientific support and their effectiveness. For Sea Level Change and Storm Intensity and Frequency, the adaptive capacity was determined to be moderate (three-point scale, low to high), and for Precipitation Change was high.

All of these scores were then combined in a final risk matrix (table A2.7) to produce an overall vulnerability score for the site's OUV as high (highest on a three-point scale). (Jones et al., 2022; Day et al., 2019)

Application of the CVI to the Sukur Cultural Landscape (September 2021)

The CVI methodology was applied to the Sukur Cultural Landscape, a WH property in northeastern Nigeria. This was the first time that the CVI was applied in an African WH property and in a cultural landscape-inscribed property.

The CVI followed the same workshop process and involved site managers, academics, community representatives, Non-Governmental Organisations (NGOs) and responsible management agencies. The workshop on this occasion employed a 'blended' format. Most of the workshop participants were based at the American University of Nigeria (AUN) in Yola and came from a range of backgrounds: seven of whom are Sukur community members, a past and current Sukur site manager, and several who had visited Sukur in the past.

As with the CVI undertaken at the HONO site, the CVI approach on the Sukur Landscape was based on an assessment of the impact of climate stressors on six key values, drawn from the Sukur Statement of OUV. Workshop participants used a pre-determined list of climate stressors to identify the three stressors which are likely to have the greatest impact on the Sukur landscape (these were identified as Drought (severity, duration, frequency); Temperature trend (air and/or water), and Storm intensity and frequency). The time scale selected by the workshop to consider impacts was c. 2050.

Unlike the HONO workshop, which used a list of 15 climate stressors, the Sukur participants were only presented with a list of eight climate stressors, as it was agreed by the steering group that the climate stressors related to coastal areas, snow and ice would be excluded as they were not deemed relevant to the Sukur cultural landscape.

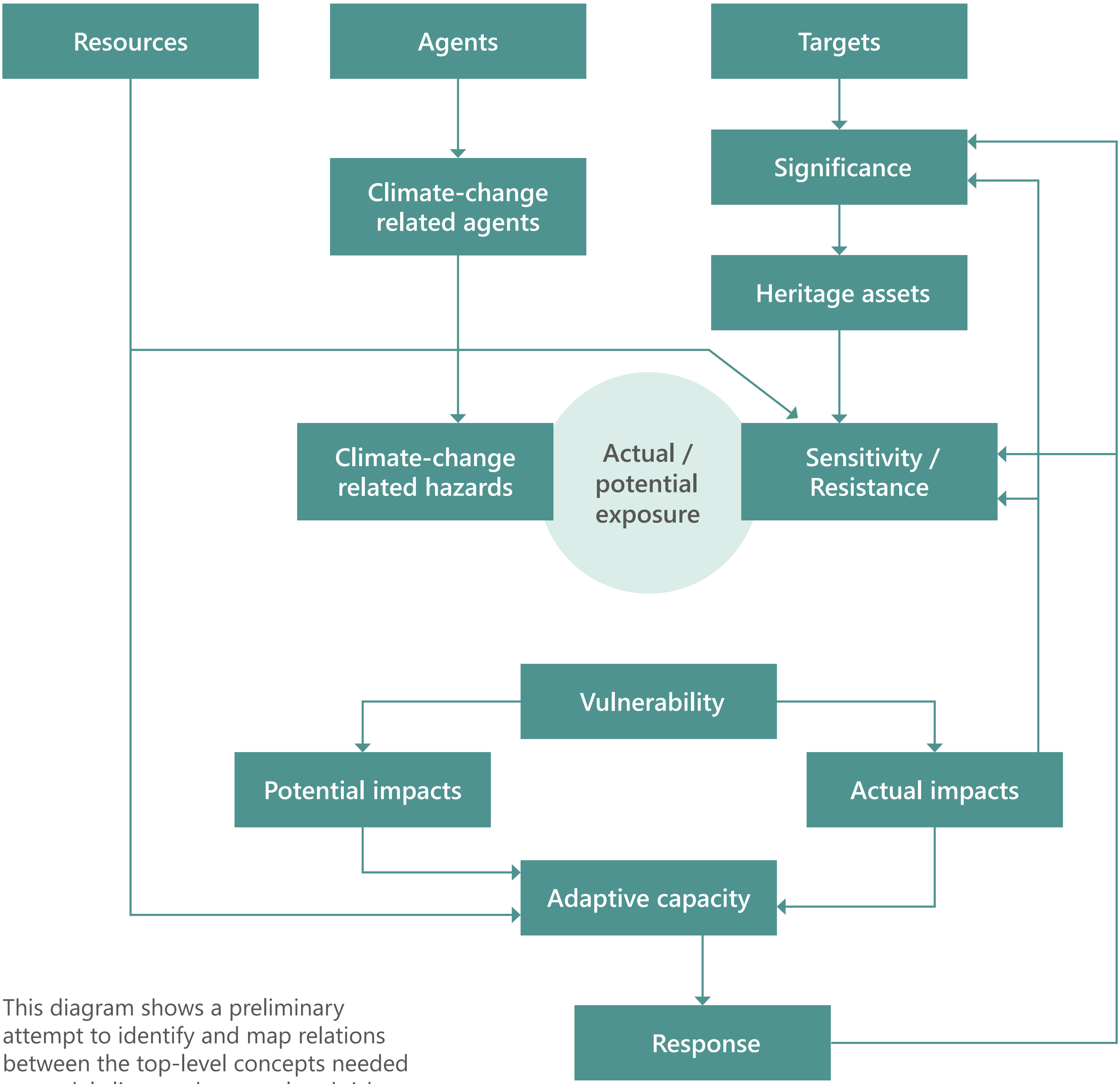
As with the HONO workshop, participants assessed the exposure and the sensitivity of the values of the site to the 3 stressors deemed to have the greatest impact on the site's OUV, using the same five-point categorical scale. Exposure to Drought, Temperature trend and Storm intensity and frequency were all deemed to be likely (67-90%, second highest category). Sensitivity of OUV to Drought was determined as moderate (middle category), whilst sensitivity to Temperature trend and to Storm intensity and frequency were each determined as low.

The compounding factors were identified as: *'Boko Haram and other militant groups operating in the Sahel and its effect of an increase in the population of Sukur and the decline in tourism; and changes in agricultural practices affecting species diversity and availability of traditional materials for construction.'*

Based on scores for exposure and sensitivity, the potential impact for drought was determined to be high (second highest on a four-point scale, low to extreme), while the potential impact for temperature trend and storm intensity was deemed to be moderate. For each key climate stressor, the adaptive capacity was determined to be moderate.

Overall, OUV Vulnerability was determined to be moderate for Drought and low for Temperature trend and Storm intensity and frequency. The combined OUV Vulnerability for Sukur Cultural Landscape was determined as Low. (Day et al., 2022)

Appendix 2: Indicative example of a high-level concept model



This diagram shows a preliminary attempt to identify and map relations between the top-level concepts needed to model climate-change related risks to heritage assets. It is not intended to be authoritative, but rather to act as a potential starting point for critical exploration and for further research and development. It does, however, seek bring some clarity to aspects of the standard IPCC framework that have emerged as problematic from the literature review.

The starting point is the highest-level description of the relevant phenomena, which can be found at the top of the diagram: 'resources', 'agents' and 'targets'. These are intended to define the broadest classes of phenomena involved in environmental risk assessments, extending beyond, but subsuming those direct relevantly to the specific kind of risk assessment in question:

- 'Targets' are, in the broadest sense, the assets that may be affected, positively or negatively, by some active process or processes.
- 'Agents' represent all the processes or phenomena liable, actually or potentially, to affect those 'target' assets that are beyond direct control of those responsible for assets.
- 'Resources' are the means or inputs, including finances, labour, materials, knowledge, and skills available to those responsible for the assets, manage the assets and/or to address the actual or potential impacts of the agents on the targets.

The language of 'targets' and 'agents' is derived from environmental health and epidemiology, while 'resources' are foundational for any kind of analysis that considers the socio-economic dimensions of change.

These classes appear to subsume within them the most basic factors not only that need to be considered in any risk assessment process, but all the factors that need to be in place for it to be of any value to attempt to carry out a risk assessment process. We need to have a set of assets that we are concerned about; we need to be concerned that those assets may be changed by some phenomenon or phenomena; and we need to have at least some resources available a) to carry out the risk assessment itself, and b) to respond meaningfully to the findings, since there would be no benefit in carrying out the risk assessment if we were powerless to make any kind of response.

The next level down seeks to pick out those agents and targets of specific interest for this research: those agents that relate to anthropogenic climate change, and those potential targets that have cultural heritage significance. This in itself indicates that it is likely to be problematic to incorporate significance into the risk assessment process *after* hazard assessment, the typical approach. The very category of cultural heritage only exists by virtue of some kind of implicit or explicit assessment of significance. It therefore seems more appropriate to treat it is one of the basic processes that define *what* is being risk assessed in the first place.

At the next level down we have a further degree of selectivity and specificity: 'hazards', that is to say those specific climate-change related agents that might have impacts on assets with cultural heritage significance, and 'sensitivities', those aspects of the assets that might be affected by those phenomena. It should be noted that this is the stage in the analysis where the 'agent' and 'target' conceptual streams become mutually dependent. Whereas both climate-change related agents and heritage assets can be identified without reference to each other, a 'sensitivity' must always be defined in relation to some 'hazard and a 'hazard' in relation to some 'sensitivity'. In addition, it should be noted that sensitivity and resilience are not separable phenomena that can be set against each other, but the extremes of a single continuum, with any heritage asset (or element with an asset) sitting somewhere along that continuum in respect of a given hazard. In addition, for the hazard/sensitivity relation to be meaningful, there has to be some realistic prospect of the hazard and the sensitivity interacting—that is to say, the two can only be relevant in as far as there is actual or potential exposure of a sensitive target asset to the hazard.

Exposure is capable of further analysis. Though this is not incorporated in the diagram, it can itself be seen as a composite of three or four basic elements. The core component is the temporal duration of exposure, which can be continuous or discontinuous (the latter measured by 'frequency'). There is then intensity of the hazard on one side; and the extent or number of the asset(s) exposed and their degree of significance on the other. The extent of exposure will therefore be a composite of the duration of exposure, the intensity of the hazard, and the degree of significance and extent of the heritage assets. Vulnerability then becomes the actual or potential impact resulting from the actual or potential exposure of the asset to the agent.

It is at this point that the main conceptual confusion in the IPCC model can be brought to the surface: we can see in the diagram that it is 'sensitivity' component of 'vulnerability' that operates on the same conceptual level as 'hazard' and 'exposure', not vulnerability, at least if vulnerability is understood, along the lines advocated by the IPCC, as a composite of sensitivity and adaptive capacity. It should also be noted that exposure seems to be a somewhat different 'type' of concept to 'hazard' and 'sensitivity'. Sensitivity and hazardousness seem to pick out intrinsic (physical) characteristics of the target asset and agent respectively, and in that sense those characteristics pre-exist their classification as sensitivities or hazards. Exposure appears to have no relevant 'upstream' conceptual predecessor.

The IPCC model treats vulnerability as the result of a combination of sensitivity and adaptive capacity. In some obviously intuitive way, it seems that the more sensitive an asset is, the greater its vulnerability, while the availability of resources to protect and modify the asset (adaptive capacity) will act in the contrary way to decrease its vulnerability. At the same time, however, it is difficult to disentangle vulnerability in the first sense from sensitivity, while adaptive capacity can only really be engaged after something is recognised as 'vulnerable'. The IPCC's treatment of vulnerability therefore assimilates into vulnerability two subcomponents, one of which (sensitivity) might properly be seen as 'upstream' and the other (adaptive capacity) 'downstream' from vulnerability. The plethora of treatments of definitions and placements within the risk assessment process of vulnerability in the literature reviewed in this study presumably reflects conceptual and analytical difficulties resulting from this conflation.

Moreover, adaptive capacity can only really be directed in a way that is genuinely adaptive when there is some kind of idea of what problems – the actual or potential impacts on the sensitive asset made by the hazard – need to be responded to. In that sense, adaptive capacity may best be placed further downstream than the actual or potential impacts.

What does, however, precede vulnerability is the more general category of resources, which we have already seen sits at the top level of the diagram. Adaptive capacity will be strongly correlated with the extent of resources – financial, human, intellectual, natural – available to those responsible for the target assets. Importantly, however, resources are also likely have significant influence on where the target assets sit on the sensitivity-resilience spectrum: a well-resourced asset owner is likely to ensure that the assets are kept in much better repair, with the probable result of making them less sensitive to environmental factors, than a poorly resourced owner.

Adaptive capacity, as a subset of resources, will similarly shape the concrete response(s) to actual or potential vulnerability. The nature of these responses may in turn feed back to influence significance – as responses may compromise or enhance significance – as well as an asset's sensitivity-resistance – as responses will either decrease sensitivity and increase resistance or, if ill-conceived or poorly executed, increase sensitivity and decrease resistance.

Response is not the only feedback loop at work, as hazard impacts on assets will also potentially have implications for significance (in potentially complex ways: not only will harmful impacts be liable to reduce significance directly, in doing so they may have the effect of increasing the rarity value of those examples of that survive undamaged so increasing their significance).

Risk, finally, emerges from the entire cycle as the probability of harmful outcomes arising from potential changes in the system. This can be stated at almost any level of generality or granularity, from specific physical impacts on particular components of a building to whole groups of assets in a specific area or of a particular type.

Bibliography

Aktürk, G., Hauser S. .J., (2021), Detection of disaster-prone vernacular heritage sites at district scale: The case of Fındıklı in Rize, Turkey, International Journal of Disaster Risk Reduction Volume 58, 102238

Ashtari, M. et al., (2021) Assessment of vulnerability and site adaptive capacity to the risk of climate change: the case of Tchogha Zanbil World Heritage earthen site in Iran, Journal of Cultural Heritage Management and Sustainable Development Vol. 12 No. 2, 2022

Atkins, (2013), Assessment of Heritage at Risk from Environmental Threat

Ballard, C. et al., (2022), Cultural Heritage and Climate Change: New challenges and perspectives for research, JPI Cultural Heritage & JPI Climate

BBC, (2023), Sandringham Royal lawn to be replaced with 'biodiverse' garden: https://www.bbc.co.uk/news/uk-england-norfolk-64334882

Bisgrove, R. Hadley, P, (2002), The Impacts of Climate Change on Gardens in the UK

Bonazza, A. et al., (2018), Safeguarding Cultural Heritage from Natural and Man-Made Disasters: A comparative analysis of risk management in the EU. Working Paper. Publications Office of the European Union

Bonazza, A. et al., (2021), 'Safeguarding cultural heritage from climate change related hydrometeorological hazards in Central Europe'. International Journal of Disaster Risk Reduction, 63

Bonazza, A., (2020), 'Managing Heritage Sites at Risk', in Cultural Heritage in Crisis: Cultural Heritage Research at European level - challenges at times of climate change and digitization (Fraunhofer Center for International Management and Knowledge Economy IMW)

Boro, M. et al., (2020), Adaptation stories Examples of risk assessment, adaptation planning and conservation management of northern historic places

Boro, M. et al., (2020), Assessing risks and planning adaptation Guidance on managing the impacts of climate change on northern historic places, Adapt Northern Heritage

Brimblecombe, P., et al., (2020), 'Mapping Climate Change, Natural Hazards and Tokyo's Built Heritage', Atmosphere, 11.

Brimblecombe, P., et al., (2022), 'Moisture as a Driver of Long-Term Threats to Timber Heritage—Part II: Risks Imposed on Structures at Local Sites', Heritage, 5.

Brum, P., et al., (2018), 'STORM: Safeguarding Cultural Heritage through Technical and Organizational Resources', ICOMOS 19th General Assembly and Scientific Symposium "Heritage and Democracy", 13-14th December 2017, New Delhi, India

Cacciotti, R., et al., (2021), 'Climate change-induced disasters and cultural heritage: Optimizing management strategies in Central Europe', Climate Risk Management, 32.

Cadw (2019), Flooding and Historic Buildings in Wales

Carmichael, B. et al., (2020), 'A Methodology for the Assessment of Climate Change Adaptation Options for Cultural Heritage Sites'. Climate, 8(8)

Carmichael, B. et al., (2017), 'Local and Indigenous management of climate change risks to archaeological sites'. Mitigation and Adaptation Strategies for Global Change 23(2

Carroll, P., Aarrevaara, E. (2018), 'Review of potential risk factors of cultural heritage sites and initial modelling for adaptation to climate change'. Geosciences, 8(9)

Chikodzi, D. et al., (2022), 'Climate change risk assessment of heritage tourism sites within South African national parks'. International Journal of Geoheritage and Parks, 10:3

Chowdhuri, I. et al., (2022), Application of novel framework approach for assessing rainfall induced future landslide hazard to world heritage sites in Indo-Nepal-Bhutan Himalayan region, Geocarto International

Cigna, F., A. Harrison, D. Tapete, and K. Lee (2016), Understanding geohazards in the UNESCO WHL site of the Derwent Valley Mills (UK) using geological and remote sensing data. Fourth International Conference on Remote Sensing and Geoinformation of the Environment, Paphos, Cyprus

Ciski, M.; Rz□sa, K, (2021), Threats to Cultural Heritage Caused by the Global Sea Level Rise as a Result of the Global Warming. Water, 13(18), 2577

Climate for Culture, (2014), Damage risk assessment, economic impact and mitigation strategies for sustainable preservation of cultural heritage in the times of climate change

Cook, I. et al., (2021), 'Climate Change and Cultural Heritage: A Landscape Vulnerability Framework'. Journal of Island and Coastal Archaeology 16(2-4)

Crowley, K. et al., (2022), 'Cultural heritage and risk assessments: Gaps, challenges, and future research directions for the inclusion of heritage within climate change adaptation and disaster management'. Climate Resilience and Sustainability, 1(3).

Daire, M-Y. et al., (2012), 'Coastal Changes and Cultural Heritage (1): Assessment of the Vulnerability of the Coastal Heritage in Western France'. Journal of Island and Coastal Archaeology 7(2)

Daly, C., (2014), 'A Framework for Assessing the Vulnerability of Archaeological Sites to Climate Change: Theory, Development, and Application'. Conservation and Management of Archaeological Sites, 16:3

Daly, C., (2017), Archaeological and Built Heritage Climate Adaption Sectoral Plan Background Study. Unpublished report prepared for the Department of Arts Heritage, Regional, Rural, Gaeltacht Affairs of Ireland

Dante-Wood, S. K., Peterson D. L., Halofsky J. E. (2018), Assessing Climate Change Effects in the Northern Rockies. In: Halofsky J. E., Peterson D. L. eds. Climate Change and Rocky Mountain Ecosystems. USA: Springer Cha, pp1-55

Dastgerdi, A. S., Sargolini, M., (2019), 'Vulnerability Assessment and Conservation of Heritage Sites in A Changing Climate'. International Journal of Landscape Architecture Research, 3:2

Dawson, T, (2013), Erosion and coastal archaeology: Evaluating the threat and prioritising action

Day, Jon C. et al., (2019), Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site. An application of the Climate Vulnerability Index, Historic Environment Scotland

Day, Jon C. et al., (2020), 'Assessing the climate vulnerability of the world's natural and cultural heritage'. The Interdisciplinary Journal of Place-Based Conservation, 36:1

Day, Jon C. et al., (2022), An application of the Climate Vulnerability Index for the Sukur Cultural Landscape. Project Report. ICOMOS Nigeria

De Angeli, S., et al., 2021, 'Archaeological site monitoring and risk assessment using remote sensing technologies and GIS', in 'A Research Agenda for Heritage Planning: Perspecitives from Europe', 2021, Edward Elgar Publishing.

Deru, J., D. Dowding, E. Crowe, H. Fluck, (2022), Mapping Climate-Related Hazards to Historic Sites, Historic England

Dimitriou, E., (2022), 'Precipitation Trends and Flood Hazard Assessment in a Greek World Heritage Site'. Climate, 10(12), 194

Dragi□evic, S., Mészáros, M., Djurdji□, S., Pavi□, D., Novkovic, I., Toši□, R. (2013), Vulnerability of National Parks to Natural Hazards in the Serbian Danube Region. Polish Journal of Environmental Studies, 22(4), pp.1053-1060

Dupont, L., V. Van Eetvelde, (2013), Assessing the potential impacts of climate change on traditional landscapes and their heritage values on the local level: Case studies in the Dender basin in Flanders, Belgium. Land Use Policy, Volume 35, 79-191

European Commission. (2018). Heritage at Risk: EU research and innovation for a more resilient cultural heritage.

Fenger-Nielsen, R. et al., (2020), 'Arctic archaeological sites threatened by climate change: A regional multi-threat assessment of sites in south-west Greenland'. Archaeometry, 62(6)

Florentin, K., et al., (2020), 'Towards a Methodological Framework for Predisaster Recover Planning in Historic Districts', in 2020 ICOMOS 6 ISCs Joint Meeting Proceedings: Advancing Risk Management for the Shared Future.

Forino, G., et al. (2016), 'A proposed assessment index for climate change-related risk for cultural heritage protection in Newcastle (Australia)'. International Journal of Disaster Risk Reduction, 19

Gandini, A., et al., (2016), 'Towards Sustainable Historic Cities: Adaptation to Climate Change Risks', International Journal, 2017, 4.

Gandini, A., et.al., (2018), 'Vulnerability assessment of cultural heritage sites towards flooding events'. IOP Conf. Ser.: Mater. Sci. Eng. 364 012028

Gandini, A., et.al., (2020), 'A holistic and multi-stakeholder methodology for vulnerability assessment of cities to flooding and extreme precipitation events'. Sustainable Cities and Society' 63

García Sánchez, F. et al., (2020), 'Cultural heritage and sea level rise threat: risk assessment of coastal fortifications in the Canary Islands'. Journal of Cultural Heritage, 44

Giliberto F. and Jackson, R. (eds.). (2022), Cultural Heritage in the Context of Disasters and Climate Change. Insights from the DCMS-AHRC Cultural Heritage and Climate Change Cohort. LeedsEdinburgh: University of Leeds and University of Edinburgh.

Harkin, D., Davies, M., Hyslop, E. (2018), A Climate Change Risk Assessment of the Properties in the care of Historic Environment Scotland, Historic Environment Scotland

Heathcote, J., et al., (2017), 'Predicting and Adapting to Climate Change: Challenges for the Historic Environment'. The Historic Environment: Policy & Practice, 8(2)

Heilen, M. et al., (2018), 'Modelling Resource Values and Climate Change Impacts to Set Preservation and Research Priorities'. Conservation and Management of Archaeological Sites, 20(4)

Heron, S. F. et al., (2022), Application of the Climate Vulnerability Index for the Ruins of Kilwa Kisiwani and the Ruins of Songo Mnara, Tanzania. Project Report. CVI Africa Project

Historic England (2015), Flooding and Historic Buildings

Historic England (2020), Flooding and Historic Buildings

Historic England (2020), Heritage and Society 2020 (Heritage Counts)

Historic England (2021), Heritage Counts 2020 - Know Your Home, Know Your Carbon: Reducing carbon emissions in traditional homes

Historic England (2022), Corporate Plan 2022-2023.

Historic England, (2022), Climate Change Strategy

Historic Environment Group Climate Change Subgroup (2019), Historic Environment and Climate Change in Wales Sector Adaptation Plan

Historic Environment Scotland (2019), A Guide To Climate Change Impacts on Scotland's Historic Environment

Historic Environment Scotland (2021), Towards a Climate Ready HES Adaptation Plan

HM Government (2022), UK Climate Change Risk Assessment 2022

Howard, A., et. al. (2017), 'Protecting the Historic Environment from Inland Flooding in the UK: Some Thoughts on Current Approaches to Asset Management in the Light of Planning Policy, Changing Catchment Hydrology and Climate Change'. The Historic Environment: Policy & Practice, 8:2, 125-142

Howards, A., et. al. (2016), 'Assessing riverine threats to heritage assets posed by future climate change through a geomorphological approach and predictive modelling in the Derwent Valley Mills WHS, UK'. Journal of Cultural Heritage 19

Hunt. A, (2011), English Heritage coastal estate risk assessment (English Heritage)

IPCC (2022a), 'Annex II: Glossary', in Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

IPCC, (2022b), 'Ch.1: Point of departure and Key concepts', in Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

Johnson, C. E., and Germano, V. (2019), 'Incorporating Local Knowledge into Vulnerability Assessments for Cultural Landscapes: Case Studies from the Pacific West Region. National Park Service

Jones, B. D., et al., (2022) 'Calculating Heritage Risks for the Climate Emergency in Aotearoa (New Zealand) (AINZ)', University of Auckland'

Jones, R. H., et al., (2022), 'Developing Climate Risk Assessments for World Heritage: the Climate Vulnerability Index'. Internet Archaeology 60

Kapsomenakis, J. et al. (2022), 'Climate change threats to cultural and natural heritage UNESCO sites in the Mediterranean'. Environment, Development and Sustainability

Kerr, J.S., (2013), Conservation Plan, 7th edition: A guide to the preparation of conservation plans for places of European cultural significance, (Australia ICOMOS)

Leissner, J., et al., (2010), Modelling climate change impact on cultural heritage the European project climate for culture. Urban Habitat Constructions Under Catastrophic Events: Proceedings of the COST C26 Action Final Conference.

Leissner, J., et al., (2014). In Climate for Culture: Built Cultural Heritage in Times of Climate Change.

Leissner, J., et al., (2015), 'Climate for Culture: assessing the impact of climate change on the future indoor climate in historic buildings using simulations', Heritage Science

Li Fu, Mingjing Ding, Qingping Zhang (2022), Flood risk assessment of urban cultural heritage based on PSR conceptual model with game theory and cloud model – A case study of Nanjing, Journal of Cultural Heritage 58, 1 – 11

Li, Q., et. al., (2022), The Risk Map of Cross-Regional Cultural Heritage: From a Perspective of Slow Degradation. Sustainability, 14(21), 1382

Li, Y., et. al. (2022), The potential impact of rising sea levels on China's coastal cultural heritage: a GIS risk assessment, Antiquity, 96(386), 406-42

Lückerath, D., et al,. (2021), 'The ARCH Project: Investigating the Impact of Climate Change on Historic Areas', Fraunhofer Institute for intelligent Analysis and Information Systems IAIS.

Lückerath, D., Milde, K., & Ullrich, O., (2020), 'ARCH – Saving Cultural Heritage from Climate-related and Other Hazards' Fraunhofer Institute for intelligent Analysis and Information Systems IAIS,

Marzeion, B., Levermann, A. (2020), Loss of cultural world heritage and currently inhabited places to sea-level rise

McCarthy, J. et al., (2001), Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change

Meghan C., L. Howey (2020), Harnessing Remote Sensing Derived Sea Level Rise Models to Assess Cultural Heritage Vulnerability: A Case Study from the Northwest Atlantic Ocean

Milde, K., et. al., (2020), Applying Simulation to Advance Resilience of Historic Areas to Climate Change and Natural Hazards, 10.11128/arep.59.a59063.

Myronyk, D., (2022), Saving Architectural Heritage: Climate Change Resilience and Conservation Management: A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfillment of the requirements for the degree of Master of Architecture. Carleton University, Ottawa, Canada

Nguyen T.L., Asahi C., Tran T.A., Le N.H., (2022), 'Indicator-based approach for flood vulnerability assessment in ancient heritage city of Hoi An, Central Region of Vietnam'. Natural Hazards, 114:2357-2385

Northern Ireland Department for Communities, Historic Environment Division (2018), Climate change risk assessment for historic building owners

Oh, J., et al., (2022), 'Assessment of the effects of projected climate change on the potential risk of wood decay in Korea', Journal of Cultural Heritage, 55.

Olstad., T.M., et. al., (2020), Preservation of Distemper Painting: Indoor Monitoring Tools for Risk Assessment and Decision Making in Kvernes Stave Church, Climate 2020, 8(2), 33

O'Neill, S. et. al., (2022), Extreme rainfall risk and climate change impact assessment for Edinburgh, World Heritage sites Weather and Climate Extremes 38

Orr, S. A., Young, M., Stelfox, D., Curran, J., Viles, H., (2018), Wind-driven rain and future risk to built heritage in the United Kingdom: Novel metrics for characterising rain spells

Pollard-Belsheim, A. et al., (2014) The CARRA project: Developing tools to help heritage managers identify and respond to coastal hazard impacts on archaeological resources, Oceans

Powell, J., et al., (2018), A strategic approach for assessing and addressing the potential impact of climate change on the historic environment of Wales

Quesada-Ganuza, L. et al., (2021), 'Do we know how urban heritage is being endangered by climate change? A systematic and critical review'. International Journal of Disaster Risk Reduction

Quesada-Ganuza, L., et al (2022), The Risk of Heat Waves to Historic Urban Areas. A GIS-Based Model for Developing a Risk Assessment Methodology

Ramadan, R. et al., (2022) Assessment of Sustainable World Heritage Areas in Saudi Arabia Based on Climate Change Impacts on Vulnerability Using RS and GIS. Sustainability 2022, 14, 15831.

Ravankhah, M. et al, (2018), 'A methodological framework to assess disaster risks at cultural heritage sites: the case of the Roman Ruins of Tróia,' 8th International Conference on Building Resilience

Ravankhah, M., et al., (2019), 'Integrated Assessment of Natural Hazards, Including Climate Change's Influences, for Cultural Heritage Sites: The Case of the Historic Centre of Rethymno in Greece', International Journal of Disaster Risk Science 10

Ravankhah, M., et al., (2020), 'A Multi-Hazard Platform for Cultural Heritage at Risk: The STORM Risk Assessment and Management Tool', IOP Conference Series: Materials Science and Engineering

Ravankhah, M., et al', (2020), 'Chapter 2 - Risk Assessment and Risk Management for the Protection of Cultural Heritage', Cultural Heritage Resilience Against Climate Change and Natural Hazards Methodologies, Procedures, Technologies and Policy improvements achieved by Horizon 2020 STORM project

Ravankhah, M., Schmidt, M. (2014), 'Developing Methodology of Disaster Risk Assessment for Cultural Heritage Sites', Proceedings ANDROID Residential Doctoral School, September 2014

Reeder-Myers, L. A., (2015), 'Cultural Heritage at Risk in the Twenty-First Century: A Vulnerability Assessment of Coastal Archaeological Sites in the United States'. Journal of Island and Coastal Archaeology 10(3)

Reimann, L., et. al., (2018), 'Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise'. Nature Communications volume 9, Article number: 4161

Resta, V., et al., (2019), 'Cultural Heritage Resilience Against Climate Change and Natural Hazards: Methodologies, Procedures, Technologies and Policy improvements achieved by Horizon 2020 - 700191 STORM project.', Pisa University Press

Ria Jhoanna C. Ducusin et. al. (2019), Vulnerability assessment of climate change impacts on a Globally Important Agricultural Heritage System (GIAHS) in the Philippines: the case of Batad Rice Terraces, Banaue, Ifugao, Philippines. Climatic Change 153:395–421

Ricci, G., D. Robadue, Jr., P. Rubinoff, A. Casey, and A. L. Babson. (2019), Method for integrated coastal climate change vulnerability assessment

Ricci, G., Robadue DD, Rubinoff P, Casey A, Babson AL., (2019), Integrated coastal climate change vulnerability assessment: Colonial National Historical Park. Natural Resource Report

Richards, J., et al., (2022), 'Moisture as a Driver of Long-Term Threats to Timber Heritage—Part I: Changing Heritage Climatology', Heritage, 5.

Richards, J., et. al., (2020), Deterioration risk of dryland earthen heritage sites facing future climatic uncertainty. Sci Rep 10, 16419

Rivera-Collazo, I. C., (2019), Severe Weather and the Reliability of Desk-Based Vulnerability Assessments: The Impact of Hurricane Maria to Puerto Rico's Coastal Archaeology

Ronco, P et. al., (2016), 'Assessing flood risk in Zurich, Switzerland: the KR-RRA approach'. Planning to cope with tropical and subtropical climate change, Warsaw, Poland: De Gruyter Open Poland, 2016, pp. 336-353

Ronco, P. et. al., (2014), The KULTURisk Regional Risk Assessment methodology for water-related natural hazards – Part 1: Physical–environmental assessment, Hydrol. Earth Syst. Sci., 18, 5399–5414, 2014

Saha, A. et al., (2021), 'Modelling multi-hazard threats to cultural heritage sites and environmental sustainability: The present and future scenarios'. Journal of Cleaner Production, 320

Sardella, A. et al., (2020), 'Risk Mapping for the Sustainable Protection of Cultural Heritage in Extreme Changing Environments'. Atmosphere, 11(7)

Sesana, E. et al., (2020), 'An integrated approach for assessing the vulnerability of World Heritage Sites to climate change impacts'. Journal of Cultural Heritage (41)

Sesana, E. et al., (2021), Climate change impacts on cultural heritage: A literature review, WIREs Climate Change, 710

Sevieri, G., Carmine Galasso, (2021), Typhoon risk and climate-change impact assessment for cultural heritage asset roofs. Structural Safety 91, 102065

Shaheen, N. A., et al., (2020), 'Environmental Risk Assessment as an Approach of Resilience to Climate Change in Architectural Built Cultural Heritage'. in Architecture and Urbanism: A Smart Outlook. Springer, Cham.

Simpson, N. P. et al., (2022), 'ICSM CHC White Paper II: Impacts, vulnerability, and understanding risks of climate change for culture and heritage: Contribution of Impacts Group II to the International Co-Sponsored Meeting on Culture, Heritage and Climate Change,' ICOMOS & ISCM CHC

Simpson, N. P., et al., (2021), 'A framework for complex climate change risk assessment', One Earth, 4(4)

Sperotto, A., et. al., (2016), 'A multi-disciplinary approach to evaluate pluvial floods risk under changing climate: The case study of the municipality of Venice (Italy)'. Science of the Total Environment 562

Stephenson, V. and D'Ayala, D, (2014), A new approach to flood vulnerability assessment for historic buildings in England. Natural Hazards and Earth Systems, 14, 1035–1048

Stucchi, L. et. al. (2021), 'Assessment of Climate-Driven Flood Risk and Adaptation Supporting the Conservation Management Plan of a Heritage Site. The National Art Schools of Cuba', Climate, 9, 23.

Tersigni, E. et al., (2020), 'Innovative Processes for Climate Risk Reduction of the Built Heritage', In: Bevilacqua, C., Calabrò, F., Della Spina, L. (eds) New Metropolitan Perspectives. NMP 2020. Smart

Ulster Architectural Heritage (2015), Impacts of Climate Change on the Historic Built Environment: A Report and Guide

UNDRR (2021), Terminology: https://www.undrr.org/terminology

US Department of the Interior, National Park Service, (2022), 'Climate change vulnerability assessments in the National Park Service: An integrated review for infrastructure, natural resources, and cultural resources (revised)'.

Valagussa, A. et al., (2021), 'Multi-risk analysis on European cultural and natural UNESCO heritage sites'. Natural Hazards, 105

Van Meerbeek, L.,, Barazzetti b, L., Valent, R., (2017), From cultural path to cultural route: a value-led risk management method for via Iulia Augusta in Albenga (Italy). University of Leuven.

Viles, H., et al., (2012), 'Global environmental change and the biology of heritage structures', Global Change Biology, 18.

Vojinovic Z., et. al. (2021), 'Adaptation to Flood Risk in Areas with Cultural Heritage', In: Babel, M., Haarstrick, A., Ribbe, L., Shinde, V.R., Dichtl, N. (eds) Water Security in Asia. Springer Water. Springer, Cham.

Wang, J.-J., (2015), 'Flood risk maps to cultural heritage: Measures and process'. Journal of Cultural Heritage 16 210-220

Watkiss, P. and Betts, R.A. (2021), 'Method', in: The Third UK Climate Change Risk Assessment Technical Report

Westley, K. (2019), 'Refining Broad-Scale Vulnerability Assessment of Coastal Archaeological Resources, Lough Foyle, Northern Ireland'. Journal of Island and Coastal Archaeology, 14(2)

Westley, K. et al., (2011), 'Impact Assessment of Current and Future Sea-Level Change on Coastal Archaeological Resources—Illustrated Examples From Northern Newfoundland'. Journal of Island and Coastal Archaeology, 6(3)

Westley, K., et al., (2021), 'Climate change and coastal archaeology in the Middle East and North Africa: assessing past impacts and future threats'. Journal of Island and Coastal Archaeology

Yagoub, M.M., Al Yammahi, Abdulla Amed., (2022), 'Spatial distribution of natural hazards and their proximity to heritage sites: Case of the United Arab Emirates'. International Journal of Disaster Risk Reduction, Volume 71

Yildirim, O., et al., (2020), 'A GIS-based Risk Mapping for the Goreme National Park and the Rock Sites of Cappadocia', in 2020 ICOMOS 6 ISCs Joint Meeting Proceedings: Advancing Risk Management for the Shared Future.

Zartarian, V.G., Ott, W. R., Duan, N., 'A quantitative definition of exposure and related concepts', Journal of Exposure Analysis and Environmental Epidemiology, 7(4) (Oc

HARLOW
CONSULTING