

Mapping Risk, Building Resilience:
Operationalising Disaster Risk Reduction for Archaeology via Geospatial Approaches

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Abstract

Archaeology sits at the frontline of accelerating environmental and political instability, yet its engagement with formal disaster risk mitigation frameworks, such as the United Nations' Disaster Risk Reduction Framework (DRR), is inconsistent. As contemporary landscapes increasingly behave dynamically, where visibility fluctuates, access collapses, and hazards outpace field logistics, the need for risk-aware, adaptive methodologies is becoming increasingly urgent. This thesis adapts and operationalises the DRR framework for archaeology through open, extensible geospatial workflows that identify, visualise, and prioritise archaeological risk under such accelerating conditions. This approach models risk across variable data environments and shrinking windows of opportunity, enabling researchers and heritage management to act in advance of material and epistemic loss. This research integrates archaeological inventories with global datasets to generate composite, DRR-compatible risk surfaces and ranked priority zones. All workflows are designed to maximise reproducibility and methodological resilience, particularly in data-poor or socio-politically unstable contexts. The framework is tested across three contrasting case studies: (1) Holderness (United Kingdom), a data-rich but rapidly eroding coastline; (2) O'ahu (Hawai'i, United States), where landslide susceptibility poses a threat to pre-contact archaeology; and (3) Sistan (Iran and Afghanistan), where desertification risk is modelled with minimal ground access to demonstrate feasibility under severe data and capacity constraints. Across the case studies, the workflows translate DRR concepts into mappable archaeological risk and triage priorities. They also demonstrate that archaeological outcomes depend as much on visibility, tempo, and governance as on hazard severity. This reinforces the need for adaptable methods that can respond to unstable, rapidly changing conditions. In doing so, the thesis delivers two principal contributions: first, a clear pathway for embedding archaeology within formal disaster risk planning (DRR); and second, accessible methodologies that standardise archaeological risk assessment across diverse and increasingly volatile contexts. While this thesis focuses on the methodological operationalisation of DRR for archaeology, implementation depends upon the legislative, policy, governance, and stakeholder contexts within which the framework is applied. These, therefore, represent important directions for future research and practice.

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Preface

This thesis arises from a long-standing interest in the relationship between humans and the landscapes they inhabit. My early archaeological training revealed a tension between the frame of excavation trenches and the wider landscapes that shape and add context to archaeological deposits. As geospatial technologies became increasingly central to archaeological research, their capacity to bridge this gap became evident, even as early limitations in data accessibility and technical proficiency complicated their adoption. My subsequent postgraduate work demonstrated that GIS and remote sensing could offer a way to engage with landscapes as dynamic, experiential, and culturally embedded. Building from these previous interests, this doctoral project was initially designed around on-the-ground collaboration with Indigenous communities in Alaska confronting coastal erosion. The COVID-19 pandemic rendered such field engagement impossible, severing responsible access and constraining collaborative pathways. This disruption forced a reorientation that ultimately broadened its methodological ambition. In adapting to the pandemic's constraints, the research shifted from a region-specific application to a multi-context framework capable of functioning across environments with different data, governance, and access conditions. What began as a geographically bounded endeavour became an inquiry into how archaeological disaster risk reduction can proceed when physical presence is impossible and when traditional field validation is no longer guaranteed.

This interruption also made visible a deeper issue: that the ability to participate meaningfully in disaster risk reduction is shaped not only by hazard exposure, but by structural inequalities in who can act, respond, and adapt when conditions change. As the project adjusted to the constraints of the pandemic, it became clear that archaeological disaster risk reduction cannot depend on uninterrupted access, specialist infrastructure, or ideal research conditions. Its methods must remain viable precisely when circumstances are unstable, when institutional capacity is limited, and when uncertainty disrupts conventional modes of working. This shift crystallised a central principle: the protection of archaeological heritage depends not only on technical knowledge but on the ability to mobilise that knowledge within the structures and expectations of disaster risk reduction. The pandemic underscored disparities in who can participate in disaster risk reduction processes, revealing inequalities in access to training, institutional support, and mechanisms for formally recognising risk. If archaeology is bound up with environmental hazards, political instability, and the resilience of the communities that steward heritage, then the frameworks used to manage risk must be open, adaptable, and capable of functioning in places where formal capacity is limited.

In this light, this thesis prioritises approaches that can be adopted without specialised infrastructures or exclusive expertise. Its aim is to lower the barriers that historically have restricted disaster risk reduction-oriented archaeological work to well-resourced institutions, where risk is more easily quantified, communicated, and acted upon. The goal is not simply to produce risk assessments, but to enable others to activate them within their own realities, recognising that safeguarding archaeological landscapes is a dispersed responsibility grounded in shared stewardship rather than isolated authority.

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Chapter 1: Introduction

1.1. Background

Disaster has been a constant in human history, from the cataclysmic eruption of Vesuvius in 79 A.D., vividly captured by Pliny the Elder, who described ' . . . ash already falling becoming hotter and thicker . . . soon superseded by pumice and blackened burnt stones shattered by fire' (Scarth, 2009), to the more recent slow-onset crises such as the severe drought that struck the Horn of Africa in 2011 and persisted for nearly a year (Nicholson, 2014). In the contemporary era, disasters are becoming increasingly intense and frequent as climate fluctuations continue to amplify (Burke et al., 2021; Sesana et al., 2021). Rising global temperatures increase atmospheric energy and moisture, amplifying storms and exacerbating heatwaves (Adeyeri et al., 2025; Anderson, 2023). While early warning systems and response mechanisms continue to improve (Reichstein et al., 2025), the concurrent increase in disasters results in profound economic losses and long-term social and ecological disruption worldwide (Botzen et al., 2019; Lawrence et al., 2021). Anthropogenic pressures magnify disasters, further weakening ecosystems, paradoxically constraining social recovery capacity (Walz et al., 2021; Pal et al., 2023).

It is in human nature, as the archaeological record repeatedly demonstrates, to adapt to risk (Jacobson, 2022). The biological imperative for survival has, in modern societies, evolved into structured frameworks aimed at reducing vulnerability and loss. The United Nations' Disaster Risk Reduction (UNDRR, hereafter referred to as DRR) framework exemplifies this collective endeavour, propelling a coordinated, global effort to minimize the human and economic toll of disasters (Botzen et al., 2019). However, within this international agenda, the archaeological record occupies a precarious position. The fragility and non-renewable nature of the archaeological record render it one of the most vulnerable resources to contemporary environmental instability. Despite growing recognition of climate-related impacts on archaeology, prevailing approaches to the issue are reactive and inconsistent. Archaeological responses are often limited to post-event assessments (Welch et al., 2023) or to salvage (Davis et al., 2020), rather than to anticipatory risk-reduction strategies (Binda et al., 2011). While some integration has occurred through heritage management and cultural protection initiatives, these remain fragmented (Chirikure et al., 2021) and rarely embedded within broader frameworks for disaster governance, such as DRR.

In contrast, DRR has matured into a globally coordinated field of policy and practice, codified through the Sendai Framework for the United Nations Office for Disaster Risk Reduction (UNDRR) (UNDRR, 2025). Archaeology, however, remains largely absent from this discourse. This omission represents both a conceptual and methodological gap: the DRR framework overlooks the temporal depth and evidence-based insight archaeology can offer. At the same time, archaeological practice

has yet to adapt DRR principles to its own distinctive challenges. This thesis is written from the intersection of loss and possibility, arguing that the framework and tools to anticipate and mitigate the impact of disasters on archaeology exist but require translation and adaptation for archaeological purposes. Disasters are place-based, as is archaeology, both defined by where events occur and by people's interactions with landscapes. Integrating DRR and archaeology thus benefits from a geospatial approach, as geospatial tools such as remote sensing, spatial modelling, and Geographic Information Systems (GIS) can reveal how hazards intersect with archaeology, allowing for the mapping of risk and resilience over time. This geospatial lens aids both fields by preventing over-abstraction, embedding DRR principles into archaeology through geospatial approaches, and enabling maps to be transformed from records of loss into instruments of risk reduction. By integrating the DRR framework with archaeology via geospatial approaches, this thesis seeks to reposition archaeology from reactive to a proactive practice grounded in resilience. This thesis does not claim to halt the impacts of disasters on archaeology; instead, it aims to make such losses intelligible and to model the at-risk archaeological record as it faces imminent transformation or loss.

1.2. Aims and Objectives

This thesis aims to adapt and operationalise the DRR framework for archaeology through geospatial approaches, developing open, transferable models that identify, visualise, and prioritise archaeological risk. By integrating DRR principles via geospatial approaches, this thesis seeks to position archaeology as an active partner in resilience planning and disaster risk reduction, instead of a passive recipient of loss. Sub objectives required to accomplish this aim include:

1) The generation and implementation of open-source geospatial workflows to model hazards (erosion, landslides, desertification) for archaeological risk, and in doing so:
    a. Determine if, and how, vulnerability and exposure can be operationalized geospatially for archaeology, and in doing so:
    b. Determine if such methods work across both data-rich and data-poor contexts.
2) Prioritisation of accessibility in all models to facilitate widespread applicability, particularly in data-poor contexts, and in doing so:
    a. Test and refine the adapted framework across three contrasting case studies: Holderness, O'ahu, and Sistan.

In pursuit of these aims, this thesis not only advances the methodological frontier of archaeological risk management but also contributes to the broader DRR discourse by demonstrating how archaeology can be operationalised within an established resilience framework. By prioritising open-

source, adaptable workflows, this thesis aims to enable others to make informed, context-sensitive decisions about archaeological disaster protection.

1.3. Contributions and Significance

The study of disasters in archaeology has long been shaped by a disciplinary bifurcation: one trajectory investigates how past societies experienced catastrophic events, while the other examines how modern hazards threaten archaeological sites and landscapes. These two lines of inquiry have developed in parallel but rarely converge. Disaster-focused archaeology has served as a lens for interpreting cultural resilience and transformation in the past (Westra et al., 2022; Riede, 2017). On the other hand, archaeological management has grappled with contemporary threats such as flooding, coastal erosion, and seismic instability (Schlanger et al., 2016; Rouhani & Romão, 2024). This division has produced valuable but fragmented knowledge on archaeology and disaster, limiting the discipline's potential to contribute to global disaster governance.

Research over the past decade has demonstrated that archaeology possesses a unique opportunity to inform resilience and adaptation strategies in the face of disaster. Studies documenting how ancient and historic communities coped with catastrophe show that cooperation and environmental adaptation can foster long-term survival (Rivera-Collazo, 2022; Burke et al., 2021). These examples illustrate that archaeology can serve as an active repository of human adaptability, offering long-term perspectives on how societies recover from environmental stress. Yet this same body of research underscores a growing urgency: the modern hazard landscape threatens the very record from which such lessons might be drawn. Coastal archaeology has become a particular area of concern, as rising sea levels and intensified erosion expose and destroy sites (Dawson et al., 2017, 2020; Elfadaly et al., 2023; Westley et al., 2023). Other hazards, including earthquakes (Giordano et al., 2023), flooding (Marchetti, 2020), wildfires (Buettel et al., 2023), and compounding or cascading hazard events (Sesana et al., 2021), have similarly become central to archaeological risk assessments. Despite this diversification of disaster and hazard research in archaeology, the field remains fragmented, with relatively few studies integrating diverse disaster risk into a coherent, globally recognised framework.

Efforts to align archaeology with formal disaster mitigation and risk reduction frameworks have emerged over the past two decades, but these efforts are often crisis-driven, arising from acute emergencies not proactive or policy-led integration. The most visible examples have tended to emerge from post-disaster archaeological management, where frameworks designed for humanitarian recovery were extended to include archaeological assessment (Corbishley 2010; Holtorf 2018). These initiatives relied on short-term collaborations between archaeological agencies and civil protection authorities, achieving valuable documentation and salvage outcomes, but rarely establishing sustained integration within national or regional disaster governance systems. A partial institutionalisation of this approach came in 2005-2015, with the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Risk Preparedness Programme, developed in the wake of the Hyogo Framework for Action (United Nations International Strategy for

Disaster Reduction (UNISDR) (2005). This represented one of the first systematic efforts to situate cultural heritage within a multi-hazard risk management model; however, its implementation was inconsistent, with the framework simply stating: the information management exchange should, 'Provide easily understandable information on disaster risks and protection options, especially to citizens in high-risk areas, to encourage and enable people to take action to reduce risks and build resilience. The information should incorporate relevant traditional and indigenous knowledge and cultural heritage, and be tailored to different target audiences, considering cultural and social factors' (UNISDR, 2005, p. 9). While certain World Heritage Sites (WHS), such as Petra in Jordan (Cesaro et al., 2023), have produced risk-preparedness plans, these frameworks tend to prioritise monumental architecture and tourism infrastructure over broader archaeological landscapes. Consequently, non-monumental, non-listed sites, which are most representative of everyday human history, remain largely outside the operational scope of international disaster protocols.

In parallel, a theoretically grounded engagement between archaeology and DRR has started to develop. Riede (2017, 2019) and Pica (2018) have argued for archaeology's inclusion as a form of long-term hazard knowledge, capable of revealing how past societies adapted to environmental extremes and thereby informing future resilience strategies. This perspective on the archaeology of disaster bridges the interpretive and applied domains of archaeological science, positioning archaeological data as both cultural evidence and a functional resource within DRR thinking. It reframes the archaeological record as a dataset that can inform preparedness and adaptation in the present. Parallel initiatives, such as the Resilient Heritage programme and the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM), United Nations Educational, Scientific and Cultural Organization(UNESCO) Culture Cannot Wait framework (ICCROM 2019-2020), have attempted to align heritage protection with the Sendai Framework's four priority areas. Yet, despite this rhetorical alignment, these projects have not achieved operational parity with disaster mitigation systems. In each case, the integration of heritage or archaeology into DRR has been conceptually advanced but, nevertheless, reveals a gap between interpretive awareness and implementation capacity.

A key limitation across these efforts lies in the absence of an intermediary framework that can translate archaeological values into the evidential and procedural language of disaster governance. Archaeological data are rarely structured according to DRR conventions. Moreover, most existing studies approach disaster mitigation from a post-event recovery perspective instead of a pre-emptive risk modelling. This orientation reinforces a reactive posture in archaeological practice, responding to disasters but rarely anticipating them. As a result, archaeology's potential as a predictive and preventative discipline, capable of identifying and modelling risk before impact, remains largely unrealised. Recent empirical studies have begun to illustrate both the promise and the persistent limitations of this engagement. Crowley et al. (2022) provide a comprehensive review of heritage risk-assessment literature, finding that most studies privilege hazard exposure while neglecting consistent definitions of vulnerability or adaptive capacity, under-represent intangible heritage values and community knowledge, and exhibit a pronounced bias toward Global North contexts. While this synthesis offers a valuable diagnosis of the assessment gap in heritage risk

research, it does little to demonstrate how such assessments might translate into actionable DRR governance, investment, or preparedness frameworks.

Others have sought to bridge this gap through conceptual or methodological innovation. Riede (2017), for instance, advances the idea of 'past-forwarding,' using ancient disasters, such as the Laacher See volcanic eruption, to inform contemporary risk awareness and scenario building. His work demonstrates how archaeology can contribute to DRR at the levels of knowledge production and public engagement but remains mainly theoretical and lacks integration into operational DRR systems. Similarly, Li et al. (2024) present a global-scale assessment of disaster risk management in WHS, explicitly adopting the terminology and conceptual framing of DRR. Their work exposes the vulnerabilities of heritage assets to multiple hazards and identifies systemic governance failures and limited integration of DRR within site-management plans. Yet while Li et al. embrace the language of the Sendai Framework, their analysis remains descriptive and diagnostic, offering insight into risk conditions without fully operationalising DRR priorities or embedding heritage into policy mechanisms. Similarly, the work of Pérez Bermúdez and Vargas Ariza (2025) applies a multidisciplinary vulnerability index to three heritage elements on Santa Catalina Island. This study moves beyond descriptive hazard assessment to a quantifiable analysis of exposure, adaptive capacity, and historical value. Though methodologically sophisticated, their approach remains highly localised and lacks explicit connection to global DRR frameworks or actionable governance structures. A similar pattern emerges in the work of Ravan et al. (2023), who propose an indicator-based methodology for evaluating the vulnerability of archaeological sites, tested through a case study at the Roman Ruins of Tróia. Their Cultural Heritage Vulnerability Index integrates both structural sensitivity and institutional adaptive capacity, marking an advance in risk-informed heritage management. Yet, like many heritage DRR studies, the work remains analytical, quantifying vulnerability without embedding the findings within the full DRR architecture. Peres and Deter-Wolf (2018) further illustrate archaeology's potential to engage with disaster processes by examining how the 2010 Cumberland River floods in Tennessee not only damaged sites but also catalysed new institutional collaborations and mitigation awareness. Their 'positive in the negative' framing demonstrates how disasters can trigger heritage mobilisations, but these remain reactive and episodic, valuable for recovery, yet detached from long-term governance or investment structures.

Taken together, these studies chart a trajectory in the evolving relationship between archaeology and disaster risk reduction. The field has moved from descriptive accounts of site damage toward more risk-informed and conceptual approaches. Yet across the spectrum, a consistent shortfall persists in operationalizing archaeological insights into DRR governance implementation. What is needed is not more evidence that archaeology is at risk, but mechanisms that make archaeological knowledge legible and actionable within the systems that govern risk. This gap underpins the necessity of this thesis. While heritage management has borrowed concepts from disaster studies, archaeology itself has rarely engaged with robust, globally established structures such as the DRR framework. As global hazard frequency and intensity accelerate (AghaKouchak et al., 2020), archaeology's marginal position within resilience and risk governance becomes increasingly problematic for the discipline. Without a structured framework for risk reduction, the discipline

remains reactive, documenting destruction after the fact rather than anticipating it. This thesis therefore contributes by advancing a paradigm shift, showcasing the integration of archaeological risk into DRR and operationalising this integration through open-source geospatial approaches. In doing so, this thesis moves archaeology from reactive, post-event recording toward anticipatory planning and mitigation.

The methodological contribution of this thesis lies in developing open, extensible geospatial workflows that enhance the consistency and reach of disaster assessment in archaeology. While geospatial approaches have significantly advanced the capacity to evaluate archaeological vulnerability, their application remains uneven, often constrained by cost, data access, or technical infrastructure (Lim et al., 2021; Nyong et al., 2007; Opitz & Herrmann, 2018; Chasmer et al., 2022). The workflows presented here address these challenges by providing structured, replicable methods that can operate effectively across varied data conditions and contexts. By integrating global hazard datasets with archaeological inventories, assessments of archaeological exposure and vulnerability can be conducted. The approaches presented in this thesis are designed to support professional archaeological and heritage management practice while facilitating broader alignment with the DRR framework. In this way, the research positions geospatial approaches as a reliable and scalable foundation for informed archaeological risk analysis.

The discipline of archaeology documents the long human story of adaptation and transformation, an archive of how societies have interacted with dynamic landscapes (Huvila et al., 2022). As climate change accelerates landscape transformation, digital documentation is becoming increasingly essential. Integrating geospatial approaches facilitates both physical and digital preservation by identifying sites most vulnerable to loss and by recording those that may soon disappear (Fradley & Bewley, 2021; Morgan, 2022). Archaeological preservation in this sense is about maintaining access to humanity's deep temporal knowledge, keeping data discoverable, interpretable, and open to future generations. At the same time, disasters expose archaeology's vulnerabilities while also creating fleeting opportunities for discovery. Landscape change reveals what was once hidden, reshaping archaeological potential (Peres & Deter-Wolf, 2018). In the Arctic, melting permafrost reveals remarkably preserved organic material (Emslie, 2021; Hollesen et al., 2022), while along Britain's coasts, accelerated erosion exposes prehistoric landscapes previously sealed beneath sediment (Wood, 2019; Wood, 2020). Yet exposure precedes destruction: in Arctic contexts, decomposition follows almost immediately after exposure (Hollesen et al., 2016; Friesen, 2018), and coastal erosion can consume sites as rapidly as it reveals them (Dawson et al., 2020; Pourkerman et al., 2018; Westley et al., 2023). This dynamic highlights both the necessity and the limitation of reactive documentation. Without anticipatory strategies, archaeology risks becoming a discipline that records its own losses but does not focus on preventing them. The preventative and anticipatory framework of DRR, proposed in this thesis, therefore aims to shift archaeology towards a strategic approach. The goal is to ensure that when loss occurs, all archaeological data (or knowledge) does not vanish with it. By integrating archaeological data and practice into DRR, this research situates disasters not as aberrations of nature but as outcomes of interactions between environmental processes and human vulnerability (Raju et al., 2022; Chmutina & von Meding, 2019). This reframing

also recasts the role of the archaeologist: not as one who fears the impact of disaster(s), but as one who interprets and adapts within it.

At the heart of this discussion lies a fundamental ethical and practical question: why should communities facing immediate socio-economic hardship or environmental instability care about archaeological preservation? Rivera-Collazo and Perdikaris (2023, p.1150) remind us that archaeological sites are not inert relics but living components of identity, sustainability, and cultural continuity. Protecting heritage is not an indulgence but a contribution to resilience itself. Archaeological knowledge offers long-term empirical evidence of human adaptability, cooperation, and transformation under stress (Bahn, 2012; Renfrew & Bahn, 2020). By safeguarding archaeological heritage, societies preserve not only the material record of the past but the knowledge systems that embody collective adaptation. Following Drury's assertion that humanity and its economy are inseparable from the natural world (Stubbs & McKee, 2006, p. 516), this thesis positions archaeology as a medium through which this interdependence becomes visible. Archaeology reveals that disasters are not isolated failures of nature but co-evolutionary phenomena linking societies and natural systems (Oliver-Smith, 2020). The discipline thus has an essential role in tracing how resilience emerges through interaction rather than isolation. By emphasising flexible, ecosystem-aware frameworks such as DRR, this research contributes to an archaeology of advocacy, one that bridges the human and environmental dimensions of risk.

This thesis is intentionally methodological in scope. Its principal contribution is the operationalisation of DRR concepts for archaeology through transferable geospatial workflows capable of identifying, modelling, and prioritising archaeological risk. It does not seek to redesign heritage policy, governance structures, planning systems, or decision-making processes, nor does it propose new models of stakeholder engagement or institutional implementation. These are recognised as important for the comprehensive application of archaeological DRR but require context-specific cultural and organisational considerations that extend beyond the scope of this thesis. Instead, this thesis provides a flexible analytical and methodological foundation that can be adapted within diverse policy, governance, and institutional settings. The flexibility of the framework, therefore, enables consistent archaeological risk assessment while allowing implementation to remain locally appropriate.

1.4. Definitions

This thesis adopts an inclusive definition of archaeology that encompasses both tangible site-level archaeological records and landscape-scale areas of interest (Foster & Gilman, 2015). In addition, the terms cultural resources and heritage are used interchangeably with archaeology when appropriate and accurate. Such a broad understanding is essential in the context of disasters, where impacts extend beyond physical damage to include the erosion of meaning, identity, and connection. Framing archaeology as a multidimensional domain of heritage allows this thesis to engage with the full spectrum of loss and resilience, developing approaches adaptable across

diverse cultural, temporal, and methodological contexts. It is neither within the remit nor the ethics of this research to prescribe which archaeology should be prioritised or preserved.

Unlike the definition of archaeology, the definition of disaster is much more contested and elusive than its frequent use implies. The apparent simplicity of the term conceals a deep fault line between natural process and human vulnerability. Concepts that frame disasters as exceptional 'acts of nature' have been validly challenged since O'Keefe et al. (1976) shared a foundational argument that there is no such thing as a natural disaster. They claim that disasters arise when environmental hazards intersect with socially produced vulnerability. This distinction remains central to the DRR framework and to the Sendai Framework's emphasis on vulnerability, capacity, and governance. Yet despite its policy formalisation, the conceptual and practical boundaries of 'disaster' continue to shift (Cui et al., 2021). For archaeology, this definitional instability poses both a challenge and an opportunity. On the one hand, it complicates attempts to translate DRR into archaeological terms. On the other hand, it aligns with archaeology's long-standing engagement with temporal and cultural variability. The archaeological record itself is a palimpsest of human–environment interaction, where moments of 'disaster' often blur into processes of adaptation (Torrence & Grattan, 2002; Heitz et al., 2021). The same flood that devastates one generation may create the fertile alluvium that sustains the next.

Within the DRR framework, disaster risk is conceptualised as the interaction between four key components: hazard, exposure, vulnerability, and capacity. A hazard refers to a potentially damaging physical event, phenomenon, or process, natural or anthropogenic in origin, that may cause adverse effects. Exposure concerns the presence of people, infrastructure, or assets in areas that could be adversely affected. Vulnerability captures the susceptibility of these elements to harm, encompassing physical fragility, social inequalities, and institutional weaknesses. Finally, capacity refers to the resources and adaptive abilities that enable communities or systems to anticipate and recover from adverse events (UNDRR, 2025). When translated into archaeological terms, these concepts require adaptation (Gill et al., 2021). Archaeological hazards extend beyond discrete events to include cumulative, often long-term, less visible processes. Exposure pertains not to human populations but to the spatial and environmental settings of archaeological sites, landscapes, and deposits, whose risks are shaped by their physical context and accessibility. Vulnerability in archaeology incorporates both material fragility (soil composition, preservation conditions) and cultural dimensions, such as the relative value and visibility of archaeology within governance systems. Capacity, meanwhile, translates into the tools, data, and institutional frameworks available to monitor, protect, and manage archaeological resources in anticipation of loss.

This thesis adopts the DRR framework's definitions of disaster and hazard, substituting what might commonly be termed a disaster with the DRR concept of hazard. Within DRR, a hazard refers to the potential, often slow-onset, drivers of disaster rather than the ultimate disaster event itself. Coastal erosion, desertification, and landslides exemplify processes whose cumulative effects threaten archaeological materials, oftentimes long before any formal disaster threshold is reached. Such

hazards rarely manifest as single catastrophic moments: instead, they generate sustained conditions of risk in which exposure and vulnerability progressively accumulate. Hazards may be chronic and incremental, as with coastal erosion, or may cascade toward disaster through compounding interactions that ultimately devastate livelihoods or, in the context of this research, the archaeological record. Archaeology, as framed in this thesis, operates primarily within the pre-disaster phase, where anticipatory knowledge and spatial insight can still influence outcomes. Therefore, for the purposes of this thesis, the operational vocabulary follows the DRR and Sendai Framework definitions. A disaster refers to a serious disruption of the functioning of a community or system due to hazardous events interacting with exposure, vulnerability, and capacity, leading to loss and impact (UNDRR, 2025). By adopting this operational framing while retaining awareness of its conceptual fluidity, this thesis situates archaeology within an established DRR lexicon without reducing its complexity. In practice, the emphasis here lies on hazard anticipation rather than post-disaster response, translating the language of risk into geospatial tools for archaeological triage and resilience planning. The upcoming Chapter 2 will provide a more thorough unpacking of DRR and the corresponding definitions.

1.4.1. Temporality

Temporality sits at the core of archaeological understanding, as an active force. Landscapes shape, erase, reveal, and rework archaeology over scales that stretch far beyond human lifetimes. Change is not an anomaly but a defining characteristic of a living planet. Coastlines migrate, rivers re-route, soils accumulate and erode, and climates shift in long rhythms punctuated by abrupt turns. Archaeology has always been entangled within these dynamics. What has changed, and what concerns this thesis, is not the presence of landscape transformation, but its acceleration. Processes that once unfolded over centuries or millennia are now compressed into years or decades. This compression unsettles the temporal buffer that typically protects buried materials, destabilising not only archaeological deposits but the institutional and methodological systems designed to steward them. It is therefore important to emphasise that the aim of this thesis is not to prevent landscape change. Attempting to halt the fundamental processes of a dynamic Earth would be as misguided (as it would be impossible). Instead, the intention is to understand and anticipate these changes as they intensify, and to act responsibly within that shifting terrain. Responsible action means recognising the inevitability of change while refusing to be passive in the face of accelerating loss. It acknowledges our obligation to respond, not with humility and determination, but with the methods, tools, and priorities required to adapt. A DRR-informed approach that accounts for temporality allows us to identify where risk is emerging, where it is escalating, and where intervention, whether documentation, protection, or strategic sacrifice, can make a meaningful difference. This temporal awareness reinforces the core premise of this research: that archaeology must operate within the pre-disaster horizon.

1.5. The Methodological Opportunity

Disasters and hazards are inherently place-based phenomena; their causes and impacts are conditioned by geography. Archaeology, too, is rooted in place: every site, artifact, and landscape is spatially anchored, with its meaning location-specific. This shared spatial dependence creates an intrinsic affinity between DRR and archaeology. Both grapple with questions of vulnerability, exposure, adaptation, and resilience, concepts that are spatial at their core. Geospatial approaches form the connective tissue between these domains. Remote sensing, spatial modelling, and GIS enable the visualization and analysis of how hazards intersect with cultural heritage. They allow mapping exposure and assessing hazard risk at multiple scales. Without an understanding of spatial extent, including where disasters occur, how they propagate, and which archaeology they threaten, both DRR and archaeology risk operating in abstraction. In essence, geospatial methods transform maps from static representations into analytical instruments, tools not only for preservation but also for foresight. Through spatial thinking, archaeologists can move beyond documenting what has been lost to anticipating what may be at risk, enabling proactive and place-based strategies for resilience. However, despite the availability of sophisticated tools to monitor, predict, and visualize risk, integration of these capabilities into archaeological workflows has been uneven, with much of the discipline remaining reactive, recording losses after they occur rather than mitigating them beforehand.

1.5.1. Summary of the Literature

While geospatial technologies have substantially advanced our ability to assess and visualise archaeological vulnerability, their practical application remains uneven, fragmented, and often constrained by cost, data accessibility, and institutional or infrastructural disparities (Lim et al., 2021; Nyong et al., 2007; Opitz & Herrmann, 2018; Chasmer et al., 2022). The research landscape demonstrates repeated cycles of technical innovation followed by limited uptake, in which methodological sophistication outpaces policy integration. Agapiou et al. (2020) exemplify this pattern through their exploration of earth-observation tools for disaster risk management (DRM) of open-air archaeological monuments in the Eastern Mediterranean. Their work successfully links remote sensing capabilities to the stages of the DRM cycle and highlights the value of technological surveillance in hazard-prone environments. Yet, despite these contributions, their model remains constrained to the monitoring dimension of risk assessment and stops short of embedding heritage management within a formalised DRR or governance framework. This reveals a broader issue within heritage-risk scholarship: even when advanced technologies are deployed, they often remain peripheral to the institutional and strategic systems that govern real-world risk reduction.

Li et al. (2023) expand this technological discourse by synthesizing digital tools, ranging from artificial intelligence to digital twins and preventive conservation, used to protect architectural heritage across disaster cycles. Their study demonstrates the increasing digitalisation of heritage risk management and underscores how these technologies can enhance monitoring and early warning capabilities. However, while Li et al. successfully maps the ‘what’ and ‘how’ of

technological integration, they leave unresolved the 'so what': the mechanisms through which these tools become embedded in the governance and institutional infrastructure of DRR. Their review illustrates the ongoing asymmetry between innovation and implementation, where digital heritage management advances rapidly at the technical level but remains detached from the systemic priorities of available disaster risk reduction frameworks.

A more structurally ambitious model is provided by Der Sarkissian et al. (2019), who deploy GIS to support the complete DRR cycle, including hazard and exposure mapping, vulnerability assessment, capacity analysis, and planning, in the Baalbek-Hermel Governorate of Lebanon. Their regional approach demonstrates the methodological promise of using spatial technologies as integrative instruments for risk governance. Yet, despite coupling geospatial methods with DRR phases, the study stops short of engaging with heritage-specific vulnerabilities, archaeological values, or the longer-term governance frameworks that enable DRR to move from analysis to implementation. When considered through the lens of the Sendai Framework's four priorities, Der Sarkissian et al. contribute meaningfully to understanding disaster risk by quantifying and visualising exposure and vulnerability, but exhibit weaker alignment across 'governance,' 'investment,' and 'preparedness.' Governance is invoked as an aspiration rather than realised as a structure; investment dimensions remain implicit; and preparedness or recovery mechanisms are treated conceptually rather than operationally. This creates a model that is technically robust but strategically partial, an instructive demonstration of GIS capacity that makes risk visible yet leaves it institutionally inert. In archaeology, this underscores the core dilemma of the discipline's engagement with DRR: geospatial tools can powerfully reveal the scale and distribution of risk but rarely provide the institutional architecture needed to act on those insights.

Rayne et al. (2023) extend this discourse directly into the heritage sector, synthesising how remote sensing, from satellite imagery to drone surveys, supports rapid, large-scale monitoring of exposure and damage to heritage assets. Their work substantially advances the monitoring and documentation dimensions of heritage-risk management, providing scalable models for identifying and quantifying damage. However, as with other technologically oriented studies, the focus remains on detection and visualisation rather than the institutional mechanisms through which such data inform governance, preparedness, or investment planning. While Rayne et al. successfully demonstrate how remote-sensing technologies can bridge gaps in field accessibility and temporal monitoring, the operational bridge to actionable DRR integration remains missing. The chapter thus epitomises both the progress and the limitations of current practice: we have achieved unprecedented technical capacity to see and measure risk, yet we still lack the systemic pathways to act upon that knowledge at policy and management levels.

Taken collectively, these studies chart the evolution of heritage-oriented disaster-risk research while simultaneously revealing its limitations. The field has achieved notable advances in data acquisition, spatial analysis, and monitoring, yet continues to struggle with embedding these insights within the functional architectures of DRR governance and investment planning envisioned by the Sendai Framework. Most heritage-related DRR initiatives excel in risk assessment but falter in

implementation; they identify and visualise threats but stop short of providing actionable, scalable solutions that directly link into institutional decision-making processes. It is precisely this action gap that the present research seeks to bridge. By developing open-source, adaptable geospatial workflows that are both conceptually simple and operationally flexible, this thesis demonstrates how archaeological risk can be modelled, visualised, and integrated into planning processes that inform mitigation and preparedness strategies. These workflows transform archaeological DRR from a descriptive or academic exercise into a practical, deployable system that enables stakeholders to make informed decisions to mitigate archaeological risk. In this way, the research not only advances methodological innovation but also repositions archaeology as an active contributor to global resilience discourse, capable of informing sustainable risk governance rather than merely recording its consequences.

1.5.2. Situating this Thesis within Existing Heritage Management Practice

Archaeological risk management is supported through a range of established heritage-management practices. Development-led archaeology, commercial archaeology, Heritage Impact Assessments (HIAs) (García-Casasola et al., 2026), Environmental Impact Assessments (EIAs) (Morrison-Saunders, 2024), rescue archaeology, and conservation planning each provide mechanisms for identifying, assessing, and mitigating threats to archaeological resources. Collectively, these approaches provide established procedures for evaluating significance and implementing mitigation where archaeological resources may be adversely affected.

HIAs and EIAs play an increasingly significant role, particularly within the UNESCO World Heritage context, where they are used to evaluate the potential effects of development on Outstanding Universal Value (OUV) (Labadi & Logan, 2013). More recently, both methodologies have expanded to consider the impacts of climate change and natural hazards on heritage values, reflecting growing recognition that archaeological resources face risks extending beyond conventional development pressures. Nevertheless, these approaches remain largely project- and site-specific, evaluating the consequences of defined interventions rather than anticipating archaeological risk across broader landscapes before a triggering event occurs.

Commercial archaeology similarly represents an established component of contemporary planning systems. Through desk-based assessment, evaluation, excavation, recording, and mitigation, it generates substantial archaeological knowledge while protecting heritage through preservation *in situ*, preservation by record, or agreed mitigation strategies (Cleere, 1990; Everill, 2012; King, 2020). Rescue archaeology further demonstrates both the value and limitations of reactive intervention. Salvage excavations undertaken ahead of engineering works and urban expansion at sites such as Tula, Mexico, revealed previously unknown residential areas that significantly reshaped understanding of the ancient city despite being undertaken under severe temporal constraints (Gamboa Cabezas, 2021). Likewise, conservation planning provides longer-term mechanisms for managing archaeological resources through Conservation Management Plans, monitoring

programmes, and site-management strategies that increasingly acknowledge the influence of climate change and environmental hazards (Teutonico, 2002; Rouhani & Romão, 2024).

Taken together, these approaches demonstrate that archaeology possesses mechanisms for managing risk. However, they share a common characteristic: archaeological intervention is generally initiated once heritage resources have entered planning processes or development frameworks. In other words, they respond to identified threats within the hazard environment. Approaches are not always proactive, but often reactive.

The framework developed in this thesis addresses an earlier stage within this risk continuum. Instead of attempting to replace in place heritage-management practice, it operationalises DRR through accessible geospatial workflows capable of prioritising archaeological risk before conventional intervention is triggered. By integrating hazard, exposure, vulnerability, and capacity, the framework supports earlier landscape-scale prioritisation and decision-making across diverse hazard environments. Its purpose is not to determine which archaeological resources should be preserved, recorded, or allowed to change, nor to prescribe heritage-management decisions that necessarily involve legal, ethical, and cultural considerations extending beyond the scope of a methodological framework. Instead, it provides evidence base capable of supporting existing heritage-management processes when difficult decisions concerning intervention become necessary.

Situating archaeological DRR within this earlier stage also aligns the framework with wider debates concerning heritage adaptation. Archaeological management is often guided by the principle that preservation *in situ* represents the preferred outcome wherever feasible (Council of Europe, 1992, Art. 4(ii)). While this remains an ideal objective, accelerating environmental change and finite resources increasingly challenge assumptions that all archaeological resources can be preserved (DeSilvey et al., 2021). Consequently, heritage management increasingly recognises that intervention may involve strategic prioritisation and difficult decisions regarding which archaeological resources can realistically be protected, or, in some cases, allowed to be lost (Holtorf, 2018). The framework developed here should be understood within this context: it identifies where archaeological risk is greatest, providing evidence that can support existing heritage-management processes as such decisions become necessary.

Although this relationship is readily demonstrated within planning-led archaeology, the institutional contexts in which archaeological risk is managed vary considerably across jurisdictions. Consequently, the implementation of archaeological DRR cannot rely upon a single governance or policy model. In England, development-led archaeology is informed by the National Planning Policy Framework (NPPF) (Ministry of Housing, Communities and Local Government, 2024), Historic England guidance (Drury, 2008) established through the Valletta Convention. In the United States, archaeological management operates through a different legislative framework centred on the National Historic Preservation Act (NHPA) (United States Congress, 1966), the National Environmental Policy Act (NEPA) (United States Congress, 1969), the Archaeological Resources

Protection Act (ARPA) (United States Congress, 1979), and associated State Historic Preservation Office (SHPO) (National Park Service (n.d.)) and Tribal Historic Preservation Office (THPO) (National Park Service (n.d.)) processes. In Iran, archaeological management is undertaken through the Ministry of Cultural Heritage, Tourism and Handicrafts and is supported by national heritage legislation, including the National Heritage Protection Act (1930) (Government of Iran, 1930), the National Heritage Registration Act (1973) (Government of Iran, 1973), and subsequent legislation governing the protection and management of archaeological and cultural heritage. Iran is also a State Party to the UNESCO World Heritage Convention (UNESCO, 1972), and archaeological management therefore operates within both national legislation and international heritage obligations. In many regions, archaeological decision-making is also shaped by Indigenous rights, community stewardship, customary law, or other national heritage legislation that differs substantially from European or North American approaches. Consequently, meaningful implementation of archaeological DRR cannot rely upon a single policy pathway.[1] Thus, the methodological flexibility of the approach provided in this thesis, is all the more useful across these varying contexts.

Archaeological management also occurs within protected landscapes and conservation estates, including National Parks, National Landscapes (formerly Areas of Outstanding Natural Beauty), Sites of Special Scientific Interest, National Nature Reserves, and land managed by organisations such as the National Trust, Forestry England, and Natural England. These settings are governed through conservation and land management policies that increasingly incorporate climate adaptation and resilience alongside heritage protection. Similarly, in the United States, archaeological management extends beyond compliance with development legislation to include federally protected landscapes such as National Parks, National Monuments, National Forests, and other public lands managed by agencies including the National Park Service, Bureau of Land Management, and U.S. Forest Service, where archaeological risk is addressed through resource stewardship and conservation planning. In Iran, archaeological sites are likewise managed through a combination of heritage legislation and protected area governance, including nationally designated protected landscapes and World Heritage properties, where conservation objectives intersect with broader environmental and land management priorities.

1.5.3. Thesis Approach

In this thesis, geospatial approaches provide a methodological bridge between DRR theory and archaeological practice. Within DRR frameworks, key concepts such as hazard, exposure, vulnerability, and capacity structure how societies understand and manage risk. Geospatial analysis makes these dimensions actionable. By mapping the spatial distribution of cultural heritage assets alongside hazard datasets, such as flood zones, landslide susceptibility models, wildfire risk

[1] This section considers only the heritage policy frameworks applicable to the case studies included in this thesis. While these jurisdictions are discussed explicitly, they are not presented as exhaustive or normative. Comparable heritage management frameworks exist internationally, reflecting broadly similar principles of archaeological protection and stewardship while differing in their legislative, administrative, and cultural implementation.

surfaces, or erosion indices, archaeologists can transform abstract frameworks into spatially explicit decision-making tools. This shift is driven by accessibility; freely available global datasets, open-source platforms, and cloud-based processing now permit practitioners to perform analyses. Low-barrier workflows enable archaeologists to integrate their data directly into DRR-compatible frameworks, converting global-scale risk metrics into locally relevant priorities. By embedding archaeological datasets into spatial risk models, potential loss can be quantified, exposure hotspots identified, and the areas where heritage is most susceptible visualized. The democratization of spatial technology represents one of the most important methodological shifts in archaeological risk assessment. By using openly accessible tools, archaeologists in data-poor or politically unstable regions can still produce meaningful analyses. In this context, geospatial methods become vehicles for equity and collaboration, translating the global DRR agenda into locally actionable heritage strategies. To evaluate this framework's adaptability, three contrasting testbeds, Holderness, O'ahu, and Sistan, illustrate how geospatial approaches can be tailored to address escalating environmental, cultural, and political complexity.

The Holderness coast of eastern England provides an ideal foundation for model calibration and validation. It is one of the most intensively monitored coastlines, with extensive historical cartography and shoreline change datasets documenting one of the continent's fastest rates of erosion. This high-resolution data environment enables fine-scale spatial modelling of hazard progression, exposure mapping of archaeological sites, and iterative refinement of predictive models. Holderness represents a controlled setting where the geospatial DRR framework can be tested under conditions of data abundance and relative political stability.

The island of O'ahu, Hawai'i, presents a starkly different challenge: sudden-onset hazards such as landslides, flash floods, and tsunamis intersect with areas of deep cultural significance and complex land tenure systems. Here, heritage protection is inseparable from issues of cultural sovereignty; thus, implementing geospatial DRR approaches in O'ahu requires sensitivity to Indigenous knowledge systems and community priorities. Culturally informed hazard modelling becomes an essential tool for negotiating between data and cultural stewardship. The case demonstrates that effective resilience planning must integrate both spatial precision and cultural legitimacy.

The Sistan Basin, straddling the border of Iran and Afghanistan, represents the framework's most extreme test case. The region is marked by advancing desertification, water scarcity, and high political instability, conditions that severely limit data availability and ground verification. Here, the challenge is in operationalizing geospatial DRR principles in the absence of conventional data and institutional support. Open-source datasets enable approximating exposure and vulnerability even in the absence of local GIS infrastructure. Sistan exemplifies how geospatial approaches can deliver meaningful insights under uncertainty, underscoring the importance of flexible, low-barrier methodologies for heritage resilience in volatile regions.

This case study progression demonstrates the framework's transferability and scalability. At its core, the model transforms spatial analysis into triage: identifying where intervention is most urgent and where archaeological loss is most imminent. In doing so, it moves archaeology closer to the heart of global resilience discourse. Geospatial approaches enable archaeologists to position cultural heritage not as a passive casualty of disaster, but as an active component of risk reduction and adaptation planning. The future of heritage management depends on the shift from reaction to anticipation.

1.6. Thesis Overview

This thesis is organised into six chapters, moving from conceptual and theoretical foundations through methodological development, case-study application, and synthesis. Each chapter contributes to the central aim of adapting and operationalising the DRR framework for archaeology through open, transferable geospatial approaches.

Chapter 1: Introduction
The first and current chapter establishes the context, rationale, and objectives of the research. It situates archaeology within the broader discourse on disaster risk, outlining how the discipline has traditionally responded to crises and identifying critical gaps. The chapter reviews the growing vulnerability of archaeological resources to environmental change. It examines how disparities in data access and technical capacity disadvantage certain regions and communities.

Chapter 2: Framework Development
This chapter lays the analytical backbone of the thesis by integrating DRR, geospatial approaches, and archaeology into a transferable framework. It reframes Sendai's variables (hazard, exposure, vulnerability, capacity) for archaeological use. It translates them into geospatial equivalents so risk can be modelled as composite surfaces. The chapter also operationalises Sendai priorities, from understanding and governing risk to investing in resilience and preparedness, showing how archaeological evidence becomes legible to planners. It then standardises an open-data strategy, establishing a pipeline that normalises, classifies, and combines indicators into actionable composite risk surfaces. Finally, Chapter 2 positions the three case studies as methodological tests: slow-onset coastal erosion (Holderness), sudden-onset landslides (O'ahu), and compound desertification (Sistan), chosen to probe transferability and limits across different hazard and archaeological contexts.

Chapter 3: Case Study I: Holderness (United Kingdom)
The third chapter applies the framework to the Holderness coastline in northeast England. It develops and tests methods for modelling coastal erosion dynamics and assessing archaeological exposure. Validation against field data and coastal management records demonstrates the approach's reliability and accessibility. The chapter concludes by discussing how these results can inform regional decision-making, highlighting the ethical and practical dilemmas of managing heritage loss within active coastal retreat.

Chapter 4: Case Study II: O‘ahu (Hawai‘i, United States)
This chapter examines landslide susceptibility on O‘ahu, integrating environmental modelling with archaeological and cultural contexts. Two geospatial models, the General Landslide Susceptibility Map (GLSM) and the Landform Landslide Susceptibility Map (LLSM), are produced using open-access datasets to predict risk zones and evaluate Pre-Contact Hawaiian archaeological vulnerability. The analysis demonstrates that open-source geospatial workflows can produce results comparable to institutional hazard assessments. It also foregrounds the role of Indigenous knowledge and cultural values in shaping ethical approaches to risk governance, illustrating how DRR can align with community-based stewardship.

Chapter 5: Case Study III: Sistan (Iran and Afghanistan)
The fifth chapter tests the framework in one of the world’s most data-limited and politically inaccessible regions, with desertification as the primary hazard. Drawing on multi-temporal Landsat imagery and environmental variables such as slope and wind speed, the study models the spatial distribution of desertification and its impact on archaeological landscapes. Despite the absence of field verification, the results demonstrate the viability of open-source data for remotely assessing archaeological risk. The discussion also engages with the ethical complexities of working in such contexts.

Chapter 6: Discussion
The sixth chapter draws together the thesis’s core findings to show how accelerated environmental change, unstable visibility, governance fragility, and shifting methodological demands collectively redefine archaeological risk across the three case studies. It evaluates how these dynamics underscore the structural need for DRR integration, highlight visibility and capacity as critical determinants of knowledge survival, and reposition landscapes as archives in motion that require adaptable and anticipatory methods. The chapter reflects on the ethical implications of working in environments where completeness is unattainable, identifies limitations linked to capacity, data, and access, and outlines future directions that include expanded modelling, enhanced validation, community consultation, and testing the framework in high-capacity contexts. It closes by calling for an archaeology that is more flexible, risk-aware, and embedded within broader DRR and climate resilience efforts.

Chapter 7: Conclusion
The final chapter consolidates the thesis’s contribution by showing how an adapted DRR framework, implemented through open geospatial workflows, can identify, visualise, and prioritise archaeological risk across contrasting hazard and governance contexts. It summarises the core methodological advances, including the translation of hazard, exposure, vulnerability, and capacity into spatially measurable forms, and critically reflects on limitations of scale, data quality, institutional uptake, and the partial fit between human-centred DRR concepts and archaeological value. The chapter closes by arguing that archaeology must move from documenting loss to actively shaping risk governance through anticipatory, ethically reflexive, and collaborative practice,

positioning archaeological DRR as a foundation for future work on community engagement, long-term landscape modelling, and the integration of heritage into wider resilience planning.

Chapter 2: Framework and Methodology

2.1. Background

This chapter establishes the key concepts and approaches that underpin this thesis, integrating Disaster Risk Reduction (DRR), geospatial approaches, and archaeology into workflows that are both conceptually rigorous and deployable across diverse archaeological and environmental contexts. This chapter begins by demonstrating how DRR, geospatial approaches, and archaeology overlap, reframing the Sendai Framework's model for this thesis's purposes, positioning archaeological risk within DRR discourse. The conceptual variables of DRR are translated into geospatially applicable equivalents, including time-series maps and composite risk surfaces. Hazards are mapped from open-source satellite imagery; exposure is calculated based on site proximity to hazard zones; vulnerability is inferred from the status of investigation or protection; and capacity is modelled, incorporating stewardship potential and institutional readiness. The final section introduces the three case studies of Holderness, O'ahu, and Sistan as methodological tests spanning the hazards of erosion, landslide, and desertification. The section continues by detailing the factors that informed the selection of these locations for integration into this analysis and shows how open-source data and user-friendly workflows enable their application. Together, these elements provide the outline for the modelling and interpretation presented in the case studies of Chapters 3, 4, and 5.

2.1.1. Foundations of Disaster Risk Reduction

The United Nations established the Open-ended Intergovernmental Expert Working Group on Indicators and Terminology (OIEWG) to standardize key concepts through the Sendai Framework on DRR. The Sendai Framework is the 2015-2030 global agreement that guides DRR policy and practice, prioritizing risk understanding, governance, investment, and preparedness. These definitions, spanning hazard, exposure, vulnerability, resilience, and disaster, form the conceptual scaffolding for DRR. These terms directly shape how risks are identified and managed, ensuring that resilience and preparedness strategies are actionable across diverse contexts. By grounding this thesis in the OIEWG's terminology, the discussion aligns with international standards while carving out space for archaeology within the broader DRR discourse. The following six definitions are pivotal for the formulation of the conceptual framework of the rest of this thesis:

> **Hazard**: '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, 2017).

> **Exposure**: 'The situation of people, infrastructure, housing, production capacities and other

tangible human assets located in hazard-prone areas.' (UNDRR, 2017).

Vulnerability: 'The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards' (UNDRR, 2017).

Capacity: 'The combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience' (UNDRR,2017)

Resilience: 'The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management' (UNDRR, 2017).

Disaster: 'A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts' (UNDRR, 2017).

The Sendai Framework

The Sendai Framework (UNDRR, 2017) was a significant advance for DRR; however, the framework is all but silent on archaeology. This thesis argues that safeguarding archaeology should be embedded across all four Sendai priorities and that geospatial approaches are the practical lever to do it. The Sendai Framework's four priorities are:

1. **Understanding Disaster Risk**
2. **Strengthening Disaster Risk Governance**
3. **Investing in DRR for Resilience**
4. **Enhancing Disaster Preparedness for Effective Response and Recovery**

Riede's (2017) call to broaden disaster horizons to longer timescales further underscores the fit: archaeology routinely operates on temporal scales that DRR struggles to capture. This thesis demonstrate how geospatial approaches can serve as a bridge between DRR and archaeology, translating the hazard–exposure–vulnerability–capacity model into scalable, transferable workflows for triage and salvage. The result of this co-mingling reframes archaeology as a passive partner in anticipatory hazard mitigation and long-term resilience to an active one. While DRR constitutes the

broader field concerned with minimizing disaster impacts through preparedness, mitigation, and resilience-building, the Sendai Framework operationalizes this vision by establishing concrete priorities and targets for implementation. The Sendai Framework provides a structured approach for integrating risk awareness into planning and governance, emphasizing proactive strategies over reactive responses. As such, the Sendai Framework functions as the strategic roadmap through which DRR principles are translated into policy and practice across multiple sectors. In the context of this thesis, it serves as a model for adapting DRR methodologies to archaeological risk mitigation.

2.1.2. Origins of Disaster Risk Reduction

The political and conceptual trajectory of DRR has been shaped by decades of evolving thought. Alexander (2020) traces this development from mid-twentieth-century civil defence, grounded in Cold War logics of emergency relief and reactive response, to a mature paradigm centred on governance and systemic risk management. Early disaster management viewed risk as an external, largely uncontrollable force, an act of nature to be endured. Thus, early disaster policy in the mid-twentieth century was dominated by the logic of disaster management and civil defence, deeply rooted in the geopolitical anxieties of the Cold War (Quarantelli, 1987; Dynes, 1994; Alexander, 2002; Tierney, 2014). During this period, disaster management was largely synonymous with emergency relief and reactive response: stockpiling aid and protecting populations during earthquakes, floods, famines, or conflict. This conceptualisation emphasised managing the aftermath rather than reducing the causes or likelihood of disasters. By contrast, contemporary DRR understands disasters as the outcome of intersecting hazards and social vulnerabilities, embedded within political and economic systems.

By the 1970s and 1980s, this perspective shifted toward preparedness and prevention, driven by an emerging recognition that disasters had profound social and political dimensions. Institutions such as the Office of the United Nations (UN) Disaster Relief Coordinator (1971) and humanitarian actors like the International Federation of Red Cross and Red Crescent Societies (IFRC) began to promote early warning systems, contingency planning, and mitigation strategies alongside traditional relief (UNDRC, 1971; IFRC, 2009). This was also the era in which disaster studies matured as a field, with scholars such as Hewitt (1983), O'Keefe et al. (1976), and Blaikie et al. (1994) reframing disasters as products of structural conditions rather than purely natural phenomena. The 'vulnerability paradigm' emerged through works such as Interpretations of Calamity (Hewitt, 1983) and *At Risk* (Blaikie et al., 1994), establishing that disasters occur where hazards intersect with fragile livelihoods and inequality. The influential 'Pressure and Release' (PAR) model distilled this synthesis by presenting disasters as the intersection of root causes, dynamic pressures, and unsafe conditions (Blaikie et al., 2003, 1994). This intellectual turn transformed disasters from inevitable acts of fate into preventable outcomes of human systems.

The 1990s brought institutional consolidation of these ideas. The International Decade for Natural Disaster Reduction (IDNDR, 1990–1999) represented a decisive attempt to shift policy from emergency response to prevention, mitigation, and preparedness (UNISDR, 2005). The Yokohama

Strategy and Plan of Action (1994) formalised these principles, emphasising the need for integrated risk management, multi-disciplinary research, and the embedding of science within governance (United Nations, 1994). However, the catastrophic 2004 Indian Ocean tsunami served as a stark reminder that the gap between global policy and local capacity remained vast. In its aftermath, the Hyogo Framework for Action (2005–2015) was introduced as the first comprehensive global blueprint for DRR. Hyogo outlined five strategic priorities: governance, knowledge, risk assessment, resilience building, and preparedness, each intended to transform DRR from rhetoric into operational practice. Yet, despite these ambitions, Hyogo exposed a persistent implementation gap: frameworks were often articulated at international scales but poorly translated into local realities, particularly regarding non-economic assets such as cultural heritage, which were rarely incorporated into disaster governance or investment priorities (Alexander, 2020).

The Sendai Framework for Disaster Risk Reduction (2015–2030) directly extended this lineage, introducing measurable targets and an explicit emphasis on governance and resilience as cross-cutting priorities. Rajabi and Jafar (2022) argue that this evolution reflects the historical maturation of disaster governance, from reactive civil defence models to proactive, systemic risk management, where anticipation, rather than response, has become the defining logic of modern DRR. Contemporary DRR increasingly relies on data-driven decision support and spatial analytics to model complex interactions among hazards and social systems. In this sense, DRR has become not merely a humanitarian or policy concern but a data-integrated, predictive science that links environmental monitoring to social vulnerability analysis. While a majority lauded these advancements, Le De et al. (2023) offer a critical counterpoint to this narrative of progress. Examining Francophone disaster studies between 1985 and 2021, they reveal how the shift towards vulnerability- and capacity-based DRR has been uneven and delayed, constrained by epistemic and governance barriers as much as by technical limitations. Their work underscores that sustaining DRR requires more than advanced analytics: it depends on inclusive knowledge production, participatory governance, and the recognition of diverse epistemologies. This insight is particularly relevant to archaeology, where the barriers are not only technical but also institutional. Archaeological risk management remains peripheral to mainstream DRR frameworks, largely because heritage is rarely considered a stakeholder within resilience policy. Developing open geospatial workflows is therefore necessary but insufficient: for risk reduction to be durable, such workflows must also engage local actors, democratise access to data, and embed archaeological heritage within formal risk governance systems.

As Rajabi and Jafar (2022) note, disaster risk management has evolved from a narrow, civil-defence orientation to a comprehensive, multi-phase system encompassing prevention, mitigation, preparation, response, and recovery. This historical progression underscores the critical shift from reactive to anticipatory risk governance, a shift that archaeology has yet to absorb fully. By positioning this research within that intellectual and policy evolution, this thesis argues that archaeology must move beyond post-impact documentation and adopt the anticipatory logic of DRR, operationalising it through open, adaptable geospatial approaches that make resilience both measurable and actionable. Building on these foundations, the Sendai Framework for DRR set a new

standard by introducing measurable targets, clearer priority areas, and a stronger emphasis on resilience and governance. For archaeology, this trajectory is instructive. While DRR has transformed the way today's societies anticipate and respond to hazards, the archaeological record has remained marginal in these debates. Yet archaeological sites are subject to many of the same physical processes as human settlements: erosion, flooding, landslides, desertification and are often more vulnerable due to limited protection, uneven documentation, and scarce resources. Positioning archaeology within the history of DRR makes clear that the discipline has much to gain from adopting its frameworks, and much to contribute to return, particularly in extending disaster horizons to longer timescales and integrating cultural value into resilience planning. While the Sendai Framework and its predecessors provide the conceptual scaffolding for understanding disaster risk, these definitions remain abstract unless translated into forms that can be measured, mapped, and applied. For archaeology, where risk cannot be expressed in purely economic or demographic terms, this translation requires methods that capture the spatial distribution of hazards, the proximity of heritage sites to those hazards, and the uneven capacities of communities and institutions to respond. Geospatial approaches provide this bridge, converting DRR's core variables into operational factors that can be visualized, compared, and combined into composite risk models. In doing so, geospatial approaches function as 'risk translators,' rendering intangible or diffuse concepts into actionable, spatially explicit insights.

2.2. Geospatial Approaches: Tools and Trajectories

The role(s) of geospatial approaches in archaeology are rapidly evolving (Luo et al., 2022), with relevance for disaster monitoring and mitigation already well-established (Le Cozannet et al., 2020). While the application of these tools to disaster threats facing archaeology is not new, the escalating risks to both tangible and intangible elements of the archaeological record underscore the urgency of adaptation (Hollesen, 2022). Given the rising frequency and intensity of hazards, archaeologists face the need to prioritize the proactive use of geospatial approaches for risk prediction and planning (Yao et al., 2023; Menéndez-Marsh et al., 2023). Every technological inflection in geospatial approaches, particularly remote sensing, has reduced the time lag between hazard detection and response. Geospatial approaches enable DRR concepts (for example, hazard, exposure, vulnerability, and capacity) to be made actionable for disaster-first archaeology.

In this thesis, 'geospatial approaches' denotes an integrated toolkit comprising: GIS and spatial analysis; (ii) remote sensing across platforms; (iii) and spatial modelling (susceptibility, exposure, and composite risk surfaces aligned to DRR variables that carry results into planning workflows (see Manfré et al., 2012; Agapiou et al., 2020; Rayne et al., 2023). Framed this way, geospatial approaches are components of a broader, DRR-oriented system rather than stand-alone techniques. The evolution of remote sensing, from its origins in hot-air balloons in the 19th century (Emery & Camps, 2017) to its current application in satellite-based remote sensing (Efremenko & Kokhanovsky, 2021), has transformed how archaeologists perceive and analyze landscapes. The legacy of early aerial photography, notably by O.G.S. Crawford (1928; 1929), laid the groundwork for a more landscape-scale, systemic view of the past (Bewley, 2003). That momentum has continued through the

archaeological repurposing of CORONA imagery (Casana, 2020), LiDAR data, and now open-source, medium-resolution satellite imagery available through platforms hosted by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). The strength of geospatial approaches lies in accessibility and flexibility. While high-resolution commercial imagery remains expensive (Satellite Imagery Solutions & Digital Map Data - LAND INFO Worldwide Mapping, 2023), open-source datasets (for example, Landsat and Sentinel) provide powerful, scalable options, alongside powerful open-access tools such as Google Earth Engine (GEE) have enabled extensive and accessible geospatial integration across many disciplines, including archaeology. These datasets and tools allow archaeologists to monitor vegetation, detect erosion, map landslide susceptibility, and model long-term environmental change.

Existing heritage vulnerability studies (Sesana et al., 2021; Reeder-Myers, 2015) have played an important role in moving archaeological risk from anecdote to quantifiable concern. While such studies have established a valuable empirical record of threatened and destroyed heritage, they often rely on expensive and or static data, manual survey techniques, and localised vulnerability scoring that cannot easily be generalised or scaled. The result is a patchwork of vulnerability assessments that describe *what* has been lost but rarely illuminate *why* or *how* that loss could have been mitigated. The dominance of post-impact documentation, salvage archaeology's long-standing domain, illustrates this reactive orientation. Although salvage practice was once valorised as the final line of defence for threatened sites, its methodological basis is inherently retrospective, operating only after destruction has begun. Daly (2014) and others have noted that this approach reproduces a crisis-response mentality ill-suited to the escalating tempo of environmental and anthropogenic hazards. In effect, salvage archaeology functions as a cultural emergency service rather than a planning instrument, reinforcing the perception that loss is inevitable. Incorporating such approaches in a framework such as DRR could help to mitigate some of these drawbacks. Studies employing GIS have typically been problem-specific, focused, for example, on single hazards such as coastal erosion or flooding, and rarely situate their findings within the wider conceptual architecture of DRR (de Ruiter & van Loon, 2022). These works demonstrate technical sophistication but seldom engage with the epistemic shift that DRR entails: a transition from describing hazard events to understanding risk as a socially and spatially produced condition. The failure to embed geospatial methods within that logic leaves a crucial gap. The potential of remote sensing to model exposure or predict hazard dynamics is clear, but unless such data are explicitly framed within an understanding of vulnerability, capacity, and governance, they risk becoming strategically inert.

As de Ruiter and van Loon (2022) argue, the complexity of hazard interactions (for example, desertification, drought, and flood as cascading hazards) renders pure prediction futile; what matters is preparedness. Within this paradigm, archaeology stands as an especially sensitive indicator of institutional readiness. Its material fabric is fragile, its recovery irreversible, and its custodial systems are frequently under-resourced. Climate change further compounds these vulnerabilities, amplifying hazards while diminishing the capacity of heritage institutions to respond. Unlike modern infrastructure, archaeological sites cannot be reconstructed or relocated; once the

contextual relationships that give meaning to material culture are lost, the knowledge they embody is unrecoverable. Thus, within a DRR framework, archaeology exemplifies the extremes of exposure and low capacity, the very conditions that transform hazard into disaster. Managing disaster risk for archaeology requires a reorientation from conservation as rescue toward conservation as foresight. Anticipatory, multi-scalar methodologies must integrate environmental modelling, spatial exposure analysis, and socio-institutional assessment to move from isolated hazard mapping to systemic risk understanding. In this respect, adopting geospatial analytics is not merely a technical upgrade but an epistemological pivot. It forces the discipline to operationalise DRR's core variables in measurable ways, thereby translating abstract risk concepts into usable data.

2.3. Integration

This thesis advances that translation by reframing each DRR variable within archaeological terms (Table 2.1). *Exposure* is defined as the measurable proximity and sensitivity of archaeological sites to present or projected hazard zones. These hazards, such as coastal retreat, slope instability, and desertification, can be quantified using spatial modelling and multispectral remote sensing indices. By converting exposure from a descriptive category into a spatially explicit variable, it becomes possible to identify at-risk archaeology, monitor change over time, and visualise the encroachment of hazard across landscapes. *Vulnerability* in archaeological terms refers to the susceptibility of sites not only to physical destruction but to neglect, under-documentation, and the absence of institutional protection. Gaps in recording, weak heritage legislation, and inconsistent resource allocation amplify risk even in areas of moderate hazard. Within a geospatial framework, such vulnerabilities can be operationalised through proxies, such as documentation density, protection-status layers, and historical survey coverage. *Capacity*, conversely, measures the potential for stewardship, the formal and informal systems that safeguard, monitor, and transmit heritage. Capacity encompasses both institutional mechanisms (digital archiving, risk management policy, emergency planning) and community-based practices (local site guardianship, participatory mapping). When modelled spatially, capacity highlights where heritage management is proactive and where it is absent, offering a counterpoint to vulnerability surfaces. Low-capacity areas become critical intervention zones, where even moderate hazards can have catastrophic outcomes. *Hazard* is treated here as a physically observable process, modelled through multispectral and geomorphological indicators. Vegetation and moisture indices derived from remote sensing reveal early signs of erosion, flooding, and instability, while Digital Elevation Models (DEMs) enable the calculation of slope, aspect, and landslide susceptibility. The incorporation of these datasets (among others) constructs a dynamic hazard layer against which exposure, vulnerability, and capacity intersect. This interaction is formalised through a composite risk surface (Equation 2.1).

$$(2.1)\ Risk = (Hazard \times Exposure \times Vulnerability) / Capacity$$

This formulation highlights the asymmetry of archaeological risk: severe hazards may not result in loss where capacity is strong, whereas even minor hazards can be disastrous where governance and documentation are weak. The composite surface thus functions as both a diagnostic and a decision-support tool, delineating priority zones for triage or mitigation, visualising risk in ways that

communicate across disciplinary and administrative boundaries. In practice, this integrated model transcends the limitations of earlier vulnerability studies and post-impact surveys by embedding geospatial analysis within the broader anticipatory logic of DRR. It translates risk from abstraction into spatial intelligence. In doing so, it argues that archaeology can become an active participant in resilience planning, its methods and temporal insights re-tooled to anticipate the hazards extant and the potential disasters to come.

Table 2.1. DRR variables translated to archaeology and operationalised

DRR Variable	Archaeological Definition	Operationalisation
Hazard	Physically observable processes posing risk to sites.	Modelled through remote-sensing and geomorphological datasets.
Exposure	Measurable proximity of archaeological sites, landscapes, and/or features to current or projected hazard zones.	Spatially explicit modelling using multispectral remote-sensing and spatial datasets.
Vulnerability	Susceptibility of sites to destruction, neglect, under-documentation, or lack of protection.	Operationalised through spatial proxies revealing uneven heritage attention.
Capacity	Potential for stewardship; systems that safeguard, monitor, and transmit heritage.	Institutional and community mechanisms.

2.3.1. Integrating the Sendai Framework

In addition to incorporating DRR's variables of exposure, vulnerability, and capacity, this thesis also responds directly to the four priorities of the Sendai Framework for DRR, each of which is adapted here for archaeological contexts and made operational through geospatial approaches (Table 2.2).

Priority 1, understanding disaster risk, is addressed by modelling the DRR variables as archaeological susceptibility and hazard impacts through open-source data and spatial analysis. In this formulation, hazards such as erosion, landslides, or desertification are mapped using various data sources (from remote sensing to ancillary climatic datasets). Exposure becomes the spatial coincidence of archaeological sites with these active hazard zones. Vulnerability is assessed by determining the level of record protection using various proxy data. Capacity is represented by indicators such as archaeological stewardship, legal frameworks, and existing site records. Importantly, this formulation highlights that risk is not purely environmental but also political and institutional, and that strong protective capacity can mitigate otherwise acute hazard conditions. Priority 2, strengthening disaster risk governance, is operationalized using geospatial tools to clarify responsibilities and enhance coordination. Open-source platforms such as QGIS and Google Earth Engine allow risk assessments to be carried out at low cost, reducing barriers for heritage professionals and local stakeholders. Geospatial visualisation supports horizontal integration by providing a shared reference frame for archaeologists, planners, environmental regulators, and civil defence authorities, while also enabling vertical integration across scales, from local stewardship groups to international frameworks. Legal and policy integration can be pursued by mapping archaeological sites against zoning or disaster planning overlays. In short, geospatial approaches allow archaeological risk to be explicitly represented in governance structures, closing the accountability gaps that often leave archaeology unprotected. Priority 3, investing in DRR for

resilience, shifts the emphasis from reactive salvage to proactive protection. In archaeology, this means undertaking early risk assessments that identify vulnerable sites before disasters occur. Geospatial methods provide cost-effective solutions: hazard overlays, susceptibility modelling, and multi-criteria decision analysis allow limited resources to be targeted where they can have the greatest effect. By embedding archaeological value in the spatial evidence, archaeology becomes legible to planners and funders as part of comprehensive resilience portfolios. Priority 4, enhancing preparedness for effective response and recovery, focuses on ensuring that archaeological protection is systematic rather than improvised. Geospatial approaches underpin this cycle from the outset. Hazard modelling, such as erosion simulations, landslide runout models, or flood forecasting, anticipates the likely impacts of cascading or compound events. When emergencies occur, composite risk maps and hazard overlays can be deployed to guide triage, identifying which locations combine archaeological value with acute hazard exposure. After disaster events, pre- and post-impact data can be compared to inform recovery strategies that respect the archaeological landscape rather than defaulting to generic reconstruction.

Table 2.2. Sendai Framework priorities adapted and operationalised for archaeology

Sendai Framework Priority	Archaeological Adaptation	Operationalization	Outcomes
1. Understanding Disaster Risk	Model archaeological susceptibility and hazard impacts through spatial analysis. Recognises that risk is environmental, political, and institutional.	Spatial modelling integrates hazards, exposure, vulnerability, and capacity as a composite risk.	Identifies high-risk sites; demonstrates how governance and capacity shape archaeological survival.
2. Strengthening Disaster Risk Governance	Embed archaeological risk into governance structures via mapping and data sharing.	Geospatial tools clarify responsibilities, enable coordination, and promote transparency.	Connects archaeologists, planners, and local authorities; integrates heritage into formal risk governance.
3. Investing in DRR for Resilience	Shift from reactive salvage to proactive protection and digital preservation.	Geospatial prioritization directs limited resources to the most at-risk sites.	Builds digital and institutional resilience; embeds archaeological data into broader resilience portfolios.
4. Enhancing Preparedness for Effective Response and Recovery	Ensure archaeological protection before, during, and after disasters.	Geospatial tools guide documentation, triage, and recovery across event cycles.	Enables systematic emergency response, preserves knowledge digitally, and informs culturally sensitive recovery.

In sum, geospatial analysis operationalizes Sendai's four priorities for archaeology by producing evidence that is intelligible to planners and usable by communities. The following section outlines how this translator has been applied to this case study's three contrasting hazard regimes: coastal erosion in Holderness (slow-onset), landslides on O'ahu (sudden-onset), and desertification in Sistan (compound and chronic), to test transferability, limits, and ethical constraints.

2.4. Thesis Case Studies

The selection of coastal erosion, landslides, and desertification as focal hazards in this thesis reflects a deliberate alignment with the Intergovernmental Panel on Climate Change's (IPCC) (Seneviratne & Hauser, 2020; Seneviratne, 2019) core disaster categories: hydro-meteorological, geomorphological, and climatic. These hazards were chosen not only for their physical diversity but for the way they expose varying archaeological conditions, data access regimes, and institutional capacities.

Holderness (Chapter 3) provides a data-rich context for examining chronic, long-term coastal erosion. With one of the most rapidly eroding coastlines in the world, the region offers an ideal landscape for validating predictive exposure surfaces using remotely sensed multispectral satellite imagery, historic shoreline retreat data, and archaeological data. The archaeological record of this region is extensive and chronologically diverse, enabling the development of a composite risk model, refined by proximity to cliff edge and erosion rate, and scored against vulnerability attributes such as shoreline protection status. This case allows the DRR triage model to operate with precision, generating ranked outputs for prioritised mitigation. It is a scenario in which the DRR framework's emphasis on exposure and targeted response finds clear spatial traction.

O'ahu (Chapter 4) introduces a hazard landscape with the potential for sudden-onset landslides triggered by rainfall, wildfire, and vegetation loss on steep volcanic terrain. The terrain is complex and the cultural record equally so, ranging from highly visible ceremonial sites to poorly documented *wahi pana* embedded in ridges and valleys. A dual-model approach to landslide susceptibility was developed using terrain, vegetation, and rainfall data, then intersected with pre-contact records to produce exposure surfaces tailored to six categories of pre-contact archaeology. Unlike Holderness, this case presented uneven site visibility and a layered planning regime. The DRR-Geospatial model was challenged to operate across cultural and epistemological boundaries, particularly regarding Native Hawaiian concerns about access and the implications of slope failure.

Sistan (Chapter 5) presents a different challenge than Holderness and O'ahu. Desertification here is driven by hydrological collapse, wind abrasion, and prolonged drought. The archaeological record is fragmented and often only partially recorded from legacy fieldwork. Political instability and access constraints preclude traditional field validation. Remote sensing became the only viable tool to assess hazard dynamics and archaeological exposure. Here, the DRR framework replaces fieldwork. This case demonstrates that DRR models can be of benefit for archaeological risk assessments even when ground access is denied and archaeological presence is inferred.

Together, these three case studies form a deliberately escalating arc of methodological and contextual complexity: from the highly documented and spatially legible coasts of Holderness, to the culturally and geomorphologically complex slopes of O'ahu, to the inaccessible, data-poor region of Sistan. These case studies were not selected because they are superior or universally representative. To suggest which archaeology should be prioritized globally is beyond the scope (and

ethical purview) of this thesis. Instead, these examples serve as evidence and potentially transferable models, demonstrating how archaeologists can use DRR-informed geospatial tools to assess risk in place-based, hazard-specific contexts.

2.5. Methodology

2.5.1. Data Sources and Processing

Practical geospatial analysis depends not only on computational precision but on the integrity and accessibility of data sources. In recognition of this, all workflows developed in this thesis are intentionally open-source or freely accessible. High-resolution commercial imagery and proprietary analytical platforms are widely used in geospatial research and can entail significant costs. They can privilege institutions with resources while excluding those without such access: archaeologists, heritage managers, and community practitioners working in data-poor, low-connectivity, or conflict-affected regions. In response, this thesis rejects the model of high-cost geospatial science and advances instead a disaster triage approach that is technically robust yet strategically open. When spatial triage tools are freely available, they can enable local documentation, community-led monitoring, and digital preservation, particularly in contexts where formal archaeological governance is weak or absent. When workflows depend on proprietary datasets, they reproduce the structural inequalities that DRR frameworks ostensibly aim to dismantle. Against this backdrop, the methodological stance of this thesis is deliberately counter-hegemonic. By constructing all analyses exclusively from open-access or free datasets, it seeks autonomy. Such openness transforms risk modelling from a closed expert domain into a participatory process where knowledge can be produced and improved.

The open-source data strategy adopted across this thesis was standardized across the thesis' three different case study regions. Consistency was critical to both the methodological integrity and transferability of the DRR-geospatial framework. Spatial scale and analytical scope are critical considerations in remote sensing workflows. Scale determines not only the resolution at which landscape change is visible but also the interpretive limits of multispectral data (Carr et al., 2015). At medium resolutions, such as Landsat's 30 metre pixel size, analysis focuses on regional trends rather than site-level precision, which is sufficient for archaeological risk assessments spanning large, data-poor areas. Integrating these datasets into GIS enables multi-scalar analysis, combining spectral, topographic, and archaeological data layers to model risk dynamically rather than statically. To bridge the differences among case studies and maintain analytical parity, three core data classes were deployed across all study areas: medium-resolution satellite imagery, globally available elevation models, and curated archaeological datasets tailored to local contexts. Landsat 5 Thematic Mapper (TM) and 8 Operational Land Imager (OLI) imagery formed the temporal and spectral backbone of monitoring across all regions. With a 30-meter multispectral resolution and a historical archive reaching back to 1999, the Landsat series offers a uniquely consistent record of surface conditions over two decades (Wulder et al., 2022). Its public, open-access availability enhances the replicability of this study's workflows and democratizes access to critical geospatial

information relevant to heritage. In this context, Landsat imagery served dual purposes: it provided the base data for generating hazard-specific spectral indices and served as a proxy for environmental monitoring in areas where fieldwork was either constrained or impossible.

Multispectral satellite imagery forms the analytical core of this study's environmental monitoring framework. By capturing reflected energy across multiple portions of the electromagnetic spectrum, multispectral sensors enable the detection of subtle surface variations, from vegetation health to soil moisture and sediment load, that are otherwise invisible in natural colour imagery (Laake, 2021). When processed through spectral indices, these datasets enable consistent, quantitative comparisons of environmental change over time (Jenicka, 2021). Spectral indices were selected according to each region's environmental pressures. The Normalized Difference Vegetation Index (NDVI) was used on both O'ahu and in the Sistan Basin to assess vegetation dynamics and identify areas of environmental stress (Junker & Ensminger, 2016). In O'ahu, NDVI trends were critical for identifying slope destabilization and post-rainfall vegetation loss in landslide-prone areas. In the Sistan Basin, NDVI served as a proxy for desertification, particularly in areas where land cover transitioned rapidly from vegetated to barren conditions. The Modified Normalized Difference Water Index (MNDWI) was used in Holderness to detect tidal incursion, storm-surge zones, and seasonal fluctuations in surface water extent, all of which accelerate shoreline retreat. In Sistan, the Topsoil Grain Size Index (TGSI) was deployed to track wind-driven sediment dynamics and identify zones of active aeolian deposition. TGSI proved especially useful in arid landscapes as a supplement to NDVI. DEMs were derived from NASA's Shuttle Radar Topography Mission (SRTM) and have a 30-meter spatial resolution, matching the Landsat archive. These DEMs supported hazard classification across diverse topographies. In Holderness, slope and elevation derived from the DEM were used to delineate cliff-edge zones vulnerable to retreat and to constrain MNDWI flood surfaces. In O'ahu, the terrain is highly sloped, and relief was a key variable in landslide susceptibility modelling. Slope thresholds were used to identify areas prone to landslides, particularly in combination with rainfall and vegetation metrics.

Each case study was supplemented with locally curated archaeological datasets. In Holderness, point data from the Archaeology Data Service (ADS)[2] were integrated, including both protected and non-designated sites. In O'ahu, spatial data were sourced from the State Historic Preservation Division (SHPD),[3] with emphasis on pre-contact records. These categories were selected for both their cultural significance and spatial distinctiveness. In the Sistan Basin, the archaeological dataset was compiled from the Endangered Archaeology in the Middle East and North Africa (EAMENA) database,[4] digitized legacy maps, and the Helmand Valley Survey (Trousdale et al., 2022). These records were georeferenced and cross-validated, despite sparse documentation and the near-total absence of recent field validation. Sistan underscored the limits of conventional exposure modelling. Many sites were undocumented, inaccessible, or already buried beneath dunes; as such, exposure could not be treated as a static overlay but as a probabilistic inference, constructed from

[2] https://archaeologydataservice.ac.uk/
[3] https://dlnr.hawaii.gov/shpd/
[4] https://database.eamena.org/

spectral anomalies and legacy survey data. Vulnerability likewise became inseparable from absence: undocumented, unprotected, and unvalidated sites were treated as the most at risk. Finally, capacity in Sistan was effectively null, with no functioning stewardship or governance structures. In this case, geospatial workflows acted as proxy capacity, digital salvage replacing institutional presence, demonstrating that in collapsed governance contexts, capacity can be effectively outsourced to open-source geospatial methods. Together, these archaeological datasets provided the foundation for exposure and vulnerability modelling across all three case studies, while also illustrating that in inaccessible or politically unstable environments, gaps and absences must themselves be treated as actionable data.

All data processing and analysis were conducted using Google Earth Engine (GEE)[5] and ArcGIS Pro 3.5 (ArcPro). Satellite imagery was accessed from the United States Geological Survey (USGS) Landsat Surface Reflectance Level 2, Collection 2, Tier 1 products, which include radiometric and atmospheric corrections (Liao et al., 2023; Liang et al., 2012; Zhou et al., 2015). Raster calculator was used to quantify risk, producing composite outputs that visualised the intersection of hazard dynamics and archaeological exposure. Terrain derivatives were generated to support hazard classification and geomorphological modelling. Hazard layers were weighted according to environmental relevance: vegetation loss, hydrological activity, slope instability, and intersected with archaeological datasets to derive exposure and vulnerability surfaces.

2.5.2. Analysis

Following pre-processing and integration, all datasets were analysed within a multi-criteria GIS environment designed to spatialise risk across the three case studies. Analysis was structured around three interlocking components: hazard modelling, exposure assessment, and vulnerability interpretation. Together, these formed a scalable analytical sequence consistent with DRR principles and archaeological risk frameworks. Hazard analysis was conducted using spectral and terrain-derived indices calibrated to the environmental processes of each region. Index values were normalised (0–1) to enable direct comparison between indices and across time. Temporal composites were generated to isolate multi-year change trends rather than single-event anomalies. In Holderness, coastal hazard zones were modelled by combining MNDWI-derived flood surfaces with DEM-sourced slope and elevation data to delineate active erosion and inundation corridors. In O‘ahu, landslide susceptibility was modelled through a weighted overlay of NDVI (vegetation loss), slope gradient, and rainfall anomaly data, generating continuous susceptibility surfaces across volcanic terrain. In Sistan, hazard modelling relied primarily on NDVI and TGSI composites to capture the interactions among vegetation decline, wind abrasion, and sediment deposition that drive desertification dynamics. Each hazard layer was classified using quantile-based thresholds.

Exposure analysis involved spatially collocating hazard surfaces with archaeological datasets. Exposure was portrayed through susceptibility maps. This framing is crucial in data-poor regions

[5] https://earthengine.google.com/

such as Sistan, where many sites are inferred rather than physically verified. The analytical process thus integrated absence and uncertainty as explicit spatial variables within the exposure model.

Vulnerability was operationalised through a combination of archaeological, environmental, and institutional indicators. Factors included protection status and proximity to protected infrastructure. Where capacity indicators were available, such as heritage management frameworks in Holderness or State Historic Preservation Division (SHPD) oversight in O'ahu, they were incorporated as mitigating variables. In Sistan, capacity was effectively null. This operationalisation aligns with the thesis's broader premise that risk is as much an epistemic condition as an environmental one.

Hazard, exposure, and vulnerability layers were normalised and combined using a weighted linear combination (WLC) approach. Weights were assigned iteratively based on literature, environmental relevance, and sensitivity testing. The resulting composite risk maps produced continuous spatial outputs depicting the intersection of environmental processes and archaeological sensitivity. Risk was expressed in relative rather than absolute terms, a triage index indicating where mitigation or monitoring would be most urgent given existing data. Outputs were validated by correlating with known impacts and qualitatively assessed for plausibility within each regional environmental regime.

Analytical outputs were not treated as static end-products but as diagnostic instruments, tools for identifying uncertainty, absence, and potential within the geospatial archive. Risk surfaces were visualised and interpreted alongside socio-political and heritage management contexts to generate region-specific insights. Thus, analysis operated on two levels: quantitatively, through reproducible GIS modelling, and qualitatively, through contextual interpretation grounded in local environmental and cultural realities.

2.6. The Role of Policy

The composite risk models developed in this thesis are designed to inform decisions and shape how archaeology is protected under conditions of accelerating hazard; however, modelling can only take archaeology-DRR integration so far. Without being embedded in governance and policy frameworks, risk surfaces remain exercises, disconnected from the structures that determine archaeological funding and protection. This is why the Sendai Framework is important, as the global roadmap for DRR; it translates technical insights into political commitments, setting out priorities that shape national disaster strategies and international cooperation. Geospatial approaches can bridge this gap by producing risk evidence in a form legible to policymakers, positioning archaeological risk within the hazard–exposure–vulnerability–capacity model enshrined in DRR definitions.

Policy functions at multiple scales, with each carrying implications for archaeological DRR. At the local level, risk models can feed into stewardship decisions: which sites are monitored and prioritised for intervention. At the national scale, integration into archaeological registers and disaster management plans can determine whether archaeology is considered alongside

infrastructure and ecosystems. The open-access and transferable design of the geospatial workflows developed in this thesis makes this integration feasible, as they provide access to under-resourced agencies, are scalable across borders, and align with international priorities.

At the global level, policy frameworks such as the Hyogo Framework for Action (2005–2015) and the Sendai Framework for DRR define the operative language and priorities of international risk governance. Both frameworks articulate a comprehensive vision of multi-hazard resilience, underpinned by the principles of prevention, preparedness, and adaptive capacity. Yet, as others have observed (Riede 2017), archaeology remains largely invisible within this architecture. Where archaeology (or heritage) is mentioned, it is often subordinated to economic or social categories, treated as an adjunct to tourism or identity rather than a discrete domain of vulnerability and resilience. This 'heritage invisibility' (Riede 2017) reflects a deeper structural bias within DRR discourse: its anthropocentric orientation privileges contemporary and operational infrastructure over cultural continuity. The result is that the material and symbolic losses represented by archaeological degradation remain unaccounted for within global systems of risk valuation.

Integrating archaeology into DRR, therefore, requires policy reframing. The DRR framework offers a useful scaffold for this integration because it accommodates multi-scalar and cross-sectoral approaches. By aligning archaeological assessments with the hazard–exposure–vulnerability–capacity model underpinning DRR policy, archaeological data can be rendered practically accessible to decision-makers. The Holderness case exemplifies this, where archaeological risk mapping aligns with existing heritage agency mandates and managed retreat policies, allowing for integration into formal governance workflows. On Oʻahu, archaeological DRR intersects with Indigenous stewardship and local land-use planning, demonstrating that policy can also operate through plural and community-based governance models. Conversely, the Sistan Basin highlights the inverse condition, where weak institutions and political instability preclude direct integration; the absence of policy itself becomes a form of risk. In such contexts, international frameworks and aid agreements (for example, UNESCO, UNDRR) serve as provisional governance mechanisms, demonstrating how archaeological DRR can operate as both a technical and a diplomatic intervention.

Crucially, policy is performative: it enacts priorities through funding and institutional mandate. Risk modelling, as developed in this thesis, can inform negotiation by providing a quantifiable basis for prioritisation, directing limited resources toward the most vulnerable or significant sites. Yet policy also determines who is authorised to act upon that information. Without corresponding institutional pathways, evidence remains diagnostic rather than transformative. Thus, one of the most urgent challenges for archaeological DRR lies in creating policy infrastructures that connect assessment with implementation: heritage risk registers and cross-sectoral planning frameworks that treat archaeology as integral to resilience planning rather than peripheral to it. At the same time, the turn toward open-source geospatial methods offer an opportunity to align archaeological DRR with global policy goals of equity and accessibility.

2.7. Disaster Risk Reduction Alignment Constraints

Integrating the DRR framework with archaeological data reveals conceptual mismatches. Standard DRR metrics focus on lives lost and economic damage, categories that do not neatly align with the value of archaeology (which can be intangible). Capacity, a core DRR component, is represented here by proxy variables such as protection or documentation; however, these proxies overlook informal stewardship, community custodianship, and intangible significance. DRR timelines typically emphasise annual hazard cycles and recovery windows, whereas archaeological processes unfold over centuries; the chronic environmental pressures modelled in this thesis mitigate the mismatch but cannot fully resolve it. Institutionally, archaeological risk remains peripheral to most disaster risk management. Without dedicated channels, susceptibility maps may have limited traction in formal decision processes. Finally, ethical restrictions on exact site coordinates, intended to curb looting, conflict with DRR norms of open data for rapid response. Masking locations protects heritage but reduces spatial specificity for external stakeholders, illustrating a persistent tension between preservation ethics and transparency in risk management. These intertwined methodological and conceptual constraints delineate the current scope of geospatial approaches for archaeological risk. They do not negate the approach; rather, they clarify the conditions under which it is most effective and indicate where future refinement is most urgently required, whether through higher-resolution data integration, systematic field calibration, or the development of archaeological-specific DRR indicators and governance pathways.

2.8. Summary

This chapter (Chapter 2) develops the methodological foundation of this thesis by integrating open-access geospatial approaches with DRR principles to establish a practical, adaptable framework for archaeological disaster risk. This chapter constructs an argument for how archaeological vulnerability can be spatially conceptualized, operationalized, and prioritized within the same conceptual framework as DRR's Sendai Framework. Hazards, exposure, and vulnerability are defined in archaeologically specific terms and anchored in spatial data. Hazards are derived from geomorphic and climatic processes that demonstrably threaten archaeological integrity, such as cliff retreat, landslides, and desertification. Exposure is calculated as the spatial proximity of archaeology to those hazard conditions. Vulnerability is interpreted through a combination of elevation, land cover context, protection status, and documentation. This formulation deliberately avoids speculative or reductive risk metrics, instead privileging variables that are observable, interpretable, and replicable across different archaeological landscapes.

The spatial triage methodology that emerges from this framework produces continuous susceptibility surfaces, which are then translated into ranked lists of at-risk sites, enabling heritage agencies and community stakeholders to identify high-priority areas for intervention. This form of prioritization aligns with the DRR's Sendai Framework's emphasis on preparedness and proactive governance, offering a route toward anticipatory conservation rather than reactivity. At the same time, the chapter is explicit about the constraints that shape and limit this approach. The use of

medium-resolution imagery limits the detection of small-scale features. While this inevitably compresses archaeological detail, it also ensures the process can be conducted with open-source software and on standard hardware, lowering the technical barrier in under-resourced settings.

Field-based validation remains constrained across all three case studies. While these limitations preclude systematic ground truthing, the models are nonetheless informed by alternative assessments of the same case studies, RS validation, proxy variables, and legacy survey data. These sources provide sufficient triangulation to calibrate vulnerability assessments and support the validity of the output surfaces as first-order planning tools. Furthermore, the chapter acknowledges a fundamental conceptual disjunction between conventional DRR metrics, which tend to prioritise human casualties, economic loss, and infrastructure damage, and the values in archaeology. The approach advanced here does not attempt to quantify such losses in equivalent terms; instead, it constructs a parallel framework for addressing archaeology, complementary to DRR terms.

In sum, this chapter asserts that archaeological risk to disaster can be modelled rigorously without abandoning the values and practicalities of archaeological work. It shows that open-source geospatial data, when treated with interpretive care, can support site-level prioritisation and strategic documentation planning. And it proposes that archaeology can, and should, play an active role in the broader discussions of disaster risk management. The chapters that follow test the validity of this relationship under various conditions. Each case study presents a distinct environmental and archaeological context, allowing the framework to be refined, challenged, and ultimately strengthened through its applied use.

Chapter 3: Coastal Erosion and Archaeological Risk in Holderness

3.1. Context and Evolution of Holderness

Holderness is located on the north, easternmost coast of the United Kingdom (U.K.), within the county of East Riding Yorkshire, bordered to the east by the North Sea and to the south by the River Humber Estuary (Figure 3.1). The landscape of today's Holderness formed during the last ice age via southward-travelling glacial deposits (Quinn et al., 2009); prior, the coastline extended 20 kilometres



Figure 3. 2. The Holderness coastline, featuring relevant reference locations

beyond its current extent[6] (Lee, 2011; Short & Evans, 2010). The coastal recession along the Holderness coast is driven by ongoing glacial melt, storm surges, a vulnerable geological composition (highly vulnerable to storm surge (Barkwith et al., 2014), and sea-level rise (Quinn et al., 2009). The dynamic coastal system of Holderness, compounded by anthropogenic development and climatic variability, represents a slow-onset, cumulative disaster scenario. Approximately 4 kilometers of coastline have been lost since the Roman period (de Boer & Carr, 1969; Olster, 1990), with erosion rates today reaching up to 2 metres per year, making Holderness one of the world's most rapidly eroding coastlines. This erosion places archaeological sites, ranging from prehistoric barrows to Cold War bunkers, at risk of direct destruction or indirect loss through the transformation of this landscape. Moreover, the region benefits from a rare combination of spatial data, a robust archaeological inventory via the Archaeological Data Service (ADS), and decades of shoreline mapping. These factors make Holderness an ideal candidate for incorporating geospatial approaches grounded in Disaster Risk Reduction (DRR) in an at-risk archaeological context.

To maintain consistency with DRR, this case study defines the prevalent hazard as coastal erosion, the proximity of the archaeological record to the hazard as exposure, the protection status of the archaeological record as vulnerability, and the presence or absence of shoreline management and stewardship programs as capacity. Using this framework, the following sections apply a spatial triage workflow to prioritize archaeological risk under conditions of limited interest and funding. This case study further holds goals to accomplish the overarching aim of this thesis (see Chapter 1), with the following key goals in mind:

1. To develop a model using Landsat remote sensing multispectral imagery to ascertain the extent of coastal change at Holderness, thereby determining the areas of the coast most exposed to the hazard of coastal erosion.
2. To utilize the remote sensing model of coastal exposure to determine the vulnerability of known archaeological sites along the Holderness coastline.
3. To combine the exposure and vulnerability model and devise it by the capacity of the Holderness region, and in doing so, provide a vulnerability map indicating the sites at the highest risk of hazard impact.

The Holderness coast, stretching 61 kilometres from Flamborough Head to Spurn Point, is a dynamic geomorphological system. This landscape in flux holds a pattern clearly visible in historical maps and oral traditions dating to the 13th century (Brown et al., 2012). This long record of landscape change and coastal inundation, ranging from the loss of entire medieval villages, such as Ravenser (Wade, 2017), to the steady narrowing of promontories, underscores the chronic, non-linear nature of the risk. The Flamborough Head to Gibraltar Point Shoreline Management Plan (Evans & Short, 2010) provides a helpful delineation of the coastline. In the Shoreline Management Plan (SMP), the Holderness coast is described as 'one system' (p. 11), divided into segments due to the geological

[6] See surface geology map of Holderness in Appendix B-1

variation along the coastline. These segments include the Chalk Cliffs, the Holderness Cliffs, and Spurn Point.



Figure 3. 2. The Chalk Cliffs, facing east

Segment 1: *The Chalk Cliffs*

The first segment extends from Flamborough Head to Sewerby. Flamborough Head comprises Chalk Cliffs (Figure 3.2), with heights varying from 30 to 50 metres. The chalk in this segment is harder than in the south and erodes at 0 to 0.4 metres per year (Short & Evans, 2010). The erosion at Segment 1 creates a headland[7] that protects the southern portion of the coastline from excessive wave action[8] (Short & Evans, 2010).

Segment 2: *The Holderness Cliffs*

The second segment of the Holderness Cliffs extends from Sewerby to Easington. Unlike Segment 1, the silts and clay making up the coastline's 40-metre-high cliffs (Figure 3.3) are soft, with an average erosion rate of 1.8 metres per year (Evans & Short, 2010).

[7] A headland is a point of land, often high and rocky, that juts out into a body of water.
[8] Wave action is the physical force exerted by waves as they move across a body of water and interact with shorelines

Segment 3: *Spurn Point*

Spurn Point (Figure 3.4) is threatened and sustained in many ways by the erosion occurring to the north along the Holderness Cliffs. The movement of eroded material or longshore drift[9] from Segment 2 nourishes the spit[10] that is Segment 3. Segment 3 then acts as a barrier protecting the Humber Estuary to the east from excessive wave action (Lee, 2011; Short & Evans, 2010).



Figure 3.3. The Holderness Coast, facing north



Figure 3.4. Spurn Point, facing south

As detailed above, each segment interacts with the others, creating a self-organizing (nevertheless) unpredictable sediment system.[11] Coastal erosion at Holderness is not isolated but interdependent, with protective or destructive effects in one zone cascading into others. This requires a landscape-scale risk model that can account for inter-segment dependencies. Thus, the scale of this case study includes all segments of the Holderness coastline to accommodate this integrated impact.

The SMP further outlines the work local management conducts to mitigate erosion along the coastline. The three steps to interact with or not interact with coastal erosion at Holderness include:

[9] Longshore drift is the movement of material along a coast by waves which approach at an angle to the shore but recede directly away from it.

[10] A spit is a narrow point of land extending into a body of water

[11] In DRR this is a compound risk landscape (van den Hurk et al., 2023).

Hold the line
Holding the line includes building sea walls to prevent the encroachment of sea level rise and further coastal erosion (Short & Evans, 2010).

Managed retreat
Managed retreat includes proactively moving structures and people away from the coastline. This process allows coastal erosion to occur (Short & Evans, 2010).

No active intervention
No active intervention indicates a management plan that allows the coastline to erode naturally, with no human prohibition or involvement in the process (Short & Evans, 2010).

In the case of both the Chalk Cliffs (Segment 1) and the Holderness Cliffs (Segment 2), the recommendation from the SMP is no active intervention (Short & Evans, 2010). Spurn Point (Segment 3) is likewise designated for no intervention. While erosion dominates the landscape, coastal expansion also occurs, particularly at Spurn Point, where up to 3-6% of eroded material from the northern segments is deposited (Ciavola, 1997; Boyles et al., 2017). This process of sediment transport temporarily reinforces Spurn Point, but the spit remains ephemeral, having historically disappeared and re-emerged due to the shifting balance of erosion and deposition (de Boer, 1964; Bateman et al., 2020).

3.2. Coastal Erosion and Archaeology: A Review

Coastal archaeology is increasingly characterised as a discipline operating under conditions of accelerating crisis, with the convergence of sea-level rise, intensified storm regimes, sediment starvation, and coastal development has effectively placed cultural heritage within a high-energy hazard zone from which few sites can reliably be protected. Global shoreline analyses sharpen the scale of this crisis: approximately 24 percent of the world's coasts are eroding at rates exceeding 0.5 metres per year, while 16 percent retreat at more than 1 metre per year, and extreme hotspots, most notably portions of the Mekong Delta, are experiencing shoreline losses on the order of 25–30 metres annually (Luijendijk et al. 2018). These stark figures quantify what archaeologists have been observing qualitatively for decades: coastal sites are disappearing faster than they can be meaningfully assessed (Erlandson 2008; Cooper & Peros 2010). While coastal erosion is a natural and long-standing process, the rates recorded over the past half-century represent an unprecedented departure from earlier baselines, with the tempo of destruction now far outpacing traditional archaeological fieldwork cycles (Reeder-Myers 2015). This has prompted scholars to claim that archaeology has entered a salvage triage era, a moment defined by uncomfortable decision-making about what can be preserved, what must be recorded before loss, and what, inevitably, must be allowed to erode beyond recovery (Dawson 2013).

In nearly all accounts, climate change functions as the primary accelerant. Rapid sea-level rise is destabilising nearshore stratigraphy and accelerating shoreline retreat across most global

coastlines (Anderson et al. 2017). More frequent storm surges and king tides are exposing, scattering, or destroying archaeological materials (O'Rourke 2017). Meanwhile, the phenomenon of coastal squeeze, created when rising seas encounter hard-engineered boundaries such as seawalls or urban infrastructure, has intensified attrition in regions already constrained by coastal development (Cooper & Peros 2010). These pressures extend into areas nominally designated for ecological or cultural protection: recent analyses suggest that nearly 37 percent of shorelines within marine protected areas are eroding at substantial rates (Luijendijk et al. 2018). The convergence of these processes highlights a structural vulnerability rooted not only in climate dynamics but also in the spatial distribution of human activity. Coasts have always been disproportionately inhabited; nearly half the global population lives within 100 kilometres of the coastline today, a demographic pattern consistent with deep archaeological time. For millennia, coastlines have served as hubs of resource exploitation, mobility, trade, and settlement, producing the dense archaeological palimpsests now confronting rapid geomorphic change. Thus, the destructive impacts of modern coastal processes are magnified by the simple fact that so much of humanity's material record was, and remains, situated precisely where environmental transformations are most acute.

3.3. The Archaeology of Holderness

Across Yorkshire's varied landscape, archaeological visibility is governed as much by sediment dynamics as by patterns of past activity. Upland peat, particularly the extensive ombrogenous deposits of the Pennines and north-east Yorkshire, plays a decisive role in this regard (Roskams & Whyman, 2005). Its capacity to seal and preserve material has long been recognised, though its concealing effect often delays the identification of prehistoric features until desiccation or erosion intervenes. The gradual exposure of lithics, carved stones, and structural traces on drying peat surfaces, first noted in the western uplands and now increasingly evident in Holderness, has periodically reshaped our understanding of regional prehistory (Roskams & Whyman, 2005; Czajlik, 2021). Conversely, persistent peat cover in certain upland regions may account for the marked scarcity of early sites, emphasising how preservation conditions rather than occupation histories can structure the archaeological record.

Patterns of archaeological discovery across the wider region similarly reflect the intersection of visibility, access, and research attention. Areas of lower encounter density, such as the north-western uplands, central lowlands, and the lower-lying landscapes of the Hull valley and Holderness, nonetheless show small but distinct clusters, typically centred on towns or long-inhabited settlements (Roskams & Whyman, 2005). In well-known historic centres, this is expected, but the same clustering around smaller market towns and even minor rural settlements demonstrates that archaeological encounters accumulate where people routinely work, live, and observe the landscape (Roskams & Whyman, 2005)

Medieval datasets across Yorkshire exemplify these issues of bias and visibility. Although chronological attribution is uneven in earlier periods, medieval sites tend to be easier to identify and classify, reducing ambiguity (Roskams & Whyman, 2005). Even so, distribution maps show notable

absences, especially parts of the lowlands and Holderness. These voids align closely with areas of poor visibility and limited investigation and are not necessarily due to true absences of activity. Elite and defensive sites present a further layer of patterning. Their concentration in the east, markedly higher than in the western uplands, suggests that symbolic and defensive architectures were preferentially located within accessible lowland zones and along riverine corridors, reinforcing political and economic influence rather than simply marking habitation density (Roskams & Whyman, 2005).

Viewed at a broader scale, Yorkshire divides into a series of distinct landscape blocks: upland, lowland, and transitional zones, integrated by river systems draining into the Humber (Roskams & Whyman, 2005). This topographic organisation gives the region an underlying unity, but the archaeology recovered from each block reflects the varied history of research praxis. Investigations across the twentieth century tended to focus on specific subregions (Roskams & Whyman, 2005): the Wolds, Howardian Hills, and eastern uplands through the foundational work of early prehistorians(Glover et al., 2016; Roskams & Whyman, 2005); the Pennines via mid-century excavations; and, more recently, the river valleys and wetlands through systematic programmes such as those undertaken in the Humber and Holderness zones (Glover et al., 2016; Roskams & Whyman, 2005). The result is an evidential landscape shaped by variable visibility, selective preservation, and the long arc of disciplinary focus.

For Holderness, these wider Yorkshire patterns underscore a key point: the archaeological record is not simply sparse or eroded but selectively illuminated. The preservation of peat, varied survey priorities, and geomorphological instability all contribute to a patchwork of data that must be read critically. What appears as absence may be concealment; what seems as clustering may reflect modern movement and observation rather than past settlement logic. Integrating these insights reinforces the need to treat Holderness as part of a broader regional mosaic, where environmental processes and research histories co-produce the archaeological patterns now available for analysis. Despite the overwhelming historic and ongoing loss of the Holderness coast (Shepherd, 1912), the region preserves a densely layered archaeological record extending from the Palaeolithic to the militarised landscapes of the twentieth century (Starkey, 2017). Its glacial till, shifting clifflines, and proximity to both freshwater and marine resources structured long-term human activity, but they also ensure that much of the archaeology survives only because, and only until, erosion exposes it. As Dinnin (1995) and Greenwell and Gatty (1910) observed more than a century apart, archaeological visibility here depends as much on preservation conditions as on past behaviour: Holderness is a place where the landscape both reveals and destroys its own past.

This study draws on 673 georeferenced records from the ADS, extracted from an initial dataset of 3,099 entries for the wider region. A 5-kilometre coastal buffer was applied to isolate the zone where archaeological exposure is likely to be highest (to be determined in the upcoming methodological assessment). These records do not always represent intact sites, but mark instances where archaeology was observed or inferred, sometimes seconds before it was lost to the sea, drainage, or development. The Yorkshire Archaeological Research Framework (YARF) highlights that such

uneven distributions are the rule rather than the exception across Yorkshire, with marked period-by-period variations reflecting differential survival, exposure, and historic fieldwork intensity rather than actual past population densities. Chronologically, the dataset (Table 3.1) spans a broad temporal range, including the Palaeolithic, Mesolithic, Neolithic, Bronze Age, Iron Age, Roman, Medieval, Post-Medieval, and Modern periods. Within the modern category, the records have been further subdivided into material related to the First World War (WWI), the Second World War (WWII), and the Cold War. There is also a residual 'uncertain' category for ambiguous records. Each period presents distinct interpretive challenges, especially regarding preservation biases, spatial precision, and recording conventions. As Cooper and Green (2016, p. 283) rightly argue, digital archaeological datasets are 'partial, disparate, and mutable,' a claim that holds weight in a coastal context where the erasure of the archaeological record is both ongoing and accelerating.

Taken together, the prehistoric records show a coastline repeatedly exploited but rarely static. Round barrows, earthworks, cropmarks, and dense lithic scatters indicate sustained use of the Holderness landscape from the Neolithic and Bronze Age onwards, allowing broad reconstructions of land use and movement (Czajlik, 2021). The sparse but telling Palaeolithic evidence, an isolated flint flake from Withernsea and a rich faunal assemblage of large mammals near Hull, points to episodic use of a resource-rich lowland edge, where refuse was routinely consigned to water bodies, in keeping with wider East Riding patterns (Greenwell & Gatty, 1910; Davis, 1888; Hardy, 2016). The structure at Withow Mere, dated to 4770 BCE, and the peat-sealed Mesolithic harpoons from Hornsea Mere and Skipsea reveal that key elements of this early coastal record now survive only because they were buried and later re-exposed by peat dynamics (Armstrong, 1992). Their meticulous manufacture and association with large game reinforce interpretations of specialised hunting strategies that resonate with broader models of Mesolithic subsistence and mobility (Leduc, 2014; Spikins, 2003). Neolithic and Bronze Age entries, including funerary monuments, a henge, a dam, and lithic-working sites, cluster around promontories such as Flamborough Head and along Bridlington and Spurn, signaling a persistent focus on elevated or liminal positions overlooking the North Sea.

From the later prehistoric into the Roman period, the dataset charts a shift from primarily mortuary and task-specific use of the coast towards more explicit integration into supra-regional networks. Iron Age square barrows, emblematic of the Arras culture and at their densest in East Riding (Dent, 2010), tie Holderness into an East Yorkshire mortuary tradition widely interpreted as drawing on La Tène influences from Champagne (Darville, 2009). Roman material distributed between Bridlington and Spurn, with an outlier east of Hull, reflects a coastline knitted into imperial transport and defence systems, likely linked to the contested port of Petuaria (Watcher, 1960; Wilson, 2017). The recorded watchtower south of Flamborough Head fits within the Gask Ridge model of linear coastal surveillance (Lewis, 2020). Medieval entries then document a coastal economy in which harbour, waterpower, agriculture, and wetland exploitation formed an integrated system. Bridlington Harbour, named as Bretlinton in Domesday (Williams, 1992; Bennett & Bilton, 1899), anchors this seaward orientation, while mills recorded in 1299 and 1597 (Williams, 1992), ridge-and-furrow, a fourteenth-century fishpond, turbary and associated grazing infrastructure speak to an intensively

managed yet intermittently inundated landscape that nonetheless prospered in the eleventh century (Sheppard, 1966; Darby, 1971; Sheppard, 1957; Siddle, 1967).

Table 3.1 Archaeological Data Service (ADS) records according to period, number of records, and chronology (Periods, from Historic England[12])

Period	Number of Records	Chronology
Prehistoric	10	Before 43 AD
Palaeolithic	4	800,000 – 10,000 BC
Mesolithic	4	10,000 – 4,000 BC
Neolithic	39	4,000 – 2,200 BC
Bronze Age	33	2,200 – 800 BC
Iron Age	21	800 BCE – 43 AD
Roman	55	43 – 410 AD
Medieval	93	410 – 1540 AD
Post-Medieval	61	1540 – 1901 AD
First World War	10	1914 – 1918 AD
Second World War	294	1939 – 1945 AD
Cold War	13	1947 – 1991AD
Uncertain	36	Undated / unknown

Post-medieval and modern records show the same coastline being repeatedly re-inscribed by changing regimes of authority, communication, and conflict. The Dissolution and subsequent break-up and sale of monastic and estate land (Gasquet, 1889; Hollis, 1994) restructured landholding and, by extension, patterns of settlement and investment. Beacons at Bridlington, south of Bridlington and north of Withernsea, formed part of the 1588 Spanish Armada warning network, embedding Holderness within a national system of maritime defence (Marx, 1968), while lighthouses. Especially the paired towers at Flamborough signal the ongoing hazards of navigation in this sector of the North Sea. Twentieth-century features, from WWI windmills, jetties, watchtowers, bunkhouses, and army camps to an acoustic mirror, to WWII anti-aircraft batteries and air-raid shelters, chart the intensification of military infrastructure along the same vulnerable stretches around Flamborough, Withernsea, Spurn, and the Humber. Cold War monitoring posts, spaced at regular intervals from Flamborough to Spurn, extend this defensive logic into the nuclear age. Read together, these phases do not simply accumulate as discrete episodes; they reveal a coastline repeatedly targeted, exploited, and fortified, where continuity lies less in specific site types than in the enduring strategic and economic value of Holderness and in the selective survival of its archaeological traces.

[12] https://historicengland.org.uk/listing/the-list/historic-periods/

3.4. Methodology

3.4.1. Review of Remote Sensing Approaches to Coastal Erosion and Archaeology

Methodological advances have reshaped archaeological responses to coastal change, pushing the field toward multi-scalar integration of geospatial and remote-sensing tools. High-resolution LiDAR, drone photogrammetry, and satellite time-series analyses now underpin most efforts to map erosion trajectories, model inundation scenarios, and detect features newly exposed by shoreline retreat (Casana et al. 2021). Predictive frameworks that incorporate geomorphology, relative sea-level rise, wave action, hydrodynamics, and cultural-site distributions have become central to determining which heritage assets are at immediate risk and which can be feasibly preserved (Anderson et al. 2017; Dawson 2013). Community-involved monitoring initiatives, most notably Scotland's SCAPE project, have demonstrated that local observers can produce dense, near-real-time datasets that far exceed institutional capacity, effectively reframing coastal heritage management as a collaborative, distributed practice rather than the exclusive domain of state agencies (Hambly et al. 2016). Yet, unlike wildfire research, where archaeological engagement has been surprisingly hesitant, the accelerating visibility of coastal erosion and sea-level rise has generated substantial scholarly and public interest (Amin & Hasan, 2024; Levy et al., 2024; Yuxin et al., 2024).

Nakhaei et al. (2024), working along the coastline of Kish Island in the Persian Gulf, combine Landsat 4–8 imagery with the Digital Shoreline Assessment System (DSAS) to model both historical and future shoreline positions, projecting potential retreat of up to ~30 metres between 2033 and 2043. By integrating NDWI outputs with DSAS-derived change rates, the authors identify archaeological sites already affected by erosion and those likely to be impacted in the near future. A foundational precursor to this type of work is Reeder et al. (2012), who developed a Coastal Resource Vulnerability Index (CRVI) for the Northern Channel Islands by integrating six variables, geomorphology, historical shoreline change, slope, relative sea-level rise, wave action, and tidal range, into a reproducible GIS-based index. Their results underscore a key spatial threshold repeatedly observed across global coastlines: sites within 100 metres of the shoreline exhibit the highest susceptibility to erosion. Complementing these approaches, Elfadaly et al. (2023) blend historic topographic survey maps (1900, 1925, 1945) with Landsat 5, 7, and Sentinel-2 imagery (1972, 1986, 2000) to evaluate long-term coastal change along the northern Nile Delta. Their analysis concludes that land subsidence, not wave energy or shoreline migration alone, is the primary driver of archaeological vulnerability in their study area. Collectively, these studies highlight both the promise and pitfalls of current practice: Nakhaei et al.'s reliance on DSAS provides strong temporal modelling but requires a proprietary ESRI environment; Reeder et al.'s CRVI is elegant but depends on environmental datasets that are often unavailable outside well-resourced regions; and while Elfadaly et al. creatively integrate historical cartography with free imagery, their method hinges on precise georeferencing, far from guaranteed in post-disaster or rapidly changing landscapes.

Flood-related archaeological research exhibits similar tensions between methodological sophistication and practical accessibility. Flooding can result from hurricanes, tsunamis,

monsoons, storm surge, or intense rainfall, all of which have increased measurably in frequency and magnitude (Robinson et al., 2021). Reeder-Myers & McCoy (2019) examine the impacts of Hurricane Harvey on archaeological sites in Houston, integrating high-resolution aerial imagery with maximum flood-extent datasets generated by the Dartmouth Flood Observatory using MODIS, Sentinel-1, ASI, COSMO-SkyMed, and RADARSAT-2. Contrary to expectations, neither elevation nor coastal proximity proved to be a strong predictor of archaeological flood risk. Instead, the most vulnerable sites were located on undeveloped agricultural lands, spaces often dismissed as inherently low-risk within traditional hazard models. The authors also demonstrate that rainfall-driven flooding, rather than storm surge alone, was the dominant mechanism of archaeological impact, highlighting a blind spot in many coastal vulnerability studies that privilege shoreline processes over precipitation dynamics. Robinson et al. (2021) reinforce this observation, arguing that rainfall amplification under climate change may reshape archaeological hazard profiles even in areas without significant coastal exposure. Yet the data required for these assessments, multi-sensor radar-derived flood extents and costly, high-resolution aerial imagery, remains out of reach for many researchers and communities, thereby limiting the transferability of these otherwise exemplary methods.

3.4.2. Case Study Methodology

The approach used to assess archaeological exposure to coastal erosion along the Holderness coastline followed a two-stage process. First, multi-decadal Landsat imagery was analysed to quantify the hazard intensity by identifying which portions of the coast have experienced the most significant coastal erosion over time. This diachronic comparison captures spatial variability and enables mapping of cumulative hazard impacts. Second, archaeological point data were overlaid onto these coastal erosion hazard zones and assessed through a regional prioritization framework to determine areas of highest exposure. Vulnerability was operationalized as the archaeological point's proximity to the most exposed and least protected portions of the coastline. Capacity was based on existing shoreline management designations under the SMP and populated centres. The purpose of incorporating populated centres as an element of capacity was first to bolster the SMP data and, second, to account for the fact that areas with high population or revenue levels are more likely to be protected against coastal erosion (Alexandrakis et al., 2021). The result is a DRR-informed, geospatial application for modelling and mitigating archaeological risk along eroding coastlines (Figure 3.5).

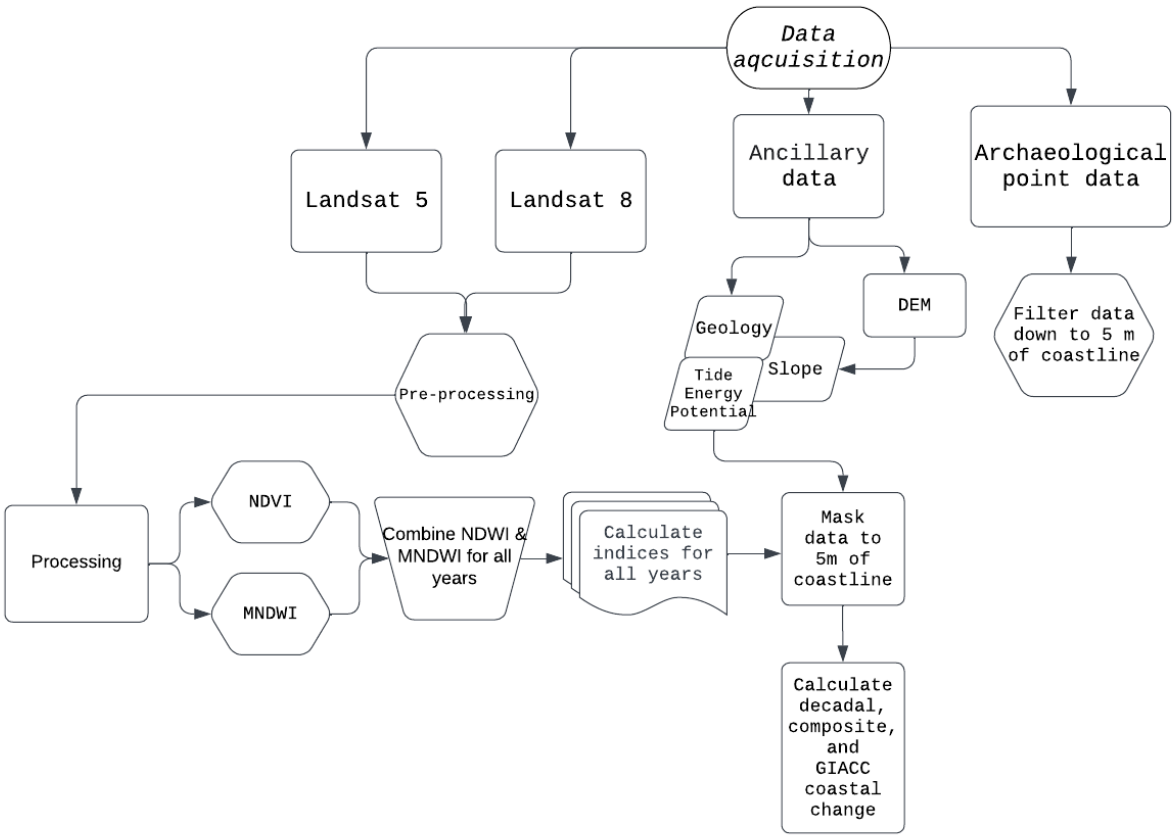


Figure 3. 5. Remote sensing imagery coastal erosion assessment workflow

Data Acquisition

Imagery was acquired from the USGS EarthExplorer API, specifically from the Landsat 5 Multispectral Scanner System (MSS), Thematic Mapper (TM), and Landsat 8 Operational Land Imager (OLI) sensors (Buscombe, 2023). Tier 1, Level 3 data specifications were used for each sensor, respectively, using download specifications accessing Bands 1–7 for spectral index processing (Table 3.1). These sensors were chosen for their spatial and temporal resolutions, as the case study requires imagery to observe coastal erosion over an extended period and identify the areas most affected. Additionally, the model required the imagery to have sufficient spatial resolution to conduct meaningful analyses concerning the effects of coastal erosion. The imagery was downloaded from 1990, 2000, 2010, 2014, 2015, 2016, 2017, 2018, 2019, and 2020, totalling 918 images across all years (Figure 3.6 and Table 3.2). The data range was chosen to provide a broad view without sacrificing spatial resolution or imposing excessive computational requirements. Imagery was collected explicitly from 1990 to 2020 to showcase decadal trends in the landscape. The imagery was also collected from 2014 to 2019, given the number of images in these years' composites, to assess whether landscape change differed with the increased availability of images.

Ancillary data (Table 3.3) was also collected, including elevation, vectorised coastline extent from Ordnance Survey, tidal energy potential from Proudman Oceanographic Laboratory (POL)[13], and surface geology from the British Geological Society. Ancillary datasets were selected to provide a comprehensive understanding of the physical processes driving coastal erosion along the Holderness coastline and to evaluate their implications for the archaeology. The DEM was used to characterise local topography, enabling the identification of low-lying areas and micro-gradients that influence inundation pathways and erosion susceptibility. The vectorised coastline extent from the Ordnance Survey[14] provided an approximate modern shoreline position, allowing the determination of retreat rates and the spatial relationships between erosion patterns and archaeological assets. Tidal energy potential from the POL offered insights into the hydrodynamic forces acting on the coastline (Howland & Thompson, 2021), helping to explain spatial variations in erosional intensity. Surface geology from the British Geological Society[15] was used to assess the erodibility of local sediments, a critical factor given Holderness's predominantly glacial till. Together, these datasets allowed for an integrated assessment of how the pivotal variables interact to shape erosion risk, thereby enabling a more robust evaluation of archaeological vulnerability in the region.

Table 3.2. Acquisition specifications for imagery

Sensor	Bands	Images	Dates
Landsat 5 Thematic Mapper (TM)[16]	1 - 7	108	January - December 1990; January - December 2014
Landsat 8 Operational Land Imager (OLI)[17]	1 - 7	810	January 2015 - December 2020

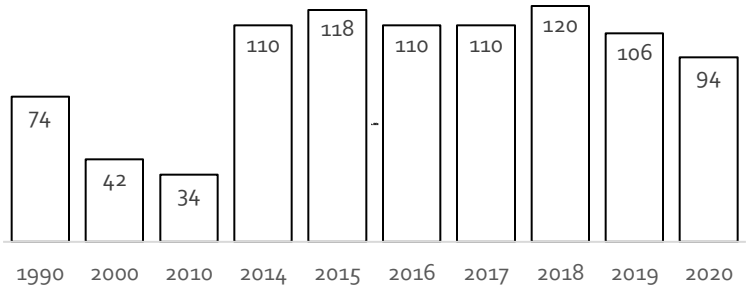


Figure 3. 6. The quantity of images contributing to yearly composites

[13] https://www.bodc.ac.uk/resources/inventories/edmed/org/48/
[14] https://osdatahub.os.uk/data/downloads/open
[15] https://www.bgs.ac.uk/datasets/geocoast-open/
[16] https://www.usgs.gov/centers/eros/science/usgs-eros-archive-landsat-archives-landsat-4-5-thematic-mapper-tm-level-1-data
[17] https://www.usgs.gov/landsat-missions/landsat-8

Table 3.3. Ancillary data and sources

Ancillary Data	Source
Digital Elevation Model (DEM)	NASA Shuttle Radar Topography Mission (SRTM)[18]
Slope	NASA Shuttle Radar Topography Mission (SRTM)
Coastline	Ordinance Survey
Tidal Energy Potential	Proudman Oceanographic Laboratory (POL)
Surface Geology	British Geological Survey

3.4.3. Processing

Imagery was processed to produce the following indices: the Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI). Before index processing, the individual bands were masked to within 5 kilometres of the coastline to prevent processing to the entire Holderness area. Post-imagery acquisition masking and processing were conducted for the study. The Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI) were selected for their established efficacy in distinguishing between terrestrial and aquatic surfaces in coastal environments (Zhao et al., 2021). NDWI (Equation 3.1), which uses the Green and Near-Infrared (NIR) spectral bands, enhances the detection of open water bodies by attenuating vegetation and soil reflectance, thereby improving the definition of the land–water boundary. MNDWI (Equation 3.2), substituting NIR with the Shortwave Infrared (SWIR) band, further refines this distinction by suppressing the influence of built-up or urban areas, which often exhibit spectral properties like those of dry land (Yang & Du, 2017). The combined use of these indices enables a comprehensive assessment of both hydrological and anthropogenic factors influencing shoreline dynamics along the coast. The analysis was spatially constrained to a 5-kilometre buffer from the coastline to maintain computational efficiency and ensure relevance to the active coastal zone. Utilizing Level 3 pre-processed imagery eliminates the need for radiometric and atmospheric corrections, demonstrating an accessible workflow for applying remotely sensed data in coastal change studies that rely on externally provided imagery.

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \quad (3.1)$$

$$MNDWI = \frac{GREEN - SWIR}{GREEN + SWIR} \quad (3.2)$$

[18] https://www.earthdata.nasa.gov/data/instruments/srtm/data-access-tools#toc-shuttle-radar%20topography%20mission%20(srtm)-srtm-data%20tools

$$(3.3) \quad Annual\ Composite = NDWI + MNDW$$

$$(3.4) \quad Change = Year_{Final} - Year_{Initial}$$

Each image composite was processed with the above indices and combined to represent an annual composite and a single raster image for each respective year (Equation 3.3). To visualise the change along the coastline, the difference in pixel values representing land and water was calculated using the raster calculator in ArcGIS Pro (Equation 3.4). The change calculation produced a grayscale image with values ranging from 0 to 1, which was converted into a colour ramp that displays land loss as blue and land gain as green. The pixels were statistically classified using natural breaks to optimise visualisation of the maximum difference between pixels (Jenks, 1967).

3.4.4. Results

The results of this methodology quantify coastal erosion as a spatial hazard and exposure surface through three progressively detailed approaches: decadal change detection, composite change, and greatest image-averaged outputs. Each method balances trade-offs in temporal granularity, data availability, and computational effort, offering scalable pathways for identifying coastal erosion intensity. Together, these outputs enable a tiered understanding of hazard chronology, spatial severity, and methodological suitability in risk-prone coastal zones. Overall, as this model was a test of methodological adaptation using geospatial analysis to expediently determine coastal change, these three outputs allow for testing the most robust results and, therefore, a useful exposure model for moving forward with the other DRR variables of vulnerability and capacity. The three outputs include Decadal Change, Composite Change, and Greatest Image-Averaged Composite Change.

Decadal Change

Imagery was processed into three decadal intervals: 1990-2000, 2000-2010, and 2010-2020, to assess long-term trends in coastal retreat and cumulative hazard accumulation. This format enables the temporal analysis of coastal erosion without requiring annual datasets or advanced processing resources. The results illustrate a progressive, directional trend in coastal erosion severity. Between 1990 and 2000 (Figure 3.7), erosion was concentrated near Skipsea, with modest land gains being recorded around Withernsea and the easternmost portion of Spurn Point. During the 2000–2010 decade (Figure 3.8), coastal erosion intensified, extending consistently from Flamborough Head to the Humber Estuary. Between 2010 and 2020 (Figure 3.9), nearly the entire Holderness coastline experienced coastal erosion, with limited pockets of land accretion[19].

[19] Coastal accretion is the process where sediment builds up along a shoreline, causing it to grow outwards or become wider over time.

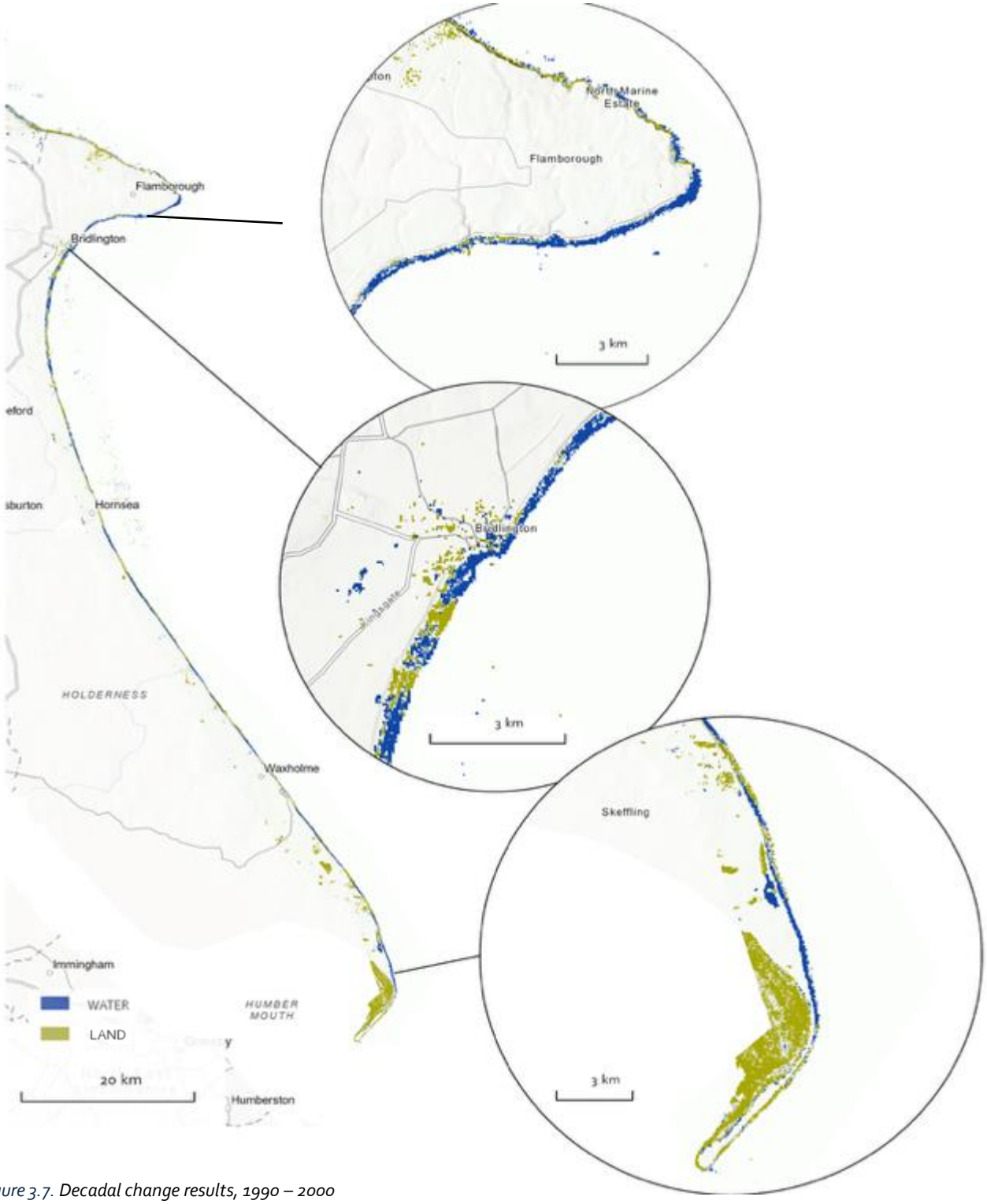


Figure 3.7. Decadal change results, 1990 – 2000

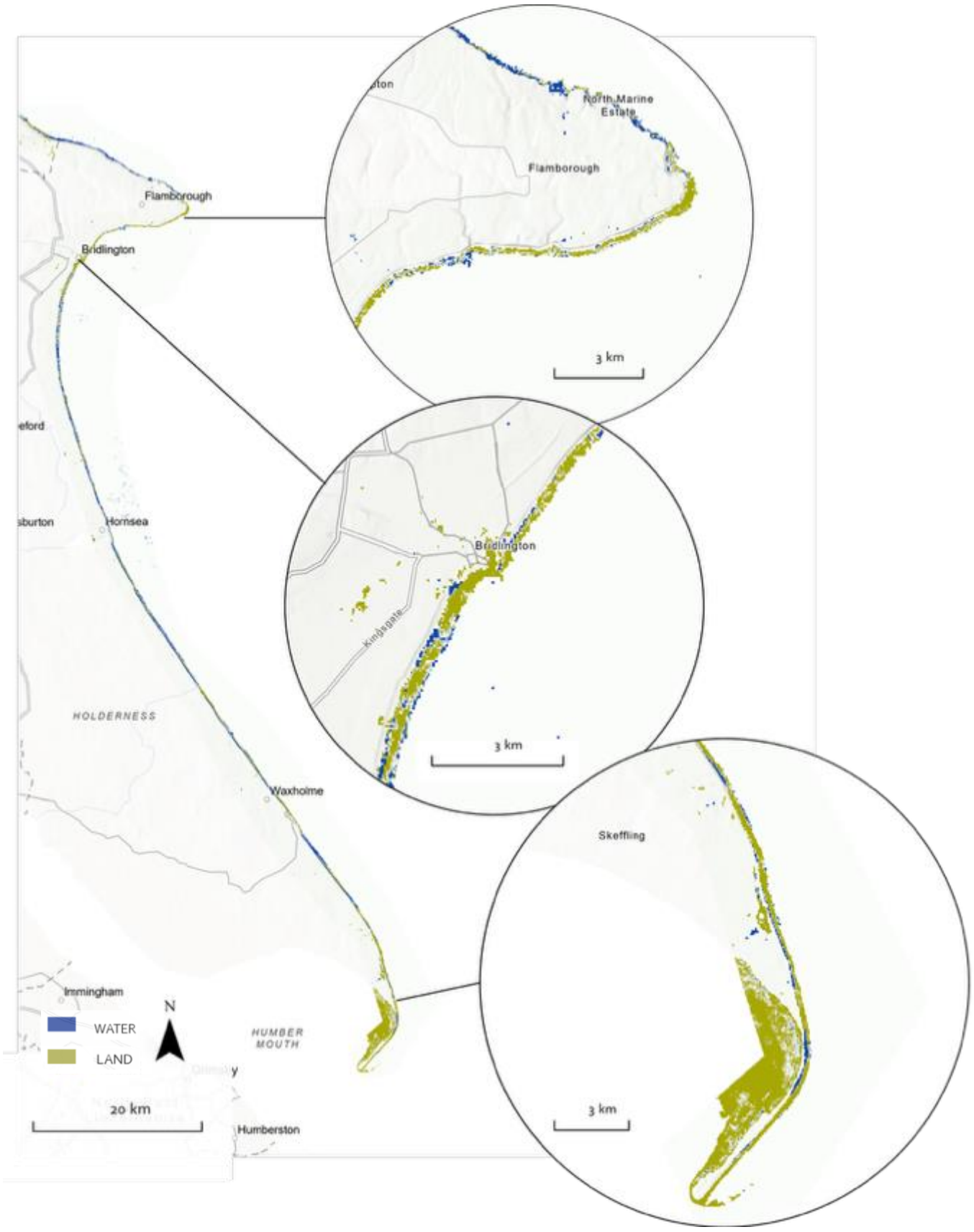


Figure 3.8. Decadal change results 2000 – 2010

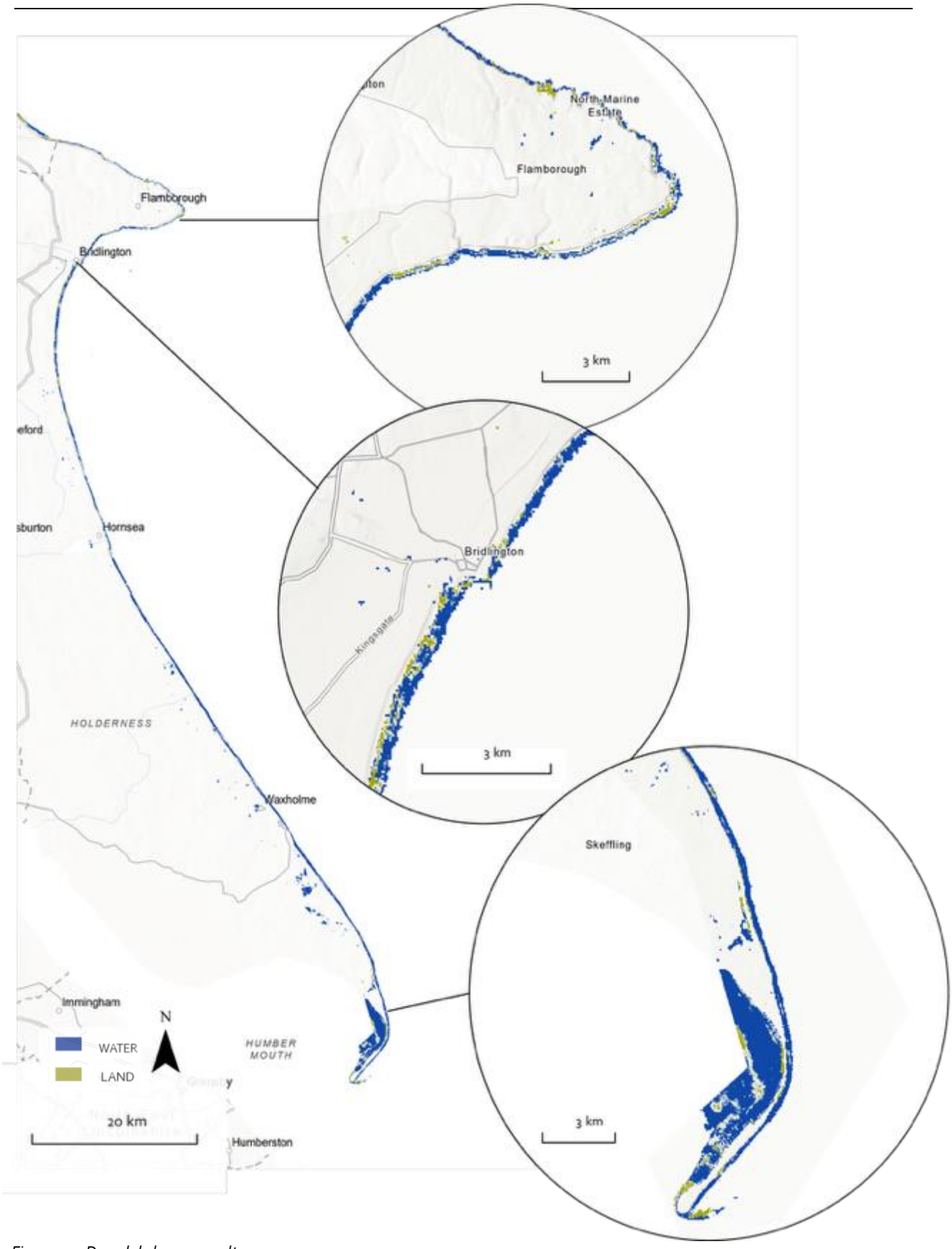


Figure 3.9. Decadal change results 2010 – 2020

Composite Change

The composite change model was generated using two images: 1990 and 2020. In contrast to the decadal approach, the composite change model streamlines processing while producing a generalised coastal erosion surface over 30 years. Results (Figure 3.10) matched the decadal findings in identifying high-erosion zones south of Withernsea and consistent land loss across the Holderness coast.

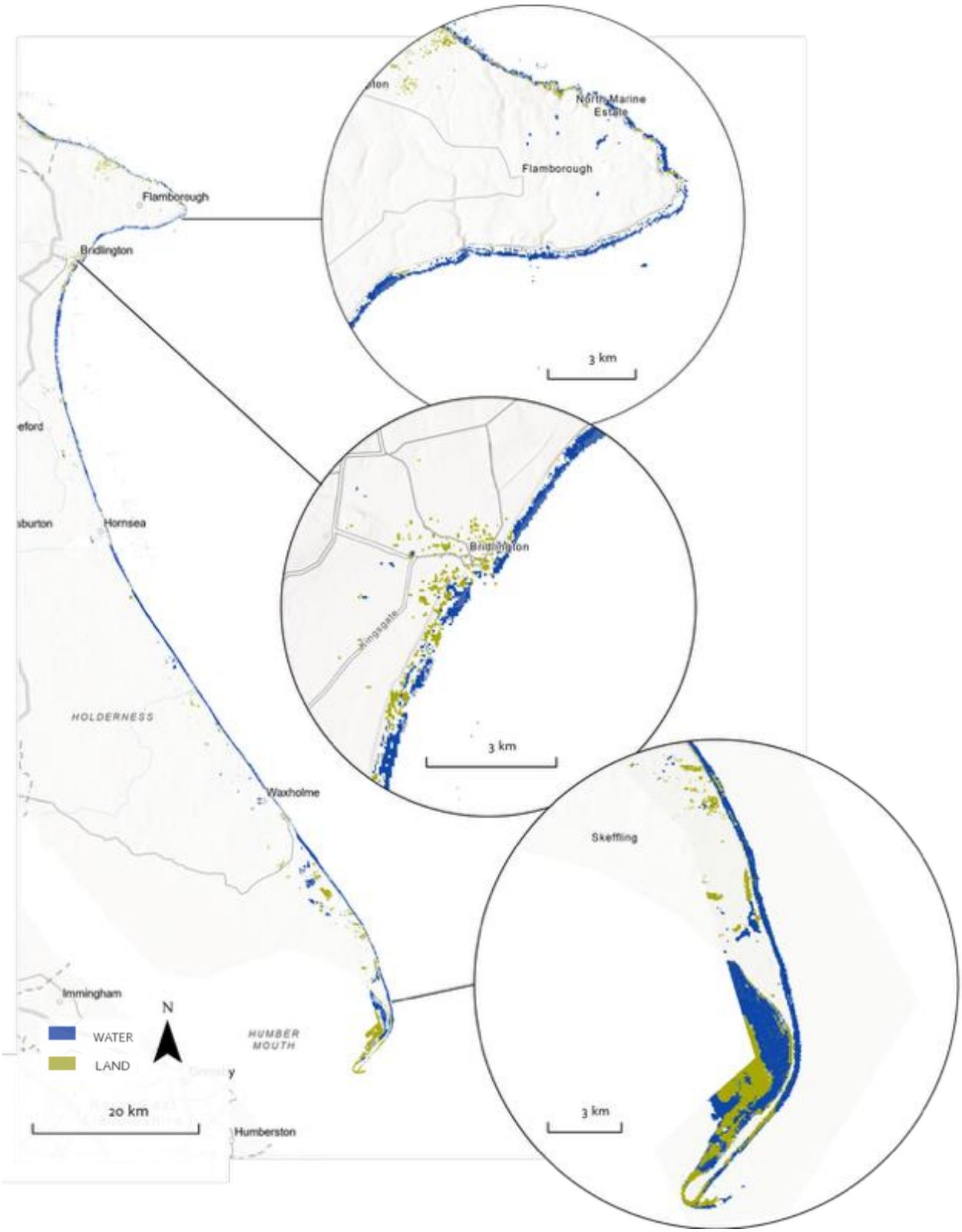


Figure 3.10. Composite coastal change results 1990 – 2020

Greatest Image-Averaged Composite Change

The final output, the Greatest Image-Averaged Composite Change (GIACC), focused on image-rich years between 2014 and 2020 (Figure 3.11), each year of which included over 100 usable satellite images. These high-density image composites enabled the most detailed and noise-reduced outputs for coastal erosion determination. The results captured micro-patterns of erosion, particularly southward land loss, mitigated loss at Flamborough Head, and fine-scale depositional activity in Bridlington Bay.

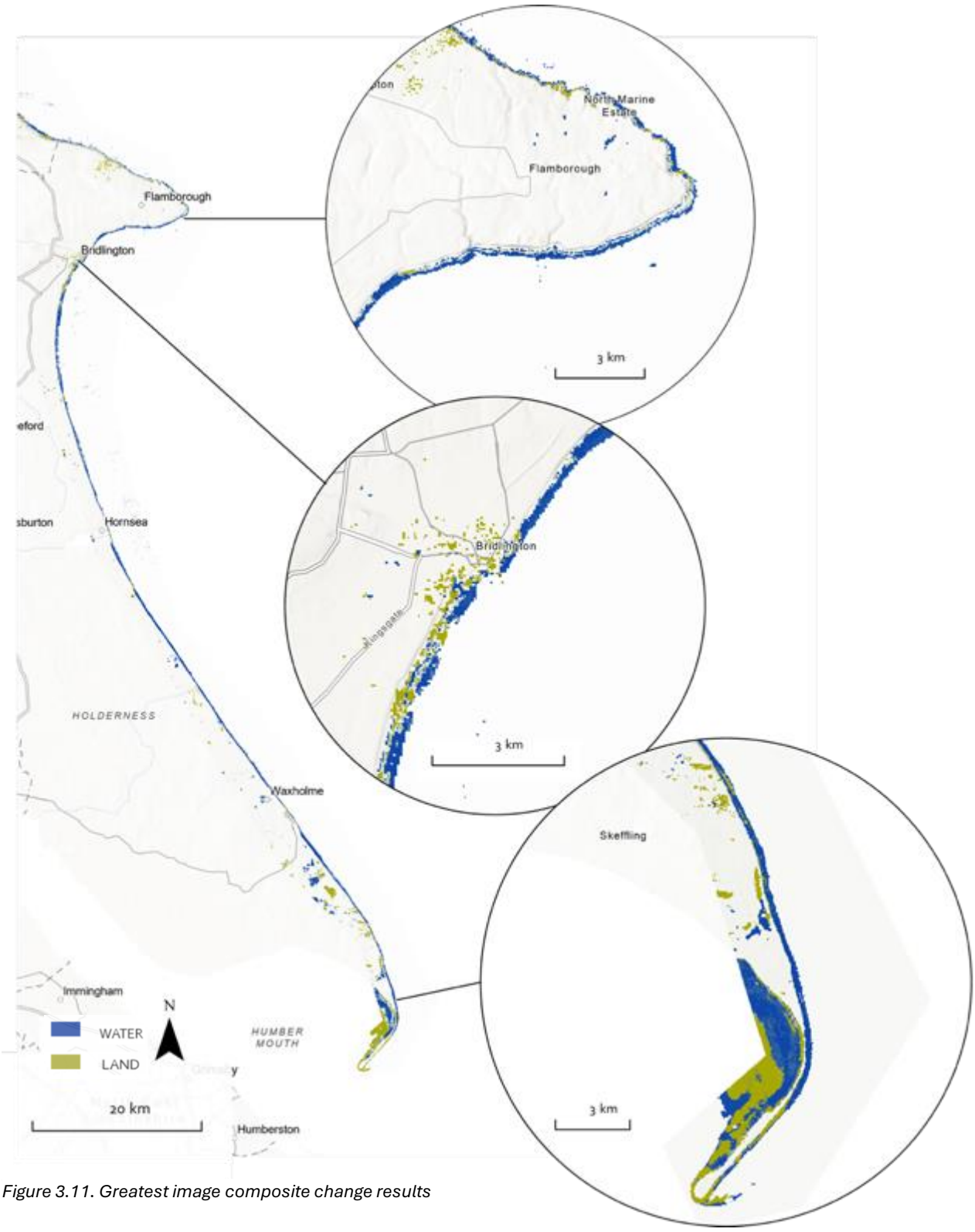


Figure 3.11. Greatest image composite change results

Validation

As demonstrated in prior studies (Lee, 2011; Nowell, 2023; Matthews, 1905), the methodological results of this study, along with in situ observations of active land recession, indicate that coastal erosion is a significant threat to the Holderness coastline (Figure 3.12). However, despite this thorough understanding, validation measures were undertaken to verify the accuracy of the model developed here. These included comparative analysis with established studies of coastal erosion in the region.

The decadal outputs produced align with previous findings: Lee (2011) documented 33 metres of cliffline recession between 1990 and 2004; Bateman et al. (2020) reported a 0.27 square kilometre loss at Spurn Point from 2000 to 2011; and Nowell (2023) confirmed ongoing erosion patterns between 2010 and 2020 consistent with this study's raster outputs. Historical records also corroborate long-term recession trends: Matthews (1905) noted variable erosion processes as early as the turn of the 20th century. More recent monitoring by the East Riding of Yorkshire Council (2006) recorded in situ recession rates between 4 and 20 metres per year, contingent on shoreline defence conditions. Castedo's (2017) Digital Shoreline Analysis System (DSAS) analysis across a 159-year time series estimated erosion rates ranging from 0.95 to 1.83 metres per year, while Pye et al. (2015) further substantiated these patterns by linking erosion severity to cliff height, sediment yield, and wave energy exposure (See Appendix B, Figures B-2 and B-3 for flood potential and historical coastal loss at Holderness).



Figure 3.12. Coastal erosion's impact on a road at Skipsea

3.4.5. Discussion

These decade-based models are especially suitable for contexts where historical comparison or hazard chronology is required, enabling a better understanding of how coastal erosion at Holderness

evolves over time, which is critical for heritage management planning in contexts of irreversible site loss. Composite change modelling provides an expedient way to visualise long-term hazard impact with minimal imagery. It is particularly well-suited to regions where computational resources, imagery archives, or technical personnel are scarce, making it directly relevant to DRR contexts in data-poor environments (UNDRR, 2015). GIACC produced the highest-resolution surface of coastal erosion-related change in this study. While image-intensive and computationally demanding, the approach is ideal where archival density supports it. For DRR practitioners or archaeologists working in well-imaged regions, GIACC offers the most refined means of hazard surface construction and can serve as a modelling benchmark. Within the framework of the Sendai Framework for Disaster Risk Reduction, the outputs presented here directly fulfil Priority 1: Understanding Disaster Risk, by offering a quantifiable, spatialised, and temporally dynamic view of coastal erosion as a chronic environmental hazard. While these models document landscape change, their primary utility lies in pre-emptive spatial triage. They support informed mitigation planning (Priority 3), targeted documentation efforts (Priority 4), and encourage coordination across governance systems (Priority 2). Most importantly, they provide a replicable, low-barrier framework for coastal archaeological risk modelling in other threatened environments, especially those facing similar pressures of chronic environmental change and limited institutional response.

The strong alignment between this study's outputs and established evidence demonstrates that the methodological framework is both reliable and replicable. This validation is precisely why Holderness was selected as the core case study: its well-documented history of rapid erosion and extensive monitoring offers a rigorous testing ground for this coastal-change methodology. By successfully reproducing known patterns of recession across multiple decades, sensors, and data types, the study confirms that the framework is not only accurate but capable of capturing the complexity of coastal processes in high-energy, soft-sediment environments. Crucially, this confirmation provides the foundation for transferring the approach to other regions where conditions may be less well understood or where monitoring data are sparse (or absent), and inconsistent. The workflow developed here, integrating multispectral imagery, ancillary geospatial datasets, and decadal-scale change detection, establishes a flexible, scalable method for assessing coastal hazard impacts. Ultimately, the Holderness case study serves as a proof of concept, demonstrating that combining medium-resolution, open-source satellite-derived coastal change metrics with targeted ancillary datasets can yield reliable assessments of landscape evolution.

3.5. Toward a Disaster Risk Reduction-Informed Risk Framework

Building on the hazard modelling outputs described above, the next stage integrates archaeological data into the coastal erosion framework to spatially triage risk. Whereas the decadal (Figures 3.7-9), composite (Figure 3.10), and GIACC (Figure 3.11) analyses quantify erosion intensity and location, they do not, in themselves, capture the archaeological consequences of land loss. To operationalise these findings within a DRR framework, archaeological point data from the ADS were systematically overlaid onto the derived hazard surfaces, enabling the measurement of exposure through Euclidean distance to the present coastline. This transition from hazard mapping to exposure analysis allows

the archaeological record to be treated as they are: embedded within the evolving coastal system. By further layering vulnerability indicators, proximity to actively eroding cliff lines, shoreline management policy, and population density, and assessing institutional capacity, the analysis moves beyond descriptive hazard mapping toward a fully integrated DRR model. In this way, the methodology directly advances the Sendai Framework's priorities, shifting from abstract documentation of erosion to actionable heritage risk assessment.

3.5.1. Exposure as Proximity

A proximity analysis was conducted using archaeological point data from the ADS overlaid onto a rasterised coastline generated from recent remote sensing imagery. The coastline vector was converted to raster format, enabling Euclidean distance calculations across the entire dataset. Each archaeological record was assigned a linear distance to the present-day coastline using the Euclidean Distance and Extract Multi Values to Points tool in GIS, resulting in a new attribute field denoting proximity in metres (Figure 3.13). From this analysis, a 50-metre distance from the extant coastline was designated as the critical exposure zone, within which sixty-three (63) archaeological sites (Figure 3.14) were identified as falling within a narrower 50-metre transect. These 63 records represent the highest exposure tier, not only spatially adjacent to active coastal erosion processes, but also the most likely to experience irreversible damage in the immediate future due to potential storm surge, cliff collapse, or sea-level rise. The decision to set the distance at 50 metres from the coastline was pragmatic, filtering the 673 records to a manageable number of the highest-threat records. Assuming the coastline continues to erode at a rate of roughly 2 metres per year, 50 metres would (in an ideal scenario) equate to a twenty-five-year period.

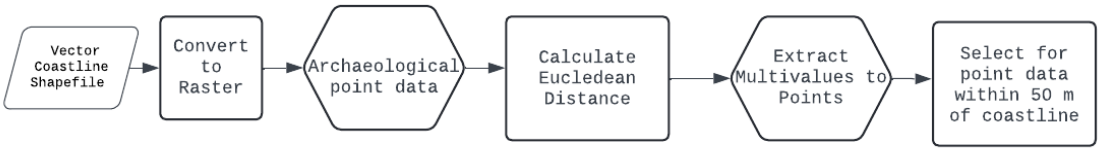


Figure 3.13. Archaeological point data proximity to coastline extraction GIS workflow



Figure 3.14. 65 sites identified as 50 m and the greatest proximity or highest exposure to the coastline

This high-exposure ADS point subset is not homogeneous but instead presents a deeply stratified, temporally diverse record spanning the Neolithic to WWII (Figure 3.14). Prehistoric material, defined here as encompassing the Palaeolithic through the Iron Age, comprises three (3) records within the 50-metre risk zone. The Palaeolithic component is represented by a single (1) record: an occupation site at Withow Mere, located south of Bridlington Bay. This rare survival of early human activity, likely tied to wetland-edge resources, provides key evidence for Pleistocene subsistence patterns in East Yorkshire. Its low-lying setting renders it highly vulnerable to drainage and coastal change. The Neolithic component is similarly modest, represented by a single (1) record of ten (10) pieces of beaver-gnawed wood, preserved in waterlogged contexts. These organic survivals, again derived from wetland margins, are particularly sensitive to ongoing peat shrinkage and desiccation (Gearey & Fyfe, 2016). The Iron Age is present in the dataset as one (1) record, albeit lacking description; given the context, it may reflect settlement or enclosure activity on the Holderness clifftop, a zone especially prone to plough truncation and active marine erosion.

The Medieval period is more robustly represented, comprising five (5) records. These include an Anglian bone comb, providing material culture evidence for early medieval presence, and a beacon site, almost certainly located on a promontory to facilitate long-distance signalling. Bridlington Harbour features prominently as a centre of maritime activity, its importance attested in both archaeological and documentary records. Additional entries include the site of Great Colden, potentially a manorial settlement, and a rectangular enclosure likely connected with agricultural management. Together, these finds illustrate a multi-functional medieval landscape, integrating settlement, trade, and subsistence. Many of these lie on or near the present coastline, and harbour features are acutely vulnerable to modern coastal development and erosion.

Roman material comprises nine (9) records. These include coins, a denarius of Hadrian, a Republican denarius, and at least two (2) coin hoards, alongside pottery assemblages and cinerary urns indicating both domestic and funerary activity. Additional features include an oval pit and mixed pottery-and-coin deposits, plausibly reflective of settlement or ritual practice. The distribution of these finds suggests a Roman presence embedded in coastal and low-lying inland zones, likely exploiting maritime access points.

First World War evidence is slight but significant, represented by a single (1) record: a jetty constructed as part of wartime logistics and supply infrastructure. Located directly on the coast, this feature is at direct risk from tidal scour and rising sea levels. The Second World War is the most densely represented period in the dataset, with sixty-eight (68) records identified. These include extensive coastal defence infrastructure: multiple lines of anti-tank cubes, a radar station, searchlight batteries, a coastal defence battery, and four (4) Diver heavy anti-aircraft batteries. Over twenty (20) pillboxes are distributed along the coast and inland margins, forming an interlocking defensive system. Additional entries include infantry trenches, minefields, weapons pits, and ancillary structures such as a section post, an army camp, and an air gunnery range shelter. These sites form part of the wider militarisation of the Holderness coast during 1940 to 1945. Cold War heritage is represented by a single (1) entry: a Royal Observer Corps underground monitoring post. This formed part of a national network established during the 1950s to 1960s.

Finally, one (1) record remains uncertain in attribution: an area of earthworks of unknown date. Such features, while challenging to classify, often represent medieval or post-medieval agricultural activity. Their location within the at-risk zone and the absence of a firm chronology render them doubly vulnerable, as they may not benefit from formal protective status.

This section operationalizes the DRR Sendai Framework Priority 1 objective of understanding disaster risk by systematically mapping archaeological exposure to coastal erosion along the Holderness coast. Drawing on the spatial logic of the Sendai Framework, coastal erosion is treated not as a uniform hazard but as a spatially and temporally variable process whose impact is shaped by both archaeological vulnerability and protective capacity. Accordingly, this analysis classifies risk across three primary axes: proximity to the hazard, regional vulnerability, and compounded exposure in unprotected high-risk zones. The aim is to triage risk spatially, informing the Sendai

Priority 4 (enhancing preparedness for effective response and recovery) through actionable exposure classification (UNDRR, 2017).

3.6. Modelling Vulnerability

On the Holderness coast, spatial vulnerability is stratified by the capacity of protective infrastructure, geomorphology, and institutional coverage. Low-lying glacial till areas such as Holmpton and Hollym exhibit heightened vulnerability due to geological instability (see Appendix B, Figure B-1 for a map of the region's surface geology) and tidal energy convergence (see Appendix B, Figure B-5 for a map of tidal energy). Governance asymmetries further compound this risk. The East Riding SMP designates only a few urban centres (for example, Withernsea, Bridlington) for active intervention, while the remainder of the coastline, where many archaeological records cluster, is marked for no active intervention (see Appendix B and Figure B-4 for a map of the SMP). This institutional gap renders archaeological capacity passive rather than proactive; archaeology may be recorded but is often not defended. As a result, governance amplifies archaeological vulnerability.

Within the DRR framework, vulnerability refers to an asset's susceptibility to irreversible loss in the event of a hazard occurring (Carr et al., 2015). In the context of Holderness, vulnerability is modelled as a function of three key variables: (1) exposure measured by proximity to active coastal erosion zones, (2) the presence or absence of coastal protection infrastructure, as delineated by the SMP, and (3) population density as a proxy for infrastructural defense collected from the U.K. Office for National Statistics (ON)[20] for East Riding of Yorkshire using SAPE (Small Area Population Estimates) [21]data.[22] This model deliberately excludes speculative factors such as documentation quality or material fragility of the archaeology in question, focusing instead on remotely quantifiable, spatially explicit indicators of physical risk and mitigation capacity.[23] This process aligns with Sendai Priority 3, emphasizing risk reduction through planning and investment in protective systems (UNDRR, 2017).

3.6.1. Scoring and Weighting

The scoring system combined three risk dimensions: proximity to coastal erosion, coastal protection status, and population density. Proximity to erosion was derived from the GIACC, with sites located more than one (1) kilometre from mapped erosion zones assigned a score of 0; sites within ten (10) metres of high-erosion raster cells received a score of 1. Coastal protection was assessed using SMP classifications: areas falling under the Hold the Line policy or benefitting from engineered defences were scored 0, whereas areas designated for No Active Intervention or lacking protective measures

[20] https://www.ons.gov.uk/
[21] https://www.nomisweb.co.uk/sources/census_2021
[22] Dataset utilized was collected from ArcGIS online portal and downloaded for incorporation into the model.
[23] The choice for this exclusion is due to the goal of reproducibility in contexts or landscapes lacking in rich archaeological documentation and in instances where structural integrity is unknown (for example, Sistan, Chapter 5).

were scored 1. Finally, population density was incorporated using ONS data, with densities below 3,000 people per square kilometre scored 0 and densities exceeding this threshold scored 1.

Each of the three variables was converted to a 30-metre resolution raster to align with the Landsat OLI 8-based GIACC resolution. The SMP and East Riding ON SAPE datasets were rasterized to assign coastal protection values to each pixel. Proximity values were calculated using Euclidean distance from the GIACC-derived erosion surface. Thus, the datasets incorporated and translated into DRR variables include proximity as exposure, SMP, and population as a combined indicator of vulnerability. Each vulnerability variable was reclassified to a 0-1 scale to enable raster-based combination for accurate modelling and ensure compatibility across spatial layers. The 50/30/20 weighting scheme (exposure/SMP/population) was chosen because exposure is the most critical variable, as it represents coastal transformation. As for the SMP, it was weighted at 30 due to its direct impact on exposure. Finally, population status was weighted at 20 due to the ephemeral nature of population and the possibility that population density may not affect the extent of shoreline protection as much as the measures offset via the SMP.

The results of the vulnerability model (Figure 3.15) identify areas most vulnerable to coastal erosion. Red pixel values indicate a greater likelihood of irreversible loss from unmanaged coastal retreat. Several high-priority clusters of vulnerability emerge just north of Great Cowden, south of Aldbrough, to the north and south of Bridlington, and at the entry to Spurn Point.



Figure 3. 15. Vulnerability results

Relative Loss Potential

To generate a composite risk surface, the vulnerability raster was multiplied by the archaeological exposure surface (Equation 3.5).



Figure 3. 16. Relative Loss Potential results

$$RLP = Exposure\ Score \times Vulnerability\ Index \quad (3.5)$$

The result (Figure 3.16) was used to produce a Relative Loss Potential (RLP) map identifying the highest-risk zones where coastal erosion, archaeological presence, and vulnerability converge (Figure 3.17 for the RLP workflow). Pixels in the 90th percentile were extracted to define the Priority-1 triage zone. In these areas, archaeological records are (i) near active erosion, (ii) lack SMP protection or sufficient population density, and (iii) as a result, face the most likely susceptibility to loss.

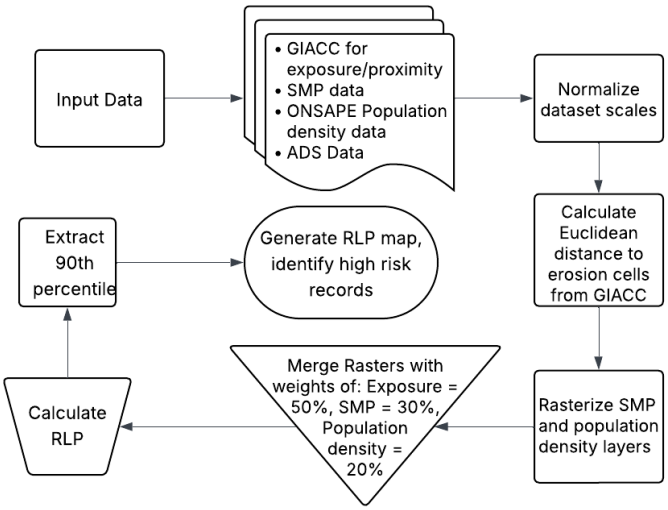


Figure 3.17. Workflow for generating Relative Loss Potential

Key, high-risk RLP hotspots include the coastline south of Horsea and north of Waxholme, with a clear concentration of vulnerability at the entry of Spurn Point. Moderate risk hotspots are littered along the coast and concentrated along segment 2 of the Holderness Coast; low RLP zones are in high population regions, including Bridlington.

3.7. Capacity

In DRR terms, capacity reflects the ability of agencies, systems, and communities to plan for, respond to, and mitigate hazards in anticipatory, coordinated, and sustained ways. In the U.K., this theoretical capacity is substantial on paper (McKie & Aitken, 2025). National heritage and planning infrastructure includes a web of statutory bodies (Historic England, the Environment Agency), local authorities, Heritage Environmental Records (HERs), and community groups, all backed by rich spatial datasets and planning guidance. Publicly available resources include shoreline erosion forecasts, SMPs, detailed LiDAR elevation data, Historic England's designation layers, and extensive archaeological inventories available through platforms such as the Heritage Gateway and ADS. These tools, interoperable and freely accessible, represent a digital infrastructure capable of

supporting risk-informed archaeological planning across coastal zones (Murphy, 2009; Scott, 2017; MHCLG, 2021). Yet, despite the availability of resources, the integration of archaeology into coastal risk planning remains the exception rather than the rule. SMPs, policy instruments for long-term shoreline management, rarely reference cultural heritage. Even in areas where archaeological records exist and coastal retreat is actively occurring, archaeological concerns are either absent or relegated. In effect, capacity is present but underutilized.

This case study contends that capacity can be measured not by institutional operations or the quantity of datasets available, but by the extent to which those resources are effectively operationalized. Here, the DRR-aligned workflow serves not just as a method for prioritizing archaeology but as a practical demonstration of capacity-building through integration. By drawing on nationally available, non-proprietary datasets and applying reproducible geospatial approaches, the model(s) transform existing information into actionable outputs that can be directly inserted into planning workflows. It does not require the creation of new institutions, but rather the alignment of the ones that already exist. This shift from policy abstraction to spatial triage constitutes a meaningful form of capacity enhancement. If adopted more broadly, it could support more anticipatory, transparent, and equitable planning responses across the UK's vulnerable archaeological landscapes.

In the spirit of highlighting capacity gaps, this study also draws attention to an often-overlooked opportunity: the revelatory potential of coastal erosion itself. While coastal erosion is correctly framed as a hazard in DRR discourse, it also accelerates loss, undermines sediment integrity, and reduces mitigation lead time, yet paradoxically exposes buried or unknown archaeological features. In the context of rapidly retreating coastlines like Holderness, the very processes that erase archaeology can also reveal it. This dual role can be operational as the coast recedes, creating windows of archaeological visibility that expose features. Many such exposures, observed between near Holmpton and Withernsea (Cadman et al., 2018), were never recorded in any official dataset and would likely have remained unknown through conventional archaeological fieldwork.

This insight reframes coastal erosion not merely as a destructive process but as a dynamic and unsolicited prospection mechanism. Leveraging this dynamic requires a shift in posture: from reactive protection to proactive documentation. In a triage context, this means focusing attention and resources on those zones most likely to yield new information before they are lost. It also implies that erosion monitoring should be embedded within archaeological workflows, not simply as a defensive measure, but as a strategic method of discovery and investigation. Taken together, these arguments position coastal erosion as both a diagnostic of institutional weakness and a potential driver of methodological innovation. When the tools already exist, but systems fail to use them, capacity is not lacking; it is latent. Whether that knowledge is captured before it's gone depends not on the erosion, but on the awareness to reduce the risk.

3.8. Archaeological Triage and Priority Mapping

Having established hazard extent and exposure, and a vulnerability model that integrates hazard and exposure factors, including proximity to erosion, coastal protection status, and population density, the analysis now moves to translating these variables into a practical decision-making framework. While vulnerability modelling identifies where archaeological sites are most susceptible to irreversible loss, it does not dictate how limited resources should be allocated across a dynamic and uneven risk landscape. To bridge this gap, the next stage operationalizes these results into an archaeological triage and priority mapping system. This approach synthesizes exposure and vulnerability surfaces into a Relative Likelihood of Preservation (RLP) index, which is then stratified into a three-tiered priority classification. In doing so, the methodology advances to actionable archaeological management, aligning with the Sendai Framework priorities by shifting the emphasis from risk characterisation to preparedness, resource allocation, and targeted intervention.

3.8.1. Priority Classification Scheme

To align with DRR planning and to operationalize this case study's triage logic, the coastline was broken into three levels of priority:

Priority 1: Immediate Action Required

Sites in this category are situated within the highest of RLP values, representing areas where hazard likelihood, archaeological density, and vulnerability intersect most. These are assets located in high-erosion zones, within unprotected stretches of shoreline, and are at a minimum of 50 metres from the coastal edge due to the imposed data filtration.[24] Actionable interventions in this context could include rapid documentation (for example, UAV survey or photogrammetry), salvage excavation, or the development of temporary mitigation strategies.

Priority 2: Monitoring and Preparedness

This category includes sites with RLP values of high exposure or vulnerability, but not both. These areas are at risk of mid-term erosion and require periodic monitoring. Mitigation can include condition assessments, community-led surveys, or pre-emptive archival research.

Priority 3: Background Risk / Low Priority

Sites in this category either lie outside active erosion zones or benefit from existing coastal defences. Although not currently under threat, they form the background landscape context and may warrant reclassification in future hazard updates or SMP reviews.

[24] See section §3.1.2 for imposed ADS filtration specifications.

Classification thresholds were operationalized through a quantile-based analysis of RLP raster values, overlaid with proximity metrics, SMP, and population density protection zones. The decision to use the top percentile for Priority 1 reflects both DRR triage logic and operational capacity limits, acknowledging that not all threatened sites can be addressed simultaneously. Ultimately, this scheme transforms a complex hazard landscape into an actionable map of archaeological priorities. It bridges the gap between abstract risk modelling and practical decision-making, establishing a



Figure 3. 18. Priority sites

defensible basis for allocating finite documentation, mitigation, and planning resources under conditions of environmental threat and institutional constraint. The results indicate that out of the sixty-five (65) records within 50 metres and high exposure due to coastal proximity, two (2) are priority level 3, nineteen (19) are priority level 2, and five (5) are priority level 1 (results are visualized in Figure 3.18).

Priority Zones

Priority 1 zones cluster along several critical stretches of the Holderness coast (Segment 2), specifically between Hornsea and Aldbrough. One of the most prominent clusters lies south of Hornsea, encompassing sites such as Little Cowden, a deserted medieval village occupied until 1517, with visible enclosures and buildings now partly lost to coastal erosion. A second site, including the Great Cowden Air Gunnery Range, a WWII bombing range with surviving structures, and nearby wartime installations such as an engine room, built for the Ringborough coastal battery's observation post. Further south, the remains of a WWII minefield, visible in 1945 aerial photographs but destroyed by 1992, are noted. The cluster extends toward Hollym, where the Royal Observer Corps Monitoring Post once stood, now destroyed by coastal erosion.

Priority 2 zones, by contrast, form transitional buffers between the high-risk Priority 1 hotspots and the more stable stretches of the Holderness coast. These zones are particularly evident along Bridlington Bay, south of Hornsea, at Withernsea, and at the northern entrance to Spurn Point. While they do not yet exhibit the extreme RLP values of Priority 1 areas, they remain within reach of projected erosion frontlines and are likely to shift categories as coastal retreat accelerates. Within these Priority 2 areas, archaeological sites are numerous and diverse. Around Bridlington Bay, notable examples include a Neolithic stone axe factory and the post-medieval fort. Further south, near Withernsea and Rimswell, a dense cluster of WWII defensive remains, including infantry trenches, weapons pits, anti-tank blocks, and a demolished pillbox, attests to the area's 20th-century military significance. Other sectors contain destroyed or buried WWII features, including minefields, weapons pits, and tank traps. At Easington, the WWI acoustic mirror, built in 1918 and representing early sound-detection technology, marks the southern limit of this Priority 2 stretch, while a WWII aircraft watch tower adds to the concentration of 20th-century heritage at risk. These zones also preserve deeper chronological depth: at Barmston, a later Bronze Age to early Iron Age lakeside settlement, and at Flamborough, extensive Neolithic and prehistoric finds, including settlements, lithic-working sites, and maceheads, all highlight the long human occupation of this dynamic coast.

Priority 3 zones dominate the more stable regions of the Holderness coastline, including Flamborough Head, portions of Bridlington, and most coastal areas not included in Priority 1 or 2. These stretches are typically designated as Hold the Line under the SMP, benefitting from established sea defences or lying beyond the currently projected erosion front. Within these areas, the archaeological record includes examples such as the WWII pillbox (Figure 3.19) at Easington,

identified from aerial photography but now destroyed by erosion, and the WWII roadblock at Easington, similarly plotted and now lost.

Collectively, these spatial patterns illustrate how risk is not evenly distributed across the landscape but is instead clustered in predictable configurations shaped by both environmental processes and planning. The triage zones generated in this case study offer a diagnosis of present risk and a platform for future planning. In this way, spatial patterns become more than analytic outputs; they can serve as operational maps for safeguarding archaeological futures in a dynamic, eroding landscape.

3.8.2. Application Pathways

This model can be adopted by a range of actors operating at different scales. Local planning authorities, such as the East Riding of Yorkshire Council, are well-positioned to use the triage outputs to inform coastal zone management, development control, and integration with SMPs. The



Figure 3.19. Eroding pillbox, Holderness (by Urbanrim, 2023).

classification system enables planners to account for archaeological risk when making land-use decisions, issuing permits, or revising coastal policies. In other regions experiencing similar issues of cultural erosion, relevant regional bodies may also make use of results from comparable models

and outputs. In addition, HER teams may use the triage zones to identify undocumented features, update at-risk records, and coordinate community engagement. Community-based heritage organizations, including local archaeological societies, coastal monitoring groups, or parish councils, can use the maps and classifications to focus volunteer-led documentation efforts, initiate local education campaigns, or advocate for site interpretation and signage before loss occurs. This is particularly critical in Priority 1 zones, where cultural visibility may disappear before it is formally recorded or interpreted. Depending on the zone's priority level, a range of interventions becomes viable. Priority 1 areas may require rapid documentation, such as UAV-based photogrammetry, 3D modelling, or laser scanning. These tools can be deployed quickly and at relatively low cost to capture archaeological features before they are lost. In some cases, interim mitigation, such as stabilization or temporary barriers may be warranted to slow loss or facilitate more controlled excavation. When physical intervention is not possible or justifiable, data rescue may be necessary. For Priority 2 zones, actions may include monitoring protocols such as UAV flyovers, walkover inspections, or time-lapse photography. Even in Priority 3 zones, the triage model has value.

3.9. Transferability and Future Use

Although the triage model developed for the Holderness coastline is tailored to a specific geomorphological and archaeological context, its underlying logic, data architecture, and alignment with DRRs make it broadly transferable. As climate change accelerates coastal and environmental risks worldwide, there is a growing need for workflows that are both scalable and sensitive to archaeological complexity. The Holderness model demonstrates how existing datasets, minimal technical infrastructure, and structured decision logic can be combined to produce actionable outputs, especially in contexts where institutional capacity exists but is underutilized. This section outlines the key conditions for reuse and the model's adaptability in data-limited environments.

Conditions for Reuse

The triage framework requires a minimal set of core data inputs, making it accessible even in modest institutional settings. At its foundation, the model requires three primary inputs:

(1) **Remote sensing imagery** suitable for diachronic (or a preferred and available timeline) land change analysis,

(2**)** **Archaeological data** with at least basic locational and temporal metadata, and

(3) **Hazard information**, ideally derived from environmental monitoring or open geospatial sources

A fourth component, governance or protection designations**,** can enhance vulnerability and capacity assessments. This can be derived from formal shoreline management policies, as in the case of

SMPs, or from informal spatial proxies such as zoning overlays, heritage designations, or protected area boundaries. The ideal institutional setting for model deployment is one where capacity is latent rather than absent**.** That is, contexts in which spatial data exist but are siloed, underutilized, or disconnected from planning processes. In these environments, common in both the U.K. and globally (Antonioli et al., 2017; Ezcurra et al., 2018), the triage framework can act as a bridging mechanism, transforming raw data into operational guidance and aligning siloed agencies (for example, heritage authorities, planning departments, environmental offices) through a shared risk vocabulary.

One of the most significant strengths of the Holderness model is its suitability for low-data or low-capacity environments. Decadal composite analysis (for example, comparing 1990 and 2020 Landsat imagery) demonstrates that, even with limited imagery, erosion surfaces can be generated. When high-frequency data are unavailable, long-term composites enable the detection of chronic trends and significant shifts. This is particularly relevant for underfunded regional heritage systems or regions with legacy colonial datasets but no updated planning integration. Where formal shoreline management plans or land-use zoning schemes do not exist, SMP-equivalent inputs can be substituted. For instance, protection status can be inferred from the presence or absence of roads, formal structures, or known development investments.

3.10. Limitations

The triage model developed here should be understood as one tool among many, valuable for its clarity and replicability, but not sufficient on its own to capture the full richness of the Holderness archaeological landscape. Its outputs are meant to inform action, not foreclose interpretation, and must always be situated within broader conversations about archaeological ethics and the shifting realities of coastal environments. While the DRR framework offers a valuable lens for structuring archaeological risk analysis, its application along the Holderness coastline exposes a range of practical and conceptual limitations that constrain its overall effectiveness. The most fundamental of these limitations concerns data quality. Archaeological risk modelling in Holderness relies heavily on legacy datasets, including ADS records, remote-sensing outputs, and shoreline management policy documents (for example, the SMP). These datasets, though indispensable, are inconsistent in precision and spatial coverage. Many archaeological records are imprecisely located or poorly described, reflecting recording practices that do not align with the analytical precision required for comprehensive, modern modelling. As a result, proximity-based exposure modelling could be unreliable without in situ verification. Similarly, Landsat-derived erosion datasets, such as those produced in the GIACC, operate effectively at regional scales but lack the spatial resolution necessary to capture micro-scale erosional processes affecting individual sites. This mismatch creates a critical disconnect between hazard modelling and site-specific vulnerability assessment.

Governance and policy structures further constrain the utility of DRR within the Holderness context. The framework presupposes institutional capacity and political willingness to act upon identified risks, an assumption that may not hold true in practice. Much of the coastline falls under the SMP's

designations of No Active Intervention, effectively leaving archaeological sites exposed to inevitable loss. Even where protective measures such as 'Hold the Line' exist, they primarily serve to defend population centres and economic assets rather than cultural heritage. Consequently, while DRR can identify areas of archaeological risk, it remains powerless to overcome entrenched governance asymmetries and the persistent prioritisation of economic and infrastructural interests over archaeological preservation.

Temporal scale also poses a challenge. DRR methodologies tend to focus on short- and medium-term intervention horizons, yet the coastal erosion processes shaping Holderness unfold across long-term, cumulative timescales of landscape loss. Under these conditions, the notion of in situ preservation becomes increasingly untenable. The framework's emphasis on preparedness and resilience, though well-intentioned, can inadvertently create unrealistic expectations of perpetual preservation. Archaeological management in such dynamic coastal zones often necessitates accepting loss, shifting the focus to documentation, excavation, and reinterpretation as proactive strategies for heritage retention. Moreover, the DRR framework's conceptualisation of erosion primarily as a hazard oversimplifies the complex dynamics of coastal change. While erosion undeniably threatens archaeological deposits, it also acts as a generative process, exposing previously unknown sites and artefacts. Along the Holderness coast, cliff collapses and shoreline retreat have revealed stratified deposits spanning from prehistoric faunal remains to Roman and medieval structural evidence. By framing erosion solely as a destructive force, DRR obscures this paradoxical relationship between loss and discovery, thereby missing opportunities to integrate processes of exposure and revelation into heritage management planning.

3.11. Conclusion

The Holderness coastline exemplifies a compound-risk environment in which geomorphological instability, chronic coastal erosion, and fragmented coastal protection converge to threaten an abundant archaeological landscape in the U.K. By applying a spatial triage framework grounded in DRR logic, this chapter has demonstrated that archaeological risk need not remain an abstract or passive concern. Instead, risk can be modelled, visualized, and acted upon through the systematic integration of hazard mapping, exposure classification, vulnerability indexing, and capacity analysis.

The archaeological record of Holderness, spanning from the Palaeolithic to the Cold War, is not only temporally rich but also spatially precarious. As erosion intensifies along this coastline, it is not merely individual sites but narratives that stand to be lost. The case study reveals that 65 archaeological records lie within 50 metres of the coastline, in areas of active coastal retreat, and lack protection. This landscape is eroding asymmetrically, with protection concentrated around urban and infrastructural nodes while vast swaths of heritage remain exposed to unmanaged degradation. The triage methodology introduced in this chapter provides an essential corrective to this imbalance. It allows spatial prioritization of archaeological risk. By classifying sites into Priority 1, 2, and 3 zones based on combined hazard intensity, proximity, protection status, and vulnerability, the model enables both immediate and long-term planning responses.

Crucially, the framework operationalizes the core objectives of the Sendai Framework for DRR. It fulfils Priority 1 (Understanding Disaster Risk) by visualizing erosion as a temporally dynamic and spatially variable hazard. It contributes to Priority 2 (Strengthening Governance) by revealing the gaps between archaeological presence and planning protections. It supports Priority 3 (Investing in Risk Reduction) by offering a defensible structure for prioritizing heritage resources in constrained fiscal contexts. And it directly enables Priority 4 (Enhancing Preparedness) by defining zones of urgency and framing archaeological loss as a preventable rather than inevitable process (UNDRR, 2017). Beyond its technical contributions, this chapter also repositions coastal erosion as more than a destructive force. Coastal erosion can also act as a catalyst for archaeological discovery, creating temporary windows of visibility into otherwise buried landscapes. This dual role of hazard and opportunity demands an engaged, responsive posture. By embracing coastal change as both a diagnostic and a data source, archaeologists and planners alike can transform the narrative from one of loss to one of strategic adaptation.

Ultimately, the Holderness case study offers a model for coastal archaeological futures: one in which risk is not simply measured but actively managed. It shows that, even with modest datasets, a DRR-aligned approach can bring clarity and foresight to heritage management amid coastal transformation. As climate change continues to reshape coastlines worldwide, the geospatially informed DRR framework developed here may become increasingly relevant.

Chapter 4: Landslides and the Pre-Contact Landscape of O‘ahu

4.1. Island, Risk, Archaeological Significance

O‘ahu, the third-largest island in the Hawaiian archipelago, presents a complex intersection of geomorphological volatility, infrastructural development, and deep-rooted cultural landscapes. Unlike the slower, attritional processes of coastal erosion that define Holderness, O‘ahu’s landslide hazards can unfold as a sudden-onset, high-consequence risk. Triggered by a mix of precipitation, drought-driven wildfires, and human modification of terrain, landslides on O‘ahu represent a direct threat not only to modern infrastructure but also to pre-contact archaeology and, subsequently, the Native Hawaiian knowledge preserved in the archaeological record. Despite its modest size, O‘ahu (Figure 4.1) is the most populated of the Hawaiian Islands and a hotspot for infrastructural development. Steep slopes carved by volcanic activity, rainfall, and fragmented vegetative cover make the island particularly susceptible to terrain instability (Gariano et al., 2016). Some historic landslide occurrences on the island were documented, with an estimated 1,779 discrete events identified in a single aerial survey spanning 1930–1989 in the Honolulu District alone (Peterson et al., 1993). Yet, this number likely underrepresents the true frequency and spatial extent of slope failures across the island, particularly in areas and years when landslides go undocumented. In this chapter, landslide susceptibility is used as a Disaster Risk Reduction (DRR) instrument to operationalize



Figure 4.2. Island of O‘ahu

hazard, exposure, vulnerability, and capacity, triaging O‘ahu’s pre-contact archaeology to produce decision products that agencies and communities can act on.

Modern landslide management on O‘ahu is centred on critical infrastructure, including roads, housing corridors, and utility lines (Earth Tech Inc., 2002). But this infrastructure often neighbours and overlays the layered remains of the pre-contact archaeological landscape. The vulnerability of these archaeological resources remains largely unquantified in landslide risk mapping, despite sustained calls to include Native Hawaiian cultural heritage in broader planning and conservation frameworks (Kawelu, 2015). This chapter directly addresses this gap, positing that if landslides can destroy modern infrastructure, they can also damage or disturb the archaeological record. By embedding landslide susceptibility modelling within a DRR framework, this chapter asks a broader question: if risk can be mapped for infrastructure, why not for the pre-contact archaeological record?

The juxtaposition of steep, geologically unstable terrain and a rich pre-contact archaeological record makes O‘ahu an ideal case study for a DRR-geospatially aligned approach to archaeology. Many pre-contact records lie in remote valleys and cliffsides (Field et al., 2011). The hazard classification used in this chapter frames landslides as analytical entry points. Unlike slow-onset risks, landslides offer little time for adaptive management. Therefore, the goal of this case study is to model exposure using landslide susceptibility and use that model as a DRR-based geospatial decision tool to flag areas of concern, identify areas where archaeological protection is absent, and deliver prioritized rankings of archaeological risk through a DRR-aligned lens. To accomplish this task, this case study proceeds with three concurrent aims to reach the overarching DRR alignment goal:

1. To determine exposure via the development of landslide susceptibility maps (LSMs) for O‘ahu, leveraging available remote sensing, terrain, and environmental data.
2. To determine archaeological vulnerability through the integration of exposure (via the LSM) with archaeological data and traditional Hawaiian land units (ahupua‘a) to identify high-risk zones of pre-contact archaeology.
3. To operationalize exposure, vulnerability, and capacity outputs into a site triage model that informs mitigation, monitoring, or documentation efforts, thereby advancing a transferable prioritization method.

While the preceding Holderness chapter grappled with the predictability of coastal erosion and the paralysis of bureaucratic response, the O‘ahu case confronts the urgency of immediate (yet potential) risk. Despite these contrasts, the analytical framework remains consistent: applying DRR principles, hazard, exposure, vulnerability, and capacity, through a geospatial lens offers a pathway to triage the danger landslides pose to O‘ahu’s pre-contact archaeological record.

4.2. Landslides and Archaeology: A Review

Between 2004 and 2016, non-seismic landslides killed nearly 56,000 people in 4,862 documented events worldwide, with roughly three-quarters of these events occurring in Asia and clear hotspots along the Andes, the Himalaya, and densely populated tropical mountain belts (Froude & Petley, 2018) Rainfall-triggered landslides alone account for more than 11,000 recorded occurrences in NASA's Global Landslide Catalog (GLC) between 2007 and 2019, underscoring how tightly mass movement is coupled to increasingly intense precipitation regimes under contemporary climate change (Kirschbaum & Kostis, 2019). Yet, landslides are habitually treated as secondary hazards in disaster databases and policy frameworks, with their impacts folded into earthquake, flood, or storm statistics rather than treated as a distinct process with its own temporal and spatial logic (Froude & Petley, 2018). Against that backdrop, the literature on landslides in archaeology has accelerated only in the last decade. Bonini et al.'s (2023) systematic review of 331 publications on landslides and cultural heritage between 2000 and 2023 shows a sharp increase in output after about 2012, but also a heavy concentration of case studies in Europe, China, and a handful of North American contexts. Latin America, the Caribbean, and most of Africa remain conspicuously under-represented relative to both hazard and population exposure.

One strand of work is explicitly geoarchaeological, using archaeological sites to reconstruct Holocene landslide chronologies and to understand how societies have navigated unstable slopes over millennia. The Moldavian Plateau in Romania has become a nice example. Niculiță et al. combine high-resolution LiDAR, landslide inventories, and the spatial distribution of fortified settlements to derive a relative chronology of past and recent landslides and to link phases of slope instability to climatic shifts during the Late Pleistocene and Holocene (Niculiță et al., 2016; 2019). . Niculiță et al.'s work shows that some hillforts are deliberately sited on, or adjacent to, large palaeo-landslide escarpments, which provided ready-made defensive topography, but that subsequent retrogressive failures partly destroyed these same sites. Such studies treat landslides as recurrent elements in landscape evolution, situating archaeological settlement and abandonment patterns within broader landscape change. They also demonstrate that archaeological datasets can significantly improve landslide chronologies in regions where absolute dating of deposits is sparse, by using cultural horizons as minimum or maximum bounds on failure events (Niculiță et al., 2019).

A second body of literature, closer to the heritage-management end of the spectrum, frames landslides primarily as a direct threat to standing monuments and UNESCO World Heritage properties. Work by Lollino and Audisio (2006) on Italian World Heritage Sites (WHS) highlights the widespread nature of slope instability in iconic cultural landscapes, from Cinque Terre to the Amalfi Coast, and argues that landslide and flood hazards are systematically under-represented in conservation planning. Nature. This concern has since been institutionalised through initiatives such as the ICL Network on Landslides and Cultural & Natural Heritage (LACUNHEN), which explicitly seeks to integrate geotechnical, geomorphological, and heritage perspectives (Margottini & Vilímek, 2014). Bonini et al.'s (2023) review confirms that some heritage-focused landslide studies now deploy landslide-susceptibility mapping around castles, historic towns, and archaeological

parks, often in Mediterranean and Alpine settings. Parallel work within the broader climate-and-heritage literature underscores that landslides are one of several geohazards expected to intensify under changing precipitation and freeze–thaw regimes, and that they are already being flagged in multi-hazard assessments for UNESCO cultural sites (Fatorić & Seekamp, 2017; Orr et al., 2021; Chen et al., 2025).

Conceptually, the field is moving beyond treating landslides purely as exogenous threats to fixed assets. Larsson's work on landslide archaeology in Scandinavia, for instance, emphasises that slope failures, abandoned farms, and buried structures together form composite cultural landscapes in which memory, risk perception, and physical transformation are entangled rather than sequential (Larsson, 2021, 2023). These perspectives dovetail with UNESCO's broader disaster-risk-reduction agenda, which stresses that heritage is not simply a passive victim of natural hazards but an active resource for resilience: historical records of slope failures, traditional siting strategies, and terminological engineering can all inform contemporary risk governance if taken seriously.

Taken together, the literature suggests three main lines of thought in current work on landslides and archaeology. First, there is a persistent geographic bias: even as global databases like the NASA GLC and the Global Fatal Landslide Database reveal major hotspots in tropical and subtropical mountain belts, most archaeologically informed studies are concentrated in temperate Europe and parts of China, with the Andes, Himalayan forelands, and East African highlands vastly under-represented relative to both hazard and population exposure. Second, landslides are still only sporadically integrated into national or local heritage-management plans, despite UNESCO strategies that explicitly call for the systematic identification, monitoring, and mitigation of geohazards at World Heritage properties (UNESCO, 2007; 2010). Third, there is an unresolved ethical and practical tension between protecting in place engineering solutions: retaining walls and slope regrading, and managed retreat or documentation-before-loss in cases where large, deep-seated failures make long-term stabilisation unrealistic or (also) ecologically damaging. Bonini et al. (2023) note that most published case studies stop at the susceptibility-mapping stage, with relatively few following interventions through to demonstrate effectiveness or unintended consequences. For archaeology, where sites can be extensive, stratified, and only partially investigated, this raises difficult questions about which portions of a landscape should be actively defended, which can be sacrificed to controlled failure, and how the resulting losses are recorded.

4.3. Pre-Contact O‘ahu

This chapter isolates pre-contact archaeology on O'ahu to address a distinct analytical interest within the broader comparative framework of this thesis. Whereas the Holderness and forthcoming Sistan chapters examine coastal erosion and desertification across available and recorded archaeological periods, the O‘ahu case deliberately narrows its focus to pre-contact sites. This restriction reflects both the geomorphological distribution of these sites, often concentrated in slope and valley-edge environments most susceptible to landslides, and their unique archaeological value as records of indigenous land use before colonial modification. Focusing on pre-contact

archaeology allows the hazard modelling to explore how environmental processes operated within a landscape structured initially by traditional Hawaiian systems of settlement and resource management. Although modern infrastructure and land alteration inevitably introduce distortions into the present-day terrain, the analytical framework enables distinguishing these recent modifications from the deeper, underlying patterns that shaped pre-contact occupation. The case study strengthens the broader comparative aim of the thesis by demonstrating that the same methodological framework here, landslide susceptibility mapping and the incorporation of the DRR-geospatially aligned exposure, vulnerability, capacity model, can reveal different insights when applied to regions with distinct histories and varying degrees of modern disturbance. In doing so, the case study illustrates both the adaptability and the interpretive range of the approach.

To contextualise the pre-contact archaeological record of O'ahu, it is beneficial to engage with the pre-contact Hawaiian worldview, which framed human existence as part of a finely balanced network of reciprocal relationships between people, land (*'āina*), and the divine (Beckwith, 2021). This cosmology, articulated by McCubbin et al. (2009), placed the individual within a series of interdependent forces that extended from the *'ohana* (family), to the broader community, to the natural environment, and ultimately the gods, with *mana* (energy or power) acting as the unifying force (Antonio et al., 2023). The pre-contact Hawaiian conception of personhood was inherently dispersed, embedded within the landscape and social networks, and maintained through mutual obligations of care and reciprocity (Kana'iaupuni, 2005). This philosophy underpinned the resilience of Hawaiian communities as they navigated complex environmental dynamics (Lane, 1960).

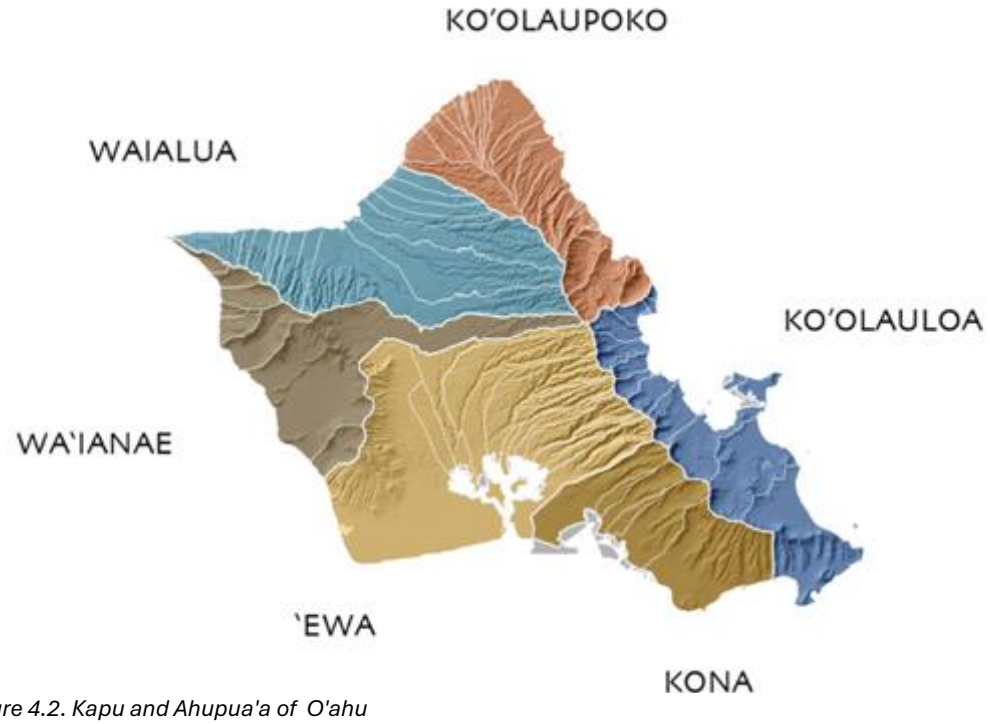


Figure 4.2. Kapu and Ahupua'a of O'ahu

Central to this worldview was the division and management of land. The Hawaiian Islands (*mokupuni*) were subdivided into large districts called moku, which extended from the mountains to the coast, ensuring access to a diversity of ecological zones and resources. Governance of these districts was the responsibility of the *ali'i* (chiefs), who oversaw the stewardship and equitable distribution of resources (Buck, 1993). Each moku was further segmented into *ahupua'a*, narrow land divisions strategically designed to maximise ecological self-sufficiency. The boundaries of *ahupua'a* often followed watershed lines, enabling resource continuity from mountain forests to nearshore marine environments (Lane, 1960). O'ahu's *moku* contained approximately 81 ahupua'a (Figure 4.2), with the size of each determined by the resource potential of the land within it (Lane, 1960; Field et al., 2011). These divisions functioned as largely self-contained socio-ecological units, with minimal evidence of systematic inter-*ahupua'a* resource exchange, underscoring the emphasis on localised autonomy and responsibility for environmental care (Buck, 1993). This system of resource governance was embedded within the kapu system, a complex socio-religious code that regulated relationships among people, between humans and the gods, and between humans and the land (Buck, 1993). The *kapu* system encoded environmental stewardship into practice, dictating when and how resources could be harvested, which areas could be accessed, and the ceremonial obligations associated with these actions (Levin, 1968). It recognised seasonal climatic variability, institutionalising adaptive cycles through two principal seasonal phases: *kua* (dry season), a period for planting, construction, and warfare, and *ho'olilo* (wet season), during which harvest occurred, and hostilities were suspended (Buck, 1993). These temporal rhythms were further interwoven with concepts of duality and balance, in which masculine and feminine principles, as described by Levin (1968), structured both cosmological interpretation and practical subsistence activities.

Mālama ʻāina (caring for the land) was central to the *kapu* system, ensuring intergenerational sustainability (Keliʻiholokai et al., 2020). Pre-contact Hawaiians understood the *ʻāina* not simply as a material resource, but as a living entity intertwined with human well-being. As Keliʻiholokai et al. (2020, p.8) note, Native Hawaiians historically and contemporarily articulate the *ʻāina* as sustenance that nourishes physically, spiritually, mentally, and emotionally. The reciprocal nature of this relationship was not symbolic alone; it manifested materially in land-use patterns, agricultural systems, aquaculture (for example, fishponds), and the spatial organisation of habitation, religious, and burial sites. Oʻahu's archaeological record reflects this embeddedness of cultural practice within environmental stewardship. The spatial distribution of temples (*heiau*), petroglyph fields, habitation complexes, and burial caves illustrates the integration of social organisation, subsistence strategies, and cosmological principles. The enduring legacy of these practices offers insight into adaptive resilience in the face of environmental variability, though it also acknowledges the constraints and challenges inherent in island ecosystems. Kirch (2014) notes that pre-contact Hawaiians, while adept stewards of their environment, were not immune to the pressures of resource scarcity, population growth, and mismanagement. In the present day, the persistence of the cultural ethos of *mālama ʻāina* among Native Hawaiians provides a link to the pre-contact period, even as the landscape faces new threats driven by contemporary climatic and anthropogenic pressures.

4.3.1 Archaeological Context

The Hawaiʻi State Historic Preservation Division (SHPD) (2022) provided the primary geospatial dataset for this study, comprising all recorded archaeological point data for Oʻahu. From this geodatabase, pre-contact sites were extracted. Spatial boundaries for moku and ahupuaʻa were sourced from the Hawaiʻi Statewide GIS Program geoportal (Statewide GIS Program, 2022). The State Historic Preservation Division (SHPD) database contains 4,130 archaeological records for Oʻahu, reflecting a geographically extensive cultural landscape. Given this breadth of distribution, much of Oʻahu's pre-contact archaeology lies within areas susceptible to landslides. The aim was not to reinterpret the cultural significance of these sites, many of which have been variously understood through competing historical accounts (Gosden, 1996), but rather to systematically assess their exposure to landslide risk. Records were consolidated into six principal categories: *heiau*, *kiʻi pōhaku*, habitation, *loko kuapā*, burials, and *ahupuaʻa* to provide thematic clarity, while retaining analytical efficiency. This filtering yielded a more manageable dataset of 104 representative records. While these categories do not encapsulate the full cultural complexity of pre-contact Hawai'i, they enable a targeted assessment of vulnerability across key pre-contact Hawaiian archaeological categories.

4.3.2 The Archaeological Data

Heiau (Hawaiian temples) are among the most prominent and well-documented features in the SHPD inventory sub-selection. The term *heiau*, likely derived from *hai*, 'to sacrifice' (Kirch, 2014, p. 171), encompasses structures ranging from simple rock alignments to elaborate architectural

complexes. Heiau were dedicated to specific *akua* (deities), with ritual offerings varying accordingly: *Lono*, associated with rainfall and agricultural fertility, received sacrifices to ensure bountiful harvests; *Kū*, the god of war, was honoured to secure military success; and *Kāne* and *Kanaloa* were venerated in coastal contexts, often in association with water sources or coral-built shrines (Stokes, 1981). Ritual activity was regulated seasonally, with sacrifices to *Lono* performed during harvest and warfare prohibited during this period, while offerings to *Kū* preceded campaigns in the dry season. The construction and use of heiau followed precise ceremonial protocols: three major ceremonies annually, supplemented by thrice-monthly rituals (Stokes, 1981). Archaeological interpretations suggest that orientation and viewshed were culturally significant, with most heiau aligned east, northeast, or north, potentially reflecting cosmological associations with specific *akua* (Kirch, 2014).

Thirty-two (32) *heiau* from the inventory are widely distributed across the island (see Appendix C for a list of records), with many located in mountainous regions. One *heiau*, *Kaunihokahi*, is situated in the northeasternmost portion of the Island. Sterling and Summers described this heiau as dedicated to a shark *akua*, 'Ka-U-niho-kahi ... had his lua at La'ie. He was a kind, harmless Akua, but, if necessary, hurt for the protection of his people, he would hurt them. Sometimes, they would feel a nip like a papa'i (crab). They would find a cut of just one tooth. Sometimes, he took the form of a small fish to warn his people not to go further' (1978, p. 159). In 1933, McAllister described this heiau as already in a state of degradation.

Kiʻi pōhaku (petroglyphs) consist of carvings incised into rock surfaces, potentially imbued with spiritual significance and potentially linked to the veneration of specific *akua*. Their functions remain debated, ranging from place-marking to narrative encoding. Still, within a pre-contact worldview, they may have operated as tangible anchors of oral traditions, reinforcing relationships between people and place (Lee, 2002; Becket & Singer, 1999).

There are ten (10) *kiʻi pōhaku* from the inventory and are widely distributed across the island along the coast and in mountainous areas of the island (see Appendix C for a list of records). One *kiʻi pōhaku* is located at *Kahapaʻaka*i on the mid-southernmost portion of the Island. The marking of this particular kiʻi pohaku is standard across the Hawaiian Islands, representing an individual. Cox and Stasack determined that these are an early Hawaiian rendition, 'the earliest Hawaiian petroglyphs were the simple linear figure and dot and circle motif' (1970, p. 61). Cox and Stasack include an age sequence of Hawaiian *kiʻi pōhaku* evolution from which the current kiʻi pōhaku in discussion is most closely related to the earliest marking of the sequence.

Pre-contact settlement patterns in Hawaiʻi were shaped by the imperative to maximise arable land. Large, nucleated villages were rare; instead, habitation sites were dispersed to align with resource zones (Apple, 1971). Early dwellings included coastal caves and temporary inland shelters, later replaced by permanent structures as the population increased (Kirch, 1985; Lane, 1960). Houses of commoners often resembled thatched haystacks, while aliʻi residences were constructed with strict spatial and ceremonial protocols to safeguard mana (Bingham, 1847). The inventory featured in this case study includes thirty-eight (38) habitation records. The habitation records in the current

inventory are widely distributed across the island (see Appendix C for a list). A high concentration of habitation records is in the Mākua Valley. The landscape context and the valley's overall significance make the concentration of habitation records sensible. The Mākua Valley, as evidenced by the archaeological record and the environment of the region, is hypothesised to have '... possessed the largest population, a result of favourable terrain, water, and soils that provided agricultural potential' (Environmental Impact Study Cooperation, 1979, pp. 2-25). The Valley is translated from Hawaiian as 'Parent' and is known as the place from which humans were brought to Earth. Paradoxically, according to Hawaiian legend, the Valley is also where the dead depart (Environmental Impact Study Cooperation, 1979).

Loko kuapā (fishponds) were a keystone of pre-contact Hawaiian aquaculture, with Oʻahu alone supporting an estimated 175 examples prior to 1900 (Costa-Pierce, 1987). These engineered enclosures exploited tidal flows to trap juvenile fish, which matured within the pond for harvest. Fishpond governance reflected social hierarchy: paramount chiefs (*aliʻi ʻai moku*) controlled island-wide resources, while local chiefs (*aliʻi ʻai ahupuaʻa*) oversaw individual installations. The construction and maintenance of *loko kuapā* required coordinated labour between the *kahuna* (priest-architect), *konohiki* (resource manager), and *kiaʻi-loko* (caretaker) (Kikuchi, 1976). The inventory featured in this case study includes ten (10) *loko kuapā*.

Ten (10) fishponds from the inventory are widely distributed across the Island (see Appendix C for a list of records). One of these records is located on the Windward side of the island. It is called *Kahouna* and is one of only four remaining examples of pre-contact Hawaiian *loko kuapā*. Unlike many resources across the Island, *Kahouna* remained in use until 1960 and was added to the National Register of Historic Places (NRHP) in 1973. The NRHP report notes that in 1973, the importance and relatively good condition of *Kahouna* was noted, stating, 'Fishponds almost always occur in favourable locations, easily developed into waterfront property, and most are private. Therefore, Hawai'i must preserve a sample of these unique structures, Kahouna included' (1972, p. 3).

Burials are among the most valuable records across the globe and throughout time, providing a glimpse into the beliefs and practices of people from the past (Alekshin et al., 1983). Pre-Contact Hawaiians held ancestors in high esteem, and when these community members passed away, their spirits were believed to linger near their corpses and bones (MacKenzie & Ayau, 1991). Burial forms were diverse, ranging from dunes and mounds to hidden sites, often in secret locations. The nā iwi (bones) were usually buried or placed near where the deceased spent the most time in human form. Thus, the nā iwi, when dedicated to or placed in the earth, were believed to become one with the earth, sanctifying the area (MacKenzie & Ayau, 1991). In early times, Hawaiian burials were regularly located in publicly known places; however, as conflicts between ali'i and subsequent tribal rivalries rose, it became customary to limit the visibility of burials to mitigate the desecration of nā iwi. Pre-Contact Hawaiians believed any desecration to nā iwi entailed a broken spiritual link between ancestors and descendants, spiritually traumatising living descendants (MacKenzie & Ayau 1991). The quality of burial depended on the importance of the individual. Some individuals did not receive

a burial at all. Instead, a loved one removed the flesh of the deceased, keeping the bones as a sign of devotion to the departed (Handy & Pukui, 1953, pp. 151-152).

Keiley notes the importance of Native Hawaiian burial protection:

> ‘Desecration or destruction of the iwi would insult or force the 'uhane [the soul] to leave the bones. Desecration historically took many forms, such as (1) leaving bones uncovered or exposed to sunlight, (2) fashioning bones into fishhooks or other tools, and even (3) using the "skull as a spittoon or as a container for discarded food. Destruction of the iwi through the burning of the bones was considered the ultimate desecration, for this act would prevent the 'uhane from reaching its final resting place." Traditionally, the bones of the first fallen enemy in battle would be burned as a sacrifice, symbolising the enemy's defeat. According to Native Hawaiian beliefs, the desecration of näiwi was an act considered to be worse than murder. In contrast, murder may end a person's life on earth; desecration of nã iwi interferes with a person's afterlife, which lasts much longer than life on earth. Native Hawaiians have a kuleana, or responsibility, to care for and protect nã iwi kupuna [elder]." "In turn, our ancestors respond by protecting us on the spiritual side. Hence, one side cannot completely exist without the other.” To protect nãiwi küpuna, Hawaiians would conceal graves so that enemies could not desecrate the remains of their loved ones." Burial practices included hiding nã iwi in caves, lava tubes, and dunes where evidence of earth-moving activities could easily be erased’ (2010, p. 325).

Because of the multitude of pre-contact Hawaiian burial practices, burial sites are not always explicit and can be challenging to identify. However, the significance for Native Hawaiians that the näiwi remain sanctified and are not desecrated further amplifies the importance of understanding the susceptibility of such records to disasters such as landslides. Thirteen (13) burials from the current inventory are widely distributed across the Island (see Appendix C for a list of records). As a result of the widespread inhabitation of the Island and the cultural tradition of burying the dead in areas they called home, it would be sensible to conjecture that places of rest are likely littered densely across the inhabited portions of the Island. Indeed, three (3) burial records are located within the Mākua Valley. As mentioned in the habitation section, the Mākua Valley is believed to have hosted the largest number of pre-contact Hawaiians.

Ahupua‘a were the foundational units of pre-contact Hawaiian resource management (Blain & Chung, 2020). Regulated by *kanawai* (laws) and guided by principles of environmental reciprocity, they integrated terrestrial, freshwater, and marine stewardship (Blain & Chung, 2000). These divisions also embody *wahi pana*, storied landscapes in which physical features are interwoven with historical events and oral tradition (Winter et al., 2018). As stated previously, the inventory featured in this case study includes eighty-one (81) *ahupua‘a*.

4.4. Landslide Susceptibility Mapping: a Review

Because landslides can be triggered by a wide range of geological, hydrological, and anthropogenic factors, their prediction remains notoriously difficult (Cui et al., 2021). Geospatial modelling has emerged as one of the few scalable approaches capable of handling this complexity, with landslide susceptibility mapping providing a framework for integrating the multiple spatial variables that condition failure potential across a given landscape. These models typically rely on GIS-based analyses, which allow users to organise, weight, and visualise the environmental parameters that either exacerbate or mitigate slope instability (Alcántara & Goudie, 2010). Slope remains the primary predictor in nearly every landslide susceptibility study, but accuracy increases when combined with other variables, including precipitation, land cover, lithology, drainage networks, aspect, elevation, and topographic indices (Kavzoglu et al., 2013; Arca et al., 2019). Selecting between these variables is rarely a purely methodological choice; data access, computational resources, and technical expertise constrain it. Because the present research aims to provide an accessible and replicable framework for evaluating archaeological susceptibility to landslides, prioritising open-source and open-access geospatial inputs is not only methodologically justified but necessary for DRR synthesis. This accessibility concern becomes even sharper when considering downstream hazards: wildfires and flooding, for instance, reshape vegetation and hydrology, creating delayed but severe landslide potential (Rengers et al., 2020).

Archaeological applications of landslide susceptibility remain sparse but instructive. Kadapa's (2024) study in Gujarat represents one of the more comprehensive attempts to evaluate landslide risk to archaeological resources through remote sensing and GIS. Using a suite of remotely sensed data products, including Cartosat DEMs and Landsat 8 and Sentinel imagery, the study calculates elevation, slope, aspect, curvature, drainage density, NDVI, land use and land cover, alongside rainfall, lithology, soils, geomorphology, and distance parameters (Kadapa, 2024). These variables are then synthesised via a weighted overlay to designate the relative susceptibility of archaeological features to landsliding. While ambitious, the study suffers from an over-accumulation of variables and an opaque weighting scheme; the more is more approach risks burying the causal signal beneath layers of redundant data. Yugsi et al.'s work in El Tambo, Ecuador faces similar issues: although the authors combine multi-temporal optical imagery with DEM-derived 3D modelling to map local landslide processes, their analysis ultimately excludes archaeological resources from the susceptibility assessment. In both cases, methodological sophistication is undercut by a lack of integration between hazard modelling and the archaeological landscapes these studies claim to address.

More broadly, the landslide–archaeology literature reflects a methodological trajectory parallel to that seen in coastal-erosion studies, but with its own specialised toolkit. High-resolution LiDAR and photogrammetric DEMs are now widely deployed to map active and relict landslides around heritage sites, capturing subtle scarps, displaced earthworks, and terrace deformations with a precision previously unattainable. InSAR and ground-based differential radar interferometry extend this capability further, detecting sub-centimetric deformation in masonry, bedrock, and earthen

features, effectively transforming monuments into long-term geotechnical sensors (Zhou et al., 2015, cited in Bonini et al., 2023). Landslide susceptibility maps in these contexts can integrate slope, lithology, land use, and hydrological indices within GIS environments, sometimes nested within multi-hazard frameworks that incorporate flood, earthquake, or coastal-process data (Lollino & Audisio, 2006; Cigna et al., 2018). A more interpretive line of work leverages the spatial intersection of archaeological features and landslide morphologies to infer relative ages, for example, hillforts truncated by younger scarps or tumuli warped by slide bodies, allowing researchers to distinguish Late Pleistocene failures from Holocene reactivations (Niculiță et al., 2016; 2019). UNESCO's DRR guidance continues to call out this gap, noting that the exclusion of local knowledge represents a missed opportunity for both modelling accuracy and cultural legitimacy (UNESCO World Heritage Centre. 2007–2010).

4.5. O‘ahu's Landslide Processes and Drivers

O‘ahu's geomorphological makeup includes rugged volcanic ridgelines rising sharply from sea level, deep-cut valleys carved by orographic rainfall, and densely populated lowlands expanding outward from narrow coastal zones. With 365 kilometers of shoreline and spanning approximately 71 kilometers north to south and 48 kilometers east to west, the island is complex and varied in terrain (Robinson et al., 2006). The twin mountain ranges (Figure 4.3), Wai‘anae to the west and Ko‘olau to the east, are remnants of shield volcanoes whose steep slopes and lithologies generate ideal conditions for slope instability (Di Traglia et al., 2017; Henriques et al., 2015). These conditions are magnified by rainfall, with precipitation over the Ko‘olau range reaching magnitudes significantly higher than those of the surrounding lowlands (Robinson et al., 2017). Yet landslides in O‘ahu are not merely the product of slope and lithology; they are also intensified by compounding climate stressors, namely drought and wildfire. Rising sea surface temperatures have disrupted rainfall patterns on the island (Longman, 2021), ushering in prolonged dry periods punctuated by extreme precipitation events (Eischeid et al., 2022). This hydrological volatility promotes wildfire ignition, especially in the increasingly desiccated vegetation of O‘ahu's interior (Zhu, 2019), which in turn strips root systems that might otherwise work to stabilise soils (Di Napo et al., 2021. Rengers et al. (2020) demonstrate that landslide risk peaks approximately three years after wildfire events, reflecting the delayed response of terrain destabilization. These conditions form a feedback loop: drought invites fire, fire destabilizes slopes, and the ensuing rainy season, typically between November and March (Eischeid et al., 2022)., promotes ideal landslide conditions. Drought is a common issue in Hawai‘i, and from 2010 to 2019, the Islands endured their most extreme drought yet (Eischeid et al., 2022). The exact number of landslides that have occurred in Hawai'i is difficult to quantify, as only a handful of studies have reported observations and counts. For the Island of O‘ahu, in the Honolulu district, an aerial photography survey indicates approximately 1,779 landslides occurred between 1930–1989 (Peterson et al., 1993). In February 2019, heavy rains induced a severe

landslide, blocking the Pali Highway for seven months and impacting one of the few critical throughways for the Island (Zhang et al., 2020).

Climatic volatility increases landslide potential across O‘ahu. Droughts, now more extreme and prolonged (Eischeid et al., 2022), have increased wildfire frequency (Treurnicht et al., 2015), which in turn destabilizes vegetative structures. On steep volcanic slopes, this can set the stage for landslides. Further, increased rainfall and sea-level rise, already impacting coastal and inland areas, combine with these drivers to transform a terrain already susceptible to episodic failure into one poised for such failure (Lainas et al., 2021). Pre-Contact societies were not immune to disaster either; Cordy (1972) notes the regular disruption of traditional agricultural cycles by drought and storm activity. Yet, what is at stake today is not only physical survival, but the endurance of memory encoded into the ‘āina (land).

Reports from Ellen et al. (1995) and Leroux et al. (2018) document both slow- and fast-onset slope failures across O‘ahu (see Appendix, D, Figure D-2 for a map of Ellen et al’s, 1995 landslide distribution), though spatial coverage remains patchy and underreported. Ellen et al. note that ‘most descriptions of past landslides are incomplete’ (1995, p. 2). reflecting both the difficulty of post-

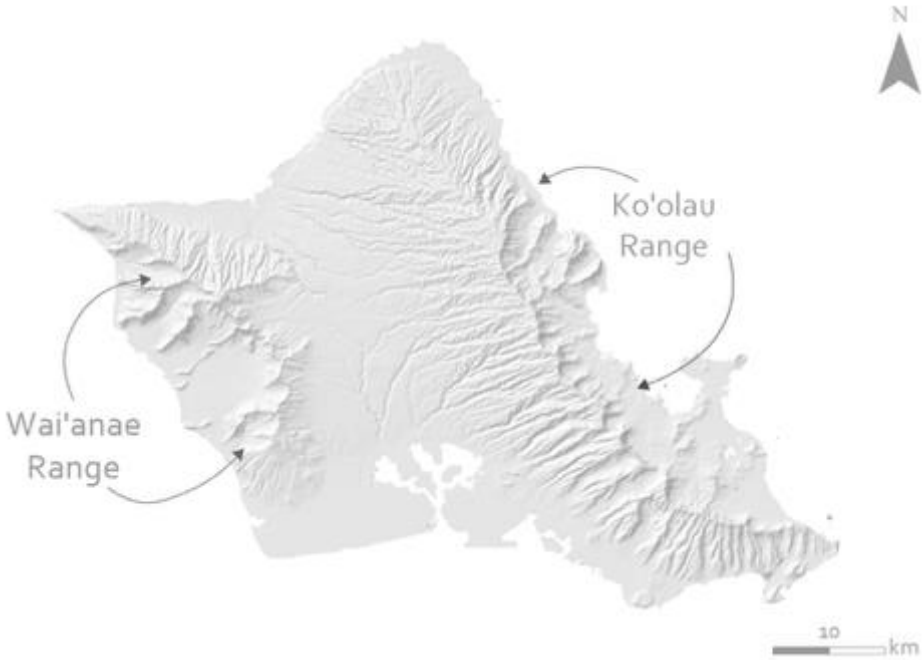


Figure 4.3. Wai'anae and Ko'olau mountain ranges

event classification and the lack of consistent monitoring. High-profile incidents, such as the 2019 Pali Highway closure caused by a severe landslide (The Seattle Times, 2019), only entered the formal record primarily through journalistic channels (Lovell, 2017). The absence of a centralized database of landslides hampers both historical understanding and predictive modelling, an issue this chapter aims to address through spatial interpolation and geospatial risk modelling. From a risk perspective, the co-occurrence of steep terrain, high rainfall, fragile vegetation cover, and intensive land use positions O‘ahu as a classic example of a sudden-onset, high-impact hazard landscape. The island’s

topography is both a generator of hazard and an archive of archaeology, and this duality demands that any susceptibility assessment treat archaeological loss as an integrated concern.

4.6. Mapping Pre-Contact Exposure and Vulnerability

The analysis for this case study modelled exposure, vulnerability, and capacity to assess how landslides threaten O‘ahu’s pre-contact archaeological landscape, using a combination of climatic, topographic, and anthropogenic datasets. Two complementary susceptibility models were developed to capture macro- and micro-scale terrain dynamics and integrated with archaeological data to quantify site-level exposure to slope instability. Vulnerability was then modelled by incorporating environmental and human disturbance factors, while capacity was inferred through the relative protection afforded by current land use and accessibility constraints. Together, these components provide a DRR-oriented framework that not only identifies where hazards are most likely to occur but also evaluates the resilience and preservation potential of O‘ahu’s pre-contact cultural heritage.

4.6.1 Exposure

A two-path modelling strategy was implemented to determine landslide susceptibility (also called exposure) for this case study. In the absence of a systematic landslide inventory for O‘ahu, open-access climatic, topographic, and remote-sensing datasets were used to develop replicable workflows. Two complementary models were developed and generated: (1) a General Landslide Susceptibility Map (GLSM), integrating slope, rainfall, and vegetation indices to capture island-wide instability patterns; and (2) a Landform Landslide Susceptibility Map (LLSM), derived from geomorphometric classifications to isolate topographic-specific variables. This dual framework was designed not only to characterise hazard potential but to situate pre-contact archaeological exposure within a multiscalar risk environment. The GLSM identifies macro-level zones of heightened susceptibility, while the LLSM exposes micro-topographic conditions in which archaeological sites are often embedded. By aligning with the Sendai Framework’s Priority 1: Understanding Risk, the modelling moves beyond susceptibility mapping to highlight the intersection of natural processes and pre-contact archaeology (UNDRR, 2017).

Data Acquisition and Processing

Imagery and ancillary data (Table 4.1) were utilized as variables to inform the LSMs. Precipitation data were collected from NOAA. The DEM from which slope data were calculated was acquired from the NASA Shuttle Radar Topography Mission (SRTM). Landsat imagery was chosen due to its temporal and spatial resolution and global availability. The imagery was accessed and downloaded from the USGS’s EarthExplorer API collection using the Landsat 8 Operational Land Imager (OLI) sensor. The Tier 1, Level 3 download specifications targeted Bands 5 (Near infrared (NIR)) and 4 (Red) for index calculations relevant to the study area.

Table 4.3. Susceptibility data and data sources for landslide susceptibility maps

Landslide Susceptibility Data	Source
Precipitation [25]	National Oceanic and Atmospheric Administration (NOAA)
Slope	NASA Shuttle Radar Topography Mission (SRTM)
Landsat 8 Operational Land Imager (OLI)	EarthExplorer

General Landslide Susceptibility Map

For the GLSM, each susceptibility variable was standardized on a 5-point scale (1 = low, 5 = high). Slope was derived from the DEM and divided into five equal-degree intervals to represent variations in gradient. The Normalized Difference Vegetation Index (NDVI) was selected as a key variable in the landslide susceptibility analysis to represent vegetation cover and its stabilizing influence on slope integrity (Niraj et al., 2023). NDVI provides a quantitative measure of vegetation density and health, derived from the contrast between the Near-Infrared (NIR) and Red spectral bands of Landsat 8 imagery. Healthy, dense vegetation exhibits high NIR reflectance and low Red reflectance, resulting in higher NDVI values that correspond to areas of increased root cohesion and surface stability. Conversely, low NDVI values indicate sparse or stressed vegetation, often associated with exposed soils or anthropogenic disturbance, which are more prone to erosion and slope failure (Uyar, 2025). The use of NDVI in this study provides an efficient, repeatable means of incorporating vegetation dynamics into the LSM, offering a spatially continuous assessment of one of the most critical natural controls on slope stability. NDVI values were reclassified into five equal intervals, with dense vegetation assigned lower susceptibility weights and sparsely vegetated or barren areas assigned higher weights. Precipitation rasters were similarly reclassified into five equal intervals to represent rainfall intensity across O‘ahu. The overall workflow (Figure 4.4) includes the NDVI calculation using the standard formula (Equation 4.1):

$$(4.1) \qquad NDVI = \frac{NIR-RED}{NIR+RED}=$$

Each variable (NDVI, slope, and precipitation) was remapped using minimum and maximum parameters to produce standardized 1–5 indices, where 5 indicates the highest susceptibility.

[25] https://www.ncei.noaa.gov/cdo-web/datasets

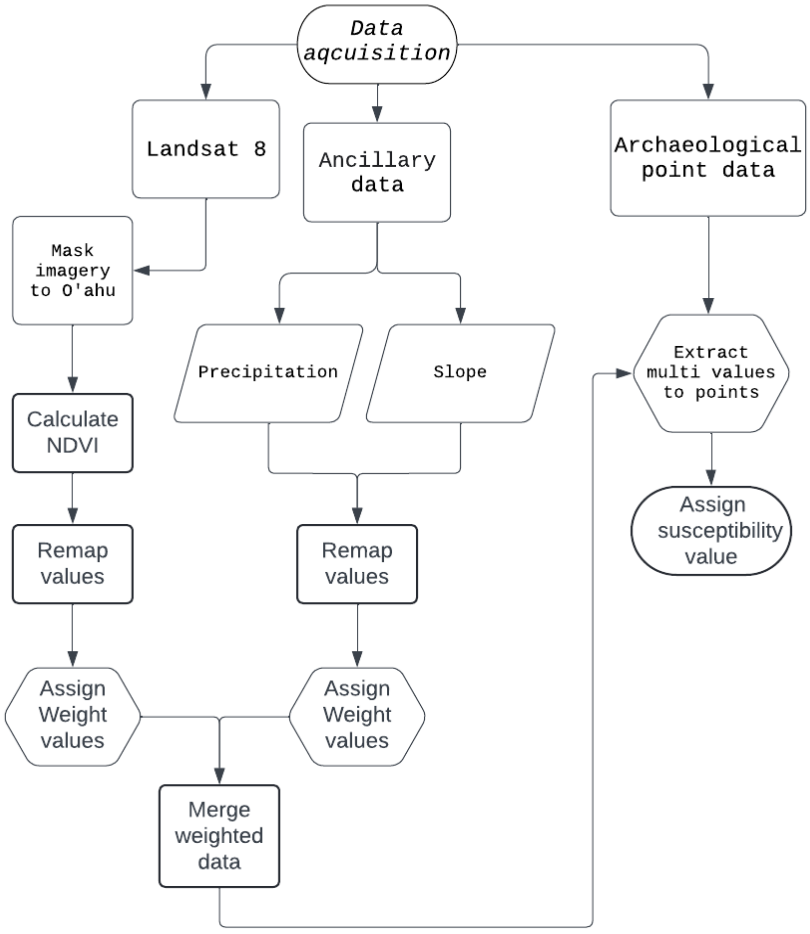


Figure 4.4. Data acquisition and general landslide susceptibility map generation workflow

Variable weights, consistent with the literature that emphasizes slope as the dominant control (Lovell 2017), were set at 40 percent for slope, 30 percent for vegetation, and 30 percent for precipitation. Rainfall and vegetation were weighted equally due to their interactive influence; areas with lower vegetation cover tend to exhibit greater instability during intense precipitation events. The resulting composite raster produced a 0–300 susceptibility score that represents the cumulative influence of all three factors. The final susceptibility scores were classified and visualised in four categories: low, medium, high, and very high.

Landform Landslide Susceptibility Map

The Landform Landslide Susceptibility Map (LLSM) was generated using the geomorphon classification method developed by Jasiewicz and Stepinski (2013). The Shuttle Radar Topography Mission (SRTM) DEM was transformed into discrete landform units following a ten-class typology: *flat, summit, ridge, shoulder, spur, slope, hollow, footslope, valley,* and *depression*. Within this framework, slope, representing the steepness or gradient of a continuous surface, served as a key

geomorphic parameter, reflecting underlying hydrological, lithological, and geomorphological processes (Luo & Liu, 2018).The workflow for generating the LLSM followed the geomorphon-based classification framework, which delineates landform surfaces from 498 unique geomorphon patterns derived from the DEM (Appendix D-3). Using ArcGIS Pro's geomorphon tool, landform features were extracted from the DEM to produce a detailed topographic classification for Oʻahu. Emphasis was placed on ridges and steep slopes, which were intersected with high-precipitation zones and archaeological locations identified as 'very high risk' in the GLSM. Integrating these datasets provided refined spatial discrimination of potential landslide-prone areas, particularly in regions where DEM or vegetation indices alone might underrepresent terrain complexity. The final LLSM output was merged with rainfall and vegetation data, previously standardized in the GLSM to enhance the accuracy of susceptibility mapping.

Results

The GLSM (Figure 4.5) illustrates a distinct gradient of landslide susceptibility across the island, with red denoting the zones of highest risk and green, the lowest. The spatial pattern reveals that the most vulnerable areas are primarily along the Koʻolau range on the Windward side of the island, where steep slope gradients, consistently high rainfall, and relatively sparse vegetation create conditions conducive to slope instability (Tao et al., 2022). These high-risk areas are not confined to the Koʻolau range; secondary corridors of elevated susceptibility extend through northern sections of the Waiʻanae range, reflecting localized combinations of steep terrain and geomorphological factors. Moderate-risk zones appear along the transitional margins between the mountains and the lowlands, particularly in coastal fringe areas situated at the base of the mountain foothills.

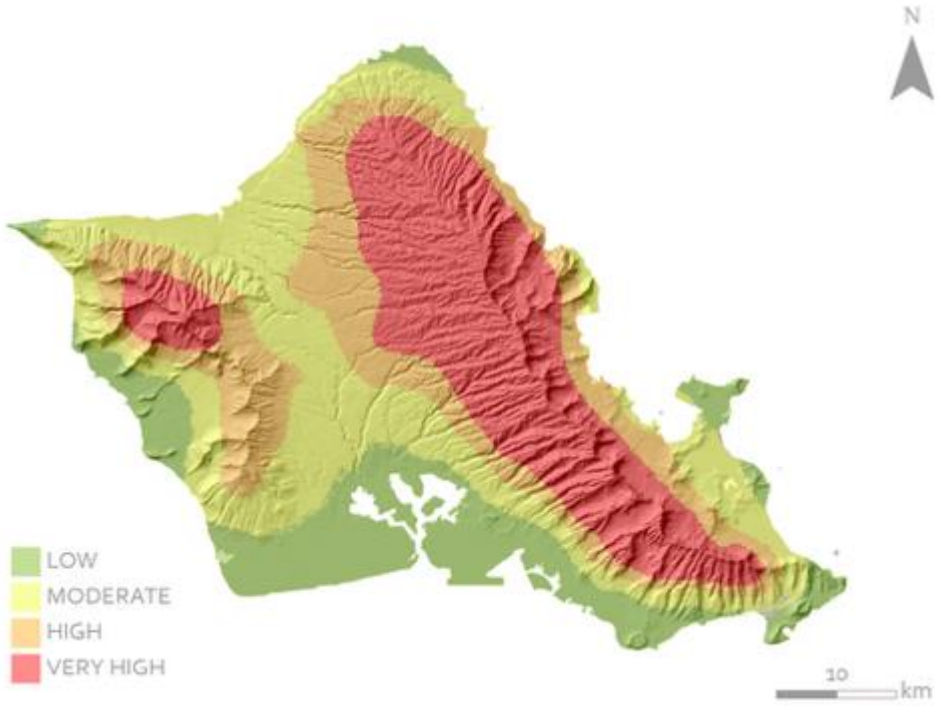


Figure 4.5. General landslide susceptibility map

Here, the topography exhibits a sharp increase in slope, and sediment is deposited into alluvial fans or channels of dry gulches, creating geomorphic conditions that can channel water and debris during intense rainfall events (East & Sankey, 2020). Such areas are susceptible to episodic slope failure, even if they do not experience the same continuous hazard exposure as high-risk zones (Li, et al., 2025). In contrast, low-risk zones are typically located in the coastal plains usually made up of the more heavily urbanised areas, such as Honolulu and Waikiki, where slope angles are minimal and rainfall intensity is comparatively low to that of the mountain ranges. Although the Waiʻanae range contains more abrupt slope profiles than many parts of the Koʻolau range, its leeward orientation results in significantly reduced rainfall. This climatic difference mitigates the overall susceptibility of the Waiʻanae range compared to the wetter, more landslide-prone Koʻolau side, underscoring the critical interplay between topography, precipitation, and vegetation in determining landslide risk.

The LLSM (Figure 4.6) provides an additional layer of understanding to the island's landslide hazard profile by focusing on terrain-driven susceptibility. Valleys, ridges, and escarpments exhibit high risk. Following Tanyaş et al. (2019), this suggests a cascading risk: where one slope failure may destabilise adjacent terrain, accelerating cumulative loss across archaeological landscapes. The pattern of risk in the LLSM is consistent with a cascade risk of hazard propagation (Alexander & Pescaroli, 2020). In this model, the failure of one slope can undermine the stability of adjacent slopes, triggering sequential failures. Such cascading processes can amplify the magnitude of landslide events and extend their impacts beyond the original point of initiation. Over time, these

recurrent and compounding events can result in accelerated slope erosion and sediment displacement.

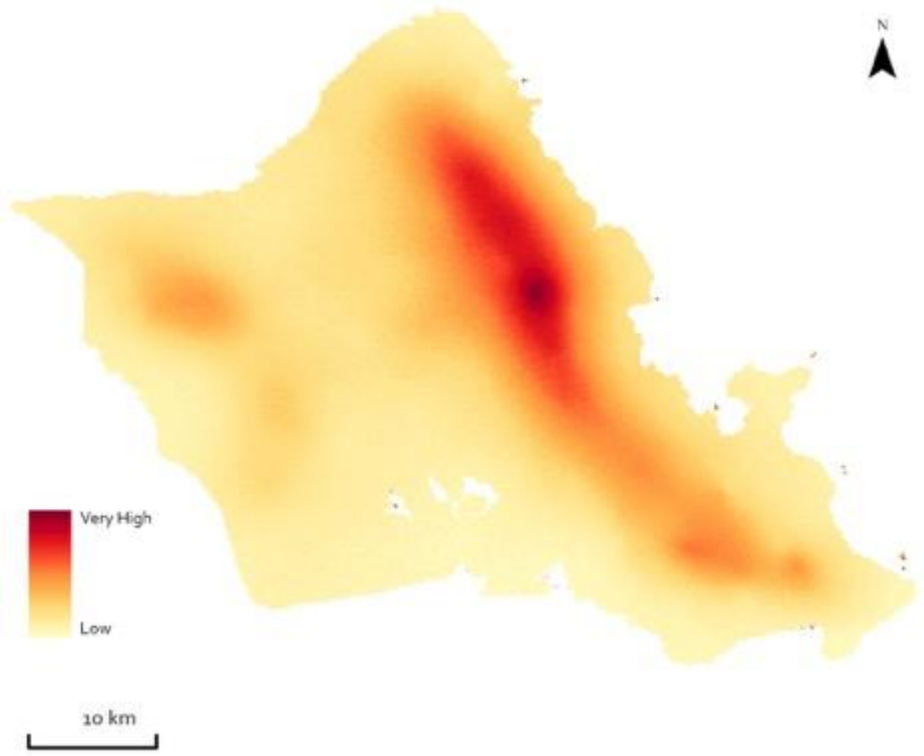


Figure 4.6. Landform landslide susceptibility map

Validation and Accuracy Assessment

To validate both LSMs, they were evaluated alongside United States' federal datasets and prior authoritative mapping efforts. Chief among these is the United States Geological Survey (USGS) landslide susceptibility map for Oʻahu (Appendix D-4), which aggregates slope data and stream-channel proximity using the National Hydrography Dataset. This product, based on expert judgment and a simple slope-stability model, identifies relative landslide initiation zones across the island (USGS, 2018). Parallel to this, the Department of Defense (DoD) geospatial product (Appendix D-5) provides a slope-based risk visualization that closely aligns with the results of the present study, particularly in highlighting elevated susceptibility within the Waiʻanae and Koʻolau ranges.

However, key differences in input variables distinguish the current case study's approach from these prior efforts. Unlike the USGS and DoD products, which rely predominantly on slope gradients, this study integrates precipitation and vegetative cover. The inclusion of these parameters better captures dynamic environmental processes that influence slope failure, including post-wildfire instability and vegetation loss. The resulting divergence is notable: while all models agree on

mountainous zones of high risk, the current case study's methodology further identifies heightened susceptibility in select lowland areas where vegetation is degraded, and rainfall accumulation is high. These discrepancies are not interpreted as errors but as evidence that the current work's expanded variable sets reveal more specificity in drivers of landslide risk across the island. The LSMs presented in the above methodology integrate climate, terrain, and vegetative variables, representing a substantial improvement over previously federally provisioned slope-only models by offering a more holistic portrait of landslide hazard potential.

4.6.2 Exposure

Proximity and colocation were used to determine the exposure of archaeological sites to potential landslides. The baseline for determining proximity was tested on both the GLSM and the LLSM for comparison. To calculate exposure, the Extract Multi Values to Points tool was used to assign susceptibility values to the pre-contact data. This exposure metric, distinct from vulnerability, captures the spatial coincidence between archaeological site locations and the physical drivers of slope instability, including slope angle, lithology, hydrological concentration, and rainfall intensity. Susceptibility values for the archaeological data were determined by matching the scores with the total weighted values from the susceptibility map. These value intervals were chosen following an extensive interpretation of the method's results, which revealed differences across the following four value breaks: 100 – 125, 126 – 160, 161 – 180, and 181 – up. Low susceptibility records were scored from 100 – 125, moderate susceptibility records were scored from 125–160, high susceptibility records were scored from 160 – 180, and very high susceptibility records were scored from 180 and up. The natural breaks were confirmed by reclassifying the exposure raster and verifying that each interval produced spatially coherent zones that aligned with slope angle, lithology, hydrological convergence, and rainfall intensity, and that the breakpoints generated consistent susceptibility patterns in both the GLSM and LLSM outputs.

Of the thirty-two (32) heiau identified in the current dataset, many occupy upland or mountainous locations. Five (5) are classified as at very high landslide risk, including Kaunihokahi in the island's northeasternmost ahupua'a. Historical accounts describe Kaunihokahi as dedicated to a shark *akua*, noted for both its protective and punitive powers (Sterling & Summers, 1978). Already recorded as degraded in 1933 (McAllister), this site faces the possibility of complete loss if a major slope failure occurs.

The ten (10) Ki'i pōhaku recorded in this dataset are dispersed between coastal and upland zones. One (1) high-significance example at Kahapa'akai, on the island's southern coast, is of a simple anthropomorphic figure, a motif Cox and Stasack (1970) identify as among the earliest Hawaiian petroglyph styles. This site, situated in a high-risk landslide zone, exemplifies the vulnerability of fragile, site-specific cultural expressions to geomorphic change.

Thirty-eight (38) habitation records are present in the dataset, with nine (9) high to very high-risk sites concentrated in Mākua Valley. Archaeological and environmental evidence indicate that this valley

supported the island's largest Pre-Contact population, benefiting from fertile soils, abundant freshwater, and marine access (Environmental Impact Study Cooperation, 1979). The valley also holds deep cultural significance, regarded in oral tradition as both the origin and departure point of humanity. Military occupation and training activities have already contributed to site degradation, and further losses through landslides would compound this cultural erasure.

Of ten (10) fishponds in the current inventory, one (1), Kahouna on the Windward coast, is in a high-risk landslide zone. Remarkably well-preserved, Kahouna continued in use until 1960 and was added to the National Register of Historic Places in 1973. Its survival underscores the importance of safeguarding the few remaining intact examples against both development pressure and geomorphic hazards.

Thirteen (13) burials are recorded in the dataset, distributed across the island, with three (3) very high-risk sites located in Mākua Valley. The density of burial sites here aligns with the valley's significance as a major habitation zone and sacred landscape. Landslides in these areas risk not only the physical loss of archaeological material but also the disruption of culturally vital ancestral connections.

Fifteen (15) ahupua'a intersect areas of very high landslide susceptibility, including Kalauao in the 'Ewa moku. Historically rich, Kalauao contained fishponds, taro fields, and freshwater springs, and was the site of the 1794 Battle of Kūki'iahu, a pivotal conflict in the unification of the Hawaiian Islands. Its significance extends beyond material heritage to encompass intangible cultural memory, making its preservation in the face of landslide risk imperative.

4.6.3 Vulnerability

Whereas the previous section mapped archaeological exposure to landslides through physical proximity, this section advances the assessment by examining vulnerability. Archaeological vulnerability on O'ahu is conceptualized not solely in terms of exposure to landslide hazard zones, but also in areas lacking economic and federal importance. In addition, and most importantly, the exposure model was utilized as a vulnerability metric. The set of vulnerability variables include:

1. **Landslide Susceptibility (LSM)**: Derived from GLSM,[26] this indicator reflects the geophysical hazard potential associated with slope gradient, lithology, precipitation regimes, and historical mass-movement records. Areas of higher susceptibility were assigned

[26] The GLSM was utilized due to the ease of transferability to other regional case studies where landform analysis may not be possible due to lack of access to appropriate software or DEMs. While the GLSM utilizes the same DEM as the LLSM, the model is not necessarily dependent on the DEM and could be based on qualitative reasoning with a generic understanding of the terrain as well as rainfall and vegetation levels. Vegetation levels can be derived globally using Landsat or Sentinel multispectral imagery to generate NDVI. In terms of rainfall levels, these may need additional qualitative in situ knowledge depending on the region in question.

proportionally higher vulnerability scores due to the potential for rapid, irreversible damage to archaeological deposits.

2. **Proximity to Major Roads**: Serving as a proxy for anthropogenic disturbance potential, this measure reflects the increased likelihood of site damage where road networks enable easier access, alter drainage patterns, or introduce vibration and erosion. Proximity was modelled as a continuous distance-decay raster, with the highest scores assigned to areas immediately adjacent to major roads.

3. **Proximity to Department of Defense (DoD) Installations**: Representing land-use regimes where military activity may lead to direct or indirect disturbance through infrastructure works, training exercises, or vegetation clearance. While some installations may inadvertently shield sites from civilian encroachment, the net balance of risk was treated as positive for disturbance potential.

Each variable (GLSM (exposure), major roads, and DoD installations) was rasterised and normalized to a 0–1 scale to enable direct comparability, with higher values indicating greater vulnerability. To ensure the robustness of the final model output, an iterative sensitivity analysis was undertaken. This process systematically varied the weighting values assigned to each input layer, landslide susceptibility, proximity to major roads, and proximity to DoD installations, within plausible ranges. Multiple model runs were conducted, each recalculating the composite Vulnerability Index (VI) using different weighting configurations. The results of each run were evaluated qualitatively by examining spatial patterns for consistency with known landslide-prone areas (based on the GLSM and LLSM). Attention was paid to identifying unstable outputs, where small changes in weighting produced disproportionately large shifts in vulnerability classification, as these indicate potential model sensitivity to parameter uncertainty.

Where instability was detected, weight ranges were adjusted, and the analysis was repeated until successive runs produced convergent outputs with minimal classification volatility. This iterative cycle ensured that the final weight allocation was theoretically justified, reducing the risk of overfitting to a specific set of weight values. By validating the model's performance under multiple plausible scenarios, the sensitivity testing strengthened confidence that the resulting vulnerability map reflects a resilient representation of archaeological risk rather than arbitrary parameter selection. The adopted scheme assigns:

Landslide Susceptibility – 0.50

Proximity to Major Roads – 0.25[27]

[27] https://www.arcgis.com/apps/mapviewer/index.html?layers=bb99eadd94ac433bb3c6c9f9f9de2827

Proximity to DoD Installations – 0.25[28]

These weights reflect the primacy of geophysical hazard in determining potential damage, while also accounting for anthropogenic factors that influence both exposure and post-impact vulnerability. Proximity to major roads can increase disturbance risk, facilitate unauthorized access, and accelerate post-failure site degradation. In contrast, the presence of DoD installations may introduce land-use restrictions, limit heritage management options, and amplify consequences for sites within restricted zones.

The composite VI was generated by a weighted linear combination of these layers, integrating them according to their assigned weights (Equation 4.2) to produce a continuous vulnerability surface. This approach aligns with DRR principles by explicitly combining environmental hazard intensity with socio-political and infrastructural constraints, enabling prioritisation of heritage management actions in contexts where both natural and human drivers shape risk.

$$(4.2) \quad VI = (GLSM \times 0.50) + (Major\ Roads \times 0.25) + (DoD\ Installations \times 0.25)$$

The resulting continuous raster surface was classified into four categories using natural breaks to capture meaningful variance in the dataset:

- **Low**: Minimal vulnerability from combined indicators
- **Moderate**: Noticeable risk from one or more mid-range hazard or disturbance factors
- **High**: Elevated vulnerability due to strong influence from multiple indicators
- **Very High**: Maximum vulnerability, typically where high landslide susceptibility coincides with both anthropogenic access and intensive land use

The classified vulnerability raster was intersected with the spatial dataset of recorded pre-contact archaeological sites using the Extract Values to Points tool. This process assigned a discrete vulnerability category to each site, enabling spatial identification of high-risk archaeology.

Patterns of Vulnerability and Cultural Risk

The VI results (Figure 4.7) indicate that low pre-contact vulnerability is concentrated in the central and southern portions of the Waiʻanae range. A dense road network and the presence of DoD installations reduce isolation and facilitate management access. There is a second low-vulnerability pocket near Wahiawā, close to a major through-road and another DoD facility. Moderate vulnerability is widespread, particularly on the central to lower slopes of both the Waiʻanae and Koʻolau ranges, reflecting moderate hazard exposure combined with partial infrastructural accessibility. High-vulnerability zones occur around the lower slopes of each range in areas lacking major roads or DoD installations, showing a spatial inversion relative to GLSM hazard hotspots, indicating that vulnerability in these cases stems more from access and management limitations

[28] https://www.arcgis.com/apps/mapviewer/index.html?layers=bb99eadd94ac433bb3c6c9f9f9de2827

than from raw hazard magnitude. Very high vulnerability is concentrated along the steepest sections of the Koʻolau range and to the north of the Waiʻanae range, as well as in a narrow strip on the

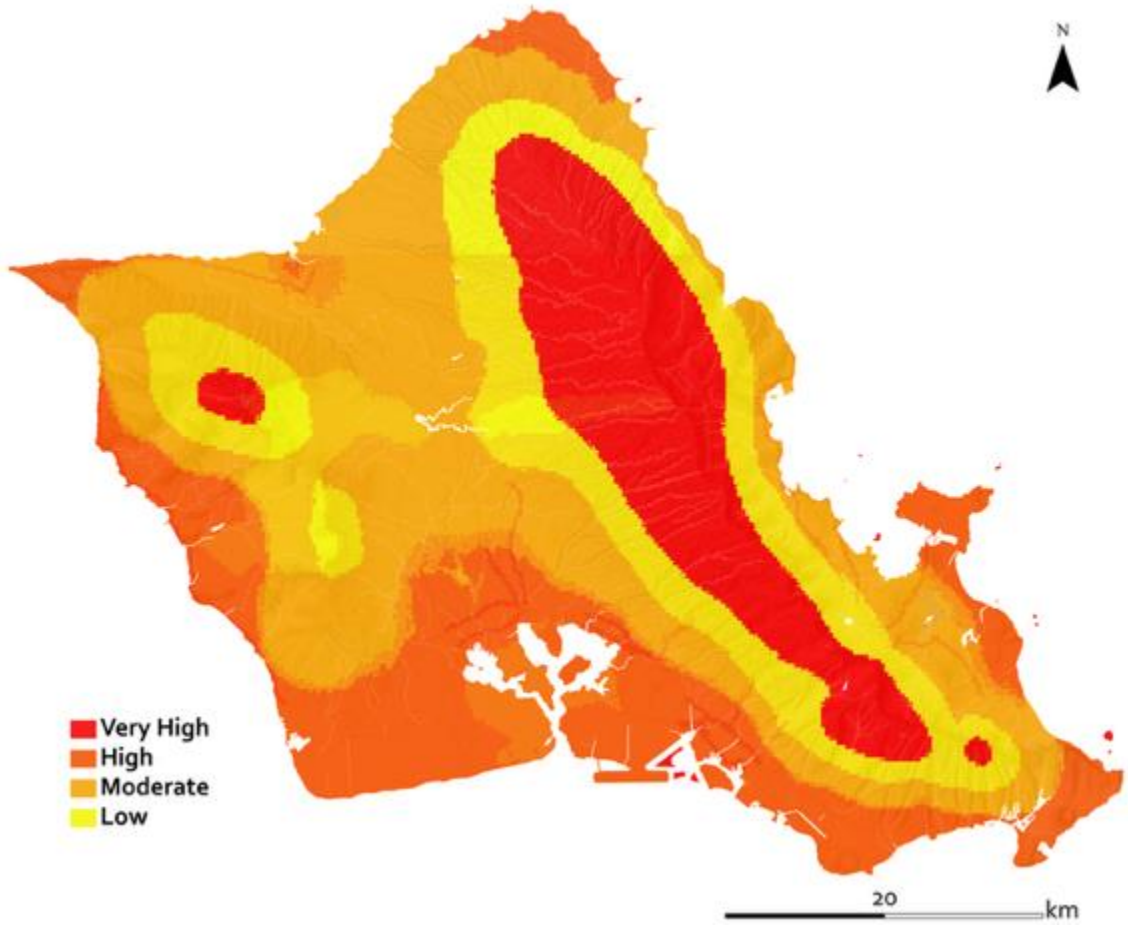


Figure 4.7. Vulnerability Index map

northeast coast where vertical slopes meet the sea and along a similar east-northeast coastal stretch, where slope–shoreline intersections create both hazard exposure and significant barriers to intervention. Comparison with the exposure results highlights that while some areas of high landslide susceptibility also rank as highly vulnerable, others maintain low vulnerability despite high exposure due to the mitigating influence of road access and DoD presence.

In contrast, certain moderate-hazard areas are classified as highly vulnerable because their isolation and lack of infrastructure amplify management challenges. The resulting vulnerability map reveals several critical insights. First, high-vulnerability zones are disproportionately concentrated in culturally saturated regions such as the Mākua Valley and Waiʻanae coast. Within the archaeological dataset, one (1) site is classified as having low vulnerability, forty-two (42) sites fall within the moderate vulnerability class, twenty-eight (28) sites are assessed as having high vulnerability, and two (2) sites are categorized as having very high vulnerability.

4.7. Capacity

The final dimension of the landslide risk triage model focuses on capacity. In archaeological contexts, this includes not only formal protections and institutional enforcement but also community-based stewardship, public participation in archaeological monitoring, and systems of traditional knowledge transmission. Priority 4 of the Sendai Framework calls for 'enhancing disaster preparedness for effective response', a task that requires prior understanding of where capacities are strongest, and where they are structurally absent (UNDRR, 2017). In Hawai'i, this theoretical capacity is significant on paper. State and county-level planning frameworks include the (SHPD), the Department of Land and Natural Resources (DLNR), the Office of Hawaiian Affairs (OHA), county planning and permitting agencies, and Department of Defense (DoD) installations, which are legally mandated to maintain on-site cultural resource management (CRM) authorities. These CRM programs are staffed by qualified professionals and guided by federal laws, such as the National Historic Preservation Act (NHPA), which requires cultural resource surveys to define the extent and area of potential effect before any undertaking. In addition, private firms engaged in development or infrastructure projects are historically required by law to conduct CRM surveys, thereby further strengthening the baseline capacity for heritage management. Layered onto this institutional framework is strong Native Hawaiian advocacy, which remains a powerful driver for the protection and perpetuation of Hawai'i's archaeological heritage, often shaping public policy, legal challenges, and grassroots stewardship initiatives.

A robust set of spatial datasets supports this institutional and cultural infrastructure: statewide archaeological inventory surveys, Hawai'i Statewide GIS Program layers, LiDAR-derived elevation models, NOAA sea level rise viewer outputs, hazard zone mapping, and statutory protection layers for historic properties and cultural sites. In theory, this combination of legal mandates, technical expertise, cultural advocacy, and digital resources enables risk-informed archaeological planning across multiple hazard contexts, including landslide susceptibility, flooding, and seismic risk. Yet, despite this abundance of resources, integrating archaeological priorities into hazard and land-use planning remains inconsistent. Hazard mitigation plans rarely explicitly reference cultural heritage, and archaeological concerns are often relegated to conditional permitting notes or post-impact compliance processes. The problem is not a lack of data or authority, but a fragmentation of workflows, siloed jurisdictions, and the absence of operational triggers that embed archaeological risk considerations early in the planning process.

The VI results of this study make these capacity gaps spatially visible. Zones of high hazard–low capacity emerge along the lower slopes of the Ko'olau and Wai'anae ranges, where landslide susceptibility is most significant but protective designations and documented stewardship are sparse. In contrast, urbanized corridors with substantial road infrastructure and DoD-managed lands often present moderate hazard–high-capacity conditions, where enforceable protections, active monitoring, and statutory compliance temper hazard exposure. Of particular concern are pockets of very high vulnerability, notably along the northeast coastal stretch, where steep slopes meet the sea, hazard intensity is extreme, and no statutory cultural protections or active monitoring

programs exist. Measuring capacity should assess whether existing tools and frameworks are actively operationalized. The DRR-aligned approach in this study, integrating legal protection layers, stewardship indicators, and community-based monitoring into a spatial capacity surface, demonstrates how available resources can be transformed into actionable, triage-ready outputs. This does not require creating new agencies but rather aligning the ones that already exist into coordinated workflows.

4.8. Composite Risk Modelling

To move from isolated hazard layers to actionable prioritisation, this section synthesises the previous analyses of hazard, exposure, vulnerability, and capacity into a single composite risk model. This model operationalises the same approach as Holderness; the Relative Loss Potential (RLP) model was generated. This included multiplying the vulnerability raster by the archaeological exposure surface (Equation 4.3), producing a multi-criteria surface that reflects the likelihood and potential consequence of landslide-induced archaeological loss on Oʻahu. The aim is triage: to identify sites and zones that require immediate action, monitoring, or further investigation. In doing so, the composite model serves as the decision engine for this chapter, converting continuous spatial variables into ranked, implementable outcomes in line with Sendai Priority 3: Investing in disaster risk reduction for resilience (UNDRR, 2017).

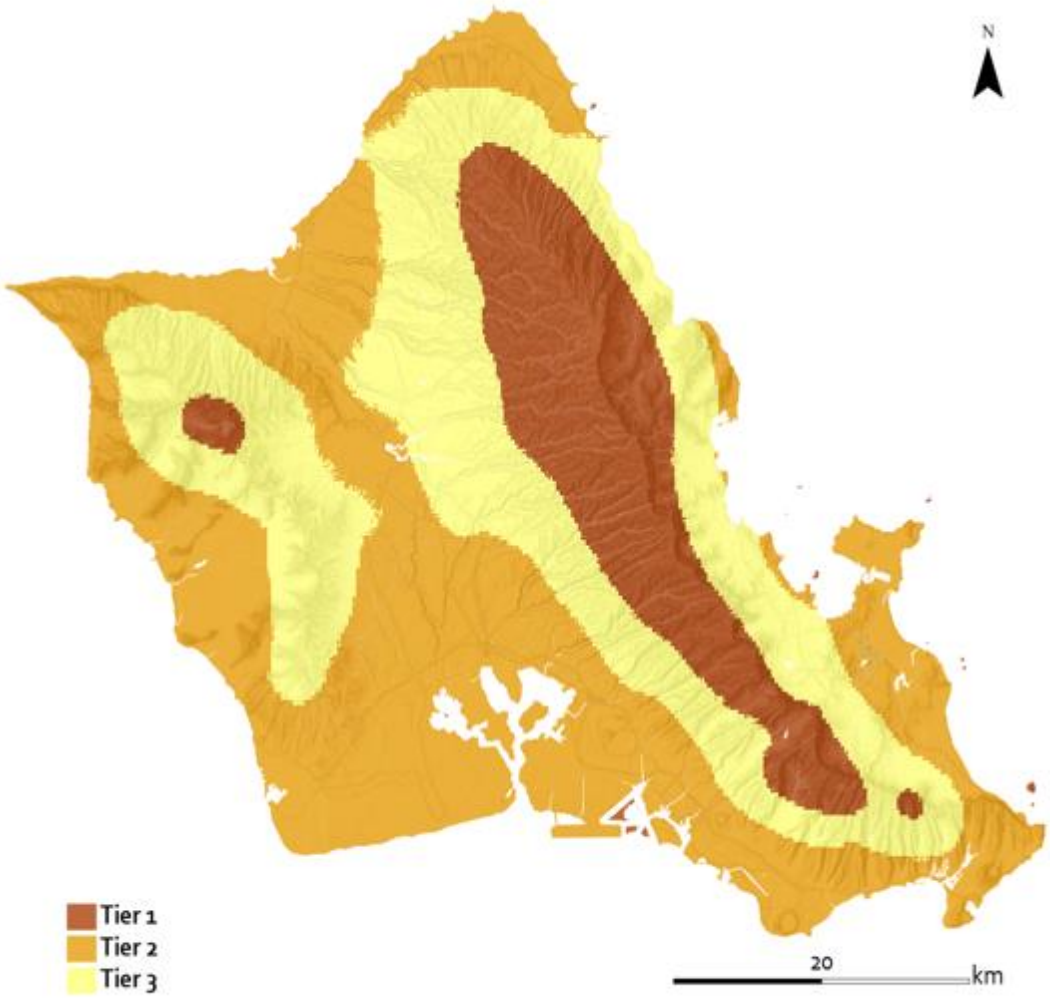


Figure 4.8. Relative Loss Potential for Oʻahu

$$RLP = Exposure\ Score \times Vulnerability\ Index \quad (4.3)$$

The final risk surface (Figure 4.8) reveals three distinct tiers of risk across the island's archaeological record. The classification schema was implemented using natural breaks in the composite raster values, generating a three-class output that was further reclassified into three action tiers.

Spatial Triage

The culmination of this chapter's composite modelling is spatial triage, as introduced in Chapter 2 and piloted in Holderness. Grounded in the composite risk model's outputs, this framework assigns archaeological sites across Oʻahu to ranked categories. These classifications translate the model's numerical outputs into actionable levels of risk, establishing a practical basis for prioritizing preparedness, monitoring, and response. Spatial triage builds on the risk outputs by overlaying these classifications with pre-contact sites. In contrast to the vulnerability model and raw site distribution, the composite model offers an integrated representation of archaeological risk to landslides across Oʻahu. As illustrated in Figure 4.9, low-risk sites are dispersed throughout the island, while the majority of moderate-risk sites cluster at the foothills of steep slopes. The highest-risk sites are concentrated along the most pronounced gradients of the Koʻolau Range, where steep terrain amplifies both hazard exposure and access constraints. The triage model allows planners and cultural managers to make transparent, evidence-based decisions while respecting the layered meanings of place embedded in Hawaiian landscapes. It acknowledges that not all sites can be saved in the same way, but that all deserve risk-informed consideration. To assign tiers across the 104 mapped records, the continuous susceptibility index values (ranging from 98 to 241) were divided into three classes using an equal-interval approach. This method provides consistent thresholds that are easy to interpret and replicate. The full range of units was split into three equal segments of approximately 48 units each, resulting in the following categories: Tier 3 (98–145), Tier 2 (146–193), and Tier 1 (194–241). Equal-interval classification was chosen because it offers a straightforward way to compare relative risks across all sites, ensuring that the classification reflects the numerical scale of the data rather than its distribution. Applying this triage framework to the composite model's outputs yields the following spatial distribution of archaeological sites across Oʻahu:

Tier 1: Immediate Documentation

Sites with high composite risk and high cultural or ancestral significance. These include known heiau complexes situated on unstable slopes or undocumented habitation terraces within high-hazard valleys. Where relocation is not feasible due to legal or cultural restrictions, emergency documentation is prioritized. These sites could be lost in a single slope failure, and that loss could constitute a rupture in Native Hawaiian knowledge if not documented.

Tier 1 sites are located primarily along the steep slopes of the Koʻolau and Waiʻanae ranges, as well as within Mākua Valley. Among these are five heiau, including *Kaunihokahi Heiau* at Laʻie, which stands on a steep ridge edge, already noted in the SHPD-provided database as being in a degraded condition. One *kiʻi pōhaku* site, *Kahapaʻakai*, situated on the island's mid-southern coast, is also at very high risk. The nine habitation sites clustered in Mākua Valley fall within this high category, as do three nearby burials that lie on unstable slopes within the same valley. One *loko kuapā*, *Kahounā* at Kahaluʻu, is the only fishpond classified as high risk due to its position below steep, debris-prone slopes. Several ahupuaʻa are also in high-susceptibility zones, including Waimea, Keana, Lāʻiewai, Kaluanui, Waiʻono, Waikāne, Waipiʻo, Waiawa, Waiau, Waiāhole, Kaʻalaea, Koʻolaupoko, ʻEwa, and Kona. In addition, the interior valleys and Pali corridor, where steep gullies and cliffs dominate, host

multiple heiau, burials, and habitation sites exposed to rapid slope failure. Tier 1 sites identified via this model include four (4) habitation records, one (1) heiau, three (3) petroglyphs, and one (1) burial.

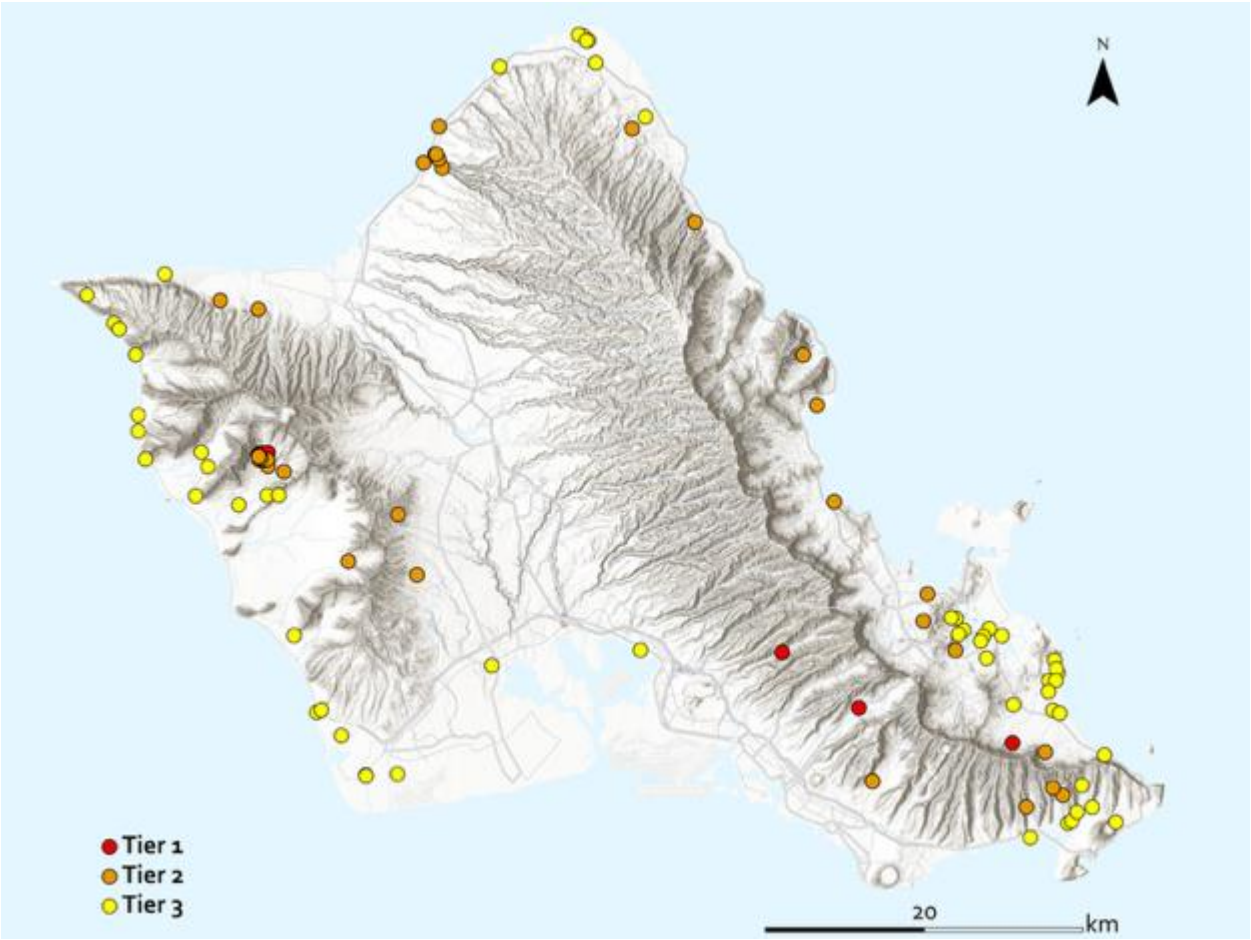


Figure 4.9. Tier 1; Tier 2; and Tier 3 sites

Tier 2: Enhanced Monitoring or Protective Intervention

Sites at moderate risk or those that possess moderate significance but are in zones with active community stewardship or partial legal protections. Examples include fishpond systems within gulches or mid-slope zones that have already experienced slope failures. Interventions here may include community science initiatives, post-storm physical inspections, or the installation of slope-monitoring devices.

Tier 2 sites occur mostly along the coastal margins beneath foothills, particularly in the northwestern and northeastern corners of the island and in the Windward embayments. These areas include a mixture of heiau, *ki‘i pōhaku*, and habitation features at valley mouths and fan toes, where slope and runoff hazards are present but less extreme. Portions of the Wai‘anae sector south of Mākua Valley also fall within this category, containing agricultural complexes, shrines, and lithic scatters on mid-slopes and valley sides. The majority of heiau not built on steep ridges, as well as most of the remaining *loko kuapā* and habitation sites outside Mākua, are classed as moderate risk.

Tier 2 sites identified via this model include twelve (12) habitation records, eleven (11) heiau, eleven (11) fishponds, four (4) petroglyphs, and two (2) burials.

Tier 3: Periodic Reassessment

Sites in low-risk zones, or those with low archaeological visibility but possible undocumented significance. These sites should not be deprioritized but placed on a cyclical reassessment schedule. This category is critical in the face of climate volatility, where today's low-risk criteria may not hold over multi-year timeframes.

Tier 3 sites are found across the flatter lowlands, especially on the Honolulu–Waikīkī plain and the southern Waiʻanae Valley floor. Archaeological features here, such as lowland heiau, habitation sites, and burials, are positioned far from steep slopes and major drainage lines. Likewise, coastal flats on the Leeward side that are distant from the toes of the Koʻolau and Waiʻanae ranges exhibit low susceptibility to landslides. These areas are the least threatened by immediate slope instability, though they may still face long-term risks from sea-level rise and coastal erosion. Tier 3 sites identified via this model include twenty-two (22) habitation records, nineteen (19) heiau, six (6) fishponds, three (3) petroglyphs, and ten (10) burials.

Conditions for Reuse:

The Oʻahu triage framework is designed to be portable beyond Hawaiʻi, relying on a small but flexible set of inputs that can be assembled in many regional settings. At its core, the model requires four primary data components:

> **(1) a DEM** suitable for deriving slope and basic geomorphometry.
>
> **(2) climatic or hydrological data** that can act as a proxy for triggering conditions (for example, precipitation or storm intensity).
>
> **(3) remote sensing imagery** to generate indices such as NDVI or land-cover classes, to represent stabilising or destabilising surface conditions; and
>
> (**4) an archaeological dataset** with minimally adequate locational accuracy. These inputs are sufficient to construct a general landslide susceptibility surface, intersect it with archaeological records, and generate first-pass exposure metrics in the absence of a formal landslide inventory.

A second tier of inputs enhances the model's vulnerability and capacity components. Proximity to roads, defence installations, or other major infrastructure can be replaced in different regions with context-appropriate disturbance proxies, such as mining concessions, logging roads, tourism corridors, or agricultural frontiers. Likewise, capacity can be approximated using layers that capture governance and stewardship, protected area boundaries, indigenous land designations,

conservation easements, or zones with active community-based management. Where such datasets are coarse or incomplete, simple distance metrics to administrative centres, ranger posts, or known heritage-management hubs can provide a workable first approximation. The key requirement is not a perfect representation of governance, but a defensible spatial proxy for where intervention is realistically possible.

Ultimately, the conditions for reuse are institutional rather than purely technical. The framework is most effective in settings where some geospatial and archaeological data already exist but remain siloed between agencies or disconnected from risk planning. In such environments, the landslide-based triage model can function as a bridging mechanism, translating disparate datasets into a shared, DRR-aligned risk language that planners, heritage managers, and local communities can all act on.

4.9. Limitations

The spatial triage framework developed in this chapter is shaped by its inputs, limited by the availability and resolution of data. Landslide susceptibility, unlike more gradual hazards such as sea-level rise, is inherently episodic and unpredictable. Even high-performing models cannot fully anticipate where or when slope failure might occur (Wang et al., 2025). They provide probabilistic risk landscapes, not certainties. This distinction matters, particularly when model outputs inform decisions that affect archaeological risk and resource allocation.

One significant limitation is the resolution of available terrain data. While the SRTM provides global coverage, its 30-meter resolution may obscure fine-scale topographic variations that are critical to predicting localized landslide triggers. Microtopographic features such as oversteepened scarps, anthropogenic terraces, or narrow ridgelines may evade detection in such datasets. This limitation is particularly acute in O‘ahu’s complex terrain, where ancient cultural modifications to the land often coexist with geophysical hazard signatures. Higher-resolution LiDAR data, where available, would offer a substantial improvement, but access remains limited due to cost, coverage gaps, and data-sharing restrictions. Equally constraining is the lack of historical landslide data. Unlike coastlines, which can be tracked over decades through satellite imagery and tide gauges, landslides leave fragmented and often unrecorded traces. Many events, especially in remote valleys, go undocumented, resulting in a ‘silent archive’ of hazard history. The absence of a centralized landslide inventory for O‘ahu required this chapter to rely on proxy variables, rather than event-confirmed patterns. As such, the susceptibility surfaces generated here represent relative, not absolute, risk. They are best used as filters for prioritization rather than diagnostic tools.

Despite these constraints, the framework demonstrates considerable value for transferability. Volcanic island systems across the Pacific, Caribbean, and parts of Southeast Asia face parallel challenges: steep terrain, fluctuating rainfall patterns, rapid urbanization, and rich archaeological tapestries with limited formal protection. In such contexts, where heritage assets are highly distributed and hazard data is sparse, a low-cost, multi-scalar, open-access approach provides a

meaningful first step toward risk-informed archaeological risk mitigation planning. Further, integrating traditional land divisions (such as ahupua‘a) offers a model for embedding Indigenous spatial logics into DRR workflows. This approach may hold value in similarly structured sociocultural landscapes elsewhere.

Any attempt to model archaeological risk on O‘ahu that ignores the cultural, political, and epistemological dimensions of risk itself is incomplete at best. The spatial triage model presented in this chapter provides a technical framework for prioritising archaeological sites threatened by landslides. But these sites do not exist in a vacuum. They are embedded in a living cultural geography where place, identity, memory, and authority intersect. For Native Hawaiians, ʻāina is not merely a substrate of potential destruction; it is a genealogical entity, a relative, a teacher, and a source of accountability. Thus, the risk to a site is not only the risk of physical erasure but also the loss of ancestral presence, intergenerational stewardship, and epistemological continuity (De Lude et al., 2024; McDougall, 2023). Understanding risk, then, requires acknowledging that dominant DRR frameworks, rooted in technocratic governance and Euro-American geospatial logics, may insufficiently reflect Indigenous ontologies of place. The goal of archaeological risk modelling is not only to prevent loss, but to support continuity. That continuity includes tangible protection of sites, as well as the resilience of knowledge systems and the transmission of ancestral practices into the future. In this sense, DRR becomes not just a safeguard against disaster, but a platform for Indigenous resurgence.

4.10. Summary

This chapter has treated landslides not only as a geotechnical hazard but as a crucible for rethinking how archaeology engages with risk. O‘ahu’s terrain, rich in cultural significance and riven with geomorphological volatility, provides a stark case study in the stakes of inaction. Here, the spatial triage framework built on the Sendai-aligned pillars of hazard, exposure, vulnerability, and capacity demonstrates that archaeological loss from sudden-onset disasters is neither abstract nor inevitable. It is foreseeable, mappable, and, with the right tools, preventable. DRR, as reaffirmed throughout this study, is not merely about post-event recovery. It is about anticipating loss before it occurs and positioning archaeology within the same preventative logics applied to infrastructure and ecosystems. The integration of DRR into archaeological methods, through susceptibility mapping, risk surface modelling, and triage-informed prioritization, signals a shift from descriptive inventory to proactive governance. It challenges the field to move faster than the hazards that threaten it.

Geospatial applications serve as the technical backbone of this shift. Remote sensing, GIS overlays, and cost-distance analysis enable archaeologists to ask better questions of their data and generate outputs that are legible across disciplinary and policy boundaries. In this chapter, GA was used not just to visualize risk, but to operationalize it, transforming disparate layers into targeted zones of concern and actionable planning units. That democratizes response, making high-stakes, high-resolution decision-making more accessible to local managers, cultural stewards, and community advocates. In the context of O‘ahu, this means identifying at-risk heiau before they collapse into

valleys, safeguarding habitation terraces that might otherwise be erased in the next wet season and flagging unknown sites that sit on unstable terrain. It also means surfacing gaps in documentation, enforcement, and capacity that can be addressed before the next trigger event. The Oʻahu case study serves as a proving ground, a test of the spatial triage model in a high-hazard, high-heritage-density environment. The lessons from Oʻahu suggest that the risk mitigation lies in pre-disaster mapping. Risk-aware preservation requires a different posture from the archaeological community, one that looks up from the trench and toward the terrain. This chapter offers one path forward.

This chapter demonstrates that DRR is not a borrowed framework for archaeology; rather, it is a logical evolution for the discipline. Integrating DRR into archaeology positions the discipline as a preventative science focused on what might yet survive. Landslides can erase centuries of memory in seconds. But through DRR-aligned modelling, heritage managers can act before the next impact rather than after it.

Chapter 5: Archaeology and Desertification in the Sistan Basin

5.1. Introduction

The 2,000 square kilometres of the Sistan Basin, spanning Iran and Afghanistan, exemplifies a slow-onset, multi-scalar hazard landscape where climate, hydrology, and politics converge (Figure 5.1). Desertification here is an ongoing process, eroding livelihoods and archaeological sites. Archaeology in Sistan is inseparable from disaster risk: visibility, preservation, and interpretation are all conditioned by a rapidly degrading environment. In a context where field access is blocked, governance is absent, and instability is constant, archaeology cannot rely on excavation or preservation. Instead, it must focus on maintaining visibility, digitally rescuing records, modelling hazard trajectories, and anticipating loss before it becomes irreversible. From a Disaster Risk Reduction (DRR) perspective, Sistan qualifies as a Priority 1 risk environment: its archaeological record is fragmentary and poorly mapped, exposure is escalating, and institutional capacity is negligible (UNDRR, 2017). Climatic pressures are extreme, with summer temperatures reaching 43.3°C and long-term warming trends across Iran rising by 0.31 to 0.59°C per decade (Soltani et al., 2016). Hydrologically, the Helmand River's declining flows and the near-collapse of Lake Hāmūn (Figure 5.2) have dismantled the basin's ecological and cultural lifeline. These losses are politically entrenched: Afghanistan controls the river's headwaters, while Iran holds the desiccated lakebed downstream. The result is a century-long hydropolitical stalemate, intensified by new dams such as the Kamal Khan, completed in 2021. Topography compounds these pressures. The basin sits at the



Figure 5. 1. The Sistan Basin, featuring pertinent deserts and topographic features

convergence of the Dasht-e Kavir, Dasht-e Lut, and Registan deserts, ringed by the Alborz and Zagros Mountains. Seasonal pressure systems from the Hindu Kush generate the 'Wind of 120 Days' (occurring from May–September), which mobilises vast beds of exposed lake sediment. The outcome is chronic dust storms that not only damage public health but also bury, erode, or displace archaeological materials (Alizadeh-Choobari et al., 2014; Miri et al., 2010).

By situating Sistan within a DRR framework, this chapter treats desertification as an archaeological hazard. The goal is to model how archaeology can persist in landscapes where loss is accelerating, governance is absent, and access is blocked. In Sistan, DRR is not about saving at-risk records, but about salvaging enough to make risk legible and prepare for futures in which conventional archaeology is no longer possible.



Figure 5. 2. Lake Hāmūn (at capacity).

5.1.1. Objectives

The DRR framework outlined in Chapter 2, and particularly the Sendai Framework's Priorities 1–3, provides a critical scaffold for interrogating the hazard dynamics of Sistan. The Sendai Framework's Priority 1 (understanding risk) demands not only the characterisation of desertification as an environmental process, but also the quantification of which archaeological assets are directly susceptible to its impacts. Priority 2 (strengthening disaster governance) highlights the acute institutional vacuum in politically fragmented regions, such as Sistan, where oversight is sporadic or non-existent. Priority 3 (investing in risk reduction) shifts the emphasis from descriptive documentation toward the urgent need for prioritisation, recognising that not all archaeology can or will be preserved (UNDRR, 2017). In Sistan, these priorities intersect by necessity with the geospatial approach employed and the region's built-in constraints, including severe curtailment of field access, political instability, and unreliable visibility of archaeological records from season to season. Under such circumstances, geospatial tools are the primary means of constructing an actionable, grounded salvage framework. In this context, this chapter applies a DRR and geospatial approach to understanding archaeological risk in the Sistan Basin, with specific objectives to include:

1. **Modelling desertification as a cultural hazard**: using multi-spectral remote sensing imagery to capture the progression of degradation of desertification from 2015 to 2021.
2. **To integrate archaeological datasets with environmental risk surfaces**: overlaying legacy archaeological records with hazard outputs to assess exposure for known archaeology in the region.

3. **To showcase a model of salvage under constraints:** reframing DRR for archaeology as the maintenance of visibility through geospatial approaches, archival rescue, and preparedness, rather than traditional interventions such as physical data recovery or preservation.
4. **To situate the Sistan case as a methodological warning and contribution**: demonstrating how geospatial-DRR approaches can be adapted to fragile, inaccessible landscapes and serve to reduce disaster risk.

The Sistan Basin presents not just a challenge for archaeology, but a broader question for disaster-informed heritage work: how do we account for what we cannot see, access, or even document? The triage model developed and applied to the previous case studies is inapplicable to Sistan. However, this methodology demonstrates that, despite the required deviation, DRR can provide Sistan with a beneficial heuristic for defining a salvage framework even in an inaccessible archaeological landscape. This approach may not save the physical archaeology, but it does offer a structured way to see, prioritise, and, where possible, reduce the risk that knowledge of the archaeology is impacted by disaster.

5.2. Understanding the Hazard: A Review of Desertification and Archaeology

Desertification has long been recognised as one of the most consequential environmental processes shaping both ancient and contemporary dryland societies, and in recent decades it has become an increasingly central concern within archaeological research. Typically defined as land degradation in arid, semi-arid, and dry sub-humid regions (UNCCD 1994; Middleton & Thomas 1997), desertification is not a single phenomenon but a constellation of interlocking processes: vegetation loss, soil depletion, salinisation, dune mobilisation, and hydrological collapse, that operate over multiple temporal scales. For archaeologists, these dynamics matter profoundly because drylands contain some of the most continuous, environmentally sensitive, and yet vulnerable cultural archives in the world. Accelerating aridity, whether driven by climatic shifts or long-term anthropogenic land use, directly alters the stability and even detectability of archaeological landscapes (Rosen 2007; Brooks 2005). Recent work underscores a political point as well: modern desertification does not merely threaten material remains but also destabilises the ecological and social contexts upon which archaeological interpretation depends (Rayne et al. 2023; Smith 2024). In other words, the very conditions that once enabled the formation and survival of dryland heritage are eroding in real time.

A growing body of archaeological scholarship stresses that desertification must be understood historically rather than treated as a novel 20th- or 21st-century crisis. Long-term records from the Sahara, the Mu Us Desert of northern China, the Karoo of southern Africa, and the Levantine desert margins demonstrate repeated cycles of aridification, degradation, and partial recovery intertwined with shifting subsistence strategies, population pressures, and political economies. In Wadi Faynan (southern Jordan), interdisciplinary research reveals how Bronze and Iron Age copper extraction, agricultural intensification, and settlement growth accelerated soil erosion and destabilised

marginal landscapes, indicating that human-induced degradation is not a modern invention (Barker et al. 2007; Hunt et al. 2004). A similar long durée view emerges from the Vera Basin in southeast Spain, where millennia of cultivation, grazing, and clearance shaped semi-arid degradation trajectories well before industrial agriculture. In northern China, alternating phases of dune mobilisation and stabilisation in the Mu Us Desert correlate strongly with historical demographic expansions, agricultural intensification, and altered patterns of pastoral mobility (Zhang & Deng, 2020). Together, these case studies dismantle climate-deterministic narratives: desertification is not simply the mechanical outcome of drought but the cumulative product of environmental variability and situated human land-use decisions across time Brooks 2005; Nicholson 2018).

This historical framing has prompted archaeologists to re-evaluate the resilience and adaptability of dryland societies. Earlier collapse-driven narratives are increasingly replaced by more nuanced understandings in which communities deployed mobility, diversification, storage systems, flexible tenure regimes, and what is now termed traditional ecological knowledge to navigate volatile and often rapidly deteriorating environments (Rosen 2007; Bar-Yosef & Belfer-Cohen 2010). Research in Inner Asia, Saharan oases, and the Arabian Peninsula shows that dryland populations possessed sophisticated environmental literacies that enabled them to maintain productive landscapes under climatic regimes that were far from stable (Humphrey & Sneath 1999; McIntosh 2005). These findings complicate any simplistic portrayal of desertification as a uniformly destructive force; instead, they reveal long-term negotiation, innovation, and adaptation embedded in the archaeological record.

Yet the contemporary acceleration of desertification introduces pressures at scales and speeds that exceed many historical precedents. Intensified agriculture, deep-aquifer extraction, overgrazing, infrastructural expansion, and climate-change-driven aridity now act synergistically, transforming dryland systems at rates far faster than past societies ever confronted (Middleton 2018). For cultural heritage, the effects are increasingly severe and, in many cases, irreversible: dune encroachment can bury or expose sites; deflation surfaces strip stratigraphy within years rather than centuries; rising salinity compromises mudbrick structures; and the abandonment of historically managed landscapes leaves formerly stable features exposed to collapse (Rayne et al. 2023; Hollesen et al. 2018). Regional inventories, such as those produced by EAMENA, demonstrate that desertification is now one of the dominant drivers of archaeological degradation across the Middle East and North Africa, often acting in concert with other stressors, such as agricultural intensification, conflict, and rapid urban growth (Bewley et al. 2016). These cumulative pressures produce heritage trajectories that are markedly different from the slow-moving, reversible processes visible in archives. Taken together, the literature shows that desertification is simultaneously a long-term historical force, a contemporary environmental hazard, and a profound archaeological challenge. Drylands have always been dynamic, but the accelerating pressures of the present threaten both the physical survival of heritage resources and the interpretive frameworks needed to make sense of them. The archaeological record of arid regions provides unparalleled insight into how societies navigated degradation, mobility, scarcity, and uncertainty in the past. Yet modern desertification risks erasing precisely the evidence that enables such reconstructions.

5.2.1. Desertification in Sistan

Climatically, the Sistan Basin has become increasingly uninhabitable due to intensifying heat and prolonged drought (Omidvar et al., 2024). Temperature increases have accelerated evapotranspiration rates, reduced the viability of agricultural production, and undermined already fragile ecological systems (Shahraki et al., 2021). Lake Hāmūn was once a vital freshwater body fed by the Helmand River, originating in the Hindu Kush of Afghanistan. Today, the lake is a shadow of its former self, its contraction the result of both persistent drought and aggressive upstream water management. As early as the 1990s, hydrological data show declining flows into the basin Darvishi Boloorani, 2022). This trend has accelerated in recent decades due to the construction of dams and irrigation infrastructure upstream in Afghanistan, including the major Kamal Khan Dam, completed in 2021 (Darvishi Boloorani, 2022; Miri et al., 2021; Ahlers et al., 2014). The century-and-a-half-long dispute over Helmand River water rights is unresolved and increasingly fraught. As Price and Hakima (2019) note, shared rivers in arid regions often lead not to cooperation, but to stalemate and conflict. This hydropolitical standoff has produced a kind of managed collapse, in which inaction and water scarcity functionally deprive downstream communities of their environmental lifelines. Iranian territory encompasses the majority of the former lakebed but has little control over water access. Agriculture has suffered, ecological baselines have eroded, and the archaeological landscape is increasingly threatened by physical damage. Further damage is caused by the Wind of 120 Days (Groll et al., 2019), a persistent, high-velocity wind system driven by pressure differences between the Hindu Kush highlands and the Iranian Plateau's thermal lows. As Lake Hāmūn has dried, its exposed silt beds have become a significant source of airborne dust. The result is a dramatic increase in dust storms, which reduce visibility, impact public health, and can actively displace archaeological materials (Alizadeh-Choobari et al., 2014; Miri et al., 2021). These winds reshape the archaeological surface, burying, eroding, exposing, or destroying sites (Rouhani and Huet, 2024).

5.3. Archaeological Context and Constraints

The Sistan Basin is a densely inhabited landscape with over 5,000 years of known cultural activity, with a current (known) chronology spanning from the Bronze Age to the Post-Timurid period (Table 5.1). Despite its importance, the archaeological record of Sistan remains fragmentary. International, national, and neighbouring conflicts have further contributed to this region's intermittent and relatively less explored nature. Nonetheless, the Sistan Basin has seen archaeological investigations conducted by international and local archaeologists (Abdi, 2001). Some of the earliest fieldwork in the region was conducted by Stein between 1926 and 1937, establishing connections with the Indus Valley and documenting painted wares and funerary structures (Stein, 1928).

Table 5.1. Chronology of Sistan from Trousdal et al., 2024

Bronze Age	3000 – 2000 BCE
Middle Bronze Age	2000 – 700 BCE
Early Iron Age	1200 – 700 BCE
Median	700 – 500 BCE
Achaemenid	500 – 300 BCE
Hellenistic	300 – 100 BCE
Parthian	100 BCE – 200 CE
Sasanian	200 – 700 CE
Early Islamic	700 – 800 CE
Saffarid	800 – 1000 CE
Ghaznavid	1000 – 1200 CE
Ghorid	1200 – 1400 CE
Timurid	1400 – 1500 CE
Post-Timurid	1500 – Present CE

Dedicated archaeological efforts in the Sistan Basin were carried out in the 1930s by the Hackin-Carl-Meunié mission (Hackin et al., 1959), followed by colleagues who excavated nearby sites throughout the nineteenth century (Dales, 1977; Fairservis, 1961). Notably, Fairservis excavated and surveyed the surrounding landscape in southwestern Afghanistan and Eastern Iran from 1949 to 1951 (Fairservis, 1961). His work marked one of the first detailed surveys of the region since the early observational reports. Fairservis's survey presented a comprehensive summary of his findings, correlating different periods with specific areas and drawing explicit connections with Stein's work (1937), particularly emphasising consistency in painted wares. Following Fairservis in 1966, a survey of the Helmand Valley (the more expansive valley, including the region of Sistan) identified 45 sites, confirming the presence of prehistoric occupation in the region (Hammond, 1970). The most recent and extensive archaeological undertaking in Sistan, the Helmand Sistan Project, took place from 1971 to 1979 (Trousdale et al., 2022). This project not only documented 200 sites from the Bronze Age to the present day but also synthesised and built upon previous research efforts in the region. It aimed to provide a comprehensive cultural overview of the region's past and present. The Helmand Sistan Project is one of the area's last large-scale and long-term research initiatives. However, the project was forced to conclude early due to safety issues and disruptions caused by the Soviet invasion of 1979. Subsequent ongoing internal and international conflicts have further compromised the feasibility of international (and, in many instances, national) scholars' archaeological exploration of the region. For example, the protracted war in Afghanistan, involving the United States and Taliban leadership, persisted from 2001 to 2021. Additionally, the Sistan and Baluchestan insurgency (Elliott, 2020) and ongoing conflicts along the Sistan border between Afghanistan and Iran (Nagheeby, 2023; MirlotfI & Jahantigh, 2018) have made archaeological fieldwork exceedingly difficult at the time of writing.

The Central Helmand Archaeological Study, conducted under U.S. Department of Defense oversight in the 2000s, used satellite imagery to revisit known sites and identify new ones (Abramiuk, 2019). Other datasets, most notably the EAMENA database, have attempted to centralize and standardize archaeological records across the region. Even so, much of the archaeological map of Sistan remains uncharted or unevenly documented. The region has been impacted by decades of armed conflict, insurgency, and border instability. Large parts of Afghan Sistan remain inaccessible to international researchers, while Iranian Sistan faces both internal insurgency (for example, Sistan and Baluchestan) and logistical neglect. In Afghan Sistan**,** heritage preservation has largely collapsed: decades of war, civil unrest, and Taliban rule have led to the systemic destruction of archaeological sites. The Taliban's industrial-scale damage to sites like Mes Aynak, together with rampant looting and loss of museum holdings, estimated as high as 70 percent, underline a region effectively closed to international researchers and heritage protection efforts. (Fitz Gibbon, 2024). On the Iranian side, Sistan and Baluchestan province has endured persistent insurgency, particularly from armed Baloch separatist groups such as Jaish al-Adl, creating an inherently unstable environment, hindering heritage governance. Ethnic-based discrimination, state marginalization, and chronic underdevelopment further erode any institutional capacity for preservation (International Crisis Group, 2025). The absence of proactive heritage protection mechanisms is especially evident: Iran's cultural institutions have frequently exhibited

underinvestment and reactive responses, closing museums only after crises or moving artifacts to storage during emergencies rather than sustained, regionally oriented preservation programs (Geranpayeh, 2025). Collectively, these dynamics suggest that cultural heritage across the broader Sistan Basin faces not only environmental threats but also a profound institutional void.

5.4. Methodology: Detecting Desertification

5.4.1. Geospatial Approaches to Desertification

Many approaches to remote sensing relevant to desertification assessment employ indices such as Albedo, the Bare Soil Index (BSI), and the Soil Adjusted Vegetation Index (SAVI), all of which have proven effective in arid and semi-arid settings and would be suitable for addressing Sistan's desertification challenges (Rivera-Marin et al. 2022; Zolfaghari 2022). The present methodology, however, prioritises simplicity and reproducibility over maximal analytical complexity, relying on a streamlined set of indices that, when correlated with ancillary environmental data, can generate accurate, sufficiently detailed results without demanding extensive processing expertise or time. For this reason, variables were intentionally limited to five: the three indices, wind speed, and elevation. By comparison, other desertification studies incorporate anywhere from one to nine variables (Rivera-Marin et al. 2022). This pared-down framework is meant to facilitate replication across diverse landscapes, allowing researchers to add or omit variables as conditions require while retaining methodological consistency.

The broader methodological response to desertification in archaeology has become increasingly sophisticated. Classical environmental-archaeological techniques, pollen, phytoliths, charcoal, faunal assemblages, and sedimentary proxies, remain foundational for reconstructing long-term trajectories of vegetation loss, erosion, and hydrological decline (Rosen 2007). Geoarchaeological studies, including those in Wadi Faynan and the Vera Basin, integrate stratigraphic analysis, soil chemistry, and geomorphological survey to trace how human land use contributed to shifting desert margins (Hunt et al. 2004). Remote sensing has further transformed the field: multi-temporal satellite datasets enable researchers to monitor vegetation degradation, dune migration, settlement abandonment, and broader landscape restructuring at scales unattainable through ground survey alone (Rayne et al. 2023). Large-scale initiatives such as EAMENA demonstrate how semi-automated classification and systematic monitoring can be deployed to identify, document, and track the deterioration of dryland heritage (Bewley et al. 2016). Together, these methodological developments show a field increasingly capable of capturing both the pace and complexity of desertification, even as researchers seek tools that balance analytical rigour with practical applicability.

5.4.2. Case Study Methodology

To characterise desertification as a hazard in Sistan, this study employs remote sensing methodology (Figure 5.3) designed to detect and map the spatial extent and temporal progression of desertification between 2015 and 2021. The aim is not merely to document desertification as a land

cover category, but to model it as an evolving process that generates measurable archaeological risk. This approach allows for the identification of hazard intensification zones, areas where site exposure, visibility loss, and sediment displacement are most likely to occur or accelerate. The methodology centres on a time series of open-access satellite imagery acquired from the Landsat 8 OLI archive. Images were sourced via the USGS EarthExplorer platform from Level-2, Collection 2, Tier 1 surface reflectance products. The imagery was filtered for cloud cover and temporal consistency, then merged into a single image for each year. These years were selected to span a sufficient interval to capture both gradual degradation and significant short-term landscape anomalies. In total, 2,185 images (Table 5.2) were incorporated, with mosaics generated using cloud masking, seasonal control, and surface reflectance standardisation.

The rationale for these temporal benchmarks is the need to understand desertification as a fluctuating process. Sistan is a region where degradation and opportunity coexist; sand may obscure one feature while simultaneously exposing another. Capturing this movement over time, rather than relying on a single static image, provides the spatial and temporal depth needed to model

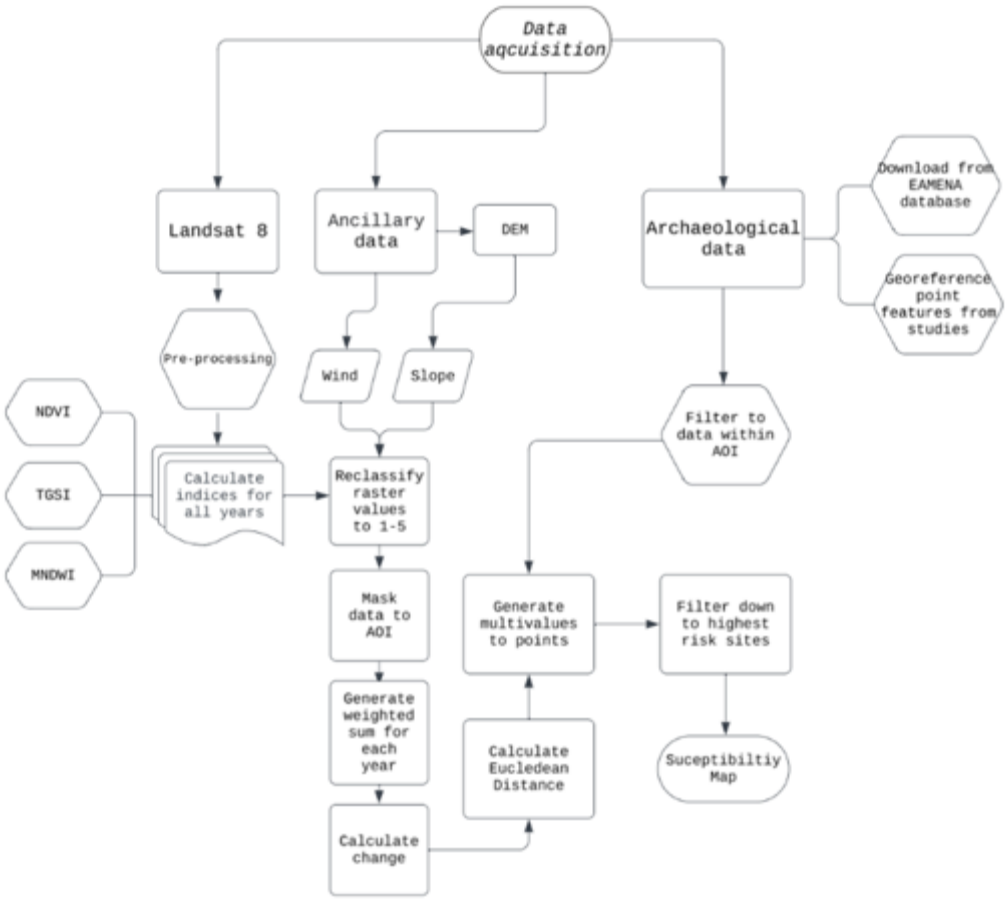


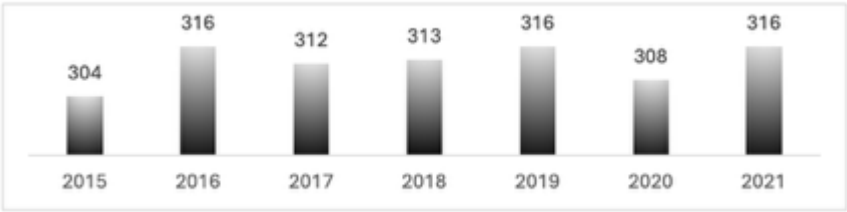
Figure 5. 3. Desertification change detection workflow

desertification as an archaeological hazard. Imagery includes composite images each year, with total image counts per year exceeding 300 (Table 5.3).

Table 5.2. Imagery data sources and specifications

Platform/Sensor	Processing Level	Dataset Type	Images	Dates
Landsat 8 Operational Land Imager (OLI)	Collection 2, Tier 1	Surface reflectance	2,185	January 2015–December 2021

Table 5.3. Total images per year as utilised in the composite



To detect and quantify desertification progression, three spectral indices (Figure 5.4) were employed, each serving as a proxy for a key dimension of land degradation. First, the Normalized Difference Vegetation Index (NDVI) was used to assess vegetation presence and health. NDVI is sensitive to chlorophyll content and serves as a reliable indicator of ecological vitality. In the Sistan context, where most vegetation is fragile and marginal, sustained declines in NDVI can signal both drought and land abandonment (Yengoh et al., 2015). Sites within low-NDVI zones are more likely to face visibility loss, wind exposure, and sediment encroachment (Yengoh et al., 2015). Second, the Topsoil Grain Size Index (TGSI) was used to assess the surface composition of soil, particularly its relative coarseness. High TGSI values can indicate areas with larger-grain, sandier surfaces, features that correlate closely with regions of wind erosion, dust emission, and archaeological burial (Micieta and Murín, 2018). TGSI is particularly valuable in Sistan, where sand movement is a primary vector of material obscuration and destruction. Third, the Modified Normalized Difference Water Index (MNDWI) was selected to map the presence of surface water features, particularly those associated with Lake Hāmūn and the surrounding wetlands. This index is especially effective in identifying ephemeral water bodies and drying wetland zones, which are often the first indicators of long-term hydrological collapse (Herlita et al., 2025). As Lake Hāmūn receded over the past two decades, these areas have transformed from riparian landscapes to desiccated dust sources. MNDWI can assist in tracing that transition and highlighting its implications. The indices were calculated for each observation year and reclassified between the 1-to-5 value range to allow for consistent combination between layers. High index values were interpreted as indicators of greater susceptibility to desertification. NDVI and MNDWI values approaching zero or negative were considered strong signals of vegetation collapse and moisture loss, whereas high TGSI values

indicated increasing sand content and wind exposure risk. Further unpacking of each index is provided below:

Normalised Difference Vegetation Index (NDVI):
NDVI measures the extent of and health of vegetation. NDVI is calculated by measuring the difference between the vegetation-reflective near-infrared (NIR) and the vegetation-absorbing red (R) bands (Equation 5.1). The chlorophyll in vegetation reflects NIR and green light while absorbing red and blue light. NDVI values range from -1 to 1, with higher values indicating denser vegetation and lower values likely indicating water. In the instance of NDVI values closer to zero, it likely means a lack of vegetation.

Top Grain Soil Index (TGSI):
TGSI computes the grain size of topsoil. TGSI is calculated utilising the Red (R), Blue (B), and Green (G) bands (Equation 5.2). TGSI values range between -1 and 1. Negative values correlate with less or no sand, and values <0.20 indicate sand cover (Mihi et al., 2022, p. 385).

Modified Normalized Difference Water Index (MNDWI):

MNDWI indicates the presence of water in imagery using the Green and Short-Wave Infrared (SWIR) Bands (Equation 5.3). MNDWI values range from -1 to 1, 1 corresponding to higher water values. MNDWI can also diminish built-up features that may be falsely interpreted as water (Singh et al., 2015). MNDWI is helpful in the present case study due to the unknown extent of water resources across Sistan.

$$(5.1) \quad NDVI = \frac{GREEN - NIR}{GREEN + NIR}$$

$$(5.2) \quad TGSI = \frac{RED - BLUE}{RED + BLUE + GREEN}$$

$$(5.3) \quad MNDWI = \frac{GREEN - SWIR}{GREEN + SWIR}$$

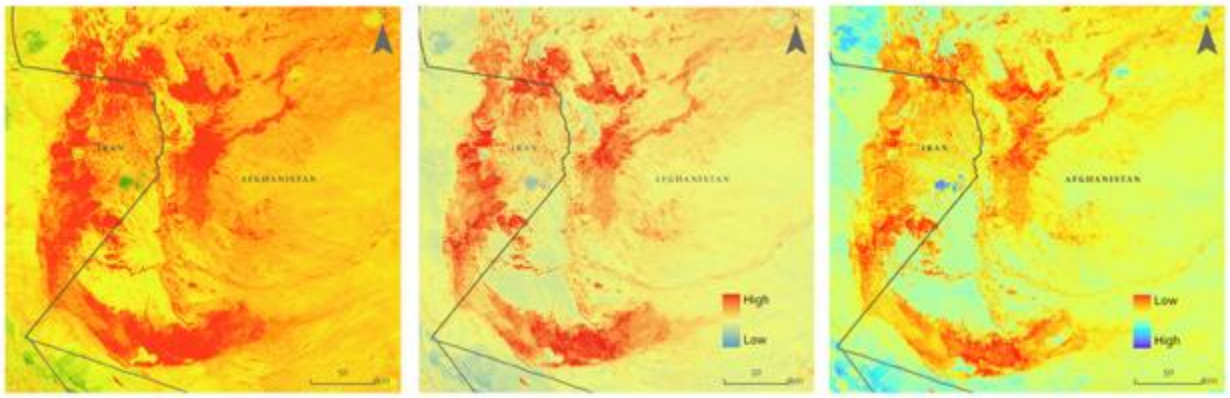


Figure 5.4. Visualised individual indices, from left to right: NDVI; TGSI; MNDWI

In addition to the above spectral indices, two environmental variables were added to contextualise landscape susceptibility. Slope was derived from STRM DEM, with steeper slopes identified as more susceptible to erosion and sediment redistribution. Wind speed data were sourced from the Global Wind Atlas,[29] which represents average annual wind intensity across the Basin. Although the spatial resolution of the wind data was coarser than that of the other layers, its inclusion was critical for modelling the aeolian component of desertification, particularly in the eastern lowlands and near the Hāmūn margins. All five variables, vegetation, soil texture, moisture, slope, and wind, were then composited using a weighted overlay approach.

All five variables, vegetation condition, soil texture, surface moisture, slope, and wind intensity, were composited through a weighted overlay procedure. Reflecting their higher spatial fidelity and direct environmental relevance, the three spectral indices were collectively assigned 75% of the weight (NDVI 0.30, TGSI 0.25, MNDWI 0.20). Slope, as a geomorphological modifier of risk, was given a moderate weight of 0.15. Wind speed, despite its importance in aeolian processes, received a minimal weight of 0.10 due to the data's coarse resolution. The resulting composite raster for each year represents the relative susceptibility of each cell to desertification across the Basin. The final product for each year was a raster surface representing the composite susceptibility of each cell to desertification.

With the composite hazard surfaces generated for each year, a temporal change analysis was conducted to identify zones of increasing or decreasing susceptibility. This was done by subtracting each raster from the next, generating delta surfaces that visualise the progression of desertification across the study period (Equation 5.4). The result is a dynamic record of change, highlighting which areas are undergoing degradation most rapidly, and which may be stabilizing or even temporarily recovering.

$$Change = Year_{Final} - Year_{Initial} \quad (5.4)$$

[29] https://globalwindatlas.info/en/

5.4.3. Results

Desertification trends for 2015–2021 were significant, with the model indicating an overall increase in desertification. The areas most affected include regions to the north, east, and west of Lake Hāmūn and to the south and southwest of the southernmost portion of the Helmand River. Lower levels of desertification were observed in the far west, northwest, and central plains near Helmand. These regions were expected to yield lower desertification, as they include either built-up urban centres (for example, Zabul in Iran) or areas of intensive irrigation in Afghanistan, often correlated with poppy production (UNODC Afghanistan Opium Survey, 2019). The years 2015 (Figure 5.5 a) and 2017 (Figure 5.5 b) experienced high levels of desertification, while 2020 (Figure 5.5 c) showed a notable decrease (see Figure 5.6 showcasing 2020 desertification levels). In contrast, 2021 again

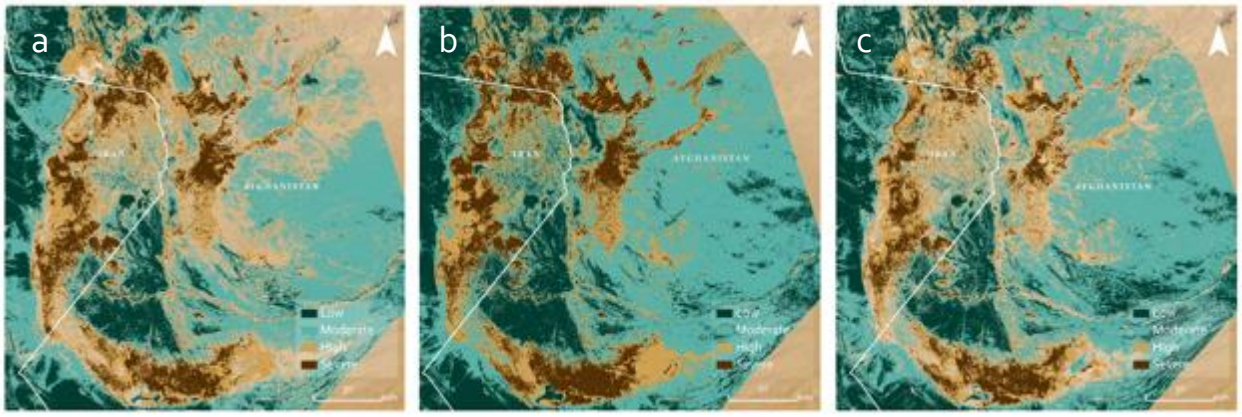


Figure 5.5. a. Desertification result 2015; b. Desertification result 2017; c. Desertification result 2021

yielded high levels of desertification. Elevated desertification between 2015 and 2020 aligns with expectations based on ongoing droughts (Miri et al., 2010; Middleton, 1986; Whitney, 2006) and inequitable water allocation from the Helmand River (Saatsaz, 2020; Darvishi Boloorani, 2022). The reduction in 2020 was expected due to flooding (Rajabi, 2020). Although flooding may appear to mitigate desertification, it can be hazardous when interacting with hardened, desiccated soils that limit infiltration (Kreibich et al., 2022; Saco et al., 2021). Such conditions increase flood velocity and pose risks to and archaeological resources (Anderson, 2023). By 2021, desertification had returned to pre-flood levels. The 2020 flood illustrates the interplay between drought and extreme precipitation: rather than counteracting drought, flooding exacerbates its impacts, as the two processes reinforce one another (Zhou, 2023). This drought–flood abrupt alternation (DFAA)

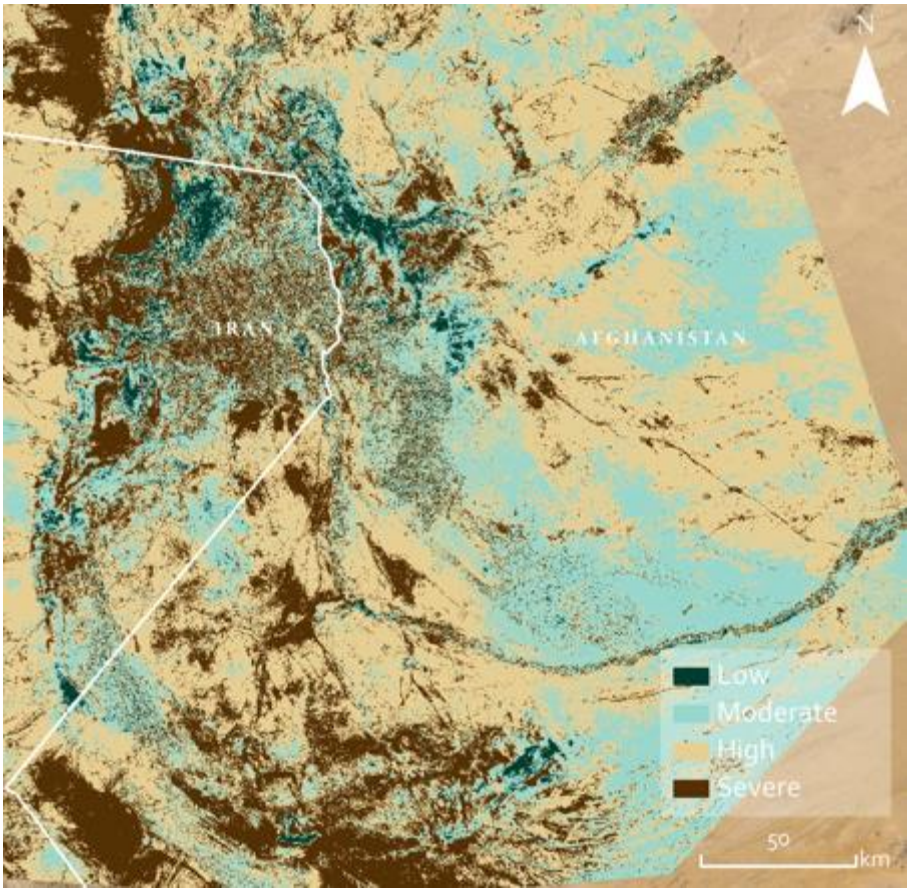


Figure 5. 6. Desertification level 2020, showcasing a decrease due to flooding

phenomenon is becoming more common under rising global temperatures (Bai et al., 2023; Abd-Elaty; 2022). The documented interplay between the DFAA and archaeology highlights additional risks beyond desertification.

Across the study area, desertification followed a consistent spatial pattern, with a pronounced build-up in the plain to the south and southwest. The pattern 'rounded' along the topography from the southeast and southwest toward the northwest. Overall, desertification increased from 2015 to

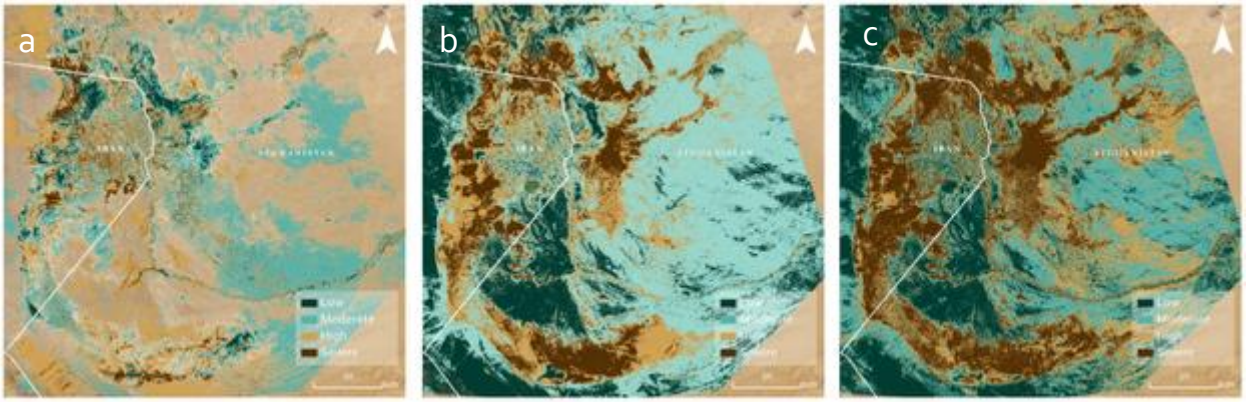


Figure 5. 7. a. Change 2015 to 2021; b. Change 2015 to 2017; c. Change 2020 to 2021

2021, despite the temporary reduction most likely instigated by the 2020 flood (Figure 5.7 a). From 2015 to 2017, desertification rose sharply (Figure 5.7.b), and from 2017 to 2021 it continued to increase, though at a slower rate (Figure 5.7.c). Near Lake Hāmūn, desertification rates remained high throughout the period, with the sole exception of 2020, after which desertification resumed in 2021.

5.4.4. Validation

To validate the desertification model, outputs were compared against a set of independent studies on hydrology, dust production, and land degradation in the region. Several key findings aligned closely with the model results. For example, Akbari and Torabi Haghighi (2022) document the sharp decline in surface water availability following the expansion of upstream irrigation and dam construction in Afghanistan. Similarly, Darvishi Boloorani et al. (2022) report up to an 80% increase in dust storm frequency as a result of the drying of Lake Hāmūn and surrounding wetlands. These studies corroborate the spatial patterns detected by the current model, particularly in the eastern and southeastern portions of the Basin. Of particular significance is the spatial asymmetry of desertification across the Basin. Areas within Afghanistan that remain under irrigation, particularly those supporting poppy cultivation, show consistently lower desertification values, with more stable NDVI and TGSI readings. By contrast, downstream Iranian zones, deprived of water and institutional support, show escalating hazard values. This spatial differentiation, visible in both the spectral indices and the composite hazard surface, confirms the model's sensitivity. The flood year of 2020 also aligns with external records. Studies of DFAA patterns in parts of Central Asia confirm the phenomenon of erosion-amplifying floods following extended drought (Bai et al., 2023). These findings suggest that the desertification model not only captures long-term degradation but is also responsive to short-term anomalies and their compound effects.

To fully understand the complex impacts of desertification across the Sistan Basin, it is important to underscore the disproportionate extent of desertification on the Iranian side of Sistan compared to the Afghan side. Once a well-integrated region, Sistan relied heavily on the qanat system for water transport (Hein, 2019). Technological advances accelerated the widespread adoption of regions like Sistan, eventually creating what appeared to be more stable ways to access water resources (Nasiri et al., 2015). The Helmand River flows through most of its length through Afghanistan. Most croplands in Iran and Afghanistan are located near rivers due to fertile soil and ease of access to water (Akbari et al., 2022; 2021). Afghanistan supplies over 80% of the global opium due to poppy cultivation (Simms et al., 2023). More relevantly, of the more than 200,000 hectares of Afghanistan utilised for poppy cultivation, over 120,000 hectares are located within the Helmand province (UNODC, 2022), which runs into Sistan. The flow of the Helmand River was interrupted by the construction of the Kamal Khan Dam in 2021 (Akbari et al., 2022). The impact of the redirection and utilisation of water resources from the Helmand River for Afghanistan's agricultural and illicit cultivation can be correlated with the decline in water levels at Lake Hāmūn (Akbari et al., 2022). The results of the desertification study directly reveal changes in desertification levels in the region around the Kamal Khan Dam, as well as lower desertification levels in Helmand province, where poppy cultivation is highest (Figure 5.8). This correlation between the current results, which show lower levels of desertification along the Afghanistan portion of Sistan, and a marked increase in desertification following the 2021 operation of the dam helps validate the current method's accuracy in predicting desertification in Sistan.

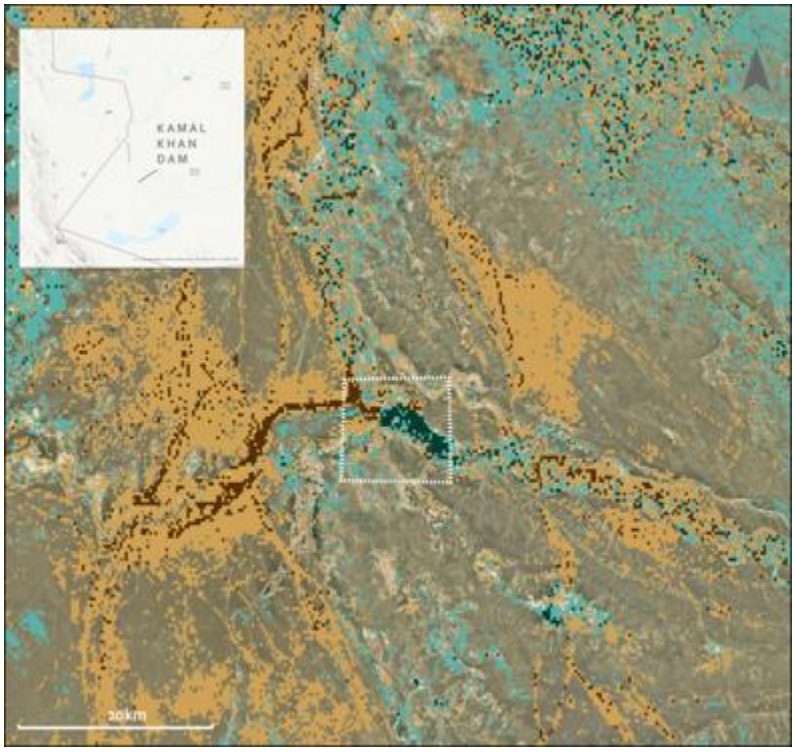


Figure 5. 8. Desertification results near the Kamal Khan Dam

Beyond internal consistency checks, the desertification model was validated against independent regional research, most notably the study by Omidvar et al. (2024) on drought monitoring in Sistan and Balouchestan Province. Their analysis combined MODIS-derived vegetation indices (with GRACE satellite data on groundwater and total water storage deficits to reconstruct drought conditions between 2002 and 2017. This long-term multi-sensor dataset provides a resolution-robust external benchmark for the present hazard model. The study utilizes low resolution imagery, as opposed to the current case study's medium-resolution imagery. However, the study conducted by Omidvar et al. also covers a much larger area, specifically the Iranian Sistan and Baluchestan Province, whereas the current study focuses only on the Sistan Basin's 18,000 square kilometre area (Rouhani & Huet, 2024). A critical point of convergence between Omidvar et al's work and the current case study lies in the demonstrated sensitivity of vegetation indices to precipitation variability. Omidvar et al. show that the Vegetation Health Index (VHI) maintained moderate (0.3–0.7) to strong (≥0.7) correlations with rainfall across more than 95% of the province. This finding is significant because it confirms that remotely sensed vegetation signals track hydrological stress with a high degree of fidelity in this region, even at low resolution. Although the current study employs NDVI rather than VHI, all three indices operate on the same principle: they measure spectral changes in vegetation greenness and canopy condition in response to water availability. The strong VHI–precipitation correlations therefore lend weight to the use of NDVI as a reliable proxy for land degradation.

Spatial validation further strengthens this connection. Both studies identify the southern and central sub-regions of Sistan as consistent drought hotspots, where vegetation stress is most acute and hazard values peak. The overlap in these spatial patterns suggests that the composite desertification model is capturing genuine ecological stress zones rather than artefacts of index processing. Moreover, Omidvar et al. highlight the role of cumulative hydrological depletion, estimating a total water storage loss of ~12.2 km^3 across all 50 sub-basins between 2012 and 2016. This result parallels the elevated hazard scores generated by the present model, providing independent evidence that groundwater decline and surface degradation are occurring concurrently. Taken together, these convergences demonstrate that the present desertification model is externally validated against independent drought monitoring. By aligning with multi-sensor evidence from both vegetation and hydrological domains, the model is shown to be sensitive to the dual pressures of surface ecological degradation and subsurface water scarcity. This cross-validation underscores the robustness of the hazard mapping framework and reinforces its suitability for exposure assessment, particularly in data-limited regions where ground-truthing is constrained.

By relying on open-access data, straightforward processing methods, and clearly interpretable indices, the method provides a replicable hazard-mapping framework for other arid or conflict-affected regions where ground-truthing is limited or impossible. From a DRR perspective, this model contributes directly to understanding archaeological hazard exposure in slow-onset disaster environments. It moves beyond static classifications and embraces the temporally dynamic nature of risk. Its outputs, both single-year rasters and temporal change maps, provide a foundation for exposure assessment and spatial triage. The following section builds directly on this hazard surface,

integrating it with archaeological records to determine which known sites lie in the path of desertification and which may already be partially or completely lost.

5.4.5. Exposure: Records in the Path of Desertification

In a region where field access is restricted, survey coverage is inconsistent, and environmental volatility is high, exposure must be treated as more than proximity to hazard; it must be understood as the physical intersection between known archaeological features and dynamic environmental degradation. This section operationalises exposure as the spatial overlay between the desertification hazard surfaces produced and the distribution of known archaeological records across the Sistan Basin. The result is an estimate of which records are located within zones of accelerating change and thus face an elevated risk of impact. The archaeological dataset used in this analysis draws on multiple sources, each with its own temporal, methodological, and political context. The base layer was compiled from digitised records of the Helmand-Sistan Project (1971–1979), a survey which included sites across the Afghan and Iranian sectors of the Basin. These records were supplemented with georeferenced site data from Fairservis's earlier survey work (1959–1963), as well as published and unpublished documentation from EAMENA, which has developed a regional inventory of cultural features using satellite imagery and legacy documentation. Where spatial uncertainty was present, particularly in legacy records lacking consistent ground control, site locations were estimated using a combination of visual alignment with satellite imagery and historical map rectification. While this introduces a degree of positional error, the purpose of this exposure analysis is not to provide exact level predictions, but to identify broad patterns of risk across the archaeological landscape. The final dataset includes over 250 archaeological records, representing a range of site types.

5.5. Vulnerability for Sistan

The analytical framework applied in the previous case studies (exposure multiplied by vulnerability, divided by capacity) was also applied to Sistan. Yet this region presented distinct methodological challenges. Beyond the physical inaccessibility of the landscape, the search for reliable vulnerability variables was severely constrained by limited and inconsistent data availability. Consequently, the analysis could proceed only by selectively incorporating variables that, while imperfect, offered partial insight into Sistan's vulnerability profile. Conflict-occurrence data from Iran and Afghanistan were included due to their regional relevance. The justification for treating conflict as a variable rest on established scholarship (Al-Obaidi et al., 2022; Bächler, 1994; Luca Raineri, 2022) documenting the environmental consequences of conflict, including land degradation, population displacement, and disruption of resource management systems.

A further variable incorporated into the framework was the border wall constructed by Iran along the Afghanistan–Iran frontier of Sistan. While a physical infrastructure, the wall was operationalized within the model as a proxy indicator of conflict, given its implications for cross-border tensions and resource access. Finally, the exposure raster developed in the preceding analysis was incorporated

as a proximity variable. This layer, enhanced by the DEM embedded within the exposure model, provided a critical spatial dimension for assessing how vulnerability variables interact with landscape morphology. Together, these components, though limited in scope, represent the only viable means of approximating Sistan's vulnerability under the adopted framework.

Conflict point data for 2020-2021 from the Humanitarian Data Exchange[30] were incorporated using kernel density estimation and subsequently rasterized (Figure 5.9). The remaining vector datasets, the border wall and associated conflict zones, were also rasterized, reclassified on a scale of 1 to 5, and combined under successive weighting schemes to assess sensitivity and influence. The Afghanistan conflict raster was divided into three intensity classes: low (1–999), medium (1000–4999), and high (≥5000), scaled to a 0–1 range. The Iranian conflict and border wall layers were simplified into binary presence–absence indicators, while the exposure raster remained continuous. This refinement enabled a more granular depiction of conflict intensity within the composite surface.

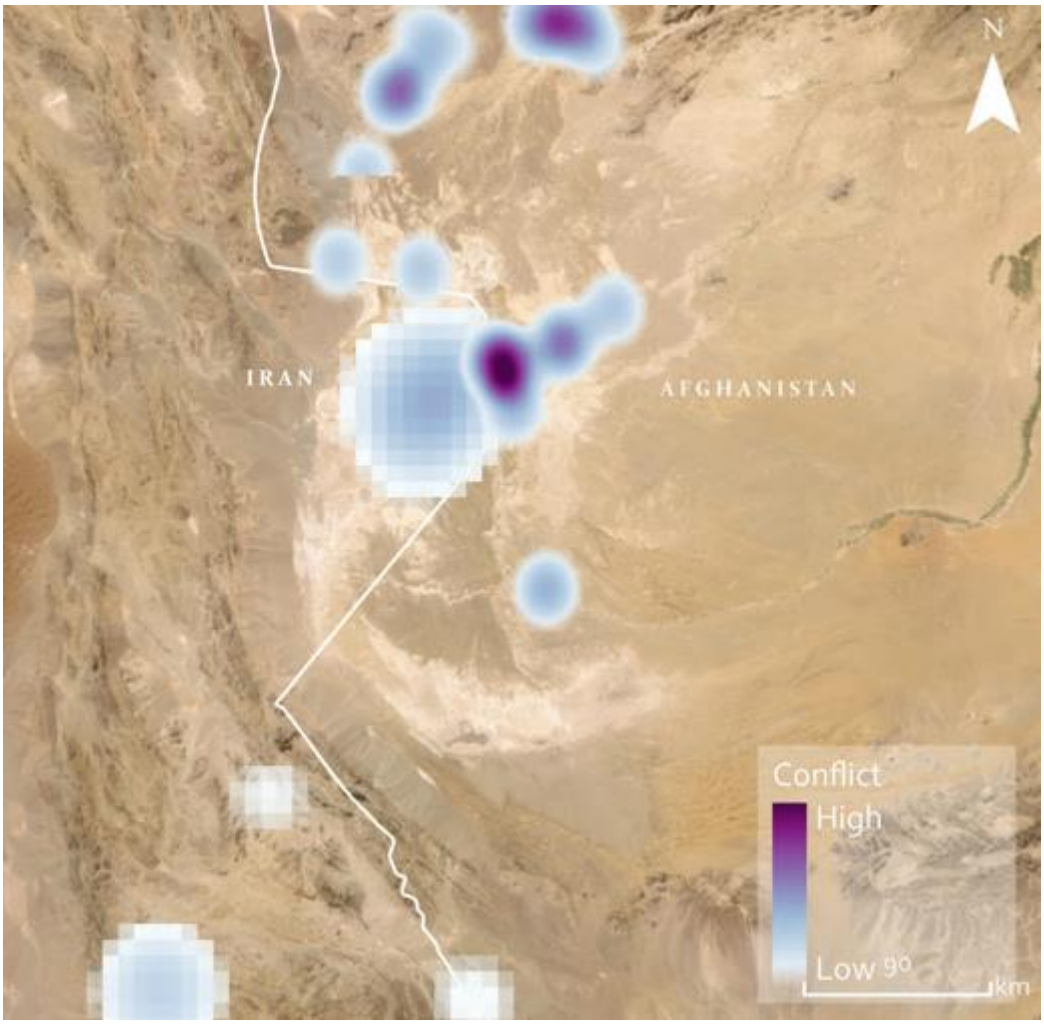


Figure 5.9. Conflict data kernel density for Iran and Afghanistan

[30] https://data.humdata.org/dataset/acled-data-for-afghanistan https://data.humdata.org/dataset/acled-data-for-iran

In the first weighting attempt, all four variables: exposure, conflict data, and border proximity, were assigned equal weights (exposure = 25%, conflict data 50%, border = 25%). Each layer was normalized to a 0–1 scale and combined to produce a balanced composite surface that assumed uniform influence among all contributing factors. The conflict data was weighted at 50% to combine the two conflict datasets (Iran and Afghanistan).

The second weighting attempt introduced differentiated weights to reflect variable reliability and influence, assigning exposure = 40%, conflict 40%, and border = 20%. Each raster was resampled to the exposure grid, reclassified, and normalized to 0-1 before integration. This configuration emphasized the dominant role of environmental exposure in determining vulnerability while retaining geopolitical and infrastructural pressures as meaningful secondary contributors.

The weighting rationale across all iterations was grounded in data quality and spatial coverage considerations, as the available datasets were neither comprehensive nor spatially extensive. Despite the adjustments, the resulting composites added minimal quantitative or qualitative explanatory power beyond the exposure raster (see the visual comparison in Figure 5.10 a and b). The persistence of this outcome indicated that the conflict and infrastructural datasets lacked sufficient density and spatial resolution and were therefore overshadowed by the higher-quality exposure surface.

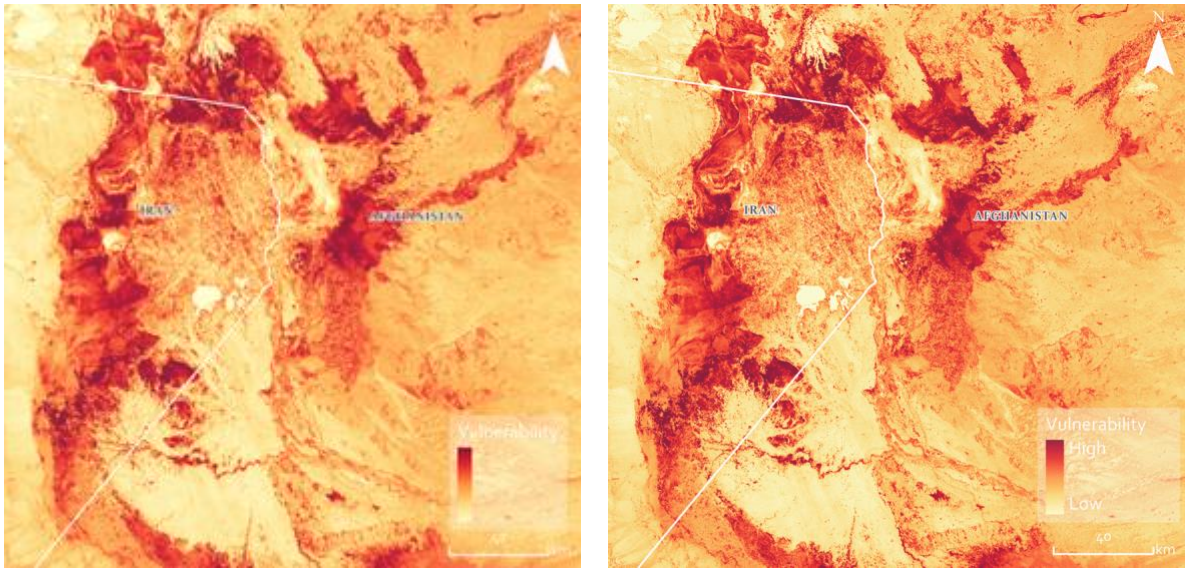


Figure 5.10. a. Vulnerability, equal weights; b. vulnerability, weighted: 40/20/20

This issue illuminated other pathways that both provide further meaning to the incorporation of DRR, geospatial approaches, and archaeology. In the Sistan Basin, vulnerability is less a matter of material fragility than of structural absence. It is produced not only by what survives of the past, but by the institutional and environmental conditions that determine whether that past can be seen, studied, or protected. The preceding case studies mapped vulnerability, emphasizing proximity to infrastructure or population density. In contrast, the Sistan case shows that the critical variables are the absence of access, the absence of governance, and the absence of current documentation. The

most endangered features are not necessarily those built in mudbrick but those that lie just beyond survey coverage, within inaccessible zones, or beneath newly desiccated floodplains. They are vulnerable precisely because no one can observe or intervene. This study, therefore, conceptualises vulnerability not as a score attached to individual sites but as a spatial condition of inoperability, zones where environmental change is accelerating while archaeological presence remains ambiguous or invisible. In DRR terms, this aligns with Priority 3: reducing underlying risk factors, particularly where those factors are the result of knowledge gaps, administrative vacuums, and chronic inattention (UNDRR, 2025).

5.5.1. Archaeological Vulnerability in Sistan

In the Sistan Basin, vulnerability cannot be reduced to the fragility of archaeological sites or the extent of site(s) protection. Rather, it emerges as a compound condition of the intersection of accelerating desertification processes and the absence of institutional systems capable of recognising or mitigating their effects. Vulnerability here is thus defined not as a score assigned to individual sites, but as a structural and spatial condition that permits archaeological loss to proceed without intervention.

Two dimensions of this condition can be identified. The first is environmental inoperability, visible in the rapid transformations recorded across the Basin: the drying and vegetation collapse around the margins of Lake Hāmūn; dune encroachment and sediment transport along the eastern corridors; and the desiccation of once-irrigated Helmand delta landscapes. In these settings, the stability of the surface can shift within weeks, alternately exposing and burying features. Archaeological visibility, and with it any possibility of documentation, becomes contingent on volatile cycles of drought, flood, and wind reworking. The second is institutional inoperability, produced through governance gaps, documentation deficits, and the erosion of archaeological infrastructure. In the Iranian sector, oversight by the Cultural Heritage, Handicrafts, and Tourism Organization (CHHTO) remains largely nominal, with no permanent monitoring in the southeast and limited conservation investment. Across the Afghan frontier, decades of conflict and insecurity have curtailed any sustained archaeological presence. What records exist derive primarily from mid-twentieth-century surveys (for example, the Helmand Sistan Project).

Taken together, these dimensions shift the analytical focus. The operative question is no longer ‘What is likely to be impacted?’ but ‘Where is impact occurring beyond the reach of observation or intervention?’ Within the DRR model, hazard expresses the probability of environmental change, and exposure identifies the placement of sites within that change. Vulnerability, by contrast, signals whether any institutional or methodological apparatus exists to detect or respond. High vulnerability in Sistan does not necessarily imply that a site will vanish in the next season; rather, if it does, it will pass unnoticed, with no possibility of rescue or response. This interpretation reconceives vulnerability as the failure point of systems, documentation systems, monitoring systems, and conservation infrastructures, rather than as a quality inherent to archaeological remains. Framed in this way, vulnerability in Sistan aligns directly with Priority 3 of the DRR framework: the reduction of

underlying risk factors. Here, risk is not mitigated through reinforcement of individual assets but through interventions that address the structural conditions: absence of access, absence of governance, and absence of documentation, which allow archaeological loss to proceed unchallenged.

5.6. Spatial Salvage

In the preceding case studies, spatial triage served as a bridge between composite risk modelling and decision-making. By systematically combining hazard, exposure, vulnerability, and capacity, it was possible to establish a defensible hierarchy of archaeological priorities. Within those contexts, triage operated as intended within the DRR framework, directing resources to where meaningful intervention was still possible. The same systematic procedure was attempted for Sistan. However, in this setting, high vulnerability represents total obstruction to action, while *low* capacity cannot be distinguished from a complete *absence* of capacity. This is the point where the logic of triage diverges. Triage presupposes an intervention framework (governmental, institutional, or otherwise) that can act and mobilise resources. In Sistan, that apparatus is absent, and the result is a methodological paradox: the model could successfully identify priorities, but those priorities cannot be translated into intervention. The exercise then becomes diagnostic rather than prescriptive, exposing loss while clarifying why a systematic response cannot proceed.

From a DRR perspective, this outcome is significant. Sendai Priority 4 emphasises preparedness, which usually assumes some degree of institutional presence and the possibility of recovery. In Sistan, preparedness reduces to informational readiness. Triage in this context shifts roles. It functions as an analytical device that demonstrates both where risk is greatest and why response is structurally blocked. The framework rests on four criteria: composite risk level, documentation, accessibility, and archaeological potential. In the earlier studies, each could be operationalised into spatial variable that supported prioritisation. The criteria remain methodologically sound, but the structural conditions of Sistan would render them heuristic rather than operational.

In DRR theory, residual risk acknowledges hazards that cannot be prevented or mitigated and highlights the importance of planning for inevitable loss (UNDRR, 2017). The zones where triage outputs fail to produce actionable categories are precisely those residual risk environments. Their identification maps degradation, but also institutional and epistemic absence. The collapse of triage into diagnosis, therefore, makes visible the structural voids in which archaeological loss advances. The reflexive recognition of this limit strengthens rather than weakens the approach. It shows that DRR frameworks can be applied rigorously to archaeology, but that their portability depends on the presence of governance structures. In Sistan, the breakdown of operational triage marks the threshold where loss moves from potentially manageable to structurally irreversible. By situating absence, inaccessibility, and neglect within residual risk, the Sistan case forces a more direct accounting of what disaster frameworks can achieve when applied to archaeology.

The solution for this in the present study is a reframing of triage as salvage. In this way, triage becomes less a mechanism for directing interventions and more a framework for retaining visibility and salvaging information under constraint. GA functions as salvage by preserving clarity on where loss has the highest potential. In Sistan, this approach increases or mediates capacity to act, not by physically rescuing archaeology, but by digital archiving and retaining the information necessary to recognise patterns of degradation and prepare for future opportunities to respond. Salvage, under these conditions, is the maintenance of visibility and the preservation of knowledge. Framed within DRR Priorities 2–4, salvage becomes an *informational* practice (UNDRR, 2017): strengthening archaeological governance by reducing underlying risk through safeguarding data, modelling potential futures, and enhancing preparedness by sustaining continuous, GA driven awareness in the absence of ground access. What follows details this salvage logic and shows how the present study already enacts it.

5.7. Archaeological Monitoring and Remote Investigation

The integration of remote sensing modelling within this case study provides a critical advance for initiatives such as EAMENA, which have relied primarily on visual interpretation of satellite imagery to populate inventories. By using remote sensing to generate composite hazard surfaces and temporal change trajectories, modelling directs attention to those areas where environmental stress is most acute and accelerating, thereby sharpening the precision of archaeological risk assessments. In practical terms, this means that EAMENA and comparable programmes are no longer constrained to mapping what is visible; they can also prioritise targeting areas where hazards are demonstrably intensifying and archaeological features are most likely to be lost or obscured. Remote sensing modelling thus transforms inventories from static registers into dynamic risk tools, enabling organisations to target monitoring, archival rescue, and capacity-building in the landscapes where intervention, however limited, will have the greatest effect.

This study operationalises monitoring as a temporal surface rather than a set of snapshots. The composite hazard layers (2015/2017/2021) and their deltas identify directional change, sustained NDVI decline, TGSI increase, and moisture loss, and convert them into alerts where trajectories steepen (cf. the DFAA pulse around 2020). In effect, surveillance is upgraded from ‘seeing a site’ to tracking the conditions that make sites appear, disappear, or disintegrate. Projects such as EAMENA have demonstrated the feasibility of remote inventories under conflict and access constraints: standardised records, explicit confidence and location precision, and consistent threat/condition attribution. The consequence is a shift from static risk flags to probabilistic futures: not ‘this site is threatened,’ but ‘this corridor is on a worsening trajectory that will likely remove this site from visibility within x seasons.’ Salvage also can include the consolidation and digitisation of legacy materials (Fairservis; Helmand–Sistan; grey reports). By assigning persistent IDs, encoding georeferencing uncertainty, and linking records to temporal surfaces, the study converts archival fragments into operational data. This is DRR Priority 3 in archaeological form: reducing underlying risk by ensuring that the evidentiary base does not decay with the landscape (UNDRR, 2013).

5.7.1. Record Prioritisation

To demonstrate how this model can move from hazard detection to actionable salvage, the desertification results from the most recent year were used to identify which archaeological records are currently under the greatest threat. Point and polygonal datasets from the EAMENA inventory were georeferenced and intersected with the 2021 composite raster to isolate those that fell within cells classified as 'severe' desertification. This exercise produced approximately 87 high-risk features (Figure 5.11), the majority of which were either undated or Islamic-period records (see Appendix E for a complete list of records included from the EAMENA database). Beyond producing a raw count, this overlay illustrates the power of geospatial-based salvage logic: the density of threatened sites can now be read directly against the density of desertification, exposing where attrition is most acute. Instead of passively registering sites that are already visible, geospatial tools become instruments for identifying where records are most likely to vanish next. In the context of Sistan, this shift matters profoundly. Archaeological records cannot be physically safeguarded, but they can be digitally prioritised, their risk trajectories mapped, and their archival futures secured. By

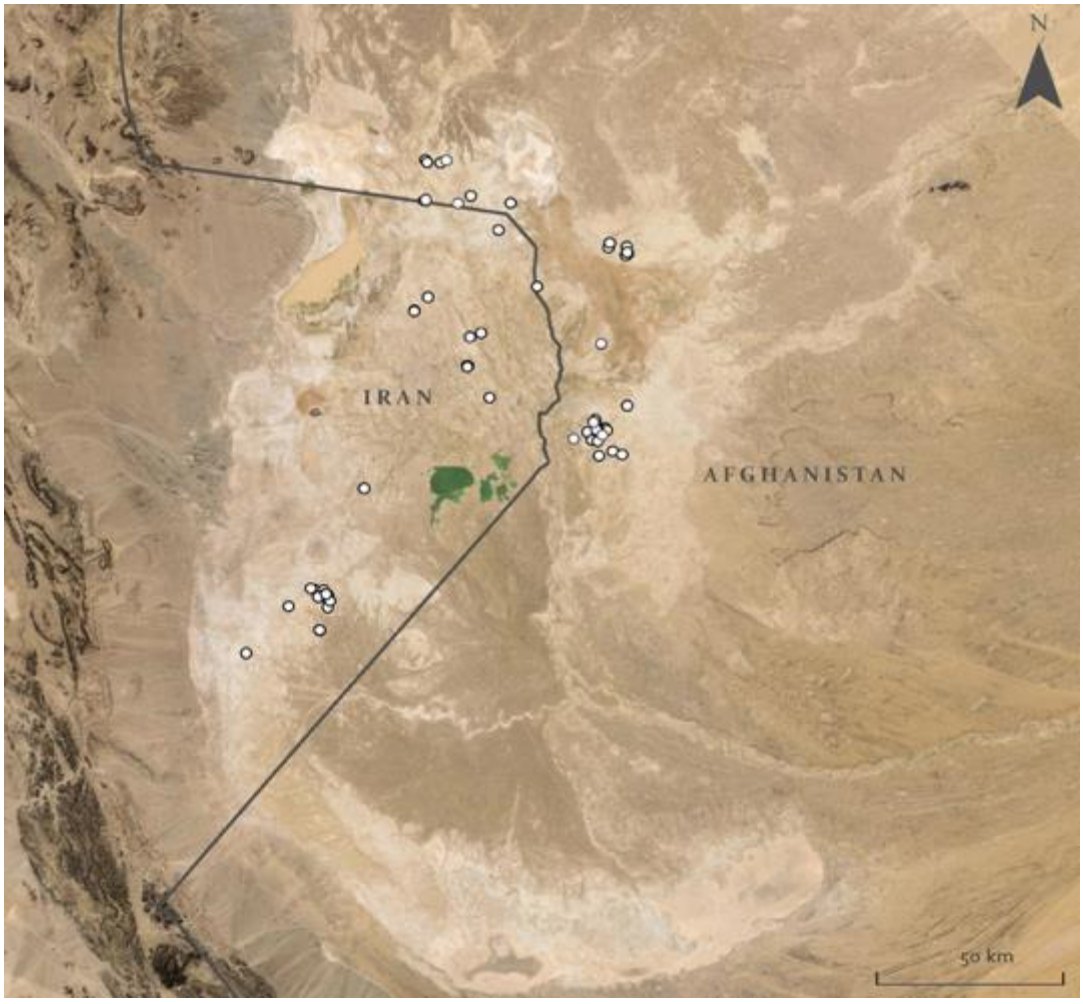


Figure 5.11. Records from the EAMENA database at high risk of desertification

embedding hazard surfaces into record management, the study demonstrates that salvage is not merely about cataloguing what exists, but about triaging what is slipping away fastest.

Fairservis' collection of 114 sites left 6 at high risk of desertification (Figure 5.12). These sites are titled sites 11, 19, 26, 39, 41, 42, 43, and 109, which he describes in detail (Fairservis, 1961). Site 11 includes a group of ruins with multiple pottery indicators in bright green, blue, and glazed painted patterns (Fairservis, 1961, p. 40). Site 19 includes low rectangular, square, and irregular mounds, from 10 to 30 feet tall and even some reaching up to 300 feet, directionally stretching from north to south (Fairservis, 1961, p. 41). Site 26 includes a hypothesised late Islamic site with glazed pottery (Fairservis, 1961, pp. 44-45). Site 39 showcases the Bronze Age site of Shahr-I-Sokhta (the Burnt City). In recording this famous site, Fairservis notes the impact of desertification on the area: 'The artefacts are heavily massed because the wind has eroded the surrounding fill. This phenomenon is widespread in Sistan and effectively militates against a stratigraphic differentiation of the cultures represented by the artefacts (p. 56). The site is notable as it is one of the few standings and known Bronze Age sites throughout the region. Site 41 includes a small, abandoned village, likely inhabited

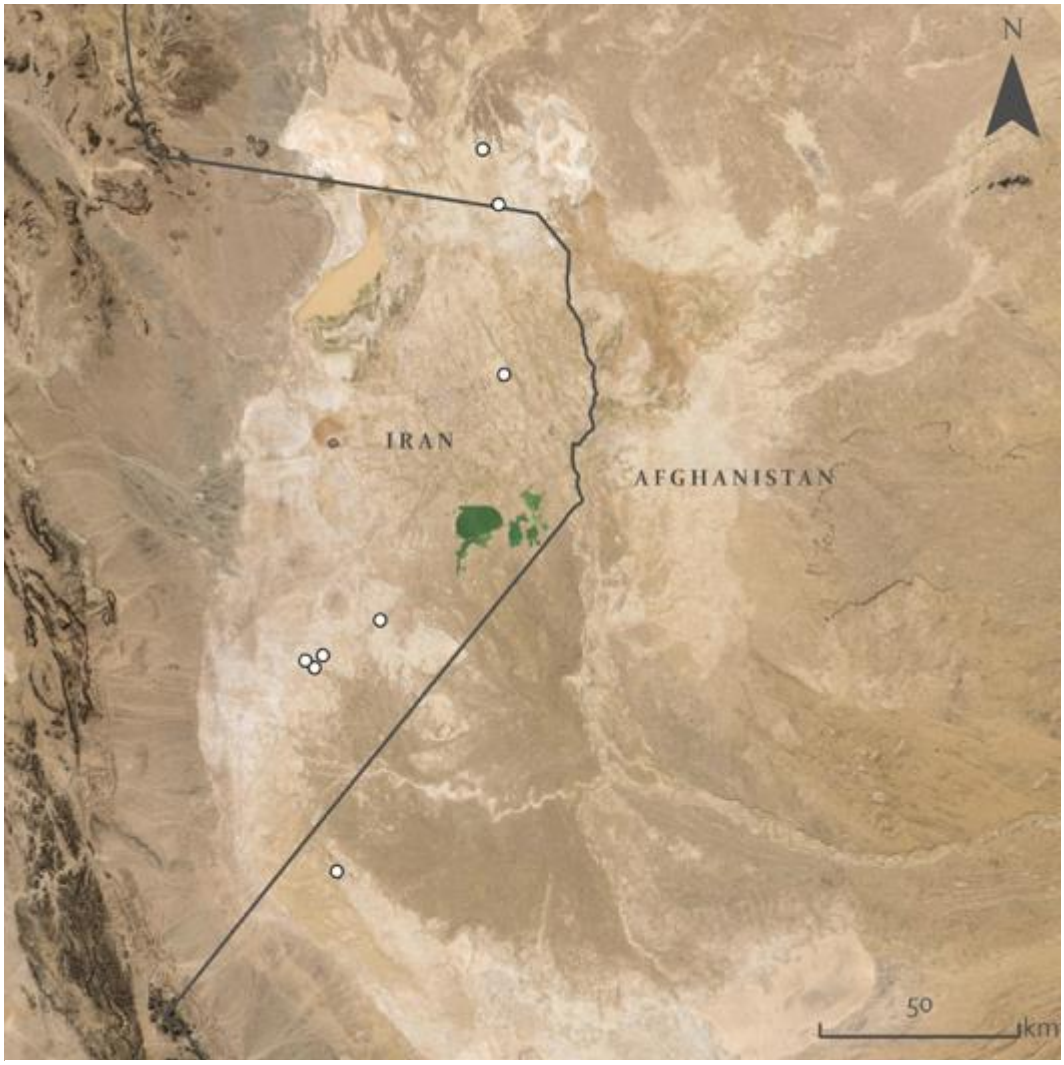


Figure 5.12. Records from Fairservis' survey at high risk for desertification

in the 19th century (p. 57). Site 42 consists of a multi-period occupied mound with evidence of occupation dating to the Prehistoric (p. 57). Site 43 includes multiple features, including a rampart and habitation area (p. 57). Site 109 includes irregularly shaped mounds, pottery heaps, graves, and numerous human remains. Fairservis frequently mentions the impact of desertification processes on site 109, stating, 'Wind and water erosion had cut deeply into the ground of the site . . . The piles of sherds were accumulated in very soft, windblown silt . . . Some of the graves had been undercut by the wind so that an occasional vessel hung out of the bluffs above our heads . . .' (pp. 69-72).

The Helmand Sistan Project's 200 sites identified 18 as high risk of desertification (Figure 5.13). These sites are located in Afghanistan (as the project did not cross into Iran) and are clustered centrally in the study area, east of Lake Hāmūn. Unlike Fairservis' survey, the Helmand Sistan Project's sites are not labelled. Still, from further research on the periods concerning the sites' discovery during the survey, the dense clustering relates to sites correlated with their Parthian, Sassanian, and Timurid period records. According to the survey, the Parthian and Sassanian periods were the most flourishing for the region to date (Trousdale & Allen, 2022). Palaces were built during this time, and Zoroastrianism became rooted, with the survey identifying several fire temples

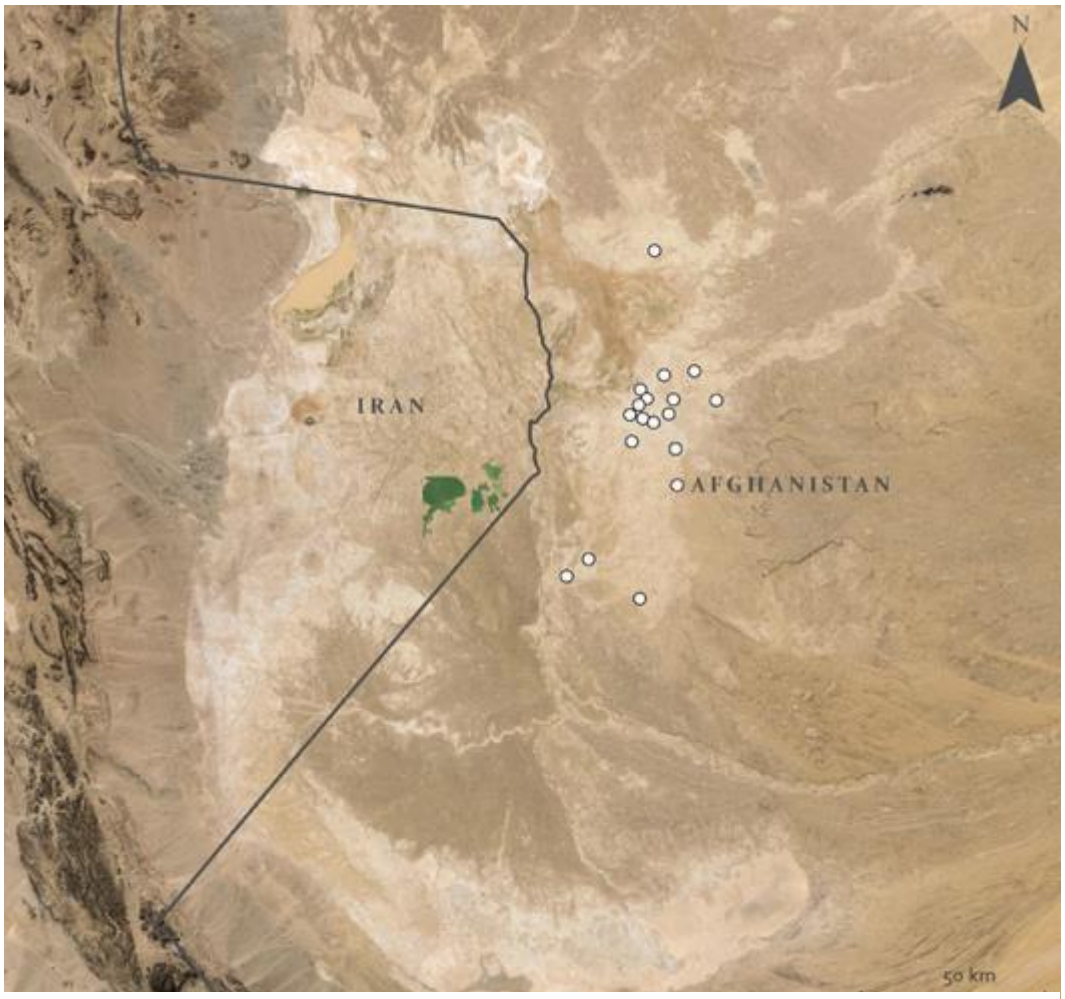


Figure 5.13. Records from the Helmand Valley Project at high risk of desertification

(Trousdale & Allen, 2022). One likely site under threat of desertification from the survey's inventory is Sar-o-Tar (Trousdale & Allen, 2022). Sar-o-Tar holds evidence that it hosted a place of extensive agriculture and prosperity. The site also showcases historic dune inundation across its relatively lengthy habitation (Trousdale & Allen, 2022). Evidence of the survey for the presence of the Timurid period under threat of desertification includes discovering several mudbrick buildings, coinage, glazed pottery, and imported goods from China (Trousdale & Allen, 2022).

This prioritisation method is simple and effective in understanding the extent of known sites across the Sistan Basin most threatened by desertification. This method is unique in that it can be utilised quantitatively or qualitatively. Due to the medium spatial resolution of Landsat data, there is ample ability to visualise the image's cells with the highest levels of desertification. The clarity of where levels are and are not high allows for quick analysis of which sites residing in these areas should be prioritised due to threat level. As the EAMENA database's records are primarily from later, unknown to the Islamic period, it would be potentially useful to explore the hypothesis that this is the result of sites existing on top of older sites or the result of sites nearby not showing up on imagery due to desertification processes, for example, being buried by sand or wind erosion over time.

5.7.2. Sites in Transition

In Sistan, desertification also visibly manifests as sand encroachment (Sankaran et al., 2023). Wind action mobilises these fine-grained surfaces, lifting and redistributing them into shifting corridors that steadily engulf fields, settlements, and archaeological remains. What emerges is a dynamic desertscape in which cultural features are alternately revealed, obscured, and ultimately buried beneath advancing dune fields. The effect is double-edged. Sand encroachment physically erases archaeological fabric while simultaneously obscuring its spectral footprint. Features identifiable in one year's satellite imagery can vanish in the next, subsumed beneath dunes that respond to seasonal winds and the progressive collapse of soil stability. Desertification in this sense operates not only as a destructive agent but also as a concealing force, frustrating remote monitoring.

Archaeological sites, both documented and undiscovered, are increasingly threatened by this process. The EAMENA database illustrates how these processes can be tracked. One site of uncertain period, interpreted as either a collapsed building or enclosure, was observed (during the current case study's iteration) in satellite imagery from 2012 and 2021. Over this interval, the structure passes through a transitory state of inundation, gradually overtaken by dunes. The imagery sequence makes this process visible: the site shifts from partial legibility to near-complete burial, as

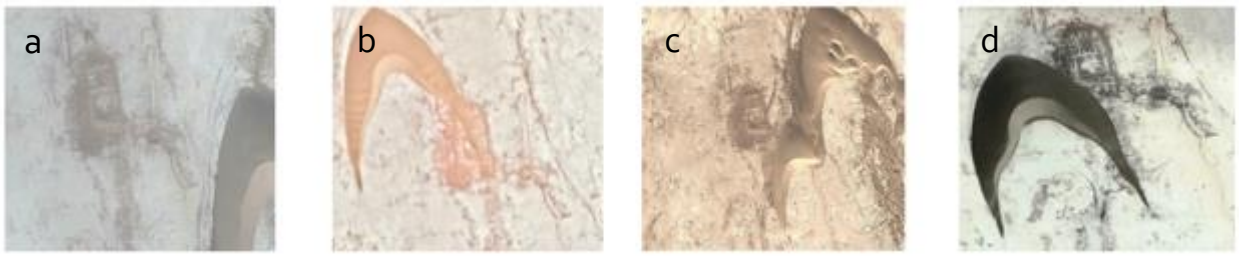


Figure 5.14. Example of high-risk site over time. a. 2012; b. 2016; c. 2019; d. 2021

captured in Figure 5.14. This site was initially targeted because of its position within an area of elevated desertification intensity.

Closer examination of the surrounding landscape revealed an additional, previously unrecorded site. Its architectural footprint, shown in Figure 5.15, suggests a large complex with formal enclosure walls and internal compartments. Although its precise chronology and function remain under investigation, the form strongly resembles a 17th-century caravanserai. Positioned strategically within the desert corridor, it appears to have functioned as an oasis and logistical station for caravans and travellers navigating the region (Bar-Oz et al., 2022).

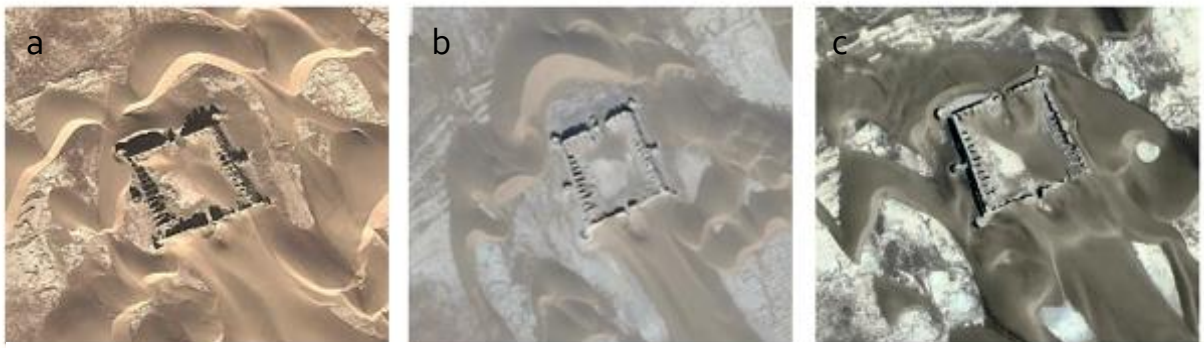


Figure 5.15. Newly discovered high-risk site over time. a. 2012; b. 2016; c. 2021

This dual outcome, tracking a site's decline while simultaneously identifying a new one, demonstrates the methodological value of focusing on sites in transition. Crucially, the caravanserai example shows that destructive processes can also make legible elements of the cultural landscape that would otherwise remain hidden, extending the reach of remote analysis even in environments of extreme vulnerability. The implications are not limited to individual sites. Transitional zones operate within wider regional trajectories of change. These intensifying patterns are visualised in Figure 5.8, which situates the site-level examples within a broader geography of environmental stress. By framing transitional sites within these regional surfaces, the analysis links localised discoveries to systemic processes of landscape degradation. Remote identification of a caravanserai or a dune-inundated enclosure cannot be followed by excavation, conservation, or stabilisation. What can be done is to preserve visibility: to record, archive, and model these transitions so that they remain legible within the archaeological record, even as the physical structures collapse.

The reframing is subtle but significant. Transitional sites reveal that in Sistan, archaeology cannot be secured *in situ*. Instead, it must be archived *in absentia*. Salvage, in this sense, is not the physical recovery of artefacts but the consolidation of knowledge: building digital inventories, retaining legacy records, modelling risk trajectories, and keeping sites visible in data even as they vanish. This shifts archaeology into a mode of preparedness aligned with DRR frameworks: ensuring that disappearance is not silent and absence is legible. Thus, the study of transitional sites not only advances archaeological discovery but also transforms how we think about loss. They make visible both the dynamics of environmental change and the structural voids where governance fails. They

demonstrate that the utility of DRR in archaeology lies not only in guiding action where intervention is possible, but in clarifying where it is not.

5.7.3. Landscape Regional Prioritisation

By collaborating with the EAMENA project and other specialists working on the region's archaeology, this research demonstrates how hazard modelling can refine both the scope and focus of archaeological inventories. EAMENA's established methodology provides comprehensive coverage through a systematic grid designed to rapidly identify and register all potential archaeological features visible in remote imagery. While this approach ensures breadth, it does not inherently account for environmental pressures or the uneven distribution of risk across the landscape. By integrating desertification intensity into the workflow, inventories can move beyond uniform coverage to prioritised targeting. Areas where desertification is demonstrably accelerating can be treated as zones of heightened urgency, allowing analysts to focus on sites most likely to have been lost, damaged, or obscured.

Between 2015 and 2021, for example, the model highlights corridors of pronounced environmental change (Figure 5.16). These zones not only signal where existing records require reassessment, but also where undiscovered or transitional features are at most significant risk of erasure. Such

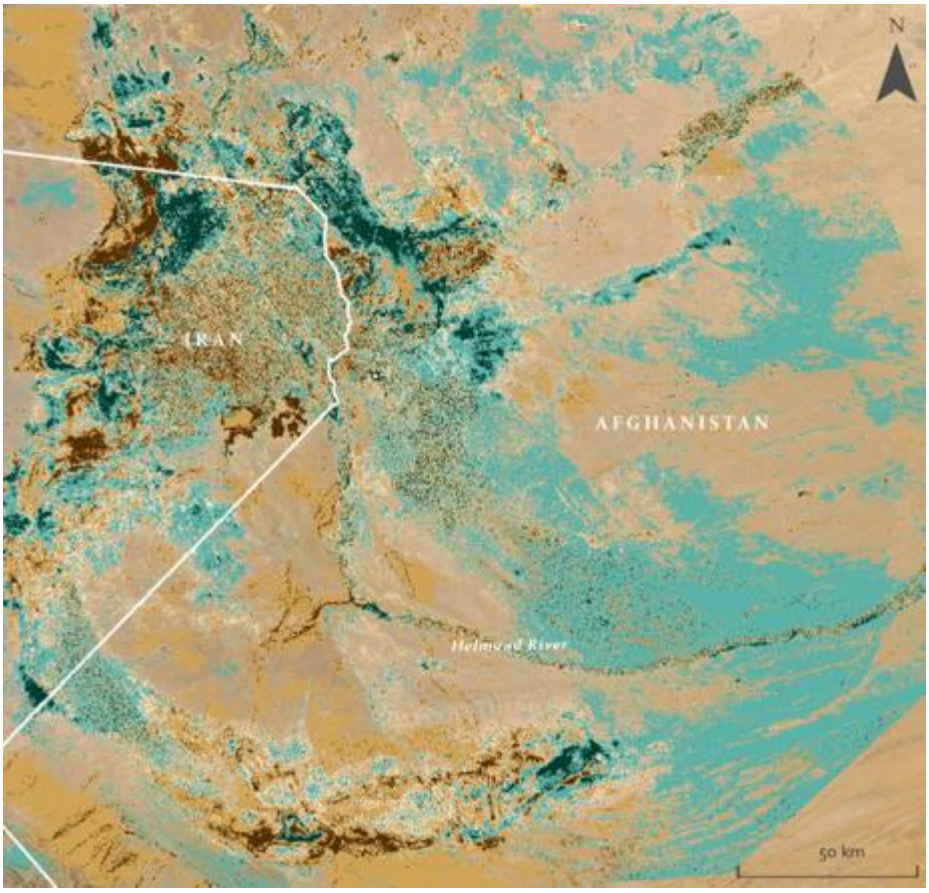


Figure 5.16. Desertification extent from 2015 to 2021

information enhances the value of inventories in two ways: first, it strengthens digital identification and documentation by directing attention to the most threatened areas; and second, it provides a framework for prioritisation should field access be restored one day. In that eventuality, archaeologists would be able to focus scarce resources on areas of proven desertification pressure, maximising the chances of recovering sites.

5.8. Limitations

Like any geospatial approach, this study is constrained by several limitations that must be acknowledged. Landsat's 30-metre spatial resolution, STRM elevation surfaces, and the coarse interpolations of the Global Wind Atlas undeniably flatten the landscape, smoothing over small-scale dynamics and reducing the legibility of site-level change. The real strength lies in the fact that these data are open-access. Unlike commercial archives with paywalls or licensing restrictions, open platforms like Landsat provide not only continuity across decades but also a democratic infrastructure: to replicate or extend this model. This creates a methodology in which monitoring does not end with the present study but can be sustained by interested users at minimal cost. In a Basin fractured by conflict and underdevelopment, the ability to keep monitoring alive through free, replicable data is arguably more valuable than the potential gains of high-resolution imagery.

Ground-truthing represents another limitation that, on its surface, appears to weaken the model. Without field verification, the results can never be fully calibrated against on-the-ground observations. But this absence forces the model into a posture of methodological discipline. In place of unverifiable claims, the analysis leans heavily on cross-validation against independent hydrological and climatic studies, explicitly acknowledging uncertainty and situating results within a comparative regional literature. In this way, the absence of in-situ observation transforms into a strength: it ensures that the model is transparent, portable, and applicable to other regions of inaccessibility, where ground-truthing is equally implausible, in contexts like Sistan, where access may be restricted for years, if not decades, the test of a method is precisely whether it can survive without in-field observation. Therefore, this thesis posits, the lack of opportunity for ground-truthing compels methodological rigor that makes the results more transferable.

The same duality runs through questions of governance and stewardship. Sistan has no centralised archaeological salvage programme or mediating institution; the archaeology is not scaffolded by state preservation authorities or international oversight. This vacuum generates an opportunity to work differently. In place of closed repositories or siloed archives, the methodological emphasis shifts toward open workflows and legacy, distributed datasets. This decentralisation reduces the risk of single-point failure; if one dataset disappears, others persist, and it lowers barriers for participation, enabling regional scholars and diaspora communities to contribute to the collective record. Institutional absence thus becomes a prompt for methodological innovation, where openness itself becomes a form of resilience.

The desertification of Sistan is inextricably tied to hydropolitics upstream in Afghanistan, yet the model necessarily constrains itself to the Basin as a unit. This means that drivers such as dam

releases or irrigation diversions are only partially represented. But here too, the limitation highlights rather than obscures: by acknowledging that external hydropolitics cannot be modelled directly, the study frames them as explicit contextual variables, foregrounding their role in shaping hazard dynamics. However, the most intractable limitation of all is the absence of any clear pathway from diagnosis to intervention. The model can identify zones of acute risk but cannot translate these into immediate preservation or protection. Yet even this is not the end of the model's utility. By shifting the emphasis from field rescue to informational preparedness: digital salvage, archival consolidation, hazard-driven watchlists, the study ensures that loss is at the very least recorded.

Taken together, these limitations define the study. Resolution, ground-truthing, governance, hydropolitics, and structural absence each pose undeniable constraints. Yet each also forces a compensating strength: replicability, transparency, openness, auditability, trend clarity, contextual awareness, and preparedness. What emerges is not a flawless model, but a resilient one, designed less to eliminate uncertainty than to make it legible, less to prevent loss than to preserve the knowledge of what might be lost. In this sense, the method's limits are the conditions that make salvage archaeology possible in a landscape where the alternative is silence.

Conditions for Reuse

The Sistan framework is built for conflict-affected, data-poor, politically blocked, and environmentally unstable areas. As such, its reuse depends less on institutional strength than on the availability of a small, robust set of open data. At a minimum, the method requires:

> **(1) multi-temporal medium-resolution satellite imagery** (for example, Landsat or Sentinel-2) from which vegetation, soil and water indices can be derived;
>
> **(2) a DEM** sufficient to calculate basic slope;
>
> **(3) at least one coarse proxy for aeolian or climatic** forcing (for example, wind fields, drought indices, or dust-emission models); and
>
> (**4) any form of georeferenced archaeological record**, even if legacy, incomplete, or spatially imprecise. Where only paper maps or narrative descriptions exist, approximate georeferencing is acceptable, as the aim is pattern recognition and salvage, not centimetre-scale prediction.

In regions lacking stable governance or systematic heritage management, the Sistan model is best understood as a salvage-and-monitoring framework rather than a full triage model. It is particularly well suited to basins, steppe margins, and arid frontiers where desertification, dust production, or drought–flood alternation are the dominant hazards. The core workflow, computing a small suite of spectral indices (such as NDVI, TGSI, and MNDWI), compositing them with slope and a climate, aeolian proxy, and then differencing yearly rasters, can be reproduced with standard GIS software

and free data. The outputs do not depend on ground-truthing; instead, they gain robustness through cross-comparison with regional hydrological and climatic studies. This makes the approach applicable in other access-restricted areas where field verification is unlikely.

On the archaeological side, the framework is most effective where some form of remote or legacy survey has already been undertaken, even if those records are fragmentary. The model assumes that physical intervention will often be impossible. Reuse, therefore, means treating hazard surfaces as guides for digital triage: prioritising which records to digitise, cross-reference, and monitor first; identifying 'sites in transition' that warrant urgent archival rescue; and flagging landscape corridors where the probability of undocumented site loss is highest. In other words, the primary output is a ranked set of places to *remember*, in databases, archives, and monitoring watchlists. The framework works best in settings where researchers are willing to accept that, in such contexts, DRR cannot deliver preservation in situ; it can only preserve knowledge. Its most appropriate reuse is in regions where risk is high, governance is weak or absent, and the realistic objective is to keep archaeological information visible and extendable for the future.

5.9. Summary

In a setting like the Sistan Basin, conventional field-based approaches, such as surveying and excavation, are systematically outpaced by environmental transformation and governance complexities. The preceding analyses have demonstrated that in Sistan, archaeology cannot be sustained through methods designed for stable contexts. Instead, it must be reoriented through the lens of DRR, where visibility, preparedness, and salvage are treated as primary objectives. Geospatial approaches in this study illustrate how DRR logics can be translated into the archaeological method. By integrating multi-temporal indices (NDVI, TGSI, MNDWI), slope and wind proxies, and legacy site datasets, a composite risk surface was produced that exposes not only where degradation is most acute but also where absence and inaccessibility converge. Where triage fails as an operational protocol, it succeeds as a diagnostic: identifying the residual-risk zones where heritage governance has collapsed and where salvage must shift from preservation in situ to the maintenance of informational visibility.

What Sistan shows with clarity is that archaeology must work with loss directly: not simply to prevent it, but to document it and, where possible, to anticipate its trajectories before they pass beyond recognition. Salvage under constraints, whether through remote sensing, archival rescue, or model-led monitoring, is a viable adaptation. The desertification of Sistan, therefore, stands as both a hazard and a methodological provocation. It reveals that the primary threat is the loss of archaeology's capacity to generate knowledge in such environments. In this sense, Sistan marks a threshold for archaeology under crisis conditions. It demonstrates that DRR-aligned practice can extend the field's relevance in contexts where preservation is no longer possible, by shifting the mandate from 'rescue' to recognition. Archaeology, when aligned with DRR, becomes less about saving everything and more about knowing enough, early enough, to act where action is still possible.

As ecological and political conditions erode the foundations of field practice, archaeology must adapt by aligning itself with DRR logics. What the Sistan case makes clear is that the discipline's future relevance will not be measured by what it rescues intact, but by how effectively it renders risk legible and sustains the possibility of future knowledge. The breakdown of triage logic here illustrates the kinds of constraints that are increasingly likely to shape archaeological practice in other slow-onset hazard contexts. By making DRR actionable via geospatial approaches, archaeology can remain relevant in landscapes where traditional methods may not be feasible.

Chapter 6: Discussion

The preceding chapters have shown that accelerated environmental and political instability is no longer an exceptional condition within which archaeology occasionally must operate, but rather it has become the prevailing context that shapes how archaeological knowledge is produce and (often) lost. Although the three case study landscapes presented in this thesis differ markedly in their environmental dynamics, archaeology, and governance structures, they collectively reveal a pattern in which the processes that alter landscapes now move faster, fluctuate more sharply, or interrupt access more frequently than the methodological and institutional rhythms that archaeology traditionally relies upon. This chapter examines these broader implications by drawing together the key themes that emerge across the cases and by considering what these patterns suggest about the current and future conditions of archaeological practice.

6.1. Landscape Transformation and the Structural Necessity of Disaster Risk Reduction Integration

No landscape is static. Archaeology, environmental processes, and contemporary hazards unfold within the same field of long-term, continuous transformation. The DRR framework, however, is oriented toward short temporal horizons: days, years, or at most a few decades. The lithic scatters, burials, aquaculture features, and Cold War structures considered in this thesis are the cumulative result of long-term interactions between people and landscape processes. They sit within what Gosden (1994) calls 'deep time.' Their visibility and vulnerability are continually shaped by the same forces, erosion, deposition, slope movement, and vegetation change that have been transforming these places for millennia. What has shifted today is not the fact of landscape change, but tempo. Present-day hazards now operate with an intensity and speed that compress timescales (Burke et al., 2021; Sesana et al., 2021) and destabilize assumptions about access and longevity. A single point on the risk surface visualisation may hold thousands of years of cultural activity yet be exposed to processes unfolding over months or days. This makes engagement with DRR and other risk mitigation frameworks necessary for understanding and responding to the risks that threaten archaeology.

Taken together, this temporal configuration has several implications for how archaeological risk is understood and managed. First, it exposes a gap between the timescales on which archaeological work is organised and the timescales on which hazards now operate. Standard archaeological workflows, such as desk-based assessments, survey design, permitting, field mobilisation, and post-excavation analysis, assume that conditions at a given locality will remain broadly similar between one stage and the next. When hazards act in the order of months, weeks, or days (UNDRR, 2017), this assumption becomes less accurate. A site identified in aerial imagery or historical

mapping may have been partially removed or rendered inaccessible by the time a team can visit (see the Sistan case study for reference). In such contexts, the problem is not only whether a site is at risk of eventual destruction, but whether there is enough time to carry out even the most basic forms of documentation before the situation changes again.

This also alters how archaeologists think about loss. In a slow-changing landscape, it is reasonable to equate loss with physical removal of material, coastal collapse, or construction impacts. Under accelerated conditions, loss increasingly occurs through shorter-term processes: intermittent visibility, fluctuating access, rapid cycles of exposure and burial (for example, Holderness's erosion phases and Sistan's desertification fluctuations). A locus might survive physically but move in and out of archaeological reach as sediment or political constraints shift (for example, Sistan). When a single point can hold deep-time assemblages shaped over thousands of years and yet be governed, in the present, by processes acting over days, the risk is no longer only that material will vanish, but that the opportunity to recognise, record, or interpret it may close without notice. Archaeological risk, in this sense, becomes as much about the erosion of workable timeframes as about the erosion of deposits. Recognising this has methodological consequences. It suggests that approaches built around infrequent, one-off field campaigns are poorly suited to environments where conditions change quickly (Heilen & Manney, 2023). Instead, there is a need for methods that can register and compare different tempos of change: repeated remote sensing, long-term environmental indicators, and models that link hazard frequency and magnitude to likely windows of archaeological accessibility (Yang et al., 2012; Franquesa et al., 2025; Alvarado et al., 2017). The emphasis shifts to treating landscape as a medium that is continually reorganising where, when, and how archaeology can be done. In practice, this means that questions about the timing of interventions are central to risk assessment.

In this context, DRR and related risk frameworks become relevant. Their temporal focus is not an exact fit for archaeological concerns, but, when appropriately adapted and applied (see Chapter 2 of this thesis), it is designed to handle situations in which processes act quickly relative to planning horizons. Probabilistic estimates of event frequency and scenarios that explore different possible futures offer ways to think about how long certain combinations of visibility and access are likely to persist. For archaeology, the value of this is not that it can stabilise landscapes or guarantee protection, but that it can help identify where accelerated hazards are most likely to curtail the time available for investigation. In other words, DRR methods can be repurposed to ask a specifically archaeological question: given what is known about hazard behaviour, where are we most likely to lose the chance to look, rather than only the material itself?

If archaeological materials are understood as part of the same continuum of transformation that shapes present-day hazards, then hazard cannot coherently be framed as an outside force intruding upon a stable record. Instead, the same processes that generate risk for the case studies presented in this thesis: coastal erosion, slope instability, and desertification, are among the processes that have long structured how the archaeological materials within those landscapes are formed, how those in the past chose the landscapes to inhabit, and how the record is preserved. What changes

under accelerated conditions is the balance between long-term accumulation and short-term disruption. This temporal framing complicates the setting of priorities. Suppose some locations combine dense, multi-period activity with high present-day hazard intensity and short lead times before further change (for example, the Sistan case study). In that case, they demand different forms of response from places with slower onset hazards (for example, the Holderness case study), even if the archaeological extent is comparable. The question is which sites sit at the intersection of long-duration value and rapidly shrinking opportunity. Integrating DRR-informed understandings of tempo into archaeological decision-making thus becomes a way of making those trade-offs explicit; the O'ahu case study showcases this well. This does not resolve the ethical or political tensions around what is saved and what is allowed to be lost but does provide a clearer basis for acknowledging that those decisions are being made under conditions of compressed time.

6.2. Visibility as a Form of Risk

Visibility, as demonstrated across the case studies examined in this thesis, must be understood as an active dimension of archaeological risk (Harris, 1983; Hayward & Goldberg, 2009). The ability to document and interpret archaeological material is not guaranteed, and this generates a form of vulnerability that can precede physical loss (for example, the case study of Sistan). Across all sites, the most significant threat to archaeological knowledge often arises not from the disappearance of deposits themselves but from the loss of the conditions that make those deposits knowable (Rouhani & Huet, 2024). Visibility, for this thesis, is considered a key factor influencing the production and viability of archaeological knowledge.

The Holderness coastline illustrates this relationship through its steady and predictable decline in visibility. The contraction of the landmass restricts the extent of surveyable terrain. Material that can be recorded one season may be gone the next, yet the true loss typically starts earlier, when the shrinking landscape prevents adequate investigation. This case shows that reduced visibility is a critical risk factor that directly shapes the ability to conduct archaeological risk prevention. O'ahu presents a contrasting pattern in which visibility can change abruptly and unpredictably. The rapid alternation between exposure and burial produced by landslides creates conditions in which the presence of archaeological material and the possibility of accessing it do not always align. A surface may be exposed only during moments when the terrain is too hazardous for investigation, while periods conducive to fieldwork may coincide with burial or disturbance. This reveals a significant vulnerability not only because materials appear and disappear, but also because knowledge depends on whether institutions can respond effectively when visibility and access coincide. The Sistan case study introduces an even more complex configuration in which visibility is shaped simultaneously by environmental conditions and political constraints on field access. Desertification creates a highly variable landscape in which archaeological surfaces appear and disappear with regularity. These natural cycles are intensified by political restrictions that can prevent fieldwork regardless of environmental conditions. As a result, the archaeological record can become effectively invisible even when it lies exposed, simply because researchers are not permitted to reach it. The patterns in Sistan illustrate how visibility can be governed not only by

landscape change but also by administrative decisions, broader political climates, and the practical realities of access. This creates a form of risk that is neither stable nor predictable, arising from the ways environmental and political factors interact to shape what can be seen.

Taken together, the case studies reveal that visibility is an active variable that determines whether knowledge can be recovered. The collapse of visibility represents a collapse of knowledge, even when the material remains intact (Frydryczak, 2023). This point has been cited by others for its implications on archaeological practice (Opgenhaffen, 2022). For this thesis, loss of visibility suggests that risk assessments must expand beyond considerations of erosion and physical loss to account for the instability of visibility itself. It also highlights the importance of recognising epistemic vulnerabilities that arise when the ability to understand the past deteriorates well before the physical record is destroyed (DeSilvey, 2017). It also establishes the conceptual basis for the following section, which examines how differing levels of institutional readiness influence the capacity to act effectively in landscapes characterised by unstable visibility.

6.3. Capacity Collapse as a Determinant of Archaeological Outcomes

Institutional capacity emerges from the case studies as a decisive factor in shaping archaeological outcomes, challenging the assumption (and confirming the DRR model) that hazard severity alone determines loss. In Holderness, slow-moving environmental pressures combine with limited but functional governance to produce a pattern of steady and predictable threat. In O‘ahu, substantial archaeological information exists, yet it sits within an administrative landscape where responsibilities for cultural resources and hazard management do not often intersect. This separation prevents archaeological knowledge from influencing decisions about slope stability, land use, or emergency planning. In Sistan, the collapse of political and administrative systems overwhelms any environmental variability and produces the most severe form of archaeological vulnerability. Here, archaeological material disappears not only through environmental deterioration but through the complete absence of systems capable of observing or recording that deterioration. The comparison reveals that risk is shaped at every stage by governance structures and by the interests they prioritise. This raises the question of whose values shape risk management. In O‘ahu, indigenous priorities rarely influence hazard planning (Mills et al., 2013). In Holderness, the needs of coastal protection and community infrastructure consistently outweigh archaeological concerns (Venture et al., 2021). In Sistan, the withdrawal of state authority places responsibility for heritage in the hands of remote analysts who have no practical means of intervention (Correia et a., 2019). These patterns show that understanding archaeological risk requires examining who is permitted to act and which interests are allowed to define vulnerability.

The collective evidence from the three cases demonstrates that archaeological vulnerability is influenced as strongly by institutional robustness or fragility as by the hazards themselves. In practice, the crucial factor is whether institutions can recognise and use hazard information to support archaeological protection. Environmental forces, however destructive they may be, do not automatically lead to loss. Loss occurs when the timing of hazardous events coincides with limited

coordination, insufficient political commitment, or administrative instability. The pattern evident in the case studies is not a commentary on the shortcomings of any single governance structure. Instead, it reflects a structural condition in which the capacity to translate knowledge into action fundamentally shapes archaeological futures.

Holderness illustrates this relationship in a particularly revealing way. The region benefits from a stable heritage framework, a long history of archaeological investigation, and planning bodies with considerable technical competence. On paper, these features suggest a strong foundation for effective risk management. Yet the archaeological record continues to erode, not because the hazards themselves are extraordinary, but because heritage considerations occupy a marginal position within broader coastal planning. The needs of contemporary communities and infrastructure primarily drive decisions about erosion control and shoreline defence. Archaeology is acknowledged but rarely influential in determining priorities. The result is a form of constrained capacity in which knowledge and technical expertise exist, yet the institutional will to apply them is limited. Holderness, therefore, demonstrates that capacity is not defined solely by the amount of available information or the presence of skilled personnel. It is shaped by political alignment, policy priorities, and the position afforded to archaeological concerns within competing agendas. On O‘ahu, capacity is structured very differently but leads to a similar pattern of loss. Archaeological surveys and cultural resource management programmes have produced extensive datasets, yet these data occupy a parallel track that rarely intersects with hazard governance. Agencies responsible for landslide modelling, emergency response, and climate adaptation seldom incorporate archaeological information into their procedures. This results in a situation where the hazard is sudden and destructive, but the loss of archaeological material occurs because institutional linkages are weak. Knowledge is abundant, yet it cannot guide action when the landscape shifts. Capacity here is not missing; it is misaligned. The O‘ahu case shows that archaeological outcomes depend on whether the administrative structures allow relevant knowledge to influence decisions about risk. The Sistan Basin provides the most striking demonstration of the consequences of capacity collapse. Political instability, weakened governance, and sustained insecurity have dismantled the institutional structures required for archaeological management. Even when environmental conditions create temporary visibility, no functioning system exists to document or protect what appears. The landscape has become a space where environmental deterioration operates in a governance vacuum. Desertification threatens archaeological material, yet the impact is catastrophic because no institutional actor is positioned to respond. The Sistan case makes clear that capacity collapse is not a secondary concern but a primary driver of archaeological loss. In such settings, even moderate hazards become destructive because they occur in an institutional void.

Across all three cases, the shared pattern is that institutional capacity serves as an amplifier or dampener of archaeological risk (as in any other at-risk resource, per UNDRR, 2017). When capacity is coherent and archaeological concerns are integrated into planning systems, significant hazards can be managed or monitored in ways that preserve knowledge. When capacity is fragmented, hazards that could have been addressed become sources of unexpected loss. When capacity fails

altogether, archaeological evidence becomes vulnerable even to minor environmental fluctuations, and the production of archaeological knowledge becomes impossible. This reinforces the idea that risk is co-produced through the interaction of environmental processes with political and financial conditions. It also clarifies that the success of any archaeological risk framework depends on the institutional environment into which it is introduced. Technical tools such as hazard maps and geospatial modelling will have limited influence if institutional conditions do not value their application.

A further implication is that capacity must extend beyond the ability to mitigate harm and include readiness to take advantage of the opportunities that hazardous processes can create (Hollesen et al., (2018). Erosion, landslides, and landscape reworking do not simply destroy material. They can reveal it. Along the Holderness coast, new exposures appear almost as quickly as they disappear, creating a narrow interval for documentation. On O‘ahu, slope failure can expose stratigraphy that is otherwise inaccessible. In Sistan, shifting dust and changes in water flow occasionally reveal architecture or surface scattering that may vanish again within days or weeks. If heritage systems lack the capacity to mobilise during these moments, knowledge is lost even when the hazard produces a brief positive outcome. Incorporating this form of preparedness into the definition of capacity reframes risk management for archaeology. Resilience depends not only on protecting sites from destruction but also on responding effectively when landscapes temporarily open themselves to observation.

These insights carry broader implications for archaeology. They show that heritage outcomes cannot be understood solely by analysing a landscape's physical characteristics or the severity of the hazards affecting it. The presence or absence of functioning governance systems shapes archaeological futures. This requires a shift in how risk is conceptualised within the discipline. Archaeologists must recognise that material vulnerability operates alongside institutional vulnerability, and that the latter often determines whether environmental change results in loss, documentation, or opportunity. The case studies reveal that many losses arise not from the extremity of environmental processes but from the absence of mechanisms capable of responding. In doing so, they show that capacity is not an external influence acting on archaeological practice. It is a fundamental element of archaeological risk itself.

6.4. Landscapes as Archives in Motion

Relational approaches to landscape have challenged the view that landscapes constitute static repositories of archaeological information, instead emphasising their continual transformation through environmental, social, and temporal processes (Ingold, 1993, 2000; Bender, 2001). More recently, heritage scholarship has similarly recognised that archaeological landscapes should be understood as dynamic systems subject to ongoing adaptation and, in some circumstances, loss (DeSilvey, 2017; Holtorf, 2018).

Building on these perspectives, the case studies examined in this thesis demonstrate that archaeological landscapes operate as archives in motion whose visibility and accessibility fluctuate through time under the influence of environmental hazards and socio-political conditions. Under these conditions, archaeological visibility becomes temporary and the continued intelligibility of the past depends on the ability to anticipate and understand the processes that drive these fluctuations. Understanding landscapes as archives in motion reframes archaeological risk as something produced within these moving systems. When landscape motion is recognised as continuous, risk becomes tied to the timing and rate of that movement. Exposure may create valuable opportunities for documentation, but only when archaeologists are prepared to act within the intervals created by environmental change (for example, Holderness and Sistan). Concealment may not physically destroy material, yet it can prevent observation for long periods and produce significant gaps in knowledge. Both processes influence the shape and extent of archaeological risk. The ability to interpret and manage archaeological outcomes, therefore, depends on acknowledging that the archive reorganises itself more quickly than most heritage systems can respond. These insights also present methodological challenges. Treating landscapes as dynamic archives requires approaches that can accommodate temporal variability rather than rely on assumptions of stability (Rainbird & Edgeworth). It demands recognition that the archaeological record available today may differ substantially from what will be visible tomorrow, not because of deliberate interventions but because the landscape is continually shifting (Bender, 2001). This challenges traditional archaeological workflows that rely on predictable sequences of planning, surveying, and analysis. Instead, it supports the development of more adaptive and opportunistic methods that remain closely aligned with the temporal patterns of landscape change. Recognising landscapes as archives in motion, therefore, provides not only a conceptual shift but a practical framework for engaging with archaeological risk in environments where stability can no longer be taken for granted.

The contribution of this thesis lies not in proposing that archaeological landscapes are dynamic, an idea well established within landscape archaeology and heritage studies, but in demonstrating how this understanding can be operationalised within a DRR framework. By treating landscape dynamism as a measurable component of archaeological vulnerability, the methodology developed here provides a practical basis for anticipating changing patterns of exposure before irreversible loss occurs.

6.5. Methodological Adaptation as Archaeological Resilience

Across the three case studies, it becomes apparent that methodological flexibility is not simply an operational choice but a form of resilience that determines whether archaeology can respond effectively to shifting landscapes and unstable working conditions. The methods deployed in each case study were shaped as much by the constraints imposed by hazards and capacity as by disciplinary preference. This suggests that methodology cannot be treated as a neutral toolkit to be applied across different environments. Instead, it emerges as a component of archaeological practice that must adjust to the temporalities and capacities of the landscapes under study. The adaptability of archaeological method is a crucial factor in the survival of knowledge, particularly in

contexts where environmental processes or political structures alter the conditions under which fieldwork can take place. Methodological adaptation, therefore, represents a form of risk management, enabling archaeology to function within landscapes whose behaviour challenges established research routines.

Taken together, the case studies show that methodological adaptation is both a practical response to environmental and political constraints and a conceptual shift that widens the role of archaeological method within risk-prone landscapes. Methodological resilience arises from recognising that no single workflow can function effectively across all temporalities and hazard contexts. It requires accepting that the conditions that enable conventional archaeological practice are not guaranteed and that methods must adapt to uneven visibility, unpredictable hazards, and fluctuating capacities (Riede, 2017). This does not diminish the value of established techniques but positions them within a broader repertoire that includes anticipatory modelling, remote sensing, and opportunistic documentation. The capacity to move between these approaches becomes a measure of resilience, reflecting archaeology's ability to maintain its interpretive goals amid accelerating change. This perspective also carries implications for how archaeological success is conceptualised. If the archive itself is in motion, and if visibility can collapse faster than field logistics can respond, then the resilience of archaeology depends not on preserving methods but on preserving (Thomas, 1996; Gell, 2023). Methodological adaptation becomes a way of ensuring that knowledge can be generated even when traditional forms of engagement are compromised. This allows archaeology to operate within landscapes where stability cannot be assumed, where hazard processes outpace documentation, and where political conditions determine the boundaries of visibility. In this sense, adaptation is not a secondary consideration but a central component of archaeological practice in an era of increasingly volatile landscapes. It provides the means through which archaeology remains viable, not by resisting change, but by developing methods that can move with it.

6.1. The Ethics of Knowing Enough

Archaeology has grappled with the ethical implications of loss, balancing the aspiration to preserve and document the material record against the practical realities of finite resources and changing landscapes (Lipe, 1984; Carver, 1996; Smith, 2006; Williams, 2015). Climate change and accelerating environmental transformation have expanded these debates beyond development-led contexts, prompting renewed consideration of adaptation, prioritisation, and the inevitability of some forms of archaeological loss (DeSilvey, 2017; DeSilvey & Harrison, 2020; Holtorf, 2018). Building on these discussions, this thesis showcases that DRR introduces an additional ethical challenge: determining what constitutes sufficient archaeological knowledge when opportunities for documentation and intervention are themselves shrinking.

This tension runs through all three case studies. The question of what it means to know enough arises when conditions supporting documentation have weakened. Some change unfolds gradually; some arrive suddenly through rapid hazard events; some occur through the failure of institutions

rather than the impact of physical processes. As hazards escalate and capacity contracts, the gap between what could be lost and what can realistically be recorded widens. The ethical aim consequently shifts from preventing all loss to ensuring that knowledge produced is resilient enough to survive the disappearance of the material itself. This does not diminish the value of preservation; it situates preservation within a pragmatic awareness of contemporary constraints (Bienvenido-Huertas et al., 2021). Knowing enough becomes a way of maintaining interpretive integrity without insisting on objectives that cannot be met. Partial knowledge, when created with clarity and purpose, holds substantial interpretive value, particularly where the alternative is allowing the record to vanish unobserved. This accepts that practice in unstable landscapes requires an ethics that values sufficient and meaningful understanding over an unattainable total preservation.

6.2. Demonstrating Transferability Across Diverse Archaeological Contexts

The three case studies presented in this thesis were selected not only because they represent contrasting hazard environments, but because they encompass fundamentally different archaeological, institutional, and governance contexts. Rather than serving as isolated demonstrations of the proposed methodology, they provide a means of evaluating whether the framework can be applied across diverse settings that differ in data availability, management capacity, environmental processes, and political constraints. Consequently, the value of the framework lies not simply in its application to multiple hazards, but in its ability to operate under substantially different conditions that collectively reflect the diversity of archaeological practice.

The Holderness coastline represents a context characterised by comparatively high-quality archaeological datasets, well-established heritage legislation, and mature governance structures. Long-term coastal monitoring, extensive archaeological inventories, and institutional capacity provide favourable conditions for implementing geospatial risk assessment. Within this setting, the framework demonstrates how DRR methodologies can support proactive monitoring and prioritisation by integrating hazard information with existing archaeological management systems. The methodology extends the capacity of existing workflows to anticipate archaeological vulnerability before irreversible coastal erosion occurs.

By contrast, O'ahu presents a substantially different institutional and cultural landscape. Archaeological management operates within a context that incorporates Indigenous heritage, complex stakeholder relationships, and rapidly changing geomorphological processes associated with landslides. Here, archaeological risk must also acknowledge differing cultural values, governance arrangements, and the temporal unpredictability of landscape change. The successful application of the framework within this setting demonstrates its capacity to accommodate archaeological decision-making in environments where hazard processes, cultural significance, and institutional responsibilities are closely intertwined.

The Sistan case study provides perhaps the most demanding test of methodological transferability. Archaeological investigation is constrained by political instability, restricted field access, and

limited institutional capacity, requiring reliance upon remote sensing and geospatial analysis in the absence of conventional field investigation. Under these circumstances, the framework demonstrates that meaningful archaeological risk assessment remains possible even where direct observation is severely restricted. Rather than depending upon intensive field-based datasets, the methodology can integrate remotely derived environmental information to identify areas of heightened archaeological vulnerability and support strategic prioritisation where opportunities for intervention are limited.

Taken together, these case studies demonstrate that the proposed framework is transferable because it remains operational across fundamentally different governance systems, archaeological traditions, data environments, and institutional capacities. From the mature heritage-management structures of Holderness, through the culturally complex and multi-stakeholder landscape of Oʻahu, to the politically constrained and data-limited environment of Sistan, the methodology maintains its ability to identify, model, and prioritise archaeological risk. This suggests that the operationalisation of DRR developed in this thesis possesses broader applicability than any individual case study alone could demonstrate, providing a flexible framework capable of supporting archaeological decision-making across a wide spectrum of environmental and institutional contexts. Importantly, the three case studies also demonstrate transferability across contrasting policy and governance environments. Rather than testing the framework solely across different hazards, they show that a common methodological approach can be adapted to planning-led archaeology in England, Indigenous governance contexts in Hawaiʻi, and regions characterised by limited institutional capacity such as Sistan.

6.3. Institutional Implications

The significance of this research extends beyond methodological development. By operationalising DRR within archaeological contexts, the framework provides a decision-support approach capable of informing archaeological management, spatial planning, emergency preparedness, and climate adaptation across multiple institutional settings. Although developed as a methodological contribution, its outputs have potential value for organisations responsible for heritage protection, planning, and disaster-risk management.

Although the framework has been demonstrated across three contrasting contexts, its implementation would necessarily differ according to local legislative and institutional settings. In England, outputs could support Historic England, local planning authorities, and commercial archaeology operating within the NPPF and associated guidance. Within UNESCO World Heritage contexts, they could contribute to HIAs and disaster preparedness. In Indigenous contexts such as Hawai'i, implementation would require engagement with Native organisations and existing cultural structures. In regions such as Sistan, where institutional capacity is limited, the framework provides an evidence base that can support international organisations and future heritage planning as governance conditions evolve. Accordingly, implementation should be viewed as *policy-compatible rather than policy-prescriptive*. Archaeological legislation, planning systems, heritage governance,

and stakeholder responsibilities differ substantially between jurisdictions. The purpose of the framework is, therefore, to provide transferable evidence base capable of informing decisions within existing governing structures.

For heritage agencies such as Historic England and equivalent national bodies, the framework offers a way to move archaeological risk assessment further upstream. Existing heritage systems often contain extensive inventories, monitoring records, and designation data, but these resources are not always integrated with hazard exposure, vulnerability, and capacity in a DRR-compatible format. The approach developed here could support more strategic prioritisation by identifying where archaeological assets are most exposed to environmental hazards, where documentation is weakest, and where intervention may be most urgent. This has implications for funding allocation and subsequent monitoring programmes.

Local planning authorities and infrastructure planners may also benefit from archaeological DRR as it provides a means of identifying heritage risk before individual development proposals or emergency interventions arise. Rather than treating archaeological assessment solely as a response to planning applications, hazard-informed geospatial modelling can help planners understand where development, coastal change, slope instability, flooding, desertification, or infrastructure maintenance may intersect with archaeological vulnerability. This could support more transparent decision-making and better integration of archaeological concerns within wider resilience and climate-adaptation planning.

Emergency-management organisations also have reason to care about archaeological DRR. Cultural heritage is often affected by disasters, but archaeological data are rarely incorporated systematically into preparedness, response, or recovery planning. A DRR-compatible archaeological workflow can make heritage information more legible to emergency planners by translating archaeological vulnerability into spatial outputs that align with existing risk-management tools. This may improve preparedness, support post-disaster assessment, and help ensure that archaeological resources are not overlooked during emergency response or recovery.

International organisations such as UNESCO may find value in the transferability of the framework. World Heritage properties and other significant cultural landscapes increasingly face climate-related hazards, yet many regions lack the resources required for intensive field-based monitoring. Open, adaptable geospatial workflows offer a scalable method for identifying areas of concern, supporting vulnerability assessment, and informing capacity-building initiatives. The framework may therefore contribute to international heritage-risk agendas by providing a practical mechanism for linking archaeological evidence with climate adaptation, resilience planning, and disaster-risk governance.

At the time of writing, beyond UNESCO, a broader international network of organisations operates at the intersection of cultural heritage protection, conflict response, disaster preparedness, recovery, and institutional capacity building. These bodies differ in mandate and structure but collectively

demonstrate that there is already an established institutional demand for methods capable of identifying threatened heritage, prioritising intervention, and directing limited resources under conditions of uncertainty. The framework developed in this thesis could contribute to this landscape by translating archaeological risk into spatially explicit evidence that is legible to funders, emergency responders, heritage specialists, and organisations responsible for programme design.

ALIPH, the International Alliance for the Protection of Heritage in Conflict Areas, is a foundation and funding body dedicated to protecting and rehabilitating cultural heritage affected by conflict, climate change, natural disasters, and other crises. Its work includes emergency stabilisation, post-conflict rehabilitation, documentation, training, and support for local heritage institutions. ALIPH, therefore, operates at the point where evidence of risk must be translated into decisions about which projects require urgent financial and technical support. Its funding model depends upon the identification of priority needs during and after crises, often in contexts where access, data quality, and institutional capacity are limited. The methodology developed in this thesis could support such decision-making by providing transparent, reproducible evidence of hazard exposure, archaeological vulnerability, and relative capacity. It would not determine which sites should receive funding but could help identify where intervention is most urgent and where limited investment may prevent irreversible loss.

Blue Shield International is a non-governmental, non-profit organisation concerned with protecting cultural heritage during armed conflict, natural disasters, and other emergencies. Its remit encompasses archaeological sites, monuments, museums, archives, libraries, audiovisual collections, significant natural areas, and intangible heritage. It works across the heritage, humanitarian, military, governmental, and emergency-response sectors and undertakes preparedness, training, damage assessment, advisory work, and post-crisis assistance. Its emergency-management resources address preparatory planning, crisis management, and crisis response, illustrating the need for heritage information that can be used before, during, and after emergencies rather than only after damage has occurred. A DRR-compatible archaeological workflow could support Blue Shield activities by producing pre-event risk maps, identifying areas requiring contingency planning, and providing baseline evidence against which post-event damage could be assessed.

ICCROM's disaster-resilient heritage programmes seek to integrate heritage into wider disaster-risk policies and programmes at local, national, and regional levels. Through initiatives such as *First Aid and Resilience for Cultural Heritage in Times of Crisis* (Tandon, 2018), ICCROM develops practical methods, tools, professional networks, and training for coordinated cultural rescue and risk-reduction operations involving heritage custodians, communities, emergency responders, and humanitarian organisations. The framework developed in this thesis aligns particularly closely with this capacity-building role. It offers a replicable geospatial method that could be incorporated into professional training, institutional preparedness exercises, vulnerability assessments, and the development of local or national heritage-risk strategies. Its use of accessible data and transferable

workflows is especially relevant where specialist infrastructure is unavailable and where training must support practitioners operating under constrained conditions.

ALEPH Strategies occupies a different institutional position. It is not an intergovernmental heritage body or an emergency grant-making foundation, but a strategic advisory and research organisation working with governments, non-governmental organisations, and international agencies. Its cultural-heritage activities include mapping and documentation in fragile and conflict-affected countries, programme design, research, evaluation, and analysis of the relationships between heritage protection, peacebuilding, livelihoods, and post-emergency recovery. Its work on engaging non-state armed groups in cultural-heritage protection further demonstrates that heritage governance in conflict settings may involve actors and authority structures extending far beyond conventional state heritage agencies. For organisations of this kind, the value of the proposed framework lies not only in producing risk maps but in supporting strategic analysis. Spatial evidence of hazard, archaeological exposure, institutional weakness, and restricted access could inform programme design, funding proposals, monitoring and evaluation, and decisions about where partnerships or capacity-building initiatives are most needed.

These organisations represent different points within the institutional architecture of heritage protection. The same archaeological DRR methodology would not be used identically by each organisation. A funding body may use its outputs to assess urgency and compare project needs; an emergency-response network may employ them for preparedness and damage assessment; a training organisation may adapt the workflow for institutional capacity building; and a strategic consultancy may use the evidence to design locally appropriate interventions. The institutional relevance of the framework, therefore, derives partly from its flexibility. It provides a consistent analytical structure without prescribing a universal governance or implementation model. This is important because heritage protection is conducted through different legal systems, funding structures, humanitarian arrangements, community institutions, and political authorities. The framework can identify where archaeological risk is concentrated, but decisions about intervention, consultation, funding, access, and acceptable outcomes must remain with the organisations and communities possessing the relevant legal authority, cultural knowledge, and operational responsibility.

Collectively, these potential applications demonstrate that archaeological DRR is not only a disciplinary concern. It offers institutions a practical way to prioritise limited resources, strengthen resilience planning, inform infrastructure decisions, improve emergency preparedness, and support evidence-based climate adaptation. The framework developed in this thesis provides the analytical basis through which = decisions can be made more transparently and proactively. Its institutional value therefore lies in making archaeological risk visible, comparable, and operational within the wider systems that already govern planning, heritage protection, and disaster response.

6.4. Future Directions

6.4.1. Community Consultation

This thesis's case studies raise a deep, contemporary question: what happens when the people most affected by environmental change no longer share ties to the landscapes being studied? In Holderness, public responses to archaeology range from active stewardship to indifference, shaped by more immediate concerns over collapsing homes, insurance, and managed retreat (Wood, 2019; O'Dwyer, 2023). In Oʻahu, the stakes are inverted: archaeological loss is a direct affront to Native Hawaiian efforts to reclaim cultural memory and to practice land stewardship (Spagnuolo, 2012; Ho-Lastimosa et al., 2019). Sistan, meanwhile, presents a landscape where archaeological significance is obscured by poverty, migration, and depopulation, raising ethical tensions between scholarly value and local disconnection (Abramiuk, 2017, 2019). Ultimately, these case studies ask not only how to model archaeological risk, but why, for whom, and under what conditions. They demonstrate that DRR-aligned geospatial approaches are not just a technical toolkit, but a political and ethical framework for navigating heritage in crisis.

A limitation of the present research is the restricted scope for direct community consultation, particularly in Oʻahu and Sistan, where ethical, logistical, and political conditions constrained sustained engagement. The models developed in this thesis were largely constructed from institutional datasets and remotely sensed imagery rather than from co-produced knowledge. As such, they necessarily reflect the priorities, gaps, and biases embedded in those sources. Future development of archaeological DRR could (and should), therefore, treat community consultation as the next phase in the method's maturation. If risk modelling is to shape real decision-making, it must be grounded in the lived understandings of those who inhabit, use, and care for the landscapes under assessment.

Community consultation could influence the framework at multiple levels. First, it would refine how significance and vulnerability are conceptualised. Local communities may attribute value to places that are under-represented in formal inventories or that do not conform to conventional site typologies, such as seasonal camps, ritual routes, or places whose importance is primarily mnemonic rather than material (Gunnarsdóttir, 2023). Incorporating these perspectives could alter which locations are treated as exposed or irreplaceable and might also change how acceptable loss is understood. Second, consultation would inform capacity assessments. Formal indicators such as the presence of a heritage agency or a management plan tell only part of the story. Informal custodianship, community networks, religious institutions, and Indigenous governance may all play critical roles in monitoring and protecting heritage yet remain invisible in geospatial datasets. Engaging with these actors would provide a more realistic picture of where resilience already exists and where external intervention may be unwelcome or ineffective.

The consultation process itself would need to be tailored to the specific context. In Holderness, this might involve working with parish councils, coastal residents, and local history groups to understand how heritage values intersect with concerns about property loss and retreat. In Oʻahu, meaningful

consultation would require collaboration with Native Hawaiian organizations, lineal descendants, and cultural practitioners, recognising Indigenous data sovereignty and protocols around sharing spatial information. In Sistan, where direct engagement may remain impossible for the foreseeable future, consultation might take the form of dialogue with diasporic communities, regional scholars, and humanitarian organisations who retain connections to the landscape. Across all cases, the objective would not be to seek community endorsement for pre-existing models but to co-design how risk is defined and acted upon.

6.4.2. Expanding and Refining the Methodology

The three case studies were intentionally chosen to probe the framework under contrasting conditions of hazard type, data availability, and governance, but they cannot represent the full diversity of environments in which archaeological DRR could prove useful. A next step is to apply and adapt the methodology in a wider set of contexts, incorporating hazards such as riverine flooding, wildfire, permafrost thaw, urban encroachment, and sea-level rise in low-lying islands. Each of these processes has distinct spatial and temporal behaviours and interacts with heritage in ways that differ from coastal erosion, landslides, or desertification. Extending the framework would test which elements of the current approach are robust across hazard regimes and where bespoke indices or modelling strategies are required. Such expansion will also necessitate refinement of the underlying datasets. The present research deliberately relied on publicly available, open data to maintain transferability. Future work can retain this principle while exploring alternative and complementary sources. For instance, higher-resolution satellite imagery (Alders et al., 2024), synthetic aperture radar (Hagage et al., 2025), LiDAR (Collaro, 2025), and UAV-based photogrammetry (Mencía et al., 2024) can provide more detailed representations of microtopography, structural condition, and subtle erosion patterns. Socio-spatial datasets, including land tenure, infrastructure networks, zoning regulations, and socio-economic indicators, could be incorporated to enrich assessments of exposure and capacity. The challenge will be to integrate these richer datasets without sacrificing the clarity and transparency that make the current workflows accessible to practitioners operating with limited computational or financial resources. Iterative refinement should also address the models' internal logic. Weighting schemes, classification thresholds, and aggregation rules are presently guided by literature, expert judgement, and pragmatic testing. As more applications accumulate, comparative analysis can be used to calibrate these parameters more systematically. Machine learning approaches could be explored cautiously, not as opaque pattern-finders but as tools to detect where current heuristics systematically under- or overestimate risk. Throughout, the emphasis should remain on methods whose assumptions are legible and contestable, so that archaeologists, community members, and decision makers can see how particular risk patterns emerge.

6.4.3. Long-Term Landscape Change Modelling

While this thesis has used multi-temporal imagery to capture change, the analytical focus has largely been on differences between discrete time points. Future work could aim to model landscape

change as a continuous process, recognising that risk accumulates and transforms over decadal rather than single-event timescales. This is particularly important because one of the thesis's central claims is that landscapes are never static and that accelerated change has become a defining feature of archaeological contexts. Translating that insight into modelling practice will require a more systematic use of time-series approaches. For coastal environments such as Holderness, this might involve combining satellite-derived shoreline positions, historical maps, and projected sea-level rise scenarios to forecast future erosion trajectories and their interaction with heritage distributions. For Oʻahu, integrating changing rainfall regimes, land cover transitions, and infrastructure development into landslide susceptibility models would allow archaeologists to see not only where risk is high now, but where it is likely to expand or contract. In Sistan and comparable basins, tracking multi-decadal patterns of vegetation decline, dust source activation, and hydrological collapse would help to identify tipping points beyond which archaeological visibility and survival change qualitatively, not just quantitatively. Long-term modelling also has implications for how urgency is framed. Rather than treating risk as a static snapshot, it allows a distinction between sites or landscapes where there is still a meaningful window for intervention and those where opportunities are narrowing rapidly. This temporal differentiation can inform prioritisation more effectively than spatial exposure alone. It can also support dialogue with climate adaptation and land-use planning communities, which increasingly use scenario-based approaches. Integrating archaeological risk trajectories into such conversations would strengthen the case for considering heritage in planning for future change, rather than only in responding to its impacts after the fact.

6.4.4. Improved Validation and Data Integration

A recurring constraint in this thesis has been the difficulty of validating remotely generated models in contexts where field access is limited, hazardous, or politically constrained. Future research must therefore focus on developing validation strategies that are robust yet realistic for such environments. This does not mean abandoning field verification altogether, but rather designing targeted, risk-aware fieldwork that maximises information gain per unit effort and exposure. Short, carefully planned campaigns could be used to ground-truth hazard classifications, confirm the presence or condition of selected sites, and refine assumptions about visibility and degradation. Partnerships with local researchers or agencies that have intermittent access may also offer opportunities for opportunistic validation. In parallel, there is considerable scope for integrating non-traditional data sources into the validation process. Historical aerial photography, declassified military imagery, crowdsourced photographs, local archives, and oral histories can all provide independent evidence of how landscapes and sites have changed over time (Ryder, 2013). In regions where formal archaeological records are sparse, these materials may be the only available means of checking the plausibility of model outputs. Incorporating them will require careful attention to issues of reliability, bias, and ethics, but their potential to enrich understanding is significant. For regions that are likely to remain inaccessible for the foreseeable future, such as parts of Sistan, validation may need to focus less on individual sites and more on verifying process-level patterns. Cross-comparison with hydrological, geomorphological, or climatological studies can help to confirm whether the spatial and temporal signatures of hazards detected by the models align with

those observed by other disciplines. Engaging with regional experts through remote collaboration can provide additional qualitative checks (Adam et al., 2022). The aim is not to eliminate uncertainty but to characterise it explicitly, ensuring that users of the models understand where confidence is high, moderate, and where conclusions are necessarily tentative.

6.4.5. Testing in Contexts with Stronger Capacity

The case studies in this thesis have, by design, emphasised contexts where institutional capacity is weak, fragmented, or collapsing. This has been invaluable for revealing how archaeological risk is amplified when there are few actors able to respond. However, a comprehensive evaluation of the framework also requires testing it in settings where heritage governance is comparatively strong and where DRR structures are already in place. Applying the methodology in such contexts would allow researchers to examine how risk models behave when there are genuine opportunities for integration into planning and management, and to understand the organisational adjustments required for that integration. In well-resourced coastal regions, for example, archaeological risk maps could be incorporated into shoreline management plans, environmental impact assessments, or relocation strategies. In urban or peri-urban areas with active planning systems, exposure models could inform zoning decisions, infrastructure placement, or redevelopment priorities. In jurisdictions with established emergency management agencies, archaeological data might be woven into hazard mitigation plans or post-disaster damage assessments. Tracking how these institutions use, modify, or ignore the models would provide critical feedback on the framework's practical utility, communicative clarity, and institutional fit. Contrasting such high-capacity contexts with the constraints documented in Sistan would also deepen understanding of the true limits of archaeological DRR. If models are underused even where capacity is strong, the barrier may be conceptual or political rather than technical. Conversely, if they are readily adopted in some settings, those cases can serve as exemplars for how archaeology can be embedded in DRR processes elsewhere. In both scenarios, the goal is to move beyond proof of concept toward sustained, routine use of archaeological risk assessment in real decision-making environments, closing the gap between diagnosing vulnerability and acting upon it.

6.10. Closing Remarks

The discussion presented in this chapter has shown that archaeological risk in contemporary landscapes cannot be reduced to the behaviour of hazards or the fragility of material remains. Instead, the case studies reveal a more complex configuration in which time, visibility, governance, movement, and methodological flexibility all converge to shape what can be known, what can be protected, and what will be lost. The tensions between archaeological and hazard timescales illustrate that the discipline continues to operate within assumptions inherited from less risk-aware perspectives, even as the tempo of environmental and political change accelerates beyond those expectations. This temporal mismatch is not a secondary observation but a structural condition that influences every aspect of archaeological practice. It defines when access is possible, how rapidly decisions must be taken, and how long evidence remains available before it is altered or removed.

Similarly, the analysis of visibility across Holderness, O‘ahu, and the Sistan case studies demonstrates that the ability to perceive archaeological material is itself complex. The loss of visibility, whether through erosion, burial, dust, vegetation change, or political inaccessibility, functions as a form of risk that precedes and can exceed physical destruction. This recognition reframes archaeological vulnerability as a problem of knowability as much as preservation, suggesting that the archive can disappear long before the material it contains is gone. The landscapes examined in the case studies underscore this point by functioning as archives in motion, where exposure and concealment alternate in ways neither predictable nor neutral. These cycles of appearance and disappearance shape what is documented and what remains unobserved, and they challenge any assumption of a stable archaeological baseline.

The discussion has further shown that the determining factor in archaeological outcomes is not limited to hazard severity or visibility but also includes capacity. This pattern is consistent across the three landscapes and becomes more salient as environmental conditions differ radically. Where capacity is present but politically diluted, as in Holderness, protection remains partial and inconsistent. Where capacity is fragmented or poorly integrated, as in O‘ahu, risk persists not because knowledge is lacking but because institutions fail to translate that knowledge into preventive action. Where capacity collapses entirely, as in Sistan, the archaeological record becomes subject to loss that cannot be mitigated or even monitored. This demonstrates that environmental hazards become archaeological hazards only when governance structures allow them to do so. Risk is therefore co-produced through the interaction of physical processes with the political and administrative systems that mediate land use, access, and response.

These themes converge in the recognition that methodological adaptation is not an optional enhancement but a necessary form of resilience. The framework applied in this thesis functions across stable, unstable, and inaccessible landscapes precisely because it adjusts to the constraints imposed by each context. In the most challenging settings, the method becomes a means of survival, enabling archaeology to operate even when traditional field-based approaches cannot. This methodological flexibility invites a broader reflection on what it means to conduct archaeological research in environments where conditions are unstable, windows of opportunity are short and the relationship between environmental change and political volatility is tightly interwoven.

A final thread running through the discussion concerns the ethics of knowing enough. The case studies illustrate that archaeology cannot pursue a model of comprehensive preservation in landscapes where hazards outpace intervention and where political conditions restrict access. In such contexts, the responsibility shifts toward documenting meaningfully and strategically rather than exhaustively. This raises difficult but necessary questions about what constitutes responsible practice when loss is unavoidable and when the chance to observe or record is brief, fragmented or uncertain. It also highlights the need to align ethical frameworks with the temporal and political realities within which archaeology now operates.

Taken together, these insights provide a coherent interpretive foundation for the thesis. They show that archaeological risk emerges from the interplay of accelerated temporalities, fluctuating visibility, variable governance, dynamic landscapes, and adaptive methodologies. They demonstrate that archaeology is increasingly situated within conditions of instability in which the archive is neither fixed nor fully accessible. They also suggest that the discipline's future relevance will depend on its ability to recognise and respond to these dynamics rather than rely on inherited assumptions about landscape stability, institutional continuity, or unlimited time. This synthesis closes the discussion by situating archaeological practice within a world where change is rapid, uncertainty is structural, and the past cannot be understood or protected without acknowledging the conditions that shape its present visibility. It establishes the analytical ground on which the thesis's final conclusions rest and clarifies why the arguments advanced here matter not only for the specific landscapes studied but for the wider discipline as it confronts an increasingly unstable future.

Chapter 7: Conclusion

This research adapts and operationalises the United Nations' Disaster Risk Reduction (DRR) framework for archaeology through geospatial approaches, reaffirming this work's central aim: to develop models that identify, visualise, and prioritise archaeological risk, thereby embedding archaeology within the broader DRR resilience agenda. While such tools are well established in environmental sciences, archaeology has not implemented such approaches as comprehensively. To bridge this divide, the thesis develops open workflows that make disaster risk modelling both feasible and transparent, transforming the DRR framework from an abstract policy model into a practical triage and salvage tool capable of functioning across diverse data and governance contexts. Tested across the eroding coasts of Holderness, the landslide-prone slopes of O'ahu, and the politically unstable landscapes of Sistan, these workflows demonstrate how vulnerability, exposure, and capacity can be operationalised geospatially across contrasting environments. By prioritising accessibility and adaptability, the framework establishes a foundation for integrating archaeological risk into both heritage management and disaster governance.

Methodologically, the thesis reframes the core DRR concepts of hazard, exposure, vulnerability, and capacity to align with the realities of archaeological presence and implements these redefinitions through open geospatial processes. Here, vulnerability is conceived not exclusively as physical fragility but as a composite measure encompassing governance conditions and data capacity. This reconceptualisation transforms risk assessment into a dynamic, context-sensitive process that reveals how archaeological sites interact with the social and environmental systems that shape their endurance. In doing so, the framework moves beyond reactive documentation to provide an operational system that supports proactive, evidence-based decision-making, enabling archaeologists and policymakers alike to visualise, prioritise, and plan for risk with clarity. Theoretically and ethically, this work argues that archaeology cannot remain peripheral to DRR. The loss of heritage is too significant, representing the erosion of cultural continuity, identity, and memory. Recognising this, archaeology must act as an anticipatory partner in risk governance. Yet this expanded role introduces other ethical tensions: between managed retreat and neglect, stewardship and intervention, and the competing imperatives of open data and site protection. Addressing these dilemmas requires a reflexive, inclusive, and context-specific approach that foregrounds local agency, cultural values, and long-term sustainability over short-term technical fixes.

Ultimately, this thesis redefines what it means to safeguard archaeology in the age of climate crisis and disaster. It demonstrates that with geospatial tools and interdisciplinary collaboration, archaeology can transition from documenting loss to mitigating it. By operationalising resilience through accessible approaches, this thesis repositions archaeology as both witness to and agent of change, a discipline capable of informing not only how we understand past human adaptation, but how we act to sustain cultural futures.

Methodologically, this thesis develops a structured integration of the DRR framework with archaeological analysis by translating hazard, exposure, vulnerability and capacity into spatially measurable components. Environmental and climatic processes were modelled to characterise hazard dynamics; exposure was defined through the spatial intersection of archaeological records with these zones; vulnerability was expanded to include contextual factors such as governance priority and existing protection; and capacity was interpreted in terms of data availability and institutional readiness. Through open geospatial workflows, these dimensions were rendered as explicit, comparable layers, enabling archaeological risk to be analysed within the same operational language used in wider DRR practice.

The Holderness case study provided the initial testing ground for this integration. Using medium-resolution Landsat imagery and simple water indices to track shoreline movement, the methodology demonstrated that chronic coastal erosion can be mapped with sufficient precision for archaeological triage using entirely open data and reproducible processing steps. By intersecting erosion patterns with the historic environment record and incorporating variables such as tidal energy and surface geology, the workflow identified zones of accelerated loss and new exposure, revealing a coastline characterised by continual reorganisation rather than steady retreat. The case shows that effective archaeological risk assessment does not depend on high-end technology, but on transparent methods that local heritage teams can replicate within existing resource constraints.

In Oʻahu, the framework was refined under conditions of rapid-onset hazard. Here, precipitation, slope and vegetation indices were combined with landform classification to model landslide susceptibility across the island. Validation against historical landslides and state hazard maps demonstrated that an open, relatively simple workflow could match, and in places sharpen, existing susceptibility assessments. When archaeological data, particularly Pre-Contact Hawaiian sites, were intersected with these models, the approach highlighted both physical vulnerability and gaps in how cultural values are incorporated into risk planning. The case also showed that such modelling can be undertaken in a way that respects Indigenous data sovereignty by using non-invasive remote datasets and withholding sensitive site coordinates, illustrating that accessibility and cultural protection can be held together within an archaeological DRR methodology.

The Sistan Basin pushed the framework to its operational limits in a context of restricted access, political instability and highly volatile environmental conditions. Here, Landsat-derived indices for vegetation, soil texture and surface water were combined with topographic and wind data to map desertification processes that alternately expose and obscure archaeological material. Multi-temporal composites allowed areas of accelerating change to be identified even in the absence of fieldwork, and comparison with independent geomorphological studies provided a measure of validation. The results revealed a paradox in which the same processes that endanger sites also facilitate their discovery, and they showed that meaningful, decision-relevant risk modelling is still possible where only remote sensing is available, provided its limitations are acknowledged.

Taken together, the three case studies demonstrate that the DRR pillars originally designed for human populations can be reinterpreted for archaeological contexts and operationalised through open geospatial tools. Holderness illustrates the framework's utility in a data-rich, managed landscape dominated by chronic hazard; O'ahu shows its applicability to complex, sudden-onset events in a culturally sensitive setting; and Sistan exposes both its reach and its limits under severe data and governance constraints. Across these contrasts, the approach remains methodologically coherent and practically deployable, while also revealing that its effectiveness is conditioned by the presence or absence of institutional capacity. Where capacity is strong, risk models can inform policy and planning; where it is weak or absent, they remain largely diagnostic. Identifying this gap between understanding risk and reducing it is itself a key methodological finding, underscoring that archaeological DRR must always be read against the institutional landscapes in which it operates.

7.1. Limitations

While the integration of DRR and archaeological practice developed in this thesis represents a conceptual advance, it is equally necessary to acknowledge the framework's limitations. These are not failures of design but reflections of structural asymmetries between a paradigm built for human-centred governance and a discipline concerned with material traces and temporal depth. The adaptation of the DRR model, hazard, exposure, vulnerability, and capacity to archaeological contexts reveals critical mismatches in scale, temporality, measurability, and ethical orientation that limit both its precision and applicability.

First, the issue of temporal and conceptual mismatch remains foundational. DRR operates on short-term, often annual, cycles of assessment, response, and recovery. Archaeology, conversely, works across longue durée processes that unfold over decades and centuries. When transposed into archaeological contexts, DRR's variables compress temporality, risking the obscuration of the cumulative, nonlinear nature of archaeological degradation. Hazards such as coastal retreat, dune migration, or salinisation are rarely events in the conventional sense; they are drawn-out processes that erode archaeological context incrementally. Consequently, the adapted framework can risk overemphasising spatial immediacy at the expense of temporal continuity, translating what is essentially chronic attrition into static maps of risk.

Second, the limits of quantification constrain how fully archaeological vulnerability and capacity can be operationalised within a DRR model. Whereas traditional DRR metrics rely on quantifiable human loss and economic costs, archaeological value can be subjective and often intangible and is not reducible to numeric proxies. Indices such as protection status or documentation density offer partial insight but fail to capture the affective or community-held significance of heritage. Likewise, capacity is difficult to measure beyond formal institutional presence. Informal guardianship and local knowledge systems often remain invisible to geospatial analysis, creating a representational deficit that can distort risk interpretation. The danger is that the absence of data becomes conflated with the lack of value. For example, in the context of the Sistan case study, if experts were unaware

of the extant state of the archaeological record across the Sistan Basin, they may not be aware of the risk measurement requirements.

Third, institutional asymmetry and governance dependence significantly mediate the framework's effectiveness. The adaptability of DRR-informed workflows does not guarantee their uptake. Where administrative structures are strong, as in Holderness, the outputs of risk modelling can be absorbed into policy, planning, and funding streams. Where governance is weak or fragmented, as in Sistan, models risk becoming diagnostic rather than actionable; the framework thus exposes the uneven geography of heritage governance: with areas most at risk often being those least capable of responding. This asymmetry reveals that the utility of archaeological DRR is contingent not only on methodological robustness but on the political will and institutional architecture that surround it. The framework's outputs, while capable of illuminating vulnerability, cannot, on their own, produce resilience.

Fourth, the technical constraints of data and scale impose practical boundaries on the precision and comparability of results. The decision to standardise all modelling on open-source, medium-resolution datasets ensures global applicability but at the cost of granularity. A 30-metre pixel cannot capture the microtopography of archaeological sites or the subtle indicators of degradation visible in higher-resolution imagery. These limitations do not invalidate the approach but delineate its interpretive scale; it is a first-pass, triage-level framework rather than a substitute for detailed field validation. Finally, conceptual universality may obscure local specificity. DRR's global lexicon, hazard, exposure, vulnerability, and capacity, achieves international coherence precisely because it abstracts away cultural differences. Yet when applied to archaeology, this abstraction risks flattening the diversity of archaeological value and ontological understandings of place. The framework's strength lies in its transferability, but its weakness lies in the tendency toward universalisation. An archaeological DRR model must therefore remain plural and adaptive, capable of absorbing divergent epistemologies rather than imposing a single schema of risk. This includes recognising that not all societies conceptualise loss or resilience through the same moral or temporal frameworks.

In sum, the adaptation of the DRR framework for archaeology should be understood as both an enabling mechanism and a site of productive constraint. Its methodological rigour and policy legibility make it a powerful instrument for rendering archaeological risk visible and actionable across scales. Yet its success depends on reflexivity, an awareness that each variable in the model encodes assumptions about time and governance that cannot be universally resolved. Rather than viewing these limitations as deficiencies, this thesis interprets them as the boundary conditions of a new disciplinary synthesis. The DRR-archaeology framework cannot erase the asymmetries it reveals, but it can make them explicit, allowing future revisions of such global frameworks to improve both archaeological integration and a more equitable inclusion of cultural nuance in disaster risk mitigation.

While the adaptation of the DRR framework to archaeological contexts demonstrates the feasibility of structured, cross-scalar risk assessment, several methodological limitations constrain precision. These limitations arise primarily from data availability, the spatial resolution of the data, and the practical constraints of integrating hazard-based logic with archaeological datasets.

First, the framework remains dependent on secondary and legacy datasets of uneven quality and completeness. The archaeological data used across the case studies are drawn from existing inventories that vary in spatial precision and chronological detail. Many features are recorded as approximations or inferred from past fieldwork rather than confirmed through systematic ground-truthing. As a result, modelled risk distributions represent indicative rather than definitive patterns. Similarly, hazard data, such as erosion rates and slope instability, are constrained by sensor resolution and temporal frequency. This trade-off between spatial coverage and analytical depth limits the framework's capacity to assess site-level risk with high confidence.

Second, the reliance on open-access data imposes uniformity at the expense of precision. Global datasets were deliberately selected to ensure methodological replicability across different landscapes (apart from the case studies of focus in this thesis), but this standardisation limits the model's sensitivity to local, finer-scale conditions. The coarse resolution of inputs can smooth or generalise hazard gradients, producing conservative or overstated estimates of exposure. Where finer-resolution data (such as LiDAR or UAV imagery) are unavailable or inconsistent, site prioritisation outputs should therefore be treated as beneficial tools for risk assessments, not as definitive decision metrics.

Third, the framework's quantitative emphasis introduces uncertainty in weighting and classification. The normalisation and aggregation of multi-variable layers, hazard, exposure, vulnerability, and capacity, depend on inherently heuristic parameter thresholds. Although these were calibrated through literature review and logical contextual assessments of conditions, they remain subject to regional variability and expert judgement. Consequently, the resulting triage scores should be interpreted as comparative rankings rather than as absolute risk measures.

Fourth, limitations in temporal comparability constrain the framework's predictive reliability. Hazard datasets are typically assembled from multi-year composites, while archaeological inventories capture temporal states at the moment of recording. This temporal asynchrony means that the model evaluates sites against hazards that may not align with the conditions at the time of their documentation. The framework therefore operates most effectively as a dynamic monitoring tool, capable of updating as new data become available, rather than as a static representation of long-term vulnerability.

Finally, the framework's operational scalability is shaped by the availability of institutional capacity for validation and integration. While technically transferable, the model outputs require interpretation within local management systems and ground verification to refine parameters.

Without periodic recalibration through field data or local hazard observation, the framework risks progressive drift from on-the-ground conditions.

In methodological terms, then, the DRR adaptation should be viewed as a replicable but inherently coarse-grained analytical platform: a decision-support system designed to identify relative zones of concern, not a substitute for detailed archaeological or engineering assessment. Its strengths lie in scalability, transparency, and data accessibility; its limitations lie in the inevitable compromises between precision, consistency, and generalisability that accompany global-scale modelling.

Beyond these methodological considerations, the practical implementation of the framework represents an additional limitation and an important direction for future research. Although this thesis demonstrates that DRR concepts can be successfully operationalised within archaeological contexts, the framework has not been evaluated through implementation within existing heritage management and planning systems. Consequently, its integration into routine archaeological practice remains to be tested through collaboration with the organisations responsible for archaeological stewardship, planning, and disaster preparedness. Equally important is engagement with Indigenous organisations and knowledge holders where archaeological landscapes are actively associated with living cultural traditions or Indigenous heritage. Such collaboration would ensure that archaeological risk assessments incorporate locally defined values and cultural priorities rather than relying solely on technically derived indicators of hazard and vulnerability. Future implementation should therefore be undertaken through collaborative and context-specific approaches that recognise the diversity of archaeological knowledge systems. Future implementation should, therefore, be undertaken collaboratively with heritage agencies, planning authorities, commercial archaeology, Indigenous organisations where appropriate, and emergency-management practitioners to ensure that methodological consistency is matched by locally appropriate governance and stakeholder engagement.

7.2. Closing Thoughts

This thesis has shown that when archaeology is reframed through the logic of Disaster Risk Reduction, it stops behaving like a discipline anchored solely to the past and instead becomes one that is actively entangled with the futures that hazards, governance, and environmental change are already reshaping. By adapting the DRR framework to archaeological contexts and operationalising it through open geospatial workflows, the research shifts archaeology from a passive archive of what has already been lost to a dynamic register of resilience, one capable of informing how societies anticipate cultural loss and intervene before it becomes irreversible. The three case studies, from the constantly rearranging coastline of Holderness to the landslide-prone valleys of O‘ahu and the unstable desert systems of Sistan, demonstrate that global DRR principles can be translated into locally meaningful tools that render archaeological risk visible, comparable, and, crucially, actionable.

Yet the work also exposes the limits of what modelling alone can accomplish. The DRR-archaeology synthesis reveals the tension between what can be spatialised and what remains stubbornly interpretive; between the precision of indices and the lived realities of stewardship; between the desire to measure risk and the recognition that not all values can be quantified. It shows that resilience in archaeological terms is less about holding back loss than sustaining continuity in the face of it, acknowledging that some degree of transformation is inevitable. These tensions are not flaws in the framework but reminders that archaeology inhabits the same uncertainty that shapes all contemporary risk governance. The value of the framework lies not in eliminating uncertainty, but in giving us better ways to navigate it.

What this thesis offers is therefore a foundation, not a final system. The workflows developed here demonstrate the feasibility of integrating archaeology into DRR practice, but they also point toward the next steps: building models that incorporate temporal dynamism more fully, grounding risk assessments in community consultation, and testing the framework in contexts where institutional capacity allows its recommendations to be implemented rather than simply observed. These future directions are not optional; they determine whether the methodology becomes a living tool or remains an academic proof of concept. The flexibility of the approach presented. In this thesis provides a transferable methodological foundation capable of supporting diverse stakeholder environments as archaeological DRR continues to mature.

Ultimately, the argument advanced throughout this thesis is both practical and philosophical. Archaeology cannot remain a witness to disaster, cataloguing losses after the fact. By embedding geospatial analysis within DRR, it can move toward intervention, offering evidence, perspective, and long-term insight at the very moment they are most needed. The question is not whether archaeology will continue to face accelerating hazards; it will. The real measure of success lies in how effectively archaeological knowledge helps shape futures in which cultural memory persists despite those hazards.

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Appendices

Appendix A

Catalogue of Archaeological point data acquired from the Archaeological Data Service (ADS) for the Holderness Coastline

Records positioned 50 metres of the Holderness coastline

Period	Description	ADS Link
Prehistoric		
	Bracer reused as a pendant or ornament	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195442
	Cropmarks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1320665
	Cropmarks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1320819
	Double edged flint scraper	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002081
	Canoe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195450
	Settlement	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002406
	Settlement, burials, lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002053
	Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1930334
	Flint	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002088
	Flint blade	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002083
Mesolithic		
	Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002012
	Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200443
	Scraper	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200441

	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839698
Paleolithic		
	Flint flake	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1225616
	Flint tortoise core	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195456
	Occupation site, Withow Mere	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200379
	Flint flake	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1225616
Neolithic		
	Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195481
	Polished greenstone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002098
	Axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002403
	Polished axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002040
	Polished stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200262
	Polished stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001974
	Polished stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200307
	Polished stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200405
	Polished stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195451
	Polished stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200414
	Polished stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002016
	Polished stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200263
	Polished stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002073
	Polished stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002079
	Flint knife and a flint sickle	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200437
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839741
	Settlement	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1889541

Stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195479
Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002089
Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001973
Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001972
Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195440
Settlement	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910573
Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002090
Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200792
Lithics and pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200250
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839751
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839752
Henge	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1889689
Round barrow	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1822749
Round barrow covering a grave	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997074
Saddle quern	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002099
10 pieces of beaver gnawed wood	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1928859
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839748
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839746
Stone ball	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002075
Axe factory	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002095
Stone battle axes	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200440
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839748
Bronze Age	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002014

Spearhead	
Axehead	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002036
Bronze Spearhead	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001971
Socketed axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002059
Flat bronze axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002109
Beaker	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002013
Halberd	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002071
Inurned cremation	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002103
Palstave	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200444
Bronze dagger	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002076
Circular cropmark	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001970
Barrows	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1822743
Round barrow	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002404
Bracelet	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002039
Flint chisel	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002097
Flint knife	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002102
Flint knife	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002084
Flint knife	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200256
Four barrows	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002176
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910570
Barrow	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002057
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839756
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839742

	Lithics	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1892122
	Occupation site	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200302
	Round barrow, uncovered and internment and urn	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997069
	Flint chisel	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002096
	Tumulus	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002052
	Two Bowl barrows	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002048
	Spearhead	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002014
	Axehead	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002036
	Bronze Spearhead	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001971
	Socketed axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002059
Iron Age	Stone axe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001958
	Gold stater	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002015
	Settlement, cremations	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1949997
	Corieltauvian stater	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195464
	Cropmarks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1308480
	Boundary ditches	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1930332
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910546
	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001964
	Gold stater	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200279
	Enclosure	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1253497
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195421
	Settlement	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839721
	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001961

	Round barrow with an adjacent square barrow	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997081
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1898224
	Settlement	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1937454
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839768
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910572
	Square barrow	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200255
	Square barrows	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200252
	Cinerary Urn	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002412
Roman		
	Enclosed Settlement	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1316627
	A denarius of Hadrian	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997133
	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002410
	A hoard of bronze coins	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997116
	Cooking pot	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002106
	Skeleton	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002105
	Bronze coin of Licinius	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002397
	Silver denarius of Faustina	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997125
	Coin hoard from Vespasian to Antoninus	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002148
	Coin hoard	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002064
	Gold coin of Magnentius	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002391
	Quern	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997123
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1899416
	Building	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002078
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839778

Rectangular camp	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002402
Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1233838
Pottery, urns	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997120
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839749
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910544
Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3514322
Pit	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1911751
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1886940
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1819437
Pottery, coins, and brooch	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002411
Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002003
Stonework	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002104
Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997117
Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997132
Settlement	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3501362
Beacons	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002401
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910567
Coin of Salonina, wife of Gallienus	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997122
Vessel	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001959
Republican coin, (denarius)	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002011
Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997131
Coins	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002107
Coins	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002037
Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002365

	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002405
	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997070
	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997071
	Vessel	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002147
	Coin of Salonina, wife of Gallienus	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997122
	Vessel	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001959
	Republican coin, (denarius)	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002011
	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997131
	Coins	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002107
	Coins	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002037
	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002365
	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002405
	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997070
	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997071
	Vessel	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002147
Medieval	Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195460
	Buildings	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195486
	Barn	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1290360
	Saxon monastery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002409
	Boundary	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1837763
	Anglian bone comb	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1233837
	Anglian cemetery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002390
	Lighthouses	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1277505
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839769

Atwick Cross	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3379672
Beacon	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002396
Bridge	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002086
Bridlington Harbour	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002061
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203163
Bull Ring	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001912
Chapel	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002146
Cleeton village	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002005
Deserted village	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002400
Ridge and furrow	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3514361
Aumale Abbey	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195448
Village: High Skirlington	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002004
Earthwork remains of deserted village	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002368
Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1250251
Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002149
Fishponds	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002108
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910514
Saxon burial	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1320385
Fair site	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002034
Ridge and furrow	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1250436
Fishponds	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997078
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002072
Hogback stone in the porch of All Saints' Church	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1001956
Great Colden	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002398

Grimston Garth or Hall	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002364
Holy Well	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002008
Hornsea Beck Village	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002394
Hornsea cross	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3379682
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910545
Grave goods	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002407
Market cross	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002393
Market cross	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002392
Medieval borough	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1207514
Earthwork	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002395
Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1867143
Mentioned 1668-9.	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002062
Mentioned in 1636	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002046
Mentioned in Domesday	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195449
Moated site	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200391
Bridge	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002054
Ridge and furrow	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3496329
Ridge and furrow	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1932489
Groundwork	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1922473
Beacons	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002006
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910539
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839755
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1819436
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910566

No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839766
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1867144
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195424
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997083
Church	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1320532
Pillory and stocks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002044
Crofts and garths	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002408
Cross	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002043
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1839757
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200247
Rectangular enclosure	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002385
Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997082
Manor house	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997082
Cloisters of Bridlington Priory.	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203178
Rolston Hall	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002399
Saxon coin	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002068
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1867317
Castle wall	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1917762
Settlement	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1917762
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1933000
Church	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997121
Watermill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195487
Watermill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200384
Old Hall	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997068

Plot boundary	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3492280
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1910530
Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002066
Prior's Lodgings	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203198
Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1321637
The Market Cross	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3379683
Moated enclosure	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002366
The Priory of Augustinian Canons	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002047
Hilderthorpe	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1865017
Shrunken village	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997130
Village documented in Domesday	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1230696
Pieces of masonry	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3502671
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002150

Post Medieval

No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002070
House	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1240748
Railway station platform	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1893995
Post hole	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1894302
All Saints Church	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1945420
Napoleonic gun battery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1277508
Barn	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1959145
Barn	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=2587692

Bridge	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002087
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002117
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002112
Cottage adjoining Patriot Cottage	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1321037
Dissenters Meeting House	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002038
House	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002120
Farmhouse	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1321040
Dwellings	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=2646335
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1850434
Farm complex	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1321205
Fort	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002063
House	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1322405
House	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002116
House	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002111
Houses	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002118
Houses	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002113
Houses	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002115
17th century building.	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002119
House	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1322655
Lighthouse	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997079
Lighthouse of 1806	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1301156
Marton Hall School	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997072
Well	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1818743
Structural evidence	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1925889

Field boundary ditch.	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1932860
Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3513689
Monument	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1167200
Monument	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1167201
Monument	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1167202
Monument	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1167203
Monument	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1167204
Octagonal look-out tower	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002386
Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1250424
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200408
Sewerby House	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997073
Building	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3491140
Dwellings	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3501403
Beacons	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200254
Beacons	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195422
Fort	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002094
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002045
Beacons	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200248
Beacons	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1200293
Lighthouses	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1277506
Dovecote	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1320646
Church	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1320945
Windmill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002067
Watermills	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002055

	Windmill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002056
	Windmill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1112688
	Windmill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002074
	Windmill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002093
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1941253
First World War		
	Windmill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1234203
	Jetty	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203375
	Observational post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1211509
	Army Camp	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204346
	Blockhouse	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203377
	Blockhouse	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203380
	Blockhouse	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1211565
	Blockhouse	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1211563
	Electric light emplacement	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203358
	Acoustic mirror	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1211694
Second World War	Battery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195582
	Road block	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1234208
	Nissen hut	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1234188
	Road block	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1234209
	Battery Observation Post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203052
	Battery Observation Post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1211507

Battery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203338
Coastal defence	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203364
Coastal defence	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1201954
Pillbox	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203281
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58216
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58237
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58189
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58188
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58190
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58187
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58218
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58183
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58184
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58638
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58186
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=55089
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=55090
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=55088
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=55095
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Engine room	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203354
Military building of unknown function	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203601
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Garrison	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203356
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Searchlight battery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204100
Section post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1195597

Fortification	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203274
Minefield	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203240
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Triple line of anti-tank blocks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1211870
Fortification	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204573
Water Tower	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203419
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204061
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Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203444
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203575
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203433
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203256
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204325
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204511
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204527
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204557
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204447
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204452
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204455
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204393
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204406
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Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204489
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204478
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204324
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1204274
Weapons Pit/Trench	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203246

Cold War		
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58185
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58267
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=55110
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=58256
	No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=55104
	Royal Observer Corps monitoring post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1202006
	Royal Observer Corps monitoring post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1211650
	Royal Observer Corps monitoring post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203535
	Royal Observer Corps monitoring post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1260865
	Royal Observer Corps monitoring post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203126
	Royal Observer Corps monitoring post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1203408
	Royal Observer Corps monitoring post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1212737
	Royal Observer Corps monitoring post	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1211699

Uncertain		
	Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3515242
	Earthwork	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1927627
	Cropmark	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002189
	Cropmark	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1308481
	Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997075
	Linear earthwork	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002186
	Two linear features	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1932843
	Disarticulated human bone	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1932438
	Large pit cut by a ditch	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3496328

No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1927879
Glass weight	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002050
Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1892126
Groundwork	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3500976
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3512442
Cropmark	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1311898
Monastic land holding	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002051
Windmill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1117431
Windmill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1112705
Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3515242
Earthwork	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1927627
Cropmark	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002189
Cropmark	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1308481
Earthworks	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=997075
Linear earthwork	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002186
Two linear features	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1932843
Disarticulated human bone	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1932438
Large pit cut by a ditch	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3496328
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1927879
Glass weight	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002050
Pottery	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1892126
Groundwork	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3500976
No description	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=3512442
Cropmark	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1311898

Monastic land holding	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1002051
Windmill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1117431
Windmill	http://archaeologydataservice.ac.uk/archsearch/record.jsf?titleId=1112705

Appendix B

Supplemental Figures for Chapter 3

Environmental and Management Maps



Figure B - 1. Surface Geology of Holderness

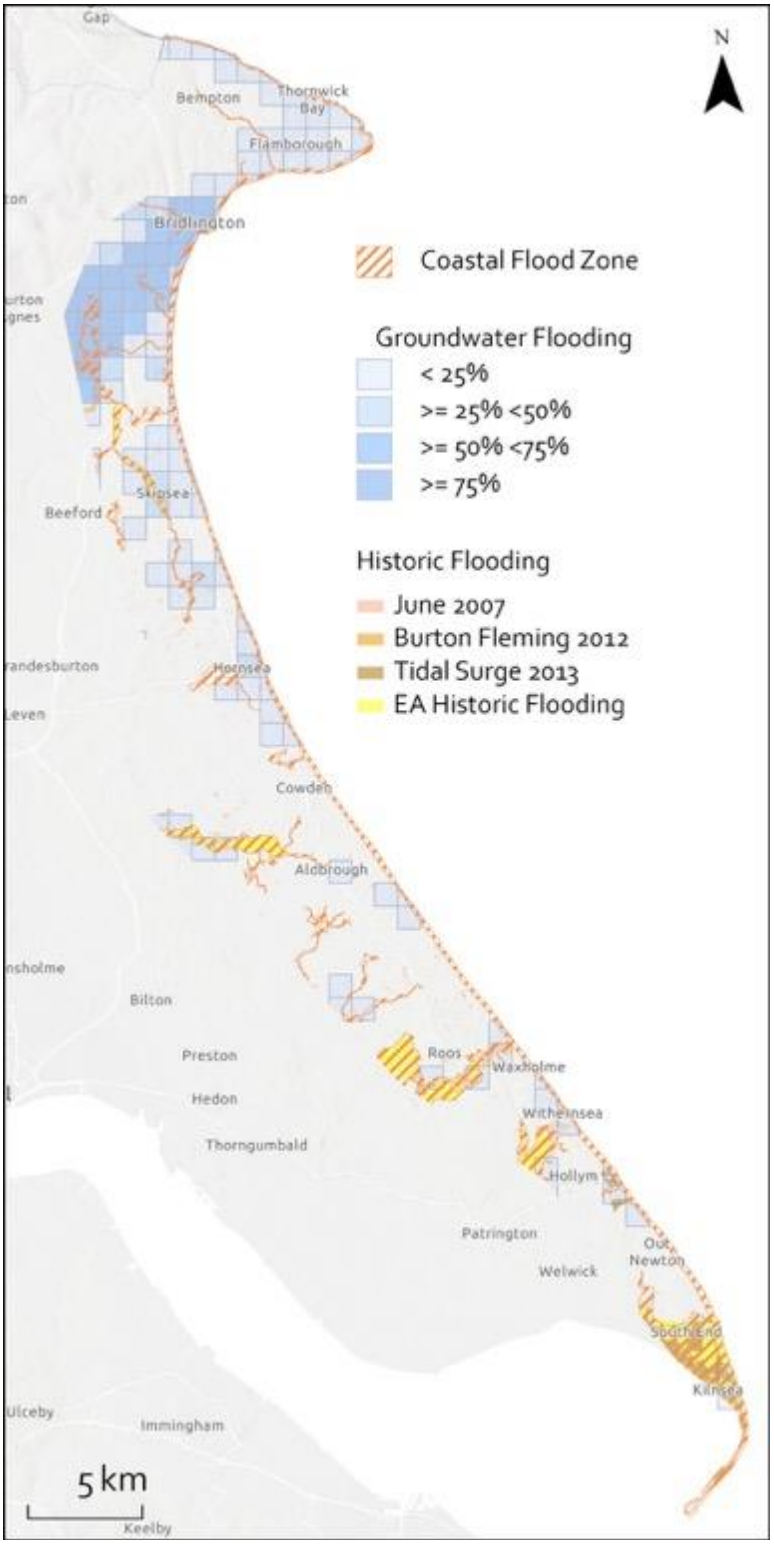


Figure B - 2. Flood metrics and historic flooding



Figure B - 3. Land lost since Roman period



Figure B - 4. Shoreline Management Plan (SMP) per coastal segment

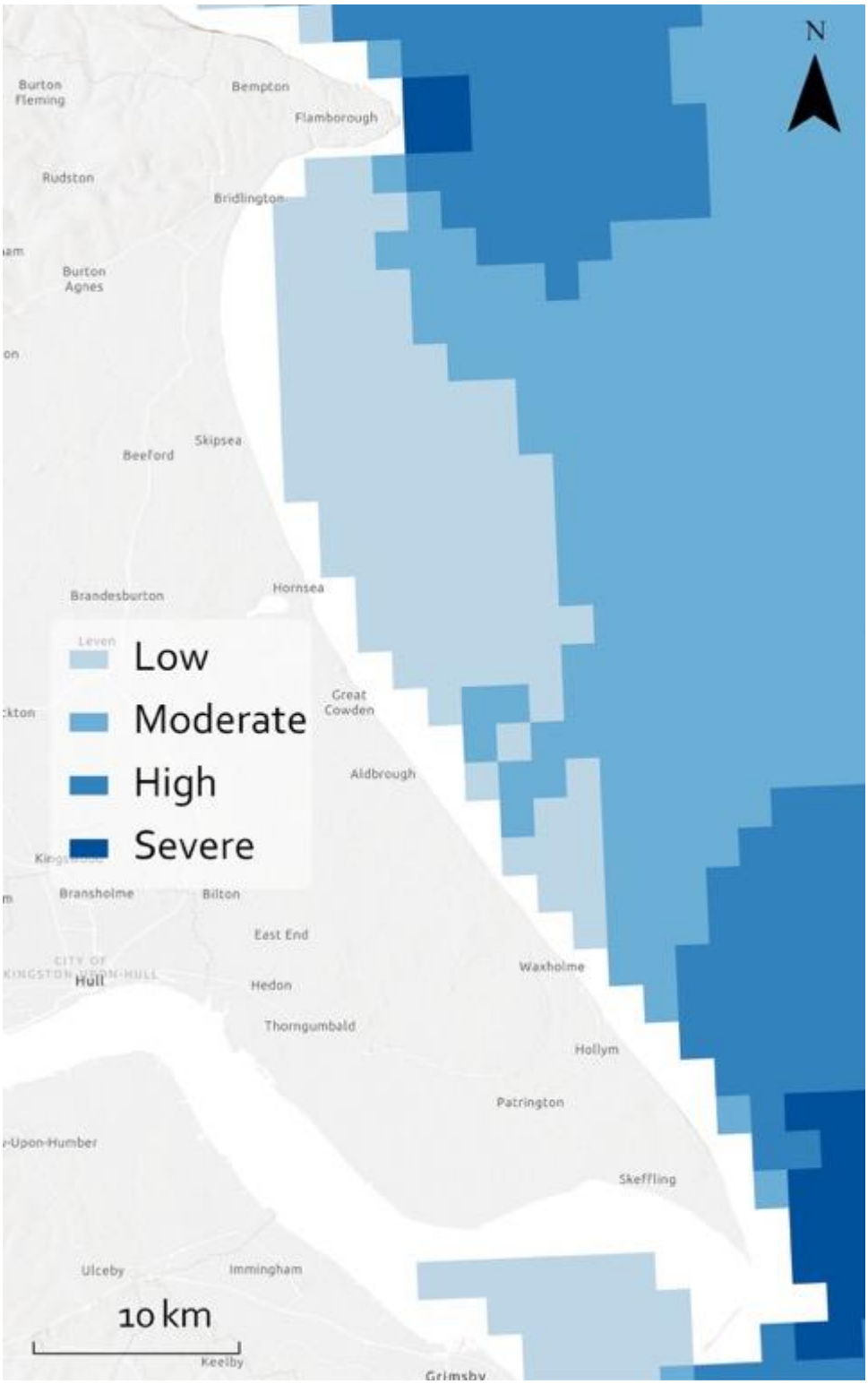


Figure B - 5. Tidal energy potential, Holderness coastline

Archaeological Distribution Maps



Figure B - 6. Prehistoric records within study area



Figure B - 7. Mesolithic records from the study area



Figure B - 8. Palaeolithic records from the study area



Figure B - 9. Neolithic records from the study area



Figure B - 10. Bronze Age records from the study area



Figure B - 11. Iron Age records from the study area



Figure B - 12. Roman records from the study area



Figure B - 13. Medieval records from the study area



Figure B - 14. Post Medieval records from the study area

]



Figure B - 15. First World War records from the study area



Figure B - 16. Second World War records from the study area



Figure B - 17. Cold War records from the study area



Figure B - 18. Uncertain records from the study area

Appendix C

Catalogue of Archaeological point data acquired from The Hawai‘i State Historic Preservation Division

Pre-contact records referenced in the O’ahu-Landslide case study and corresponding tiers of priority

Type	Description	Triage Tier
Burial	House Sites	Tier 3
Burial	Cultural deposit with burials	Tier 3
Burial	Overhang	Tier 3
Burial	‘Ōhikilolo Sand Dune Site	Tier 3
Burial	Kaluanui Modified Natural Stone Cavity Complex 2901	Tier 3
Burial	Kaluanui Burial Cavity Complex 2909	Tier 3
Burial	Subsurface Cultural Layer	Tier 3
Burial	Burials and Hearth	Tier 3
Burial	Subsurface Cultural Layer	Tier 3
Burial	Subsurface Cultural Layers	Tier 3
Burial	Enclosures & Platform	Tier 2
Burial	Mound - Possible Burial	Tier 2
Burial	Terrace & Platform	Tier 1
Fishpond	Waikalua Loko Fishpond 349	Tier 2

Fishpond	Loko Opu	Tier 3
Fishpond	Fishing Shrine	Tier 3
Fishpond	Paiko Pond 1166	Tier 3
Fishpond	Maka Lei Tree at Kawainui	Tier 3
Fishpond	Kalou Fishpond	Tier 3
Fishpond	Aliʻi Swimming Pool	Tier 3
Fishpond	Moli'i Fishpond	Tier 2
Fishpond	PALIPILO KO`A 245	Tier 2
Fishpond	Kahaluu Fishpond (Kahouna)	Tier 2
Habitation	Malaihakoa Heiau, Waianae-waena	Tier 3
Habitation	Kamiloiki Valley Terraces	Tier 3
Habitation	House Site No.1	Tier 3
Habitation	Habitation Complex	Tier 3
Habitation	Habitation Complex	Tier 3
Habitation	House Site	Tier 3
Habitation	Cultural deposit	Tier 3
Habitation	Cultural deposit	Tier 3
Habitation	Cultural deposit	Tier 3
Habitation	Cultural deposit	Tier 3
Habitation	Habitation Deposit	Tier 3
Habitation	Subsurface Cultural Deposit	Tier 3
Habitation	Bellows Beach Sand Dune Occupation Site	Tier 3
Habitation	Subsurface Cultural Layer	Tier 3
Habitation	Keawaula Kahua Hale	Tier 3

Habitation	Remnant Rock Terraces & Enclosure (Degraded)	Tier 3
Habitation	Keawaula Coral Wall	Tier 3
Habitation	Bellows Habitation Site	Tier 3
Habitation	Pahua Heiau	Tier 3
Habitation	Kukanono Habitation Site	Tier 3
Habitation	Kawainui Cluster	Tier 3
Habitation	Bedrock Cavities	Tier 3
Habitation	Platform/Mound	Tier 2
Habitation	Keahuo O Hapu`U Complex 244	Tier 2
Habitation	Platform and Enclosures	Tier 2
Habitation	Mokulēʻia Village Site	Tier 2
Habitation	Kapa'a Complex	Tier 2
Habitation	Stacked Cobbles	Tier 2
Habitation	Waimea Religious Platform	Tier 2
Habitation	Low Rectangular Paving	Tier 2
Habitation	Habitation Complex	Tier 2
Habitation	Enclosures & Platform	Tier 2
Habitation	Platform & Enclosures	Tier 2
Habitation	Enclosures	Tier 1
Habitation	Punanaʻula Heiau	Tier 1
Habitation	Platform & Enclosures	Tier 1
Habitation	Enclosures	Tier 1
Habitation	Kumaipo Habitation Site	Tier 1
Heiau	Kamaile Heiau	Tier 3

Heiau	Kepuhi Sacrificial Rock (aka Pukahea)	Tier 3
Heiau	Mokaʻena Heiau (aka Mokuʻena Heiau)	Tier 3
Heiau	Small Heiau	Tier 3
Heiau	Ilihune Heiau	Tier 3
Heiau	Hauone Koʻa	Tier 3
Heiau	Haununaniho Pu'uhonua (Heiau)	Tier 3
Heiau	Platforms	Tier 3
Heiau	Hawea Heiau	Tier 3
Heiau	Small Heiau	Tier 3
Heiau	Kukuipilau Heiau (Heinau Heiau)	Tier 3
Heiau	Ulu Po Heiau	Tier 3
Heiau	Stone Platform	Tier 3
Heiau	Adze Quarry (aka Adz Quarry)	Tier 3
Heiau	Waimanalo Heiau	Tier 3
Heiau	Waimanalo Heiau	Tier 3
Heiau	Holomakani Heiau	Tier 3
Heiau	Holomakani Heiau?	Tier 3
Heiau	Holomakani Heiau	Tier 3
Heiau	Kāne Heiau Complex	Tier 2
Heiau	Small Heiau	Tier 2
Heiau	Kuhale Ko` a 248	Tier 2
Heiau	Kawa'ewa'e Heiau	Tier 2
Heiau	Kuka`o`o Heiau	Tier 2
Heiau	Nioiula Heiau	Tier 2

Heiau	Kuli`Ou`Ou Terrace 50	Tier 2
Heiau	Enclosure Heiau 133	Tier 2
Heiau	KALAI-A HOUSE SITES 163 (Aka Kalaiʻa Habitation Site)	Tier 2
Heiau	Pueo Heiau	Tier 2
Heiau	KAUNIHOKAHI HEIAU 286	Tier 2
Heiau	Possible Heiau	Tier 1
Heiau	Pohakunui Heiau	Tier 1
Petroglyph	Keaʻau Petroglyphs	Tier 3
Petroglyph	Waimanalo Gulch Petroglyphs 4110	Tier 3
Petroglyph	Petroglyph Boulder	Tier 3
Petroglyph	Sunset Beach Petroglyphs, Pupukea	Tier 2
Petroglyph	Hahaione Valley Petroglyphs 4096	Tier 2
Petroglyph	Hahaione Valley Petroglyphs 4096	Tier 2
Petroglyph	Hahaione Valley Habitation & Agricultural Site 3996	Tier 2
Petroglyph	Pohaku ka Luahine	Tier 1
Petroglyph	Pohaku ka Luahine	Tier 1
Petroglyph	Kahapaʻakai Complex	Tier 1

Appendix D

Supplemental Figures for Chapter 4

Environmental Maps

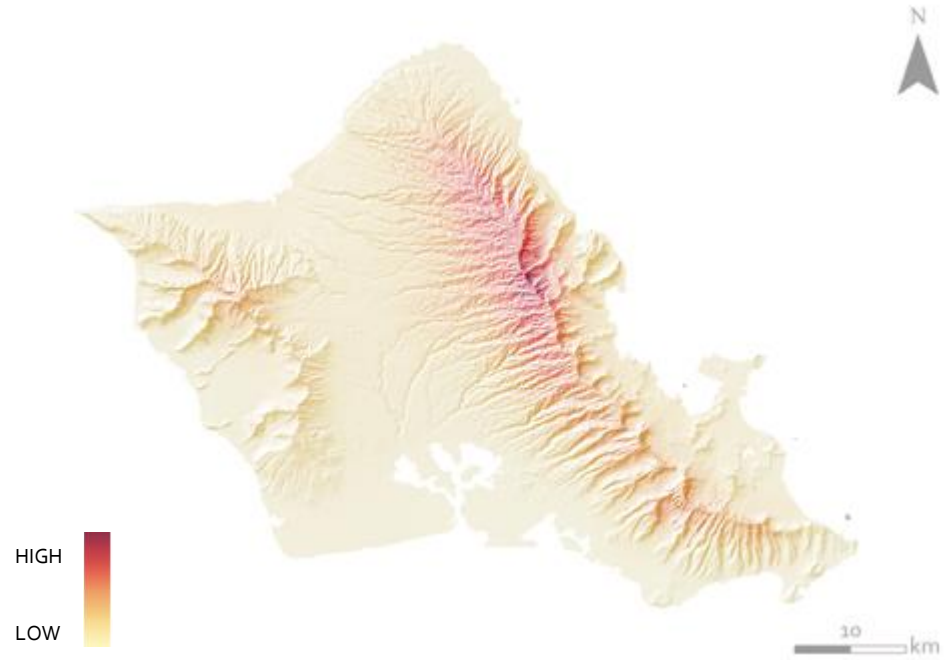


Figure D- 1. O'ahu precipitation distribution map

Historic Maps

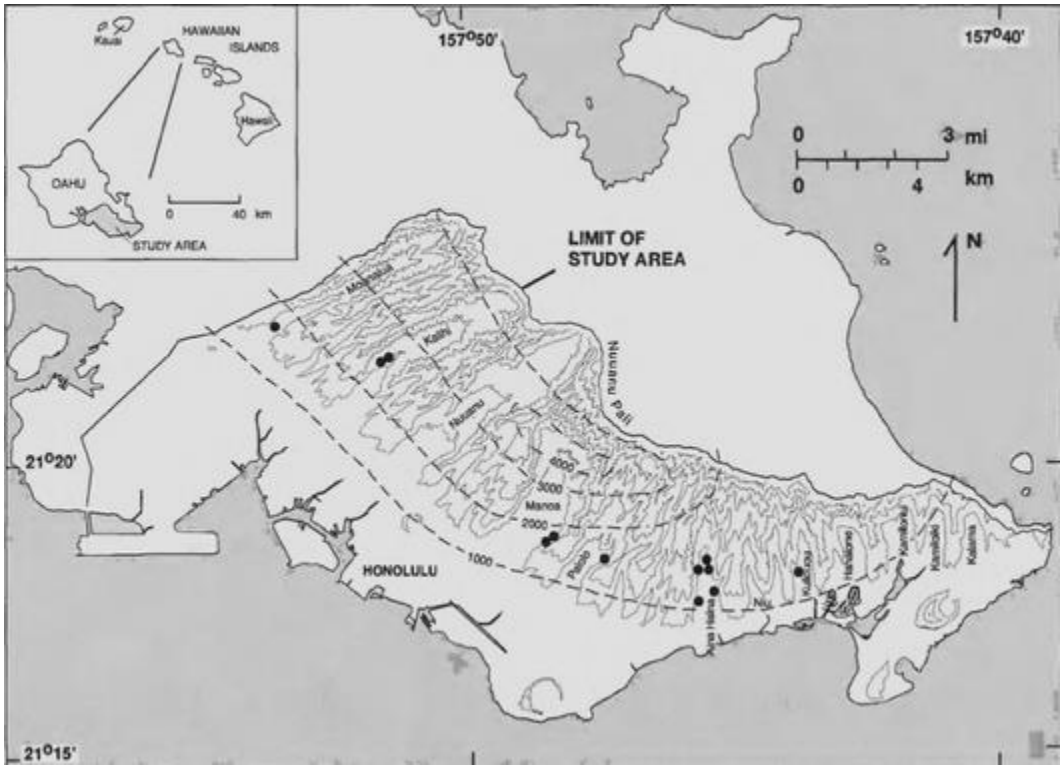


Figure D- 2. Slow-moving landslide locations across southwest O'ahu. From "Relation of slow-moving landslides a to earth materials and other factors in valleys of the Honolulu District of Oahu, Hawaii," by Ellen et al., 1995, pg. 3 .

Methodological Process Maps

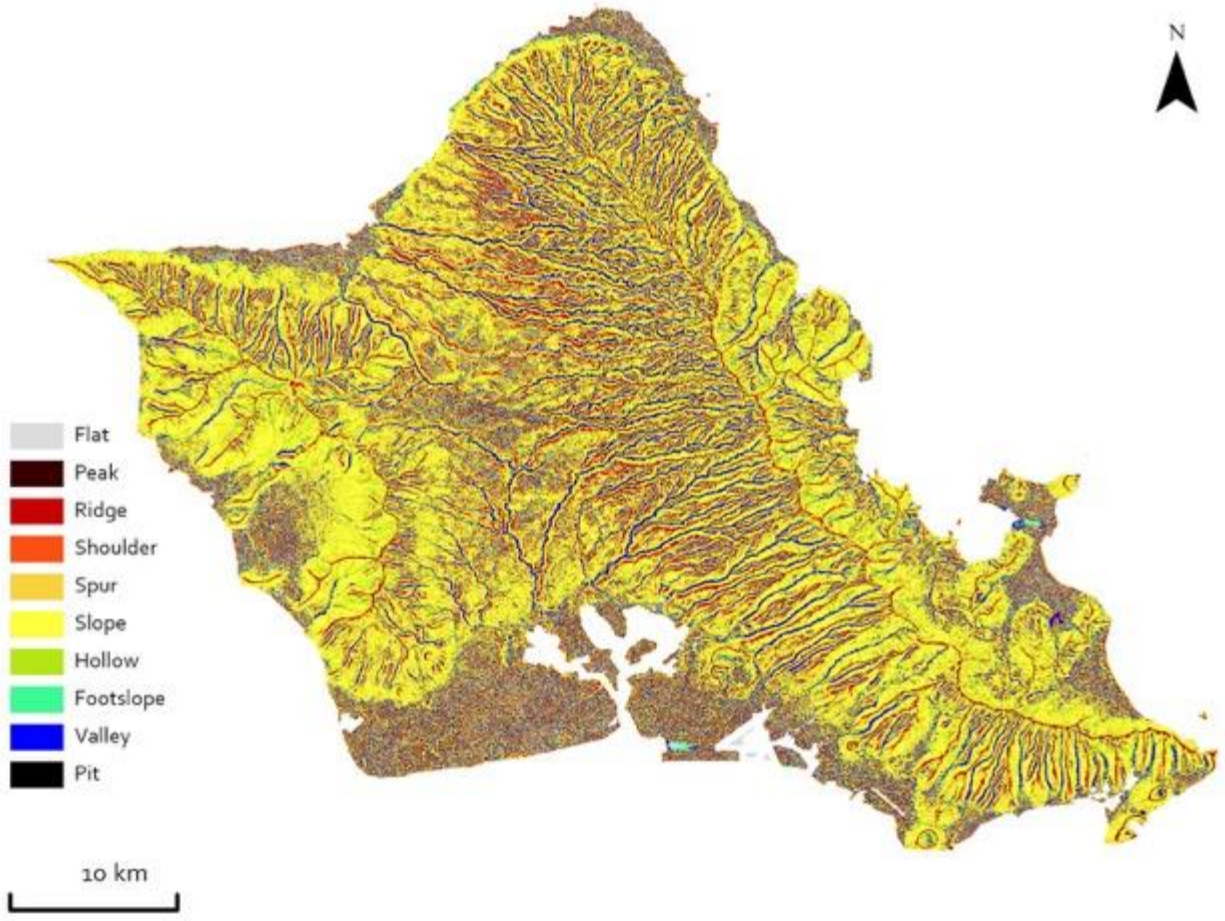


Figure D- 3. Geomorphon extraction from the digital elevation model (DEM)

Validation Maps

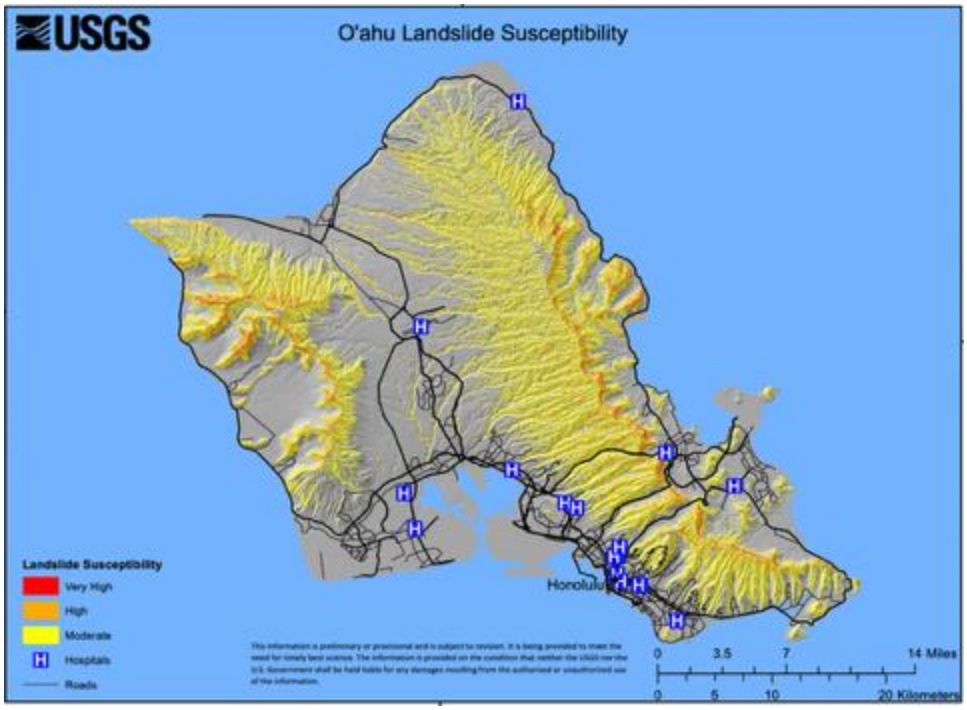


Figure D- 4. Landslide susceptibility map created by USGS

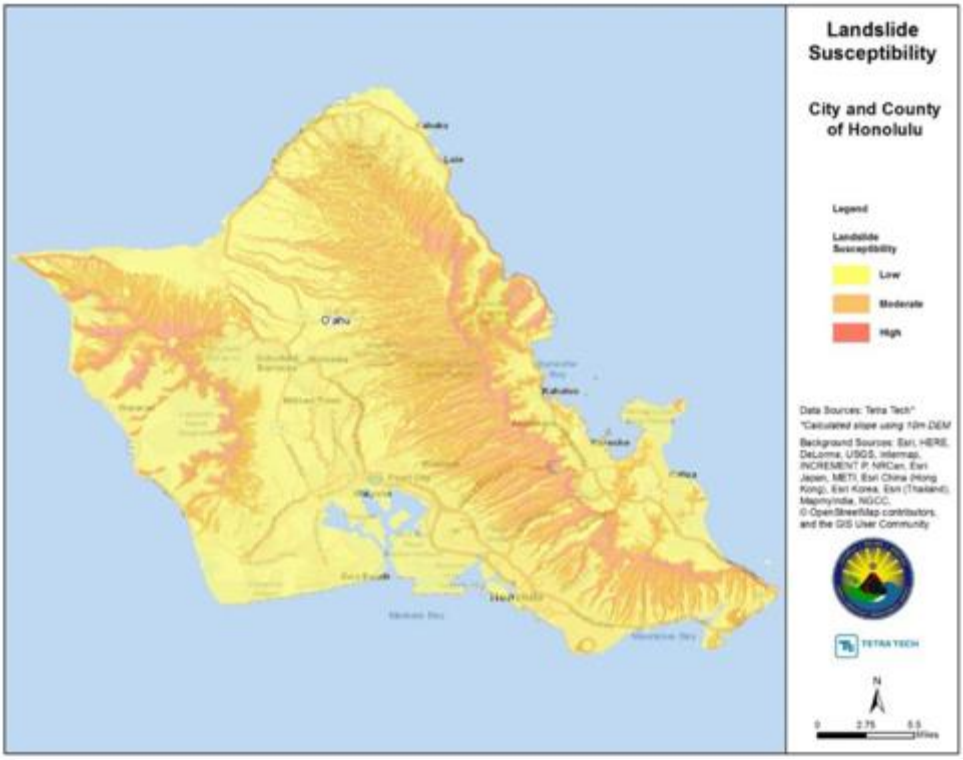


Figure D-5. Landslide susceptibility map created by the DOD

Appendix E

Catalogue of Archaeological point data acquired for desertification case study from the EAMENA database

High-risk records

Country	Description	EAMENA ID
Afghanistan	Building/Enclosure	EAMENA-0230818
Afghanistan	Building/Enclosure	EAMENA-0230991
Afghanistan	Building/Enclosure	EAMENA-0230998
Afghanistan	Building/Enclosure	EAMENA-0231096
Afghanistan	Building/Enclosure	EAMENA-0231451
Afghanistan	Unknown	EAMENA-0231439
Afghanistan	Field System	EAMENA-0231440
Afghanistan	Building/Enclosure	EAMENA-0231466
Afghanistan	Unknown	EAMENA-0218157
Afghanistan	Building/Enclosure	EAMENA-0230838
Afghanistan	Tell	EAMENA-0230864
Afghanistan	Tell	EAMENA-0230867
Afghanistan	Tell	EAMENA-0230873

Country	Description	EAMENA ID
Afghanistan	Tell	EAMENA-0230872
Afghanistan	Building/Enclosure	EAMENA-0230911
Afghanistan	Tell	EAMENA-0230929
Afghanistan	Building/Enclosure	EAMENA-0230946
Afghanistan	Building/Enclosure	EAMENA-0230975
Afghanistan	Building/Enclosure	EAMENA-0230979
Afghanistan	Building/Enclosure	EAMENA-0230982
Afghanistan	Building/Enclosure	EAMENA-0230986
Afghanistan	Building/Enclosure	EAMENA-0230990
Afghanistan	Building/Enclosure	EAMENA-0231006
Afghanistan	Building/Enclosure	EAMENA-0231007
Afghanistan	Unknown	EAMENA-0231032
Afghanistan	Building/Enclosure	EAMENA-0231038
Afghanistan	Building/Enclosure	EAMENA-0231041
Afghanistan	Building/Enclosure	EAMENA-0231097
Afghanistan	Building/Enclosure	EAMENA-0231099
Afghanistan	Building/Enclosure	EAMENA-0231100
Afghanistan	Building/Enclosure	EAMENA-0231101
Afghanistan	Building/Enclosure	EAMENA-0231102
Afghanistan	Enclosure	EAMENA-0231104

Country	Description	EAMENA ID
Afghanistan	Unknown	EAMENA-0218150
Afghanistan	Unknown	EAMENA-0218153
Afghanistan	Unknown	EAMENA-0218158
Afghanistan	Building/Enclosure	EAMENA-0231417
Afghanistan	Tell	EAMENA-0231432
Afghanistan	Building/Enclosure	EAMENA-0231435
Afghanistan	Building/Enclosure	EAMENA-0231437
Afghanistan	Building/Enclosure	EAMENA-0231453
Afghanistan	Building/Enclosure	EAMENA-0231470
Iran	Building/Enclosure	EAMENA-0193268
Iran	Building/Enclosure	EAMENA-0193272
Iran	Building/Enclosure	EAMENA-0193273
Iran	Building/Enclosure	EAMENA-0193274
Iran	Building/Enclosure	EAMENA-0193275
Iran	Building/Enclosure	EAMENA-0193277
Iran	Building/Enclosure	EAMENA-0193279
Iran	Building/Enclosure	EAMENA-0193283
Iran	Building/Enclosure	EAMENA-0193284
Iran	Building/Enclosure	EAMENA-0193289
Iran	Building/Enclosure	EAMENA-0193290

Country	Description	EAMENA ID
Iran	Cistern	EAMENA-0193291
Iran	Building/Enclosure	EAMENA-0193294
Iran	Unknown	EAMENA-0193295
Iran	Building	EAMENA-0192494
Iran	Building	EAMENA-0192496
Iran	Building	EAMENA-0192580
Iran	Building	EAMENA-0192582
Iran	Building	EAMENA-0192723
Iran	Farm Building	EAMENA-0192292
Iran	Settlement/Habitation Site	EAMENA-0192345
Iran	Settlement/Habitation Site	EAMENA-0192346
Iran	Tomb/Grave/Burial	EAMENA-0192473
Iran	Tomb/Grave/Burial	EAMENA-0192559
Iran	Cemetery	EAMENA-0192472
Iran	Cemetery	EAMENA-0192558
Iran	Cistern	EAMENA-0192485
Iran	Cistern	EAMENA-0192571
Iran	Unknown	EAMENA-0192474
Iran	Unknown	EAMENA-0192560
Iran	Unknown	EAMENA-0207132

Country	Description	EAMENA ID
Iran	Unknown	EAMENA-0207192
Iran	Unknown	EAMENA-0207133
Iran	Caravanserai/Khan, Fort/Fortress/Castle	EAMENA-0207131
Iran	Settlement/Habitation Site	EAMENA-0192407
Iran	Mill (wind)	EAMENA-0193632
Iran	Building	EAMENA-0193633